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Development of An Energy Modeling Approach to Analyse Historical Building Permorfance

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Relatore:
Chiar.mo Prof. **Francesco Ubertini**

Candidato:
Marco Giuliani

Correlatori:
Ill.mo **Roberto Lollini**
Ill.mo Prof. **Gregor P. Henze**

Coordinatore del Dottorato:
Chiar.mo Prof. **Alberto Lamberti**

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Chapter 1

Energy Efficiency in Historical Buildings

This chapter introduces the review of literature related to different projects of research that focus their attention on the analysis of the possibility to increase the energy efficiency of historical buildings. The interaction between Conservation aspects and Energy Efficiency aspects that characterized this class of building is presented considering different experience around Europe. The limitations on the intervention, the needs, and the best practise are analyzed. The chapter concludes with the presentation of the research questions and the summary of this work.

Contents

1.1 Problem Statement and Research Hypothesis

An energy qualification is defined as a refurbishment which reduces the energy consumption of a building. That means taking some improvement on the building like the installation of insulation as well as the renewal of the heating and cooling system or the improvement of existing windows. One may ask why I am dealing with this topic, especially since listed buildings are exempt from the obligation of energy efficiency improvements in most countries. The answer is: It will become more and more necessary for historic buildings to be energy-efficient. On one hand the EU demand for the reduction of carbon dioxide emission will rise because environment has to be protected. Therefore the plan of EU commission for 2050 shows that EU will take the most advantage from the decarbonization of the economy and in general of the society. For the building sector all countries have revised their demand of energy saving in existing building stock and new construction at least in the past 20 years. This means even the historic buildings and monuments are in competition with the rest of the building stock.

On the other hand, the prices for energy are still rising and owners and tenants will not pay unlimited energy costs. Therefore, even historic buildings might have to reduce their energy consumption to remain attractive and in use. Only a building which is being used will be maintained and thereby preserved in the future. This is especially true for historic residential building. Historic buildings have to be economically viable to be competitive with new buildings. Presently the listed buildings may be exempt from the legal energy qualification demands but in the future they might not be. The political developments in some countries hint at a movement in this direction. Furthermore, that the energy efficiency standards for new buildings will be assigned to historic buildings as well must be reckoned with.

Those problems are diffuse all around in Europe, and different collaborative projects between institution across countries are taken place in the last years. One of this is $Co^2olBricks$[1]. It stress the change of prospected around the relationship between protection of historic building and mitigation of climate change. For the Head of Department for Heritage Preservation of Hamburg, Andreas Keller, "the results of $Co^2olBricks$ make clear that there is no longer really any controversial debate about 'whether' energy efficiency rehabilitation can go hand-in-hand with historically appropriate building restoration. It is much more a question of 'how', and here still many detailed questions to be answered and much practical experience to be gained"[2].

The project ATTESS[3]is a local experience of Conservation Institution, Metadistretto Veneto dei Beni Culturali, with the collaboration of association Metadistretto della Bioedilizia that take place in Veneto in 2010. The result is a guideline for the intervention on historical building take in consideration also the energy efficiency criteria. ATTESS gives importance to the meaning of the architecture style in relation with the context and with the collocation in space and time, value lost in the conformation of nowadays expression of the architecture. The guidelines expose several consideration for all phases of the refurbishment. They consider energy-efficiency measures very important for the reduction of maintenance cost, as consequence they have conservative value itself. More over a detail study with insite measurements are needed because the experience on modern building are not enough to make good evaluation of the performance in this context. System integration should take the principle of 'minimum intervention'[4] that evaluate the equilibrium between quantity, quality and efficacy of action, in synergic relationship with the material and symbology value of the artefact. Also compatibility and reversibility of system installation are important parameters in the design process.

From the building conservation point of view, two things are absolutely imperative. First of all, historic building is unique and has its own individual historic value. That means that, in contrast to new building projects, there are no standard methods that can be applied, instead each case needs to be analysed in detail so that tailor-made solution can be developed and implemented. Secondly processes and technology, both are new and there are not any long-term experience with energy refurbishment strategies. Moreover the energy efficiency rehabilitation of historic buildings requires the involvement of additional experts such as energy consultants what makes the procedures more complex. As consequence cultural value has to be defined more precisely and analysed in detail before the implementation of suitable measure of refurbishment for energy saving, to avoid that some feature will be destroy during the intervention, and after assess the state and check if the measures implemented keep them preserved. A description of the cultural value as to be made in order to prepare for the implementation of measure. As those experience show what an be permitted is a matter of interpretation and it is crucial to know how different measure affect the heritage value of a building, in order to enable a discussion between technicians, that develop and implement the measures, and conservatories that develop policies. As an example [1] show that external and internal insulation are allowed in same cases in Germany, Denmark and Latvia, it is forbidden in Estonia and in Poland where only internal insulation is allowed. In Addition, where insulation is allow, it depends from the interpretation of the monuments protection officer in the different countries. For example in Hamburg the exterior insulation was only permitted because it was done on a parts of building which are not visible from public space, on the façade to the backyard. In baltic area a common method of refurbishment for the energy efficiency is the implementation of measures on the inside of building. This method seems to increase the energy efficiency of a historic building. The big advantage derived from this measure is that the original façade and thereby the appearance of the building will be preserved.

From the energy efficiency point of view those experience present common characteristic. The energy-savings potentials differ greatly. Energy consumption cannot directly be connected to the measures implemented. The energy consumption in buildings in which no measures were implemented is not as bad as generally assumed. The measures implemented is based on theoretical calculation of heat transfer, energy consumption and energy saving potentials using theoretical value. These calculation are base on empirical study but are finally generalized and thereby again theoretically value. Moreover they were made for the construction of new buildings, but historical ones have completely different feature. The analysis of value do not consider the individual feature, their components and their function. These feature have to be analyzed before the implementation of the refurbishment. No real value were collected for the foundation for implementation of measures in historic building. Moreover the calculation are done for single components and do not provide a comprehensive concept for refurbishment for energy efficiency. Without an extensive analysis measures can not be implemented in the correct way and they will not provide an accurate energy-saving effect. Measures have to be evaluated after the refurbishment and has to be clear what the exact effect of measures is. Important questions to answer are: how much energy can be saved in reality? Does the measure save as much as was envisaged? Most the refurbishment today are not evaluated in reality afterwards. Usually the theoretically calculations are trustworthy, but they cannot describe the reality. This has to be changed. The project ATTESS[3] suggest to study the complex dynamics of historical building with appropriated tool nowadays available and the simple applying of standard like UNI EN 11300 is not enough.

Looking at the state of the art for existing buildings, the refurbishment to very low energy demand is possible and economically feasible/convenient[5], but it is not yet as common. The need is, however, recognised. Residential electricity consumption is one of the fastest-growing areas of energy use, especially in developing countries. In the commercial sector, electricity consumption is growing faster than the overall economy, especially in countries with air conditioning requirements. There are many potential improvements to be made in this sector[6].

Table 1.1 of realised energy refurbishments (non-exhaustive!), provides an idea on what has already been achieved and where further development is needed in the context of historic building. It shows, that also for historic buildings, energy refurbishment potentials between Factor 2 and Factor 10 have shown to be feasible, but a general 'target' is nearly impossible to define, since the relevant conditions for each individual building vary too much in most cases. Serious facts, could limit such a potential, for example: Can (part of the) façade be altered? Is internal insulation possible (are there frescoes, etc.)? To which extent can the windows be improved? Is the installation of ventilation with heat recovery possible? Is the integration of renewable energy sources (RES) and RE technologies (RET) possible?

A review of different projects on energy refurbishment show that each country and each team involved in a case study choose a particular strategy and a particular solution for the refurbishment. The result of this approach is not the display of high-class refurbishment project stressing the performance achieved. It shows the wide variety of different approaches towards energy-efficiency improvements used across countries and the choice depend on several things: the criteria of selection related to the task of institution, the composition of the team of work, the role of each participating partner and data, technologies, skill available.

These experience enrich the knowledge around the theme of a energy efficiency on historic building. Several consideration are common across the case studies. One is the definition of relationship between conservation and refurbishment for energy efficiency, other the understanding the unique of each building and that many strategies exist and the work could be focus on find the most correct one in each case. There is the consciousness on need of doing more studies on field to enrich the knowledge and in general there is a need of research in several field, on the develop procedure, on the tools of evaluation, on diagnostic pre and post intervention, on developing a specific solution. Best practises are considered that ones take in account a multidisciplinary approach considering conservation authorities and technicians contribution on measures selection[7].

1.2 Significance of Research

Historic buildings are the trademark of numerous European cities, towns and villages: historic centres and quarters give uniqueness to our cities. They are thus a living symbol of Europe's rich cultural heritage and diversity. As these areas reflect the society's identity they are precious and need to be protected. Yet, this is also an area where the high level of energy inefficiency is contributing to a huge percentage of greenhouse gas emissions, mostly due to inefficient insulation, obsolete technological plants and inevitable replacing of original use. With climate change posing a real and urgent threat to humanity and its surroundings, also to historic buildings and surrounding infrastructure, it is necessary to act in this area and guide an improved approach to all refurbishment actions in historic buildings.
In numbers, more than 150 towns and urban fragments in Europe are declared to be World Cultural Heritage sites. Going from the level of monuments of exceptional interest to a broader definition of historical urban areas, further, highlights the significance of the built cultural heritage even more: this includes over 55 million dwellings across Europe dating before 2nd World War, with more than 120 million Europeans living in these buildings[8].
The 'old Europe' is an important drawing card for tourists all over the world, and maintaining

Refurbishment	**Result**	**Measure Description**
Baroque building in Görlitz (Germany)	Nearly Passive House	Detailed monitoring system installed. Information directly available to the project(1).(TUD)
Orangerie of Ansitz Kofler in Bolzano (Italy)	factor 10. KlimaHaus A (<30 kWh/m^2a)	listed building from 17th century, internal and external insulation, windows, ventilation. Detailed monitoring of energy flows and hygrothermal behaviour. Information directly available to the project(2). (EURAC)
Gründerzeit buildings 'Kleine Freiheit' in Hamburg (Germany)	factor 4. factor 5 for PE.	Solution for beam end restoration tested. Special issue: Air tightness. information available to project through TUD(3).
'Jugendstilhaus' in Nürnberg (Germany)	factor 2.5	listed building from 1912, internal insulation and vapour barrier (U=0.28 W/m^2K), retrofit of old box type windows (U=1.1 W/m^2K), ventilation with heat recovery, ecological materials, rain water for toilets and garden. Monitoring installed(4).
Passivhaus in Günzburg (Germany)	15 kWh/m^2	listed building from the 18th century; external and partitions insulation, windows restoration and integration with 3-pane glass, basement insulation, heat pump using exhaust air for DHW. Issue: air-tightness of the intrinsically flexible construction(5).
Schlacht und Viehhof in Nürnberg (Germany)	heating demand -75%, PE -80%	new utilization as kinder garden. Internal and external insulation (insulating plaster), major effort put in reduction of thermal bridges, decisions on thicknesses and materials based on hygrothermal simulations(6).
'Jugendstil' villa (Germany)	CO2 emission -40 kg/m^2	from 1905, refurbished conserving the specific Jugenstil elements, internal insulation with adaptive vapour barrier and special solution for decorative glazing with lead glass(7).
Historic Building in Modena (Italy)	factor 5 for PE	insulation measures, improved windows and solar thermal collectors(8).
Apartment building from 1898 in Zürich (Switzerland)	factor 4 for PE	insulation, new windows, heat recovery system, pellets boiler and solar collectors(9).
Rowhouse, Henz-Noirfalise in Eupen, (Belgium)	PHPP standard (-95%)	internal insulation, triple glazed windows, heat recovery and solar thermal collectors(10).
Renewable Energy House (Belgium)	no fossil fuel at all	information available to project through(11).

Reference

(1) BINE Informationsdienst,http://www.energie-projekte.de/popup.php?action=print&id=577
(2) Troi, A., Benedikter, M. Kultureller Wiedergewinn und energetische Sanierung, Faltor 10 im denkmalgeschÃ¼tzten Altbau, 2th Internationales Anwenderforum Enegieeffizienz im Bestand, Kloster Banz, February 2008
(3) BINE Informationsdienst,http://www.energie-projekte.de/popup.php?action=print&id=607
(4) BINE Informationsdienst,http://www.energie-projekte.de/popup.php?action=print&id=216
(5) BINE Informationsdienst,http://www.energie-projekte.de/popup.php?action=print&id=148
(6) BINE Informationsdienst,http://www.energie-projekte.de/popup.php?action=print&id=343
(7) BINE Informationsdienst,http://www.energie-projekte.de/popup.php?action=print&id=432
(8)IEA SHC Task37,http://www.iea-shc.org/publications/downloads/task37-710-Modena.pdf
(9)IEA SHC Task37,http://www.iea-shc.org/publications/downloads/task37-Zurich.pdf
(10)IEA SHC Task37,http://www.iea-shc.org/publications/downloads/task37-210-Eupen.pdf
(11) European Renewable Energy Council, The Renewable Energy House, 2008

Table 1.1: Example of Refurbishment of historic buildings

this has a significant economic impact. Cultural heritage is a major contributor to the income from tourism, which stands for 5.5% of the EU GDP, generates more than 30% of its revenues from trade in external services, and employs 6% of the EU workforce. Tourism has an expected growth rate of 57% in the period 1995-2010. On May 2008, the Assembly of European Regions (AER) Committee 3 with regional politicians and officers from across wider Europe, outlined the position for cultural tourism and its impact on the employment sector[9]. Alan Clarke, an expert from the University of Pannonia, stated that 'Developing cultural tourism not only creates a sense of knowledge and pride regarding local history and identity, but also helps to conserve cultural heritage, foster economic growth and create new employment opportunities'.

Seen from this perspective, as well as in context of expected rising prices of fossil fuels (e.g. gas and oil), energy security and climate protection, there is clearly a need to reduce energy use in these buildings as well, which make up a huge number of building stock in Central, Eastern and Western Europe: more than one forth of building stock dates from before 1945, its energy demand related CO_2 emissions can be estimated to 300 Mt, a definitely not negligible amount. Furthermore the comfort of users and 'comfort' of heritage collections are also important factors to consider.

A reduction of Factor 2 to Factor 10 in energy demand is achievable, also in historic buildings, respecting their heritage value is feasible, if an multidisciplinary approach guarantees the implementation of high quality energy efficiency solutions, specifically targeted and adapted to the specific case. This is the basic concept behind 3ENCULT[10]. This project developed necessary solutions, both adapting existing solutions to the specific issues of historic buildings and developing new solutions and products. A wide partnership involving all the stake-holders allow a holistic approach considering all the aspects of the problems towards the definition of shared solutions. In this case project consortium includes all relevant players, either as direct partners or in local teams/advisory board.

Our unique heritage and resource can be conserved if maintained as living space and as SUIT underlines 'urban areas are living systems, where private action and investment are crucial'[11]. Not (or at least not only) a top down approach leads to good results, but the involvement and mobilisation of end-users and stake-holders; therefore target groups such as architects, municipalities, builders, owners (usually proud of its own building quality and performances) are addressed by 3ENCULT. Technical solutions for energy retrofit of historic buildings very often involve SMEs due to the specialist knowledge needed (e.g. 90% of all construction works in the field of historic buildings are performed by regional craftsmen enterprises[12]). General public engagement and improved awareness on the necessity for energy optimization is also needed, with a vast potential for action in historic buildings.

1.3 Research Objective and Question

From the review of other projects and case study, several question still open, especially related to the effectiveness of energy saving measure, to the evaluation of measures selected and to the way how to choose one kind of measure instead other one. With this work I want to give a contribution to answer to these question. I consider the conservative authorities point of view very important and I think that the starting point is the understanding the real thermal behavior of building into detail, only afterwards we could implement, in the right way, some measures to increase the energy efficiency and understand their effectiveness. To do all the process we need a detail and accurate simulation tool, able to describe the real thermal behavior of building as much as possible. Moreover using just simulation environment is not enough, because to much uncertainty are related to the sensitivity of the energy modelers when they build the model, therefore in situ monitoring data are very important to know the real behavior of the building and help the modelers in their works. As shown in this work, I did an extensive use of real data in different phases of my research, for a diagnostic purpose and for the calibration of my model. I focus my attention on one case study of 3encult prject[10], Palazzo D'Accursio in Bologna for the characteristic that the building has, huge thermal mass and because is used as office building. These characteristics are common into Italian city and I would investigate if is possible to use the characteristics of building itself, namely the thermal mass effect to reduce energy consumption. I investigate different strategy of refurbishment considering passive and active solution, from improving thermal performance of the envelope, to the use of natural ventilation, improving system and control strategy. I focus the attention not only on the developing of most efficient strategy to reduce the consumption but on the integration on different ones and their optimization. This approach focus more on the minimization of the objectives that you want to prefigure, give more flexibility to the measures that could help to achieve them. The result will be a set of nearly optimum solutions that could be used in the multidisciplinary decision-making process, when also other qualitative criteria are taken into account, to select which set of measure should be adopted.

The core questions I try to answer are listed here.

- There are two main family of energy balance simulation, static and dynamic. how much they are accurate applied to an historical building and to simulate high thermal mass effects? what I have to consider when I have to choose the tool?
- Is it possible to have more accuracy into the model? Have a measure of it? How could I calibrate it?
- How much systems interact with thermal mass? which consequence I have on thermal balance and design? It is possible to use this characteristic for reduce the energy consumption?
- It is possible to have a simulation tool integrated with decision-making process?

1.4 Organization and Summary

The thesis is divided in four main arguments. In the first part, the results of experimental activity is presented. The result is a methodology for building energy audit where the different technics are not presented as separate technology possible to use, but they are organized in a structured framework with clear objective: the analysis of the building and the reduction of uncertainty into the estimation of energy used. All the activities are carry out from the author during the project 3encult to verify and testing which set of technics is useful into the context of historical building. The energy audit is presented applied to a case study to give a practical example of real problem and possible solution. The result of the Audit is the performance of energy model, one static and other dynamic and than compare them with data of consumption. As the data show big discrepancy, I decide to investigate on the capability of the modeling technics and choose the most accurate one.

In the second part is presented the validation of dynamic building energy model, used to select the software to use in the further part of this research. In particular I analyzed the capability of different software to simulate huge thermal mass wall, as this is one of the main characteristic of historic building in Italy, and also of the selected case study for this thesis.

To improve the capability of model to represent the real behavior of the building, Calibration procedure is investigated into the Third Part where hourly data of monitoring system is use to calibrate the building response.

In the fourth part it is presented an optimization procedure for the design phase of the retrofit. Firstly several aspect of the model are investigated alone: control strategy, occupancy model, natural ventilation. Secondly they are joint together into a general setup of the optimization to analyzed if it is possible to take advantage for the develop of energy efficient measure from the interaction of passive and active measures. The concept behind the optimization approach and the selection of optimizer is also presented.

In the last part main results, conclusion and future works are presented.

Chapter 2

Building Auditing

Several guidelines are available for an energy audit of the building. It is a simple tool of analysis and very useful for the decision process inside the building management area. The importance of audit depends from the capability to make fruitful the information achievable. As the audit could cover many aspects, which different level of details, it is important to manage it in order to cover what is really useful, to achieve the objectives that the building management group expects. The information could be provided at different levels. The proposed procedure starts from general aspects and goes step by step to more detailed one with the aim to clarify the uncertainties related to principal components of the energy consumption. It focuses in the case study considered to give a practical understanding of the capabilities to the readers.

Contents

2.1 Methodology

One of the main aspect to deal with in the context of refurbishment of historic building is the lack of information regarding the building. In Italy, the last important refurbishment usually took place after the World War I or II and the documents regarding the structure and the intervention is not easy to recover. In the last decades just small interventions were done, circumscribed to a small area or singular problem, limited to a conservation point of view. Just few years ago the attention on a better managements of historic building and their systems has grown, in relation of the sustainability of our society and the problem of climate change. From that there is a need to deepen the knowledge of the 'as-in-state' condition also from the energetic point of view to plan a better management or future intervention. The implementation of a methodology should be take in consideration the needs of the owner of the building, as the police maker and the technician that are working on the sector. The information delivered should be available from different point of view and at different level to many people. Only the interaction of many actors could develop a well awareness for the preservation of value of the building and the preservation of the function and the role of the building inside of the community. Historic buildings are part of our culture and they are deponent of the evolution of our city and building techniques.

Here one methodology to deal with the audit of historic building is presented. The main points are the following:

- Record information regarding the building construction, feature and material stressing the peculiar characteristic of building. Strong interaction with Conservation Authority is suggested, to define which is the value of the building, to list the features that are not possible to change and which should be preserved.

- Record information related to the thermal performance of the main features of the building, starting from the wall composition and materials. Detail information of windows and systems are also suggested. The evolution on time of the building should be analyzed to understand the thermal behavior of each functional units.

- Perform an energy audit of the building as deep as possible. The result should be a clear overview of the energy consumption divided into subcategory and into systems.

- Perform a diagnostic campaign with the aim to fill the lack, founded in the previous step. Second objective should be a more detailed analysis of more problematic components.

2.2 Building Characteristic and Feature

The Palace is located in the historical centre of Bologna, in the core of an ancient formation where the original Roman urbs used to be. The northern view is towards the ancient Via Emilia (now known in that stretch, as via U. Bassi). Maggiore Square, on which the main facade of the Palace overlooks, is the hub of the public life in the city, where the public and religious festivities are celebrated. The actual structure of D'Accursio Palace is the result of several interventions, beginning with the construction of the original thirteenth-century nucleus of the so called Biada Palace. Follow three main phases of intervention and transformation of the Palace: up to 1336, the Original nucleus protected by a square perimeter of walls; between 1365 and in 1508, crenellated walls interspersed with towers were erected; the building façade in front of Maggiore Square, was completed by the architect Fioravanti, following a fire burst, in a typical local late-Gothic style (1425), finally the walls were reinforced around the main nucleus with white and red merlons (1508). In the following phase between 1513 and 1796, when the city was ruled by a mixed government composed by a senate appointed by the citizens and a Cardinal directly designated by the Pope, whose apartments were hosted by the Palace, one at the ground floor and another at the second, where a chapel was built during the second half of year 1500 by Galeazzo Alessi and then frescoes by Prospero Fontana. At the end of the sixth century, the building showed the consistency it has nowadays, apart from the area of the botanical garden, where the Stock room was built in 1886.

The building is currently used as the headquarters of the institutional offices, museum, and the largest public library in the city. Inside the project 3encult [10] the studies have been focused on two main areas, the 'Collezioni Comunali' museum and one office area located in the south wing of the building. The latter is selected as principal case study of this thesis for the peculiar characteristic: orientation, high thermal mass and high level of interior load due to the related use. The building is 4 floor building of $775m^2$ of surface for each floor with oil heating plant that supply energy to the building through a water radiator system. An overview of the building is shown in Figure 2.2.

Construction and Feature

The materials used for building the palace are typical of the area: brick for the bearing structures, with two or three heads; sandstone for the decorative pieces; and with some exception marble to embellish the architecture (present only in the lancet windows of the facade on the Maggiore Square). The oldest parts of the building, such as the Biada palace facing Maggiore Square and the South wing from the ground floor to first floor (the old fortification wall), the towers (Lapi tower, Pusterla tower and the Accursio tower) have walls whose thickness varies between 60 cm and 120 cm, whereas the other parts of the building have load-bearing walls which are 30-60 cm thick. The oldest parts of the building, including the Biada palace facing Maggiore Square and the South wing from the ground floor to first floor, and the towers have walls whose thickness varies between 60 cm and 120 cm, whereas the other parts of the building have load-bearing walls which are 30-60 cm thick. The floors of the first and second floor of the Palace that overlooks the East side are mostly made of brick arches, with screeds of lime, sand and fill to the sides made of brick debris or stones. The ceilings on the second floor are made of thin plaster arches or sometimes of a wooden structure on which lays a wooden plank. The parts which were added from the fifteenth to the nineteenth century generally have flat wooden floor, while the roof is made of brick, with the exception of part on Maggiore Square, which has a roof of copper plates. The windows are single-glazed with wooden frames except for the Sala Borsa's ones, substituted in 1980/90, shaded by wooden doors or 'Bolognese' tents.

2.3 Energy Audit

Common data available are the utility bills, annual or monthly data, related to the entire building. From the diagnostic point of view they are not very useful because the disaggregation of data to a part of a building, or to a source of consumption is difficult practice and generates several uncertainty. Understanding than, the source of mains consumption, the presence of inefficiency and their impact on total consumption could generate misunderstanding and inefficient measures. To avoid this problem a strategies was implement in this case study.

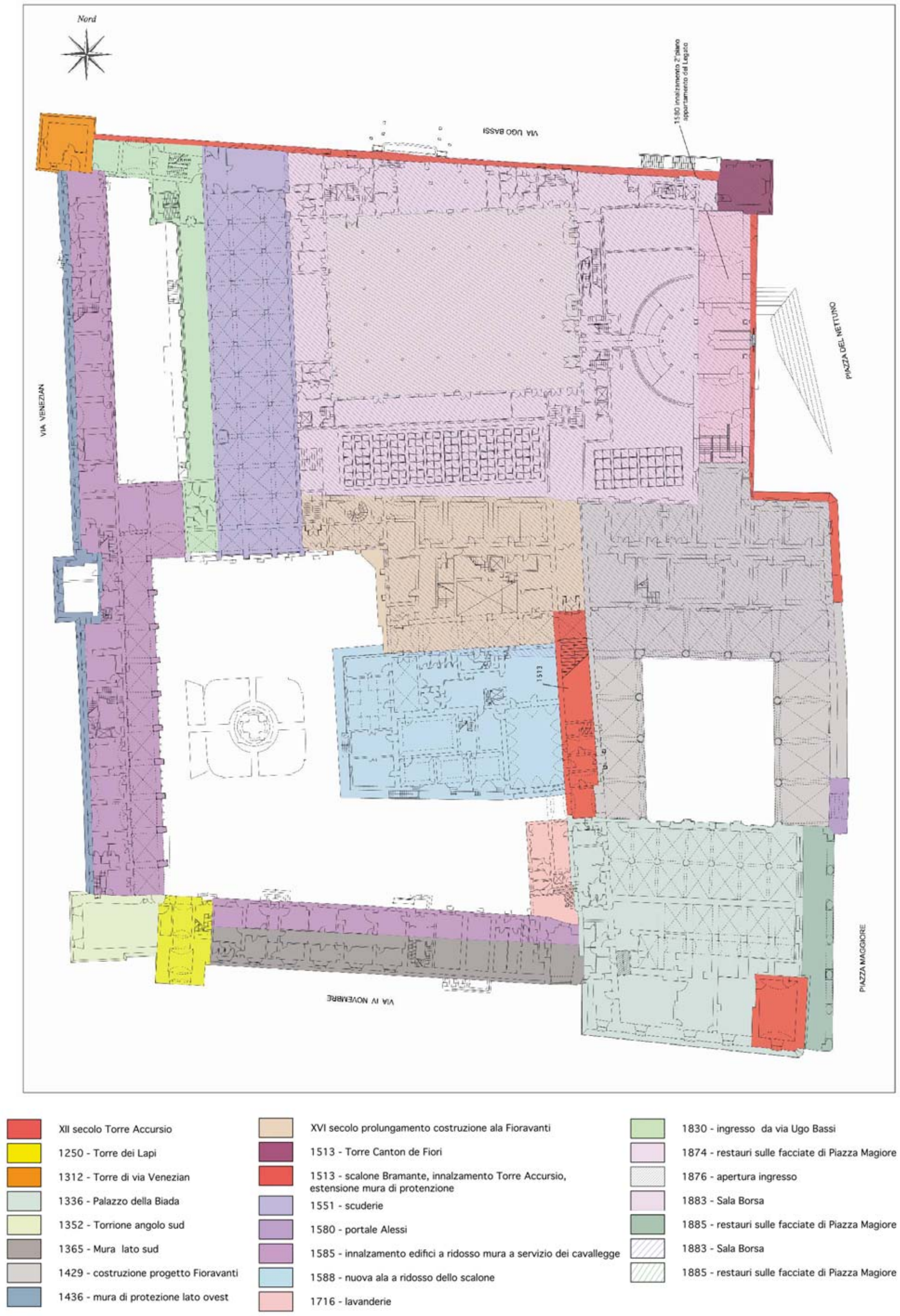
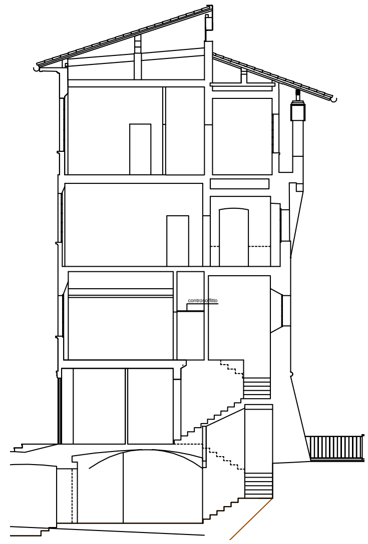


Figure 2.1: The figure shows the floor plan highlighting by color the various phases of construction of the buildings.

(a) South façade

(b) North façade



(c) Building vertical section

(d) Aereal view of South façade of entire building

Figure 2.2: Overview of the Case Study: main façade, section and context.

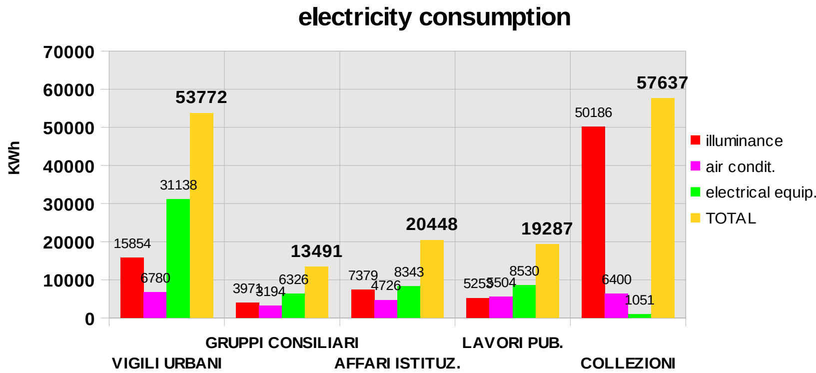
Electric Energy Audit

The audit campaign was performed by Energy Office of Municipality of Bologna on areas occupied by the offices and rooms used as a museum housing the municipal collections. A detailed analysis of the electrical apparatuses and schedule of use was carried out in each room by an inventory of the equipments, by questionnaire given to the occupants and by some measurement into general switchboards. The result is presented, divided by source of consumption and areas, in Figure 2.3 for two different year. With this level of information is possible to take some general decision on measure to implement if there are one or two dominant components, like the case of Museum area 'Collezioni' where the main components, also with high level, is related to lighting system. In this case Changing halogen lamp with wallwash LED lighting system, developed inside 3encult project, will reduce the consumption of 30%. Considering the control system of the light flux with presence sensors, the saving is expected up to 53%. Moreover the quality of illumination will improve and the ratio lumen/watt will shift from 11 to 80. This is and example where the careful use of modern technologies can result in significant benefits. Looking at the data related to others areas, especially for office, the variability is high and just qualitative assumption is possible. The reasons of that are different but mainly related to the occupants behavior and to managements of office schedule. For example, the assumption regarding the increasing of energy of HVAC was correlated to the increase of use of heat pump during winter, contrary, the decrease of energy related to the equipments and to exterior illuminance, were correlated to the number of office use during 2013 and to the switch to fluorescent lamps respectively. More detailed analysis are advisable to better correlate consumption and source, to implement effective measures.

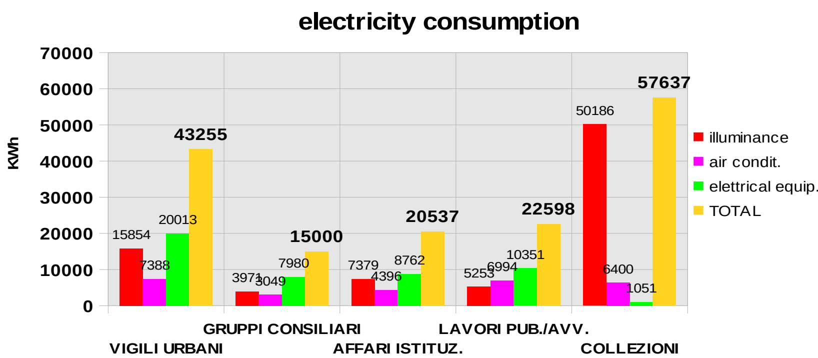
Heating and Cooling Energy Audit

An energy certification is good instrument to understand the energy balance of the building. In that case was selected the Passive House Protocol (PHPP[13]) because is one of the most detail protocol for a steady state thermal balance. PHPP is developed for the design of passive buildings and there are several input to facilitate that project. With small adaptation in the calculation process (changing some setting without the protection mode), is possible also to use it for the evaluation of the as-in-state condition of other class of buildings. All the information derived from the diagnostic phase are used here to produce the analysis, from the blower door test to the in-situ conductance measurements, monitoring data and energy audit. Considering also that thermal mass affect the dynamic balance, other tool is selected, a more detailed one, Energyplus [14], and both are compared with real data of consumption, extrapolated from global consumption. Considering that each method incorporate same uncertainty the result on this comparison allow a better estimation of the 'real' energy balance and the validation of the assumption considered in the analysis.

First interesting observation comes form the consumption data, Table 2.1, where the variability over 4 year is 20% respect to the average which has value generally much lower that expected, and the years which have lower number of Degree Day (GG) have higher consumption. The Energy Office of Municipality Bologna consider the low level of consumption as an anomaly, if they compared this data with data come from other building in the city center. Moreover they explicate the variability with the high uncertainty that come with the data.



(a) Electricity Consumption 2011



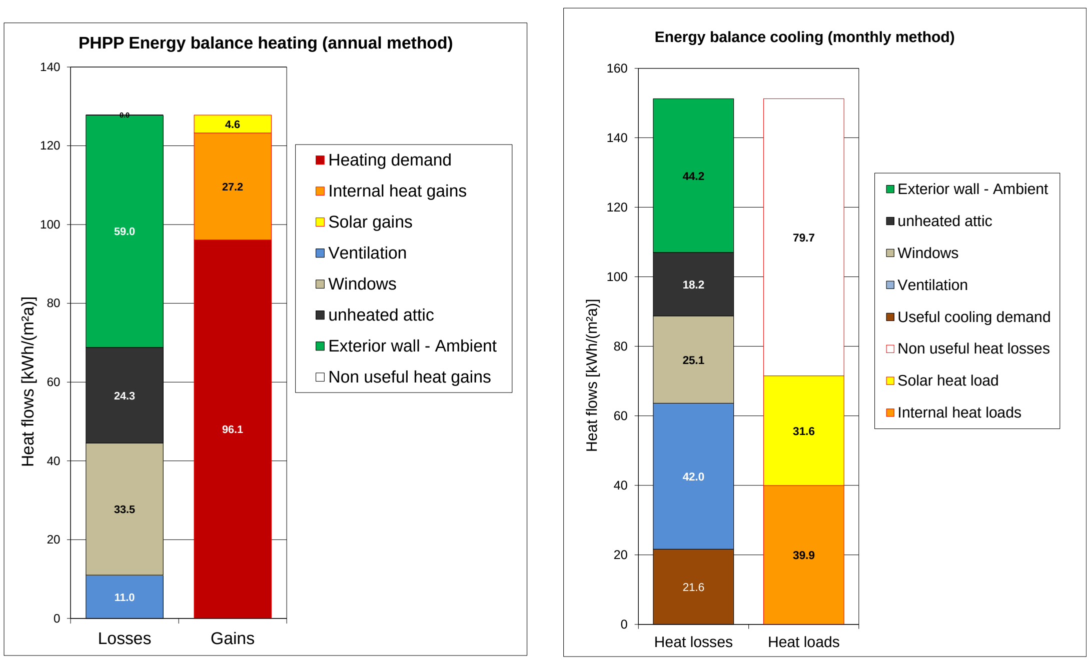
(b) Electricity Consumption 2013

Figure 2.3: Electricity Consumption graph - November 2011 (a), Electricity Consumption graph - November 2011 (b). Source: [Tutino, F. 2013], ©Municipality of Bologna

Possible deductions considering just this data are: other sources of energy have been used for heat the building, like heat pumps which are present in part of the building; or the strategy of control adopted. Looking at the analysis done with PHPP, Figure 2.4, the estimation of Heating demand remains lower that expected but much higher compared to the 'real' consumption, and internal heat gain are consistent according with the use of the building (office building). The main components of Energy losses are the conduction through the exterior wall, than through to window and unheated attic. The high level of internal heat gains increases the risk of overheating during Summer, estimated in 20% of hours. Ventilation losses are comparable to external wall as the building are natural venting by manually openable windows. Solar Gains are higher than in reality because manual shadings are not considered in this simulation. The more interesting result of this first comparison is that there is a considerable difference between heating consumption and estimated heating demand. For the improvement of the heating demand estimation the thermal setpoints of the plants are analyzed using monitored temperature data and it results that temperature setpoint of $20°C$ is correct. To obtain similar data of consumption the setpoints should be $17°C$ but it is clear inconsistent. More reliable conclusion could be that both are wrong and better estimation should be in some part in between 60 and 90. This level of uncertainty is of course unacceptable and more deep investigation are necessary, from the modeling point of view as well as from the empirical one.

Year	Degree Days	Heating kWh/a	kWh/m2a
2007/2008	2163	82147	76
2008/2009	2238	66682	62
2009/2010	2406	73017	68
2010/2011	2130	74274	69
Average	**2234**	**74030**	**69**

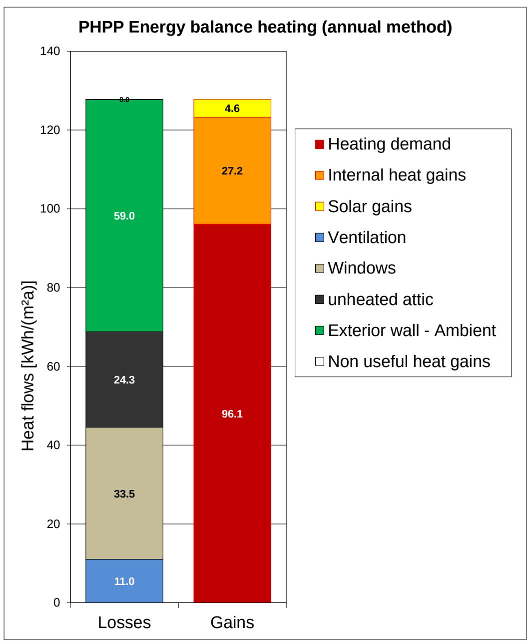
Table 2.1: The data of consumption are derived from plants and systems analysis to allow the extrapolation of the consumption to a building block interest from this study.



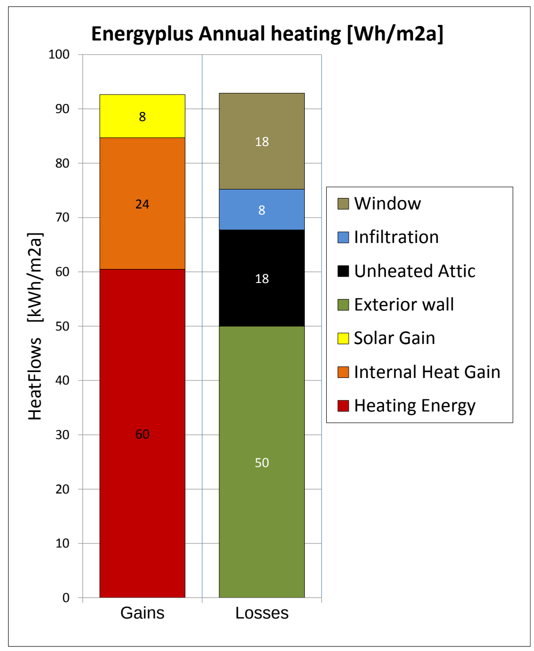
(a) PHPPheating (b) PHPPcooling

Figure 2.4: PHPP Annual heating (a), PHPP Annual cooling (b)

A second model was developed, using Energyplus, for having a better description of building dynamic and assessing the heating consumption through the model. To allow the comparison with PHPP and 'real' consumption, results are presented aggregated yearly as in PHPP. Figure 2.5. Both model consider the same information derived from diagnostic phase and one recognizable feature is the internal gains, very close in the models. The main difference is the loss through the windowsAn analysis base on yearly data is not enough to understand which are the reasons that generate this consumption, moreover the uncertainty related to the estimation is not controlled and the only possible assumption, also considering the result of dynamic simulation, is that the uncertainty of model estimation is the same on the 'real' consumption, 20%. In order to reduce this variation and obtain a model that can better describe the complex interaction between climate, occupants, building and system, it is necessary and suggested more detailed analysis and measurements. Internal loads have to be analyzed as they are consistent in office building and influence heating and cooling loads. As natural ventilation is the main cooling strategy, it has to be investigated joined with occupancy behavior model. The connection between building and system has also to be analyzed considering control strategy and comfort requirements. The necessary tools for doing this analysis are monitoring system and dynamic building model to produce sub-hourly calculation and hourly or daily energy and thermal balance.



(a) PHPP heating



(b) Energyplus heating

Figure 2.5: Annual heating balance compute with PHPP and Energyplus. Comparison between steady-state model and dynamic model of massive building considering same input data.

2.4 Diagnostic

The Work Package 4 of 3encult project [10] have the objective to analyze the state of the art of monitoring system, and developing a new system tailored for historic building where multiple objective are important: diagnostic, control for preservation, keep comfort and reduce the energy consumption. The minimization of energy consumption has to maintain indoor condition in a way to not stress historic surfaces. The concept on which this group has worked is: *"The aim is, by means of a suitable sensor network, to collect data of all the relevant parameters and metrics for characterizing the energy behaviour of the building, the climate situation and comfort in the rooms, the climate-related stress on valuable surfaces, moisture and heat situation in the energy upgraded building construction and energy consumption. With the assessment of all these state variables, an evaluation of the energetic and physical behaviour of a building can reliably be evaluated."* This concept is the result of analysis of several real case study, like the one described in this thesis.

In the energy analysis described above arise clearly that the estimation of energy consumption is uncertainty, and the division into subcomponents, regarding the model of building block, and into subcategory, regarding the building consumption, are even more uncertain. The first aim of a diagnostic campaign should be fill this gap of knowledge and reduce the uncertainty on building response description. For achieve this result 4 technology were utilized:

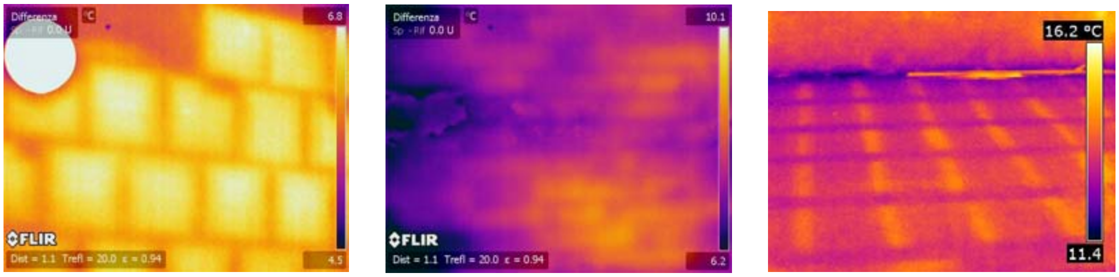
- IR Thermography.
- Blower Door Test
- Heat flux measurements.
- Monitoring system for building response analysis and detailed energy consumption analysis.

2.4.1 IR thermography

This Non-Destructive-Testing (NDT) technology was selected for the capability to not damage the object of analysis, and because could be use for energy and structural analysis. Through a quick inspection is possible to have an overview of the conservation state of the building. Using the Active and Passive Technique is possible to obtain information on the composition of construction, very helpful to focus better the destructive inspection on the only part where their are needed, as well as to detect condensation problem, thermal bridges and to improve the quality of transmittance measurements. More detailed information are available on author's works are publish in [15]. And example of detection of construction composition are presented in Figure 2.6.

2.4.2 Thermal flux measurement

Database of material characteristics of historic walls is limited and theoretical value as to be verify through a measurement. The thermal characterization of historical wall response is achievable with thermal flux measurement. In accordance with the need of the Public Work Office, this work is the beginning of the activity to develop a abacus of wall structure. An example is reported in Figure 2.7 where theoretical and measured value are reported. Almost all the measurements have value lower than theoretical one and the difference grows with the increase of wall's thickness. It suggest that discrepancy on material properties are present. The methods used for the estimation are two to obtain more consistent estimation, based to ISO 9869.



(a) IR hollow brick (b) IR solid brick (c) Floor structure

Figure 2.6: Examples of IR Thermography for construction composition detection. Active thermography is a powerful and easy technic to identify the wall texture. Figure (c) show the stratigraphy of floor in historic building where there is overlapping of construction techniques over the time. A steel frame structure with hollow brick overlap a wood frame ceiling (yellow line).

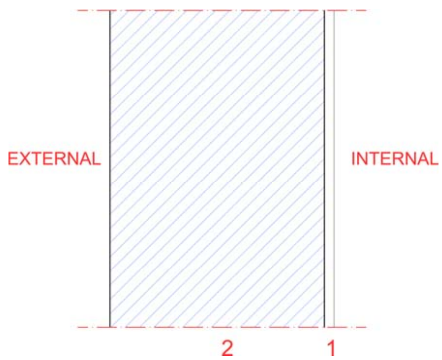
2.4.3 Monitoring system for building response analysis and detailed energy consumption analysis

In order to assess the energetic behaviour of a historic building, a building monitoring is required. The system design in the context of this work is composed of two different wireless networks that work individually. One focus on recording indoor and outdoor climate and construction thermal response, the other recording data of consumption and occupancy behavior. This integration allow a complete control of building dynamic response. Wireless sensor network allow to better interact with an historical building compared to the wire ones. This technology doesn't interact with building structure, advantage for installation in building with paint and frescos, allows a plug and play installation that is very powerful for diagnostic purpose, and allows an easy installation also in indoor condition where people are working or living without causing discomfort for the occupants.

Sensor network for building thermal response analysis

The system is design as star network 2.8(a) where a hierarchic layout allows the distribution of nodes inside the building maintaining reliability and extensibility. To improve these characteristics an improvement on firmware was installed where the star nodes can also communicate between them (red arrows). The layout was developed to satisfy the several objective of the installation describe above, trying to reduce the number of nodes as much as possible to improve the cost/effective ratio of this technology. A typical configuration is presented in figure 2.8(b). The characteristic of the network are the following:

- Node dimension: 90x59x35 mm, see Figure 2.8(c)
- Integrated omnidirectional antenna;
- 7 analog input modules (0-2.5 V) for NTC sensors with a resolution of 0.6 mV;
- Selectable low pass analog filter at 50 Hz;

ID masonry	**M-M-F2-1**
Building	Palazzo D'Accursio
Current Use of the area	Municipal Collections
Plan	Second
Type	Solid brick masonry with five heads
Period of building up the study area	Around 1580
	
	Exposure: South-West

LAYER	**THICKNESS** [cm]	**CONDUCTIVITY** [W/mK]	**RESISTANCE** [m^2K/W]	**SPECIFIC HEAT** [J/kgK]	**DENSITY** [kg/m3]
1 Internal lime plaster	1	0.800	0.025	1000	1600
2 Solid brick wall facing	75	0.810	0.914	840	1800
3 External plaster	-	-	-	-	-
Total thickness	**76 cm**				
Transmittance calculated	**0.881 W/m^2K**				
Transmittance measured	**0.642 W/m^2K**				

(a) Page example of Abacus of historic wall

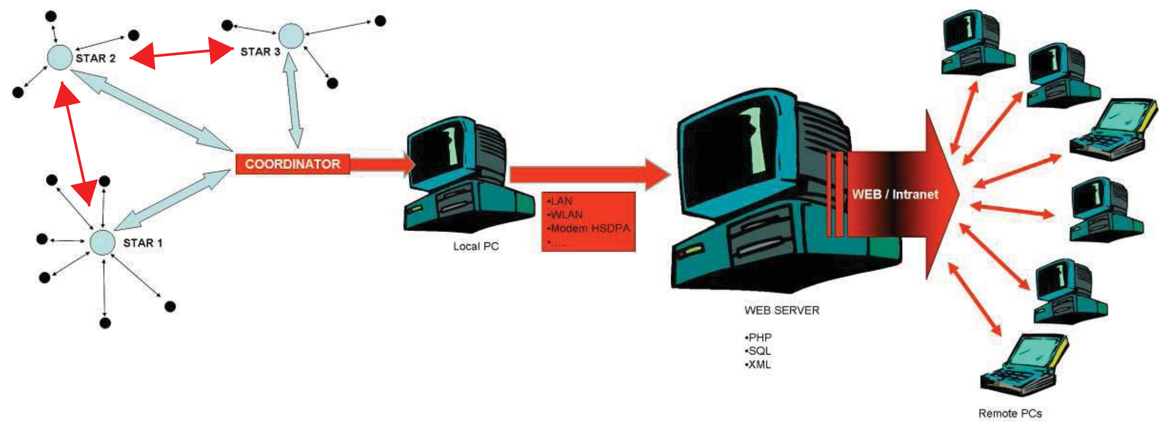
Figure 2.7: The Abacus of construction record together several information: Location, type of construction, stratigraphy, theoretical value and measured value, and photo of wall.

- T and RH sensors on board (Sensirion SHT11):
  - Resolution of 0.01℃/ 0.05 %RH (typ.)

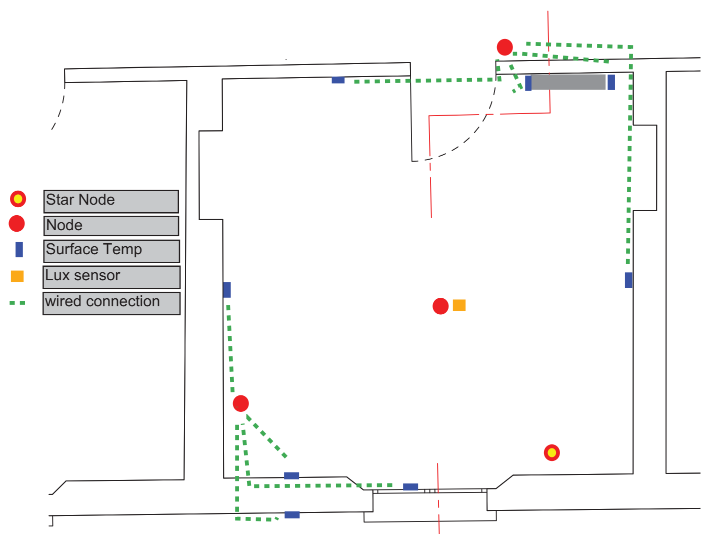
  - Accuracy ± 0.4℃/ ± 3 %RH (typ.)

- Powering: 1 3.6V battery
- Sleep mode current: $< 0.1\mu$A
- Selectable acquisition rate: 5 minutes min, 30 minutes max
- radio transitter
  - 2.4 GHz IEEE802.15.4 compliant;
  - Sleep mode current: < 0.1mA
  - Inter operability with all 2.4 GHz standard devices
  - Encrypted data transmission
- Thermistor external sensor
  - Model: Cantherm CWF4B103G3380
  - Resistance in Ohms 25℃: 10k
  - Resistance Tolerance: ± 0.5%
  - B Value Tolerance: ± 0.5%
- Air Humidity external sensor
  - Model: Honeywell HIH-4030
  - Accuracy: 3.5%
  - Repeatability: ± 0.5%
  - Settling time: 70 ms
- Air velocity
  - Model: Omron D6F-V03A1
  - Operating temperature: -10 ÷ 60℃
  - Flow Range: 0 ÷ 3 m/s , 25℃, 1 atm

The winter and summer interior condition are analyzed. A typical summer week is presented into Figure 2.9(a). In general the operative temperature is high, compared to the comfort condition of adaptive comfort criteria, express in EN 15251 considering Category III. During days where occupants open the window the thermal conditions are satisfy, like office number 2 in the graph. From the figure result also clear that the occupants keep open the window all working hours or the windows are closed during lunch time as happen August 23 and August 24. The effect of natural ventilation is the discharging of thermal mass, resulting in lower value of temperature also during no occupancy time and it creates an advantage for obtaining comfort condition in the following days. This suggest that a better control of windows could improve the comfort condition. The systems control strategy implemented in the building is base on only one measure of indoor temperature and a measure of outdoor temperature. As effect, the indoor temperature is different between areas of the building as reported



(a) network configuration



(b) model of network layout in a office

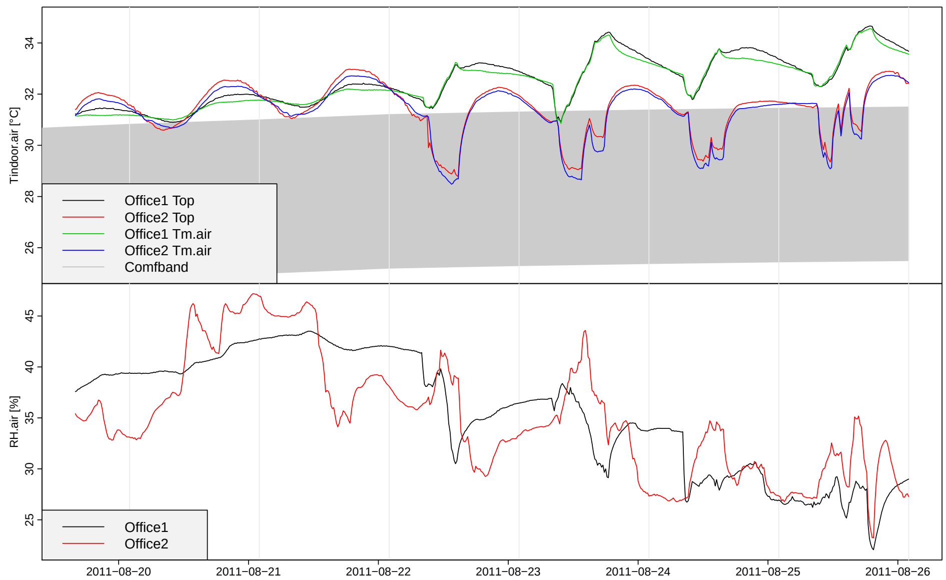
(c) Wireless Node

Figure 2.8: Wireless sensor network characteristic and one sample of layout. The base network is extensible using wire sensor for specific purpose.

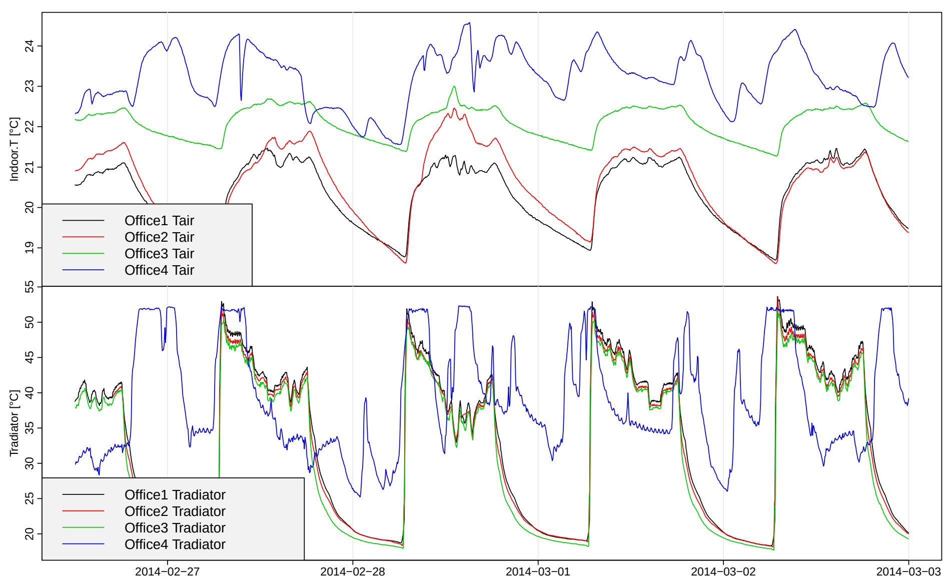
in Figure 2.9(b). A clear difference between floor 3 (office 1 and 2) and floor 2(office 3) is present, as effect of lack of control, and office 4 are heated from different system with different strategy. The comfort condition during winter period are satisfy but consistent savings should be possible with a better control of setpoints.

Detailed energy consumption analysis

A second wireless sensor network it is utilized to perform a detailed analysis of occupancy behavior and to analyzed the internal load and electric consumption. In previous section the position of the windows is deduced from the temperature profile base on the experience of



(a) Indoor Summer condition



(b) Indoor Winter condition

Figure 2.9: Indoor condition during summer and during winter in different office in the building. Figure (a) describe comfort condition during days when windows remain close all the time and others when occupants open the windows during working hours. The gray area is the comfort band in according with EN 15251. Operative temperature, mean air temperature and relative humidity are reported for each zone. Figure (b) describe indoor temperature in different office. Temperature of radiators are reported to better understand the relationship between control strategy and zones temperature. A generalized lack of control is evident.

the author. In general this approach could generate misunderstanding, especially if different person are involved in network installation, data analysis, energy audit and building modeling. A cheap and powerful way to keep the control of window position is the use of dedicated sensor. Each sensor was chosen for a specific purpose considering cost effective ratio and the integration on the two system into energy audit and building energy model.

The characteristic of the network are the following:

- gateway:
  - wireless: 802.11 b/g/n Z-Wave
  - dimension: 240 x 140 x 50 mm
- open/close window and door sensor:
  - power: 3 battery AAA
  - signal range: 30m
  - Frequency of transmission: 868,42 MHz
- power supply meter/attuator:
  - power: 230 Vac from grid
  - signal range: 30m
  - Frequency of transmission: 868,42 MHz
  - meter range: up to 3000 W or 13 A
  - repeater function
- amperometer:
  - power: 230 Vac from grid
  - signal range: 30m
  - Frequency of transmission: 868,42 MHz
  - meter range: from 0.02 to 200 A/phase
  - repeater function

From the diagnostic prospective is possible to understand if anomalies are presented, which is the occupant behavior using the equipments provided them and which is the consumption of each equipment and office. These are very useful information for planning energy efficiency measure for the electricity consumption. The office number 2 2.10 is used once a week and the consumption is in accordance with the use. Office number 5 and 6 are used each working day but quite often the occupants leave the equipments on(basically the personal computer), when they leave the office, also for several days. Office number 8 has different consumption profile, the occupant use and electric heater in the office with clearly drastic increase on energy use. The short and high pick, often present in office 5 and 6, are related to printers and others equipments use occasionally. As the measurements have sample time of 1 min, short time events are also recorded.

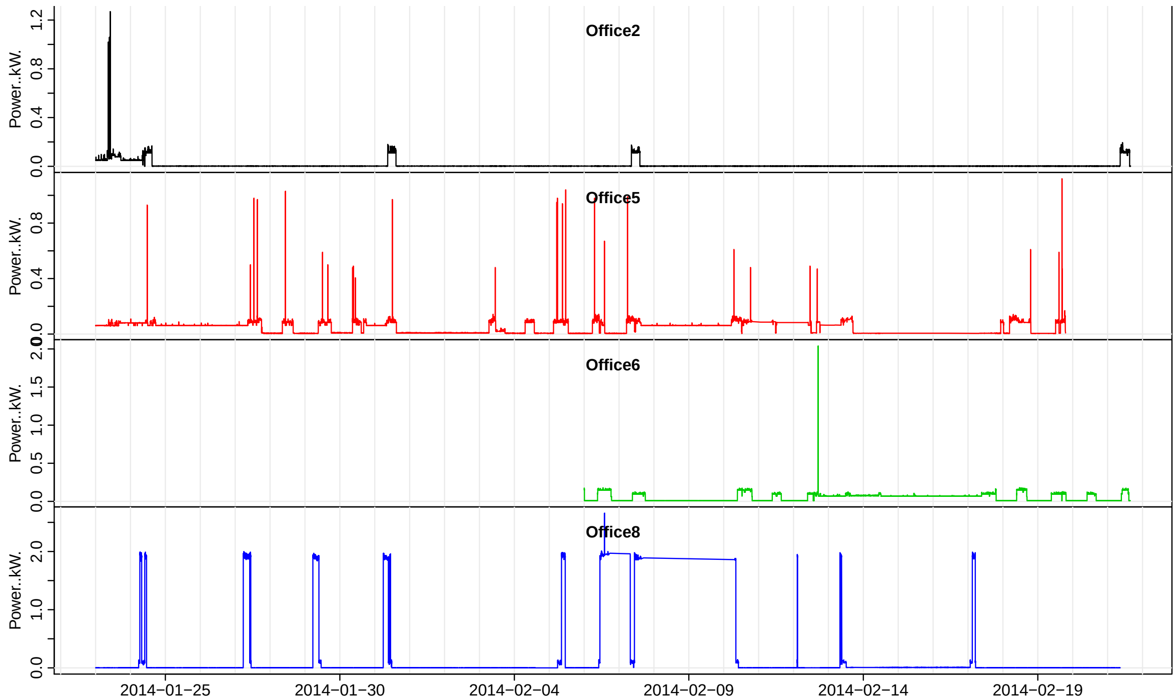


Figure 2.10: Profile of electricity use by equipments in 4 different office.

The main result from the analysis of the electric power used for the equipment, is that the consumption is strongly dependent from the occupancy behavior and this aspect should be considered in the energy audit, in the modeling phase and into the design of energy efficiency measure. From the quantitative point of view is possible to estimate an average of consumption for occupants. There is some variability between offices due to the number of equipments connected, but the estimation in this case is between 100 e 150 W for person. From the modeling point of view this is an important input parameter for controlling the simulation output, especially for office buildings.

2.5 Discussion and conclusion

Performing and estimation of the real consumption of an historical building is not an easy task. The complexity of building itself, the uncertainty related to the structure composition, the lack of information regarding the geometry and the system, the lack of data, the lack of similar case study contribute to generate uncertainty quantification of the as-in-state performance of this kind of building. The comparison between dynamic and static models, suggest to use dynamic models to perform the energy analysis of historic buildings, in particular if consistent thermal mass characterize the building. The static tools are a simplify models of thermal interaction in a building and should be calibrate on a specific class of buildings to satisfy the need of the user, like PHPP protocol for passive houses. A simple transferability of models from one class to other is not possible, especially for simplified model. In this case the difference between them is unacceptable, the difference of heating demand stood at 36 kWh/m2a (37,5%). In order to perform the analysis is necessary to follow a procedure of energy audit to obtain enough data from buildings. Performing a measurement of energy consumption of the entire building join with an energy audit, like described in previous paragraphs, could produces some general indications, but several uncertainties remain on the subdivision of total consumption to subcategories and subsystems. To solve that is necessary to organize more detain campaign of diagnostic that focus on uncertainty reduction by assess at list the consumption related to the subcategories. Building energy model is one of the best way to make a synthesis of the produced information and obtain an instrument of analysis of connection between consumption and building subsystem. The diagnostic campaign could be reduced to essential analysis useful for energy purpose, or extended to conservative analysis, depending on budget and the aim of this activity. The selected technics are a basic and organized set to achieve good assessment of building behavior.

Considering the case study, it is possible to generalized that not always historic building are more energy-intensive than modern building. This case suggests to better investigate the peculiar characteristic of building itself and to develop tailored energy efficiency solutions without transfer preformed solutions from other class of building. Several measure for the energy efficiency are possible without changing the building but with an improvement of control and building management. It is necessary to investigate deeper the buildings thermal response to analyze if more energy saving is achievable.

As the models and real building consumption have many uncertainty, more detailed investigation have been done in order to asses how much the model could represent the real building behavior. Taken in account the capability of models considered and obtained results, dynamic model is selected to perform the next steps of the analysis. In the next sections the dynamic model itself and modeling technics are presented, starting from the analysis of thermal mass wall to verify if the model itself is correct. The main aspect of investigation will be the dynamic response of thermal mass, the natural ventilation coupled with occupancy behavior model, dynamic control strategy for system and building components, and the optimization of retrofit for historical building.

Chapter 3

Model Validation

The use of validated tool is a basic requirement to perform a correct analysis. The class of building considered in this thesis have peculiar feature that are not considered into validation test suite utilized for the validation of common software. This work gives a contribution to verify the capability of commercial software to simulate very massive and thick walls, that characterize historic building. The validation is accomplished through the comparison of different software to a reference software write in Matlab, where the error of the thermal conductance is set to a very low and controlled value, compared to the theoretical one. In this chapter are presented also the reasons why is "white" model chosen to perform the further steps of the work presented into this thesis.

Contents

3.1 Model Selection

Purpose of my research is also investigate which is the most suitable simulation software to utilize. For the correct simulation of historical building, where huge thermal mass is present and window surfaces are considerable and generally low insulated, it is important not only have a software engine enable to characterize the energy use of the building, but also enable to replicate the dynamic thermal response of the building to the outdoor climate, at list hourly. This characteristic allows the energy simulator to take in consideration control strategy, to implement all kind of passive and active and, first of all, to simulate the real behaviour of the building in the 'as in state' condition. Historical buildings have several regulation on the possible intervention and only understanding the dynamic behaviour of their features and using them, it is possible to achieve good results of energy saving and reliable refurbishments.

There are several type of modeling approaches to simulate the energy performance of buildings. The basic three family of model are 'white' model, 'black-box' model and 'grey-box' model. White model is based on first principle of thermodynamics and in general is the pure forward models implemented in most the more common software for this purpose. The black-box model are statistical tools that do not consider the buildings physics and use monitoring data to train the model. Grey-box model join the good aspects of other two because contain phisicś information given in the structure of the model and is trained on monitoring data with and inverse procedure. Unfortunately just simple kind of system are possible to insert in the models due to difficulties to embed the non-linearities characterizing complex system.

The model use in this works is the white model of Energyplus engine. It is an open source software program, capable to simulate several kind of building structure and system considering non only steady state condition but also transient heat transfer condition. The choice of use just the engine without the user interface allow to have the complete control of the engine and use all the capability as, for example, communicate with other tool and self-written code to extend the capability. Several interfaces have been developed in last few years and I choose Legacy OpenStudio Plug-in[16] to communicate with SketchUp[17] and reduce the work to build the geometry. This study take in consideration also refurbishment design problems and white model are better tool for this aim compare with the others because allows the modeler to change building structures and system configurations more easily.

I investigate also the developing of Inverse gray-box model. They are largely based on methods described by Braun[18] and Chaturvadi[19]. This methodology utilizes an electrical circuit analogy for the description of building structure as network of thermal resistance and capacitance (RC network) base first principle of thermodynamic in a reduced-order form. More advance research embed on this formulation a stochastic state space model, based on research of Kristensen[20]. For basic problem were the system are not too complicated and for few thermal zone the methods work well but the developing of the model still needs several time. The advantages of this modeling approach is simulation speed and self-training of parameters. Those characteristic are very precious for building control implementation. A combination of both, White model for the design and Gray model for the control, is probably the best configuration. Consider the state of the art of these tools is probably more efficient use white model and spend extra time to configure correctly the model. I use gray-box model to characterize the building construction (R and C) without considering the system interaction. This information is utilized for make energy audit more reliable. In my approach I choose to calibrate a white model based on monitoring data, procedure and result are presented in section 4.1.

Energyplus is constantly validated and upgraded using a stable process and strengthened over the years. BESTEST (Building Energy Simulation TEST) is a method for testing, diagnosing, and validating the capabilities of building energy simulation programs. BESTEST test suites consist of analytical solutions and tests that allow a given building energy simulation program or design tool to be compared with the current state-of-the-art building energy modeling. The tests are sequenced with diagnostic logic so that the reasons for discrepancies can be quickly determined. The BESTEST is included in more large framework of ASHRAE Standard 140 [21] where the validation are divide into more subgroup: envelope and different class of HVAC system. The procedure considers different building model with peculiar characteristics and allows to verify if the model achieves good result in several situation, from high or lower thermal mass, free-floating environment, shading and windows test (just considering only the envelope) and many others. Other method to verify the capability of BES is the test suite ASHRAE 1052-RP Toolkit where BES is compared to analytical solution. In this approach the analysis is divide in several step, each one considers a single aspect of heat transfer through the building and in this way verify the capability of BES for well none problems.

Modern dynamic energy models are quite complex tool and a lot of work was done for their developing, considering also validation and testing, but in the same time the attention was also focus on the improvement of calculation speed that usually is in contradiction with accuracy. The compromise between them was taken considering traditional construction as the main need of the building physicist and modeler. From the review of the BESTEST and ASHRAE 140, the building components considered are few and they can not to be representative of the reality, especially if you considered different country with different building techniques. The reference model that analyze thermal mass consider just few centimeter of massive wall (up to 20cm in one case). Hence the model can not be considered as validated also for 100 cm of wall thickness. Moving from that reason and from others presented in the next section that I decide to verify if dynamic model implemented in commercial software are able or not to simulate huge thermal mass wall.

The analysis is limited to a conduction, without consider convection and radiation processes to not take the risk into incurring in overlapping of more problems. Convection was analyzed just comparing the several model available into Energyplus but meaningless differences have been found between the models. ASHRAE 1052-RP Toolkit shows good agreement between theoretical model of short wave radiation and energyplus, the only point remained open is the verification of long wave radiation that presents consistent discrepancy with theoretical one in therm of heat flux. This problem is well known also to the developers but needs a specific task that goes beyond the intention of this thesis and it will not considered. Looking at the result of ASHRAE 140 Energyplus satisfy almost all the test, and when it doesn't the discrepancy is around 5% from the average of others software.

3.2 Conduction Model Analysis

It is reported in literature and known by the user community that, under certain circumstances, simulating heat conduction in massive walls with commercial software gives rise to numerical stability problems or reduced accuracy in the results, impeding a precise assessment of the thermal behavior of the wall and eventually the thermal energy balance of a building. As many historical buildings have thick walls with high thermal mass, this work wants to give quantitative answers to when numerical problems arise in commercial simulation software and what's their impact on accuracy. To this end, the thermal responses of several massive walls to step and sinusoidal forcing functions and external temperatures from a weather file were simulated in Trnsys, EnergyPlus, Delphin, and MATLAB. For the sinusoidal excitation, the calculation proposed by EN ISO 13786:2007 was performed and used as reference.

I have done this work for the European project 3encult on energy efficiency in historical buildings[10]. A major aim of the project is to develop a strategy for the conservation of listed buildings combined with energy efficiency measures. The conservation issue makes a correct assessment of energy performance even more important than for not listed buildings. Such an assessment includes an accurate calculation of the heat conduction through walls with dynamic simulation programs. In case of homogeneous wall compositions, small boundary effects and negligible thermal bridges, one-dimensional (1-d) heat conduction models are adequate. Different numerical methods and software implementing these methods have been developed and compared in the literature. Different numerical methods and software implementing these methods have been developed and compared in the literature. Several articles on software validation take into account ASHRAE building stock and summer climate with the aim of finding an accurate heat transfer model for massive walls and defining some useful parameters to evaluate their behaviour[22]. However, few publications deal with the typical properties of such walls. Cellura et al.[23] analysed the errors of different implementations of the Conduction Transfer Function (CTF) method for wall thicknesses up to 100 cm. Chen et al.[24] compared the analytic frequencies of heat conduction through a wall with those obtained with numerical methods on ASHRAE building stock. Li et al.[25] compared the CTF coefficients calculated with three different popular methods. The authors proposed a strategy to assess the errors of the CTF coefficients based on wall properties. They reported improved performance of frequency-domain regression (FDR) compared to state-space (SS) and direct root-finding (DRF) methods. Acceptable errors were reported for SS and DRF methods for $1/(Fo * S_ie)$ less than 600 in case of a single-layer and less than 1200 in case of a multi-layer slab. Fo denotes the Fourier number and S_ie the thermal structure factor as defined in the paper.

However, there still remains the need to assess the accuracy of commercial dynamic simulation software in the calculation of energy performance in historical buildings. In addition to the SS and DRF methods, we have considered other methods such as the response factor (RF), the finite difference (FD) and the finite control volume (FCV) method to take a broader view of possible issues.

3.3 Modeling Methods

Throughout the paper, we consider a single exterior wall of a building with varying thickness L made of one or two homogeneous layers with fixed thermal properties. We focus on 1-d heat conduction, purposely neglecting radiation exchanges. Fourier's law and energy conservation yield the following equation (3.1) for 1-d heat conduction in a homogeneous material[26]

$$\frac{\partial T}{\partial t}(x,t) = \alpha \frac{\partial^2 T}{\partial x^2}(x,t) \tag{3.1}$$

The initial conditions are given by the steady-state for constant outdoor and indoor air temperature with (constant) heat flux, Fig. (3.2):

$$q_0 = \frac{1}{(\frac{1}{h_{ex}} + \frac{1}{G} + \frac{1}{h_{in}})}(T_{a,ex} - T_{a,in}) \tag{3.2}$$

Boundary conditions are presented in Fig. (3.3):

$$\begin{aligned} T_{s,ex}(t) &= f(t) \\ T_{s,in}(t) &= 20 \end{aligned} \tag{3.3}$$

$f(x)$ denotes the forcing function (FF).
In the following, we present the numerical methods considered in this paper to solve Equation 1.

Response factor method

The idea of the RF method[27] is to approximate outdoor and indoor temperature fluctuations by a series of triangular pulses, each with a base width of $2 * \Delta t$ and a height corresponding to the temperature; the less the time difference Δt between two consecutive pulses, the better the approximation. Δt is called time base. The response factors (RFs) X_j, Y_j and Z_j, $j = 0, 1, 2, \ldots$ represent the responses at time $j * \Delta t$ of a monolayer wall to a single triangular temperature pulse at time zero: at the external (X_j) / internal (Y_j) surface to an outdoor pulse and at the internal surface to an indoor pulse (Z_j). In Equation (3.4), we give the RF X_0 as an example:

$$\begin{aligned} X_0 &= \frac{\lambda}{\alpha}\frac{L}{\Delta T}\left(\frac{\alpha}{L^2}\Delta T + \frac{1}{3} - \frac{2}{\pi^2}\sum_{k=1}^{\infty}\frac{\phi_k}{k^2}\right) \\ \Phi_k &= exp\left(-\frac{k^2\pi^2\alpha}{L^2}\Delta t\right) \end{aligned} \tag{3.4}$$

The other RFs are given by analogous formulas and are reported in the literature[28]. $X_0 = \frac{\lambda}{L} + \ldots$ has the same unit as thermal transmittance. It follows that the RFs are numerically equal to heat fluxes produced by unit triangular pulses of 1 Kelvin. The RFs of a two-layer wall can be computed from the RFs of the single layers[28] following Equation (3.5):

$$\begin{aligned} S &= X^{(2)} + Z^{(1)} \\ X &= -(Y^{(1)} * Y^{(1)}) \overset{-1}{*} S + X^{(1)} \\ Y &= (Y^{(1)} * Y^{(1)}) \overset{-1}{*} S \\ Z &= -(Y^{(2)} * Y^{(2)}) \overset{-1}{*} S * Z^{(2)}) \overset{-1}{*} S \end{aligned} \tag{3.5}$$

$X^{(j)}$, $Y^{(j)}$, $Z^{(j)}$ denote the RFs of the j-th layer and X, Y, Z the RFs of the wall. The layers are numbered in ascending order from exterior to interior. We have used the discrete convolution / deconvolution operators defined in Equation (3.6) by:

$$\begin{aligned} (a * b)_j &= \sum_{k=0}^{j} a_k b_{j-k} \\ b \overset{-1}{*} a &= x \ \ suchthat \ \ a * x = b \end{aligned} \tag{3.6}$$

The RF method has been implemented in MATLAB. Series as the one in Equation (3.4) are truncated when the terms summed in reverse order (for higher precision) stop altering the result. The number N of computed RFs is determined such that the difference between the steady-state heat flux caused by a temperature unit step of either external or internal air temperature at time zero and the thermal conductance of the wall is less than $0.001 W/m^2$:

$$\left(G - \sum_{k=0}^{N} RF_k \right) * 1\ K < 0.001\ W/m^2 \tag{3.7}$$

In Equation (3.7), RF has to be replaced in sequence by X_k, Y_k and Z_k. The thermal conductance of the wall has been calculated analytically by summing the layers transmittances, $G^{(j)} = \lambda^{(j)}/L^{(j)}$. Wall surface temperatures and heat fluxes at time $t_j = j * \Delta t$ have been computed by solving the following two linear equations

$$\begin{bmatrix} q_{ex}(t_j) \\ q_{in}(t_j) \end{bmatrix} = \sum_{k=0}^{j} \begin{bmatrix} X_k & -Y_k \\ Y_k & -Z_k \end{bmatrix} \begin{bmatrix} T_{s,ex}(t_{j-k}) \\ T_{s,in}(t_{j-k}) \end{bmatrix} = \begin{bmatrix} h_e x \left(T_{a,ex}(t_j) - T_{s,ex}(t_j) \right) \\ h_i n \left(T_{s,in}(t_j) - T_{a,in}(t_j) \right) \end{bmatrix},\ j = 1, 2, \cdots \tag{3.8}$$

with respect to $T_{s,ex}(t_j)$ and $T_{s,in}(t_j)$ for $j = 1, 2, \cdots$ and then computing $q_{ex}(t_j)$ and $q_{in}(t_j)$.

EnergyPlus FD and Delphin FCV method

EnergyPlus[14] offers two FD schemes. We have used the semi-implicit Crank-Nicholson scheme based on an Adams-Moulton solution approach. Delphin [**?**]uses a variable-order, variable-step multistep method of the CVODE integrator of the SUNDIALS pack-age. The order varies between one and five according to integration error estimates. For the numerical solution of the balance equations, the FCV method is applied. For orthogonal, equidistant grids, the FCV method yields the same discretized equations as the FD method. Advantages of the FCV method are the applicability to unstructured grids and the mass-conserving formulation of fluxes over control volume boundaries. For a better comparison, we have set up the FD and FCV method with the same number of nodes.

EnergyPlus CTF and TRNSYS CTF method

EnergyPlus uses the state space (SS) method to calculate the CTF coefficients. The internal states, that is, the nodal temperatures, can be eliminated. The result is a matrix equation that directly relates the heat fluxes at the wall surfaces to the interior and exterior air temperatures. The CTF method, implemented in the TRNSYS[29] building model (Type 56), is a further development of the RF method[30]. The method is explained in[31] and [32]. The wall surface heat fluxes are calculated as shown in Equation (3.9), using the convolution operator defined in Equation (3.6) as shorthand notation. For the convenience of the reader, I have written out the computation of the internal heat flux. The CTF coefficients $a = (a_0, a_1, \cdots), b, c, d$ are computed with the DRF method[33].

$$
\begin{aligned}
&d * q_{in} = b * T_{s,ex} - c * T_{s,in} \\
&d * q_{ex} = a * T_{s,ex} - b * T_{s,in} \\
&q_{in}(t_j) = \sum_{k=0}^{j} b_k T_{s,ex}(t_{k-j})
\end{aligned}
\tag{3.9}
$$

Simulations

Fig. 3.1 show the wall layers used and the simulated wall compositions.

LAYER	λ [W/mK]	ρ [kg/m³]	c [J/kgK]
Brickwork	0.6	1560	850
Insulation	0.043	91	840

(a) Wall Material

WALL NO.	EXTERIOR LAYER	INTERIOR LAYER
1	40 cm brickwork	-
2	70 cm brickwork	-
3	15 cm insulation	70 cm brickwork
4	70 cm brickwork	15 cm insulation

(b) Wall Simulated

FF NO.	FF NAME	31 DAYS	28 DAYS
1	Step	0 [°C]	10 [°C]
2	Sinusoid	0 [°C]	Amplitude: 5 [°C] Period: 1 day
3	Weather file temperature time series	2 [°C]	Dry-bulb air temperatures in Bologna in February

(c) Exterior Forced Function

Figure 3.1: Wall Material(a), Wall composition(b) and Exterior Forced Function(c).

As there is no radiation exchange, we have assumed constant convective surface heat transfer coefficients for each wall surface in accordance with EN ISO 13786:2007: $h_{ex} = 17.76\ W/(m^2K)$ for the exterior and $h_{in} = 3.07\ W/(m^2K)$ for the interior, respectively. We have set the wall emissivity to zero if the software allows it, otherwise to 1e-9. As geometric reference, we have used a Cartesian coordinate system with the yz-plane parallel to the wall surfaces and $x = 0$ on the external and $x = L$ on the internal wall surface. Two accuracy scenarios have been considered, Fig. 3.2. Simulations with EnergyPlus FD have been performed only for Scenario A as EnergyPlus allows only simulations with the FD method for a time step smaller or equal than 3 minutes. We have chosen three time series $f(t)$ for the external air temperature to assess different aspects of the wall response (Fig. 3.1(c)). Simulations have been run for all walls, forcing functions, software and accuracy scenarios, for a total of 120 runs. The first month has been simulated with constant $f(t)$ to reach the steady-state. For the massive walls, depending on the initial conditions set by the software, the steady-state could not always be reached in one month. In those cases, an additional month has been simulated before the excitation. The weather file has been retrieved from the EnergyPlus website[34]. As reference, we have used our RF method imple-mentation in MATLAB with a time step and a time base of 30 seconds (RF0.5) or EN ISO 13786:2007.

PARAMETER	SCENARIO A	SCENARIO B
TRNSYS		
Time step	0.5 min	0.5 h
Active Layer (AL)	Yes	No
Time base	Wall 1: 6 min Wall 2: 15 min Wall 3: 45 min Wall 4: 45 min	Wall 1: 0.5 h Wall 2: 1.5 h Wall 3: 2.5 h Wall 4: 2.5 h
Delphin		
No. of nodes	Wall 1: 45 Wall 2: 78 Wall 3: 92 Wall 4: 92	Wall 1: 45 Wall 2: 78 Wall 3: 92 Wall 4: 92
Tolerances	Trel=Tabs=1e-8	Trel=1e-5 Tabs=1e-8
Max time step	0.5 min	0.5 h
Max order	5	5
Output time step	1 min	0.5 h
EnergyPlus FD		
No. of nodes	As in Delphin	NA
Time step	1 min	NA
Inverse Fourier coefficient	3	NA
Relaxation factor	1	NA
Intra-layer tempera-ture convergence criterion	ΔT<0.02 K	NA
EnergyPlus CTF		
Time step	1 min	0.5 h

Figure 3.2: Parameters of the accuracy scenarios

3.4 Results

Accuracy of our RF method implementation

First, we have checked the convergence of our code by performing simulations on Wall 2 for different time steps tending to zero. For FF 1, the maximum difference in external heat flux between a simulation with $\Delta t = 1$ min (RF1) and one with $\Delta t = 30$ sec (RF0.5) has been 2.7 W/m2 one minute after the jump of the FF (where the analytical external flux is infinite). The difference at the end of month 2 has been less than machine accuracy (less than 1e-15). For FF 2, the maximum difference between RF1 and RF0.5 has been 3.8e-4 W/m2 (relative error 9.0e-6) in external heat flux and 2.2e-4 K (relative error 4.7e-5) in external surface temperature. As the internal wall surface heat fluxes and temperatures are smoother, the relative errors have been less. All simulations performed and especially those shown in this paper have been useful to check our RF method implementation for systematic error.

Comparison of step FF simulations

We have calculated delay and settling times of $T_{s,ex}$ and $T_{s,in}$ of both scenarios and all walls, forcing functions and software, and have compared them with those of the reference. Delay time is the time required for the response to reach the average between initial and final value the very first time. We have defined settling time as the time required to remain within a range of 2% of the difference between initial and final value. Delay and settling times of q_{ex} are not well-defined as the flux is infinite at the jump of the forcing function. q_{in} is proportional to $T_{s,in}$ (as $T_{a,in}$ is constant) and thus has the same delay and settling times as $T_{s,in}$. Figure 3.3 shows the reference values of RF0.5.

DELAY TIME			SETTLING TIME	
Wall no.	$T_{s,ex}$	$T_{s,in}$	$T_{s,ex}$	$T_{s,in}$
1	22m	1d0h53m	1d15h58m	3d21h12m
2	24m	2d15h40m	2d22h59m	9d11h56m
3	2m	5d22h39m	57m	22d17h23m
4	26m	4d13h3m	6d10h22m	18d12h43m

Figure 3.3: Delay and settling time reference values

Figure 3.5 shows the delay time differences in minutes with respect to the reference. Positive values indicate higher delay times as those reported in Figure 3.3, negative values lower delay times.

SOFTWARE	WALL NO.	SCEN A [min]	SCEN B [min]
TRNSYS	1	+3	+8
TRNSYS	2	+7	-24
TRNSYS	3	0	-2
TRNSYS	4	+20	-26
Delphin	1	+6	+38
Delphin	2	+5	+36
Delphin	3	+1	+28
Delphin	4	+5	+34
E+ FD	1	0	+8
E+ FD	2	-1	+6
E+ FD	3	0	+28
E+ FD	4	-1	+4
E+ CTF	1	1	+8
E+ CTF	2	-22	-24
E+ CTF	3	0	-2
E+ CTF	4	-24	-26

Figure 3.4: Delay time differences for $T_{s,ex}$ for both scenarios

Delay times for $T_{s,in}$ vary by less than 2% in all simulated cases. Settling times for $T_{s,ex}$ vary by less than 2% in most cases. Figure 3.5 reports those cases where settling times have varied by more than 2%. As in 3.5, positive values indicate higher settling times as those reported in 3.3, negative values lower settling times. Settling times for $T_{s,in}$ vary by less than 2% in all cases except one. For E+ CTF, Wall 1 and Scenario B, the difference has been 4%.

SOFT-WARE	WALL NO.	SCENARIO	[min]
TRNSYS	3	A	-13
E+ CTF	3	A	+44
TRNSYS	3	B	+123
Delphin	3	B	+33
E+ CTF	3	B	+63

Figure 3.5: Settling times for $T_{s,ex}$ in case of more than 2% difference

Comparison of sinusoid FF simulations

For all simulated runs, we have calculated the periodic thermal transmittance Y_12 and the decrement factor f in two ways: numerically and according to EN ISO 13786:2007. The reference values are shown in Figure 3.6 together with the thermal transmittance of the wall. In accordance to EN ISO 13786:2007, the negative time shift indicates that the internal wall surface heat flux lags behind the external air temperature. Of course, the best damping with the highest time shift is achieved for the externally insulated wall. As $|Y_12|$ is very small, errors in the numerical computation of $|Y_12|$ vary considerably according to whether the steady-state before and after the excitation is reached or not. Therefore, we have simulated two additional months both before and after the excitation, and errors have been below 5% in all cases. The errors in the phase of Y_12 are less than 2% for Scenario A. For Scenario B, the errors range from 1 to 30 minutes.

WALL NO.	U [W/m²K]	$\|Y_{12}\|$ [W/m²K]	$arg(Y_{12})$	f [-]
1	0.95	0.097	-13h44m	0.10
2	0.65	0.0066	-1d0h0m	0.010
3	0.20	0.00029	-1d3h59m	0.0015
4	0.20	0.00066	-1d2h57m	0.0033

Figure 3.6: Periodic thermal transmittance and decrement factor calculated according to EN ISO 13786:2007

Comparison of real temperature FF simulations

We have used the Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and time integral over February as metrics. The RMSE gives a relatively high weight to large errors and is always larger than or equal to the MAE. We have calculated the difference between the RMSE and the MAE to obtain the variance in the individual errors in the time series. Integrating the absolute differences in the heat fluxes over time gives the absolute error in energy transmitted through the wall surface over the simulated time period. Results for the external wall surface heat flux q_{ex} are reported in Figure 3.7. q_{ex} has been chosen for the purpose of demonstration as the errors are more evident than for q_{in}. In terms of RMSE, Scenario A yields smaller errors than Scenario 2 in 28 (58%) of the total 48 cases (Walls 1-4, the three software TRNSYS, Delphin and E+ CTF, and the four time series for $T_{s,ex}$, $T_{s,in}$, q_{ex} and q_{in}). On average, the RMSEs of Scenario B are more than double (210% as big as) the RMSEs of Scenario A. In some cases, the RMSEs of Scenario B are more than 4 times (up to 412% as big as) the RMSEs of Scenario A. In terms of MAE, results are similar. Scenario A yields smaller errors than Scenario B in 30 (63%) of the cases. On average, the MAEs of Scenario B are 205% as big as the MAEs of Scenario A. In some cases, the MAEs of Scenario B are up to 418% as big as the MAEs of Scenario A.

		SCEN A	B – A	B/A
SOFT-WARE	WALL NO.	q_{ex} [W/m^2]	q_{ex} [W/m^2]	[%]
TRNSYS	1	0.1580	-0.0435	72%
TRNSYS	2	0.3260	0.9705	398%
TRNSYS	3	0.1295	0.1584	222%
TRNSYS	4	0.7497	1.2926	272%
Delphin	1	0.1580	-0.1151	83%
Delphin	2	0.3260	-0.0604	90%
Delphin	3	0.1295	0.0660	145%
Delphin	4	0.7497	-0.0574	91%
E+ FD	1	0.0871	NA	NA
E+ FD	2	0.0871	NA	NA
E+ FD	3	0.1025	NA	NA
E+ FD	4	0.0871	NA	NA
E+ CTF	1	0.5994	1.2982	317%
E+ CTF	2	1.5367	0.1667	111%
E+ CTF	3	0.0902	0.0397	144%
E+ CTF	4	1.5935	0.2371	115%

Figure 3.7: Comparison of RMSEs of q_{ex}. Column 4 shows the difference in value between Scenario A and B. Column 5 shows the ratio between Scenario B and A

We report some interesting cases. The Wall 1 temperatures and heat fluxes simulated in TRNSYS are more accurate in Scenario B than in Scenario A, Figure 3.8. The absolute errors in Scenario B are 12% to 73% as big as the errors in Scenario A. With regard to massive walls, we have observed the opposite: for Walls 2-4, Scenario A has been more accurate than Scenario B (detail shown in Figure 3). Scenario A is also better than Scenario B for the calculation of $T_{s,ex}$ and q_{ex} for all walls simulated with the EnergyPlus CTF method. We have observed the biggest improvement for Wall 1, Figure 3.9. $T_{s,in}$ and q_{in} have been more accurate in Scenario A for Walls 1-3 and slightly less accurate for Wall 4 than in Scenario B. In the case of Delphin, results do not indicate a clear preference for either Scenario, but this is due to offsets in the solutions (see the Discussion).The differences in energy due to errors in the computation of q_{ex} over one month are reported in Figure 3.10, Figure 3.11 and Figure 3.12. Figure 3.10 shows a comparison between the accuracy scenarios. Comparisons between software are reported in 3.11 and Figure 3.12 taking RF0.5 as reference. We have chosen to present the results for the external heat flux as the errors are more evident.

In the following text, all errors are reported in $kWh/(m2month)$. The errors vary between 0.036 and 0.90 for the external heat flux and between 0.00011 and 0.73 for the internal heat flux. The average for the external heat flux is 0.22 for Scenario A and 0.44 for Scenario B.

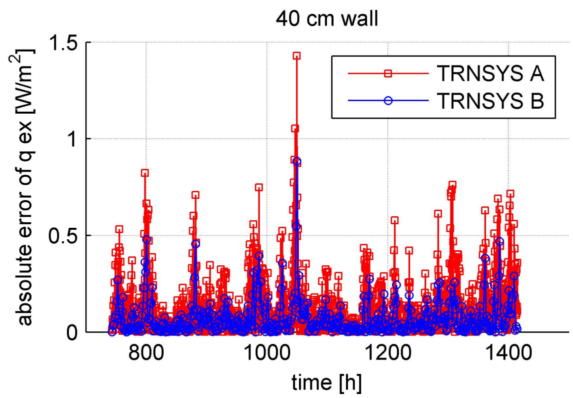


Figure 3.8: Absolute errors of q_{ex} for Wall 1 simulated in TRNSYS

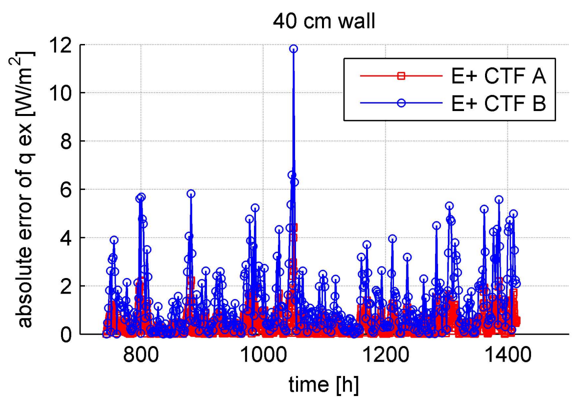


Figure 3.9: Absolute errors of q_{ex} for Wall 1 simulated in EnergyPlus with the CTF method

The average for the internal heat flux is 0.15 for Scenario A and 0.036 for Scenario B.

We have obtained the error of 0.90 for the TRNSYS simulation of Wall 4 and Scenario B (see Figure 3.13). We have attributed the error to the jaggedness of the curves caused by the large time base. Although the solution in Scenario A appears more jagged, the error is less because of the smaller time base. The errors in energy due to errors in q_{ex} in Scenario A simulated with E+ FD are between 0.040 and 0.047 for all walls. The errors due to q_{in} range from 0.00011 to 0.00065.

The simulation of Wall 4 with E+ CTF in Scenario B has an error in energy of 0.847 similar to that of TRNSYS, but for a different reason. The solution is not jagged, but slightly displaced, and peaks are underrated (Figure 3.14). The error in energy due to q_{ex} is less in Scenario A for all walls.

3.5 Discussion and Conclusion

The assessment of the periodic thermal transmittance in case of a wall with high internal mass and external insulation is very sensitive to the steady-state. Different strategies are

ERRORS IN ENERGY [kWh/(m² month)]				
SOFT-WARE	**WALL NO.**	**SCEN A**	**B – A**	**B/A [%]**
TRNSYS	1	0.0662	-0.0175	73%
TRNSYS	2	0.1369	0.4337	417%
TRNSYS	3	0.0544	0.0689	227%
TRNSYS	4	0.3243	0.5727	277%
Delphin	1	0.3582	-0.0530	85%
Delphin	2	0.3133	-0.0268	91%
Delphin	3	0.0888	0.0236	127%
Delphin	4	0.3354	-0.0239	93%
E+ FD	1	0.0404	-	-
E+ FD	2	0.0404	-	-
E+ FD	3	0.0465	-	-
E+ FD	4	0.0404	-	-
E+ CTF	1	0.2731	0.6134	325%
E+ CTF	2	0.7089	0.0841	112%
E+ CTF	3	0.0359	0.0201	156%
E+ CTF	4	0.7335	0.1133	115%

Figure 3.10: Comparison of scenarios with respect to the error in energy due to errors in q_{ex}

ERRORS IN ENERGY [kWh/(m² month)] AMONG SOFTWARE – SCENARIO A				
Wall no.	**TRNSYS**	**Delphin**	**E+ FD**	**E+ CTF**
1	0.0662	0.3582	0.0404	0.2731
2	0.1369	0.3133	0.0404	0.7089
3	0.0544	0.0888	0.0465	0.0359
4	0.3243	0.3354	0.0404	0.7335

Figure 3.11: Scenario A: comparison of errors in energy among software due to errors in q_{ex}

ERRORS IN ENERGY [kWh/(m² month)] AMONG SOFTWARE – SCENARIO B			
Wall no.	**TRNSYS**	**Delphin**	**E+FD**
1	0.0486	0.3052	0.8864
2	0.5706	0.2865	0.7930
3	0.1233	0.1125	0.0560
4	0.8971	0.3115	0.8468

Figure 3.12: Scenario B: comparison of errors in energy among software due to errors in q_{ex}

used among software to compute the wall surface temperatures and heat fluxes before the excitation. Our implementation computes the steady-state analytically from the known air temperatures and convection coefficients. By default, Delphin and TRNSYS start from a different steady-state than that indicated in Figure 3.1(c). Therefore, the computation of the periodic thermal transmittance will not be precise if the steady-state indicated in 3.1(c) is not reached before and after the excitation. For Wall 3 and RF0.5, the computed $|Y_{12}|$ has an error of 28% after 28 days of periodic external air temperatures because the steady-state has not been reached after one month. Simulating for another month, the error drops below 1%.

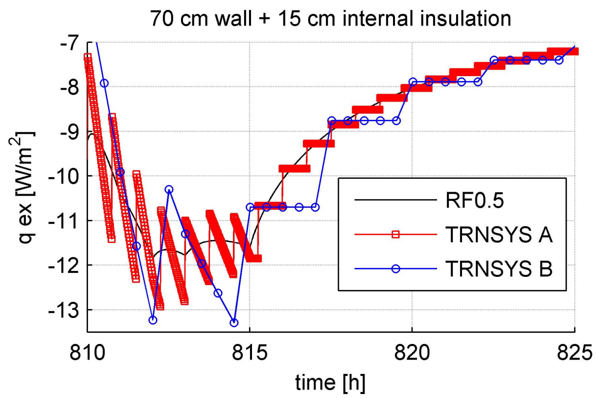


Figure 3.13: q_{ex} for Wall 4 simulated with TRNSYS

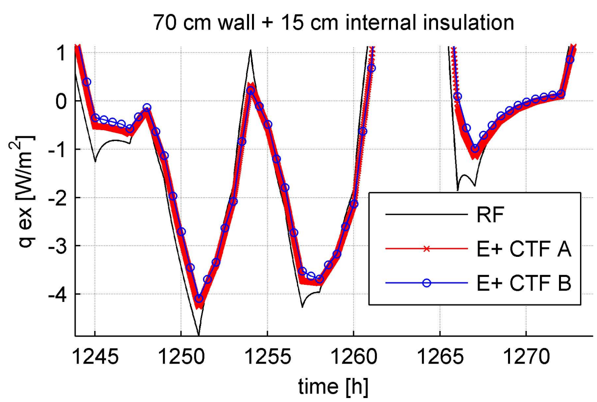


Figure 3.14: q_{ex} for Wall 4 simulated with E+CTF

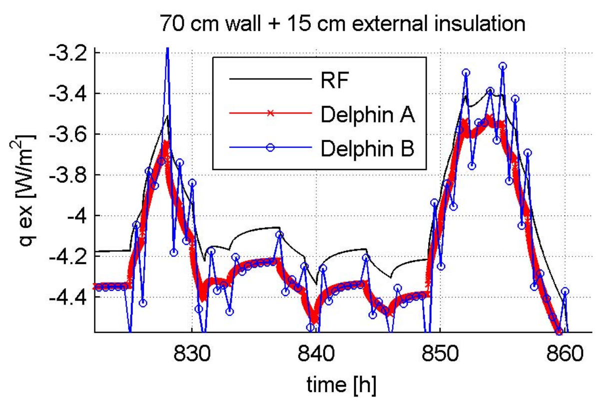


Figure 3.15: q_{ex} for Wall 4 simulated in Delphin

It is common practice to use Equation (3.10) to verify that the CTF coefficients determined by EnergyPlus and TRNSYS yield the correct steady-state heat transfer.

$$\begin{aligned}\frac{\sum_{k=0}^{N_x} X_E^k}{1-\sum_{k=1}^{N_\varphi}\varphi_E^k} = \frac{\sum_{k=0}^{N_y} Y_E^k}{1-\sum_{k=1}^{N_\varphi}\varphi_E^k} = \frac{\sum_{k=0}^{N_z} Z_E^k}{1-\sum_{k=1}^{N_\varphi}\varphi_E^k} \approx G \\ \frac{\sum_{k=0}^{N_a} a_k}{\sum_{k=0}^{N_d} d_k} = \frac{\sum_{k=0}^{N_b} b_k}{\sum_{k=0}^{N_d} d_k} = \frac{\sum_{k=0}^{N_c} c_k}{\sum_{k=0}^{N_d} d_k} \approx G\end{aligned} \tag{3.10}$$

For the walls considered in this work, this is not always the case. The smaller the time base and the longer the response of the wall, the more coefficients have to be calculated to capture the entire response of the wall. A smaller time base means that less time passes between two temperature pulses. Therefore, more coefficients are needed to record the response of the wall for the same amount of time. In EnergyPlus and TRNSYS, the number of calculated coefficients varies only to a certain extent; therefore, the terms in Equation (3.10) become generally less precise for small time bases. On the other hand, a large time base means that temperatures and fluxes are recorded less frequently, causing again inaccuracies. It is well known that the calculation of only a small number of CTF coefficients causes the simulation to become unstable or even diverge for too small time bases, especially in case of massive walls. Moreover, commercial programs are optimized for the common case in terms of speed and memory; therefore, round-off and truncation errors as well as numerically ill-conditioned algorithms like the computation of the coefficients of a polynomial from its roots are involved. Indeed, the implementation I used is stable for very small time bases such as 30 seconds, because much attention has been paid to the calculation of the series in Equation (3.4), only basic algebra has been used, and almost 100,000 RFs have been stored in case of the 70 cm brick wall with 15 cm insulation. TRNSYS does not simulate in that case reporting a stability error. EnergyPlus uses staggered CTF coefficient histories combined with interpolation to keep the accuracy for a decrease of the time step up to 1 min. The cross coefficients have an error of about 3% with respect to the analytical conductance of all walls, but the inner and outer coefficients are 2400% wrong in the worst case for Wall 4 and a time step of 1 min. In the case of TRNSYS, all errors are below $0.001W/m^2$ as too small a time base cannot be used a priori. In RF implementation, the errors are below $0.001W/m^2$ by design.

In most cases, if accuracy is of concern, I recommend Scenario A. Of course, a time step of 30 seconds will be exaggerated for most applications. Time steps of 3 to 15 minutes should be accurate enough if systems with fast responses are controlled. Otherwise, time steps of half an hour or an hour will usually suffice. We have seen that in special cases Scenario B is even better. Scenario B is better for Wall 1 simulated in TRNSYS because the time base is equal to the time step and the actual flux is not changing rapidly within one time step. An issue that arises in TRNSYS, especially for small time bases, can be seen in Figure 3.13. The small time base produces a jagged curve that is accurately tracked due to the small time step. Although local values are not so reliable, the moving average follows the reference solution quite well. Note the arcs of the reference solution. These are caused by the linear interpolation of the hourly temperatures taken from the weather file. In case of massive walls, TRNSYS behaves better due to the smaller time base (Figure 3.13). The smaller time base has been possible thanks to the insertion of an active layer (AL). In this case, the time step could be larger as there is no need to track the jagged curve with such precision. Using the CTF method of EnergyPlus, this problem does not arise as the CTF coefficients are computed using staggered temperature and heat flux time histories and interpolation.

In Delphin, Scenario A is generally better than Scenario B, especially near non-differentiable points produced by the linear interpolation of the weather file temperatures (see Figure 3.15). For very smooth solutions there is no real need to use a very small time step. Delphin is clearly offset with respect to the reference solution because of a slightly different initial steady-state. Indeed, the RMSEs have been only 12% larger than the MAEs in that particular case. The initial steady-state found depends on the number and position of the intra-wall nodes. Shifting the solution upward so that the curves overlap, Delphin tracks the reference solution with very slight differences. We have found similar results for the E+ FD simulations.

Chapter 4

Model Calibration

Calibration is a very important aspect for energy simulation. Assess how much one model is closed to the real behaviour of the building is useful for many applications, from a realistic energy auditing to a correct assessment of energy conservation measure and for the developing on good control strategy to apply to the building and also for the faults detection. This chapter analyzed the common practice on calibration procedure and an improvement is suggested and presented. The main difference is the introduction of sensitivity analysis, the used of hourly data and the redefinition of the metrics. The infrastructure remains the same of the reference for allowing an easy implementation, the calculation is performing with Montecarlo methods but the use of optimization is straightforward.

Contents

4.1 Calibration of Building Energy Simulation

4.1.1 Literature Review and Objective

One of the main reference for these studies is the ASHRAE guideline 14[35]. The aim of this guideline is the correct assessment of energy and demand saving considering three different scenario: whole building energy analysis, isolated intervention of retrofit and whole building calibrated simulation. For each scenario it gives several and clear indication of which information are needed, period to consider, way to consider the uncertainty of the measure, metrics for the assessment of the error in the calibration of the building simulation and the related levels of error that are allowed. The guideline considers just the energy balance and the energy consumption of the building and this is the main limitation for old building and in particulary for the historical one, where the complexity of construction as the uncertainty related to the structure and systems are more high. In my case study, very complex and big building, there is also other problem: the systems are not documented and the distribution network is unknown. Just some rough assessment of which heating sub-plant supply heats to which part of the building, have been taken out in the past.

Others and more recent studyies are taken out from Reddy[36]. Based on their studies, they develop a methodology that could be apply easily and with high consistency and giving the benefit to many software developer of adding this capability to they software. The basic idea is that it is unlikely that any one solution can be deemed the b̈estsölution, and it is more robust to identify a set of most plausible solution. Also their methodology is based on utility billing data. The procedure can be resume in the follow five part:

- Create a preliminary simulation input file of the building as realistic and error-free as possible.
- Reduce the dimensionality of the problem space by resorting to walk-through audits and heuristics, considering realistic variability field of the parameters.
- Perform a 'bounded' coarse grid calibration using MC simulation to identify more sensitive parameters using a mid-point Latin Hypercube Monte Carlo. This result in a filtering of weak parameters performing a regional sensitivity analysis.
- Perform a guided search calibration for a refinement
- Rather than using one plausible solution to make the prediction of energy saving, use a small number of solutions estimating their associated prediction uncertainty as well.

The methodology described in [35] and [36] is verified in the context od historic building. The idea is divide the uncertainty related to the building model and envelope from the uncertainty related to the system and to the bill and the estimation of the consumption. Also Reddy stresses the concept than a satisfactory overall calibration to the utility billing data will not guarantee accurate identification of the individual parameters in the simulation programm. With this procedure parameters estimation still not possible, especially for the heterogeneity of historic buildings and their structure, and others technics should be applied for that purpose, but rough estimation of parameters values are possible and could improve significantly the accuracy of simulation model.

Some recent experience of model calibration with hourly data started to be publish in the last years, as more monitoring system start to be used extensively. An example is Coakley[37] where data from BMS are used to calibrate the model using ASHRAE-Guideline 14 as reference for the implementation. The result that the author stress is the difficulties to obtain a good calibration result with hourly and daily resolution. The reliability and accuracy of 'calibrated' Building Energy Simulation (BES) models depends on the quality of the measured data used to create the model, as well as the accuracy and limitations of the tools used to simulate the building and it's systems. Throughout the course of this study, it has been found that it is very difficult to obtain the level of data required for detailed calibration, even in modern buildings with relatively large quantities of data readily available.

4.1.2 Objective

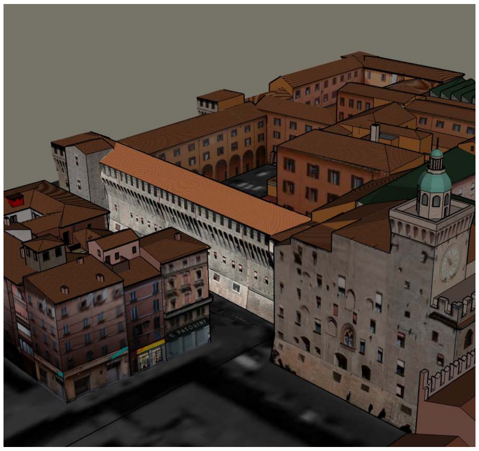
The objective is the develop of calibration methodology for the historic building where the thermal response of the building is difficult to represent due to the lack of knowledge of buildings structure, where thermal mass is consistent and where improvements possibilities of the energy performance are limited from regulation for the preservation of buildings characteristic. A detailed description is necessary to evaluate possible energy efficiency measures. The methodology should consider hourly data and focus on thermal response of building than energy consumption. Best practices are analyzed and verified for the context considered.

4.2 Methodology

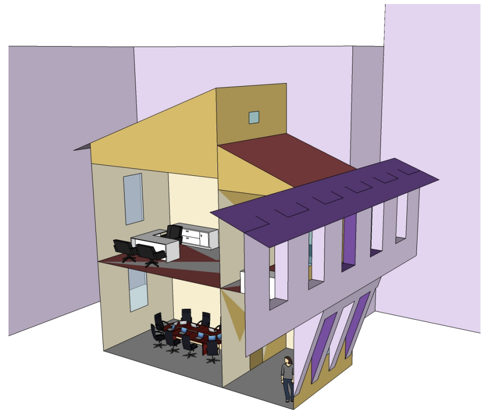
The objective of this approach is the calibration of the building behavior to assess how much the model could reproduced the real building response to the climate, which indoor microclimate is generated. Only at the end which is the energy need and which is used to produce a good level of indoor comfort condition for people and for the preservation of artworks. Therefore calibration is focus on the thermal response of the building where the outdoor climate is the input and the temperatures in the building are the output, on which the metrics is applied. As describe in chapter 2.1 exterior climate, indoor air temperature, surface temperature of window, walls and floors are measured. Since the building presented not common feature, modeling has been treated with care. The result is a reduced model that maintain all the characteristic of the entire building, reduced because the thermal zone are just two each floor, south and north oriented, for a total number of 6. The urban context is also a characteristic of this building and shade effect are modelled in detailed. The entire building model and reduced model are presented in Figure 4.1.

4.2.1 Procedure

The proposed procedure of calibration is divided in 4 main block, as presented in Figure 4.3. First step is the analysis of monitoring data. A time period in which the building is subjected to a free floating environment should be selected in order to reduce the uncertainty into model



(a) SketchUp Model of Building



(b) Reduced model of Building Block

Figure 4.1: In Figure (a) the Building block is evidenced from the entire building. Figure (b) shows the reduced model used for the energy analysis. The most important feature of building are modeled, as the shading effect from other building or part of the building itself. The reduced model is consistent with the thermal balance of the entire Office Block.

calibration. If it is not possible you could select a period when the system is not running, but interior load should be measure. Climate data are recording from local weather station installed on the building, and used to create local weather file as input for Energyplus. Radiation data are provided from satellite measurement [38]. Indoor microclimate and surface temperature on main structure are also measured and used to calculate the metrics. Periods with lack of data are selected only if the length of lack is less the two hours, and they were interpolated. For the sensitivity analysis all parameters related to the envelope and the interior wall are selected for the screening and the Sensivity Analysis is carried out, as described in section 4.2.4, with the selected metrics, as discussed in section 4.2.3. Second model with just sensitive parameters is created and used to build second experiment, MC analysis. Same metrics used in Sensitivity Analysis is used also in this second experiment. Sample strategy selection are discussed in section 4.2.2. In general is better to use Latin hypercube sampling or Sobol's Sequence sampling. Increase the number of simulations is a general rule that allow to achieve good estimation. For the selection of best set of parameters some heuristic is utilized to make the selection physical meaningful. It depends on the parameters taken in consideration. In this procedure some parameters are physical dependent from others and have to be considered into the selection, as solar absorbance and thermal absorbance. Second step of selection is done considering the metrics and taking the best 20 simulation. The number is chosen base on previous study of Reddy [36], base case chosen for comparison. Time series plot are also performed to check graphically the results.

The procedure is also repeated during winter time, to consider a period on which the systems are working. As the control on setpoints is not present in the building, it is chosen to use monitored indoor temperature as setpoint considering the same plant schedule of the real building and systems sized accordingly. The error is than calculated in the same way used in summer condition. This procedure allows to analyze the response of the building to heating system. The discrepancy during the period on which the system is not running gives the measurement of the accuracy of the losses estimated from the model, and the thermal response of the building.

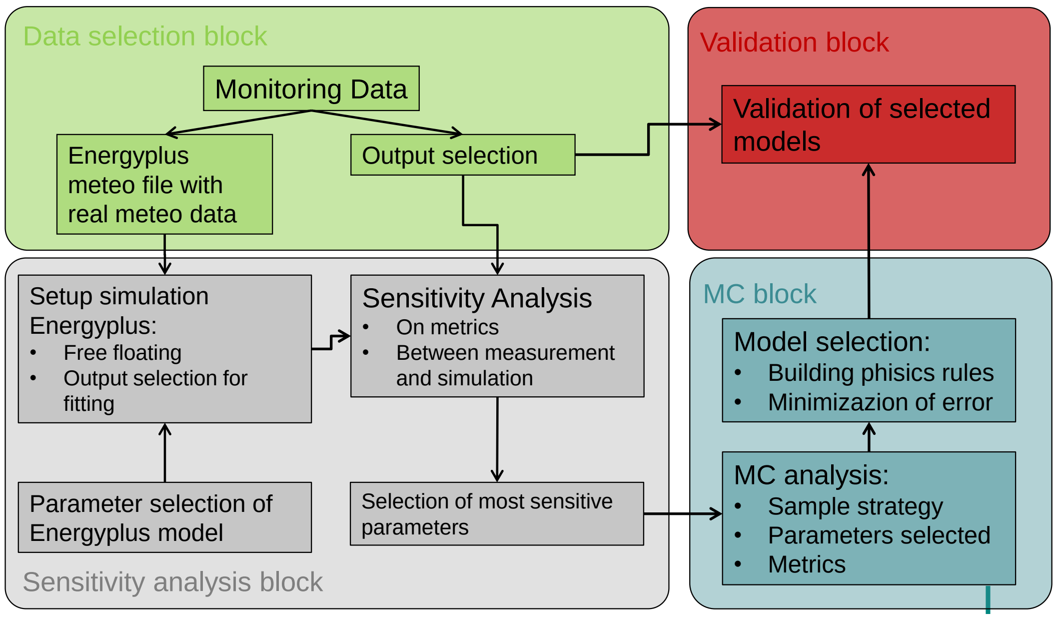


Figure 4.2: Calibration Procedure

4.2.2 Sampling

As first step of Monte carlo (MC) methods is selected because require a low level of mathematics while providing adequate robustness especially when the number of input parameters is large, along with large uncertainty in the input parameters, and when the input parameters are interdependent and nonlinear, even if it remains computationally more demanding comparing with an optimizer. More over it gives the possibility to test the Reddy methodology considering different kind of metrics and different objective of calibration.
The goal of MC technic is the possibility to explore the entire input parameters space with a reasonable number of sample (sample size = N) compare to a full factorial analysis. The input parameters space is k-dimensional space where k is the number of parameters, thus N increase quickly with the increase of k. The sample size defines the computational cost of the experiment since N is the number of simulation to run. Several studies focus on the sampling strategy and several technic are nowadays available. The most common technics are Random or Pseudo-Random Sampling(RS and PRS), Stratified Sampling(SS), Latin Hypercube Sampling (LHS), Sobol's Sequence Sampling(SSS). Basically these strategies show differences in robustness and accuracy if the analyst want to decrease considerably the sample size, this is necessary, for example, in problem where uncertainty analysis is considered. In these problems, several MC analysis are repeated to evaluate the uncertainty propagation in models.

Burhenne[39] follows the work of Mcdonalds[40] and compares different sampling strategy considering: velocity of estimator's convergence calculating the mean at different sample size, robustness measuring the standard deviation of the estimated mean. The way utilized to visualize the robustness is to compare the empirical cumulated density functions (CDFs). The Results are that LHS and SSS had the fastest convergence of the mean estimates and the comparisons of the estimated CDFs showed that the SSS has the least variations in the CDFs. Having less variations proves that this sampling technique produces the most robust results. These results are taken into account in the developing this approach and SSS strategies is used without investigate the different sampling strategy. Since just one MC analysis is needed for the calibration, I choose to have a good description of input parameters space in accordance to [36] and N = 4000 is chosen. As first step, before MC analysis, I insert a sensitivity study to reduce the number of parameters, increasing in this way the capabilities of MC analysis. The technic is presented in 4.2.4.

4.2.3 Metrics

In this section I review popular metrics, algorithms currently used to quantify the discrepancies between time histories in various fields and in general statistical measurements used for model evaluation. The list presented is not exhaustive but advantages and disadvantages of the metrics considered are presented. When time histories are discretized the most popular global statistical measure used is the norms one and two. For example It's common to take the average of hourly temperature value by day. The comparison of Mean Estimation M_e and Mean Observation M_o could give a raw estimation on the accuracy of model prediction. Considering ϕ_{ei} the estimation at time i and ϕ_{oi} the observation at time i, the subscripts "e" and "o" correspond to model-estimated and observed quantities, respectively, the subscript i refers to the ith hour of the day and N the length of time vector of measure and simulation M_e and M_o is reported in Equation (4.1). Norm two, or standard deviation, is other global statistic that gives an estimation of the dispersion of data from the mean. The formulation of standard deviation for observation SD_o and estimation SD_e is reported in Equation (4.2).

$$M_e = \frac{1}{N-1}\sum_{i=1}^{N}\phi_{ei} \qquad M_o = \frac{1}{N-1}\sum_{i=1}^{N}\phi_{oi} \tag{4.1}$$

$$SD_e = \left[\frac{1}{N-1}\sum_{i=1}^{N}|\phi_{ei}-M_e|^2\right]^{\frac{1}{2}} \qquad SD_o = \left[\frac{1}{N-1}\sum_{i=1}^{N}|\phi_{oi}-M_o|^2\right]^{\frac{1}{2}} \tag{4.2}$$

Differential statistic base on norm one and two are useful to analyse the discrepancy between the model and the observation. Norm one of the hourly residual in Mean Bias Error (MBE) define in Equation (4.3). Normalized Mean Bias Error is given by Equation (4.4) than Mean Normalized Bias Error in Equation (4.5) in which the normalization take place in each residual calculation obtaining more precise normalization and makes the metric independent from time. The Bias is derived from the average signed deviation of the residual. A distinct disadvantage is that positive and negative differences at various points may cancel each other out. Standard Deviation of Residual Distribution, Equation (4.6), describes the 'dispersion' of the residual distribution about the estimate of the mean. It measures the average 'spread' of the residuals, independent of any systematic bias in the estimates. No direct information is provided concerning sub-regional errors or about large discrepancies occurring within portions of the diurnal cycle.

$$MBE = \frac{1}{N-1}\sum_{i=1}^{N}(\phi_{ei} - \phi_{oi}) \tag{4.3}$$

$$NMBE = \left[\frac{1}{(N-1)M_o}\sum_{i=1}^{N}(\phi_{ei} - \phi_{oi})\right] * 100 \tag{4.4}$$

$$MNBE = \left[\frac{1}{(N-1)}\sum_{i=1}^{N}\frac{\phi_{ei} - \phi_{oi}}{\phi_{oi}}\right] * 100 \tag{4.5}$$

$$\begin{aligned} r &= \phi_{ei} - \phi_{oi} \\ SD_r &= \left[\frac{1}{N-1}\sum_{i=1}^{N}(r - M_o)^2\right]^{\frac{1}{2}} \end{aligned} \tag{4.6}$$

Mean Gross Error overcomes the problem of MBE taking the absolute value of the residual. It is formulated in two way, Mean Absolute Gross Error (MAGE) and Mean Normalized Absolute Gross Error (MANGE). The formulation is given in Equation (4.7). The gross error quantifies the mean absolute deviation of the residuals. It indicates the average unsigned discrepancy between hourly estimates and observations and is calculated for all pairs. Gross error is a robust measure of overall model performance and provides a useful basis for comparison, among model simulations, across different model grids or episodes. The Root Mean Square Error (RMSE), as with the gross error, is a good overall measure of model performance. However, since large errors are weighted heavily, large errors in a small subregion may produce large a RMSE even though the errors may be small elsewhere. RMSE could be divided in two components, Systematic one gives the estimation of model'e linear bias, Unsystematic one is a measure of how much of the discrepancy between estimates and observations is due to random processes or influences outside the legitimate range of the model. First step is the calculation of coefficient a and b by linear least-squares regression. Than the resulting linear model in Equation (4.9) and (4.10) could be used to compute the RMSE components.

$$\begin{aligned} MAGE &= \frac{1}{N-1}\sum_{i=1}^{N}|\phi_{ei} - \phi_{oi}| \\ MANGE &= \left[\frac{1}{(N-1)}\sum_{i=1}^{N}\frac{|\phi_{ei} - \phi_{oi}|}{\phi_{oi}}\right] * 100 \end{aligned} \tag{4.7}$$

$$\begin{aligned} RMSE^2 &= RMSE_s^2 + RMSE_u^2 \\ RMSE &= \left[\frac{1}{N-1}\sum_{i=1}^{N}|\phi_{ei} - \phi_{oi}|^2\right]^{\frac{1}{2}} \end{aligned} \tag{4.8}$$

$$\begin{aligned}\hat{\phi_{ei}} &= a + b * \phi_{oi} \\ RMSE_s &= \left[\frac{1}{N-1}\sum_{i=1}^{N}\left|\hat{\phi_{ei}} - \phi_{oi}\right|^2\right]^{\frac{1}{2}}\end{aligned} \tag{4.9}$$

$$\begin{aligned}\hat{\phi_{ei}} &= a + b * \phi_{oi} \\ RMSE_u &= \left[\frac{1}{N-1}\sum_{i=1}^{N}\left|\phi_{ei} - \hat{\phi_{ei}}\right|^2\right]^{\frac{1}{2}}\end{aligned} \tag{4.10}$$

A 'good' model will provide low values of the root mean square error, RMSE, explaining most of the variation in the observations. The systematic error, $RMSE_s$ should approach zero and the unsystematic error $RMSE_u$ should approach RMSE following from the Equation (4.8).

AHRAE Guidaline 14[35] uses the following three indices to represent how well a mathematical model describes the variability in measured data. They are:

- Coefficient variation of the Standard Deviation (CVSTD)
- Coefficient of variation of the root mean square error (CVRMSE). As given by Equation (4.8) divide by arithmetic mean of observations.
- Normalized mean bias error (NMBE). As given in Equation (4.4)

CVSTD don't take in account simulation data but is only a metric to describe the variability of measured one. More over it is not possible to use Coefficient Variation on Temperature in degree Celsius, because temperature data are in interval scale. It has meaning just for data in ratio scale, as these are measurements that can only take non-negative values. To use this metric conversion to Kelvin scale is possible, but is not applied in this study. The guideline suggest to use the other two metric for Calibration Problems.

In this work the procedure described in next section is repeated with the metrics suggested from ASHRAE[35] to check how much the procedure achieve good results also with hourly data taking different kind of measurements to check if the problems that others researcher[37] are persisting. Also other metrics are considered, in particular all metrics above have been checking at least one time. Taking into account the characteristic describe above, I select RMSE, with its components, as alternative to the [35]. RMSE is generalized metric without the need of post-normalization that make the metrics dependent from the period considered. More over, it still simple and easy to use, and the two components could give precious information on modeling and quality of measurements.

4.2.4 Sensitivity Analysis

Background and Objectives

A possible definition of sensitivity analysis is the following: The study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input [41]. Sensitivity analysis (SA) can uncover technical errors in the model, identify critical regions in the space of the inputs, establish priorities for research, simplify models and defend against falsifications of the analysis [42], therefore it could be used for validation and calibration problems. Several technics of SA are available and they could be divided into two class, global and local. The global one could be divided into quantitative and qualitative. Qualitative could be use as first raw analysis to understand if there are some strong relationship between parameters and between input and output parameters, like a scatter plots. More interesting are quantitative methods that give an estimation of more sensitive parameters with an associated measure that joint the total sensitivity of one output to each input parameters. The selection of method to use should be based on the objective of the analysis, computational cost of running the model, number of parameters. In this case the objective is to understand which parameters are influential for the calibration, in particular on the metrics I have selected. As usual just few parameters are influential on model results, and fixing the other to a nominal value is useful to reduce the dimension of MC analysis that will run in second step of calibration procedure. This sensitivity analysis setting are called Factor Fixing (FF). Powerful method that support this setting is Elementary Effect Method (EEM).

Elementary Effect Method

This method is an evolution of OAT design (One-at-a-time) where just one parameter at time change value between consecutive simulation inside the design. This method overcame the problems related to derivative-based approach.

It is simple method of screening a few important input factors of a model with a moderate computational cost compared to other global methods.

Morris is the owner of the idea of this method that proposing the construction of two sensitivity measures for finding which input could have effects which were

- negligible,
- linear and additive,
- nonlinear od involved in interaction with other factor

Consider a model with k independent inputs $X_i, i = 1, \ldots, k$, which varies in the k-dimensional unit cube across p selected levels. Input space is discretized into a p-level grid Ω. For a given value of X, the elementary effect of the i-th input factor is defined in Equation (4.11).

$$
\begin{aligned}
&\Delta = \frac{p}{2(p-1)} \\
&X = (X_1, X_2, \ldots, X_k) \qquad \textit{is value in}\, \Omega \\
&EE_i(X) = \frac{[Y(X_1, X_2, \ldots, X_{i-1}, X_i + \Delta, \ldots, X_k) - Y(X_1, X_2, \ldots, X_{i-1})]}{\Delta}
\end{aligned}
\tag{4.11}
$$

Y(Â·) is the result of the evaluated function at the coordinates indicated within the parentheses and Δ is the step size in the domain of the input parameter. This method is sensitive to the choice of p, Δ and r. First $r = 400$ trajectories are generate and than the selection of best 20 are done base on the criteria of maximization of distance among them propose from Campolongo[43]. These strategy of selection improve the capabilities to explore input parameters space without increasing the number of simulations. A convenient choice for parameters p and Δ is p even and Δ as Equation (4.11). I chose $p = 6$ to achieve at least a minimum number suggested in[42].

The statistical measures related to parameter 'i' follow the Equation (4.12),(4.13),(4.14). μ_i represent the average of the effect. μ_i^* is a good proxy of the total sensitivity index S_T, measure of overall effect of a factor on the output (inclusive of interactions)[43], σ_i^2 is a measure of parameter interaction and nonlinearities. The number of simulation required to apply this method is $r(k+1)$ where k is the number of parameters.

$$\mu_i = \frac{1}{r}\sum_{j=1}^{r} EE_i^j \tag{4.12}$$

$$\mu_i^* = \frac{1}{r}\sum_{j=1}^{r} \left| EE_i^j \right| \tag{4.13}$$

$$\sigma_i^2 = \frac{1}{r-1}\sum_{j=1}^{r} \left(EE_i^j - \mu \right)^2 \tag{4.14}$$

EEM is often used in the context of building energy simulation. Brohus used EEM for the screening of parameters related to yearly heating energy consumption in residential building [44] and to analyze the influence of Occupant's Behaviour on energy consumption [45]. Hrebik used EEM for the estimation of uncertainty in the calculation of heat transfer coefficient of window [46]. Monari applied EEM to simplified model used for certification [47].

4.2.5 Implementation and tool

This procedure requires a software tool that can be used to change simulation input files, execute the simulation using batch file, postprocessing the result of each simulation and save the results. In the context of this work R is used to manage all the step of the analysis. MC analysis and EEM are also implemented in R. The implementation in based on R scripts with defined objectives. Main.R does the initialization of the problem, reading monitoring data, setup of all directory needed and call other script. It is also use for plotting the result. Second script is dedicated to parameter's value extraction, third script is dedicated to write simulation input file, fourth script runs the simulation, fifth create MC experiment, sixth create EEM experiment, seventh reads and analyzes the results of each simulation (postprocessing).

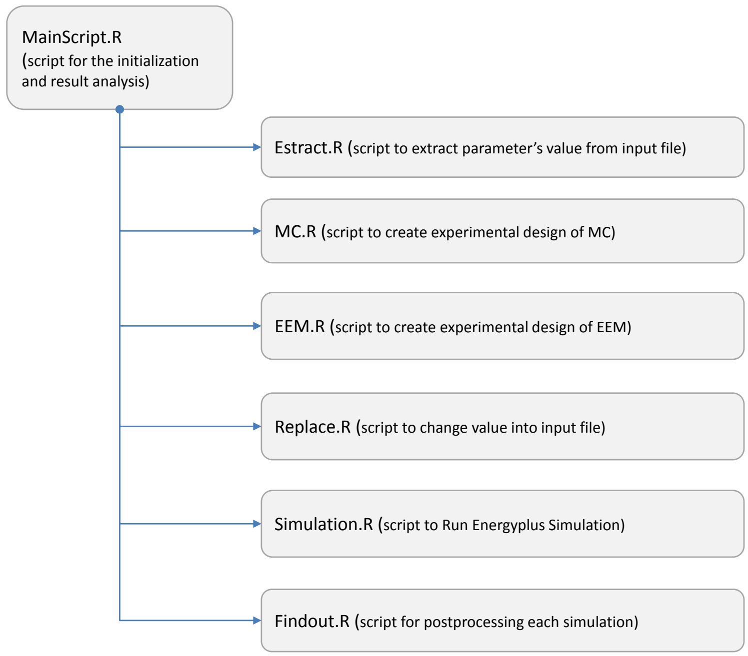
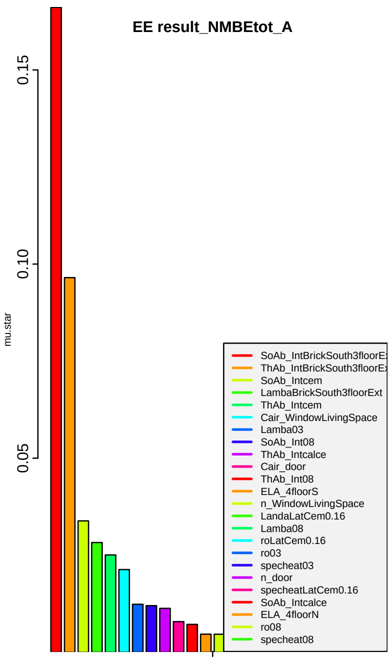


Figure 4.3: Calibration Procedure

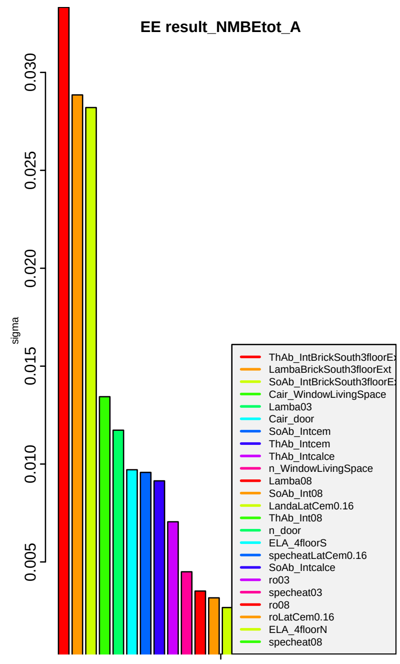
4.3 Result and Comparison

4.3.1 Sensitivity Analysis

The EEM is applied to the same model considering two different metrics: the RMSE and NMBE, CV(RMSE). This step is used to verify if different metrics describe well the error or not and if they are able to identify same sets of sensible parameters of the model. The independence of the parameters adopted by the metric is one of the main requirements. The bar plot, Figure 4.4, is reported only for NMBE because the criteria of independence is respected. The most sensible parameters are the same for both metrics. The only difference between them is that RMSE amplifies the differences of importance between the parameters, the score, assigned to the most important, is one order of magnitude bigger compared to the rest of parameters. This is due to the formulation of RMSE, it describe better the large error losing sensibility of smaller one. The choice should be done consider the specific application. The analysis is performed with free floating environment during summer. The most sensible parameters are the thermal characteristic of external wall, thermal and solar absorbance. According to the formulation of the energy transfer these parameters have strong non-linearity and interaction with others parameters.



(a) NMBE: μ^*



(b) NMBE: σ

Figure 4.4: Sensitivity analysis of building parameters using GOF-NMBE. Value is reported for the case where metrics is calculated on indoor air temperature and surfaces temperatures.

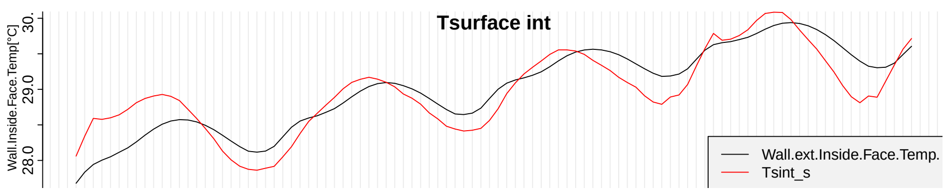
The result of sensitivity analysis is the selection of most sensible parameters to reduce the dimension of MC analysis that follows this step of the procedure. MC analysis is performed using just 6 parameters starting from 24 and using the same metrics. The Analysis is repeated during winter time also to consider the application of the calibration when system are active on building. The result show that most sensitives parameters remain thermal characteristic of external wall. As second there are the parameters of interior wall, as they act as thermal mass. The exterior wall of last floor exposed to south is the most influencing component of the building.

4.3.2 Model validation an selection

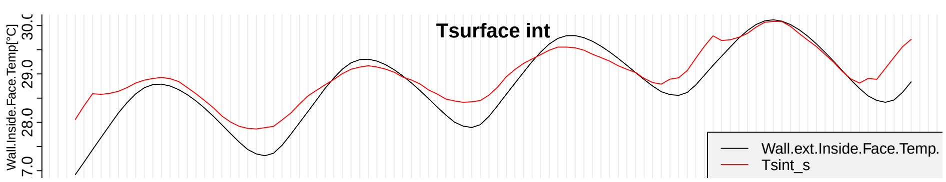
The calculation is performed considering the calculation of metrics just on indoor air temperature (method A) or considering also the surface temperature (method B). The two configuration are considerer to analyzed which is the better configuration to calibrate the building simulation. The results of MC analysis are filtered using the same metrics using into EEM obtaining the best 20 set of parameters for equivalent numbers of models. The GOF metrics applied in method A gives a NMBE and CV(RMSE) lower than 1.65% and 2% respectably. The corresponding value of the same metrics, considering method B, are 7% and 20%. Applying the selection criteria to the method B directly gives a NMBE and CV(RMSE) lower than 1.9% and 15% respectably. The corresponding value of the same metrics, considering method A, are 1.65% and 2% as before. The error of the fitting that consider large numbers of measurements reduce the error as expectable.

The RMSE metrics applied in method A gives a RMSE lower than 0.37. The corresponding value of the same metric, considering method B, are 4.42. Applying the selection criteria to the method B directly gives a RMSE lower than 3.96. The corresponding value of the same metrics, considering method A, are 0.43. Also with RMSE, considering large numbers of measurements reduce the error as expectable.

The improvement is more meaningful because prevent the selection of parameters value of the construction that are not realistic. Since the aim is the calibration of the building response, surface temperature are important as well as the indoor air temperature, for example to calibrate the material properties of the surface. As consequence the estimation of simulations about condensation effect and mean radiant temperature would be more realistic. A comparison between the effect of method A and B of the surface temperature is presented in Figure 4.5.



(a) Surface temperature without fitting



(b) Surface temperature with fitting

Figure 4.5: Do not considering the surface temperature into the fitness allow the selection of parameters that create more picks of temperature during day. Also in the data are present occasionally but they are noise, without physical meaning. In free floating environment during summer the different is not so consistent

4.3.3 Result and Discussion

The result of calibration is presented into the Figure 4.6 and 4.7 where a comparison between calibrated model and not calibrate one is presented. In general the not calibrated model overestimate all the temperatures. A discrepancy of 2 degree characterized indoor air temperature and surface temperature. The outdoor surface temperature has the largest discrepancy. This behavior is not depending from the climate because real data were used to built the input file of energyplus, but is strongly correlated to the definition of model and to the building structure.

The Calibration improves the performance of the model to an acceptable level. All the measures considered are well approximated from the model. However, some observations should be made. The large discrepancy is related to the exterior surface temperature, and it is considered the main cause of the discrepancy also of the others measures. Part of the reason is probably also due to a wrong position of the sensor to have a representative surface temperature of the wall, as the wall has complex shading system due to the defensive wall that are present in this area of the building. More sensor are suggested to used instead of just one. The shape of the exterior surface temperature show the effect of strong shading effect compare to Energyplus. The indoor air temperature has very close amplitude but at least one hour of time shift that should be investigate.

Considering winter time data 4.8, there is perfect agreement between indoor temperature measured and simulated one as the data are utilized as setpoint into Energyplus. When systems are switched off the discrepancy increases showing the difference thermal behavior between model and real building. The objective of the calibration is the minimization of this discrepancy. During time when systems are On there are occasionally some variation that should be related to other factor that should be investigated. Applying the calibration and considering the indoor air temperature as metric, produce a sensible reduction of the discrepancy. Considering the surface temperature inside the fitting, in this case, it does not improve much more the model 4.10. In particular in some case the accuracy improves, like Ts_ext, in others the accuracy decreases, like $Tair2N$. This behavior suggests that there is other factors to consider to achieve further improvements. The results for the indoor temperature are satisfactory but the envelope calibration needs further investigation that will take in account in next work.

The proposed procedure gives good result with hourly data of temperature, overcoming the problems presented in literature, and the sensitivity analysis allows to investigate which are the parameters to improve significantly the model. All the metrics considered produce good result. I suggest to use RMSE with the two component for the following reasons. First of all is generalized metrics and could be applied to any variable and into all intervals, NMBE is not. Secondly the use of the subcomponents allow to have a measure of how much the problem of calibration is related to the model and how much to the data.

4.3.4 Conclusion

The calibration of model is one of the most important aspect of simulation. The review of approaches utilized in common practice shows that they presents several problems when hourly data are considered. A review of metrics suggests that the problem is not related to the choice of one instead other one. Problems are related to the selection of sensitive parameters and on calibrations of their value. The sensitivity analysis helps in this task showing a sensible improvement of the model as this work shows. EEM is powerful method for factor screening, in particular for Factor Fixing, but also other methods should be investigated to consider also the interdependency of the parameters into the analysis. A monitoring system is powerful method to obtain data for this kind of analysis but some care is needed during the installation especially in complex context like the historic buildings. The use of data for this kind of study allow the understanding how to improve the monitoring system and it was a really lecture learned in the context of this thesis.

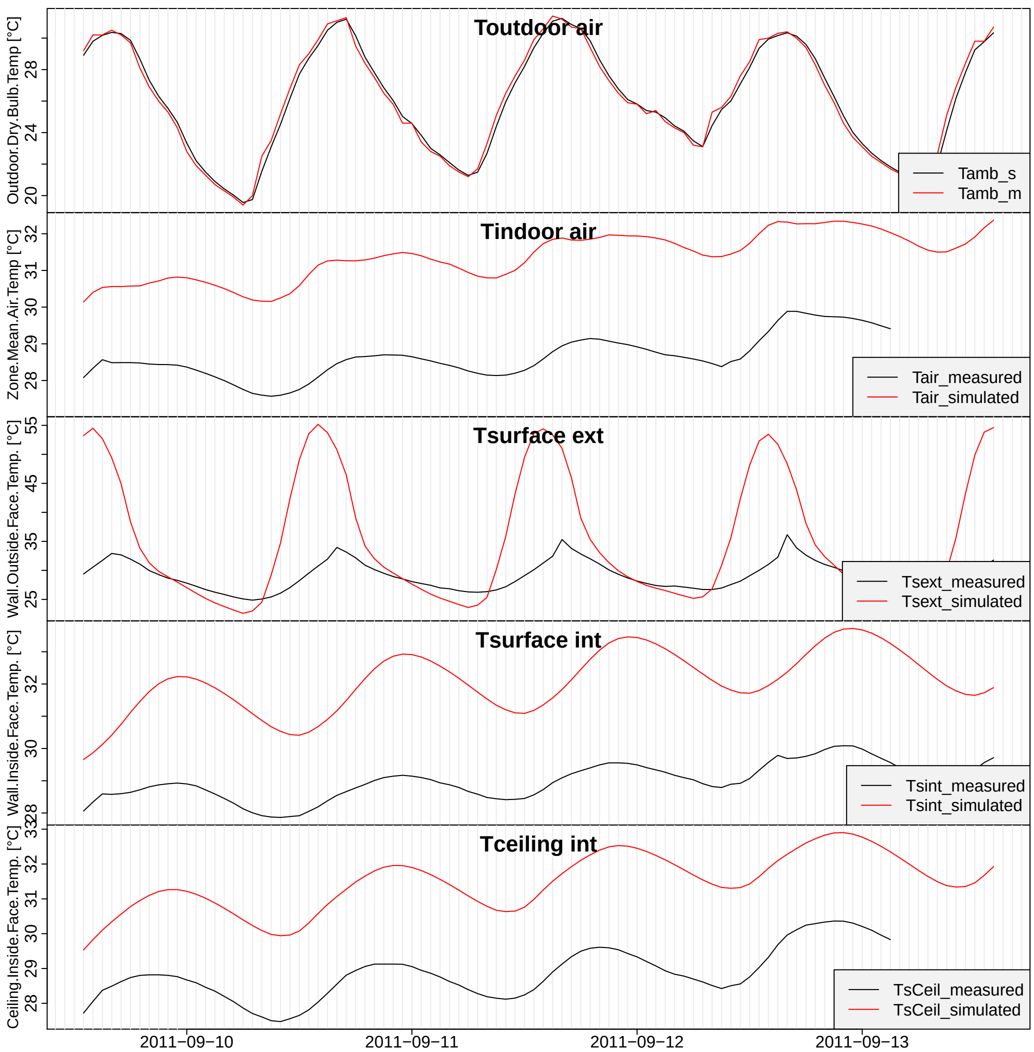


Figure 4.6: The Figure shows that using real data climate file as input in the simulation, and classical material characteristic, from predefined database, produce a model with large discrepancy if hourly temperature are considered. Model Calibration are necessary step into modeling procedure. This comparison is realized using monitoring data provided by the wireless sensor network developed in the context of this thesis.

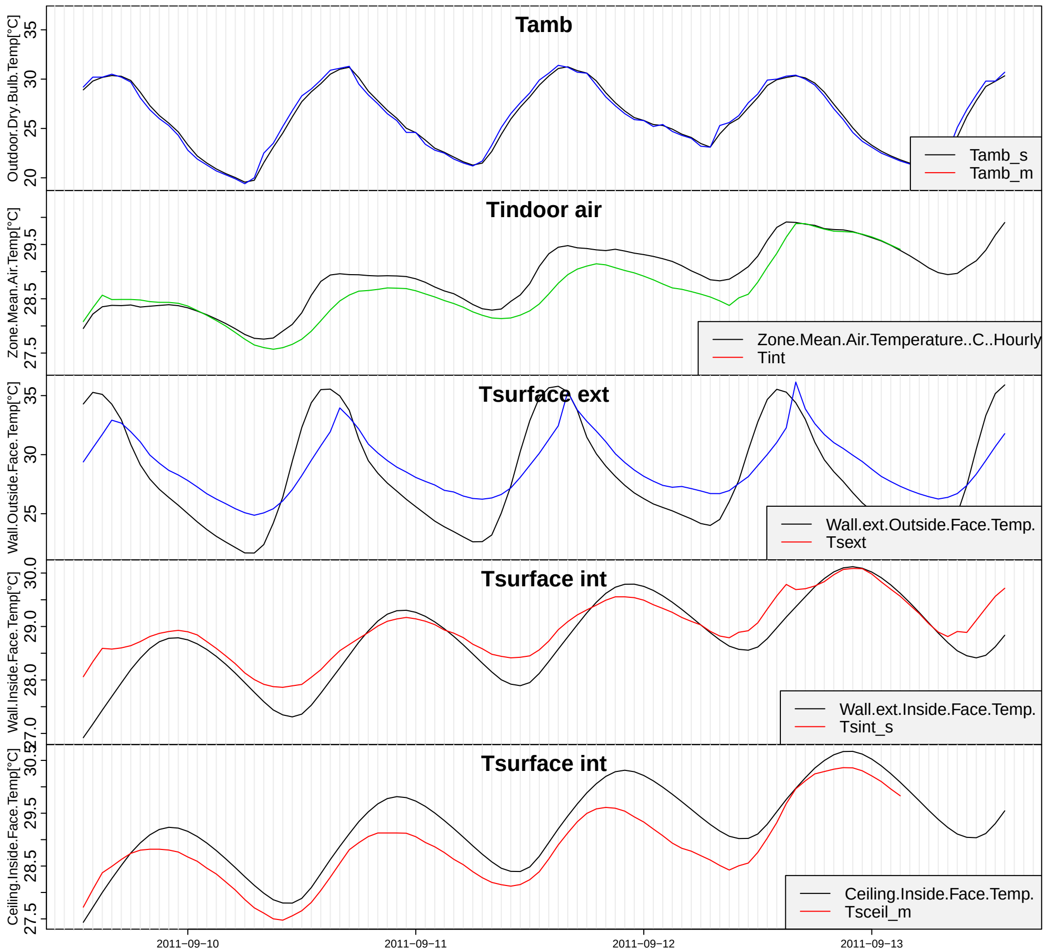
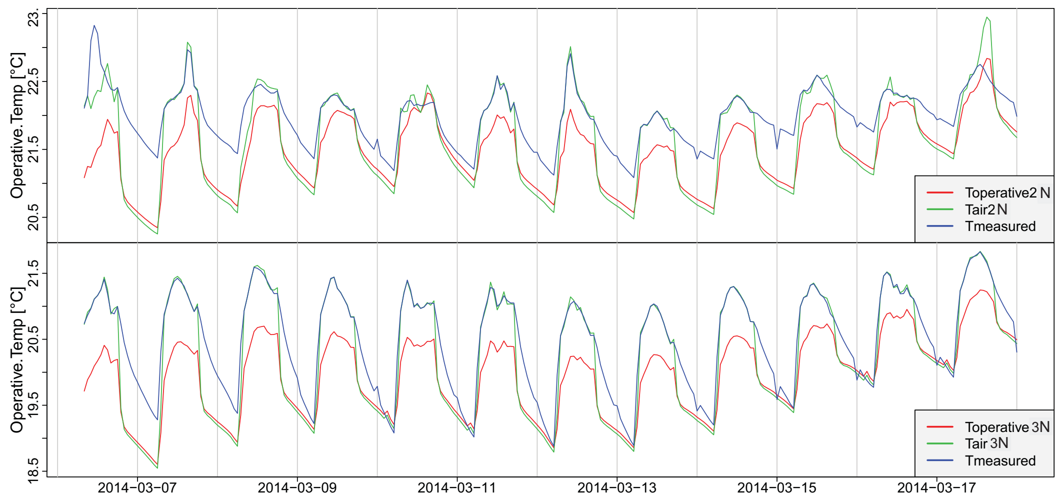
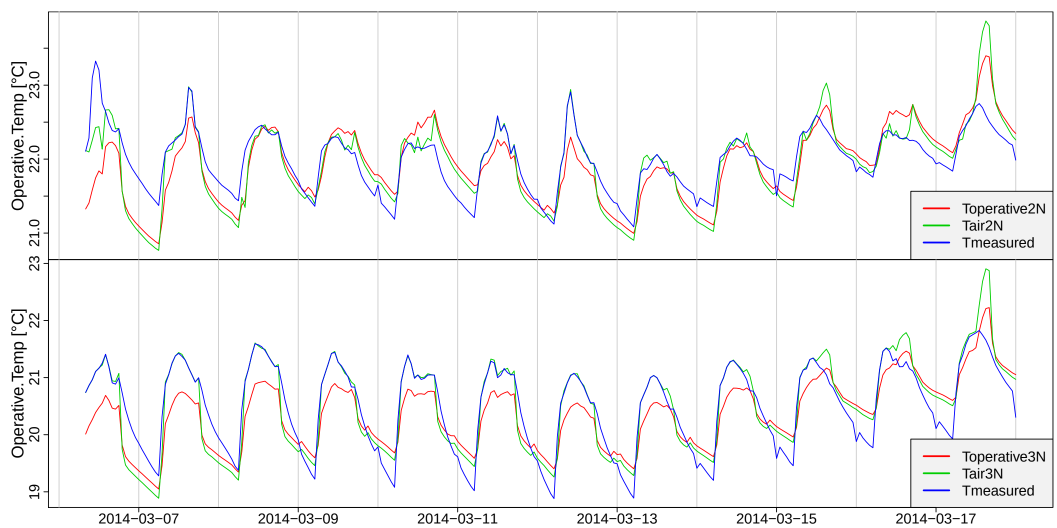


Figure 4.7: The Figure represents the result of calibration procedure proposed in this thesis, considering also the inclusion in the metrics of the surface temperature.



(a) Not Calibrated model



(b) Calibrated model

Figure 4.8: The improvement of model with the winter calibration are presented. In this case the fitting is applied to the indoor air temperature of each room. When systems are switched off the discrepancy of model results evident and is due to the different thermal response of the model respect to the real building.

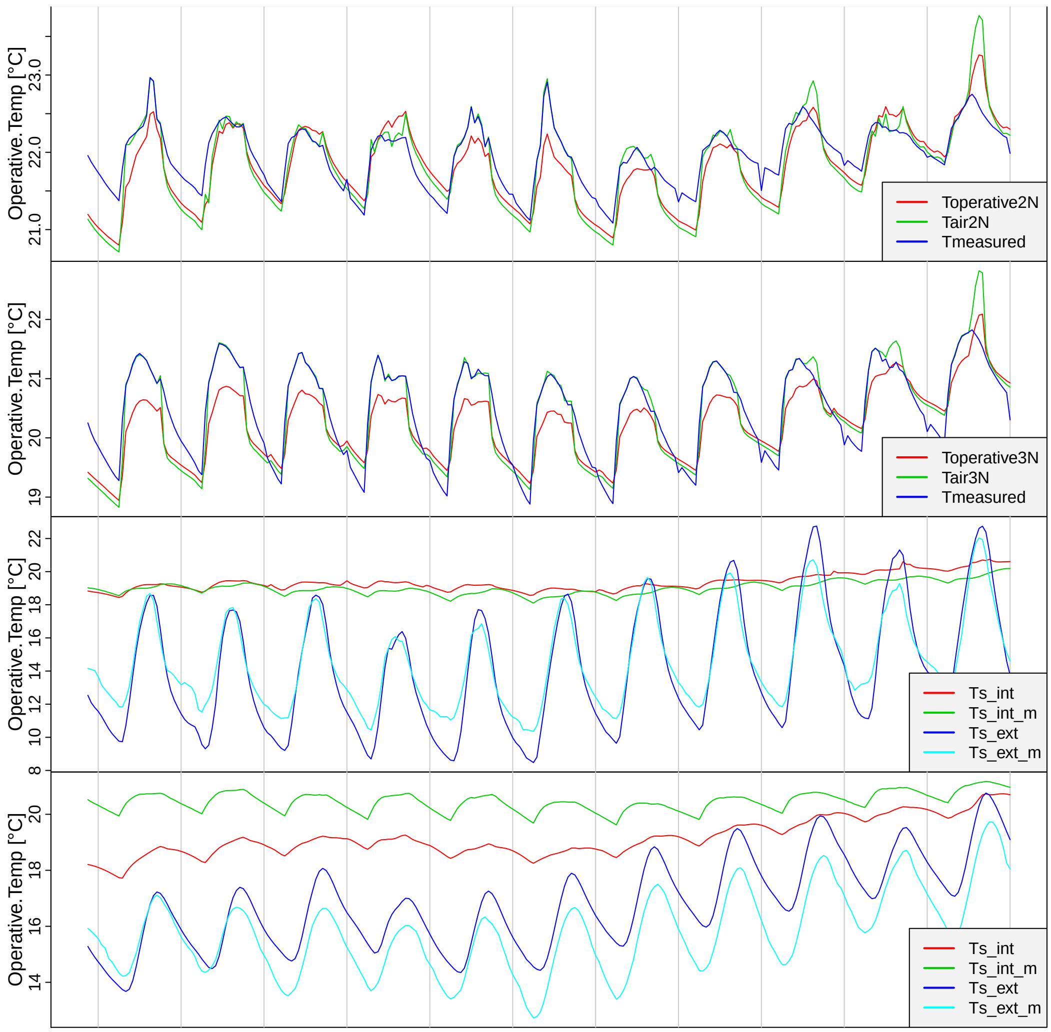


Figure 4.9: Figure related to the calibration on indoor air temperature. The Figure show the differences of model from the real building considering the surface temperature.

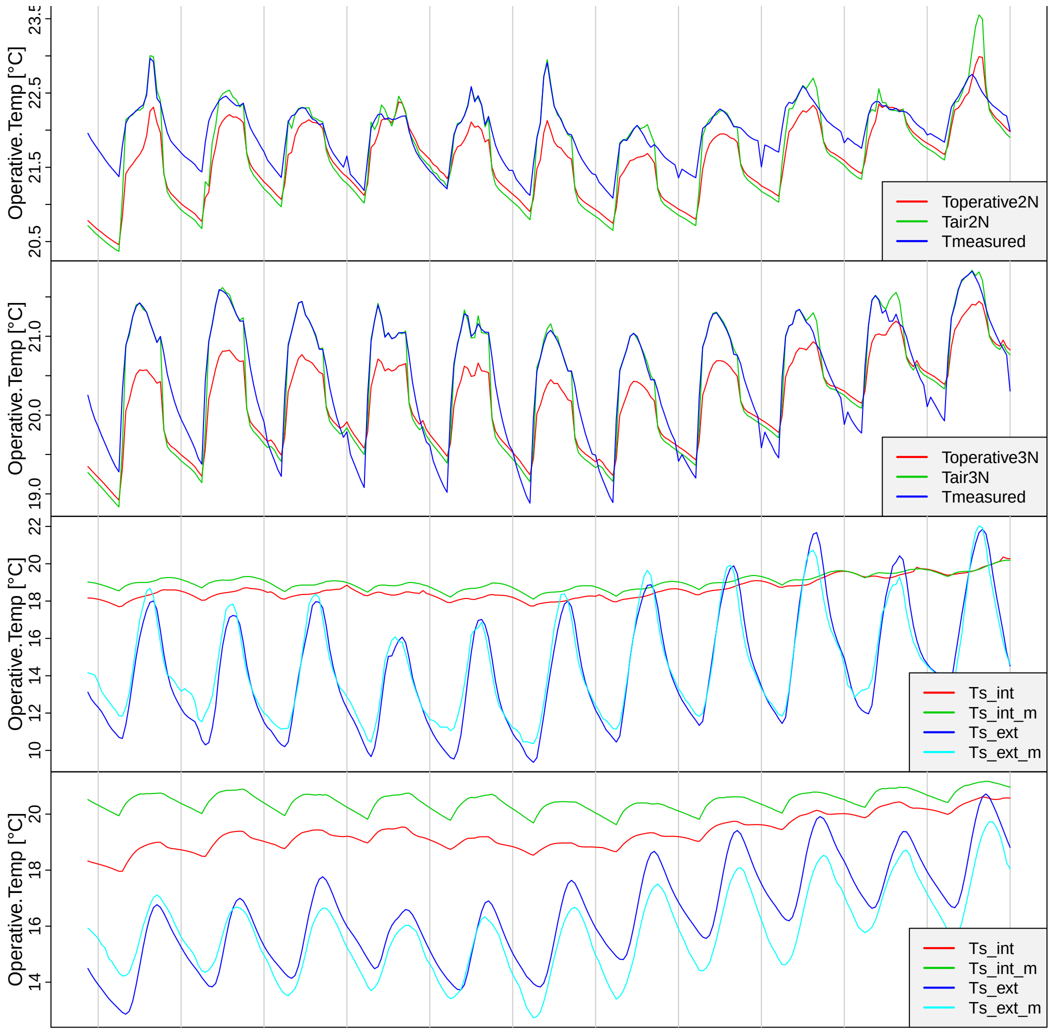


Figure 4.10: Figure related to the calibration on indoor air temperature and surface temperature. The Figure show the differences of model from the real building considering the surface temperature.

Chapter 5

Design Optimization

This chapter describes the design phase of the refurbishment. The approach proposed is developed considering it should take part of more complex process, the decision-making process, for the selection of measures to implement considering also qualitative criteria of conservation's aim. The concept behind is presented. The process of design is divided into two main part. Firstly control strategy, occupancy behavior and natural ventilation are treated separately to analyzed the influence of them on the energy balance. Secondly all them are considered together in the model adding also other active and passive strategy. The resulted model is used inside an optimizer for the selection of possible measures to implement. Multi-objective optimizer is selected and the objective function are presented. The result is a Pareto front vector or possible configuration of the refurbishment considering all the interaction between occupants behavior, building response and control strategy.

Contents

5.1 Concept development

The optimization procedure propose in this thesis is though like a part of more complex and multidisciplinary process, the decision-making process for the refurbishment of building. Different research activities propose methods and procedure to help the stakeholders involved in this process to take right decision. Brandt [48] and Wittchen [49] proposed e methodology for office building based on use a database infrastructure TOBUS which collects the information related to the "as-in-state" condition of the different components of buildings and cost related to the single intervention. The main phases of their approach are: 1-Collection of documents(energy bill, geometry and construction type, etc.), inventory characteristic of building and installation, identify major problem to personal interview; 2-Use questionnaires to take information from employees on IEQ; 3- One day visit survey focus on specific question results from previous steps in order to perform TOBUS analysis; 4-perform analysis with TOBUS that incorporate four categories of analysis (degradation, functional obsolescence, energy, IEQ). This methodology give a gross estimation of needs of the building in multi-criteria way and could suggest scenario of improvement. The limitation of the infrastructure for old building is stressed starting from the authors, as the difficult to obtain the necessary data for more detailed analysis. They consider as priority to give the possibility to join this database with other tool for more detailed analysis. Kaklauskas [50] proposed a deeper analysis of possible strategies following a multi criteria approach. Several step of qualitative analysis for the selection of feasible solution are performed considering as input an exhaustive number of quantitative evaluation carry out by energy simulation. They can be the result of parametric study or optimization. The qualitative analysis is performed by giving a score to many aspect of the project and then summed together to perform the global index. This approach look more promising but several question should be formulated on the qualitative part: Which is the criteria to give one score or other? which is the way to balance the weigh of the different criteria? This question could be answered in the context of homogenous building type and for commercial or modern buildings, but probably not in the context of historic one. for example which is the criteria to assert that one building has value higher than other? And if they reference at to different century and comunity? The good aspect of this approach is that could consider as input deeper energy analysis and optimization technics. Juan [51] proposed a more integrated procedure where sustainability criteria are inserted in a global optimization process. In this case the criteria are more generalized because is base of international protocol and one search algorithm is use to select the combination of retrofit the maximize the score. In this approach the researcher doesn't take into accounts a deeper energy analysis of building that could suggest other possible solution but it is a top down approach. Other example of multi-objective optimization [52],[53] consider static building energy balance.

For historic building the Top Down approach, based on standard and reference cases, could not be already developed because of lack of several and well documented experience on this class of building. The applicability in future is also doubtful considering the singularity of each building, but should be verify. The effective assessment of pre - intervention condition and the real impact of energy measures adopted have to be included in the documentation used to develop the Top Down approach. As well organized qualitative criteria, if their are possible to develop, should be incorporate if a framework of evaluation to take into account the value and the peculiar characteristic of each building. This approach could be useful as screening of possible solution. From the other hand the bottom up approach fill the gap of knowledge but is more tailored on a specific building and specific problem. A combination of both is advisable and should be a theme of specific research.

Considering this context, the idea behind this thesis is to give a flexible infrastructure to analyzed in deep the real behavior of the building, as well as to allow the evaluation of several possible energy efficiency measure, each one optimized to satisfy different objective, and considering the limitation characterized each building. The result is a set of optimal and nearly-optimal solution and not just the one that maximizes the energy saving. This set should be a solid base which the multidisciplinary team could analyze and use for select the final set of measures to implement: a kind of negotiation space (Figure:5.1) between preservation and energy efficiency measures, usually in contradiction, where the selection of the measure to adopt for each building will be the best compromise, hence optimized considering quantitative and qualitative aspects. As discuss along this thesis a qualitative selection is a necessary phase, because many aspect that are advisable to take into account are not easily translatable into general and quantitative criteria. However a solid assumption should be based on solid quantitative study, to assess the real as-in-state condition as described in previous chapters, and to implement pre-evaluated solution based on model that are representative of the building and its possible configuration. This allows to have confident control of the process. The approach presented can be use for different configuration of the design process. The qualitative analysis could take place at the end, at the beginning or both. Cycling process produces better results as is well known. The flexibility on the optimization itself and on the definition of the objective is one of the main advantage of that design process.

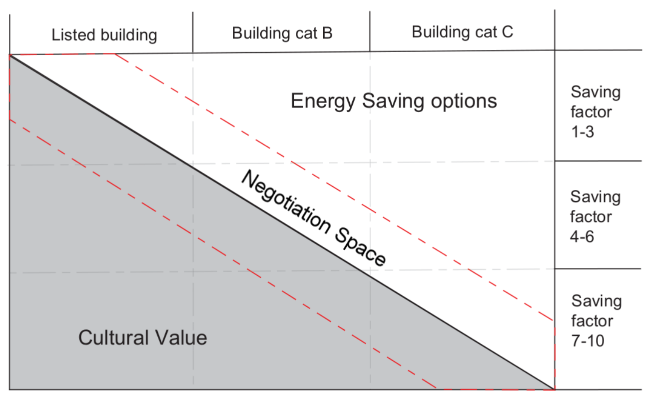


Figure 5.1: In the context of historical building it is more important to take the right choice. Looking just to the more efficient measure is not enough. It is more valuable to look for the optimized solution for the specific case.

The design phase presented is divided in two main phase. Into the first one the focus is the develop of the model and the separate analysis of the two main aspect that influence the comfort condition and the consumption: the occupancy behavior model and the control strategy. As result the more promising strategy is selected to be part of the set of energy saving measures. The reason of that is that occupancy behavior is a part of the complex interaction inside the building energy balance and should be considered for make the design more reliable. As the energy consumption depend on the control strategies and these interact with building response and occupancy behavior, control strategies should be also included into early design phase to allow the retrofit design to take the most benefit from that interaction. Into the second phase the retrofit strategies are selected and the optimization is performed for different configuration.

5.2 Modeling

5.2.1 Building model

The building considered in this thesis is the main building of Municipality of Bologna in Italy. The entire building is a complex combination of several units with different types of construction that are superimposed over the centuries and with use of heterogeneous destinations. To facilitate the verification of the procedures proposed in this thesis I have chosen to focus on one part. This is characterized by a north-south orientation, with high thermal mass and intended for office use. In the following part of the thesis I will refer to part analyzed call it "Office block". More detailed information regarding the building and its characteristic are provided in the section 2.2.

For simplicity, a representative zone of office building is modeled for the investigation propose in this thesis. The area considered has same occupancy schedule and is served from the same systems and plant. This reduced model 4.1 allows to decrease the computational cost maintaining the characteristic of real building and allows doing a representative energy analysis of entire building. There is not need to model the entire building. The model is six thermal zone and describe the last two floor and attic of the entire building, considering two thermal zone each floor, one south and other north oriented. Model physical dimensions, material constructions, schedules, loads, and HVAC systems are consistent with real building. With the exception of the North and South facing walls, all model exterior surfaces are assumed to have adiabatic boundary conditions, following from the assumption that this representative zone is surrounded by other similarly conditioned spaces. The model also includes manually operable windows, an heating system with radiator, and an air flow network to account for natural ventilation. Depending from the model analyzed in the phase of design of refurbishment, also other features are considered in the model like: a dedicated outdoor air system, or automatic operable window, different type of insulation and windows.

5.2.2 Occupancy Behavior model

Occupancy Behavior model selection

Occupants affect the thermal zone within which are inserted to create a comfortable situation [54]. They adjust blinds, windows, door, lights and temperature setpoints. Occupants itself, with their presence, introduce a production of moisture, CO_2 and heat gain. All of this, result in changing of space load, comfort criteria and performance of HVAC systems. Modern energy building performance simulations do not take in consideration of realistic interaction of occupancy behaviour and building energy balance. Common way is fixing some schedule for heat gain at different setting for different period of day and years.

During the last years several researchers develop algorithm to predict the probability that occupants do some action or take some decision. This algorithm are derived from data collected in field study and depend also from the particular climate and region. They form a good base for a developing a generalized model, some improvement in that direction are presented in [55].

The building considered for this thesis is cooled by natural ventilation that depend on occupants decision since windows are manually operable. The standard design criteria for this kind of building follow EN 15251. Including this model in the design allows the modeler to create a better base case, and implement retrofit strategy that are more close to the real behavior of the building. It is well known that increasing the insulation of the building, generate the increase the cooling load, and the designer could decide to insert a cooling system also in building where it was not present before the refurbishment, with the increase of energy used in summer. One of the reason is that the occupancy behavior model is not taken into account, without consider that probably, the occupants decide to open more time or longer the windows with the increase of heat loss. This consequence has to be evaluated before take the decision to install a cooling system. I choose to implement the model strictly related to the EN 15251 to satisfy this criteria in the design phase, and take in account the heat loss by natural ventilation during summer. The model considered is implemented from Rijal [56]. It is based of the study of Humphreys who develop an algorithm to predict the state of a window based on indoor and outdoor temperature using probability distributions drawn from field studies in 15 buildings in the UK between March 1996 and 1997; some of this buildings were naturally ventilated and other were air conditioned in order to understand the comfort band for different environment. The algorithm considers outdoor and indoor temperature and comfort level and gives a probabilities that occupants take a decision to do an action (open, close or leave open the window). The main advantage of this method is that, it comprehends the impact of adaptive comfort, driven from window opening behaviour, specific to the building and climate rather than making more generalised assumptions.

Occupancy Behavior model implementation

The Building Controls Virtual Test Bed (BCVTB) is a software environment that allows expert users to couple different simulation programs for co-simulation. It is particulary useful to implement advance control strategy in simulation tool. As first, this tool was selected for the implementation of manually operable window model. Tanner [57] analyzed several control strategy in a mixed mode building focus the attention of the influence of occupancy behavior model on model predictive control. Base on his study it was evident that using BCVTB produce extra input file increasing the computational time. In second instance it was chosen Energy Management System (EMS), a subsystem of Energyplus that allow modelers to manipulate the state of virtually any simulation input, schedule, or control parameter. The computational time and the complexity of simulation infrastructure are reduced, and this will be a value for implemented also the optimization into the design phase.

5.2.3 System control strategy

The Energy Building Regulations aim to ensure the health and safety of building users, promote energy efficiency, facilitate sustainable development. They provide a framework of flexible functional requirements within which buildings can be designed and constructed. The role of building control is to help ensure that the building works accord with these objectives, but at the same time this service should be effective, efficient and minimise cost and delay for those carrying out such work. The attention on the control and more in general on the management of building system grow in the last years due to the need to achieve better performance on buildings. It is well accepted that energy saving are achievable not just with a good design but also with a well planned commissioning and management of the operational phase. The benefit of Building Management System (BMS) are provided to the owner, the tenants, the occupants, the maintenance company. In the context of historic building should be even more important since the needs on reducing consumption join the preservation aspects. The investigation on the control strategy should be of primary importance starting from the design process, specially for refurbishment, where many limitation are provided in the building itself since that old building don't have construction that respect the requirements today in force, and often is not possible change enough the building structure.

Historic building have some characteristics that produce strong interaction with the HVAC system implemented, like thermal mass, higher inner height of rooms, higher windows surface area. This interaction should be investigated to verify if some energy efficient measures could take benefit of them. In the building taken in consideration for this thesis, I considered the interaction of system with thermal mass, and the natural ventilation benefits for the improvement of comfort and the reduction of consumption. This features are investigated separately and included in the design optimization.

Automatic window control strategy

The Automatic window control are often use in high performance buildings to achieve energy saving combining natural ventilation with HVAC system to reduce the energy consumption of mechanical systems. This strategies are here investigated to verify if natural ventilation could be use, by controlling the windows to improve the comfort condition during the summer. In the building considered there is not cooling system, just few inefficient single unit splits are present, because the temperature grow up to discomfort level during part of summer. The shape of the building and the context of historic building suggest to verify if some improvement are possible by low level refurbishments and comparing them with more deeper intervention like installing new system able to ensure better comfort condition. The goal of investigation is to verify if night ventilation is possible, to cool down the building, even in a humid climate like Bologna. More over if it could be able to control the humidity level inside into acceptable level. The strategies considered are presented in Figure 5.2. In strategy (a) windows are opened at night during summer when the condition on humidity are satisfy. Strategy (b) are similar to (a) but with condition on temperature. In strategy (c) windows are opened during winter at any time to reduce the Relative Humidity inside. All strategy have $1°C(2\% for RH)$ deadband to prevent excessive cycling on control. Since during occupancy hours open and close of window is leaved to the occupants the automatic control do not take control of them. The strategy are implemented into Energyplus model using EMS subsystem, like Occupancy behavior model for ventilation during daytime. Strategies with condition on temperature and humidity are considered separately and joint together to investigate this strategy on humid climate. Good climate condition that satisfy both criteria are rare (plot 1-3 and plot 7-9 in Figure 5.3 are identically as just conditions on RH are satisfy). The control condition on temperature cools the building but increase the inside RH. This generate large daily swing of RH, since that opening the windows during occupancy hours has the opposite effect. Strong fluctuations are generally to be avoided and the strategy using RH is investigated stressing this concept and verifying if natural ventilation could be used to control relative humidity. During winter the control doesn't take action, during intermediate seasons and summer the control keep RH lower then 70% almost all time and could be considered valid alternative to dehumidification system for part of the year. The investigation consider different setpoints and value presented in Figure 5.2 represent the best configuration for the model. Each thermal zone has separate control and all them are presented in Figure 5.3.

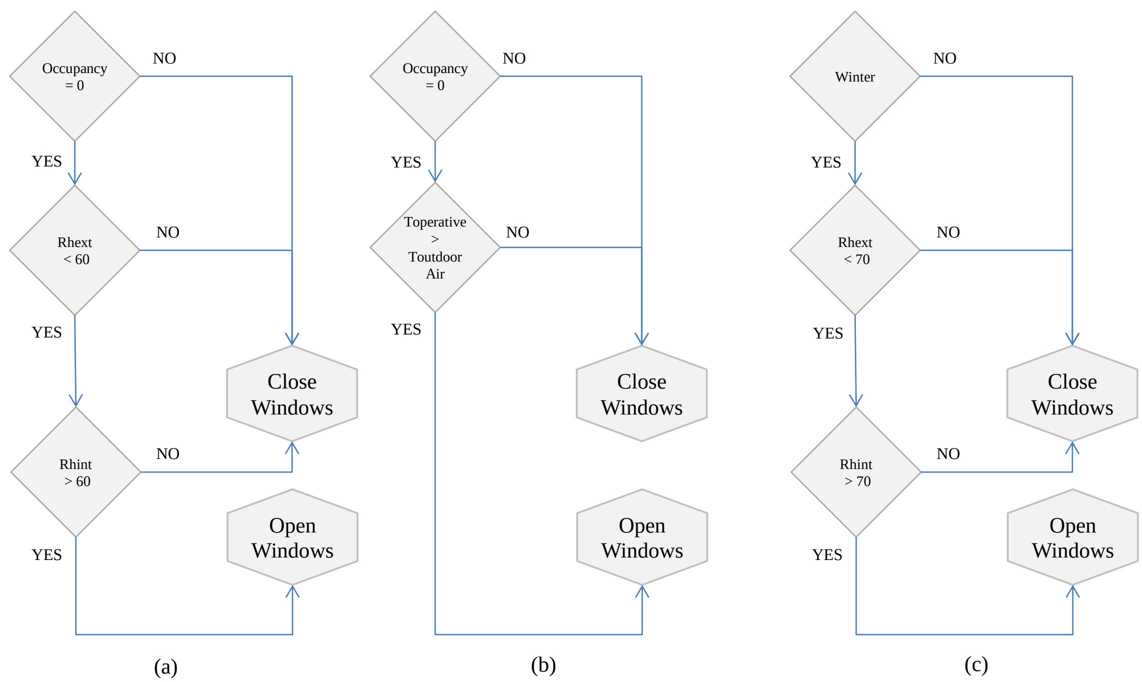


Figure 5.2: Automatic Control strategy: (a) Humidity priority during no occupancy time in summer,(b) Temperature priority during no occupancy time, (c)Humidity priority during winter

An other meaningful evaluation is the assessment of the improvements achievable with automatic window control strategy compared with a traditional manual one provided from the occupants. Figure 5.4 shows no improvements in therm of lowering of indoor temperature. On contrary the effect on humidity regulation are undoubted. In general Automatic Control are probably more effective because is not subjective. On the other hand the subjectivity satisfy better the specific comfort condition of each person. Person can not predict the climate condition and the evolution of indoor climate for the next hours and the consequence on energy consumption. It is probably better, at least give them same suggestion, on how to manage their space through visual signal, on how is better to ventilate or not, or consider some hybrid configuration in which one part is configure as automatic to guarantee a fixed level of ventilation in specific period.

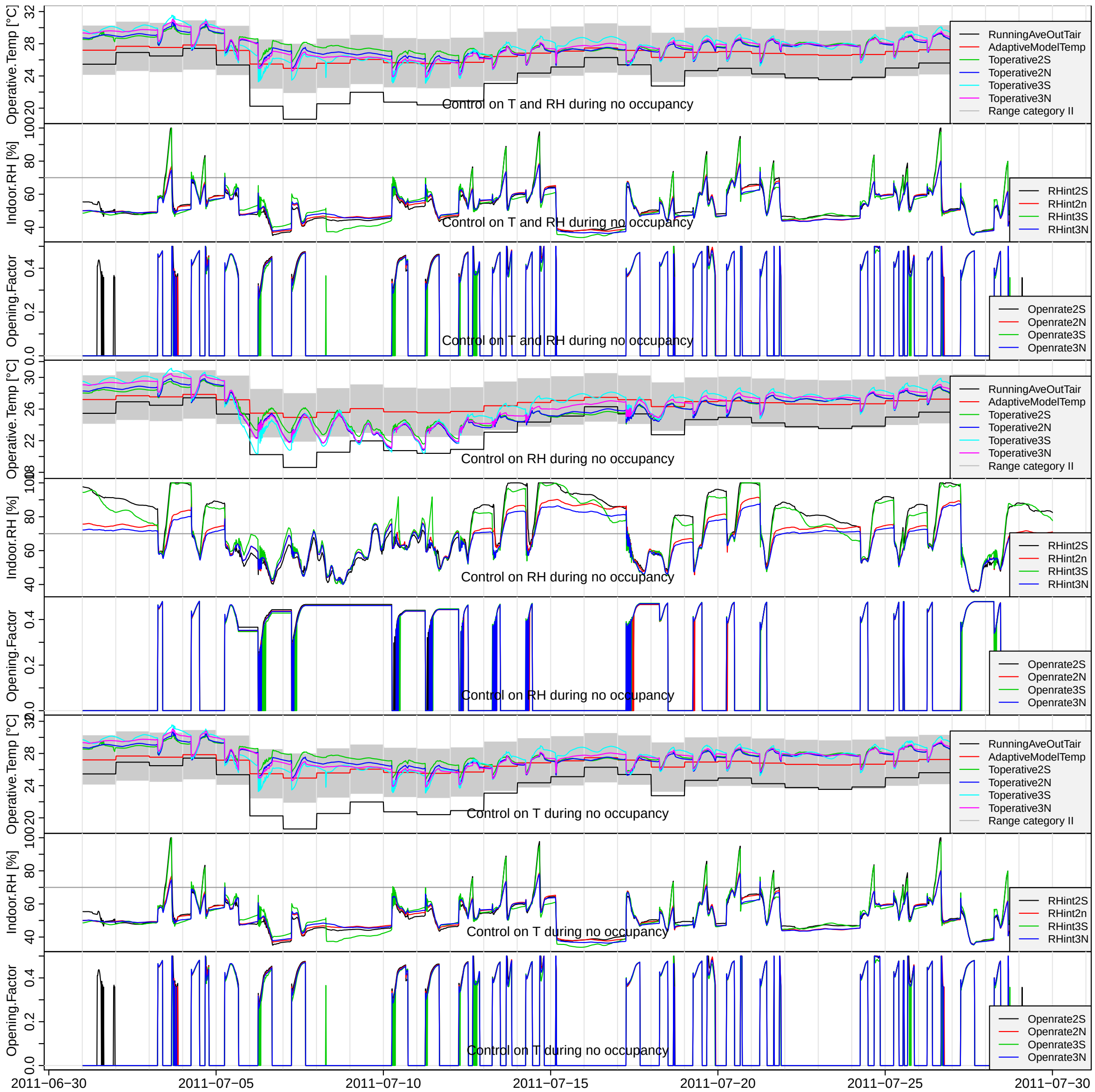


Figure 5.3: Window Control strategy: All graph consider Rijal model for occupancy model with window control. Plot 1-3 refer to control on T & RH during no occupancy period, Plot 4-6 refer to control on T during no occupancy period, Plot 7-9 refer to control on RH during no occupancy period. In each combination Operative Temperature (Top), Indoor Relative Humidity (RH) and Window Open Factor (Of) are presented for four model's thermal zone. Top is presented with Comfort band (grey area) according to EN 15251.

System control strategy

The heating to the building is provided from a gas boiler heater using radiators, classic heating terminals used in Italy. The heat is transfer to the zone by natural convection around the radiators and by radiation of the hot surface of the radiators. Several way of control are

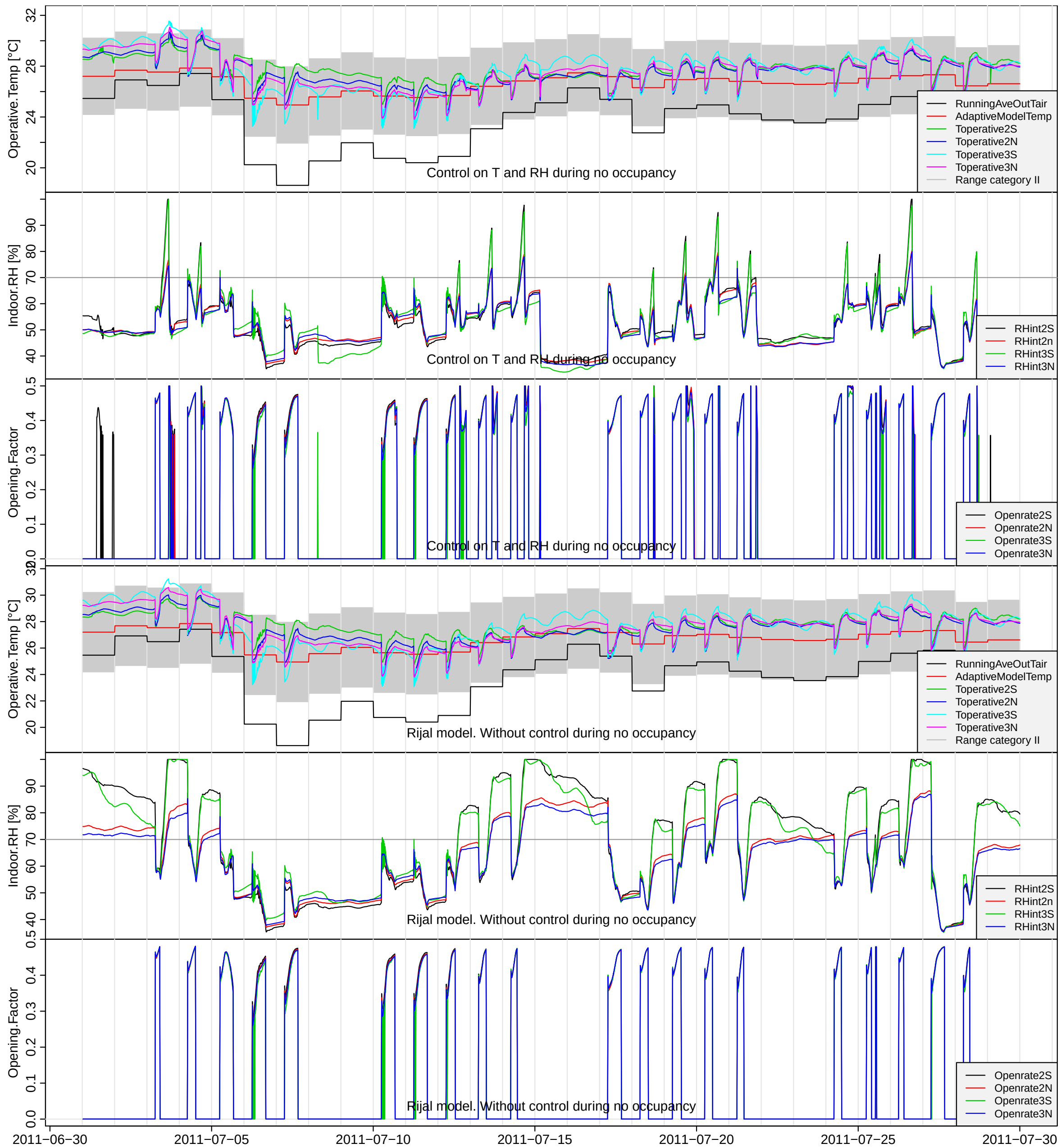


Figure 5.4: Occupancy driven ventilation rate and improvement derived from adding automatic control when people are not inside: All graph consider Rijal model for occupancy model with window control. Plot 1-3 refer to automatic control on T & RH during no occupancy period, Plot 4-6 do not consider automatic control. In each combination Operative Temperature (Top), Indoor Relative Humidity (RH) and Window Open Factor (Of) are presented for four model's thermal zone. Top is presented with Comfort band (grey area) according to EN 15251.

possible for this kind of system, using flow rate, temperature and combination of both. The model is built in Energyplus in accordance to the system already present in the building and a parametric study is performed on zone's setpoints, pump schedule, and radiator's power checking the effect on total energy consumption on a period of two months keeping comfort in the band suggested of EN 7730 ($-0.5 < PMV < 0.5$). The estimated consumption change consistent if we consider that system is working all time (strategy 1 to 7 in Table 5.1) or in intermittent mode (strategy 8 to 12 in Table 5.1).

Figure 5.5 show the Main Air Temperature and Operative Temperature during one week in winter. Blue and Red represent two different zone of the building. The two zone has similar infiltration rate while windows surface is higher in zone Red, as wall conductance as well. Considering strategies within plant always working, is possible to save some energy lowering the setpoint to $19°C$, the PMV for the worst zone floating around -0.45. The consumption of electricity for pumps is considerable compared to the total because of the many working hours.

If plant is shut down during the entire weekend and during holidays, a lot of energy should be used to came back to comfortable conditions, since the building is not insulated and has high capacity, and time of pre-heating will depends on systems capacity. In massive building like this example, could be more expensive then other strategy and lack of knowledge of system could generate uncomfortable conditions. To avoid it, in this systems are switched "On" 2 hours before working time. Also with this pre-heating time some no comfortable situation is generated in some Monday morning and I increase radiators power, like strategy 12 to satisfy the Standard.

The setback strategy achieve good result but some consideration should be taken. If just temperature setpoints is lowered the energy spent for pumping doesn't decrease a lot with a total saving around 5%, but a good control of indoor microclimate is generated. two different strategy to increase the saving are tested: lowering setpoints, if same strategy is applied all days, or using different setpoints for working days and holidays. They do not differ substantially in terms of savings.

Intermittent strategies prefigure better scenario of savings opportunities. Choosing the right time to heat the building, with a good setting of setpoints and taking in consideration the building dynamic and the outdoor climate has good potential. The first analysis presented here show a potential saving of 28% respect to a standard setback strategy.

It is important, to make these result achievable, having a precise capacity in the radiator, and from this comes the importance of design and to consider control strategy inside of the design phase.

5.3 Retrofit strategy

5.3.1 Constraint condition and protection

Principles of protection by the Authority for Cultural Heritage

Precise indications about the type of renovation admitted for buildings of historical and architectural interest are given the article n. 25 of the Urban Building Regulation Code. In particular the interventions can be:

1. the renovation of the architectural features and the restoring of altered parts: renovation of outer facades or interiors, philological re-construction of eventually missing parts of

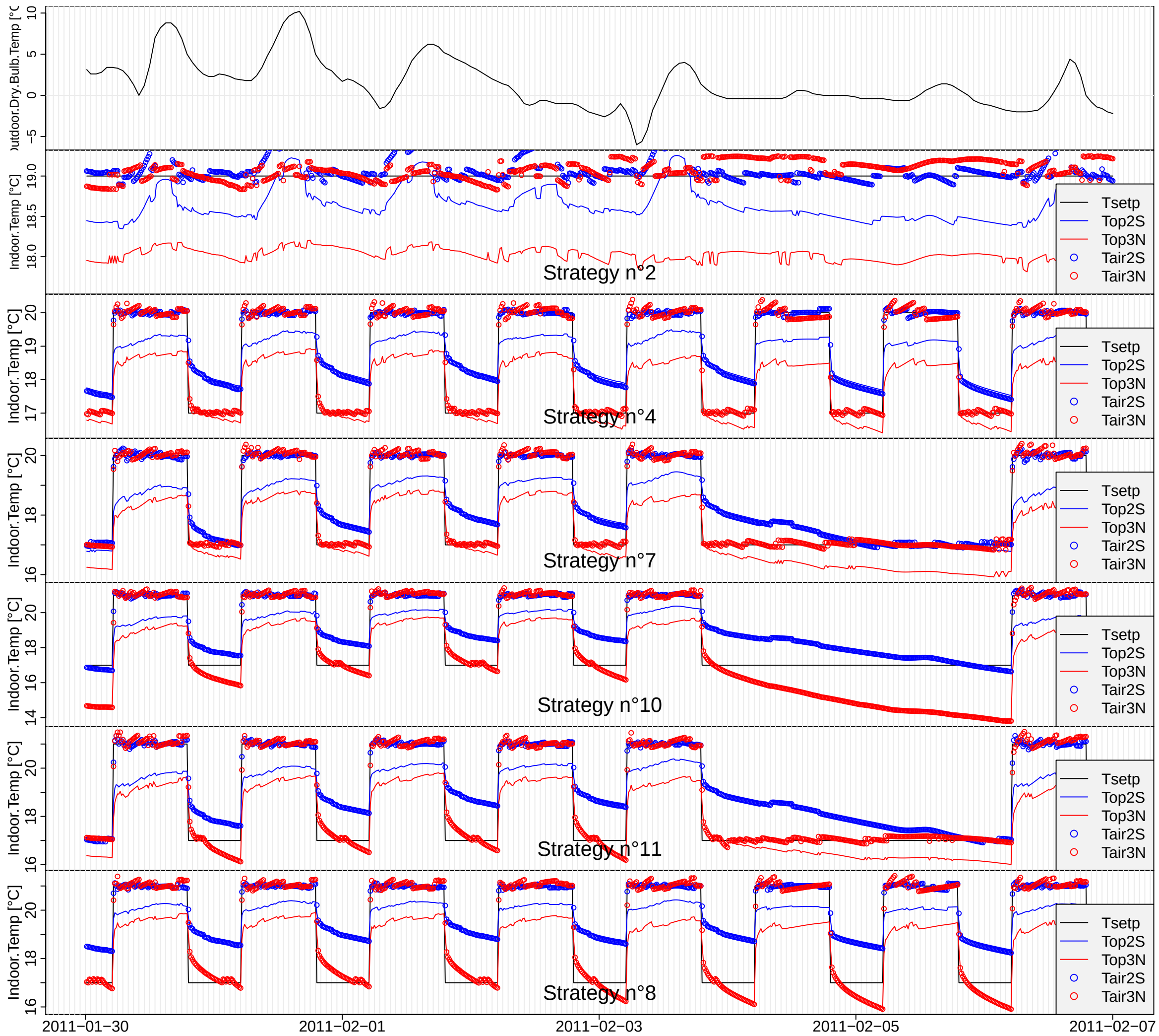


Figure 5.5: Winter control strategy for radiator

the building, conservation or restoring of shared spaces like courtyards and gardens;

2. the consolidation with substitution of un-repairable parts without modifying the position and height of major walls, lofts, ceilings, stairs and roofs (with re-making of the original roof covering;

3. the removing of elements that have been recently added or are incoherent with the original scheme of the building;

4. the insertion of essential technological and sanitary installations, respecting the previously given constraints.

The building is qualified as building of historical and architectonic interest in the Urban Building Regulation Code, and therefore admits only respectful interventions of renovation

Strategy	Result	Electricity System	Gas system	Tot system
1	Energy[kWh] Cost[€]	711 121	2401 156	3113 277
2	Energy[kWh] Cost [€]	711 121	2169 141	2880 262
3	Energy[kWh] Cost [€]	608 103	2406 156	3014 260
4	Energy[kWh] Cost [€]	671 114	2177 141	2848 255
5ⓐ	Energy[kWh] Cost [€]	703 119	1999 130	2702 249
6	Energy[kWh] Cost[€]	641 109	2197 143	2837 252
7ⓐ	Energy[kWh] Cost [€]	686 117	2030 132	2716 249
8	Energy[kWh] Cost [€]	410 69	2164 141	2574 210
9	Energy[kWh] Cost [€]	413 70	1925 125	2337 195
10ⓐ	Energy[kWh] Cost [€]	293 50	2022 131	2315 181
11	Energy[kWh] Cost [€]	493 87	2222 146	2715 233
12	Energy[kWh] Cost [€]	293 50	2022 131	2315 181

Strategy Description

(1)-Radiator always On. Tsetpoint=20°C cost
(2)-Radiator always On. Tsetpoint=19°C cost
(3)-Radiator always On. Tsetpoint=21°C(17) h=5-19 (h=0-5&19-24)
(4)-Radiator always On. Tsetpoint=20°C (17) h=5-19 (h=0-5&19-24)
(5)-Radiator always On. Tsetpoint=19°C (17) h=5-19 (h=0-5&19-24)
(6)-Radiator always On. Tsetpoint working days=21°C (17) h=5-19 (h=0-5&19-24).Tsetpoint other days = 17°C cost
(7)-Radiator always On. Tsetpoint working days=20°C (17) h=5-19 (h=0-5&19-24). Tsetpoint other days = 17°C cost
(8)-Radiator availability all days:h=5-19 Tsetpoint=21°C
(9)-Radiator availability all days:h=5-19 Tsetpoint=20°C
(10)-Radiator availability working days:h=5-19 Tsetpoint=21°C
(11)-Radiator availability working days:h=5-19 Tsetpoint=21°C. Other days Tsetpoint=17°C cost
(12)-Radiator availability working days:h=5-19 Tsetpoint=21°C (like 10 increasing power installed)
ⓐ-This strategies do not provide good level of Comfort

Table 5.1: Radiator Control strategy: Analysis on January and February

and maintenance. The typologies of intervention and modification admitted are described at the art. n. 57 of the Building Regulation Code, specifically with requisites nr. IS 1, 2, 3.

In particular, the Regulation Code prescripts to preserve the original integrity of every architectonic, artistic and decorative element of it. For the preservation of original characters of the building, the limitations, given by the requisite IS nr. 1 of the Code, are the following ones:

Strategy	Result	Electricity System	Gas system	Tot system	Electricity Equip&Light
1	Energy[kWh] Cost[€]	2134 363	6173 401	8307 464	2572 437
2	Energy[kWh] Cost [€]	2660 452	8468 550	11128 1002	2572 437
3	Energy[kWh] Cost [€]	2148 365	6149 400	8298 765	2572 437
4	Energy[kWh] Cost [€]	1863 317	5746 373	7609 690	2572 437
5	Energy[kWh] Cost [€]	2291 389	7073 460	9364 849	2572 437

Strategy Description
(1)-Radiator with night setback & DOAS On during Occ hours
(2)-Radiator with night setback & DOAS Always On
(3)-Radiator with night setback & DOAS with NatVent in Concurrent mode
(4)-Radiator with night setback & DOAS with NatVent in ChangeOver mode during Occupancy time
(5)-Radiator with night setback & DOAS with NatVent in ChangeOver mode during No-Occupancy time

Table 5.2: Performance of Radiator system with DOAS considering different control strategies for DOAS.

1. to preserve and conserve the building roof in its original shape and consistence, and this concerns specifically interventions like the insertion or addition of chimneys, skylights, gutters or pluvials; in particular, in the conservation of the original shape of the roof, every new component put in substitution must have the shape and colour of the previous original one.

2. roof insulation and ventilation must be extended to the whole roof surface, keeping the thickness inferior to 20 cm, eventually rising the roof's height;

3. to insert small chimneys for airing in order to conserve the original shape of the roof, putting them close as possible to the roof top, avoiding products made of cement, fibre-cement, or plastic ;

4. to keep the technological installations for the reception of signals (like parabolic antennas for TV/Earth satellite signals) within the number of one for building, placing them inside indoor locations or on secondary pitches;

5. to satisfy the need for lighting of every indoor room, avoiding the opening of slots in the roof pitches, using only skylights, keeping these aligned to the existing ones, at a distance of at least 1,5 m from the gutter's line;

6. to keep the gutters and the pluvial in good conditions: in case of substitution, products made of plastic or zinc laminate must be avoided;

7. To keep the original shape and design of every façade: this concerns specifically the opening of new windows or the changing of the dimensions of the existing ones, the making of terraces, balconies, bow-windows or façade chimneys which is avoided for all the facades facing external public spaces. Only the re-opening of previous existing

windows is permitted. Modifying existing openings is allowed only if the façade overlooks minor patios or backing spaces and if it collaborates to the rational reordering of the façade image.

8. The impact on the façade of the positioning of electrical wirings must be reduced as far as possible; the wires and the installations components must be hidden in every possible way, as far as the norms on safety allow it, by locating them inside the building or under the paving of the street or the one of the porch, When on main facades, they should be aligned and positioned in order not to interfere with decoration or painted parts. It is avoided to install heat pumps, boilers, air conditioners, or motor condensing units on roof pitches, on main facades and under porches.

9. To extend the maintenance of original plasters and superficial coatings to every coated façade of the building, in order to preserve them as they were.

10. To keep the original window infixes and shading elements in every external perimeter wall. In case of substitution, which is admitted only if the original components cannot be repaired, the new inserted elements must have the same partition, material, colour and shape of the previous.

Then, for the preservation of the historical characters and of the original indoor distribution scheme of the building, the constraint, expressed by the requisite IS n.2 of the Code, prescript to maintain the original status; In particular:

1. adding new dividing surfaces is allowed only if they do not interfere with the façade's openings;

2. original dividing walls, even the secondary ones with no structural function, with architectural value or original decorations, original garrets or suspended ceilings with historical value must be maintained and renewed;

3. New lofts located inside the rooms must be fixed to the opposite wall facing the external one with windows and openings, at a distance of at least 2,40;

4. The whole area of the new single rooms located inside the historic building can't exceed the 30% of the whole area of the building;

5. new rooms can be located in the under-roof space only in case the electrical installations and wiring needed do not interfere with existing elements of architectural and historical value;

The constraint for the preservation of external and open spaces of historical buildings, given by the requisite IS n.3, prescripts to keep the original organization and conditions of gardens and courtyards. Therefore:

1. the installation of service lifts, anti-fire stairs or elevators, which cannot be done by means of enclosed volumes, is permitted only in minor courtyards and patios, on minor architectural value façade, positioning them outside of the optic cone of the inner major rooms or entry porches.

2. The ecological balance of gardens cannot be altered.

3. Original garden pavements and furniture must be maintained in the original conditions.

Limits and prescriptions arising from Area Regulations

According to the Emilia Romagna Regional Law, the Structural Plan of Bologna (PSC) has listed Palazzo d'Accursio as one of the "Buildings of Historical and Architectural Interest". Some of those buildings are also listed by the national law. The PSC has set the aim of the preservation (to maintain the value of the buildings of historical and architectural interest in the urban context or in the landscape) and some rules for any interventions and change in use. Any kind of intervention that involves those buildings which are also listed by the national law (like Palazzo d'Accursio) must be allowed by the authority for the preservation of the cultural heritage, namely the so-called "Soprintendenza ai beni architettonici". Therefore every action or use modification involving the buildings only listed in the PSC must respect the restoration criteria set. For more detailed rules, the PSC refers to the Urban Building Regulation (RUE).

5.3.2 Refurbishment Strategies Selection

In previous section all the limitation regarding the city center of Bologna are reported to stress how peculiar is an intervention on this kind of building. A well suited analysis, as presented in section 2.2, is a good way to understand which are the real condition of building, which is the needs and which are the possibility to achieve good results combining preservation and energy efficiency measure. A well suited analysis gives also valuable information for the screening of possible solution to design. From that analysis, it is clear that the control of heating plants are inefficient, that the heat losses are concentrated on exterior wall, unheated attic and windows. More over during the summer, uncomfortable condition are generated during very hot days, especially if natural ventilation is not activated from the occupants. Considering the limitation presented above I select same possible passive and active strategy that could be realized to reduce the losses during winter.

In particular the insulation of attic floor is selected instead of roof top insulation, this allows the cost reduction of intervention and to not touch at all the roof structure. The advantages of this solution is an easier control of thermal bridges, faster installation and easier maintenance. The insulation of exterior wall is considered just on the north wall 2.2(b), in accordance with the preservation of the aesthetic of the defence wall that characterize the Office Block in the south façade. The insulation has also several limitation on thickness and typology seeing it should be configured as removable solution. For that it was chosen a special insulated plaster than do not need anchoring system to the wall. The advantages are also the high water vapor permeability that guarantee the conservation of the wall and the good thermal bridges correction. The thickness allowed is the other limitation but same centimeters are possible to gain removing completely the old plaster. As the developed control strategies for the window allow a better control of indoor condition, the windows substitution with high thermal performance glass and frame, including also automatic system for opening and closing, is considered. All the windows will be substituted but different glasses are selected for south and winter façade. All this measures are implemented in the same model considering a parametrization of the performance of each one. I left the optimizer to chose all the value and just the constrain on upper and lower value are defined. As active solution I select radiator system and DOAS system, following the idea to preserve as max as possible without considering deeper intervention.

5.4 Optimization procedure

As describe in the section of concept development, the retrofit strategy selection should take into account different aspects, often in contradiction. Almost all real-world problems involve contradicting objectives. Also without considering the qualitative aspects of conservation issue and the identification of the 'value' of the building, that are in contradiction with energy saving measures, others contradictions come out into the building thermal balance. One is the relationship between comfort condition and energy consumption, basically to keep the indoor condition into a comfort band, we have to use energy, and the reduction of energy used, following to keep comfort, is not an easy problem, especially considering that Standards suggest that after the refurbishment the comfort band should be reduced. Other one is between energy consumption and investment cost for the refurbishment, to minimize both is not easy. Other is between energy consumption for heating and for cooling where often the energy efficiency measures that minimize the consumption for one season produce an increase for the other.

Several research activities were performed to solve each of this problems developing different tool able to perform an optimization of the parameters to minimize/maximize one objective. Some of this tool are general optimizer that are used in several context of optimization problems and other are more building oriented like GenOpt [58]. In this thesis we are looking for a set of optimal retrofit strategy were different objective are considered. For this application a multi objective optimization is selected. A general formulation of the problem is reported in Equation (5.1).

$$\begin{aligned}
&min\,[f_1(x), f_2(x), \cdots, f_N(x)] \\
&x \in S \\
&S = x \in R^m : h(x) = 0, g(x) \geq 0
\end{aligned} \tag{5.1}$$

This kind of optimization allow the minimization of more objective function together producing the Pareto front vector, or its approximation. A multi-objective problem is often solved by combining its multiple objectives into one single-objective scalar function. In more detail, the weighted-sum method minimizes a positively weighted convex sum of the objectives, as reported in Equation (5.2) that represents a new optimization problem with a unique objective function.

$$
\begin{aligned}
& min \sum_{i=1}^{N} \gamma_i f_i(x) \\
& \sum_{i=1}^{N} \gamma_i = 1 \\
& \gamma_i > 0, \qquad i = 1, \cdots, N \\
& x \in S \\
& S = x \in R^m : h(x) = 0, g(x) \geq 0
\end{aligned}
\tag{5.2}
$$

This technic has some problems. Firstly the weight should be defined from the modeler and it is not clear a-priory if one objective is more important than other. More over weighting coefficients do not necessarily correspond directly to the relative importance of the objective functions. The relationship between the objective function weights and the Pareto curve is such that a uniform spread of weight parameters, in general, does not produce a uniform spread of points on the Pareto curve. Non-convex parts of the Pareto set cannot be reached by minimizing convex combinations of the objective functions. Also other technic to solve the problem by aggregation of the objective function are developed but other approach look more promising for the application considered, in particular those that try to reach an approximation of Pareto front through a nondominated sorting approach[59]. Non-dominated Sorting Genetic Algorithm-II (NSGA-II)[60] is standard approach and Selection Evolutionary Multiobjective Optimiser Algorithm (SMS-EMOA)[61] is an improved approach, and they will be use in this thesis.

The design optimization procedure utilized is presented in Figure 5.6. Different strategies of retrofit are developed building different Energyplus models. For each model one optimization is performed varing same selected parameters, output of Energyplus are post processed to create the objective functions for each iteration. The objective functions to minimize are the differential investment cost (dIC) , the differential life cycle cost (dLCC) and the hours of discomfort during occupancy time in one year(HnoConf). This objective are in contradiction and they are all important in the definition of the measure to select. The dIC considering the initial investment cost of each candidate. The dLCC is use to considering the reduction of the consumption and for analyze the economical feasibility of the refurbishment. The HnoConf is used to analyze which solution generate better comfort condition, but also to compare solution that don't have consumption connected to the measure, for example different window control strategy for the same measure adopted. Detailed information are presented into the next section. The flexibility of infrastructure allows to consider more objective functions depending from the specific need. For example it could maintenance cost, payback time, peakload power, hours of system use in specific time windows and so on. Sustainability aspects and also others criteria could be added.

The result of optimization procedure is a vector of solutions that approximate the Pareto front surface of the objective space. Pareto optimality, is a state of allocation of resources in which it is impossible to make any one individual better off without making at least one individual worse off. The vector is that analysed to select a group of solution that satisfy specific constrains. This sub selection will be used to obtain general indication on the performance that are advisible for each measure and to helping in the selection of final measure to implement. The qualitative analysis that will take place in the end have quantitative consequence on the performance. The formulation of the problem allows to have an overview of that consequence immediately without performing other simulations.

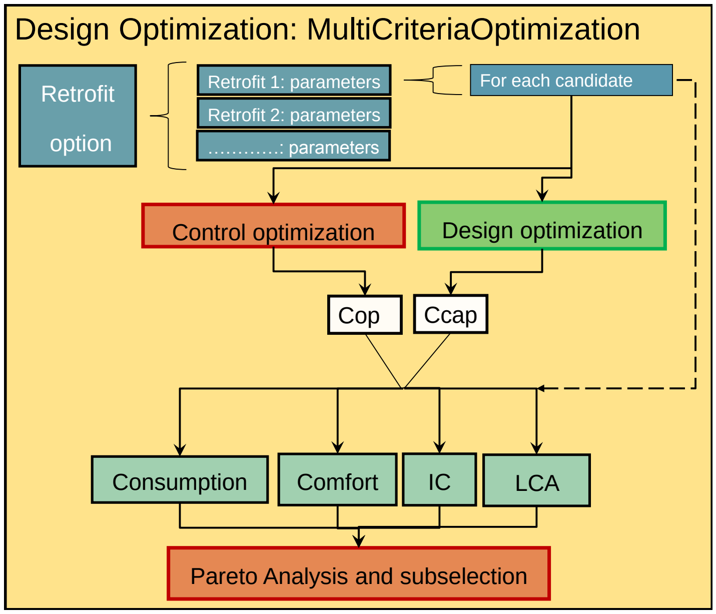


Figure 5.6: Flow chart optimization used. Each retrofit strategy is optimized considering the optimization of the control together with the optimization of the passive strategy in order to select the better configuration. More reliable estimates of operational cost (Cop) and capital cost (Ccap) are obtained. From these and others output of Energyplus simulation, the code computes the objective function.

5.4.1 Optimization Criteria Selection

Life cycle cost analysis

For this criteria I take as reference the guideline of NIST [62]. A very clear definition of LCCA is reported in the same manual. : *"Life-cycle cost analysis (LCCA) is an economic method of project evaluation in which all costs arising from owning, operating, maintaining, and ultimately disposing of a project are considered to be potentially important to that decision. LCCA is particularly suitable for the evaluation of building design alternatives that satisfy a required level of building performance (including occupant comfort, safety, adherence to building codes and engineering standards, system reliability, and even aesthetic considerations), but that may have different initial investment costs; different operating, maintenance, and repair (OM&R) costs (including energy and water usage); and possibly different lives. However, LCCA can be applied to any capital investment decision in which higher initial costs are traded for reduced future cost obligations. LCCA provides a significantly better assessment of the* *long-term cost effectiveness of a project than alternative economic methods that focus only on first costs or on operating-related costs in the short run."*

LCCA is a better tool of economic analysis comparing to Payback period, Savings-to-Investment Ratio and other. As such, it requires more information than do analyses based on first-cost or short-term considerations. As the analysis considers longer time period, same assumption on discounted cash flow, energy price escalation, inflation rate has to be considered. Considering also that we are looking for effective measures of energy saving, it is unacceptable to ignore the long-run cost consequences of investment decisions, and reject profitable investment opportunities just considering short window of time accepting higher-than-necessary utility costs.

Differential Life-cycle Cost(dLCC), utilized here, is the different between LCC of each case (LCC_i) and the reference case (LCC_r). This formulation simplify the calculation because is not necessary to include cost data for all components but only the differences produced by the variation of specific parameters from the reference case. Since maintenance cost is considered constant, it is not considered. The differential Initial Investment Cost (dIC) is the sum of the differences in the initial investment cost for the variables involved in the retrofit considered. dOC is the differential operative cost and dRC is the differential replacement cost. The resulting formulation is presenting in the Equation (5.3).

$$\begin{aligned} dLCC_i &= LCC_i - LCC_r \\ dLLC_i &= dIC_i + dOC_i + dRC_i \end{aligned} \tag{5.3}$$

The dIC formulation depend on each measure selected because some measure has fixed cost that other do not have. A general formulation is expressed in Equation (5.4) where C_1 is the cost related to the demolishment, scaffolds,etc., C_2 is the fixed cost related to the measure and C_3 is the coefficient of the variable part of the cost that multiplies the parameter. Parameters could be the thickness of one components like the insulation, the power of one system component, the thermal property or the surface, depending on the parameterizations decided by the modeler and from data available.

$$\begin{aligned} &dIC_i = \sum_{j=1}^{t} dIC_j \\ &dIC_j = C_{1j} + C_{2j} + C_{3j} * p_j \\ &p_j = value\ of\ the\ parameter \qquad j = 1, \cdots, number\ of\ varible\ in\ one\ measure \end{aligned} \tag{5.4}$$

The dOC take into account the variability of price of energy during the week due to policy, the escalation of price during years and interest rate and inflation rate. The weekly variability is inserting as input in the energy model, the escalation of price is estimated from the data available from AEEG [63]. The variability of price depending from many factors, the main one is the policy that create an oscillation especially considering a short time of some years. To reduce this effect is important to consider a longer period where other factor became more important. Data available for the analysis of electricity price for long period are not easy to find, and the policy made this data not more homogenous and some assumptions are needed to use them, especially for electricity. As we are interested to obtain a general estimation of energy price over a long period other data are possible to use, the Prezzo Unico Nazionale (PUN). This parameter is the price formed into Electricity Exchange in Italy, for that is not the real final price for the consumer, but this data could be use to calculate the index that we are looking for. Data are available for the last 10 year (longer should be better) and plotting this time series cycle phenomenons is presented but also a general tendency is clear 5.7.

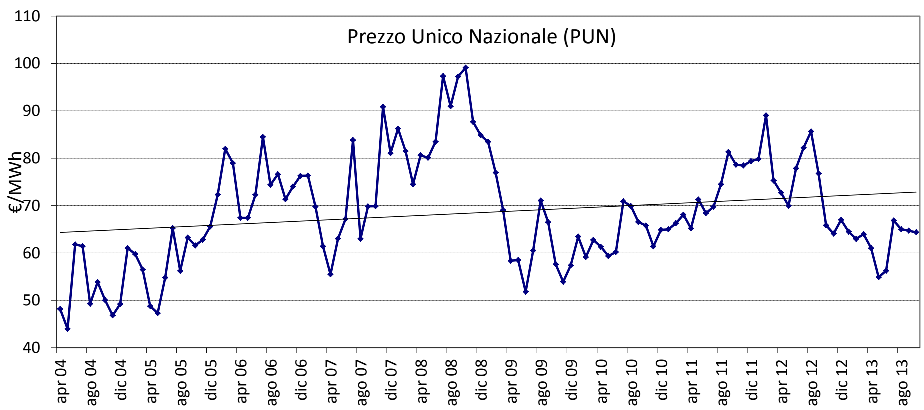


Figure 5.7: Trend of Prezzo Unico Nazionale over the last 10 years. Data from AEEG [63].

The escalation of electricity energy price (e) is calculated as the average of the yearly escalation of PUN over 10 years. The escalation of gas price (g) is calculated over 5 year of data available for the class of consumer. The formulation of dOC is presented in Equation (5.5). The parameter f is Inflation Rate, i is Nominal Interest Rate, r is Real Interest Rate, a_e and a_g are the total discount factor for the Electricity and for the Gas respectively where n is the length of period considered for the analysis. dE_i is the annual cost of Electricity taking also into account the weekly variation, dG_i is the annual cost of Gas.

$$
\begin{aligned}
& dOC_i = a_e * dE_i + a_g * dG_i \\
& a_e = \frac{1-(1+r_e)^{-n}}{r_e} \\
& r_e = \frac{r-e}{1+e} \\
& a_g = \frac{1-(1+r_g)^{-n}}{r_g} \\
& r_g = \frac{r-g}{1+g} \\
& r = \frac{i-f}{1+f} \\
& i = 6\% \qquad f = 3\% \qquad e = 3.6\% \qquad g = 3.9\%
\end{aligned}
\tag{5.5}
$$

Replacements of components due to a shorter life time of them comparing to the horizon of the analysis are considered by a specific rate. Considering the differential cost of replacement (dR_k) of a specific components the dRC_i is calculated through the Equation (5.6) considering n_k the years when the replacement is assumed to take place and z the number of components.

$$
\begin{aligned}
dRC_i &= \sum_{k=1}^{z} dRC_k \\
dRC_k &= dR_k(1+r)^{-n_k}
\end{aligned}
\tag{5.6}
$$

Comfort objective function

The thermal comfort objective function is defined as the number of hours during the years when the criteria it is not satisfy ($h_{discomfort}$). The calculation is divided into winter and summer because the natural ventilation occur during summer and the comfort criteria changes accordingly. During winter is base on PMV value and during summer is base on adaptive model category II. We consider that the refurbishment should be able to improve the indoor comfort condition during summer from category III to category II. A general formulation of this objective is presented in Equation (5.7).

$$
\begin{aligned}
h_{discomfort} &= \sum^{heated\ zones} \sum^{year} (h_{summer} + h_{winter}) \\
h_{summer} &= (\ h \in time : day \in Summer, Occupancy > 0, \\
&\quad \cap\ CEN15251 : CategoryII\ is\ not\ satisfied\ ) \\
h_{winter} &= (\ h \in time : day \in Winter, Occupancy > 0, \\
&\quad \cap\ PMV < -0.5\ \&\ PMV > 0.5\ )
\end{aligned}
\tag{5.7}
$$

5.5 Result and Discussion

The First optimization results presented is related to a design of refurbishment where all passive strategy are implemented joint with the setpoint of zones for the heating. The Figure 5.8 represents the Pareto front approximation of the analysis. The complexity of the problem means that the Pareto front is not easy to find in the whole domain for the three objective functions considered. Some holes are present in some areas, but in the area where we search for the optimal set of solutions, we obtained a good discretization. From a first overview of the results, there are several configuration that improve the comfort condition. If the aim is to maximize the comfort, the investment will grow to level where it will not be more economic feasible. It is possible to set the constrains on the objective function inside the optimization but it was preferred to analyzed all the Pareto front. A strategy of selection of the result is adopted here. If dIC is minimize we obtain dIC = 6786, with a little improvement of the comfort condition because the Hdisc goes from 311 to 293, but dLCC is positive and the investment is not economically convenient. If dLCC is minimize we obtain a very convenient configuration, dLCC=-4030, with and investment dIC=8188 and Hdisc=307, hence comfort condition remain the same. Considering to allow 250 hours of discomfort in a year, and keeping dLCC inferior to -1500 to have an economical advantage in the investment, the 20 best model are selected. The result are presented in Table 5.3. The analysis of the parameters gives interesting information regarding the selection of measure to implement. The transmittance of the window have large variability between 1.8 and 0.68. It is therefore sufficient to consider windows with transmittance of the frame of 1.6 for all the windows. The Glass pane properties has bigger impact on the performance and the optimizer choose a thickness around 17 millimeters for the spacer. The losses through the envelope are the principal influence on the heating consumption and the optimizer choose almost the maximum thickness for North exterior wall and for the attic floor.

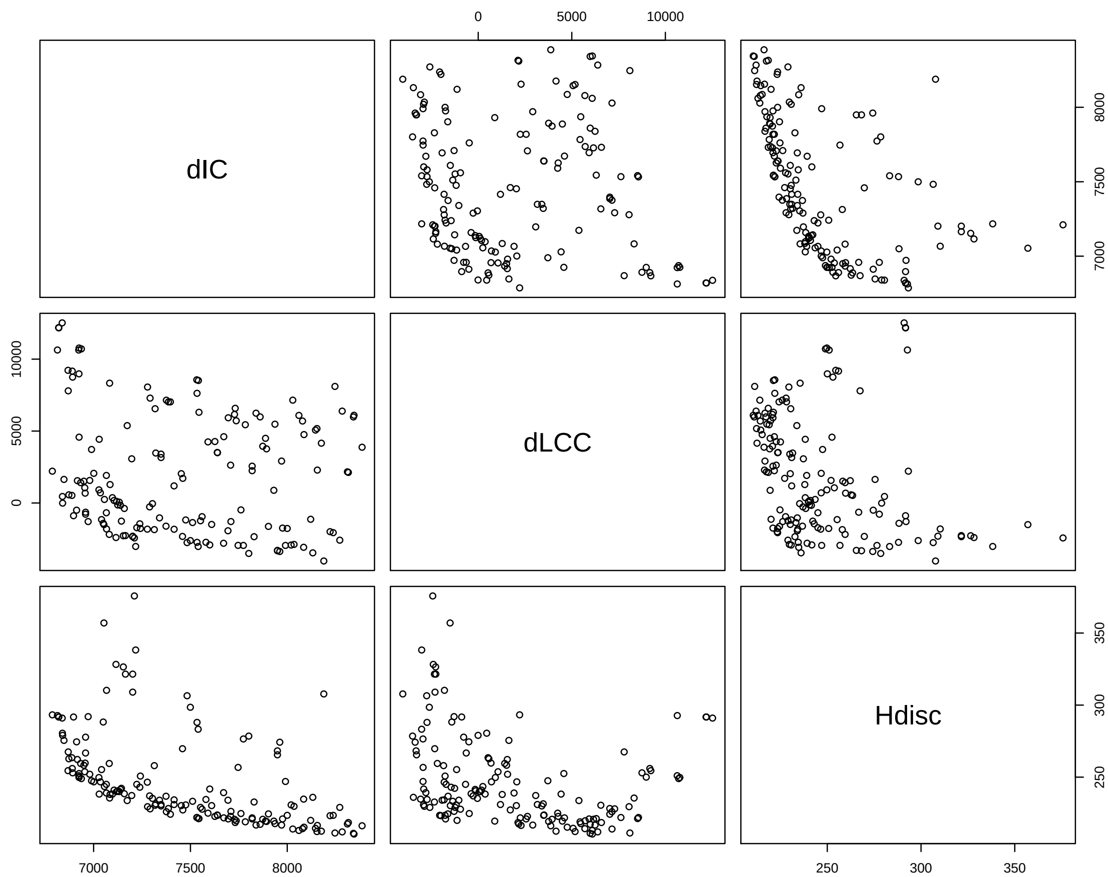


Figure 5.8: The Pareto front for the design optimization. All passive solution describe above are considered. Active solution are radiator system with improved control where the setpoints of each zone were optimized.

The setpoints of heating system are also part of the optimization parameters. The time is divided into 4 block associating one parameter to each block: first for hours before 5am, second for working hours, third for hours after 6pm and fourth for holiday and weekend. Winter is considered time from January to April, and Autumn time from October to December. This division allow to have a year long parameterizations of setpoints. The Result of the optimization is presented in Table 5.4 for the 5 best set of solutions according with the previous selection. Some variability between the solution is present, especially in Autumn H5 and H24. In general the optimizer choose three different setpoints differently from the classical setback strategy where the setpoints level are 2. Here there are one for hours before 5am, one for

measure	opt1	opt2	opt3	opt4	opt5
Ins.Ext.Wall.North[m]	0.04	0.044	0.043	0.048	0.048
Ins.Attic.Floor.S[m]	0.05	0.054	0.058	0.049	0.049
Ins.Attic.Floor.N[m]	0.06	0.053	0.058	0.059	0.059
Ins.Attic.wall.NS[m]	0.052	0.031	0.03	0.05	0.049
Glass.spacer[m]	0.018	0.017	0.018	0.017	0.018
FrameW3Fsud[W/m2-K]	0.73	1.78	1.59	1.69	1.69
FrameW3Fnord[W/m2-K]	1.08	1.60	0.77	1.34	1.33
FrameW2Fsud[W/m2-K]	1.61	0.96	0.85	0.68	0.68
FrameW2Fnord[W/m2-K]	0.78	0.84	1.32	1.54	1.54

Table 5.3: Model of radiator system with thermostat control and natural ventilation. Parameters value of passive measures for the 5 alternatives optimized solution of retrofit.

working hours and one for hours after 6pm and holiday days. Into the setback strategy all no-working hours have the same setpoint. Looking at the setpoint of working hours result clear that the optimizer chose a lower value compare to the setpoint of the reference case. This is due to the fact that after the retrofit the mean radiant temperature will be higher and because the criteria of comfort allows the optimizer to keep the PMV value more closer to the lower limit of the band. As Result the hours of discomfort during winter time will increase but remain in the limit of 5%.

Annual Setpoint	opt1	opt2	opt3	opt4	opt5	Ref
WinterH5	18.4	18.5	18.5	17.5	17.5	17
WinterH18	19.5	19.7	19.3	19.5	19.5	21
WinterH24	15.9	16.3	16.6	16.5	16.5	17
Winter.HolidaysH24	15.9	15.5	16.7	15.9	15.9	17
AutumnH5	17.2	19.4	19.6	15.9	15.9	17
AutumnH18	19.7	19.4	19.3	19.8	19.8	21
AutumnH24	16.5	15.8	15	16.6	16.6	17
Autumn.HolidaysH24	15.3	15.6	15	15.4	15.4	17

Table 5.4: Model of radiator system with thermostat control and natural ventilation.Parameters value of control strategy for heating season. Comparing value of reference case with 5 optimized solution.

Looking at the performance of this strategy of refurbishment, Table 5.5, it is achieved a substantial reduction of energy used, with an improvement of comfort condition and making the refurbishment economically feasible. Generally an increase of thermal insulation in the building has the effect to increase the indoor temperature during the summer, with, if the balance is not well analyzed, the decrease of comfort. Considering the occupancy behavior model joint with the natural ventilation model allow to better understand the real thermal balance and generates the condition for the optimizer to select the best thickness accordingly. In the LCCA it was not consider any kind of financial incentives and tax breaks. If any of this are available the investment will be cover in less time and more expensive and well suited measure will be adopted. Considering for example the case presented here, the Payback Time is calculated considered the Incentive of Energy Efficiency currently in force in Italy, Figure 5.9. The 55% +19% of the investment is deductible in constant rate for 10 years where the maximum deductible amount is 100000 €. The Payback time decrease from 19 years to 9 years, and it makes the investment feasible. From the practicable point of view it is difficult that such investments are otherwise undertaken.

Evaluation Parameters	**opt1**	**opt2**	**opt3**	**opt4**	**opt5**	**Ref**
Consumption.Elect [kWh]	3864	3812	3907	3840	3846	4408
Consumption.Gas [kWh]	1329	1350	1105	1137	1134	4675
Consumption.Pump [kWh]	1292	1240	1335	1269	1275	1836
Consumption.Equip [kWh]	768	768	768	768	768	768
Consumption.Light [kWh]	1803	1803	1803	1803	1803	1803
Energy [kWh]	5193	5163	5012	4978	4981	9083
Electricity [€]	645	637	652	642	643	735
Gas [€]	95	96	78	81	81	334
Cost.Tot [€]	740	733	731	723	724	1079
dIC [€]	6556	6736	6778	6873	6878	-
dE.Year [€]	-63	-72	-57	-66	-65	-
dG.Year [€]	-235	-233	-251	-248	-249	-
dOC [€]	-10357	-10581	-10695	-10938	-10914	-
dLCC [€]	-3800	-3845	-3916	-4064	-4036	-
Hour.NoComfort.Tot [h]	238	236	245	242	242	312
Hour.NoComfort.W [h]	14	12	21	18	17	4
Hour.NoComfort.S [h]	224	224	224	224	224	308
Hour.Open.Year [h]	1021	1033	1030	1038	1037	976

Table 5.5: Model of radiator system with thermostat control and natural ventilation. Evaluation of the performance of the retrofit. All optimized alternative give very close performance, stressing that optimizer has found near optimal solution. The energy use in the building is sensible decreased, both gas and electricity. No changes are considered for equipment and light. The economic feasibility is verified. The comfort condition are improved. The natural ventilation allow to keep comfort condition increasing the ventilation hours.

One interesting point is the analysis of hours of discomfort. The reference case, as well as the retrofit solution, gives too high value of hours of discomfort during the summer. Looking at the time distribution, Figure 5.10, they are concentrated in spring and autumn when the building is in the condition of totally climate driven because it is not allowed to switch on the heater, because of the local policy, but is not to hot to use natural ventilation to control the indoor condition. For example there are a high temperature excursion in few days because

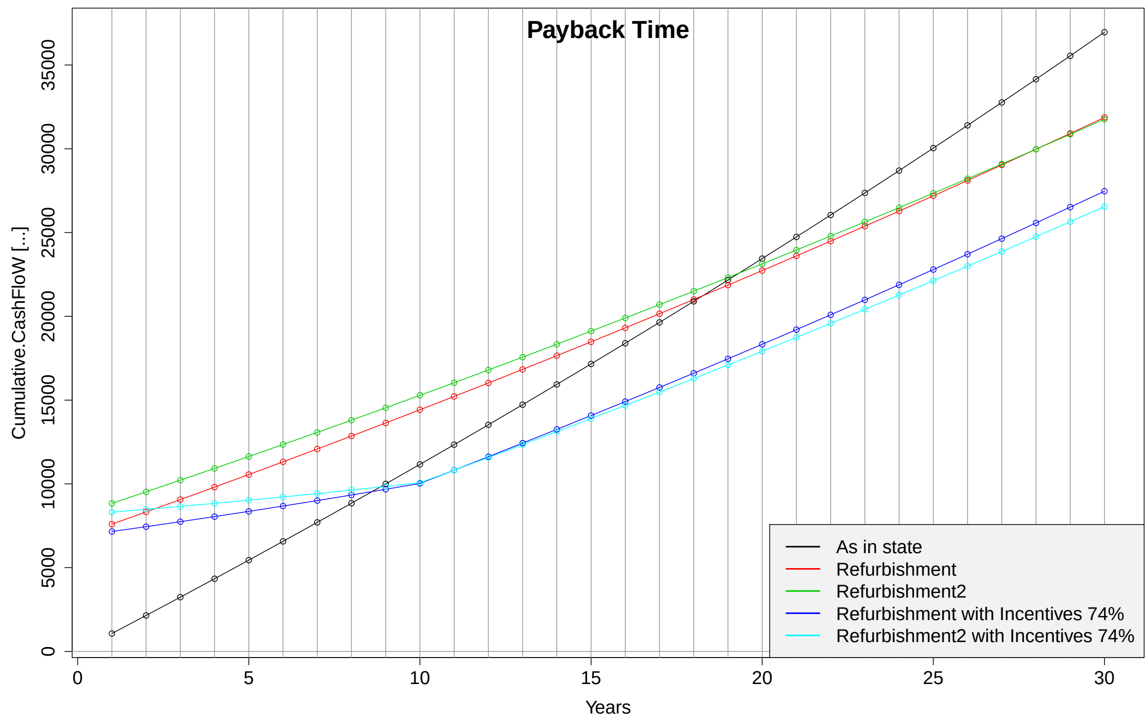


Figure 5.9: Payback time analysis considering the Utilization of Incentives and without.

of heavy rain days or strong sunny days. The consequence of that is that the number of discomfort hours yearly are higher than the limit, in this case 125, but is not a representative evaluation of the real condition. The consequence of that will be that systems that can run yearly long, Heat Pump of VAV system for example, result as better solution of retrofit because generate better comfort also in these period of year, of course with an increasing of energy consumption. This assumption is not generally true because the operation time is different. Looking at the Figure 5.10 is also clear that the discomfort point is related to a single zone of the building, the South zone at Third floor, while the others show good comfort condition. The formulation that I considered gives strong penalties and the conditions inside the building, in average, are better. Analysis the data of discomfort result that 148 hours are located from April 15 to May 15 and just 76 from May 15 to October 15. From that, I considered that a discomfort limit of 250, take into account also winter time should be stringent enough for the design.

A comparison between the situation before and after the refurbishment is presented in Figure 5.11, where Annual Heating is compared divided into the mains components. All the losses components are decreased accordingly with the measure adopted. As the measure did not consider equipments and light, the interior load remain the same. In this components a further energy efficiency measure should be studied.

Other strategies of retrofit are taken into account. First of all a Dedicated Outdoor Air

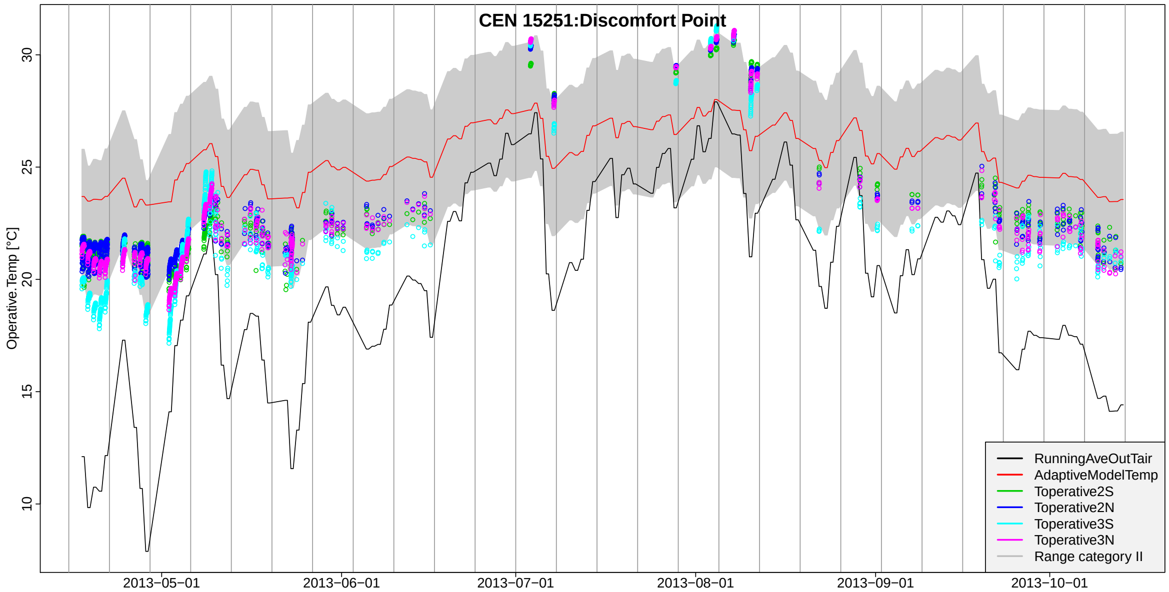
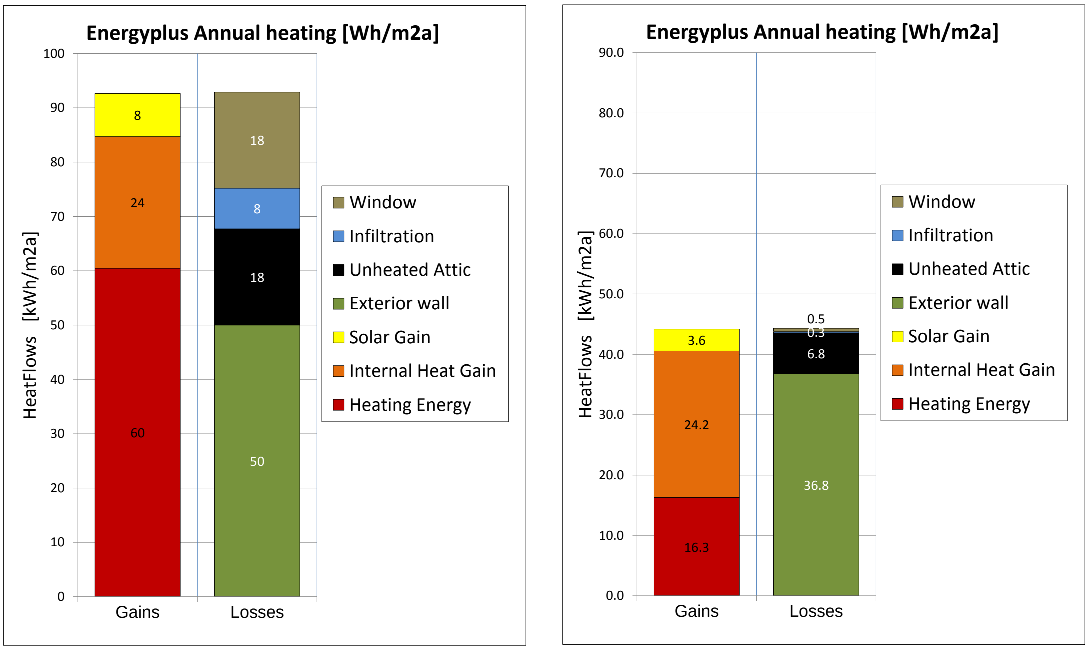


Figure 5.10: Hours of discomfort distribution during Summer season. The limit from EN 15251 should be 125. 148 hours are located from April 15 to May 15 and just 76 from May 15 to October 15. The policy on heating season has strong effect on the evaluation.

System (DOAS) is considered, to improve the air quality inside the building and control the humidity. The strategy described here is the same of above adding the DOAS. As climate in Bologna is very humid all year long the DOAS could be a good solution to control Humidity level when natural ventilation is not used, during Winter and intermediate seasons and during Summer in change over control strategy. The Scatter plot 5.12 of the result shows that solution is not economically feasible, the comfort will generally be improved but the initial investment cost and the increasing of energy consumption make that this solution is less advantageous from the economic point of view. One of the best solution is reported on table 5.6. It shows that there is a small reduction of use of electricity but an increase of use of gas compare with the reference case where the DOAS is not present. The passive solutions adopted do not guarantee a global reduction of energy use to allow the implementation of DOAS system. This solution could be chosen if humidity and air quality control is considered so important as to justify the increase of energy consumption.

In the section 5.2.3 different system control strategies are discussed and the effect on the consumption are consistent. Other optimization is set including into the parameters also the availability of the system joint with the setpoints. In this way it is verified if the interaction of passive and active strategy could allow to produce more saving and minimize much more the objective functions compare to the case in which they are treated separately. Looking at Table 5.7 there are a general reduction of the insulation compare to table 5.3. Looking at the control strategy, Table 5.8, there are two main typology. The case in which the plant is on more time with lower setpoints (opt3) and the case in which the plant is on as less as possible with higher setpoints (all the others alternatives). Compare to the reference, in general, the



(a) Pre-Intervention Analysis (b) Post-Intervention Analysis

Figure 5.11: Annual heating balance compute with Energyplus. Comparison between Before and after the refurbishment.

optimizer choose to switch on, just it is necessary. Considering the days of no occupancy, the optimizer choose to switch on the plant at least one time, according to the analysis presented in section 5.2.3. It is more expensive to reheat all the thermal mass than keep it at certain level of temperature. The performance of the refurbishment achievable with this design optimization are presented in table 5.9. An improvement of the design is in general achievable with the concurrently reduction of energy consumption and making the investment more profitable. This is possible considering active and passive solution and dynamic control strategy together, in order to take in account the interaction between them inside the optimization process. The different sets of parameters show that different configuration are possible, also using very low level of insulation of the north wall (opt3 and 4). The control strategy play very important role and this example shows the importance to take account of them inside the design phase.

An example of result of design is presented (opt6) in Figure 5.13. During winter the comfort conditions are satisfied during the occupancy time by the switch on the systems. During no occupancy time systems are used just to maintain a constant temperature in the building and to preheat the zone when energy has lower price. During Summer the comfort is satisfied as into the condition of pre intervention, on which the control strategy of ventilation through the windows are developed. The Natual Ventilation keeps the comfort and the automatic one during no occupancy time keeps the humidity lower the 70 %. Just few hours in one months the temperature, or humidity are above of the respectively limits.

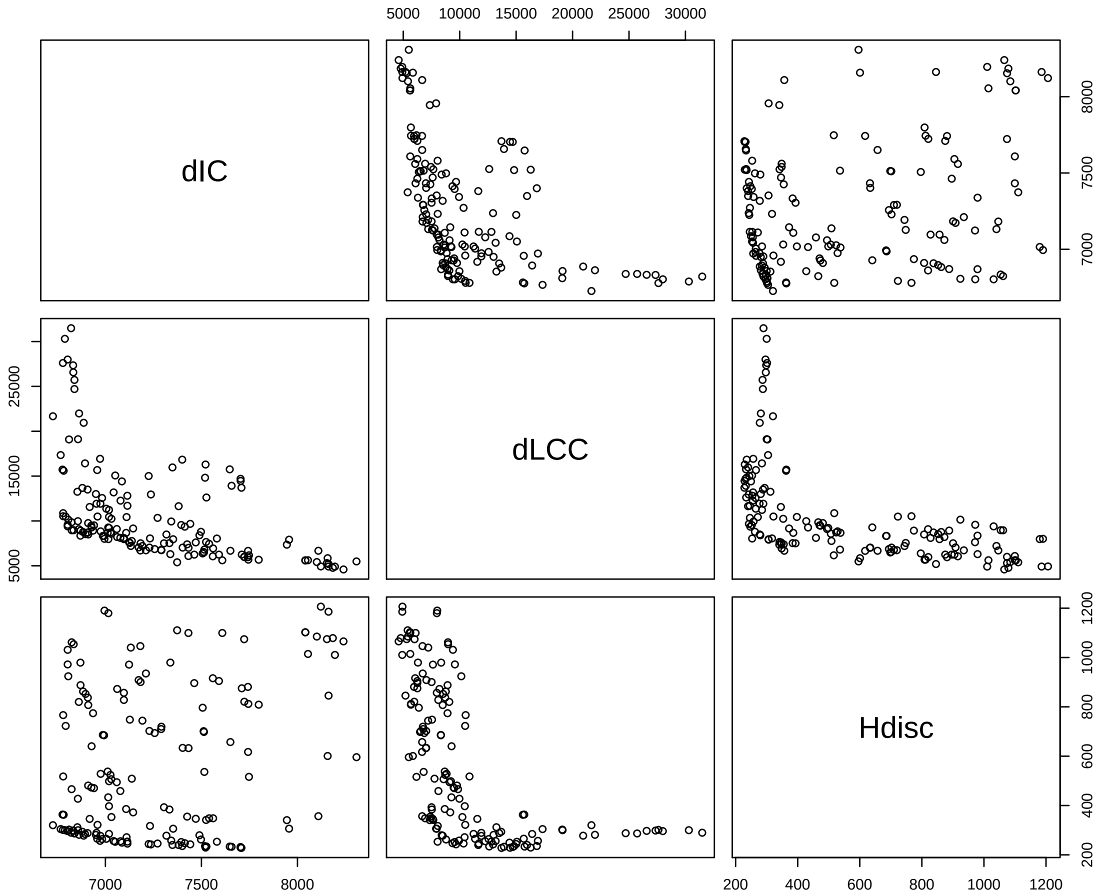


Figure 5.12: Optimization result for retrofit strategy considering: All passive measures as describe above, Radiator with Gas Boiler, natural Ventilation by windows and DOAS with changeover control.

5.5.1 Conclusion

Dynamic building models offer the possibility to consider dynamic schedules and to model the control strategy inside the design phase. For class of building where several limitation are presented, it is a very powerful technology to evaluate the effective potential saving derived from the implementation of specific measure. The effectiveness of control strategies of energy consumption is well presented in the case study considered. If thermal mass is present, they allow to use the thermal mass to reduce the energy consumption and to improve the comfort. The design optimization approach presented here allows to take advantages of the complex interaction that characterizes the building and, without the installation of new system, the objectives of the design are satisfied. Moreover a long term measures are suggested as the main focus of the approach start from the concept of using better what is already present.

Evaluation Parameters	opt1	Ref
Consumption.Elect [kWh]	4345	4408
Consumption.Gas [kWh]	5045	4675
Consumption.Pump [kWh]	1189	1836
Consumption.Equip [kWh]	768	768
Consumption.Light [kWh]	1803	1803
Energy [kWh]	9391	9083
Electricity [€]	726	735
Gas [€]	361	334
Cost.Tot [€]	1087	1079
dIC [€]	7650	-
dE.Year [€]	-8.6	-
dG.Year [€]	26.44	-
dOC [€]	639	-
dLCC [€]	8290	-
Hour.NoComfort.Tot [h]	248	312
Hour.NoComfort.W [h]	17.5	4
Hour.NoComfort.S [h]	230	308
Hour.Open.Year [h]	1874	976

Table 5.6: Model of radiator system with thermostat control and natural ventilation and DOAS system with changeover control.

measure	opt1	opt2	opt3	opt4	opt5	opt6
Ins.Ext.Wall.North[m]	0.048	0.045	0.032	0.007	0.003	0.046
Ins.Attic.Floor.S[m]	0.048	0.05	0.043	0.037	0.055	0.045
Ins.Attic.Floor.N[m]	0.044	0.056	0.049	0.042	0.033	0.055
Ins.Attic.wall.NS[m]	0.036	0.043	0.036	0.039	0.027	0.002
Glass.spacer[m]	0.012	0.016	0.013	0.014	0.011	0.012
FrameW3Fsud[W/m2-K]	0.73	0.85	0.87	0.84	1.19	1.57
FrameW3Fnord[W/m2-K]	1.77	1.69	1.69	1.63	0.7	1.55
FrameW2Fsud[W/m2-K]	1.06	1.36	0.91	1.5	0.83	1.57
FrameW2Fnord[W/m2-K]	0.94	1.17	1.41	1.44	0.65	1.93

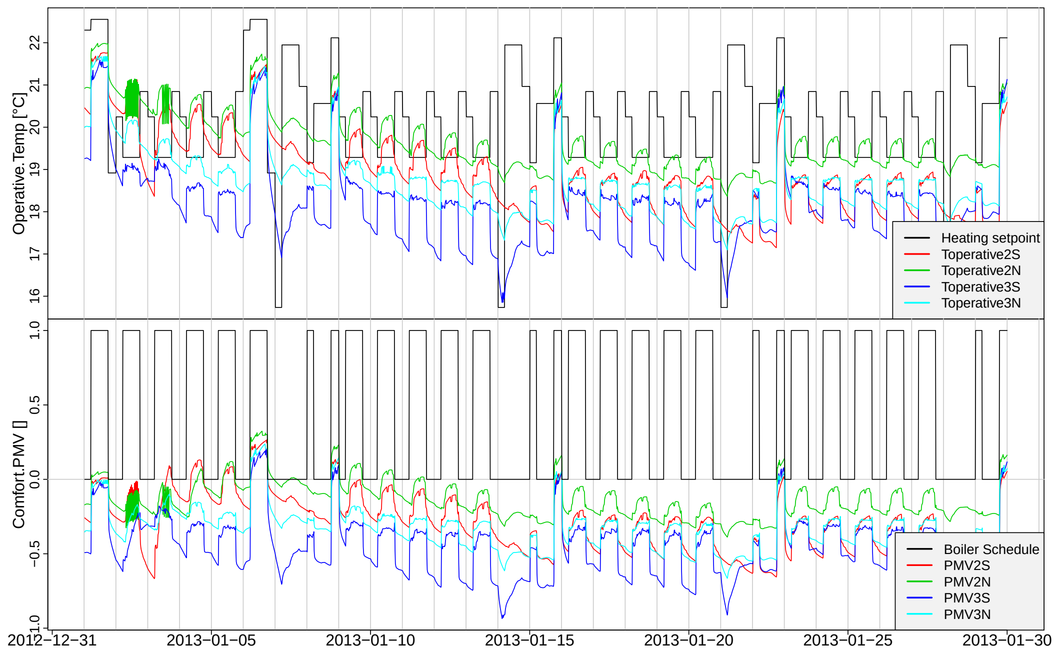
Table 5.7: Model of radiator system with thermostat control and natural ventilation. Parameters value of passive measures for the 6 alternatives optimized solution of retrofit considering also the system availability into the design.

Annual Setpoint	**opt1**	**opt2**	**opt3**	**opt4**	**opt5**	**opt6**	**Ref**
WAvailH5	0	0	1	0	0	0	1
WAvailH18	1	1	1	1	1	1	1
WAvailH24	0	0	1	0	0	0	1
WAvailSatH5	0	0	1	0	0	0	1
WAvailSatH18	0	0	0	1	0	0	1
WAvailSatH24	0	0	1	1	0	0	1
WAvailSunH5	0	0	0	1	0	1	1
WAvailSunH18	0	0	0	0	0	0	1
WAvailSunH24	1	1	0	1	0	1	1
WAvailOtherH5	0	1	1	0	1	0	1
WAvailOtherH18	1	0	0	1	1	1	1
WAvailOtherH24	0	0	0	0	0	0	1
AAvailH5	0	0	1	0	0	1	1
AAvailH18	1	1	1	1	1	1	1
AAvailH24	1	0	0	0	0	0	1
AAvailSatH5	1	0	0	1	0	0	1
AAvailSatH18	0	1	0	0	1	0	1
AAvailSatH24	0	0	0	0	1	1	1
AAvailSunH5	0	0	1	1	1	0	1
AAvailSunH18	0	0	0	0	0	0	1
AAvailSunH24	1	1	1	1	0	1	1
AAvailOtherH5	0	1	0	0	0	0	1
AAvailOtherH18	1	1	1	1	0	1	1
AAvailOtherH24	1	0	1	1	0	1	1
WinterH5	19.3	22.5	19	20.6	16.5	20.2	17
WinterH18	20.7	19.5	19.5	19.4	20.3	19.3	21
WinterH24	19.8	20.9	18.2	18.5	19.7	20.8	17
Winter.SatH5	20.9	17.2	15.5	22.4	15.4	15.7	17
Winter.SatH18	21.2	22.3	22.3	21.1	21.5	22	21
Winter.SatH24	20.9	21.6	18.7	16.6	22.7	20.9	17
Winter.SunH5	20.4	20	18.9	20.8	19.1	19.2	17
Winter.SunH18	22.5	21.8	21	20.8	21.1	20.6	21
Winter.SunH24	16.6	18.9	15.6	16.8	21.8	22.1	17
Winter.OtherH5	22.8	22.6	22.47	22.2	20.1	22.3	17
Winter.OtherH18	19.6	21.7	19.6	22.9	21.9	22.6	21
Winter.OtherH24	15.1	19.4	23	21.4	19.9	18.9	17
AutumnH5	22.8	16.1	16.3	19.8	15.7	15.7	17
AutumnH18	20.3	20.7	19.7	19.7	20	20	21
AutumnH24	18.3	22.7	16.25	21.4	15.4	22.3	17
Autumn.SatH5	22.7	22.5	19.6	17.5	21.2	16.1	17
Autumn.SatH18	19.6	22.2	22.5	20.3	20.2	20.3	21
Autumn.SatH24	18.1	21.6	15.2	21.2	15.6	17.7	17
Autumn.SunH5	20.2	20	20.9	20	19.4	21.1	17
Autumn.SunH18	22.3	20.9	22.1	20.4	20.6	19.4	21
Autumn.SunH24	19.2	21.3	17.6	21	18.6	19.2	17
Autumn.OtherH5	17.8	21	21	21.2	22.5	18.3	17
Autumn.OtherH18	22.1	21.6	19.2	20.7	21	22	21
Autumn.OtherH24	22.2	19.2	22.7	18.8	20.5	19.6	17

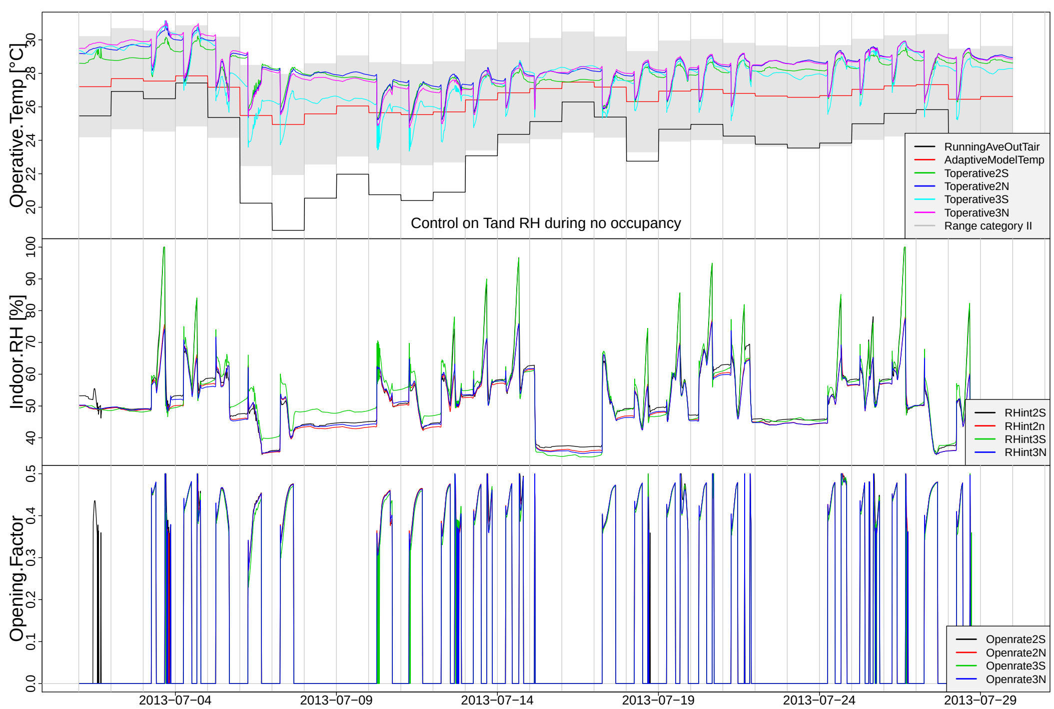
Table 5.8: Model of radiator system with thermostat control and natural ventilation. Design Optimization considering also system control strategy. Value of Schedule are reported for 6 optimized solution of the Pareto front vector.

Evaluation Parameters	**opt1**	**opt2**	**opt3**	**opt4**	**opt5**	**opt6**	**Ref**
Consumption.Elect [kWh]	3440	3372	3682	3448	3386	3396	4408
Consumption.Gas [kWh]	1249	985	1033	1410	1640	796	4675
Consumption.Pump [kWh]	868	800	1111	876	814	824	1836
Consumption.Equip [kWh]	768	768	768	768	768	768	768
Consumption.Light [kWh]	1803	1803	1803	1803	1803	1803	1803
Energy [kWh]	4689	4357	4716	4858	5026	4192	9083
Electricity [€]	579	567	617	580	571	570	735
Gas [€]	89	70	73	101	117	56	334
Cost.Tot [€]	668	638	691	680	688	627	1079
dIC [€]	8149	8303	7860	7288	7107	8152	-
dE.Year [€]	-52	-63	-14	-51	-60	-61	-
dG.Year [€]	-295	-314	-310	-284	-267	-327	-
dOC [€]	-12094	-13138	-11362	-11672	-11385	-13517	-
dLCC [€]	-3945	-4834	-3500	-4384	-4278	-5364	-
Hour.NoComfort.Tot [h]	241	240	240	250	242	241	312
Hour.NoComfort.W [h]	0.75	1.5	2.5	1.25	0	2	4
Hour.NoComfort.S [h]	240	239	238	248	242	239	308
Hour.Open.Year [h]	2076	2256	1605	1683	1541	1835	976

Table 5.9: Model of radiator system with thermostat control and natural ventilation. Design Optimization considering also system control strategy. Value of performance are reported for 6 optimized solution of the Pareto front vector.



(a) Indoor winter condition and related control strategy



(b) Indoor summer condition and related control strategy

Figure 5.13: Result of Optimization number 6 of table 5.9. Good condition of comfort is generate joint with low level of consumption.

Chapter 6

Conclusion

This chapter describes the main results of this thesis retracing all chapter. A discussion of the contribution of this thesis is also presented, following the research questions that have direct this work.

Contents

6.1 Summary of Most Important Result

Several guidelines are available for an energy audit of the building. It is a simple tool of analysis and very useful for the decision process inside the building management area. The importance of audit depends from the capability to make fruitful the information achievable. As the audit could cover many aspects, which different level of details, it is important to manage it in order to cover what is really useful, to achieve the objectives that the building management group expects. The information could be provided at different levels. The proposed procedure starts from general aspects and goes step by step to more detailed one with the aim to clarify the uncertainties related to principal components of the energy consumption. It focuses in the case study considered to give a practical understanding of the capabilities to the readers. The subdivision into the multilevel scale of access to information is provided through different reports and database, from general graph to monitoring data. Synthesize the information into the construction of dynamic model is the better way for decision support tool and the differences between tools are provided compare them to real consumption and considering uncertainty. Wireless sensor network is very promising technology for building audit because simplifies the audit and provides very valuable information for diagnostic and for modeling task.

A review of literature revealed that several uncertainty of models performance are present compare to real building and in particular building with high level of thermal mass. This suggests to verify the mathematical formulation used in different commercial software tools. Different formulation are analyzed and the results show that each tool presents specific problem. Looking at the thermal flux through mass wall, the error on one month and one day is acceptable, or technic for each tool are available to satisfy the need of the modeler. The only uncertain part of the model remain the long wave radiation balance that should be investigated.

The revision of calibration procedure of dynamic model shows some problem on the estimation of hourly performance of building. The proposed procedure allows the achievement of good agreement with experimental data during year. The used of monitoring data for the calibration stresses the importance of well planned building auditing. A functional monitoring system to model calibration is developed taking care of network cost reduction and accuracy achievable. The complexity of the class of building analyzed needs more investigation on merging measurements and modeling to developing cost effective solutions.

The design optimization strategy is valuable process to investigate the possible solutions of refurbishment of historic buildings. It suggests different combination of parameters for each configuration of strategy selected. The result will be a large set of near optimum solutions that are powerful information to take part of decision making process where also qualitative aspects are taken into account. The multicriteria optimization produce a set of solutions that are a result of compromise between objective in contradiction, and for that characteristic, appears as the perfect tool for the production of this set of solutions. The objective functions selected allows to take into account the principal aspects of the investment and the selection of suited measures for the specific building. The importance on considering passive and active solution and control strategy together is presented into the result. Natural ventilation through controlled windows provide good comfort level if they are used in the right way, also considering as-in-state condition. Occupancy behaviour changes completely the thermal balance and considering it into the model provide more realistic balance. Control strategy represents a real measure for the energy efficiency.

All the activities presented are related to an historic building that results more efficient than expected. This means that preformed concept that cames from other class of building are not to be transferred to the class considered but the specific features should be studied. As result we obtain awareness on the building energy balance, higher level of conservation of building, better management. From the other hand the procedure look consistent for improve to higher level an already efficient building and suggest that even better result should be expected considering inefficient building. The result of the Design Optimization for this building is that saving of Factor 3.7 is achievable considering the heating consumption. Moreover the comfort will be improved and the financial investment is convenient. This result confirm which other example of refurbishments, considered at the beginning of this thesis, have reached.

6.2 Contribution and Future Work

Chapter one introduced several questions that have direct this research. Each one is summarized and given separate treatment below to highlight the contribution of this work, limitations and suggestions for future research.

"There are two main family of energy balance simulation, static and dynamic. how much

they are accurate applied to an historical building and to simulate high thermal mass effects? what I have to consider when I have to choose the tool?"

The importance of using simulation tools for the analysis of building energy balance and to design the refurbishment strategy is well known. It is common practice to use static tools for every kind of building for many reasons: Standard suggest them, mandatory requirement of law, they are simple and needs few hours to complete the job, they give easily understanding results useful for the design of the refurbishments, and anyone could use it. That reasons allow a good penetration of this analysis with a general increase of implementation of energy efficiency measure that produce good effect on our society but they are a simplified model of the complex interaction that characterize the building's energy balance and should be used for the class of building used for their developing. A simple transferability to other class of building introduce more uncertainty that ones already presents in the class on which they are developed. The effects could be that wrong decision on measure to implement will be taken. This is in general unacceptable, but even more for the class of historic building where the preservation aspects are more important. As many systematic works on the energy assessment of historic building are not presented in literature, this work gives a contribution to create a solid reference for the energy analysis of historic building and their refurbishments. Dynamic and static model are analyzed and applied to a real case study where thermal mass is one of the main characteristic of building. Usually static models are used to analyzed heating and cooling demands and related components and, from that, same measures are developed and implemented. This tools allow to identify the components but their estimation present and excessive error. Just this it is enough to develop solution that when will be implemented will generate different performance in terms of energy and investments. More over this kind of analysis doesn't take in consideration many others aspects of buildings energy balance, as comfort, occupancy behavior,control strategy, etc. , so that the decision space is limited to pre ordered set of solutions coming from common practise in others class of buildings. A significative contribution of this work is the demonstration that considering all the aspects of the energy balance together, allows a better understand of real behavior of building and allow a better development of long term energy efficiency measures. Well setting of dynamic tools allows this and is the only possible alternatives to obtain detail analysis of buildings, especially with high thermal mass. Moreover they should be validated from theoretical and empirical point of view. This work presented a quantitative analysis of conductance thermal response of high thermal mass wall for commercial dynamic tool as the references of tools validation do not consider this analysis in their validation test and the literature review shows some calculation problem for the algorithms implemented for this class of wall. The validation is performed only through a computational point of view and empirical one should be performed in future works.

"Is it possible to have more accuracy into the model? Have a measure of it? How could I calibrate it? "

Performing a simulation with dynamic model is also not enough, if the description of all components of energy balance of buildings is the aim. A calibration process base on real data is necessary and the improvements applying the calibration is presented in this work. The analysis of calibration procedure available and others experience of applying the technic to real building are presented and analyzed. The developed procedure is consider as an improvement of what is consider common practise and it will focus more on the calibration of thermal response of building envelope. This choice is related to the focus of this work, historic building present uncertainty in material construction and complex feature, and the calibration focus more of the reduction of discrepancy between model and building. The result of the calibration is an improved model and a measurement of the discrepancy with the real building. For a complete evaluation of model accuracy, Uncertainty analysis should be performed join with sensitivity study in a calibration process under uncertainty. This aspect will be treated in future in a separate task, here the calibration is presented as a necessary step of buildings modeling.

"How much systems interact with thermal mass? which consequence I have on thermal balance and design? It is possible to use this characteristic for reduce the energy consumption? "

Historical building originally are design in epoch where energy was not easy to provide and manage, more over the comfort conditions were very different from nowadays. As consequence the building construction itself and the interaction with climate, like opening and orientation were study to maximize the indoor comfort condition. Just in the late Middle Age, with the developing of economy into the city and the further increase of population in city and the demanding of house, the original shape of building change to one that focus on the maximization of use for square meter. The consequence were that also extensive used of system enter into the houses. Thermal mass and natural ventilation were the principal passive solutions for the indoor climate regulation. In this work they are investigated deeply to analyze if the building preserve these characteristics also into the nowadays configuration. It was investigated not just the thermal lag of building and construction but the possibility to use those feature to reduce the energy used. Nowadays Standards gives prescription on the degree of thermal lag that a new construction has to generate for the reduction of indoor temperature during summer. Here it was investigate also the effect of using thermal mass to save energy during winter time considering different control strategies. Important saving are achievable, especially if the design of the controls take place into the early phase of the design. The Design optimization presented here helps into this kind of investigation also in the design phase as the interaction of building, system and occupance are taken into account. The results are optimized control strategy over seasons. More detailed analysis will be done in future consider shorter optimization horizon for the controller and the implementation in real building.

"It is possible to have a simulation tool integrated with decision-making process?"

The decision-making process is investigate in the context of building construction and in the context of refurbishment of historical building. In both of them there is a need to take into account qualitative criteria join with quantitative assessment. Several discussion inside the project 3encult, and others projects on energy efficiency in historical building provide that better results are achievable in a multidisciplinary decision-making process where the focus is more on the optimization of the energy saving instead of maximization of it. One of the objective of this work was to give a quantitative and flexible tool to buildings physicist enable them to joint that process with and infrastructure that provide a set of possible solution that satisfy defined objective functions. The peculiarity is that set of solution are a Pareto front vector that allows to estimate the consequence of one decision easily, for the characteristic of Pareto front vector, and create a more proactive and confident discussion of the possible final solutions to adopt. For this reason this work give a significant contribution on the developing a concept of the integration of simulation tools inside the decision-making process. The question is partially open because several way of judgements of the solution are possible, and probably should remain in this condition, where local authority take the responsibility on the choice. However more research studies should be done to develop enough experience on the process to transfer to authorities and stakeholder involved.

References

[1] *$Co_2olBricks$*, 2013. *$Co_2olBricks$*. Climate Change, Cultural Heritage and Energy Efficient Monuments. http://www.co2olbricks.eu/.

[2] *$Co_2olBricks$* and Project Partner, 2013. *$Co_2olBricks$*. Energy Refurbishment of Historic Buildings in the Baltic Sea Region - Final Report. http://www.co2olbricks.eu/.

[3] ATTESS, 2010. ATTESS. Edilizia Storica e SostenibilitÃ Ambientale http://www.attess.it/.

[4] G. Bonsanti. *Il minimo intervento nel restauro*. Nardini, 2004.

[5] Burkhard Schulze Darup. *Energetische GebÃ¤udesanierung mit Faktor 10*, 2004.

[6] Expert Group on Energy Efficiency. Realizing the potential of energy efficiency: Targets, policies, and measures for g8 countries.

[7] M. Funch, 2011. *$Co_2olBricks$*. Energy Refurbishment of Faestigens Materialgard.

[8] A. Troi. Historic buildings and city centres. the potential impact of conservation compatible energy refurbishment on climate protection and living conditions. *Energy Management in Cultural Heritage*, 2011.

[9] New Europe Brussels team, 2008. Employment up 11% thanks to cultural tourism. http://www.neurope.eu/article/employment-11-thanks-cultural-tourism.

[10] 3encult, 2014. 3encult - Efficient Energy for EU Cultural Heritage http://www.3encult.eu/.

[11] A. Dupagne, C. Ruelle, J. Teller, and B. CornÃ©lis, 2008. SUIT. Sustainable Development of Urban Historic Areas through Active Integration in Towns.

[12] Committee for Protection of Monuments. *International Conference 'Preservation and Employment' in 1999 held under the German EU Presidency*, 62, 2000.

[13] Passiv House Institute, 2013. PHPP - the energy balance and Passive House planning tool http://www.passiv.de/en/04_phpp/04_phpp.htm.

[14] EnergyPlus. EnergyPlus Energy Simulation Software: http://apps1.eere.energy.gov/buildings/energyplus/.

[15] M. Giuliani and C. Colla. Analisi termografica: esempi di sviluppi applicativi della tecnica ir per la diagnostica strutturale degli edifici storici. *Proceding of AIMETA*, 2011.

[16] NREL. Legacy OpenStudio Plug-in for SketchUp. http://apps1.eere.energy.gov/buildings/energyplus/openstudio.cfm.

[17] sketchup. http://www.sketchup.com/it.

[18] J.E. Braun and N. Chaturvedi. An inverse gray-box model for transient building load prediction. *HVAC&R RESEARCH*, 8(1):73–100, 2002.

[19] N. Chaturvedi and J.E. Braun. Analitical tools for dynamic building control. *Final Report for Research Project 985-RP Implementation of Thermal Storage in Building Mass*, 2000.

[20] N.R. Kristensen, H. Madsen, and S.B. Jorgensen. Parameters estimation in stochastic grey-box models. *Automatica*, 40:225–237, 2004.

[21] ASHRAE. Standard 140-standard method of test for the evaluation of building energy analysis computer programs. *American Society of Heating,Refrigerating and Air-Conditioning Engineers, Inc.*, 2011.

[22] H. Asan. Numerical computation of time lags and decrement factors for different building materials. *Building and Environment*, 41:615–620, 2006.

[23] M. Cellura, L. GiarrÃ¨, V. Brano, and A. Orioli. Thermal dynamic models using z-transform coefficients: an algorithm to improve the reliability of simulations. *Proc. 8th International IBPSA Conference*, 2003.

[24] Y. Chen, J. Zhou, and J.D. Spitler. Verification for transient heat conduction calculation of multilayer building constructions. *Energy and Building*, 38:340–348, 2006.

[25] X.Q. Li, Y. Chen, J. Spitler, and D. Fisher. Applicability of calculation methods for conduction transfer function of building constructions. *International Journal of Thermal Sciences*, 48:1441–1451, 2009.

[26] J.R. Cannon. The one-dimensional heat equation. *Reading, MA Cambridge, UK: Addison-Wesley,Cambridge University Press*, 1984.

[27] D.G. Stephenson and G.P. Mitalas. Room thermal response factors. *ASHRAE Transactions*, 73(2):III.2.1–III.2.10, 1967.

[28] C.P. Underwood and F.W. Yik. *Modelling methods for energy in buildings*. MA: Blackwell Publishing, Malden.

[29] TESS. Trnsys. Retrieved from http://www.trnsys.com/.

[30] D.G. Stephenson and G.P. Mitalas. Calculation of heat conduction transfer functions for multi-layer slabs. *ASHRAE Transactions*, 77(2):117–126, 1971.

[31] B. Delcroix, M. Kummert, A. Daoud, and M. Hiller. Conduction transfer functions in trnsys multizone building model: current implementation, limitations and possible improvements. *Proc. SimBuild 2012 - IBPSA-USA*, 2012.

[32] C. Giaconia and A. Orioli. On the reliability of ashrae conduction transfer function coefficients of walls. *Applied Thermal Engineering*, 20:21–47, 2000.

[33] G. Mitalas and J. Arseneault. Fortran iv program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs. *Division of Building Research, National Research Council Canada.*

[34] energyplus/weatherdata. Retrieved from EnergyPlus Energy Simulation Software: http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm.

[35] ASHRAE. *Guideline 14 Measurement of Energy and Demand Savings.* American Society of Heating,Refrigerating and Air-Conditioning Engineers, Inc., Atlanta.

[36] T.Agami Reddy, I. Maor, and C. Panjapornpon. Calibrating detailed building energy simulation programs with measured data - part i: General methodology. *HVAC&R RESEARCH*, 13-2, 2007.

[37] D. Coakley, P. Raftery, and P. Molloy. Calibration of whole building energy simulation models: Detailed case study of a naturally ventilated building using hourly measured data. *Proceding of 1th Building Simulation and Optimization Conference*, 2012.

[38] GeoModel, 2014. Geomodel Solar http://geomodelsolar.eu/home.

[39] S. Burhenne, D. Jacob, and G.P. Henze. Sampling based on sobol's sequences for monte carlo techniques applied to building simulations. *Proceding of 12th Conference of International Building Performance Simulation Association*, 2011.

[40] I.A. Macdonald. Comparison of sampling techniques on the performance of montecarlo based sensitivity analysis. *Proceding of 11th Conference of International Building Performance Simulation Association*, 2009.

[41] A. Saltelli, S. Tarantola, F. Campolongo, and M. Ratto. *Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models.* John Wiley & Sons, Ltd, 2004.

[42] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola. *Global Sensitivity Analysis: the primer.* John Wiley & Sons, Ltd, 2008.

[43] F. Campolongo, J. Cariboni, and A. Saltelli. An effective screening design for sensitivity analysis of large models. *Environmental Modelling & Software*, 22:1509–1518, 2007.

[44] H. Brohus, P. Heiselberg, A. Simonsen, and K.C. SÃ¸rensen. Uncertainty of energy consumption assessment of domestic buildings. *Proceding of 11th Conference of International Building Performance Simulation Association*, 2009.

[45] H. Brohus, P. Heiselberg, A. Simonsen, and K.C. SÃ¸rensen. Influence of occupant's behaviour on the energy consumption of domestic buildings. *Proceding of 10th Rehva World Congress: Sustainable Energy Use in Buildings*, 2010.

[46] P. Hrebik. Application of sensitivity and uncertainty analyses in the calculation of heat transfer coefficient of window. *Slaovak jornal of Civil engineering*, XX-3:27–34, 2012.

[47] F. Monari, P. Strachan, and J. Ortiz. Employing local and global sensitivity analysis techniques to guide user interface development of energy certification and compliance software tools. *Proceding of 13th Conference of International Building Performance Simulation Association*, 2013.

[48] E. Brandt and M.H. Rasmussen. Assessment of building conditions. *Energy and Buildings*, 34:121–125, 2002.

[49] K.B. Wittchen and E. Brandt. Development of a methodology for selecting office building upgrading solutions based on test survey in european buildings. *Energy and Buildings*, 34:163–169, 2002.

[50] A. Kaklauskas, E.K. Zavadskas, and S. Raslanas. Multivariant design and multiple criteria analysis of building refurbishments. *Energy and Buildings*, 37:361–372, 2005.

[51] Y.K. Juan, P. Gao, and J. Wang. A hybrid decision support system for sustainable office building renovation and energy performance improvement. *Energy and Buildings*, 42:290–297, 2010.

[52] E. Asadi, M. Gameiro da Silva, C.H. Antunes, and L. Dias. Multi-objective optimization for building retrofit strategies: A model and an application. *Energy and Buildings*, 44:81–87, 2012.

[53] C. Diakaki, E. Grigoroudis, and N. Kabelis. A multi-objective decision model for the improvement of energy efficiency in buildings. *Energy and Buildings*, 35:5483–5496, 2010.

[54] F. Nicol and M.A. Humphreys. Derivation of the adaptive equations for thermal comfort in free-running buildings in european standard en15251. *Building and Environment*, 45(1):11–17, 2010.

[55] F. HALDI. Towards a unified model of occupants' behaviour and comfort for building energy simulation. *ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE*, THÉSE NO 4587, 2010.

[56] H.B. Rijal, P. Tuohy, M.A. Humphreys, J.F. Nicol, A. Samuel, and J. Clarke. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. *Energy and Buildings*, 39:823–836, 2007.

[57] R. Tanner. Stochastic optimization of building control systems for mixed-mode buildings. *Phd thesys at Department of Civil, Environmental, and Architectural Engineering*, 2013.

[58] Lawrence Berkeley National Laboratory, 2011. Genopt: generic optimization program http://simulationresearch.lbl.gov/GO/.

[59] E. Zitzler, K. Deb, and L. Thiele. Comparison of multiobjective evolutionary algorithms: Empirical results. *Evolutionary Computation 8(2): 173-195*, 8-2:173–195, 2000.

[60] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan. A fast and elitist multiobjective genetic algorithm: Nsga-ii. *IEEE TRANSACTIONS ON EVOLUTIONARY COMPUTATION, VOL. 6, NO. 2, APRIL 2002*, 6-2:182–197, 2002.

[61] O. Mersmann, 2010. emoa: Evolutionary Multiobjective Optimization Algorithms http://cran.r-project.org/web/packages/emoa/index.html.

[62] S.K. Fuller and S.R. Petersen. Life-cycle costing manual for the federal energy management program. *NIST Handbook 135*, 1995.

[63] AEEG, 2014. Autority for electricity and gas http://www.autorita.energia.it/it/index.htm.