eman ta zabal zazu

DOKTOREGO-TESIA - PhD THESIS

Kontrol Prediktiboa, eraikinen energia erabilera hobetzeko era

Predictive Control, a way to optimize energy use in buildings

Presented in the Thermal Engineering Department by
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Gure Amari,
belaunaldi arteko kultura-mugalari izan zena

To my Mother,
who was a culture smuggler between generations

Preface

Developing, writing and defending a PhD Thesis is not a simple task. There are some years since I began the process and the goal it seems to be close. There have been very good moment and must to forget ones. I have found good friend but also the worse of the society.

Energy and Work is not the same, although they have the same units. The energy is necessary to obtain work, and that work is what we use in order to improve our welfare state. Entropy and Exergy tell us when and how can we use energy and which is the efficiency we can get. World is changing quickly, welfare state is spreading around the world, and those that in other ages had not importance are asking for their place. They need energy to convert in work and to improve their state.

That energy need can have a negative global influence. Although it is not possible to ensure about its consequences, weather and climate are changing. Even when this clearly has positive effect in some sectors, very negative consequences are sensed and appear in other ones. In this challenging moment, Europe is promoting a responsible consumption of energy. Buildings use 40 % of the energy consumed by developed societies, and half of this energy is used to ensure the thermal comfort of the building users. There is an important number of researchers working in this field, trying to improve the efficiency of our energy use.

The number of researchers and research teams focused in this field is significant; from private corporations to universities and research centres. During the development of this PhD Thesis, I had the opportunity to be in one of them and I want to thank it. Dank U, Lieve by accepting me in your team, dank U Sysi team. Damien, thank you for letting me the model and for your hours improving it, ah, I would still be in a kayak without your help. Stefan, thank you for your help with YALMIP, it is a powerful tool to simplify the minimization problem design. Dieter, you are quite strict as reviewer. Bram, fine researcher and musician, you help me in Leuven's ins and outs. Thank you excellent Sysi team and all other friends from KU Leuven, see special mention. You are doing a great work Lieve.

Thanks to all of you that have help me. Izaskun, you have been very patient. It has been delays in most of the deadlines and you continued encouraging me. That is a promotor! With this last one we will arrive on time!! Thank you for the English revisions, I know it has been a very hard work.

Dr. Juan Luis, you finished yours before me. Thank you by the advices and the language revisions.

Aloña, Nekane you also finished it later. Amaia, yours was already done. Irantzu, Ziortza we will celebrate all of them together.

Thanks to all of you that have help me during this time.

Hitzaurrea

PhD Tesi bat burutzea, idaztea eta defendatzea ez da gauza erreza, badira urte batzuk hori egiten hastea erabaki nuela eta antza denez helmuga hurbil dago. Tartean, momentu onak eta txarrak egon dira. Bidean, lagun onak topatu ditut, baita gizadiaren miseriarik handienak ere. Beharrik ez zegoenean laguntza eskaini didaten adiskideak eta bi ogerlekoengatik beste edozeinen ama saltzen direnak tesi honen garapenean topatu ditut.

Energia eta Lana ez dira kontzeptu bera, nahiz eta unitate berdinak izan. Energia behar dugu lana lortzeko eta lan hori behar dugu ongizate gizartea garatzeko. Entropia eta Exergia bezalako kontzeptuek esaten digute noiz eta nola erabil daiteke dugun energia, eta zer etekin atera diezaiokegun. Bizi garen mundua arin aldatu da. Ongizate gizartea gero eta gehiago zabaltzen ari da, eta lehenago garrantzia eta influentzia ez zutenek haien tokia eskatzen dute munduan. Eta energia behar dute lan bihurtzeko, eta ondo bizitzeko.

Energia behar horrek, kolokan jar dezake gizadia. Horren eragina noraino hel daitekeen ziurtatzerik ez badago ere, eguraldi eta klima aldatzen ari dira, eta honek arlo batzuetan eragin positiboak ekarriko baditu ere, beste arlo batzuetan nabaritzen diren eraginak kaltegarriak dira. Bizi garen une erabakigarri hauetan Europak energiaren erabilera arduratsu baten alde apustu egin du. Eraikuntzaren sektoreak, gizarte garatuetan kontsumitzen den energiaren % 40 erabiltzen du, horren erdia ongizate termikoa ziurtatzeko erabiliz. Lagun asko dira arlo honetan lana egiten dutenak, erabiltzen den energia ahalik eta era eraginkorrenean aprobetxatzeko.

Ikerkuntza arloan asko dira esparru honetan aritzen diren ikertzaile eta ikerketa taldeak, bai enpresetan zein unibertsitate eta ikerkuntza zentroetan. Haietariko batzuekin egoteko aukera izan nuen eta lerro txiki hauetatik aukera hori eskertu nahi diet. Eskerrik asko Lieve, zure taldean toki txiki bat egiteagatik, baita Sysi talde osoari. Damien, eskerrik asko modeloa uzteagatik eta doitzeagatik, ah, zure langintzarik gabe oraindik kayak batean egongo nintzateke. Stefan, eskerrik asko YALMIPekin laguntzeagatik, asko errazten du minimizazioaren definiziona. Dieter, oso zorrotza zara zuzentzerakoan. Bram, ikertzaile eta musikari bikaina, Leuveneko nodik-norakoetan lagundu ninduena. Eskerrik asko Sysi talde bikainari eta KU Leuveneko beste lagunei, aipamen berezia ikusi. Lan handia egiten ari zara, Lieve!!

Eskerrik asko bide honetan lagundu nauteneei. Izaskun, zurea bai pazientzia. Entregatzeko datetara beti berandu heldu eta zu animatzen jarraituz, hau zuzendaria. Azken honetan garaiz helduko gara! Eskerrik asko ere zure laguntza ingelesarekin, lan handia eman dizut.

Dr. Juan Luis, arinago bukatu zenuen, eskerrik asko emandako aholkuengatik eta egindako orrazketengatik.

Aloña, Nekane, zuek ere aurreratu zineten. Amaia, zu bazinen. Irantzu eta Ziortza, zureak honekin batera ospatuko ditugu.

Ezkerrik asko bidai honetan lagundu nauzuen guztioi.

Speciaal voorwoord

Met deze paar lijnen tekst zou ik ook graag willen bedanken voor de ondersteuning die deze doctoraatsthesis en ikzelf hebben mogen ontvangen tijdens mijn onderzoeksverblijf aan de KU Leuven. Lieve, dankjewel om mij toe te laten in je onderzoeksteam. Het waren mooie momenten, en de steun liet mij toe om het onderzoek in deze thesis uit te werken. Eerlijkheidshalve zou je een van de officiële begeleiders van deze thesis moeten zijn, maar administratieve problemen hebben ervoor gezorgd dat ik je dit niet kon vragen. Het minste dat ik kan doen is vermelden hoe belangrijk je steun is geweest, Lieve.

Dank ook aan het team van The SySis, aan jullie allemaal. Lieve, je hebt een fantastische groep bijeengebracht. Dieter, Damien, Filip, Stefan, Brecht, Arnout, Joachim, Roel, Maarten, Alessia, Nicholas, Ercan, Mats, Alessandro, allemaal bedankt en veel succes in de toekomst. Ook veel succes voor de nieuwe uitbreiding, Annelies, Iago, Yamid, Javier en Ján. Ik wens jullie succesvol onderzoek. Valérie, dankjewel (en alle mensen in het secretariaat)! Bijzondere dank gaat uit naar jou, Bram, je was een grote steun in het begin en tijdens mijn verblijf in een nieuwe stad.

Wim, Thanos, Cornelia, Dries, Kris, Sarah, Kenneth, Kenneth, Kristel, Maarten (de pol), Niels… We hebben samen prachtige momenten beleefd: het TME Weekend, TME BBQ, Happy Hour… Tot ziens, vrienden!

De tijd in Leuven was erg mooi; een aangename stad, een kwaliteitsvolle universiteit en aardige mensen. Een aantal nieuwe gebruiken, maar ook veel oude tradities. Drie klassieke orkesten, fantastische Lenteconcerten! Verplaatsingen per fiets zijn hier de standaard! Een prachtige wetenschapscampus met het Kasteel van Arenberg er middenin. Voor het middageten, een bezoek aan de Alma of broodjes halen bij de Moete. En op vrijdag, iets specialer, Happy Hour vanaf vijf uur in de namiddag, een geschikt moment om bij te praten en elkaar beter te leren kennen, dankjewel Laurens!

Ik heb ook de kans gegrepen om een beetje rond te reizen en de omgeving te leren kennen: Brussel, de hoofdstad van Europa; Gent en Brugge, de mooiere historische steden; Oostende, wie beweerde er dat Vlaanderen geen strand heeft? Vleteren, Westvleteren, het bekende verhaal: bellen, nummerplaat van de auto en mobiel nummer doorgeven en je mag op bezoek gaan ;-) Antwerpen, Mechelen, en niet te vergeten: Limburg. Er waren ook internationale bezoeken: Maastricht (je was een bekwame gids, Bram, en mooi om de katholieke en protestante kerken zij aan zij te zien. Zeeland, een subliem stukje ingenieurswerk om de kracht van de oceaan te bedwingen. Amsterdam ;-), je weet wel, de plaats waar je naartoe moet om wat plantaardige producten te kopen;

spijtig genoeg was de zeepbel van de tulpenbollen al lang verleden tijd. Köln, Bonn, Aachen, mooie historische Duitse steden.

Nogmaals dankjewel aan iedereen voor de grote steun die jullie betekend hebben.

Contents/Edukiak

Abbreviations/Laburpenak

A collection of abbreviations used in this PhD Thesis document.
PhD Tesi dokumentu honetan erabilitako laburpenak

AC	Air Conditioning
ACH	Air Changes per hour
AHU	Air Handling Unit
ANN	Artificial Neuronal Networks
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASHRAE HOF	ASHRAE Handbook - Fundamentals
BES	Building Energy Simulation
BRCM Toolbox	Building Resistance-Capacitance Modelling Toolbox
BS	Blind System
BSC	Blind System Control
CCA	Concrete Core Activation
CHTC	Convection Heat-Transfer Coefficient
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of Performance
CTSM-R	Continuous Time Stochastic Modelling package for R
DLF	Direct Feedback Linear
DR	Draught Rate
DTU	Technical University of Denmark
EBC	Energy in Buildings and Communities
EER	Energy Efficiency Ratio
EN	European norm
ET	Equation of Time
FL	Fuzzy Logic
GA	Genetic Algorithms
GCHP	Ground Coupled Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
IAC	Indoor solar Attenuation Coefficient
IEA	International Energy Agency
ISO	International Organization for Standardization
ITER	International Thermonuclear Experimental Reactor
LORD	LOgical R-Determination
LP	Linear programing
LTI system	Linear Time-Invariant system
MPC	Model Predictive Control
MIQP	Mixed Integer Quadratic Programing
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PD	Percentage Dissatisfied

PEX	Cross-linked polyethylene
PI control	Proportional Integral control
PID control	Proportional Integral Derivative control
PMAC	Pulse Modulation Adaptive Controller
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PRAC	Pattern Recognition Adaptive Controller
PRBS	Pseudo-Random Binary Signal
QP	Quadratic Programing
RBC	Rule-Based Control
ROLBS	Randomly Ordered Logarithmically Distributed Binary Sequence
SHGC	Solar Heat Gain Coefficient
SoA	State of the Art
SoC	State of Charge
TABS	Thermally Activated Building System
TMY	Typical Meteorological Year
TOU	Time of Use
TPSC	Two Parameter Switching Control

List of figures/Irudien zerrenda

List of tables/Taulen zerrenda

Abstract

The energy requirements of our globalized world carry out interdependence conditions and instability in certain areas. In developed societies, buildings expend about 40% of the total energy, and half of it is used by the building climate systems to ensure thermal comfort. It must also be remarked that more than a half of the consumed power in Europa is imported. For these reasons, the reduction of the amount of power used in buildings has become an objective for the European power policy. This PhD Thesis studies two specific problems, referred to the power management in building climatization, heating and cooling, systems, dealing with them from a control perspective.

The first problem is given by the big stock of aged poor quality residential blocks that are still in some districts of modern cities. The use of a Model Predictive Control (MPC) to control the heating system, allows using the weather forecast to reduce the energy use ensuring thermal comfort. Results of the study show potential energy savings about 9 % when compared with the ones of a thermostatic control. The use of an MPC with a Time of Use (TOU) power rate shows also important economic benefits although there is no energy savings.

The second problem that handles this PHD Thesis is to improve the blind system control of an office building in order to reduce the energy required need to maintain the comfort conditions in the offices. The analysis is checked with the two-office module found in the literature. This module is made of high quality materials, north-south oriented, and climatized by an MPC-controlled main TABS and auxiliary AHU systems. The novel enhanced blind system control uses the information of the required energy use foreseen by the MPC to regulate the blind system. Obtained results show a potential energy use reduction of 15 % in South oriented office when the novel system is compared with a hysteresis blind system control.

Laburpena

Nabaria da gaur egun nazioartean, energiarekiko dagoen ziurgabetasun egoera. Eraikinetan ematen den energia kontsumoa, kontsumo osoaren %40 izan daiteke, eta horren erdia klimatizazio sistemetan, berotze eta hozte prozesuetan, erabiltzen da erabiltzaileen ongizate termikoa ziurtatzeko. Esan behar da ere, nola Europan erabiltzen den enegiaren erdia baino gehiago inportatua den. Arrozoi hauengatik, eraikinetan erabiltzen den energia murriztea helburu bihurtu dela Europako politika energetikorako. PhD Thesi honetan, eraikinen klimatizazio sistemeen kudeaketan agertzen diren bi problema aztertzen ditu, beti ere kontrol ikuspuntutik.

Aztertuko den lehen egoera, hirietako hainbat auzoetan dauden kalitate urriko eraikin zaharkituekin lotuta dago. Etxeko berotze sistema *Model Predictive Control* (MPC) baten bidez kontrolatzeak, eguraldi aurreikuspena erabiltzea ahalbidetzen du energia kontsumoa gutxitzeko ongizate termikoa mantentzen den bitartean. Ikerketa honen emaitzak, etxebizitzetan normalean erabiltzen den kontrol termostatikoarekin alderatzen direnean erakusten duten energia aurrezpen potentziala %9 da. Ikerketak, *Time of Use*, TOU, energia tarifa erabiltzeak dakartzan onura ekonomikoak ere aztertzen ditu.

Tesiak aztertzen duen bigarren problema hau da: bulego eraikin baten errezelen kontrol-sistema nola egokitu behar den energia erabilera murrizteko barneko ongizate baldintzak betez. Ikerketa, bibliografian erreferentzia den bi bulegoko moduluaren oinarritzat hartuz egin da. Modulu hau, kalitate handiko materialak erabiliz eraikita dago, Ipar-Hego orientazioa dauka eta klimatizazio sistema, MPCak kontrolatutako TABS eta AHU sistemez osatzen da. Aurkezten den errezel sistemaren kontrol aurreratu berria, MPCak dituen energia erabileraren aurreikuspenak hartzen ditu errezel sistemaren egoera zehazteko eta horrela energiaren erabilera murrizteko. Kontrol berri honekin lortzen diren emaitzak, histeresi kontrolarekin alderatzen direnean, aurrezpen potentzialak hegoaldeko bulegoan % 15 izan daitezkeela erakusten dute.

1.

Introduction

1.1 Motivation

The energy security situation in a globalized world means an interdependence condition and the impossibility of insulation against global instability situations. Recently, United Kingdom celebrated is first coal free day since the beginning of the industrial revolution. This is, coal was not used to power thermal plants to obtain electricity. On the other side of the ocean, meanwhile, the new administration of the United States of America wants to improve the use of carbon in electricity generation, proposes to shell half of its oil strategic reserve and will withdraw the Paris Climate Agreement. In the middle of 2014, Brent barrel cost $114.81 [1]. At the beginning of 2015 it price fall to $48.79, being the maximum price that year $65.37. At the beginning of 2016 the price dropped to $28.94, which questioned the feasibility of the extraction by fracking and slowed the renewable energy development. At mid-June 2017, the barrel price is below

$50. Although there are some regasification plants in Europa, there is an important dependence on Russian natural gas, which has influence in the geopolitical context. After the nuclear incidents of Chernobyl and Fukusima, Germany resolved to shut its nuclear plants down for 2022. Meanwhile, Finland and the United Kingdom are developing new reactors. France, which has an important nuclear dependence, is working to reduce the number of nuclear plants in its territory. It can be said that in a general way, the use of renewable energy is increasing, once its viability and profitability has been proved. Nowadays, in addition to the hydropower, wind and solar (photovoltaic and thermosolar) are the main renewable energy sources. There are other sources with a limited use or in process to be fully developed. Fusion power is already under development, the plant of the ITER is still under construction and its Tokamak complex is supposed to develop its first plasma in March 2025.

Due to the Climate Change, some countries have decided to reduce their greenhouse gas emissions in the Tokyo and Paris climate summits. In order to fulfil those objectives, in addition to increase the use of renewable power it is also necessary to promote a responsible use of the energy. More than a half of the consumed power in Europa is imported [2]. In order to decrease the dependence that this situation creates and to face the climate change, energy saving policies have been developed. Buildings, industry and transport are the main power user sectors in developed societies. Power consumption in buildings is about 40 % of the global consumption [3], and half of it is used in building climate systems in order to provide heating and cooling. The reduction of the amount of power used in buildings has become an objective for the European power policy. A strict legislation has been developed for new construction buildings, developing a normative for nearly-zero energy buildings. The improvement of the construction materials has supposed an important enhancement of the façade and windows insulation. The upgrade of the heating and cooling systems and the introduction of renewable energies, thermosolar panels or geothermal power for example, have increased in a significant way the thermal efficiency of the buildings. Nevertheless, there are an important percentage of buildings in the cities, which constructed in the so-called boom development era with low quality materials, are not in line with the desired thermal quality standards. Their rehabilitation is necessary to improve their thermal efficiency, although this can suppose an undesired economic situation for its users. In order to study if the heating system control can help to implement a saving energy policy in these buildings, this PhD Thesis proposes the study of the thermal behaviour of that kind of buildings under an MPC. The knowledge of the weather forecast supposes an advantage for the control when calculating the control action. It should reduce the energy use. The indicators provided by the results of this studio are supposed not to be restricted to the studied building but to be appropriate for buildings with the mentioned constructive deficiencies.

On the other hand, office buildings must face large thermal charges due to the user activity or the office appliances and lighting system. Weather influence is necessary to be added. In this kind of building, the use of heating and cooling systems is usual in order to maintain the thermal comfort of the users. A well-developed environmental thermal comfort is necessary due to the relationship between the thermal comfort and work quality, as it will be shown in Chapter 6. Thermally Activated Building System (TABS), also called Concrete Core Activation (CCA) systems use the structure of the building to store and distribute the thermal energy, heat or cold, needed to ensure the comfort conditions of the building. This system shows different advantages that will be studied in this document. The structure of the building can be used to store cheap thermal energy due to its large thermal inertia and use it in more expensive moments. Still, an air-handling unit (AHU) must be added to the system in order to ensure correct ventilation. AHU also manages the changes in the indoor environment that weather conditions and indoor charges provoke and the slow TABS dynamics cannot face.

Model Predictive Control (MPC) is an appropriate control for the slow dynamics of the TABS. The Rule Based Control (RBC) is usually implemented in this kind of systems under error-based controls as the *on-off* thermostatic or the well-known proportional-integral-differential (PID) control. The control action proposed by the MPC is not based on the committed error but on the predicted disturbance values that affects the system. The multiobjetive nature of the MPC also allows controlling the comfort characteristics of the environment while minimizing the energy use.

The use of the MPC is spreading among the buildings climate systems. Still, it is necessary to provide the MPC with a model of the building that must be controlled in order to get an accurate response. A new model must be developed for each building considering its specific characteristics. Nowadays, this is the main problem MPC must face in order to get a wide expansion in this sector.

Lighting inside the building is another of the comfort parameters to be taken into account. Besides comfort considerations, lighting is a heat source and a power consumer that must be considered and evaluated for a correct response of the control action. New lighting systems have reduced its power consumption and dissipated energy, decreasing the influence that these factors have in the control action. Nowadays, it is not strange to maintain the lighting system on during the working day irrespective of the outdoor luminance. The optical discomfort effect that a high solar radiation can produce can be mitigated by using the adequate blind system.

Blind system not only provides solution for the lighting excess. It can also be used to reduce the thermal effect the solar radiation has over the indoor environment and decrease the cooling power needs during summer. Solar radiation not only arrives in the visible spectrum range. The radiation that arrives in infrared range can suppose a large thermal influence in the indoor environment of a building. Treating the window glass is possible to reduce the solar radiation through the window in the entire radiation spectrum or in a part of it. Blind systems allow regulating the amount of radiation that passes through the window system. For automatic blind system, the control deployed is based on a hysteresis band or on parameters like indoor temperature. Considering the effect the solar radiation has over the thermal comfort and the energy use, Chapter 7 of this study proposes an enhanced blind system control that must reduce the energy use of the climate control operation of an office-building module. In summer, under a large solar radiation conditions and for a south orientation (in north hemisphere), the control provides promising results for energy savings that can suppose a 15 % of the used energy.

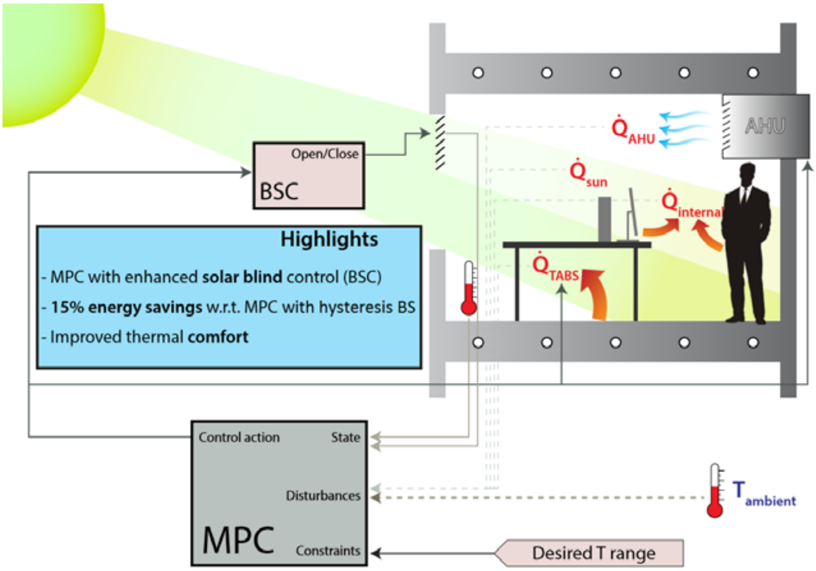

Figure 1.1. Proposed blind system control integration with the MPC that controls the TABS and AHU system in an office building module

Although the structure of this PhD Thesis document will be discussed in the next section, it is necessary to introduce some aspects about the linguistic treatment of the text. Considering the reduction of the amount of energy that MPC, TABS or blind system provide enough motivation to write this document, it is necessary to indicate that the linguistic mixture of the test has also been an inspiration source. The reader is ask for forgiveness in relation with the linguistic tangle that the document presents. The will to write to document in English and Basque and the lack of time to translate the entire test have created this lovely language mixture. The document looks for some equilibrium between two languages in this tiny chaos. In order to give the reader the opportunity to follow the text. The main research parts of the document are two papers published in the journal *Energies*. In this way, reader can follow these Chapters with no special difficulty. The use of mathematical language must also help to understand the contents of the text. The text also provides a small summary of those chapters written in Basque to improve the reader's comprehension. It must be said that the building climate control is not the unique field that is being improved over the time. What was impossible some years ago is nowadays becoming possible. At a research stay in Katholische Universitet (KU) Leuven it has been necessary to read, or better said to understand the famous paper that Gnielinski published in 1975 *Neue Gleichungen für den Wärme- und den Stoffübergang in* *turbulent durchströmten Rohren und Kanälen* [4]. It was necessary to study the Nussel correlations for the study of Chapter 3, and at when a copy of the original paper was obtained, it was in the language of Goethe of course. This supposed a small problem since the German language knowledge of the writer of these lines is not too high. However, nowadays there are tools in continuous improvement that allow the translation of a text in a foreign language. Helped by a well known automatic translator, the paper became understandable. At this moment the poor quality of the translation and the length of the text makes difficult that kind of solutions for this PhD Thesis. Basque language is an old and small language that wishes to be accesible and to come into view in this global world with its hat “txapela” on. So, dear reader, pardon the tangle. The tools needed for a good understanding of the text are improving. Be patient to untie the knot leaving the technique of Alexander the Great aside.

1.2 Objectives

The main objective of this PhD Thesis is to look deeply into the knowledge of two well defined problems related to the power use of building climatization, providing an MPC based solution. The first problem is given by the big stock of aged poor quality residential blocks that are still in some districts of modern cities. The study evaluates the potential improvement that an MPC provides regarding the common on-off thermostatic control. Chapter 5 develops the analysis published in an indexed journal by Carrascal et al. [5]. The analysis also shows the economic benefits that provides the MPC when a time of use (TOU) power rate is applied.

The second problem that handles this PHD Thesis is to improve the blind system control of an office building in order to reduce the energy required need to maintain the comfort conditions in the offices. The analysis is checked with the two-office module found in the literature. This module is made of high quality materials, north-south oriented, and climatized by an MPC-controlled Heating, Ventilation and Air Conditioning (HVAC) system composed by TABS and an auxiliary AHU. The offices support important heat gains; human activity, office appliance and solar irradiation that help to heat the office in winter, but must be compensated in summer by the climate system. From those gains, solar irradiance is the only adjustable one. Chapter 7 proposes a novel enhanced blind system control: it uses information of the energy use foreseen by the MPC to regulate the blind system. Chapter 7 introduces the results of this study published in [6]. The results show important energy reduction respect the hysteresis control.

The building sector represents 40 % of the global energy expense in developed society. Half of this energy is used to maintain the comfort conditions in the building. The MPC is a promising control paradigm, which predictive characteristics make it a suitable control for the buildings HVAC systems. Figure 1.2 shows the results of a search in *scopus* under these keywords: *KEY (("MPC" OR "Model Predictive Control") AND ("HVAC" OR "Building" OR "office" OR "TABS" OR "CCA" OR "concrete core* *activation")).* Figure shows the increasing publication number related to these subjects during the last years.

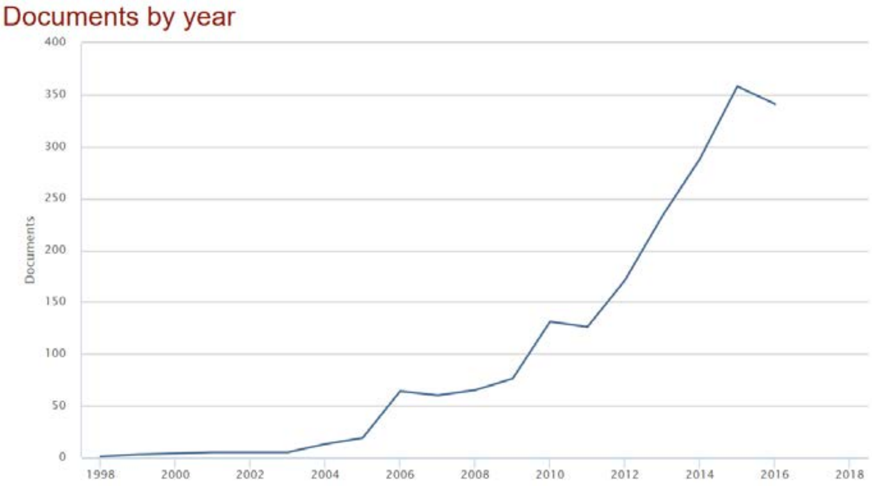

Figure 1.2. Reference search. Number of publications about MPC and building climate systems published in the last twenty years (*scopus*)

1.3 Structure of the document

Thesis document is divided in 8 chapters, and as it has been already explained, aims to balance the use of English and Basque languages. After this small introduction of Chapter 1, the structure of the PhD Thesis is as follows.

Chapter 2 provides a literature revision of the main subjects of this Thesis. Thermally Activated Building System (TABS), Model Predictive Control (MPC) and blind systems are studied in this chapter.

Chapter 3 focuses in the TABS as element for heating store and distribution. After a historic introduction about radiation systems, the chapter introduces the physical study about heating transfer modes. Then, it studies the modes the heat transfer appears in TABS. The chapter ends with a characterization of a TABS slab using the module Continuous Time Stochastic Modelling package for R (CTSM-R) [7]. Information for the characterization was collected from an ANSYS simulation. The work of Van der Hejde *et al.* [8] explains how the results of the simulation were used for the study about the State of Charge, SoC, of the concrete slab of a TABS.

Chapter 4 studies the use of the MPC in buildings. This control is used in the two research chapters of this Thesis and gives information about state-space expression or the minimization problem and their bounds. Chapter also studies how the building model can be created in order to implement it in the MPC. It also considers the most common parameters used in the MPC.

Chapter 5 compiles the results of the first published research work [5]. It studies the benefits that the implementation of an MPC in a poor quality aged building can suppose when controlling the heating system. The study compares the results with those obtained using a thermostatic *on-off* system, showing promising results. Finally, the study implements a TOU energy rate within the MPC. Although the study does not show energy use reduction, it obtains important economic savings.

Chapter 6 develops some concepts that will help to understand the second research work of Chapter 7. The first part of the chapter introduces the thermal comfort concept and the normative that regulates it. The specifications of ASHRAE 55 [9], ISO 7730 [10] and EN12251 [11] are collected and explained. The second part of the chapter studies weather and climate concepts, especially the solar radiation, which is an important heat source in summer. The chapter also provides information about the Typical Year Dataset (TMY3) that makes available a database with the most usual climate parameters of a location. This information is normally used in simulation works. The last part of the chapter studies windows and blind systems, based on the normative associated with the calculus of the radiation that passes through the system; ASHRAE HOF [12], ISO 9050 [13], ISO 10292 [14], ISO 15099 [15] and EN 13363 [16].

Chapter 7 shows the results of the second research work [6]. In this case, it takes a common literature model: good quality materials, north-south orientation two-office and corridor module with TABS and AHU climate systems and an MPC as its main control. This model is the base to study the energetic improvement that a proposed enhanced blind system control provides. The enhanced control uses predictive information of the main MPC and gets a potential improvement in energy use around 15 % when compared with the normally used *on-off* hysteresis control

Chapter 8 is the last chapter of the Thesis and it presents a small summary of the most important factors and conclusions covered in it. The chapter also exposes some open ways to continue the already done work.

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1.

Sarrera

1.1 Motibazioa

Nabaria da gaur egun nazioartean, energiarekiko dagoen ziurgabetasun egoera. Orain dela egun gutxi, Bretainia Handiak industri iraultza hasi zenetik ikatzik gabeko lehen eguna ospatu zuen. Hau da, ez zuten erabili ikatz zentralik energia elektrikoa sortzeko. Ozeanoaren beste aldean, Amerikako Estatu Batuetako administrazio berriak ikatzaren erabilera elektrikoa sustatu nahi du berriro haien petroleo-erreserbak erdira jaistea proposatzen duen bitartean. 2014aren erdian, Brent upela $114.81-etan [1] ordaintzen zen. 2015aren hasieran, prezioa $48.79-era jaitsi zen. Tarteko preziorik altuena $65.37 izanik, 2016 hasieran $28.94-etan ordaindu zen, *fracking* bidezko erauzketa zalantzan jarriz eta energia berriztagarrien inplementazioa moteldu. Horren prezioa 2017.eko ekainaren erdian $50 azpitik dago. Europak birgasifikazio plantak eduki arren, Errusiako gas naturalaren menpekotasun handia du, egoera geopolitikoan eragina duena. Chernobyleko eta Fukusimako istripu nuklearren ondoren, Alemaniak dituen plantak 2022 ixtea erabaki du. Bitartean Europako beste herrialde batzuk, Finlandiak eta Bretainia Handiak, erreaktore berriak eraikitzen ari dira. Frantziak, energia honen dependentzia handia duen herrialdea, planta nuklearren kopurua murriztuko du. Orokorrean, energia berriztagarrien inplementazioa bultzatzen ari da horren errentagarritasuna eta bideragarritasuna argi geratu baita. Gaur egun, aspalditik erabiltzen den hidraulikoaz gain, eolikoa eta eguzkitikoa, fotovoltaikoa zein termikoa, dira iturri nagusiak. Beste iturri batzuk ere erabiltzen dira, nahiz eta horien erabilera mugatuagoa izan edo garapen fasean egon. Fusioak oraindik bidea egin behar du. ITER planta eraikitzen ari da eta horren Tokamak konplexuak 2025eko martxoan lehen plasma sortu beharko luke.

Aldaketa klimatikoa dela eta, hainbat herrialdek onartu dute berotegi efektuko gas-emisioen murrizketak Tokio eta Parisko Klima Gailurretan. Helburuak betetzeko, energia berriztagarrien erabilera bultzatzeaz gain, energia kontsumo arduratsua bilatzen da. Europan kontsumitzen den energiaren erdia baino gehiago inportatua da [2]. Egoera horrek sortzen duen menpekotasuna ekiditeko eta klima aldaketari aurre egiteko, energia kontsumo arduratsua bultzatu nahi da. Eraikinena, industria eta garraioarekin batera, gizarte garatuen energia gehien erabiltzen duten sektoreetariko bat da. Eraikinetan ematen den energia kontsumoa, kontsumo osoaren %40 [3] izan daiteke, eta horren erdia klimatizazio sistemetan, berotze eta hozte prozesuetan, erabiltzen da. Europako politika energetikoaren helburu bihurtu da energia erabilera hori murriztea. Hori lortzeko arautegi zorrotza proposatu da eraikuntza berriko eraikinentzako, zero energi kontsumotik hurbil dauden etxeen arautegia definitzen den bitartean. Eraikuntza materialen etengabeko garapenak eraikinen isolamendu termikoaren hobekuntza ekarri du fatxadan zein leihoetan. Bero eta hotz ekipoen etekinen hobekuntzek, eta energia berriztagarrien sarrerak, eguzki panel termikoak edo geotermia adibidez, eraikin berrien efizientzia termikoa era nabarmenean handitu dute. Hala ere, esan beharra dago gaur egungo hirietan, aurreko garaietako eraikinak badaudela, zeinetan eraikitze teknikak eta materialak gaur egungo kalitate estandarretik urrun dauden. Hauen eraginkortasun termikoa txikia denez, energia kontsumoa gutxitzeko birgaipena beharrezkoa da, nahiz eta batzuetan honen kostua handia izan erabiltzaileentzat. Era honetako etxebizitzen kopurua handia da hiri batzuetako auzoetan; auzo oso baten etxeak daude maiz baldintza hauen pean eraikita. Hau dela eta, ongizate termikoaren kontrol aldetik egin daitekeen ekarpen bat aztertzen da lan honetan: eguraldi parametroen aurreikuspenak kontutan hartzen dituen kontrol baten inplementazioak ekar ditzakeen energia aurrezpenak aztertzea. Lortutako emaitzak ez dira bakarrik era honetako etxebizitzentzako adierazgarriak, antzeko eraikuntza teknika zaharkituak erabili dituzten beste eraikinetako motarako erreferentzia ere izan daitezke.

Bulego eraikinek beste aldetik, duten aktibitatea dela eta, bero karga handiak jasan behar dituzte: jendearen erabilera, bulego materiala, argiztapena... Horiei, eguraldiak duen eragina gehitu behar zaie. Eraikin hauetan, bero- eta hotz-sistemak beharrezkoak dira erabiltzaileen ongizate termikoa ziurtatzeko. Barne ingurumenaren ongizatearen kudeaketa garrantzia berezia du jende kopuru handiengan eragina duelako baita hauek egiten duten lanaren kalitateengan ere.

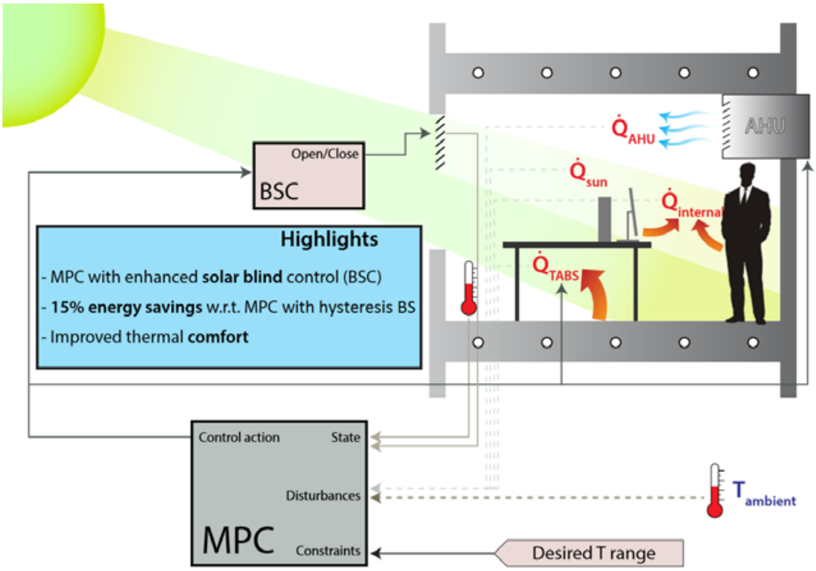
Thermally Actibated Building System-ek (TABS) edo *Concrete Core Activation* (CCA) sistemek, eraikinen egitura erabiltzen dute energia termikoa, bero edo hotza, metatzeko eta banatzeko. Sistema horrek dokumentu honetan aztertuko diren abantaila nabarmenak ditu. Duen inertzia termikoa handiaren ondorioz, eraikinaren estruktura energia termiko biltegi moduan erabili ahal da, energia merkea metatuz behar denean. Hala ere, sistema horren erabilpenak, beharrezkoa egiten du airea tratatzeko unitatea, *air handling unit* (AHU), sisteman integratzea aireztatze beharrak betetzeko. TABS-en dinamika geldoak kudeatu ezin dituen perturbazioen, eguraldiaren eta barne bero kargen, aldaketa azkarrei erantzuna emango die AHU-ak.

Ereduan oinarrituriko kontrol prediktiboa, *Model Predictive Control* (MPC), TABS-ek duten dinamika geldoak kudeatzeko kontrol egokia da. Bulego eraikinetan normalean erabiltzen diren arauetan oinarritutako kontrolak, *Rule Based Control* (RBC), erreferentzia batekiko egiten den akatsean oinarritutako *on-off* edo *proportional-integral-differential* (PID) kontrolak inplementatzen ditu behe mailan. MPCek proposatzen duen kontrol ekintza, aldiz, ebaluazio momentuan eta etorkizunean agertuko diren sistemen perturbazioetan oinarrituta dago. Horrez gain, MPC helburu anitzeko kontrola izanda, ongizate baldintzak ziurtatzen ditu aldi berean energia erabilera minimizatuz.

MPCaren erabilera eraikinen girotze sistemen kudeaketan zabaltzen ari da. Hala ere, eraikin baten eredu termikoa lortzea ez da erreza eta kontrola era egokian inplementatzeko, ondo doituta dagoen eredua behar da. Eraikin bakoitzarentzat eredua garatu behar da dituen berezitasunak kontutan harturik. Gaur egun hau da MPCaren zabalkuntza mugatzen duen faktore nagusia.

Argiztapenak ongizatean duen eragina ere kontutan hartu behar da. Ongizate parametroa izateaz gain, bero iturria ere bada eta energia kontsumitzen du. Hala ere, merkatuan agertzen ari diren argiztapen era berriek faktore honen kontsumoa eta disipatutako potentzia gutxitzen ari dira. Ez da arraroa argiztapen sistema piztuta egotea lan jardunaldia irauten duen bitartean kanpoko baldintzei muzin eginez. Kanpotik datorren argiak, ezerosotasuna sor dezake erabiltzaileengan. Hau ekiditeko, hainbat errezel-sistema mota erabiltzen dira gaur egun.

Errezel-sistemek ez dituzte soilik argitasun larregiko arazoak konpontzen. Udan, eguzki erradiazioa bero-iturri garrantzitsua bilakatzen da eta horren eragina era nabarmenean handi dezake hozketa-sistemak behar duen energia. Heltzen zaigun eguzki erradiazioa ez da eremu ikusgaian bakarrik hedatzen. Infragorri eremuan heltzen den energia, eraikin baten ingurumenean eragin termiko nabaria eduki dezake. Posible da leihoen alde gardenean, hau da beiran, tratamenduak ezartzea heltzen den erradiazioa murrizteko, bai horren uhin-luzera eremu guztian, baita tarte jakin batean ere. Errezel-sistemek, hala ere, sartzen den erradiazioaren erregulazioa ahalbidetzen du. Errezel-sistemaren automatizazioa, izanez gero, heltzen den erradiazioarekiko histeresia edo barne- tenperatura gisako parametroetan oinarritzen da normalean. Eguzkiaren erradiazioak ongizatean eta energia erabileran duen eragina aztertuta, sistema aurreratuagoa proposatzea egokia izan daitekeela ikusten da, are gehiago, MPCak sortzen dituen aurreikusitako balioak erabil daitezkeenean. Udan, eguzki erradiazioa handia denean, eta hego orientaziorako (ipar hemisferioan) ondo egokitutako errezel-sistema baten kontrolak sor ditzakeen energia aurrezpenak nabariak izan daitezkeelakoan burutu da ikerketa lan hau.



1.1 Irudia. Proposatutako errezel-sistemaren kontrolaren integrazioa MPCarekin TABS eta AHU duen bulego batean

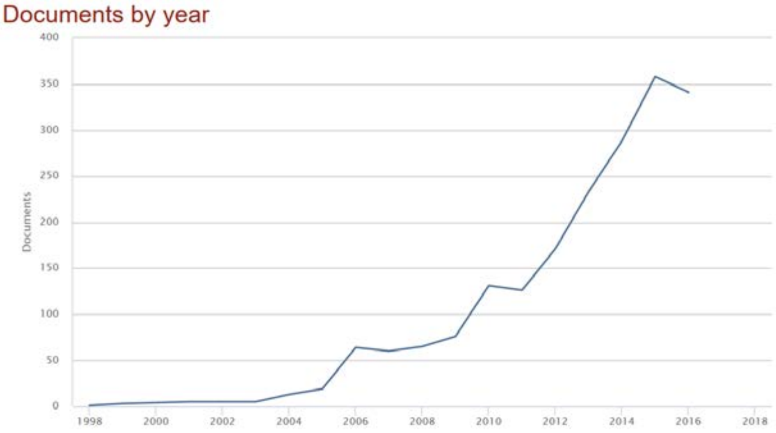
Tesi dokumentu honen egitura hurrengo sekzioan azaltzen den arren, bi hitz esan behar dira lanak jaso duen hizkuntz trataerari buruz. Eraikinek duten energia kontsumoaren murrizketa aukerak aztertzea MPC, TABS edo errezel-sistemak erabiliz ikerketa lan hau burutzeko nahiko motibazioa bada ere, hori idazteko erabili diren hizkuntzak ere inspirazio iturri izan dira. Irakurleak parka dezala dokumentuan agertzen den hizkuntza nahaste-borrastea. PhD dokumentua euskaraz eta ingelesez idatzi nahi izateak eta hizkuntzen arteko itzulpena egiteko beta faltak, aurrean dagoen hizkuntz nahasketa maitagarria sortu du. Hau horrela izanda, saiatu da hizkuntzen arteko oreka bilatzea kaos txiki honetan irakurleak testua jarraitzeko aukera izan dezan. Dokumentuaren muina diren ikerkuntza atalak, *Energies* aldizkarian argitaratutako bi artikulutan oinarritzen direnez, irakurleak arazo barik jarrai ditzake. Matematika hizkuntza unibertsala izatea lagungarri bihurtuko da ziur hainbat kontzeptuen ulermenean. Ingeleseko sarrera bat gehitu zaie euskeraz idatziriko atalei hauen ulermena hobetzeko. Azkenik, gizartearen aurrerapena eraikuntzen klimatizazio kontroletan soilik ez dela gauzatzen esan behar. Orain dela urte batzuk ezinezkoa zena gaur egun posible bihurtzen ari da. Katholische Universitet (KU) Leuvenen egonik, Gnielinski-k 1975-ean argitaratu zuen paper famatua, *Neue Gleichungen für den Wärme- und den Stoffübergang in* *turbulent durchströmten Rohren und Kanälen* [4], irakurri edo, hobe esanda, ulertu nuen. Nusselen korrelazioak gora eta behera ibilita azkenean jatorrizko artikuluaren kopia lortu zen Goetheren hizkuntzan, noski. Arazo txiki bat sortu zuen honek, alemana ezer gutxi menperatzen duelako lerro hauen egileak. Hala ere, gaur egun badira etengabe garatzen ari diren itzulpen tresnak. Itzulpen automatikorako tresna erabilita artikulua ulergarria bihurtzen da. Gaur egungo itzulpenen kalitatea onena ez bada ere, eta testuaren luzera kontutan harturik, arlo honetan dauden etengabeko hobekuntzek laster ahalbidetuko dute era honetako irtenbideak. Euskara hizkuntz zaharra eta txikia da. Hala ere, ulergarri egin nahi du bere burua txapela jantzita globalizatuta dagoen mundu honetara ateratzeko. Horrela, irakurle lagunak barka beza endredoa. Testua ondo ulertzeko behar diren tresnak garatzen ari dira. Pazientzia izan korapiloa askatzeko Alexandro Handiak egindakoa errepikatu barik.

1.2 Helburuak

PhD tesi honen helburu nagusia, eraikinen klimatizazio sistemen energia erabilerarekin lotuta dauden bi problemen azterketa da. Ondo definitutako problema hauen konponbidea MPCaren erabilerarekin bilatzen da. Lehen problema, hirietako hainbat auzoetan dauden kalitate urriko eraikin zaharkituekin lotuta dago. Ikerketak, energia erabilera hobetzeko MPCaren erabilerak ekar ditzakeen onurak aztertzen ditu eta horrelako eraikinetan normalean erabiltzen diren *on-off* sistema termostatikoekin alderatzen du. 5 Atalak, Carrascal *et al.*-en [5] JCR-dun ikerketan oinarrituta dago. Ikerketak, *Time of Use*, TOU, energia tarifa erabiltzeak dakartzan onura ekonomikoak ere aztertzen ditu.

Tesiak aztertzen duen bigarren problema hau da: bulego eraikin baten errezelen kontrol-sistema nola egokitu behar den energia erabilera murrizteko barneko ongizate baldintzak betez. Ikerketa, bibliografian erreferentzia den bi bulegoko moduluaren oinarritzat hartuz egin da. Modulu hau, kalitate handiko materialak erabiliz eraikita dago, Ipar-Hego orientazioa dauka eta klimatizazio sistema, MPCak kontrolatutako TABS eta AHU sistemez osatzen da. Bulegoek bero karga handiak jasaten dituzte: gia-jarduera, bulegoko materiala eta eguzki-erradiazioa. Bero karga hauek bulegoa berotzen laguntzen dute neguan, baina udan klimatizazio beharrak handitzen dituzte. Karga hauen artean, eguzki erradiazioa da doi daitekeen bakarra. 7. Atalak, berrikuntza bezala, errezel sistemarentzako kontrol aurreratu bat proposatzen du. Kontrol honek, MPCak dituen energia erabileraren aurreikuspenak hartzen ditu errezel sistemaren egoera zehazteko eta horrela energiaren erabilera murrizteko. 7. Atalak, [6]-an argitaratuta izan ziren ikerketa honen emaitzak erakusten ditu. Emaitzek, lortzen diren energia aurrezpena ohiko histeresi kontrolarekin lortutakoarekin alderatzen dute.

Gizarte garatuetan, eraikinek energia osoaren % 40 erabiltzen dute; honen erdia eraikinen ongizate termikoa ziurtatzeko erabiltzen da. MPCa, etorkizun oparoa duen kontrol paradigma da. Haren ezaugarri prediktiboek, eraikinen klimatizazio sistemak kontrolatzeko egokia bihurtzen dute. XXX Irudiak, MPCa eraikinen klimatizazio sistemekin batera urtez urte *scopus*-en artikuluen hitz gakotan agerpenen kontaketa erakusten du: *KEY (("MPC" OR "Model Predictive Control") AND ("HVAC" OR "Building" OR "office" OR "TABS" OR "CCA" OR "concrete core activation"))*. Irudiak joera gorakor nabarmena erakusten du, gaiak duen interesa azpimarratzen duena.



1.2 Irudia. Erreferentzia bilaketa. Azken hogei urteetan MPC eta eraikinen klimatizazio sistemarekin loturik dauden argitalpen kopurua (*scopus*)

1.3 Dokumentuaren egitura

Dokumentua 8 ataletan banatuta dago, eta jada azaldu den bezala, euskararen eta ingelesaren arteko oreka mantentzen saiatu da. 1. Atala den sarrera txiki honen ostean, hau da dokumentuaren egitura, non Atal bakoitzaren azalpen txiki bat agertzen den.

2. Atalean, lan honetan agertzen diren elementu nagusiei berrikuspen bibliografikoa egiten da, garrantzia berezia izango elementuetan arreta ipiniz. Horrela, *Thermally Activated Building System*-ei (TABS), *Model Predictive Control*-ei (MPC) eta errezel-sistemei azpiatal berezia eskaintzen zaie.

3. Atalean, bero banaketarako TABS-ak aztertzen dira. Bero igorle sistemei buruzko sarrera historikoa egin ondoren, horien jokaera ulertzeko beharrezkoak diren bero transferentziaren oinarri fisikoak azaltzen dira. Ondoren, TABS-etan agertzen diren bero transferentziak aztertzen dira. Bukatzeko, TABS baten parametroak karakterizatzen dira *Continuous Time Stochastic Modelling package for R* (CTSM-R) R-ren modulua [7] erabiliz. Datuak lortzeko ANSYS-ekin simulatu zen TABS-aren jokabide termikoa. Karakterizazio hau, van der Heijde et al.-ek [8] egindako hormigoiaren karga egoera termikoari, *State of Charge*-ri (SoC), buruzko azterketaren lehen pausua da.

4. Atalean, ikerketa lanetan erabiliko den MPCaren ezaugarri nagusiak aztertzen dira, hala nola espazio-egoeraren adierazpena edo problemaren minimizazio eta mugak, Atal honek, eraikin baten eredu bat lortzeko erabil daitezkeen metodo eta tresnak ere

aurkezten du. Bukatzeko, eraikinen klimatizazio kontrolean erabiltzen diren ohiko parametroak aztertzen dira.

5. Atalean, argitaratutako lehen ikerkuntza lanaren [5] emaitzak aurkezten dira. Honetan, hirietan dauden kalitate txarreko materialez eraikitako etxe zahar baten beroketa sistema MPC baten bidezko kontrolaren simulazioa egiten da. Hasiera batean, eraikin baten beroketa sistema kontrolatzen duen MPCak dituen ezaugarriak aztertzen dira. Ondoren, MPCrako lortutako emaitzak etxebizitzetan normalean erabiltzen den *on-off* kontrol termostatiko batek ematen dituen emaitzekin alderatzen dira. Bukatzeko, MPCaren eboluzioa aztertzen da, energia orduaren arabera aldatzen den, *Time of Use* (TOU), tarifa pean.

6. Atalean, bigarren publikazioa ulertzeko lagungarriak diren hainbat kontzeptu azaltzen dira nazioarteko arautegiren eskutik. Atal honen lehen zatian, ongizate termikoaren kontzeptua aztertzen da ASHRAE 55 [9], ISO 7730 [10] eta EN 15251 [11] arauen arabera. Bigarren zatia, eguraldi eta klimari eskainita dago. Eguzki erradiazioa eta ohiko urtearen informazio bilduma, *Typical Year Dataset* (TMY3) definitzen dituzten parametroetariko batzuk ere aztertzen dira. Atalaren azken zatian leiho sistemak eta errezelak azaltzen dira, leihoak eta errezelak osatzen duten sisteman zehar pasatzen den eguzki erradiazioa kalkulatzeko. Azterketa hau, ASHRAE HOF [12], ISO 9050 [13], ISO 10292 [14], ISO 15099 [15] eta EN 13363 [16].

7. Atalak, argitaratutako bigarren ikerketa lana [6] aztertzen du. Argitalpenetan sarritan proposatutako bi bulego modulua, kalitate oneko materialaz eraikita, ipar–hego orientazioa, eta TABS-AHU klimatizazio sistemak dituena aztertzen da. Errezeletan ohikoa den on-off histeresi sistemaren ordez, sistema aurreratu bat proposatzen da. Sistema honek kontutan hartzen ditu HVAC sistema kontrolatzen duen MPCak aurreikusitako kontrol ekintzen balioak, energiaren erabilera. Ikerketak lortzen duen energia aurrezpena nabaria da, %15-era ere hel daiteke.

8. Atalak bukaera ematen dio dokumentuari. Dokumentuak planteatzen dituen gai nagusiak laburbildu ondoren, lortutako ondorioak biltzen ditu. Azken azpiatalak, tesiak irekita utzitako etorkizuneko lan ildoak proposatzen ditu.

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2.

State of the Art

English summary

This chapter provides a revision of the *state-of-the-art* of the main aspect that must be considered in order to study the climatization systems of the buildings and their control via an MPC.

The first part of the Chapter considers the different systems and controls used to ensure thermal comfort in buildings. In residential blocks, gas boilers, individual or collectives are the most common heating source, even when the use of renewable energy sources can be developed in buildings. The usual control way in residential case is the thermostatic *on-off* control. On the other hand, office buildings must fulfill further requirements. They must provide heating and cooling as well as ventilation and humidity control. Air handling units, AHU, are commonly used as a heating/cooling systems ensuring ventilation although sometimes radiant systems are also introduced. Thermal

energy production can vary from boilers to heat pump or cogeneration systems. Renewable systems, solar, geothermal or natural night cooling can also be used. District heating systems are not usual in Basque Country.

In office buildings, thermal energy can be distributed in different ways. The already mentioned air based systems are regulated by ANSI/ASHRAE 113 [1], EN 15251 [2] and ISO 7730 [3]. This system also fulfils ventilation needs. Chilled beams are used too for heating and cooling large buildings. Water passes through a pipe beam suspended from the ceiling. Air, by natural or forced convection, exchanges heat with the water pipes fulfilling the thermal needs of the environment. As cooling system, this is more effective than the air systems. EN 14518 [4] and EN 15116 [5] group the regulations about this system. Finaly, other considered systems are the water based radiant systems. In this case, at least a 40 % of the transfer thermal energy is exchanged by radiation. Water pipes are developed in floor, celling or walls and the system can be integrated in panels, floor or in the building structure itself. ISO 18566 [6] studies panel based systems. ISO-EN 11855 [7] studies floor integrated systems and concrete integrated systems. This last system, called Thermally Activated Building Systems (TABS) or Concrete Core Activated (CCA), is the main heating/cooling system in the office module of Chapter 7. For this reason, it has been studied in a wider way. This Chapter provides information about the latest works on TABS of some relevant research team around the world. This topic is studied in Chapter 3.

The second part of the Chapter studies the different classes of control used in the building climate systems providing literature examples about the proposed controls. Classic control designs the typically used *on-off* and PID. Between the hard control methods, it may be included non-linear controls, adaptive controls, optimal controls and model predictive controls (MPC). Soft Controls use the system tendencies to control the climate systems. This group integrates controls like artificial neuronal networks or fuzzy logic. Hybrid controls combine some of the also mentioned control methods.

Finaly, proposals for MPC as main control of building climate systems have been collected in the third section of the Chapter. A small comparison with a PID shows the difference between predictive controls and error based controls like PID. Predicted actions take into account weather forecast and use patterns of the building, providing an important advantage in the control action as showed in the presented literature. The cost function gives the MPC a multiobjetive character that allows regulating the control action policy between energy savings and no deviation from a reference temperature. Different examples about MPC use in buildings shows potential energy savings between 15 and 30 % [8, 9, 10, 11, 12, 13]. Literature shows the behaviour of the MPC implementing a time of use, TOU, energy rate [12, 14, 15]. Predictive capacities allow the control to decrease the operative cost by using lower energy rates. This energy use shift is also implemented to decrease the demand peaks allowing a softer energy use curve.

The last section of the Chapter shows some studies about blind systems in order to introduce them for the study of Chapter 7.

2.

Gaur egungo teknikaren egoera

Atal honek, eraikuntzan agertzen diren klimatizazio-sistemen eboluzioa eta azken joeren, *state-of-the-art*-en (SoA), berrikuspena aurkezten du, dokumentuan garatuko den ikerketaren abiapuntu gisa. Lehen zatian, eraikinek duten klimatizazio-sistemak eta haien eboluzioa aztertzen da. Bigarren zatian, klimatizazio-sistemen kontrolen azterketa egiten da, modelo gaineko kontrol prediktiboaren, *Model Predictive Control*–aren (MPC), erabilera era sakonean aztertzen. Azkenik, 7. Atalean erabiliko diren errezel-sistemei buruzko informazioa biltzen du.

2.1 Eraikinen klimatizazio-sistemak

Eraikinen klimatizazio-sistemen betebehar nagusia erabiltzaileen ingurumenaren ongizatea ziurtatzea da, besteak beste, beroa, hotza, aire berritzea eta hezetasuna egokituz. Beste aldetik, Europa mailan eraikinen energia aurrezpen politika bultzatzen da. Eraikinek, gizarte garatuetan, energiaren %40 inguruan erabiltzen dute [16] eta agerikoa da Europaren menpekotasun energetikoa [17, 18]. Hau horrela izanik, klimatizazio-sistemen betebehar nagusia ongizatea ziurtatzea dela kontsumo edo kostu energetikoa ahalik eta txikiena bermatuz.

Etxebizitzetan, gure inguruan galdara kolektiboak eta banakakoak dira beroa sortzeko ohiko era, gasa erregai nagusia izanik. Etxebizitza unifamiliarrak kontutan hartuz gero, biomasa, kogenerazioa, bero-punpak eta geotermia ere erabiltzen dira. Eguzki-sistemek edota erradiadore elektrikoek merkatuan toki txikia dute. Beroa, erradiadoreen bidez banatu ohi da, nahiz eta kasu gutxi batzuetan zoru igorleak ere erabiltzen diren. Tenperaturaren kontrola, termostato bidez egiten da. Etxebizitzetako sistemarik ohikoenak bero sorrerakoak dira, nahiz eta aire egokitutakoak gero eta arruntagoak izan. Airea berritzeko eta hezetasuna kontrolatzeko sistemak ez dira ohikoak.

Bulego eraikinetan sistemen dimentsioak behartuta gauzak aldatzen dira. Eraikinaren adina, materialak, erabilera eta tamainaren arabera, berotze, aireztatze eta aire-girotu, *heating, ventilation and air conditioning*, (HVAC) elementuak aldatzen dira. Airearen hezetasunaren kontrola gehitzen zaio sistemari eta aire-berritzea era automatikoan burutzen da ohikoak diren aire unitateen bidez, *air handling unit*, (AHU) bidez. Antonov-ek [19] bere PhD Tesian azaltzen duen bezala, eraikinen berotze- eta hozte-sistemek hiru zati nagusi dauzkate: energia-iturria, bero/hotz sortze-sistema eta bero/hotz banatze-sistema.

Energia-iturria, tokiko baldintzetara moldatzen da, ohikoak diren elektrizitate eta erregaiaz (gasa normalean) gain, beste sistemak ere agertzen dira, hala nola, eguzkikoa, geotermikoa edo bero-metatze sistemetatik lortutakoa.

Beroa sortzeko hiru era nagusi erabiltzen dira. Lehenengoa, oinarrizko energiaren eraldaketarekin du erlazioa, non energia-iturria bero edo hotz bihurtzen den. Berogailu elektrikoak, erregai galdarak edota barrutiko beroketarekin, *distric heating*, loturiko bero-trukaketa da. Laugarren belaunaldiko *distric heating*-ek tenperatura baxuko bero/hotza berriztagarriak eta bero birziklatzea gehitzen diote sistemari. Bigarren bat bero-punpak, *heat pump*-ak, dira. Horiek ziklo termodinamikoak erabiltzen dituzte ingurumenaren energia xurgatu eta eraikinaren klimatizazioan erabilgarria den bero edo hotz gisa erabiltzeko. Horien oinarrizko energia-iturria, elektrizitatea edo gasa da eta etekin-koefizientea, *Coefficient of Performance,* (COP), hiru ingurukoa izan ohi da. COP-a airetik lortutako eta sistemari emandako energien arteko erlazioa da. Beroaren berreskurapena da beroa lortzeko azken era. Beste prozesuetan erabilgarria ez den beroa edo hotza berreskura daiteke HVAC sisteman erabiltzeko. Eguzki-energiaren erabilera termikoa multzo horretan sartu ohi da.

Hotza lortzeko, bero-transferentziarako sistemak erabil daitezke, hala nola, hozte-dorreak, bero-disipagailuak edo sistema geotermikoak. Lehen aipatu den bezala, ziklo termodinamikoetan oinarritutako bero-punpak hozteko ere erabil daitezke disipatutako beroa eta emandako energiaren arteko ratioa efizientzia energetikoaren erlazioa, *Energy Efficiency Ratio* (EER) delarik. Horren balioak 4-tik hurbil egon daitezke. Hauen erabilera sistema geotermikoekin, lurrarekin loturiko bero-punpak, *Ground Coupled Heat Pump*-ak (GCHP) aukera oparotako sistema bezala ikusten da, batez ere exergia txikiko bero banaketa-sistemekin lotzen denean [20]. Azkenik, absortzio bidezko hozte-sistemak aipatu behar dira. Jariakin baten lurrunketan ematen den bero absortzioan oinarrituta dago. Lurrunketa burutzeko behar den beroa, hozte-zirkuitutik lortzen da, jariakinaren tenperatura igoaz. Lurrundutako jariakina, substantzia baten bidez absorbatzen da. Ondoren, nahasketa bero bidez disoziatzen da zikloa errepikatuz. Ziklorik erabiliena ura-litio bromuroa da, ura lurruntzen den substantzia izanik. Metodo honen abantaila nagusia, hondar-beroa erabiltzeko eskaintzen duen aukera da.

Bero-banaketari dagokionez, Kazanci eta Olesen bikoteak [21] Nazioarteko Energiaren Agentziaren, *International Energy Agency*–ren (IEA), energia eraikin eta komunitateetan, *Energy in Buildings and Communities,* (EBC), programaren *annex* 59-rekin lotutako ikerketan aztertzen dute gaia. Orokorrean, banaketa-sistemak hiru mota nagusitan sailka daitezke: airean bakarrik oinarritutako sistemak, habe hotzak eta uran oinarritutako bero eta hotz sistema igorleak. Sistema horiei, bulego esparruetan hain erabiliak ez diren *fan-coil* trukagailuak, konbektoreak, erradiadoreak eta tutu igorleak gehitu behar zaizkie ikuspen osoa lortzeko.

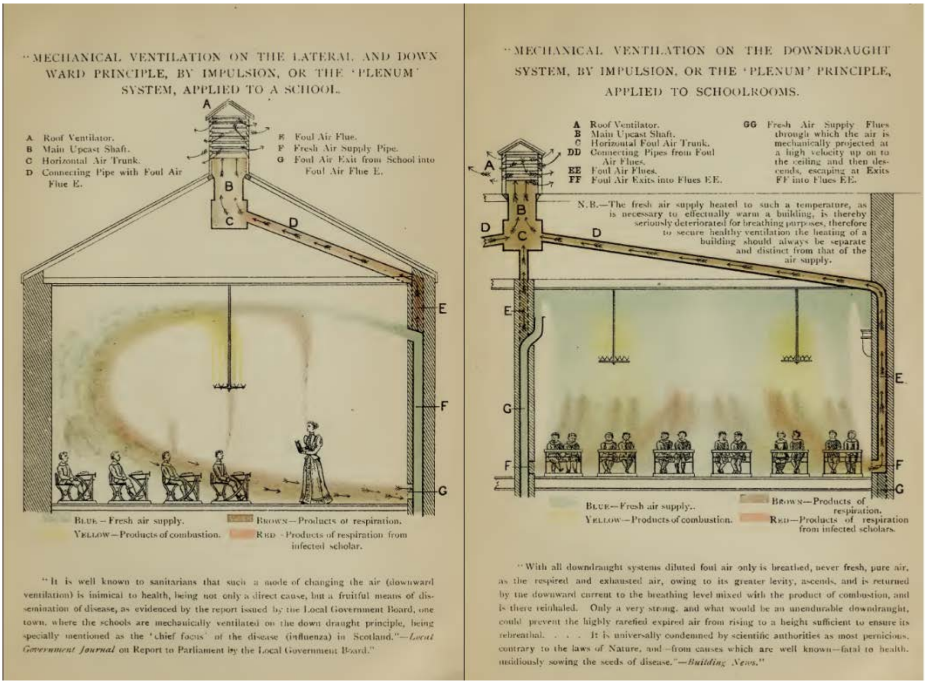
2.1.1 Banaketa-sistemak – Airean oinarritutako sistemak

2014ko haien artikuluan, Cao *et al.*-ek [22] airean soilik oinarritzen diren sistemen sailkapena egiten dute, guztira zortzi sistema identifikatzen dituzte: aire nahasketan oinarritutako aire berritzea, ordezkapen bidezko aire berritzea, norbanakoentzat aire berritzea, aire banaketa hibridoa, geruzatutako aire berritzea, okupatutako eta babestutako zonaldearen aire berritzea, tokiko ateratze bidezko aire berritzea eta pistoi bidezko aire berritzea. Horien artean, aire nahasketan oinarritutako aire berritzea edo *mixing ventilation*, da ohikoena eta tesi honen alde praktikoan simulatuko da. Horretan, ingurumena baino beroago edo hotzago dagoen aire garbia sartzen da gelan, erabilitako airearekin nahastu eta airearen kalitatea eta tenperatura egokiak lortzeko. Horrela, aire banaketa "uniformea" lortzen da, estratifikazioa kontutan hartuz. Aireztatze metodo hori erabilita, airearen hezetasuna ere doitu daiteke.

Boyle eta haren semeak [23] 1899-an teknika hori proposatu zuten gela batean ziren kandelek eta erabiltzaileek kutsatutako airea berritzeko. 2.1 Irudiak haien liburuaren eskola baten aire berriketarako sistemarentzat bi proposamen erakusten ditu. XIX. mendetik hona aire berritze eta, honen bidez, tenperatura eta hezetasunaren egokitzapenean hobekuntzak etengabeak izan dira. Boylerenaz gain, XIX. mendeko beste teknika batzuk agertzen dira bibliografian: Harris-ena [24] 1858-an, Butler-ena [25] 1873-ean eta Billington eta Roberts-ena [26] 1892-ean.

Gaur arte, arloan hainbat azterketa egin eta argitaratu dira. Horietako batzuk, Awbi-renak [27, 28], Sandberg *et al.*-enak [29, 30] edo Müller-ena [31] dira. Ikerketa horiek, nazioarteko estandarren hazia izan dira: ANSI/ASHRAE 113 [1], EN 15251 [2], ISO

7730 [3] eta. Kontutan hartu behar da sistema hauetan, airearen sarrera eta irteeraren abiadurak mugatuta daudela, aire eta beroa konbekzio bidez nahasten direlarik.



"MECHANICAL VENTILATION ON THE LATERAL AND DOWNWARD PRINCIPLE, BY IMPULSION, OR THE 'PLENUM' SYSTEM, APPLIED TO A SCHOOL.

A Roof Ventilator.
B Main Upcast Shaft.
C Horizontal Air Trunk.
D Connecting Pipe with Foul Air Flue E.
E Foul Air Flue.
F Fresh Air Supply Pipe.
G Foul Air Exit from School into Foul Air Flue E.

BLUE – Fresh air supply.
YELLOW – Products of combustion.
BROWN – Products of respiration.
RED – Products of respiration from infected scholar.

"It is well known to sanitarians that such a mode of changing the air (downward ventilation) is inimical to health, being not only a direct cause, but a fruitful means of dissemination of disease, as evidenced by the report issued by the Local Government Board, one town, where the schools are mechanically ventilated on the down draught principle, being specially mentioned as the 'chief focus' of the disease (influenza) in Scotland."—*Local Government Journal* on Report to Parliament by the Local Government Board."

"MECHANICAL VENTILATION ON THE DOWNDRAUGHT SYSTEM, BY IMPULSION, OR THE 'PLENUM' PRINCIPLE, APPLIED TO SCHOOLROOMS.

A Roof Ventilator.
B Main Upcast Shaft.
C Horizontal Foul Air Trunk.
DD Connecting Pipes from Foul Air Flues.
EE Foul Air Flues.
FF Foul Air Exits into Flues EE.
GG Fresh Air Supply Flues through which the air is mechanically projected at a high velocity up on to the ceiling and then descends, escaping at Exits FF into Flues EE.

N.B.—The fresh air supply heated to such a temperature, as is necessary to effectually warm a building, is thereby seriously deteriorated for breathing purposes, therefore to secure healthy ventilation the heating of a building should always be separate and distinct from that of the air supply.

BLUE—Fresh air supply..
YELLOW—Products of combustion.
BROWN—Products of respiration.
RED—Products of respiration from infected scholars.

"With all downdraught systems diluted foul air only is breathed, never fresh, pure air, as the respired and exhausted air, owing to its greater levity, ascends, and is returned by the downward current to the breathing level mixed with the product of combustion, and is there reinhaled. Only a very strong, and what would be an unendurable downdraught, could prevent the highly rarefied expired air from rising to a height sufficient to ensure its rebreathal. . . . It is universally condemned by scientific authorities as most pernicious, contrary to the laws of Nature, and—from causes which are well known—fatal to health, insidiously sowing the seeds of disease."—*Building News.*"

2.1 Irudia. 1899an Boyle eta haren semeak eskoletako aire berritzen sistemen proposamenaren irudiak **[23]**

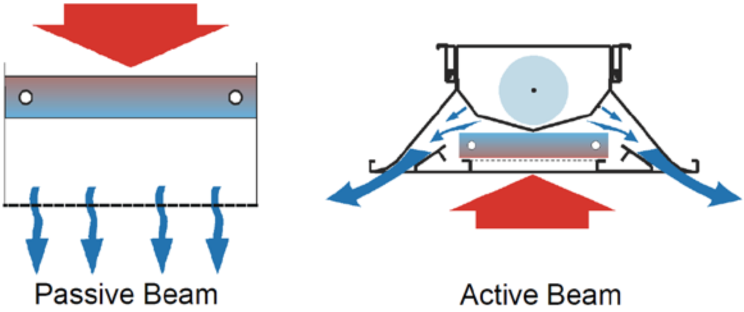
Cao-ren [22] arabera, aire berriaren tenperatura 34 °C-raino hel daiteke beroketan eta 14 °C-raino jaitsi daiteke hozteko. Hala ere, nahasketa egokia izan dadin, sartzen den eta gelan dagoen airearen tenperatura diferentzia 10 °C baino handiago ez izatea aholkatzen da [31]. Recknagel *et al.*-en [32] arabera, metodo hori erabilita 90 W/m^2-ko hozte potentzia lor daiteke. Hala ere, normalean balio kontserbadoreagoak erabiltzen dira.

2.1.2 Banaketa-sistemak – Habe hotzak

Sistema honetan, sabaitik eskegitako eta ur zirkuitu bat osatzen duen hodei multzo batek, habea, berotze eta hozte lana egiten du airea haren inguruan pasatzerakoan. Sistema hau aire sistema baino nabarmen merkeagoa dela aipatu behar da. Woollett eta Rimmer-ek horien deskripzio sakona egiten dute [33]-an, ohikoak diren bi sistemak deskribatuz:

Habe hotz pasiboak: Ur beroa edo hotza tutuetatik pasaraztzen da eta konbekzio bidez beroa trukatzen da. Habe hotz pasiboak normalean hozteko baino ez dute balio, beraz, berotzeko beste sistema bat beharrezkoa da. Airea berritzeko beste sistema bat ere beharrezkoa izango litzateke. Sistema hori, gomendatua da bero karga 40 eta 80 W/m^2 denean Virta *et al.*-en arabera [34].

Habe hotz aktiboak: Ur tutuen inguruan airea pasarazten da era behartuan. Horrela posiblea da espazioa hotzaz, beroaz eta aire garbiaz hornitzea. Hotz-moduan 60 eta 80 W/m^2 sor dezakete, horien berotze ahalmena 25 eta 35 W/m^2 tartean dagoen bitartean [34]. Bi sistema hauen funtzionamendua, 2.2 Irudian agertzen da.



2.2 Irudia. Habe hotz pasiboen eta aktiboen hotz sorrerarako lan egiteko era **[34]**

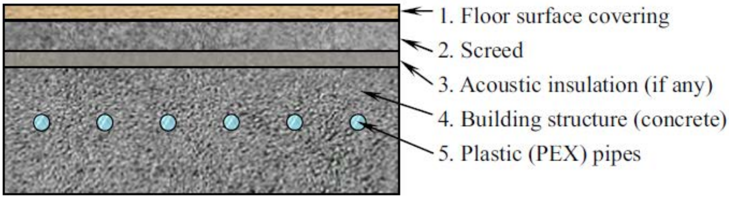
Hari hotz pasiboen eta aktiboen eskakisunak, Europar arauetan, EN 14518:2005-ean [4] eta EN 15116:2008-an [5] biltzen dira. Aipagarria da ere *Federation of European Heating and Air-conditioning Associations* (REHVA) deritzon elkarteak argitaratutako gida [34].

2.1.3 Banaketa-sistemak – Urean oinarritutako bero- eta hotz-sistema igorlea

Uran oinarritutako sistemek jariakin hau erabiltzen dute bero-energia, hotza zein beroa, garraiatzeko. Beste aldetik, sistema igorle bezala definitzen da energiaren zati adierazgarri bat, %40 gutxienez erradiazio bidez transferitzen denean. Hiru multzo nagusitan sailka daitezke uran oinarritutako bero- eta hotz-sistema igorleak: bero edo hotza igortzen duten panelak; zoru igorleak, non bero-energia daramaten tutuak eraikinaren egituratik, hormigoitik, isolatuta dauden; eta termikoki aktibatutako eraikuntza sistema, *Thermally Activated Building Systems* (TABS), edo aktibatutako hormigoizko nukleoa, *Concrete Core Activated* (CCA), non ura garraiatzen duten tutuak hormigoi barruan dauden. Sistema horrek dituen ezaugarriak, aukera interesgarria izan daiteke sistema geotermikoekin batera lan egiten duenean (GEOTABS) [20]. Arauei dagokionez, ISO 18566-ak [6] panel igorleei buruzko galderak argitzen ditu, ISO-EN 11855-a [7] zoru igorleaz eta hormigoian integratutako sistemez arduratzen den bitartean.

Thermally Activated Building Systems (TABS)

Dokumentu honen 3. Atal osoa TABS-i eskainita dago. Hala ere, aipamen txiki bat egingo da puntu honetan. TABS-a bero edo hotz metatze- eta banatze-sistema da, zeinak eraikinaren estruktura barnean integratzen duen energia termikoa daraman zirkuitua. Horrek, klimatizazio-sistemaren inertzia termikoa era nabarmenean handitzen du. Energia termikoaren banaketa-sistema zoruan eta sabaian integratzeak bero-transferentziarako gainazal handia sortzen du. Horrela, posiblea da tenperatura jausi txikiagoak erabiltzea ingurumena hozteko zein berotzeko. Exergia txikiko sistema bezala funtzionatzeak bero galeren murrizketa suposatzen su eta efizientzia termiko handiago. Sistema igorlea izateak, beste aldetik, beroketarako inguruneko airearen tenperatura ohikoa baino baxuagoa dela suposatzen du ongizate ikuspuntu batetik, TABS-ak igortzen duen energia zuzenean heltzen baitzaio erabiltzaileari. Desabantaila da, HVAC-ean aire berritze sistema integratu behar dela. Hala ere, berritze airea sistema laguntzaile gisa beroa edo hotza sortzeko erabil daiteke. Horrela erabiliko da dokumentu honetan egingo den simulazio esperimentalean. 2.3 Irudiak TABS baten estruktura tipikoa erakusten du.



2.3 Irudia. TABS nukleoaren ohiko sekzioa **[35]**

Konbekzio koefizientearen balioa, **h** edo CHTC iturriaren arabera, bero-transferentziaren balioa zehazten du. 3. Atalean ikusiko den bezala, inguruaren tenperaturentzat posible da mota berdineko erradiazio koefizientea definitzea. TABS sistemaren funtzionamendua definitu edo modelizatu nahi bada, balio egokia lortu behar da. Hainbat ikerketa egin dira balio hauek lortzeko eta zuzentzeko. Babiak eta al.-ek [36]-n proposatzen duten koefiziente konbinatuak (konbekzioa gehi erradiazioa) honako hauek dira: 11, 8 eta 6 W/m^{2}K berotze zoruan, hormetan eta sabaian. Hozte balioak, berriz, 7, 8 eta 11 W/m^{2}K zoruan, hormetan eta sabaian dira hurrenez hurren. Erradiaziorako, 5.5 W/m^{2}K balioa proposatzen da. Balio horiekiko desbideraketa txikia aurkezten dute Awbi eta Hatton-ek egindako berrikuspenean [37] proposatutakoekiko. [36]-k 99 eta 44 W/m^2-ko potentziak proposatzen ditu zoruarentzat berotze eta hozte prozesuetan. Sabaiarentzat balio hauek trukatzen dira 44 eta 99 W/m^2 balioak hartuz hozte eta berotze aplikazioetarako. Sourbronen [38] ikuspegi kontserbakorragoak, zoruarentzat 42-65 W/m^2 arteko balioak hozketarako eta 79-86 W/m^2 beroketarako proposatzen ditu.

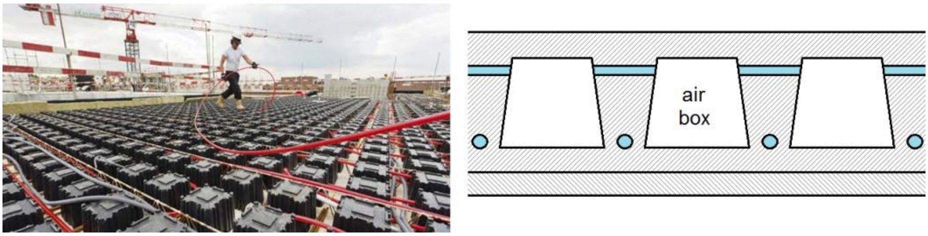
Hurrengo atalean sistema igorleei eta bereziki TABS-i buruzko sarrera historikoa egiten bada ere, gaur egungo ikerketa egoera aipatzea interesgarritzat hartzen da. Ma *et al.*

[35] TABS-i buruzko egungo ikerketa-talde batzuen egoera aztertzen du. Horretan, Meierhans-en publikazioak aipatzen dira [39, 40], non hormigoiaren masa erabiltzen den hotz sistema igorle batean. 1999-an, Meierhans eta Olesen-ek *Betonkernaktivierung* [41] liburua argitaratu zuten (*Concrete Core Activation*) non TABS-ak ekartzen zituen onura ekonomikoak aurkezten ziren. Olesen-ek bere aldetik, sistema igorleen aukera eta arazoak aztertu zituen: gainazalen tenperaturak eta lor daitekeen hozte-potentziaren muga argitaratzen du 1997-an [42]. 2000-an, hozketarako bero-transferentziaren koefizientearen balioak neurtzen ditu [43]. 2003-an, [44]-k proposatutako kontzeptuek eragin zuzena daukate ISO 11855-aren garapenean. Beste ikerketa batzuen artean, dokumentu honetan agertuko den bi bulegoetako modulua ere aztertzen du [45]-an.

Beste talde batzuen lana ere goraipatzen da, besteak beste Koschenz eta Lehmann-ek egindako lana. 2000-an argitaratutako liburuan [46], TABS-etan agertzen den bero-transferentzia unidimentsionaltzat hartu, eta bero-transferentziaren analogia elektrikoa proposatzen dute. Weber *et al.*-ek sistemaren RC modelo baliokidea aurkezten dute [47]-n, gero [48]-an denbora eta maiztasun domeinuan baliostatzen dena.

Beste batzuen artean, Suitzako ETH Zurich-ek eta Siemmens-ek *Opticontrol* [49] proiektupean, TABS-en jarduera MPC kontrolarekin aztertzen dute. Egindako lan askoren emaitzak bilduz, Gwerder-en eta Gyalistras-en taldeak burututako proiektuaren bukaerako txostenak proposatzen dira [50, 51]. Talde honen partaideek, MatLab-en *BRCM toolbox* [52] garatu zuten eraikinen diseinuak MPC-an era errezean inplementatzeko.

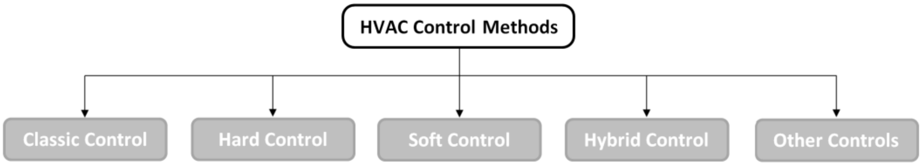
University of Colorado-ko Henzek, efizientziari buruzko ikerketak egin ditu [53], eta TABS-ek lortutako energia primarioaren aurrezpena ohiko aire sistemekin alderatuz %20a izan daitekeela baieztatzen du. Balio horren inguruan daude bibliografian agertzen diren antzeko saiakuntzen emaitzak. KU Leuveneko SySis taldeak Helsen-en gidaritzapean lan oparoa egin du simulaziorako modeloak prestatzen, hala nola *Modelica*ren [54] *IDEAS Toolbox* [55] edo elementuen modelizazioa [56]. TABS-en karakterizazioan lanak ere egiten dira, van der Heijde-rena bezala [57], edo geotermiarekiko integrazioa [20]. Egitura arintzeko, inertzia termikoa egokitzeko eta materiala aurrezteko, 2.4 Irudiaren moduko aire kutxaz beteriko TABS-en gaineko azterketak ere egin dira [58].



2.4 Irudia. Aire kutxak dituen TABS egituraren prestaketa eta horren eskema

2.2 HVAC kontrolatzeko erabiltzen diren kontrol motak

Erregeletan oinarritutako kontrolean, *Rule-Based Control*-ean (RBC), integratutako *on-off* kommutazioa eta proportzional integral, *Proportional Integral* (PI) kontrolak bulego eraikinen klimatizazio-sistemen ohiko aukera badira ere, energia eta kostuen aurrezteko nahiak beste kontrol mota aurreratuagoak aztertzeko eta inplementatzeko bidea ireki du. Horrela, bibliografia oinarri hartuta, 2.5 Irudian agertzen dira eraikinen HVAC sistemen kontrolak sailkatzeko bost multzoak.



2.5 Irudia. HVAC sistemen sailkapena

Kontrol Klasiko izenpean, RBC kontrolak agertzen dira. erregela multzo proposatzen dira zuhaitz estruktura batean eta hauen arabera sistemaren ekipoen *on-off* eta PI kontrolak aktibatzen dira. Kontrola, erreferentzia batekiko akatsean oinarritzen da. HVAC-en hainbat ekipo kontrolatzeko baliagarria da eta bibliografiak adibide ugari eskaintzen ditu. Kulkarmi-k eta Hong-ek [59] barne-tenperaturaren kontrolerako erabiltzen dute eta Jette *et al.*-ek [60] hotz sorrera kontrolatzeko. Lin *et al.*-ek [61], berriz, *on-off* kontrola erabiltzen dute fase-aldaketa materialezko, *Phase-Change Material*-ezko (PCM), xaflak eraikinen egituretan integratzerakoan. PI kontrola erabiltzen denean ohiko arazoa da kontrolaren doiketa, kasu batzuetan kontrolaren parametroak berriro doitzea edo berezko doiketa erabiltzea ez baitira beti aukerarik egokienak [62].

Kontrol Gogorra denominazioak hainbat kontrol mota biltzen ditu. Haien artean, irabazpenaren planifikazio kontrola, *gain scheduling control*, dago. Horretan, kontrolaren eskema, aurredefinitutako parametroekin aldatzen da sistemaren egoeraren arabera [63]. Kontrol ez-linealak ere talde horretan sartzen dira [64]. Kontrol optimoak, kostu funtzio baten minimizazioan oinarritzen dira eta egokiak dira helburu anitzeko kontrol gisa. Minimizazioan sartzen diren ohiko parametroak, energia erabilera eta ongizate termikoak dira. Henze-k *et al.*-ek [14] energia era egokian biltzeko denboraren menpeko, *time-of-use* (TOU), tarifa elektrikopean aztertu zuten. Sun-ek eta Reddy-k [65] kontrol mota hau bero- eta hotz-sistemetan erabiltzen dute. Verhelst-ek *et al.*-ek [66] zoruko bero-sistemarentzako aire-ura bero-punpa kontrolatzeko erabiltzen du kontrol optimoa. MPC ere kostu funtzioaren minimizazioan oinarritzen da, sistemak dituen mugak kontutan hartuz. Kasu horretan, kontrolak denboran zehar hedatuko du balizko kontrol-ekintza sistemaren erantzunak helburuak bete ditzan. Etorkizun oparoko kontrol metodo bezala ikusten da eta bibliografian agertzen den argitalpen kopurua zabaltzen doa etengabe. Kontrol adaptatiboak, modeloaren parametroak aldatzen ditu horiek sistemaren dinamiketara egoki daitezen [67].

Kontrol Biguna. Izen hau, sistemaren joera susmatzen eta aurreikusten duen kontrol metodoei ematen zaie. Honen barnean sare neuronalak, *Artificial Neuronal Networks* (ANN), eta logika lausoa, *Fuzzy Logic* (FL), daude. Algoritmo genetikoak multzo honetan ere sar litezke. Cambay-ek *et al.*-ek [68] ANN-ak erabiltzen dituzte zentro komertzial baten energia erabilera murrizteko, Hamdi-k *et al.*-ek ongizate termikoaren pertzepzioa eta FL nahasten dute [69] eta Yu *et al.*-ek [70], berriz, algoritmo genetikoak erabiltzen dituzte bero-iturri eta biltegien diseinu optimoa lortzeko. Ikerketa horietan aurkezten diren emaitzak oparoak dira.

Kontrol Hibridoa. Ohikoa da lehen aipatutako metodoak elkarren artean nahastea. ANN eta FL nahastuta agertzen dira hainbat ikerketetan [71, 72, 73]. Beste batzuetan kontrol biguna eta gogorra mailakatzen dira kontrol biguna begirale bezala egonik. Liuk eta Henzek ikaste-kontrola eta MPCa nahasten dituzte [74, 75], eta Gouda-k *et al.*-ek quasi-adaptatiboa den FL kontrola proposatzen dute [76]. Killian *et al.*-ek fuzzy eta MPC nahasten dituzte [77], emaitza aipagarriekin.

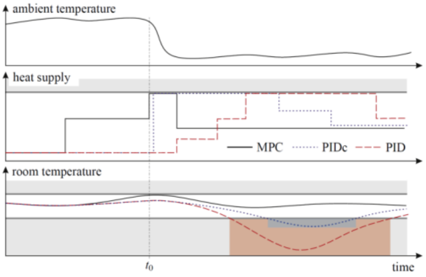
Beste kontrol motak. Ikerketa arloan, beste kontrol mota ebaluatu dira eraikinen klimatizazioan eduki dezaketen baliagarritasuna aztertzeko. Bibliografiak aipatzen dituen artean, honako hauek dira nabarmenak: lineala den *feedback* kontrol zuzena, *Direct Feedback Linear* (DFL) *control* [78]; pultsu modulazio bidezko kontrol adaptatiboa, *Pulse Modulation Adaptive Controller* (PMAC) [79]; parametroen igarketaren bidezko kontrol adaptatiboa, *Pattern Recognition Adaptive Controller* (PRAC) [80]; aurreikuspen kontrola, *preview control* [81] eta bi parametroen arteko aldaketa-kontrola, *Two Parameter Switching Control* (TPSC) [82].

Bibliografiak adibide gehiago ere aurkezten ditu. Aipatutako ikerketa batzuk eta gehiago honako berrikuspen lan hauetan ikus daitezke: Zun *et al.* [83], Afram eta Janabi-Sharifi [84], Shaikh *et al.* [85] eta Subbaram Naidu eta Rieger [86, 87].

2.3 *Model Predictive Control* (MPC)

TABS-ek, bero edo hotz banatze-sistema gisa ongizate termikoa sortzeko duten egokitasuna argia da. Sortzen duten energia aurrezpenak ere aipatu dira. Gwerder-ek *et al.*-en lanean [88], azaltzen dute TABS-ei lotutako dinamika geldoak eta inertzia termiko handiak dituzten sistemak aproposak dira MPC-entzat. 2.6 Irudiak, Killian eta Kozek-ek [89] proposatutako simulazioa aurkezten du: MPC-ak eta PID bi kontrolek gela baten tenperatura kontrolatzen dute. MPC-aren izaera prediktiboak, PID-aren izaera zuzentzaileen aurrean nabarmenki nagusitzen da. MPC-aren energia erabilera denboran zehar giro tenperaturaren jausiari aurreratzen da.

Aurreko puntuan ikusitako kontrolek emaitza egokiak ematen badituzte ere, MPC-ak baditu eraikinen kontrolerako egokia egiten duten ezaugarriak. Haien artean, 4. Atalean ere azalduko diren honako ezaugarri hauek ditu: helburu anitzeko kontrola da, minimizazio funtzioak sistemak dituen murrizketak era propioan hartzen ditu, sisteman eragiten duten aurreikusitako parametroak (adibidez, eguraldiaren informazioa), minimora integra daitezke, kontrolak denborarekiko sistemaren aldaketak onartzen ditu...



2.6 Irudia. tenperatura-kontrola MPC eta PID-en bidez gela batean. PID-ak ongizate eremutik ateratzen dira MPC-a mantentzen den bitartean **[89]**

Aurreko puntuan ikusitako kontrolek emaitza egokiak ematen badituzte ere, MPC-ak baditu eraikinen kontrolerako egokia egiten duten ezaugarriak. Haien artean, 4. Atalean ere azalduko diren honako ezaugarri hauek ditu: helburu anitzeko kontrola da, minimizazio funtzioak sistemak dituen murrizketak era propioan hartzen ditu, sisteman eragiten duten aurreikusitako parametroak (adibidez, eguraldiaren informazioa), minimora integra daitezke, kontrolak denborarekiko sistemaren aldaketak onartzen ditu...

Ikerketen emaitzek MPC-ak lortzen dituen energia aurrezpenak egiaztatzen dituzte. Adibide gisa, De Coninck-ena eta Helsen-ena [8] aipa daiteke, non Bruselako eraikin batean, emaitzek %30-eko energia aurrezpena erakutsi duten. Široký-k *et al.*-ek [9], MPC-a erabiltzen duten eraikinak aztertu ondoren, horien energiaren aurrezpen potentziala %15 eta %28 artean dagoela argitaratzen dute. West *et al.*-ek [10], Australian egindako ikerketek %19 eta %32 arteko energia aurrezpenak atzeman dituzte. Privara *et al.*-ek [11], Pragako *Czech Thechnical Univerity*-n, egindako ikerketek energia aurrezpena % 15-era hel daitekeela iradokitzen dute. Normalean, MPC-aren erabilera eraikinen klimatizazio-sisteman, bulego eraikinetan zentratzen da. Hala ere, kalitate baxuko etxebizitza bloke baten modeloekin egindako simulazioetan, Carrascal *et al.*-ek [12] lortzen dituzten energi aurrezpenak %15-era hurbiltzen dira. Patteeuw eta Helsen-ek egindako lanak [13], MPC-ek etxebizitzei loturiko CO_2-ren emisioen murrizpen-muga aztertzen du, baita honek dakarren kostua ere.

Esan den bezala, MPC-ak ematen duen beste aukera, energia-kontsumoan agertzen diren gailurrak gutxitzea eta mugitzea da. Honek, energia-sarearen saturazioa gutxitzen du eta aurrezpen ekonomikoa lortzen du kontsumoa tarifa merkeagoetara mugituz. Chen *et al.*-ek [90] energiaren erabileraren programazioa aztertzen du etxebizitzetan, Carrascal *et al.*-ek [12] TOU tarifak erabilita aurkezten dituzten emaitzek MPC-a erabilita aurrezpen ekonomikoa %19-ra hel daitekeela erakusten dute. Kasu horretan ez da energia aurrezpenik lortzen. Henze *et al.*-ek ere TOU tarifa erabiltzen dute MPC-arekin [14] energia bilketa aztertzeko. Oldewurtel *et al.*-ek [15], MPC eta uneko elektrizitatearen kostua erabiltzen dute ager daitezkeen kontsumo gailurrak gutxitzeko. Patteeuw *et al.*-ek

[91], kontsumo energetiko baxuko etxeetako karga termikoen mugimenduak sarean sor ditzaketen hobekuntzak aztertzen dituzte. Baeten *et al.*-ek [92]-an bero-punpek sor dezaketen gailurrak energia-metatze tankeen bidez nola gutxitu aztertzen dute.

Kontrolaren egiturari dagokionez, MPC-a PI kontrolekin batera egitura hierarkiko batean integratu daiteke [9]. MPC zentralizatuak kontutan hartu beharreko aldagai eta iterazio guztiak batera lantzen ditu. Horrek kontrolaren minimizazioa ebazterakoan arazoak sor ditzake, sistemaren estatu kopuru handiaren ondorioz. Banatutako MPC-etan, *distributed MPC*, kontrola haien artean komunikatzen diren eremutan banatzen da. Horrek, kontrolaren ebazpena arintzen du eraginkortasuna galdu barik. Bibliografiak honen adibide ugari erakusten ditu [93, 94].

Eguraldi parametroak eta barne bero kargak eragin handia izango dute MPC-engan. MPC-en arrakastarako beharrezkoa da horien balioak era egokian definituta egotea. *Opticontrol* programak faktore horietaz arduratzen da hainbat publikazioetan [50, 51, 95]. Zhang *et al.*-ek [96], eguraldiaren eta eraikinaren erabileraren gaineko aurreikuspenetan egon daitezkeen desbideraketak aztertzen dituzte. Oldewurtel *et al.*-ek [97] eraikinaren erabiltzaileen aurreikusitako informazioa barneratzen dute.

Orokorrean, MPC-a eraikinen HVAC sistemak kontrolatzeko egokia dela esan daiteke. Agerikoak dira honen inplementazioak TABS-a duen eraikin batean dituen onurak, kontutan hartzen bada eraikinaren inertzia termiko handia eta kontrolaren aurreikuspenerako diseinua kontutan hartuz gero.

2.4 Errezel-sistemak

7. Atalean izango duen garrantzia jakinda, atal honek errezel-sistemak ongizate egoeraren kontrolean duen eraginari buruzko informazioa biltzen du. Eguzki erradiazioak eraikinaren fatxada eta leihoak erasotzen ditu. Fatxadara heltzean, horren tenperatura igoarazi eta bero fluxua sortzen da hormaren barnealdera, hormaren barneko gainazala eta gela berotuz. Leihoetara heltzean, erradiazioaren zati batek beira zeharkatzen du, gelaren zorua eta hormak berotuz eta, ondorioz, barneko airea ere. Efektu hau desiragarria izan daiteke neguan, baina udan, hozte energiaren hazkunde bat suposa dezake [98]. Errezel-sistemaren kontrol egokiak energia gastua murrizten du eta ongizatea, berriz, handitu.

Egindako zenbait ikerketetan, errezel-sistema *on-off* histeresi kontrol baten bidez kontrolatzen da; Sturzenegger *et al.*-ek [99], *OptiControl* proiektuan [50, 51], Sourbron-en PhD-k [38] edo Verhelst-enak [100] normalean ez dute errezel-sistema MPC-an integratzen eta aipatutako kanpoko *on-off* histeresi kontrol baten bidez kontrolatzen dute. Le *et al.*-en ikerketak [101], errezel-sistemak energia erabileran duen eragina aztertzen du. Hasiera batean sistema hibridoa proposatzen du: lau posizio finko dituen errezel-sistemaren kontrola MPC-an integratuta dago. Ikerketaren bigarren zatian, ikasketa prozesua erabiltzen da kontrol optimotik euskarriko bektore makina erabiliz. Lawal-en [102] erreferentzia barne-tenperatura da MPC-an era hibridoan integratuta dagoen errezel-sistema kontrolatzeko. Sistemak hiru posizio finko ditu. Dussault *et al.*-ek [103], algoritmo desberdinak aztertzen dituzte leiho adituak, *smart windows*-ak, aztertzen.

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3.

Thermally Activated Building Systems, TABS

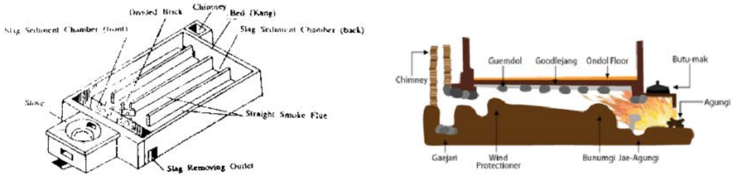
The use of enhanced quality materials in current buildings generates an improvement in its energetic efficiency as well as an increment in their thermal inertia. As a low exergy system, radiant systems provide an efficient way for building climate that uses the extensive surface of the rooms as heat exchanger. This characteristic allows for the reduction of the temperature step, increasing the efficiency of the climate system and reducing the losses associated to a high temperature difference.

By embedding thermal carrier water pipes in the concrete structure of the building, floor and ceiling, the inertia of the climate system increments the stability of the environment against the variations of the external influences as outside temperature, solar irradiation or human activity. In addition, by using an adequate control system, it is possible to reduce the consumption peaks and to store the thermal energy shifting the consumption toward more competitive energy prices.

3.1 Historical introduction to radiant systems

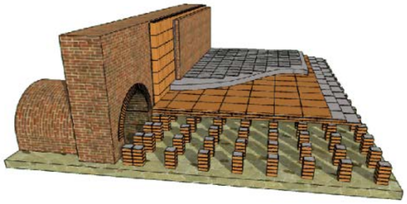
There are archaeological evidences of the use of warning systems developing radiant heating form 5000 BC in China denominated *kang*, bed-stove [1]. During the Neoglacier period, Korean *ondol* heated floor system appears also in Alaska and Russian Far East [2]. A modernized version of these systems is wide used in Asian regions nowadays. In Europe, the use of *hypocaust* was widespread in Greece and Magna Graecia during the classic period [3]. Its use was assimilated and improved by romans as described by Vitruvius in his Ten Books on Architecture, where is described as the underfloor heating air system that can also provide hot water and is used for heating houses, hot baths and other kind of buildings.

After the Roman Empire fall, hypocaust use is lost for some centuries, meanwhile the development of the floor heating system continues in Asia. According with Peizheng *et al.* [4], radiant cooling systems first evidences appear in the Kurdish settlement of Nevali Çori [5, 6], flooding space under floor with water in summer dated back in the Neolithic and in the actual Irak in 8th century using snow-packed walls [7]. In XIV century, an *hypocaust* type system is developed to heat Polish monasteries and Teutonic Malbork Castle [8]. Besides, the Turkish Baths during the Ottoman Empire were also heated with a *hypocaust* type system.



Kang bed -stove

Ondol

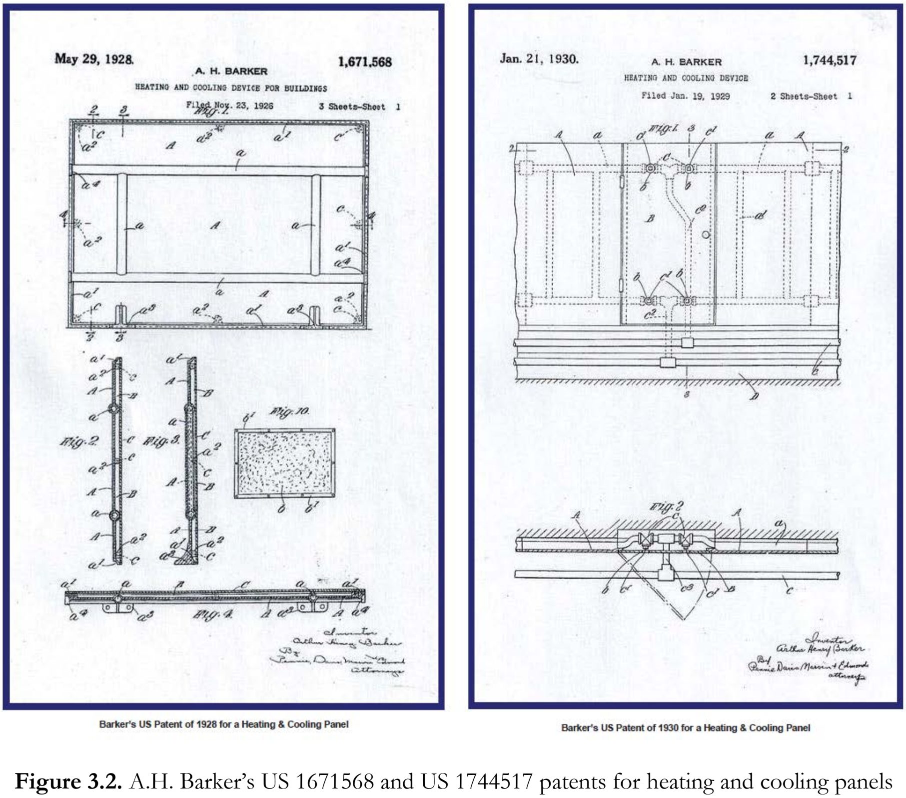


Hypocaust

Figure 3.1. *Kang*, *ondol* and *hypocaust* heating systems

After the study of French and Asian cultures, in 1741 Benjamin Franklin developed the Franklin stove; in that time, steam based radiant pipes were used in France. During the industrial revolution that took place in XIX, the properties and nature of the heat are studied and the water boiler and piping systems developed. During the American Civil War, the hospitals used *ondol* type heating systems [9]. The historic Reichstag building that was inaugurated in 1894, was already endowed with central heating, humidification and summer cooling systems using the thermal mass of the building. By the early 20th century, Liverpool Cathedral was heated by a hypocaust-based system. At that time, the architect F.L. Wright during his first trip to Japan discovered *ondol* system; he began to apply this concept to the radiant heating systems for his house designs in 1937.

Prof. A.H. Barker introduced a low-temperature radiant heating by means of hot-water panels in the floor or fixed to walls in the patent BP28477 with date 1907. Later, his patents US1671568A of 1928 [10] and US1744517A of 1930 [11] claim for a radiant heating and cooling systems for buildings. In the thirties, O. Faber used water pipes for radiant heating and cooling system in large buildings. In the forties, water based radiant systems using copper pipes are developed for home heating, although the experience was not successful. After World War II, the Bank of England building was endowed with a concrete embedded water pipe system providing heating in winter and cooling in summer.



Barker's US Patent of 1928 for a Heating & Cooling Panel

Barker's US Patent of 1930 for a Heating & Cooling Panel

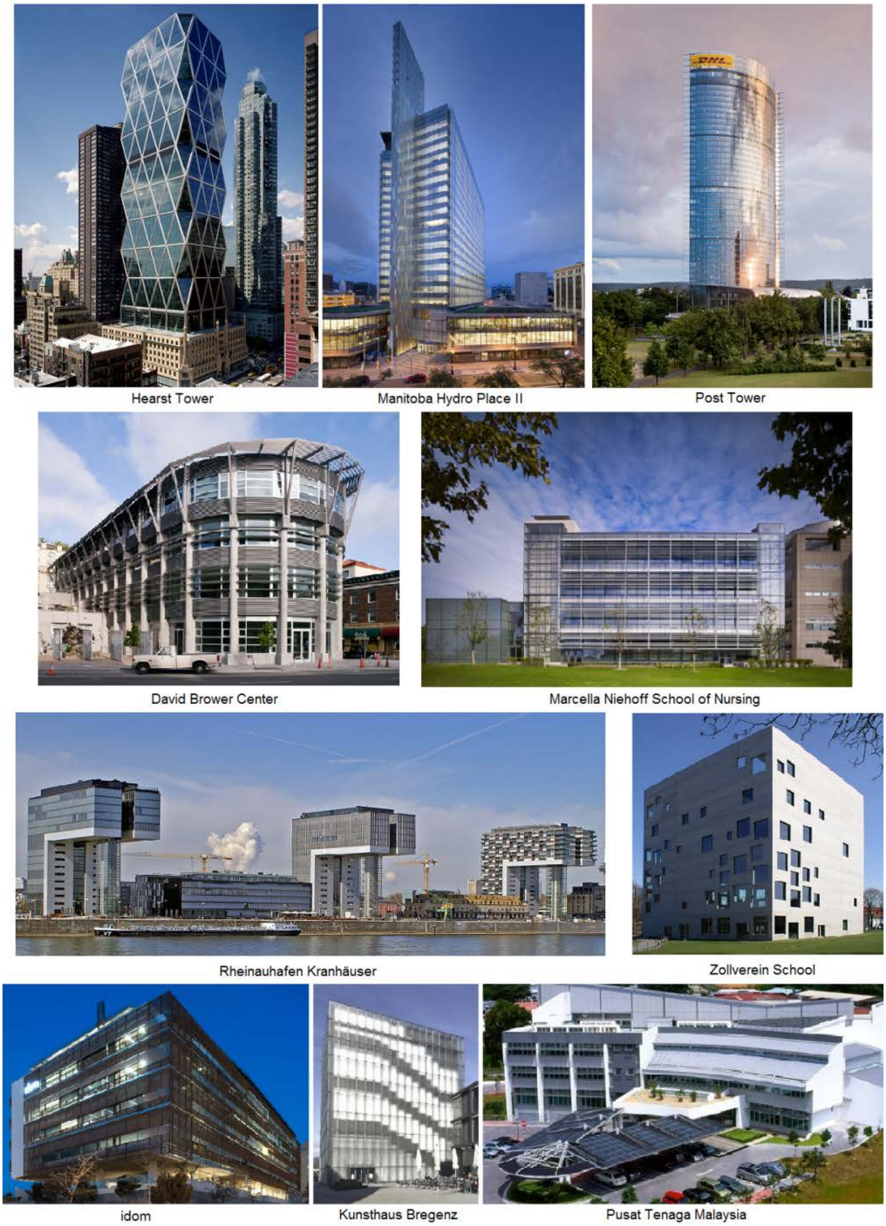
Figure 3.2. A.H. Barker's US 1671568 and US 1744517 patents for heating and cooling panels

In the fifties, plastic pipes were tested as water conductors over three years instead of copper pipes. The behaviour of polyethylene, vinyl chloride copolymer, and vinylidene chloride pipes was studied [12]. The introduction of PEX, Cross-linked polyethylene in 1968, solved most of the problems associated with the water pipes, which brought about improvement of the heating and cooling systems. Around that time the first standards for floor heating are developed in Europe, where the system becomes usual for residential buildings at the begin expanding later on its use to commercial and office buildings. In Asia, *ondol* system evolves using water. The appearance of condensation, main problem in cooling operations is solved by providing an adequate ventilation system.

Since the beginning of the 21st century, the use of low temperature heating and high-temperature cooling using Thermally Activated Building Systems (TABS) is widely used by high area radiant systems for both residential and not residential buildings. The integration of the concrete mass into the Heating, Ventilation and Air Conditioning (HVAC) system by embedding the pipes of the heating and cooling system into the concrete during the building construction increases the thermal inertia of the system.

By enlarging the heating/cooling transfer surface to the floor and ceiling of a room, it is possible to reduce the temperature gap for heat transfer allowing the use of low exergy systems and minimizing the thermal energy losses. A significant number of large modern buildings use radiant heating and cooling, specifically Thermally Activated Building Systems (TABS) or Concrete Core Activation (CCA) systems. Some representative examples are:

- Kunsthaus Bregenz (1997): Bregenz, Austria. 47°18'06.12" N 9°26'42.72" E. Total area: 1,900 m^2. Exhibition/Museum building.
- Zollverein School (2006): Essen, Germany. 51°29'16.43" N 7°02'51.42" E. Total floor area: 5,000 m^2. Higher education building.
- Hearst Tower (2006): New York, USA. 40°46'03.98" N 73°59'04.04" W. Total floor area: 80,000 m^2. Floor count: 46. Office building.
- Pusat Tenaga Malaysia (2007): Bandar Baru Bangi, Selangor, Malaysia. 2°57'26.62" N 101°45'03.94" E. Total floor area: 4,000 m^2. Floor count: 5. Office building.
- Kranhaus (2008): Cologne, Germany. 50°55'43.49" N 6°57'54.89" E. Total floor area: 7,100 m^2. Residential/Hotel/Dormitory building
- Manitoba Hydro Place (2009): Winnipeg, Manitoba, Canada. 49°53'32.63" N 97°08'47.04" W. Total floor area: 64,591 m^2. Floor count: 24. Office building.
- David Brower Center (2009): Berkeley, USA. 37°52'12.89" N 122°15'58.81" W. Total floor area: 4,460 m^2. Office building.



Hearst Tower
Manitoba Hydro Place II
Post Tower
David Brower Center
Marcella Niehoff School of Nursing
Rheinauhafen Kranhäuser
Zollverein School
idom
Kunsthaus Bregenz
Pusat Tenaga Malaysia

Figure 3.3. Buildings of different typologies that use TABS to provide heat or cooling

- Post Tower (2009): Bonn, Germany. 50°42'55.35" N 7°07'48.85" E. Total floor area: 55,000 m^2. Floor count: 46. Office building.
- IDOM Madrid Building (2010): Madrid, Spain. 40°30'15.29" N 3°42'39.05" W. Total floor area: 15,300 m^2. Floor count: 4. Office building.
- Marcella Niehoff School of Nursing, Loyola University (2012): Chicago, USA. 41°59'54.91" N 89°39'25.93" W Total floor area: 5,400 m^2. Higher education building.

The Radiant System Research project of the Center for the Built Environment at UC Berkeley [13] compiles an increasing list of buildings using radiant systems. Most of the representative buildings using radiant technology are classified by the radiant technology they use as well as by the building type they represent. Figure 3.4 provides a geographic location of these buildings highlighting those that use TABS. The usage varies from only heating use in high latitudes to only to cooling in equatorial latitudes. The system is used in different kind of buildings as residential, offices, higher education, museums, government building… Figure 3.4 also adds an actualized map with a brief description of these buildings.

3.2 Use of TABS: Advantages and limitations

The comfort need in buildings has supposed the development of different systems to ensure that all of the parameters included in the comfort definition fulfil their specifications. In this way, air based systems are one of the most used climate methods to provide heat and cooling besides ventilation. This system is widely used in all kind of buildings, although it may not be adequate for big-mass vertical air volumes, as an industrial warehouse. The use of low surface/high temperature radiation systems can be a solution in that case. High surface/low temperature radiant system like the TABS provides a homogeneous heating and cooling climate system that can improve the comfort sensation with a controlled energy use. The thermal activation of the concrete provides the system a big inertia and the great surface that floor, ceiling or sometimes even walls, increase the weight of the thermal radiation in the heat exchange. Bibliography denotes this climate system as ACC or TABS. The system provides some advantages compared with other climate system as Annex 44 [14] describes.

· The use of the thermal inertia allows reducing and shifting heating and cooling peaks, which allows for a more competitive electric-rate decreasing the operative costs.

· The air system function can be reduced to ventilation and support purposes, further decreasing the maintenance and operation costs of the system.

· Temperature of the cooling/heating water is close to the comfort objective. This allows the use of heat pumps or geothermal energy as power source for the climate system with an improved efficiency. That temperature range also reduces the power losses associated to the water transport improving the efficiency of the system.

· The use of heating/cooling surface creates a homogeneous distributed climate system, which provides a more comfortable and safe environment.

· A conservative power ratio of 50 W/m^2 for heating and cooling supplies enough power to ensure the thermal comfort of the environment.

There are however some barrier and limitations for the implementation of these systems:

· The climate environment must be considered for an adequate use of the system.

· The system must be implemented at construction time and it requires high quality material.

· At the implementation, the thermal comfort is not associated with a temperature but a temperature band.

· In cooling period, the appearance of condensation can limit the cooling power of the system.

· The use of a high thermal inertia system requires an advanced control to take advantage of its associated benefits and avoid the comfort and economic problems related to an inaccurate control response.

Considering those advantages and limitations, it can be said that the main use of the TABS is located in Central Europe and North America, as it has been seen in Figure 3.4. Due to the specific climatic behaviour of these zones, the system operates as heating or heating/cooling provider. Even so, social evolution and climate change increases the need of cooling. Current buildings as the multipurpose building *Charles Hostler Student Recreation Center* (2008) at the American University of Beirut, in Lebanon; the office building *Infosys* (2008) in Hyderabad, India, or the *Pusat Tenaga* building (2006) in Bandar Baru Bangi, Selangor, Malaysia, use TABS to provide radiant cooling due to the climate needs of these regions.

3.3 Thermally Activated Building Systems. Concepts

The use of the structure of a building as heat storage and cold and heating system provides different benefits as it has been already mentioned. ASHRAE Handbook – Fundamentals (ASHRAE HOF) [15] and ISO 11855:2012 [16] provide normative and information about the heating and cooling radiant systems, with specific chapters for the TABS. Figure 3.5 shows the preparation of the water pipes before the creation of the concrete slab.

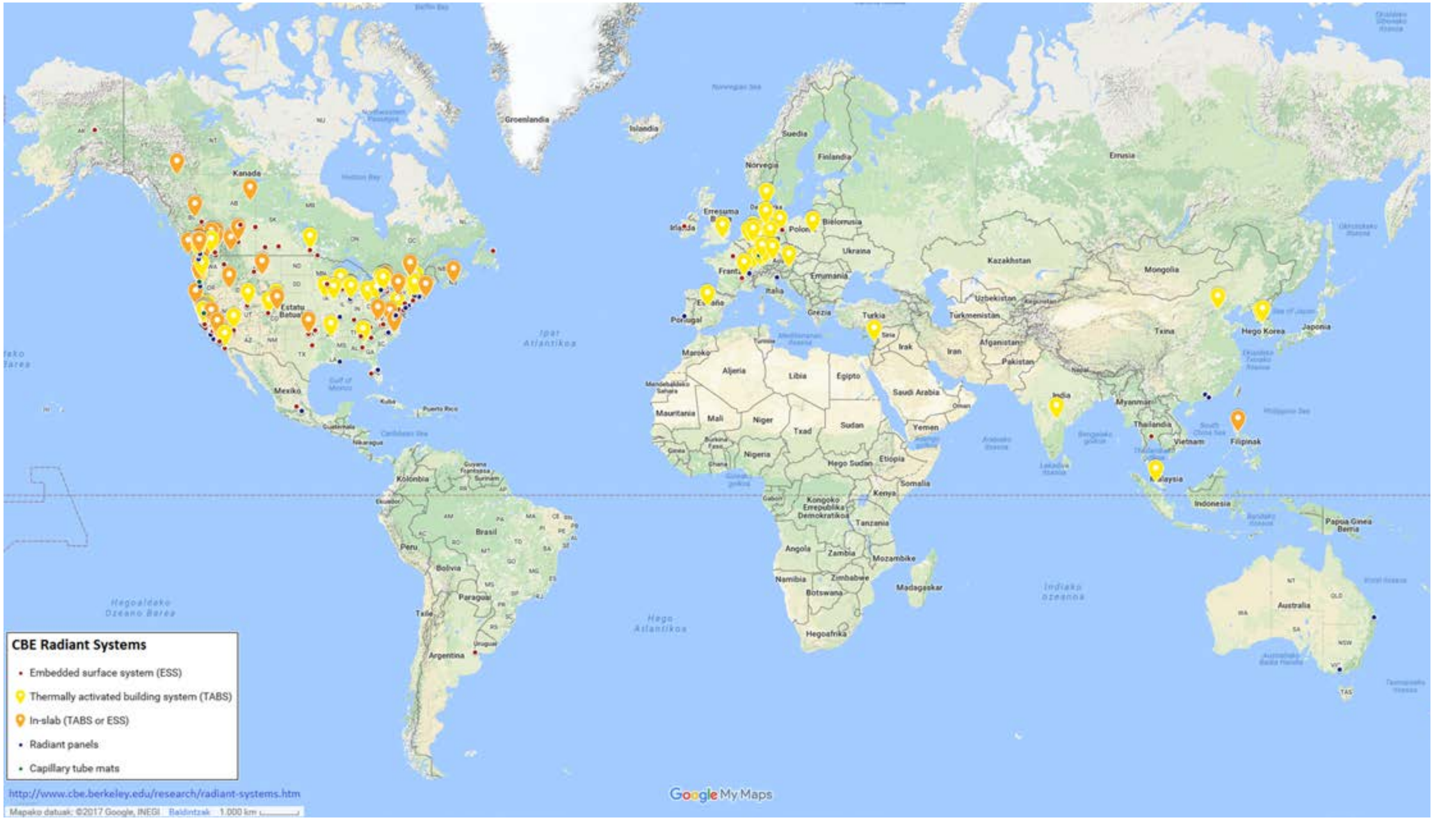


Figure 3.4. Map of representative buildings using radiant system around the world. TABS and in-slab using buildings have been highlighted https://www.google.com/maps/d/u/0/viewer?mid=1LiVk7CwSdIlwZp5YX_hWasEkv0s&ll=21.970534657892944%2C2.6110469000000194&z=2

TABS is an heat accumulation-exchange system used for heating/cooling of environments. Its integration in the concrete slab provides the system with a high-energy storage capacity that will be deployed later to climatize the building. The integration of the water pipes in the floor and ceiling slab provides a big surface, so the heat exchange is performed at a lower temperature difference and in a more homogeneous way than in a conventional heater system. The use of natural convection reduces the use of fans and auxiliary elements associated to other types of climate systems. This characteristic also increases the weight of the radiation in the heat exchange, which can reduce the energy need in high rooms.

Figure 3.5. Water pipe preparation before dropping the concrete to create TABS slab

3.3.1 Operative Temperature

One system is considered radiative when provides more than a half of its power in a thermal radiative mode. In this case, it is possible to define an operative temperature, T_{op}, that considers both radiation and convection effects. In ISO 7730:2005 [17] and in ASHRAE 55 [18], operative temperature is defined as

> T_{op}: The uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment.

ASHRAE HOF [15] considers that "for air velocities less than 0.4 m/s and mean radiant temperatures less than 50 °C, the operative temperature is approximately equal to the adjusted dry-bulb temperature, which is the average of the air and mean radiant temperatures".

> T_{op}: The average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients.

$$T_{op} = \frac{h_c T_a + h_r T_{mr}}{h_c + h_r} \tag{3.1}$$

where,

h_c is the convective heat transfer coefficient (W/m^2°C)
h_r is the radiative heat transfer coefficient (W/m^2°C)
T_a is the air temperature (°C or K)
T_{mr} is the mean radiant temperature (°C or K)

Under the assumption of similar heat transfer coefficients for convection and radiation, which is assumable for ambient temperatures, indoor air velocities below 0.1 m/s, no direct sunlight and near sedentary activity, which can be close to an office environment, ASHRAE 55 [18] simplifies the expression to

$$T_{op} = \frac{T_a + T_{mr}}{2} \tag{3.2}$$

Under air velocity consideration, ISO 7726:1998 [19] proposes the next expression for operative temperature:

$$T_{op} = \frac{T_{mr} + (T_a \times \sqrt{10v})}{1 + \sqrt{10v}} \tag{3.3}$$

where v is the air velocity in m/s.

3.3.2 Resistor and Capacitor RC model

Due to the behaviour of the thermal system, it is possible to develop an analogy between thermal and electrical systems when both are considered lumped systems, the well know Ohm's Law is written:

$$I = \frac{\Delta V}{\mathrm{R}} \tag{3.4}$$

where:

I is the current through a conductor (A)
R is the resistance the conductor opposes to the current (Ω)
ΔV is the potential difference between the conductor terminals (V)

It is also know that the heat transfer flux has dependence of the temperature difference among flux is.

$$\dot{Q} = \dot{Q}(\Delta T) \tag{3.5}$$

For the different types of heat transfer[1], considering a lumped system, it can be concreted as:

$$\dot{Q} = \frac{\Delta T}{\mathrm{R_{Thm}}} \tag{3.6}$$

where:

$\dot{Q}$	is the heat flux (W)
$\mathrm{R_{Thm}}$	is the thermal resistance to the heat transfer (°C/W)
ΔT	is the temperature difference (°C or K)

Therefore, it is possible to define an analogy between thermal and electric models:

Figure 3.6. Equivalency between thermal (left) and electric (right) circuits in stationary mode

For a nonstationary situation, it is also possible to define a relationship between the two systems. In this case, the amount of energy the system stores changes over time, losing or increasing it.

In order to obtain a correct model of a building, it is necessary to take into account the temperature variation and the energy stored in the construction materials in TABS, walls, façade… This behaviour is characterized by a capacitance as in an electric model. The material will exchange thermal energy with the environment, according to the temperature difference of its bounds. Figure 3.7 shows a scheme of the heat transfer among a wall considering its thermal capacitance.

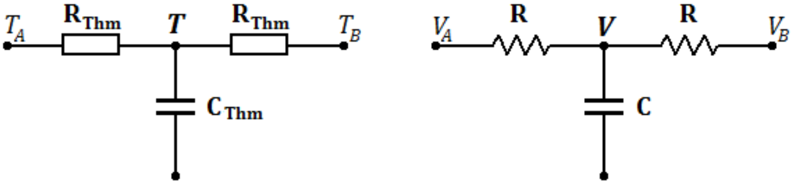


Figure 3.7. Representation of a thermal RC model (left), 2RC, and its analogous electrical model (right) for a nonstationary system. Thermal and electric capacitances accumulate energy

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[1] Radiation transfer is expressed by $(T^4 - T_{sur}^4)$, but for ambient temperatures this expresion can be aproximate to $cte(T - T_{sur})$ as it will be seen in point 4.4.4.1.

For an electrical analogy, it is possible to define the variation of the potential in the intermediate point $\boldsymbol{V}$. Considering the definition of a capacitance, $C = Q/V$, that the charge variation over is the intensity, $\dot{Q} = I$, and the Ohm's law, Equation 3.4, it is possible to obtain the expression

$$C\dot{V} = \frac{V_A - V}{R_A} + \frac{V_B - V}{R_B} \tag{3.7}$$

that indicates how the electric energy is stored in the capacitance over the time using $\dot{V}$ value to indicate the potential variation for that point, this is the system dynamics.

In a similar way, it is possible to define for a thermal system how a material accumulates energy from a heat flux passing through it by using the expression.

$$C_{Thm}\dot{T} = \frac{T_A - T}{R_{ThmA}} + \frac{T_B - T}{R_{ThmB}} \tag{3.8}$$

where $C_{Thm}\dot{T}$ is the term that determinates the thermal energy storage velocity, being C_{Thm} the thermal capacity of the material where the flux passes through and $\dot{T}$ is temperature variation over the time of the material temperature T.

Due to this analogy, it is possible to establish a relationship between the terms as represented in Table 3.1:

Table 3.1. Equivalence between thermal and electric RC models

Thermal concept	Electric concept
Heat flux: $\dot{Q}$	Electric current: I
Temperature: T	Voltage: V
Thermal Resistance: R_{Thm}	Resistance: R
Thermal Capacitance: C_{Thm}	Capacitance: C
Heat flux source	Current source

The heat flux sources in building systems will design factor like the solar radiance or the heat associated to the occupancy or the use of electrical appliances.

3.3.3 Order of the thermal systems

Previous section has constructed a thermal analogy of the electrical lumped parameter systems to describe the heat transfer in a system where energy storage appears. T state characterizes the system dynamic behaviour. In order to create a better characterization considering different materials or to give better response in transitory against high level harmonics [20], it is possible to increase the order that define the system, so the already defined 1st order system (2RC) can be also represented as a 2nd order system (3R2C) where 2 states define the dynamics. If necessary, it is possible to increase the order of a system as much as need, although the system complexity will be also increased.

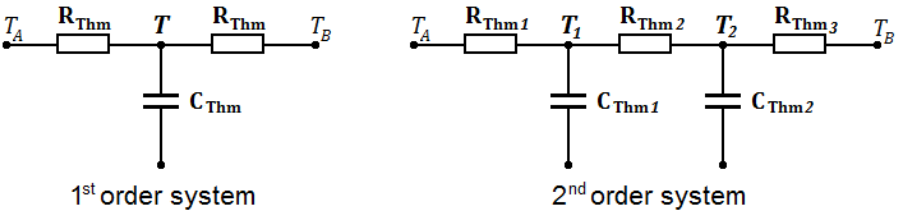


Figure 3.8. First and second order representations for a thermal system

3.3.4 Description of the TABS

TABS develop its heating or cooling task by exchanging thermal energy from a pipe circuit embedded in the building concrete to the concrete and its covering, and then, to the environment that must be climate. The characteristics of the concrete vary from a density of 1750 kg/m^3 and thermal capacity of 0.96 kJ/kgK for light concrete to 2400 kg/m^3 and 0.75 kJ/kgK for heavy concrete. These characteristics together with the large area (volume) associated to the TABS provide the system a high thermal storage capacity and inertia. This heat energy storage and the delay associated to the heat transmission suppose a handicap for the control design of the system. However, under the appropriate control design, the thermal inertia can ensure a more stable environment and the power delay provides a way to take advantage of cheaper energy rates and to avoid peak consumptions.

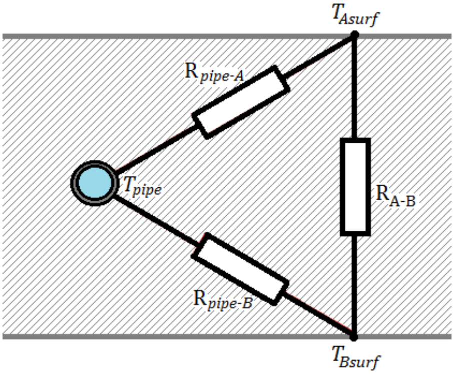


Figure 3.9. Heat fluxes in the concrete slab from water pipe to upper and down surfaces and between these surfaces

The water circuit inside the concrete is the energy source in TABS. Heat propagates through the concrete from/to the water pipe, depending on heating or cooling design, to the concrete. Heat flows in the concrete slab from water pipe to upper and down surfaces and between these surfaces. Figure 3.9 simplifies the heat fluxes that appear in TABS, where no storage action has been considered for the concrete.

3.4 Heat transfer mechanisms

The main mechanisms for heat transfer are conduction, convection and radiation. These three main transmission mechanisms are fundamental in the TABS and their description appears in the next subsections.

3.4.1 Conduction

Conduction is the mechanism for energy transfer among particles related to their interaction. Energy flows from high energy level particles to the ones with a lower energy level. Solid, liquid and gases present this form of heat transfer, while in fluids its effect is less representative than convection. In solids, molecular vibration and free electron movement are the main mechanism for the heat conduction. Heat flux across a conductor is determinate by its length, shape and material composition, as well as the temperature difference between ends. For a stationary situation, **Fourier's law of heat conduction**, published in the study *Théorie Analytique de la Chaleur* in 1822 [21], defines the heat flux for a conductor:

$$\dot{Q} = -kA\nabla T \tag{3.9}$$

where:

$\dot{Q}$ is the thermal flux across the medium (W)
k is the thermal conductivity coefficient of the medium (W/mK)
A is the cross area of the medium (m^2)
∇T is the temperature gradient in the medium $\nabla T = \frac{\Delta T}{L}$ (K/m)

Considering the previously defined thermal-electric analogy, it is possible to rewrite Equation 3.10 defining a thermal resistance, as

$$\dot{Q} = \sum \frac{\Delta T}{R_{Thm}} \tag{3.10}$$

where the thermal resistance is

$$R_{Thm} = \frac{kA}{L} \tag{3.11}$$

In this sense, the stationary heat transfer though the TABS slab can be characterized as the thermal circuit represented in Figure 3.10 (a). There are three heat fluxes: from the pipes to the upper and down surfaces and to between the surfaces. It is possible to see the standard Δ structure of the electric circuits that can be transformed to the star (or Y) representation in Figure 3.10 (b) using the well-known transformation expression for each resistance of the star

$$R_Y = \frac{R'R''}{\sum R_\Delta} \tag{3.12}$$

where R_Δ, are all the resistances of Δ circuit: R_{pipe-A}, R_{pipe-B} and R_{A-B}, while R' and R'' denote the resistances adjacent to the studied node: R_{pipe-A} and R_{pipe-B} for R_{pipe} resistance.

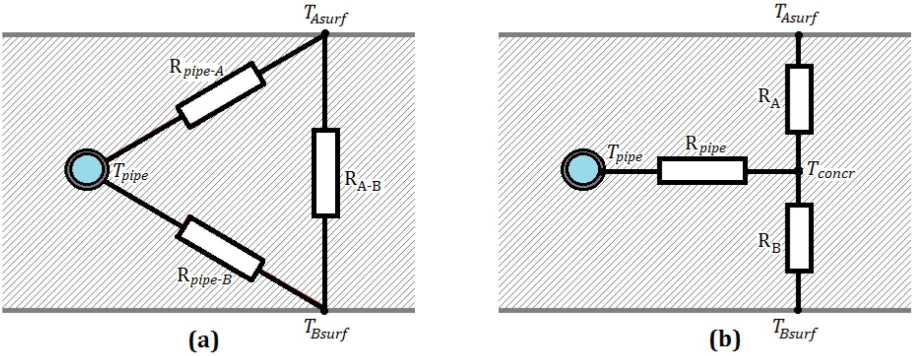


Figure 3.10. Delta (a) – Star (b) equivalence for resistance circuits

Star representation offers a central node that can be used to represent the thermal capacitance of the system for transitory studies, and that will be use to determinate the state that describes the system (temperature). As it has been already mentioned, the system can increase its order to improve the precision, so it is possible to define the same system with a 2nd order model, 4th or higher order models as Figure 3.11 shows.

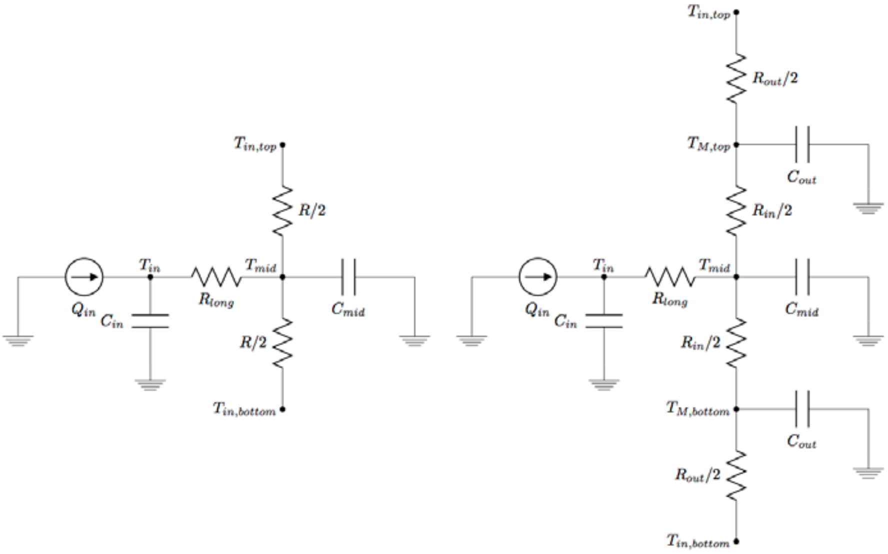


Figure 3.11. RC representation of the heat transfer in a TABS slab. Second order circuit is in the left side while a forth order system is in the right side. Current source represents the heat flux from the water pipe to the concrete

The thermal model of a building includes a high thermal inertia and a constant variation of the perturbations that affects the system such as outdoor temperature, solar radiation or building use. This characteristic impedes the use of a stationary model to represent the behaviour of the building. The study must include the energy storage variation of the concrete over time, so the description of the heat transfer at *i*-node for a transitory situation is given by the equation:

$$C_i \frac{dT_i}{dt} = \sum_j \frac{T_j - T_i}{R_{ij}} + \sum_k \dot{Q}_k \tag{3.13}$$

where

C_i is the thermal capacitance of the concrete (J/K)
T_i is the temperature in *i*-node (°C or K)
T_j is the temperature of the j-nodes connected to *i*-node (°C or K)
R_{ij} is each of the thermal resistances that provide a heat flux to *i*-node. (K/W)
$\dot{Q}_k$ are the heat fluxes that directly actuate over *i*-node (W)

3.4.2 Convection

Convection denotes the heat transfer between a heat source and a fluid, associated to the movement of the fluid. In the case under study, it is the heat transfer between TABS, floor and ceiling, and the air of the stance. Close to the TABS surface, the alteration of the air temperature provokes its density variation, which induces buoyancy adjustment by movement of the heated or cooled air inside the unaltered air mass. This is called free convection. The **Newton's Cooling Law** defines the heat transfer by convection as

$$\dot{Q} = Ah(T_{surf} - T_{fluid}) \tag{3.14}$$

where

$\dot{Q}$	is the thermal flux from the concrete to the air (W)
A	is the cross area of the medium (m^2)
h	is the convection heat-transfer coefficient, CHTC (W/m^{2}K)
T_{surf}	is the temperature at the concrete surface (°C or K)
T_{fluid}	is the temperature of the air in the room (°C or K)

Despite the simplicity of the expression that describes the convection phenomena, its evaluation is not as trivial as one may think. The convection heat-transfer coefficient, CHTC, *h*, depends of many different factors as:

- The temperature difference between the surface and the fluid.
- The temperature of the fluid and some parameters associated with it: specific capacity, $\mathbf{c_p}$; density, $\boldsymbol{\varrho}$; the fluid thermal conductivity, **k**; and the fluid viscosity, $\boldsymbol{\mu}$ (dynamic) or $\boldsymbol{\nu}$ (kinetic).
- The geometric configuration of the heat focus.
- The roughness of the heat focus.
- The convection type, forced or free, and the fluid flow type, laminar or turbulent.

The variations of any of these parameters alter the value of *h*, so it is hard to determinate its value in a free environment where the aforementioned factors are continuously changing. The most commonly used bibliography values for *h* may be those provided by ASHRAE HOF [15], the ones of CIBSE Guide [22], the values provides by Alamdari and Hammond [23] or those provided in the revision-study of Awbi and Hatton [24]. These studies provide experimental values for *h* coefficient in walls, windows and floor between 1 and 6 W/m^{2}K according with different parameters. Under the same study conditions, *h* value in the ceiling varies between 0.1 and 1.2 W/m^{2}K. Lomas [25] studied the influence of *h* value over the energy consumption, obtaining a variation of a 27% in the annual heating demand depending of the algorithm used to calculate the *h*. Other studies also indicate that the indeterminacy of the obtained value can be as big as 15 %.

3.4.2.1 Theoretical values of convection coefficient, h

The theoretical value of the CHTC, *h*, for free convection is calculated by using Nussel number, Nu

$$Nu = \frac{h \cdot L}{k} \tag{3.15}$$

where L is the characteristic length defined by the relation between area, A_s, and perimeter, p, of the surface: $L = A_s/p$.

The value of the Rayleigh number, Ra is used to obtain the Nussel number in free convection

$$Nu = Nu(Ra) \tag{3.16}$$

This expression varies for the TABS according to the considered surface, top or down, and the function of the system, heating or cooling. Table 3.2 shows the typical values of Nu accepted in academia for horizontal surfaces

Table 3.2. Values of Nu in function of geometry and Ra

Geometry	Nu	Ra use range
Upper surface of a hot plate or lower surface of a cold plate	Nu = $0.54Ra_L^{1/4}$ Nu = $0.15Ra_L^{1/3}$	10^4 - 10^7 $10^7 - 10^{11}$
Upper surface of a cold plate or lower surface of a hot plate	Nu = $0.27Ra_L^{1/4}$	$10^5 - 10^{11}$

The Rayleigh number is calculated using Grashof, Gr and Prandtl, Pr dimensionless numbers.

$$Ra = Gr \cdot Pr \tag{3.17}$$

$$Gr = \frac{g\beta\rho^2\Delta T L^3}{\mu} \tag{3.18}$$

$$Pr = \frac{c_p\mu}{k} \tag{3.19}$$

where

g is the gravity constant (m/s^2)
$\beta = \frac{1}{T}$ is the coefficient of thermal expansion (K^{-1})
ρ is the air density (kg/m^3)
ΔT is the temperature difference between TABS surface and air (°C or K)
μ is the dynamical viscosity of the air at the room temperature (m^2/s)
L is the characteristic length of the surface (m)

c_p is the thermal capacitance of the air (J/kgK)
k is the thermal conductivity coefficient of the medium (W/mK)

Considering the typical values for TABS in a room, *h* varies between 2.57 and 3.71 W/m^{2}K for ΔT variations between 3 and 9 K degrees.

Nonetheless, it is necessary to consider the differences that the free convection in an open environment or the feedback circulation produces in a closed environment such as a room. Even more, as mentioned in the work of Awbi and Hatton [24], *h* value varies when it is near the walls of other obstacles. Values proposed in this experimental work are slightly different to the theoretical ones. For long surfaces, the values obtained for heating floor and ceiling are defined in Table 3.3.

Table 3.3. Experimental expressions of Nu and *h* obtained by Awbi and Hatton [24]

Geometry	Nu	h	Correlation coefficient
Floor	$\mathrm{Nu} = 0.269Gr^{0.308}$	$\mathrm{h} = \frac{2.175}{D^{0.076}}\Delta T^{0.308}$	r = 0.997
Ceiling	$\mathrm{Nu} = 2.376Gr^{0.133}$	$\mathrm{h} = \frac{0.704}{D^{0.601}}\Delta T^{0.133}$	r = 0.97

The experimental values given in the Table 3.3 were obtained in a closed room being the hydraulic diameter 1.025.

3.4.2.2 Thermal resistance associated to the convection

The heat flux between TABS and air for plane geometry when radiation is not considered, is determined by the following expression

$$\dot{Q} = -k\left.\frac{\partial T}{\partial L}\right|_{surf} = Ah\left(T_{surf} - T_{fluid}\right) \tag{3.20}$$

There is a boundary layer in the immediate vicinity of the bounding surface where the air temperature varies between the surface temperature and the air temperature. Considering Equation 3.20, it is possible to define the thermal resistance associated to the convection as

$$R_{Thm,conv} = \frac{1}{Ah} \tag{3.21}$$

The convection effect may therefore be added to the schemes of Figure 3.11 adding an additional resistance, which represents the heat transfer by convection. Figure 3.12 shows this effect in the second order representation of the TABS.

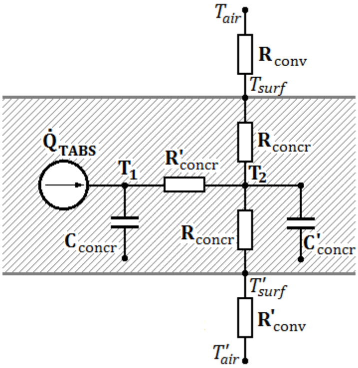


Figure 3.12. Addition of the convective effect to the TABS slab

Further aspects can be taken into account, as the stratification of the air temperature in the room, which supposes a difference between the air temperature considered for thermal comfort, usually at 1.5 m, and the air temperature for convection, at few centimetres of the surface of the slab. The difference is normally assimilated by the *h* as described in Sourbron's PhD Thesis [26].

3.4.3 Radiation

The definition of the TABS as a radiative system assumes that a significant part of the heat exchange by the system for heating or cooling is developed in this way. Radiation can be defined as the energy transfer associated to the electromagnetic waves produced by the thermal activity of any body.

For any temperature over 0 K, all bodies emit an electromagnetic spectrum that has temperature dependence. For a blackbody the energy emission density is given by the expression:

$$E(T) = \sigma T^4 \tag{3.22}$$

where

σ is Stefan-Boltzmann constant, $\sigma = 5.670 \times 10^{-8}$ (W/m^{2}K^4)
T is the heat emitter absolute temperature (K)

Plank's law gives a spectral representation of the radiation pattern for a given temperature.

$$E_\lambda(\lambda, T) = \frac{2h\left(\frac{c}{n}\right)^2}{\lambda^5} \frac{1}{e^{\frac{h\frac{c}{n}}{\lambda k_B T}} - 1} \tag{3.23}$$

where

h	is the Planck constant, h = 6.625·10^{-34} (Js)
c	is the speed of light in vacuum, c = 2.997·10^{8} (m/s)
k_B	is the Boltzmann constant, k_B = 1.38·10^{-23} (J/K)
n	is the refractive index of the medium
λ	is the wave length of monochromatic emissions (m)
T	is the surface temperature of the body (K)

Figure 3.13 displays a representation of the emission distribution of a black body for different temperatures. The main figure shows the variation in the emission power from 0 °C to 5000 °C. The emission peak at 5000 °C, which is the sun surface temperature, falls inside the two vertical lines that indicate the visible spectre wavelength. Inside the figure, there is a close approach for emittances at ambient temperature, TABS emission range. For those temperatures, wavelength distribution is located in the thermal infrared, far away from the visible and the emitted power falls six orders.

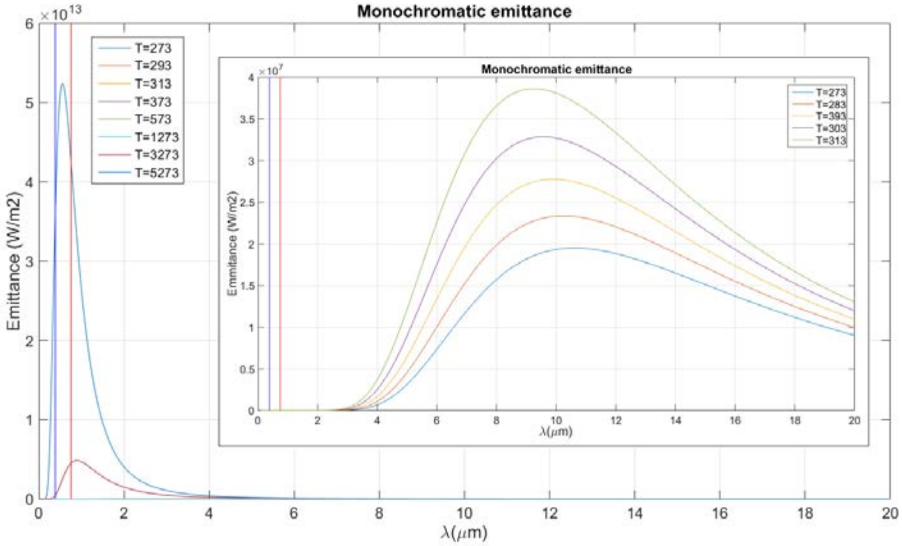


Figure 3.13. Spectral emission of black body according to its surface temperature. Blue and red vertical lines determinate the visible range

Common bodies, which are called grey bodies, also emit radiation, but it is reduced by an emissivity factor ε(λ) in comparison to the black body at the same temperature. That emissivity factor will be near 0 for polish metal surface and between 0.85 and 1 for construction materials as Table 3.4 shows. For grey bodies, Equation 3.22 is defined as

$$E(T) = \varepsilon\sigma T^4 \tag{3.24}$$

Heat transfer between a surface and its surroundings is a function of their temperatures and may be designed by:

$$E(T) = \varepsilon\sigma(T^4 - T_{sur}^4) \tag{3.25}$$

Table 3.4 shows the emissivity values for the surfaces of different construction and cover material, which determinate the emitted radiation

Table 3.4. Emissivity values of several construction materials as provided by the Engineering ToolBox [27]

Material	Emissivity (ε)	Material	Emissivity (ε)
Basalt	0.72	Oak, planed	0.89
Black Paint	0.80 - 0.93	Plaster	0.98
Cement	0.54	Pine	0.84
Clay	0.91	Porcelain, glazed	0.92
Concrete	0.85	Plastics	0.90 - 0.97
Concrete, rough	0.94	Rubber, foam	0.90
Concrete tiles	0.63	Sandstone	0.59
Granite	0.45	Soil	0.90 – 0.95
Limestone	0.90 - 0.93	Tile	0.97
Marble White	0.95	Wood Beech, planned	0.935
Masonry Plastered	0.93	Wood Oak, planned	0.885
Mortar	0.87	Wood, pine	0.95

Considering that it may be surrounded by surfaces at different temperatures, it is necessary to introduce view factors, F_{ij}, that define the fraction of the radiation emitted by *i*-surface that *j*-surface receives. These values depend on the surfaces geometry.

TABS and building surfaces are opaque grey surfaces for ambient temperatures, long wavelengths, so it is possible to consider Kirchhoff law when evaluating the thermal energy transfer associated to the system

$$\varepsilon(T) = \alpha(T) \tag{3.26}$$

where ε is the emissivity and α the absorptivity of the surface, to define an *i*-surface resistance to radiation, R_i, that gives a relation between the radiation leaving the surface (reflected and emitted) and the incident radiation over it.

$$R_i = \frac{1 - \varepsilon_i}{A_i \varepsilon_i} \tag{3.27}$$

Radiation transfer between *i* and *j* surfaces is defined as the radiation that leaving *i* surface arrives to *j* surface minus the radiation that leaving *j* surface arrives to *i*. This *ij*-space resistance to radiation can be define as

$$R_{ij} = \frac{1}{A_i F_{ij}} \tag{3.28}$$

And using electric circuit analogy, it is possible to express the radiation transfer between two surfaces as

$$\dot{Q}_{ij} = \frac{\sigma\left(T_i^4 - T_j^4\right)}{\frac{1 - \varepsilon_i}{A_i \varepsilon_i} + \frac{1}{A_i F_{ij}} + \frac{1 - \varepsilon_j}{A_j \varepsilon_j}} \tag{3.29}$$

As represented in Figure 3.14.

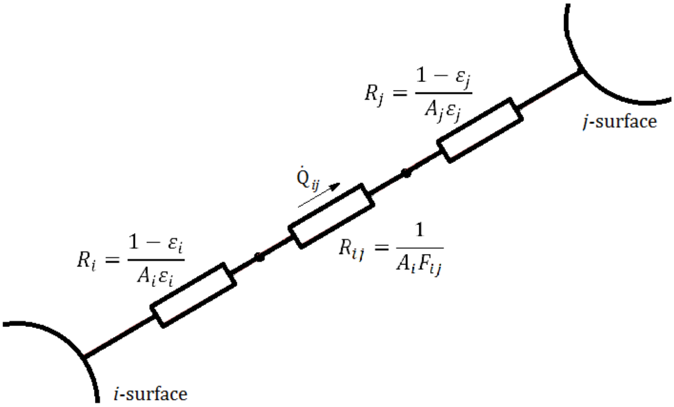


Figure 3.14. Heat transfer by radiation between two surfaces *i* and *j*

ASHRAE HOF [15] provides explanations about the use of this method for an enclosure with three surfaces that can be assimilated to a room with a TABS in ceiling and floor as is represented in Figure

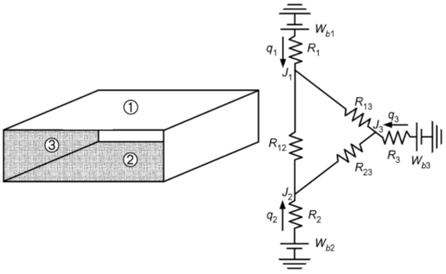


Figure 3.15. ASHRAE HOF proposed RC model as an example for the study of the radiation heat transfer in a room

A simpler, generalized expression can be proposed according to the general radiative heat exchange theory for heat transfer between any two surfaces of the enclosure.

$$\dot{Q}_i = \varepsilon_i A_i \sigma \sum_j F_{ij}(T_i^4 - T_j^4) \tag{3.30}$$

3.4.4 Convection and radiation

Transference of heat in a close environment is mostly associated to convection. However, TABS like systems have a high radiative component, close to the 50 % of the exchanged thermal energy, so when studying the heat exchange in those systems, convective and radiative components must be considered. This point simplifies the equation associated to the heat transfer by radiation under environmental temperature range in order to obtain an expression that combines the effects of radiation and convection.

3.4.4.1 Linearization of the Radiation

TABS has been described as a radiative system, which has a big radiative influence in addition to a convective component. Figure 3.16 shows the power radiated by the surface of a black body, $\varepsilon = 1$, for different emission temperatures to a 283 K surrounding. Although the observed behaviour is clearly nonlinear, it is possible to observe that for environmental temperatures and the relative small temperature difference that appears between TABSs and its surrounding, the heat transfer follows a linear trend, Equation 3.25.

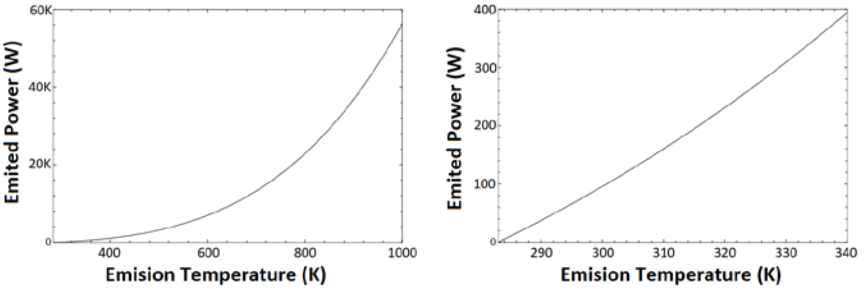


Figure 3.16. Emission power behaviour for different temperature ranges considering a surrounding temperature of 283 K. Nonlinear behaviour for high temperatures (left) and quasilinear behaviour for environmental temperatures (right)

Under this consideration is possible to simplify the expression by linearizing it as proposed in Equation 3.32 or by using the well know mathematical expression

$$(a^2 - b^2) = (a + b) \cdot (a - b) \tag{3.31}$$

that it is explicitly developed in Equation 3.33. This gives an expression that depends on the temperature difference between the emission surface and the surroundings.

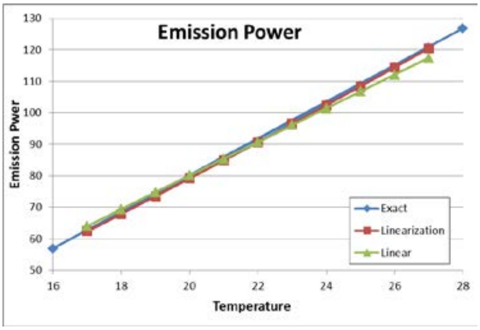
$$\dot{Q} \cong A\varepsilon\sigma 4T_m^3(T - T_{surr}) \tag{3.32}$$

$$\dot{Q} = A\varepsilon\sigma(T^2 + T_{surr}^2)(T + T_{surr})(T - T_{surr}) = A \cdot kte(T - T_{surr}) \tag{3.33}$$

where

$$T_m = \frac{T + T_{surr}}{2} \tag{3.34}$$

This linearization effect can be observed in Figure 3.17 for both approximations



	Emision (W/m²)		
T(K)	linear	linearization	Exact
290	64.06	62.34	62.37
291	69.40	67.89	67.93
292	74.74	73.50	73.55
293	80.07	79.17	79.22
294	85.41	84.89	84.96
295	90.75	90.67	90.75
296	96.09	96.51	96.60
297	101.43	102.40	102.51
298	106.77	108.36	108.49
299	112.10	114.37	114.52
300	117.44	120.44	120.61
Eq	**(3.33)**	**(3.32)**	**(3.25)**

Tsurr = 278 K

Figure 3.17. Linear behaviour of the TABS energy emission by radiation for different approximation for TABS surface range

Figure 3.17 shows that the behaviour of the energy emission can be given as a linear function of the temperature difference instead of the difference of the fourth power

$$\dot{Q} = \dot{Q}(T - T_{surr}) \tag{3.35}$$

This supposes that under TABS use conditions, it is possible to define a radiative heat transfer coefficient in the same way than the convection one.

$$h_{rad} = \varepsilon\sigma 4(T^2 + T_{surr}^2)(T + T_{surr}) \cong A\varepsilon\sigma 4T_m^3 \tag{3.36}$$

Figure 3.17 also show a better behaviour for the linearized expression provided by Equation 3.32 than for the mathematical expression of Equation 3.33 due to the variations of the temperature values. The associated thermal resistance can be defined as

$$R = Ah_{rad} \tag{3.37}$$

Therefore, considering the temperatures to be used in TABS, it is possible to express the heat transfer associated to radiation as

$$\dot{Q}_{rad} = Ah_{rad}(T - T_{surr}) = \frac{(T - T_{surr})}{R_{rad}} \tag{3.38}$$

3.4.4.2 Combined effect

Considering that heat transfer in TABS unifies convective and radiative effects, it is possible to define it as

$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{rad} \tag{3.39}$$

and using the Equations 3.27 and 3.38

$$\dot{Q} = Ah_{conv}(T - T_{air}) + Ah_{rad}(T - T_{surr}) \tag{3.40}$$

Assuming also a well-insulated structure, the temperature difference between air and room enclosure is no bigger than some degrees, so an approximation that considers the same temperature for air and enclosure is usually admitted. The approximation defines a common heat transfer coefficient that lumps both radiation and convection effects together

$$\dot{Q} = A(h_{conv} + h_{rad})(T - T_{air}) = Ah_{common}(T - T_{air}) \tag{3.41}$$

being

$$h_{common} = h_{conv} + h_{rad} \tag{3.42}$$

This expression provides a large simplification in order to realize heat transfer calculations. Figure 3.18 shows the effect of convective and radiative heat transfer in an indoor space.

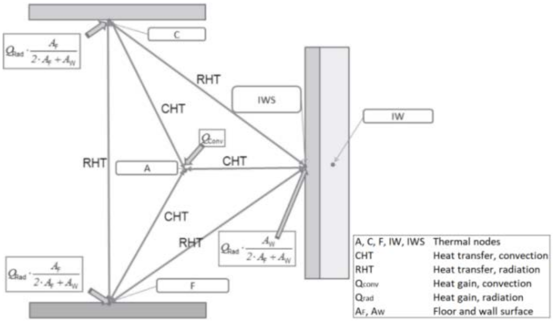


Figure 3.18. Convective and radiative effects in a closed space (ISO 11855)

3.5 Types of radiant systems

Radiant systems can be integrated in floor, ceiling and walls of a room. The usual configuration is heating floor and cooling ceiling. ISO 11855 provides a simplified expression to evaluate the heat flux density, $\dot{q}$, between the radiant surface, floor heating and ceiling cooling, at $T_{s,m}$ temperature and the environment, with an operative temperature, T_{op}, that is given by Equation 3.43, which is almost linear for usual environment temperatures

$$\dot{q} = 8.92\left(T_{s,m} - T_{op}\right)^{1.1} \tag{3.43}$$

The document also provides expressions for the heat flux when wall heating and cooling is used as well as for heating ceiling and cooling floor. According to ISO 11855 normative, radiant systems can be classified in seven groups depending on construction characteristics such as the pipe position in the system or the structure material, concrete or wood. Table 3.5 provides a brief description of these system types and Figure 3.19 represents them graphically.

Table 3.5. Types of radiant systems (ISO 11855)

Type	Description
Type **A**	pipes embedded in the screed or concrete ("wet" system)
Type **B**	pipes embedded outside the screed (in the thermal insulation layer, "dry" system)
Type **C**	pipes embedded in the levelling layer, above which the second screed layer is placed
Type **D**	plane section systems
Type **E**	pipes embedded in a massive concrete layer (TABS)
Type **F**	capillary pipes over concrete surface
Type **G**	pipes embedded in a wooden floor construction

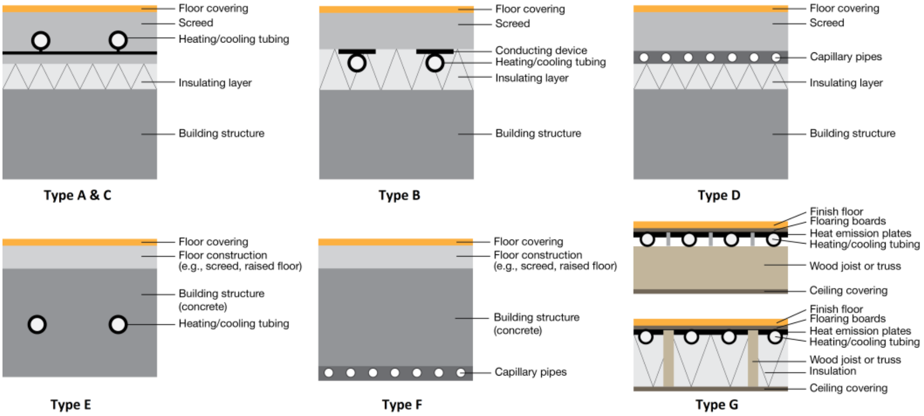


Figure 3.19. Schemes of the different radiant system types

The annex A of ISO 11855-2 provides a simplified method to calculate Types **A** to **D**. Furthermore, ISO 11855-4 is fully dedicated to Type **E**, which is Thermally Activated Building Systems (TABS).

3.6 Heat transfer in TABS

The use of TABS as terminal elements of heating and cooling systems supposes the thermal activation of the concrete structure of a building by passing water pipes through it. The concrete absorbs thermal energy from the water pipes that subsequently releases it to the environment. A stationary study of the TABS must provide the thermal resistance that the system opposes to the heat flux. Under a transitory behaviour, it is necessary to consider the high thermal inertia that the concrete provides to the system by adding the effect of its thermal capacitance. Figure 3.20 (ISO 11855) shows the response of an office building cooling system. Line 1 shows the thermal gain during the day that must be balanced by the cooling system. Line 2 shows the thermal power that an AHU has to manage during office hours. The use of TABS during the night, line 3, allows storing cold in the concrete that will absorb part of the heat gains during the day, reducing the power peak, power difference 4, that AHU has to handle and surely providing some economic savings by the use of a Time of Use (TOU) electric rate.

The figure clearly shows the use of the accumulated energy, which reveals the delay that appears in the system since the concrete absorbs thermal energy from the pipes and is used later to thermally adequate the environment.

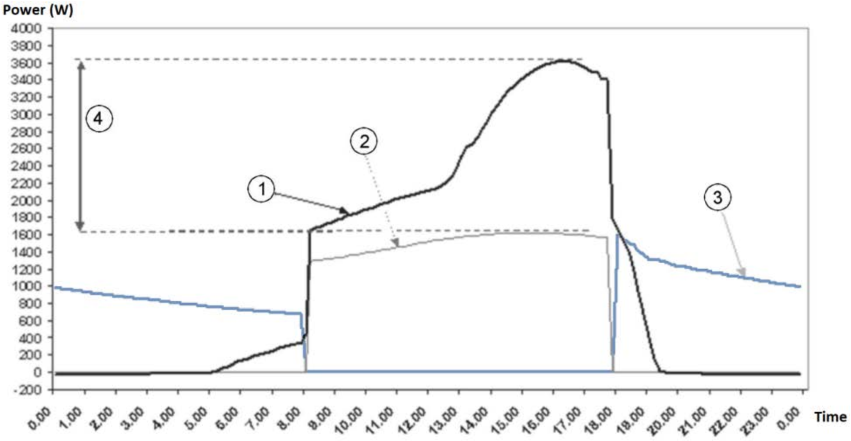


Figure 3.20. Reduction of the peak cooling need in an office building by using TABS (ISO 11855)

Figure 3.11 shows a second and forth order representation of a TABS that provides a model of the system using an RC representation. Studying the physical heat transfer phenomena that appears in the TABS is possible to characterize it in base to these effects.

ISO 11855 as well as Sourbron's PhD document [26] study the stationary behaviour of the TABS and describe the resistances that appear in the system. Considering the resistance structure of Figure 3.12, it is possible to determinate the resistances that affects the system. It enables to define a resistance R_t that considers the effects associated to the thermal transfer from the impulsion water temperature to the concrete core medium temperature and from here to both sides of the slab. This is

$$R_t = R_z + R_w + R_r + R_x \tag{3.44}$$

Being resistances

R_t	is the resistance between the water supply temperature and the average temperature of the concrete
R_z	is the imaginary resistance associated to the advection that appears in the water flux inside the TABS's pipes between the water supply temperature and the average temperature of the water in the circuit
R_w	is the resistance associated to the convective heat transference between the water and the inside wall of the pipe
R_r	is the conductive resistance of the pipe's wall
R_x	is the resistance between the outside of the pipe and the concrete average temperature in the conductive layer

For thermal stationary state, R_t can be obtained through the expression [16]

$$R_t = \frac{1}{\dot{m}_{H,sp} \cdot c \left[1 - \exp\left[-\frac{1}{\left(R_w + R_r + R_x + \frac{1}{U_1 + U_2}\right) \cdot \dot{m}_{H,sp} \cdot c}\right]\right]} - \frac{1}{U_1 + U_2} \tag{3.45}$$

where

$\dot{m}_{H,sp}$ is the mass-flux of the cooling/heating fluid through the pipes in kg/s
c is the specific heating power of the cooling/heating fluid
U_1 is the heat transfer coefficient between the concrete conductive layer and the room

Considering the solid concrete slab represented in Figure 3.21, is possible to define the resistance values as

$$R_z = \frac{1}{2 \cdot \dot{m}_{H,sp} \cdot c} \tag{3.46}$$

$$R_w = \frac{W^{0.13}}{8\pi}\left(\frac{d_a - s_r}{\dot{m}_{H,sp} \cdot L_r}\right)^{0.87} \tag{3.47}$$

$$R_r = \frac{W \cdot ln\left(\frac{d_a}{d_a - 2s_r}\right)}{2\pi\lambda_r} \tag{3.48}$$

$$R_x \approx \frac{W \cdot ln\left(\frac{W}{\pi \cdot d_a}\right)}{2\pi\lambda_b} \tag{3.49}$$

The method can be simplified for these two conditions to obtain the expression given in Equation 3.44:

$s_1/W > 0.3, s_2/W > 0.3$ and $d_a/W > 0.2$

$\dot{m}_{H,sp} \cdot c \cdot (R_w + R_r + R_x) \geq \frac{1}{2}$

The values of U_i represent the thermal transfer coefficient; these are the inverse of the thermal resistance from the conductive layer to the room air, and are given by Equation 3.50.

$$U_i = \frac{1}{R_i} = \frac{1}{\frac{1}{h_i} + \frac{s_i}{\lambda_b}} \tag{3.50}$$

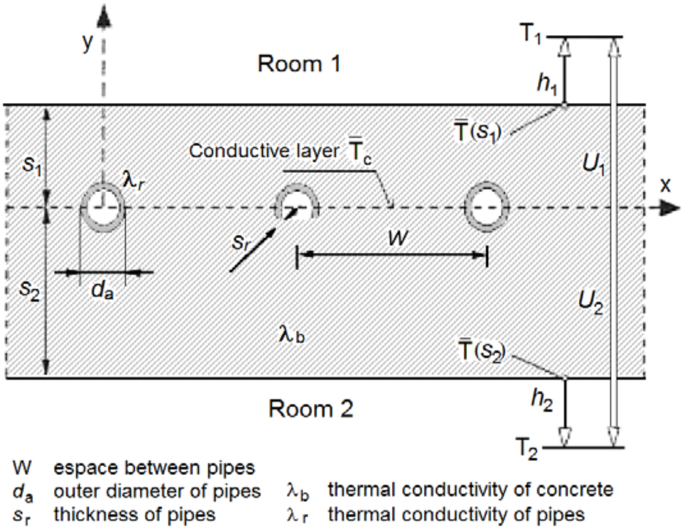


Figure 3.21. Characterization of a TABS concrete slab

So, is possible to define the global resistance structure from the heating/cooling supply represented in Figure 3.22

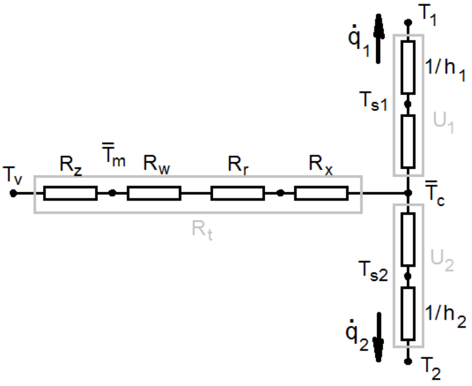


Figure 3.22. Global resistance net of TABS from heat/cooling supply to environment of rooms

where

T_v	is the supply cooling/heating temperature
$\overline{T}_m$	is the average temperature of cooling/heating fluid
$\overline{T}_c$	is the average temperature in the conductive layer
T_i	is the temperature in the *i*-th room

T_{si} is the temperature of the TABS surface in the *i*-th room

In addition, the specific heat fluxes of the TABS to the upper and down rooms come definite by the expressions

$$\dot{q}_1 = \frac{1}{R_1 R_2 + R_1 R_t + R_2 R_t} \left[R_t (T_2 - T_1) + R_2 (T_v - T_1) \right] \tag{3.51}$$

$$\dot{q}_2 = \frac{1}{R_1 R_2 + R_1 R_t + R_2 R_t} \left[R_t (T_1 - T_2) + R_2 (T_v - T_2) \right] \tag{3.52}$$

3.7 TABS characterization

The previous section has provided information about the stationary representation of the TABS based in ISO 11855 normative. Despite the fact that the great thermal inertia that the TABS bring into a building can help to manage the indoor environment in a quasi-static mode, the need of heat and cold required to maintain this situation provokes variations in the heating and cooling energy stored inside the concrete core. Those variations of the stored energy put the concrete thermal behaviour away from the studied static representation forcing a transitory study that considers the thermal capacitance of the concrete, between 0.75 and 0.96 kJ/(kg·K). Furthermore, that dynamic behaviour allows the passive refrigeration of buildings taking advantage of the lower night temperatures that helps to decrease the power peaks by storing energy and it is a way to exploit the TOU electricity rates.

These reasons make it necessary to include the dynamic effects when deploying a TABS model. In order to obtain the concrete dynamic characterization it is possible to develop different tests that show the thermal response of a concrete slab under a heat/cold activation pattern and a controlled environment. By considering the heat flux that the thermal fluid provides and the temperatures in the slab geometry, it is possible to propose different RC models for the TABS slab as shown in Figure 3.11. The experimental work of Vega [28] provides the characterization of an airboxes filed TABS slab by proposing a RC model and obtaining the values of its resistances and capacitances using the Grey Box toolbox [29] or CTSM-R [30] like software. An experimental study was implemented using the "Heat Transfer Conditioned Test Room" of the of the research group of Prof. Helsen at KU Leuven.

Figure 3.23 shows the experimental installation described in the study of Sourbron *et al.* [31] and the proposed model for the airboxes filed TABS. This construction solution reduces the thermal inertia of the structure at the same time that lightens it and saves material. The model representation clearly shows how the air cavities decouple the heat flux through the concrete and the air cavity itself.

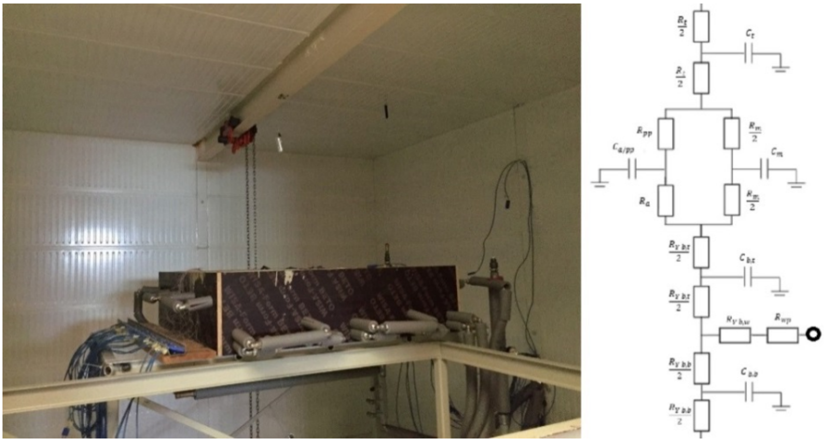


Figure 3.23. Experimental installation for TABS parametrization at KU Leuven and a proposed 6th order model for the characterization of an airbox filed TABS

In order to characterize the TABS, it is also possible to simulate its thermal response by using Computational Fluid Dynamics (CFD) or Finite Element Method (FEM) software. The work of van der Heijde *et al.* [32] characterizes a TABS slab using ANSYS [33] in order to obtain an indicator for the state of charge (SoC) of a TABS by an experimental simulation method. Unlike the experimental method where the data about the thermal behaviour of the TABS was obtained from real elements, the study of van der Heijde *et al.* proposes the definition of a 3D concrete slab with core activation and the thermal effects that affects its behaviour for a FEM simulation. Using the typical symmetry reductions applied in this kind of programs, the element under study is represented in Figure 3.24. Side surfaces are thermally insulated to simulate the symmetry over the space, which reduces the problem to a periodic one. Top and bottom surfaces are thermally active by convection and radiation. In order to calculate the stored energy and the SoC it was necessary to develop a 3D model.

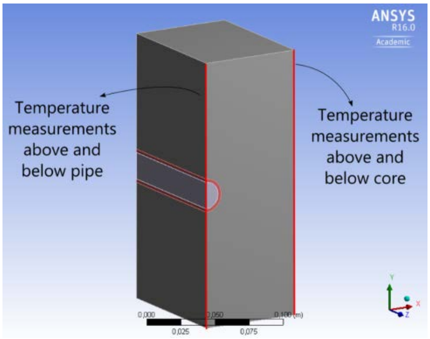


Figure 3.24. Simulated part of the TABS slab

The slab section has these characteristics; it is 200 mm height, 100 mm deep and 75 mm width, half of the distance between pipes. Heating/cooling pipes have polyethylene wall, 25 mm outer diameter and 20 mm inner diameter. Heat transfer from water to pipe is calculated according to the Gnielinski [34] correlation for turbulent flow in tubes with an inner convective coefficient of *h* = 7097.3 W/m2K for a constant 30 l/min flow rate. When the flow stops, *h* becomes zero. Heat transfer in the top and bottom surfaces are modelled according the aforementioned ISO 11855 that replaces EN 15377:2009 [35] European Normative. Radiative heat transfer is defined by the concrete emissivity, ε = 0.85 as defined in Table 3.4. The rest of the material properties are given in Table 3.6.

Table 3.6. Propieties of the materials in the simulation

Material	Concrete	Polyethylene	Water
Mass density (kg/m^3)	2300	950	998.2
Isotropic thermal conductivity (W/mK)	2.2	0.28	0.6
Specific heat (J/kgK)	780	296	4182

The TABS is excited by a pseudo-random binary signal (PRBS) [36] that switches the convective action of the water *on-off*. In order to study low temperature heating, water supply temperature, that is supposed not to change in the circuit, is fixed at 30 °C. Surroundings temperature is fixed at 15 °C. Temperature probes have been positioned around the concrete structure to monitor the test evolution and to get an average value for the top and bottom concrete surfaces and for the pipe surface.

ANSYS simulates the system evolution providing the values that should be similar to those obtained under real experimental conditions in the described Test Room. In order to obtain a slab model, it is necessary to propose a RC design. In the case under study, the 2nd and 4th order systems represented in Figure 3.11 are proposed as characterized in Figure 3.25.

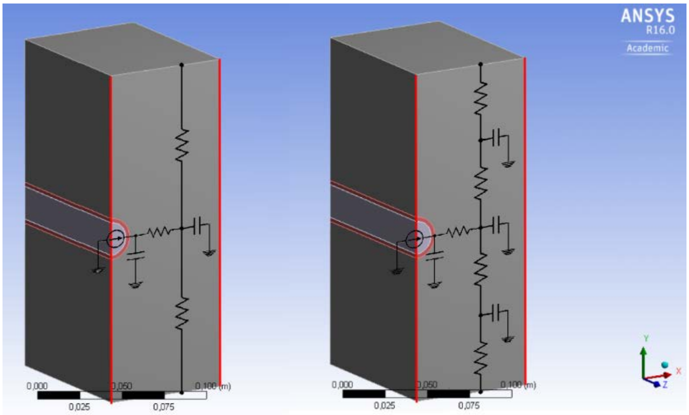


Figure 3.25. 2nd and 4th grey box order models over the TABS slab

Figure 3.26 shows the evolution of the heat transfer over the concrete slab for a heating configuration. In order to provide a better comprehension of the process, heating water temperature is fixed at 35 °C and heating switches are reduced.

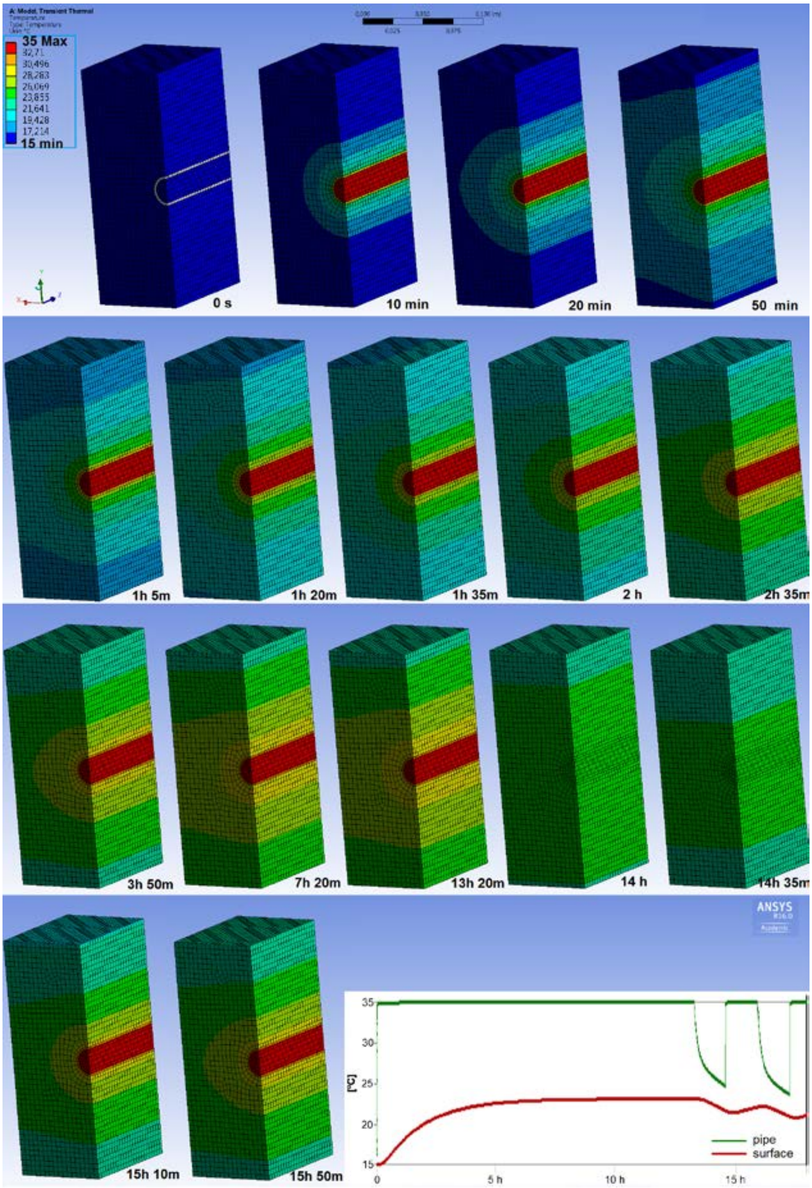


Figure 3.26. ANSYS simulation of the thermal behaviour of the TABS slab

It is possible to observe the heat propagation and accumulation through the concrete slab. Activation delay clearly appears in Figure 3.26, which also shows how the TABS continues dissipating the stored energy even when water circulation stops. Simulation also shows different behaviour for top and bottom surfaces according with the different value of the convection coefficient *h* in both surfaces.

Using a PRBS signal to switch on and off the heat transfer from the supply water, the simulation provides information about the temperature in surface as well as the heat flux through the pipe. By defining the 2nd and 4th order models of Figure 3.11 and Figure 3.25, the stochastic differential equation based CTSM-R module is able to yield the values of thermal resistances and capacitances that are given by Table 3.7

Table 3.7. Estimated parameters for 2nd and 4th order model

	C_{in} [J/K]	C_{mid} [J/K]	C_{out} [J/K]	R_{long} [K/W]	R or R_{in} [K/W]	R_{out} [K/W]
2nd order	237.4	1728	-	2.572	8.284	-
4th order	182	1594	148.3	3.464	2.76	5.523

The results obtained applying those models agree with the ones obtained in the FEM simulation, as it can be seen in Figure 3.27 and Figure 3.28. Figure 3.27 shows the response of the system against an input heat signal. First picture shows the heat input to the slab, given by a PRBS switch sequence. Second picture show the average temperature of the top and bottom surfaces. T_{Out} is the concrete core temperature used in the parameter recognition process that corresponds to the T_{mid} temperature in the parametrized models. In the already studied ISO 11855 this node is designed as $\overline{T}_C$.The last two pictures show the temperatures of the inner nodes of the 2nd and 4th order models.

Figure 3.28 compares the response of the three models. No differences can be appreciated in the temperature response. The error representation shows a deviation lower than 1% for the temperature, this is, temperature deviation does not excess 0.2 °C under normal operation conditions. No substantial differences appear between 2nd and 4th order model, although as expected, the 4th order model shows better behaviour against transitory changes.

It is possible to obtain an RC model for a dynamic representation of the TABS based on experimental or FEM simulation results. These models greatly simplify the model complexity without introducing any significant deviation from the *real* behaviour and speeding up the calculations more than 400 times respect to a FEM simulation. This kind of models can also be implemented in predictive HVAC controls like the model predictive control (MPC), which will be study in the next section. The results show similar behaviour for both 2nd and 4th order models under TABS normal operating conditions. When the TABS response is the unique factor to be study, this result has not special importance, but when deploying an MPC, the use of the 2nd order model instead of the 4th order one provides significant advantage since the resolution of the MPC minimization has a high dependence of the state number. Same parametrization was obtained using Grey Box toolbox and more examples of the modelled system good behaviour can be found in [32].

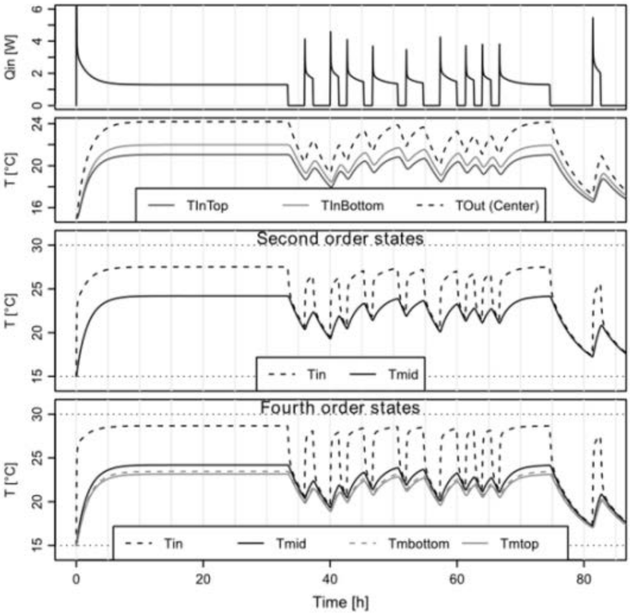


Figure 3.27. Temperature response of the FEM simulation and 2nd and 4th order models

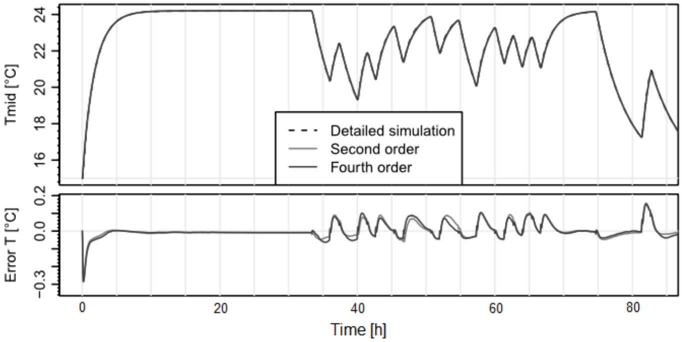


Figure 3.28. Response and response error in the T_{mid} node for the three models

3.8 Summary

This Chapter introduces the Thermally Activated Building Systems (TABS), also called Concrete Core Activated (CCA) systems. Integrated in the building structure this system stores and distributes thermal energy for heating and cooling exploiting the high thermal inertia of the concrete and the great heat-transfer surface provided by the floor and ceiling. After a historic introduction about radiant systems, the Chapter presents the advantages and limitations of this system. Then the Chapter introduces the RC thermal analogy, which allows a state-space representation of the TABS. The Chapter continues studding the theoretic heat-transfer modes and how they are applied to the TABS. The last part shows an experimental characterization of a TABS slab. The heat transfer has been simulated in ANSYS and the values of the thermal resistance and capacitances that define the slab behaviour by using CTSM-R and Grey Box toolbox.

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4.

Building climate control, MPC

Model Predictive Control, MPC is a multiodjective advanced control algorithm that using the model of the dynamics of a system is able to obtain an optimum control response not only at the current time step but also for a predicted time-horizon period, which allows anticipating future changes or disturbances over the system. However, only the first control action that corresponds to the current time is implemented in the feedback loop, rejecting all the other calculated actions. For future control actions, MPC redoes all the calculus from the new state by taking into account the new real and predicted conditions that affect the system.

MPC is one of the advanced controls that have been successfully introduced in the industrial process sector due to its natural treatment for multivariable control and innate integration of restrictions. The paper of Richalet *et al.* [1], dated in 1978 and associated to the chemical processes, is considered the first publication about MPC where authors consider a new methodology to handle problems too complicate for conventional PID controls. Cluter and Ramaker work [2] in 1980 proposed a predictive control that using linear programing, LP, manages a plant optimal control under constraints. Evolution of MPC has diversified its application field and nowadays it is possible to find studies and applications related to a wide field spectre. Among the applications, some examples could be the plasma control simulations of Garrido *et al.* [3, 4], the trajectory generation of unmanned aerial vehicles as describe Singh and Fuller in [5], the management of the energy for electric vehicles provided by Ji *et al.* [6] or even in the treatment of diabetes as described in [7]. The aforementioned characteristics of the control, constraints treatment and multiobjetive solution, makes the building comfort control a promising implementation field for this control. Figure 4.1 shows a basic scheme of an MPC that must follow a predetermined reference trajectory, and the control action at each time step.

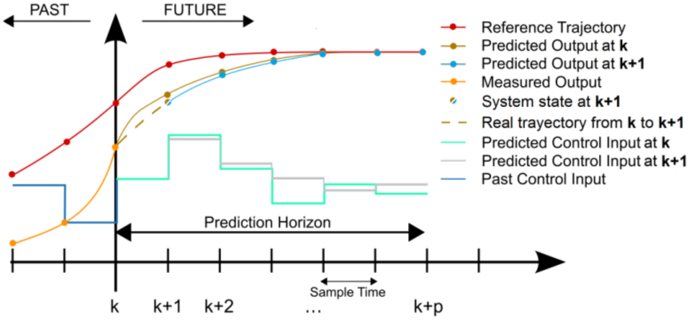

Figure 4.1. Representation of a system evolution under an MPC

The MPC calculates the optimum trajectory for the prediction horizon from **k**-th moment and implements it. At time **k+1**, the control calculates the trajectory again, given states at the time **k+1**.

In order to predict a trajectory of the system, it is necessary to describe the system dynamics and represent them adequately so as to calculate the required control action that yields the desired system response. The most common system representation through a mathematical expression is the state-space representation.

A state-space model represents a system by a set of input, output and a state variable vector related by a first-order differential equation set. The state vector represents the system conditions at a given time, the input vector refers to the actions, controlled or not that actuate over the system and the output vector provides information about the system. The differential equations, represented in a matrix form, describe the system dynamics and its evolution over the time. A continuous linear system state-space representation takes the form

$$\begin{aligned} \dot{\boldsymbol{x}} &= \mathbf{A_c}\boldsymbol{x} + \mathbf{B_c}\boldsymbol{u} \\ \boldsymbol{y} &= \mathbf{C_c}\boldsymbol{x} + \mathbf{D_c}\boldsymbol{u} \end{aligned} \tag{4.1}$$

where $\boldsymbol{x} \in \mathbb{R}^{\mathrm{n}_x}$ is the state vector and n_x the number of states, $\boldsymbol{u} \in \mathbb{R}^{\mathrm{n}_u}$ is input vector that defines the n_u action that actuates over the system. The output vector $\boldsymbol{y} \in \mathbb{R}^{\mathrm{n}_y}$ contains the n_y values observed in the system. $\mathbf{A_c}$, $\mathbf{B_c}$, $\mathbf{C_c}$, $\mathbf{D_c}$ are the matrices that define the system. $\mathbf{A_c} \in \mathbb{R}^{\mathrm{n}_x \times \mathrm{n}_x}$ defines system dynamics, $\mathbf{B_c} \in \mathbb{R}^{\mathrm{n}_x \times \mathrm{n}_u}$ represents the effect of the input vector action, $\mathbf{C_c} \in \mathbb{R}^{\mathrm{n}_y \times \mathrm{n}_x}$ and $\mathbf{D_c} \in \mathbb{R}^{\mathrm{n}_y \times \mathrm{n}_u}$ give the values of the system output.

A discrete system conserves the same state-space representation, once $\mathbf{A_c}$ and $\mathbf{B_c}$ matrices have been defined in a discrete mode. $\mathbf{C_c}$ and $\mathbf{D_c}$ remain unaltered during the discretization process, and will be denoted $\mathbf{C}$ and $\mathbf{D}$. So, for the $\mathbf{i}$-th time step

$$\begin{aligned} \boldsymbol{x}_{\mathbf{i+1}} &= \mathbf{A}\boldsymbol{x}_{\mathbf{i}} + \mathbf{B}\boldsymbol{u}_{\mathbf{i}} \\ \boldsymbol{y}_{\mathbf{i}} &= \mathbf{C}\boldsymbol{x}_{\mathbf{i}} + \mathbf{D}\boldsymbol{u}_{\mathbf{i}} \end{aligned} \tag{4.2}$$

For a time dependent system, the matrices $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, $\mathbf{D}$ take the form $\mathbf{A}(\mathrm{t}_i)$, $\mathbf{B}(\mathrm{t}_i)$, $\mathbf{C}(\mathrm{t}_i)$, $\mathbf{D}(\mathrm{t}_i)$, which express the time dependence of the system.

Under control supervision, the input vector and its effect can be split in two vectors. One of them will determine control action and it is usually denoted by $\boldsymbol{u}$. The other one, which is usually denoted by $\boldsymbol{v}$, represents the action of the disturbances, measured or predicted, that influence the system. After decoupling the input vector, the state-space representation at the instant $\mathbf{i}$ can be written as

$$\begin{aligned} \boldsymbol{x}_{\mathbf{i+1}} &= \mathbf{A}\boldsymbol{x}_{\mathbf{i}} + \mathbf{B}_{\boldsymbol{u}}\boldsymbol{u}_{\mathbf{i}} + \mathbf{B}_{\boldsymbol{v}}\boldsymbol{v}_{\mathbf{i}} \\ \boldsymbol{y}_{i} &= \mathbf{C}\boldsymbol{x}_{\mathbf{i}} + \mathbf{D}_{\boldsymbol{u}}\boldsymbol{u}_{\mathbf{i}} + \mathbf{D}_{\boldsymbol{v}}\boldsymbol{v}_{\mathbf{i}} \end{aligned} \tag{4.3}$$

where the new vector $\boldsymbol{u}_{\mathbf{i}} \in \mathbb{R}^{\mathrm{n}_u}$ represents the actuators of the control and $\boldsymbol{v}_{\mathbf{i}} \in \mathbb{R}^{\mathrm{n}_v}$ represents the uncontrollable disturbances that actuate over the system. $\mathbf{B}_{\boldsymbol{u}}$ and $\mathbf{D}_{\boldsymbol{u}}$ represents the control action and $\mathbf{B}_{\boldsymbol{v}}$ and $\mathbf{D}_{\boldsymbol{v}}$ introduces in the system the effect of the disturbances.

By having knowledge about the control action $\boldsymbol{u}$ and the evolution of the disturbance vector $\boldsymbol{v}$ over the time, it is possible to calculate the system evolution. In some systems, it is possible to get predicted values for disturbance vector, and determine the control action $\boldsymbol{u}$ for a desired system state evolution given by a reference vector $\boldsymbol{\omega}$.

The multiobjetive nature of the MPC allows asking the control to follow some state references while minimizing its control action. It is possible to define a cost function of the system fulfilling these conditions. Although it is possible to define a linear cost function, so that the optimization is a linear programing (LP) problem, it is usual to define a quadratic cost function to ensure convergence, so that the minimization is a typical constrained quadratic programming (QP) problem represented by Equation 4.4.

$$\mathbf{min}_{\boldsymbol{u}_0\ldots\boldsymbol{u}_{\mathrm{N_p}-1}} \sum_{\mathbf{k=0}}^{\mathbf{N_p-1}} \left((\boldsymbol{\omega} - \boldsymbol{y})_{\mathbf{k}}^{\mathbf{T}} \mathbf{Q} (\boldsymbol{\omega} - \boldsymbol{y})_{\mathbf{k}} + \boldsymbol{u}_{\mathbf{k}}^{\mathbf{T}} \mathbf{R} \boldsymbol{u}_{\mathbf{k}} \right) \tag{4.4}$$

Subject to

$$\boldsymbol{a}_{\mathbf{k}} \leq (\boldsymbol{\omega} - \boldsymbol{y})_{\mathbf{k}} \leq \boldsymbol{b}_{\mathbf{k}} \qquad \forall\, \mathbf{k} \in \mathbb{N}_{\mathbf{0}}^{\mathbf{N_p-1}} \tag{4.5}$$

$$\boldsymbol{u}_{\mathbf{min,k}} \leq \boldsymbol{u}_{\mathbf{k}} \leq \boldsymbol{u}_{\mathbf{max,k}} \qquad \forall\, \mathbf{k} \in \mathbb{N}_{\mathbf{0}}^{\mathbf{N_p-1}} \tag{4.6}$$

$$\boldsymbol{\Delta u}_{\mathbf{min,k}} \leq \boldsymbol{\Delta u}_{\mathbf{k+1|k}} \leq \boldsymbol{\Delta u}_{\mathbf{max,k}} \qquad \forall\, \mathbf{k} \in \mathbb{N}_{\mathbf{0}}^{\mathbf{N_p-1}} \tag{4.7}$$

where $\boldsymbol{y}$ is the output vector that stores the parameters to be controlled and $\boldsymbol{\omega} \in \mathbb{R}^{\mathrm{n}_y}$ is the reference that these parameters must follow over time. $\boldsymbol{u}$ is the vector that represents the different control actions the system can handle. To ensure a convex problem, the weigh matrices $\mathbf{Q} \in \mathbb{R}^{\mathbf{n}_y \times \mathbf{n}_y}$ and $\mathbf{R} \in \mathbb{R}^{\mathbf{n}_u \times \mathbf{n}_u}$ must be positive definite or semidefinite matrices, these matrices weigh the parameters to be considered in the minimization: the deviation of the output vector values from the reference value and the amount of control. Both terms compete in the minimization and the relation between $\mathbf{Q}$ and $\mathbf{R}$ matrices will penalize one or other, which allows the implementation of different control policies. $\mathbf{N_p}$ is the length of the prediction horizon and $\mathbf{k}$ is the time instant of the prediction horizon. Equations 4.5, 4.6 and 4.7 represent the constraints of the system. Equation 4.5 limits the deviation of the output from a reference while 4.6 constraints the value of the control action. Equation 4.7 limits the variation of the control action during the time step between k and k+1. Normally, this equation is not used in building climate control field.

If the minimization parameters, $\boldsymbol{u'} \subset \boldsymbol{u},$ are defined to be integer, $\boldsymbol{u'} \in \mathbb{Z}^{\mathrm{n}_{u'}}$, the minimization problem becomes a Mixed Integer Quadratic programing (MIQP) problem, which can increase the computation time more than an order of magnitude.

Although LP problems can be resolved more quickly than QP ones, nowadays this difference is not significant. These methods provide different solutions for the minimization problem. Figure 4.2 represents the solution z^* of a bi-variable LP and QP problem constricted to a space $\mathcal{P}$. The cost increases in the arrow direction. In LP, the solution of the minimization problem will be always in one of the constraints intersections except if the slope of one constraint is the same than the one of the cost function (a). The solution is robust with respect to the cost function; the cost function slope must vary substantially before the optimal solution changes, but when it changes the minimization solution moves to another intersection point. When system constrictions change, the solution must also change. LP is usually implemented to hold the system robustly in a fixed operating point, although that point is not necessary a true optimum.

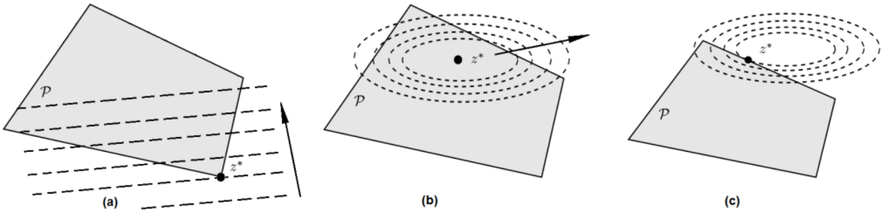

Figure 4.2. LP (a) and QP (b,c) optimization solutions for a bi-variable cost function inside the 𝓟 constricted space. Minimization solution for LP (a) is always in one of the constraints intersections, while for QP can be inside the allowed region 𝓟 (b) or in the boundary (c). Dashed lines represent constant cost contours

The behaviour for QP formulation is different. And the minimization solution z^* can be inside the constrained region or in the boundary. In this last case, the system tries to maintain the operation point near the optimum but within the allowed 𝒫 region. Due to the knowledge that the predictive control has about the constraints and the nonlinear effect when the operation point approaches the constraints, this point can be located closer to the constraints than with a LP formulation. QP formulation provides great flexibility that is reflected indifferent aspects as:

- The operation point can be placed and moved inside 𝒫 region. In LP formulation, it should be placed at the boundary.
- Relative weights in cost function can be changed to alter the unconstrained behaviour.
- The operation point z^* can be altered in (c) around the constraint line by changing the weight relation.

These characteristics provide QP with an important advance by giving a linear behaviour when the constraints are inactive or fixed allowing the use of all of the linear control theory tools to analyse the controller, which is not allowed with LP formulations.

Different constraint types may be implemented over input, output or state variables. The most common ones are a value band for $\boldsymbol{y}$ parameters, the definition of maximum and minimum values for the control action and the definition of a limit for the control action change from one time instant to the subsequent one. Table 4.1 [8] shows some of the common constraint forms that appear in building climate control.

It is possible to define two kind of constraints, *hard constraints* do not allow the system variable to trespass it in any way. In contrast, *soft constraints* allow the variable to trespass the bounds but it suffers a heavy penalty in the cost function as longs as it is out of the allowed region.

Table 4.1. Constraint types for the parameters of the minimization

Constraint type	Mathematical description
Linear constraint	$Ax_k \leq b$
Convex quadratic constraint	$(x_k - \bar{x})^T Q (x_k - \bar{x}) \leq 1, \quad q \preccurlyeq 0$
Chance constraint	$\mathbb{P}[Ax_k \leq b] \geq 1 - \alpha, \quad \alpha \in (0, 0.5]$
Second order cone constraint	$\lVert Ax_k + b \rVert_2 \leq Cx_k + d$
Switched constraint	if $condition,$ then $A_1 x_k \leq b_1$ else $A_2 x_k \leq b_2$
Nonlinear constraint	$h(x_k, u_k) \leq 0$

Different solvers can provide a solution for the minimization problem. CPLEX [9], MOSEK [10] or GUROBI [11] provide solution for a wide group of minimization problems and are free for academia. In order to ease their implementation and to provide a high freedom degree in the design of the minimization problem, it is possible to integrate YALMIP [12] in its resolution.

4.1 Basic concepts about MPC in buildings

The control of residential and no residential building dynamics presents different challenges that must be resolved considering multiple factors such as the thermal restrictions for comfort, equipment limitation or the external disturbances that influences the system: ambient temperature, solar irradiation or building use. All these factors influence the control action that must fulfil some main objectives. The control must maximize the building user comfort while minimizing the energy use necessary to maintain that comfort. Sometimes, energy cost minimization or CO_2 emission reduction conditions can be added or replace the energy use minimization.

The effective control of building climate parameters by a heating, ventilation and air conditioning (HVAC) system introduces challenging conditions related to other kind of systems that defines the control characteristics. Some of these peculiarities are described in Afram and Janabi-Sharifi study [13]:

- Long-time control step.
- Time-varying dynamics.
- Time-varying disturbances.
- Time-varying setpoint.
- Nonlinear dynamics.
- Use of uncertain predicted information for weather or building use conditions.

These characteristics, in addition to the importance of getting energy saves have led to the development of numerous control algorithms in order to improve the energy use. The intuitive *on-off* controller provides a response that can be adequate for simple distribution but may show some shortfalls when applied to high thermal inertia buildings. PID family controls are also commonly used in buildings. Again, high thermal inertia of buildings and the degeneration of the control characteristics away from the design parameters difficulties an appropriate control when this error based algorithm is used. Other control algorithms studied to improve the energy use are based on artificial neural networks (ANN), fuzzy logic (FL) or genetic algorithms (GA).

Rule Based Controls, RBC, are the classic option implemented in most large commercial buildings. In order to fulfil thermal comfort conditions, the RBC checks the state of comfort parameters and yields a control action based on a predefined decision tree and implemented by *on-off* or PID control. The main objective of this kind of control is to ensure thermal comfort of the users leaving in background the aspects related to the energy use.

MPC is an advanced multiobjective control that is based on the dynamics of the system and the perturbations that actuate over it. It provides a control action minimizing a cost function. The minimization not only considers the system at the evaluation moment but also in a posterior period denoted predictive horizon, Np. The control commands are predicted considering the perturbations over the predictive horizon and minimized over that period based on the cost function design. The control implements only the first action and recomputes all commands with new conditions for the next sampling instant. When applied to building climate control, the control action should take into account the effect of the HVAC systems and the perturbations that influence the system, such as the outdoor temperature and solar radiation as well as the human and appliance effects. MPC presents special characteristics that make it adequate for building climate control:

- It is not an error-based control. The control anticipates its action taking into account building dynamics and the effects of the disturbances over the predictive horizon.
- It is a multiobjetive control. The control action can be focused in more than one objective. The relevance of these objectives is defined in the cost function by varying the weigh associated to each parameter.
- The control admits restrictions.
- The control admits the variation in system dynamics and in other parameters such as restrictions, comfort bounds or minimization weights over time.
- To improve the control efficiency, when needed, it is possible to create distributed control schemes.
- Due to the predictive capacities of the control, and in addition to TABS like elements, it is possible to optimize the energy use by softening consumption peaks and shifting the energy consumption to a cheaper electric rate.
- The long-time constant associated to the buildings dynamics ensures the system stability.
- It is considered to be an adequate control to integrate renewable energy sources.

Successful MPC implementations have been achieved in buildings getting potential savings over 15 % in energy use and providing other environmental benefits. In the questions about the implementation of MPC in buildings, Killian and Kozek [14] provide different examples about this point that complete the ones of the Chapter 2.

After considering all the above elements, there are still some difficulties to implement the MPC in buildings:

- The main remark is that it is necessary to develop an accurate mathematical model of the building, which is not trivial and it must be done for every building MPC is implemented in.
- The control action is based on predicted information, so differences may appear between these values and the predicted ones.

In order to reduce these issues, some solutions have been developed. The Matlab Building Resistance-Capacitance Modelling (BRCM) Toolbox [15] developed in ETH Zurich "provides a means for the fast generation of (bi-)linear resistance-capacitance type models from basic geometry, construction and building systems data. Moreover, it supports the generation of the corresponding potentially time-varying costs and constraints". IDEAS [16] module integrated in Modelica [17] allows the linearization from a Building Energy Simulation (BES) model to a state-space mathematical model, which enables another way to ease the model creation. The use of state estimation as the Kalman filter [18], reduces the differences that appears when predicted perturbations and state values are considered instead of real ones. Its use can also reduce the control error derived from the difference between the real behaviour of the building and the modelled one.

Figure 4.3 shows a scheme of the elements that integrate an MPC controlling a building. There appear some of the already mentioned elements: model, predicted and real disturbances, energy use policies…

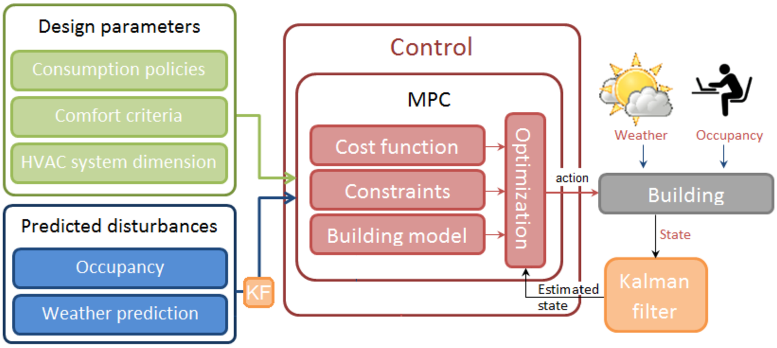

Figure 4.3. Integration of the different parameters in an MPC controlled building

The main characteristics of the MPC are described in the next subsections.

4.2 Model Predictive Control applied in buildings

4.2.1 Model of the building

In order to determinate the evolution of the system over the time and the minimum action of the control actuators that fulfils the design specifications, MPC requires a mathematical model of the system plant. In the case under study, this supposes that it is necessary to define a model of the building dynamics and how external influences and HVAC action influence it. The model is designed using state-space representation for the building.

4.2.1.1 Types of building models

According with the physical description the model provides, it can be classified in three types:

- White-box model:

White-box models are defined according to the physical proprieties of the system dynamics. System states have physical meaning and once the model is created its dynamics must be validated. A good model definition usually supposes a very large number of states that should be reduced when implemented in an MPC. A correct parametrization of the physical phenomena is crucial in order to obtain a reliable model.

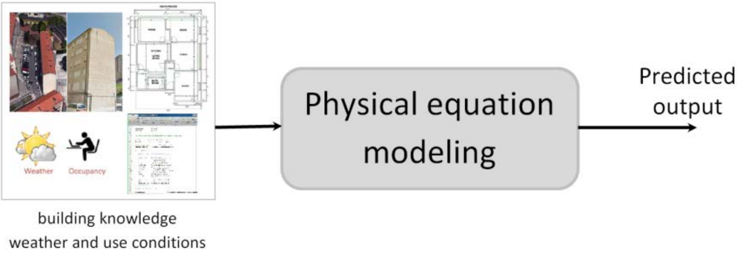

Figure 4.4. White box model representation. Physical knowledge of the system is included into the model

- Grey-box model:

Grey-box model combines partial physical information of the system with experimental data to complete a model. Model structure and parameters are defined so that the obtained states have physical meaning even though it is not always possible to measure them. The different order RC models for the TABS heat propagation obtained in Chapter 4 are an example of Grey-box model.

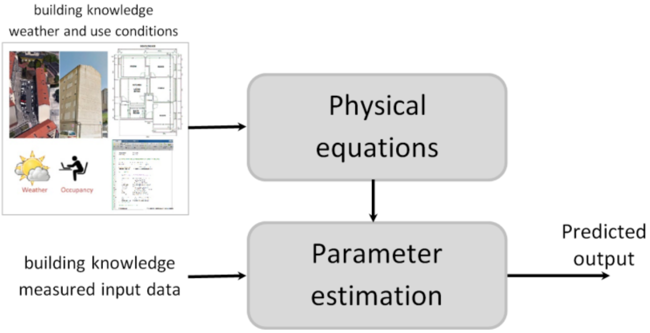

Figure 4.5. Grey-box model representation. The model is based on physical knowledge and estimated parameters

- Black-box model:

Black box model is a mathematical model that relates the system input and output without any knowledge about the internal working. Mathematical algorithm, linear or nonlinear, does not provide any information about the system physics. The states that characterize the system do not have any physical meaning and the parameters of the model can be defined by estimation.

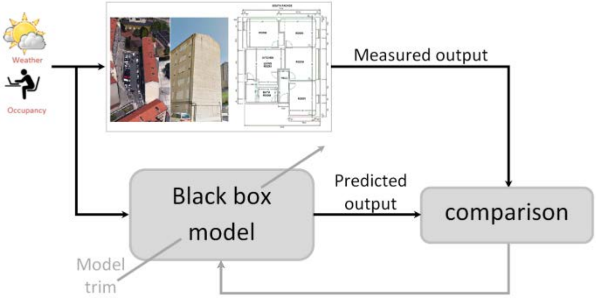

Figure 4.6. Black-box representation. The model is a function of the system's input and outputs. States have not physical meaning

4.2.1.2 Model creation, system identification

As previously mentioned, it is necessary to define a model of the building in order to apply an MPC. Although it is possible to soften the influence of the deviations that appears between real behaviour of the building and the proposed model, in order to ensure a correct control response, the model design must be as accurate as possible. The building model can be obtained in different ways:

- Direct RC model

It is possible to design the building model based in the physical characteristics of the building materials and geometry. The theoretical representation of the space and walls using the construction materials and the relations between room and other zones defines the RC model. A wall is represented by the different material layer it has and their thickness, which provides different resistances and capacitances for each material layer. The model complexity and size is given by the precision the system is represented with. In order to avoid too complex systems that can influence the MPC performance due to the state number, a wall or a wall set for example, is usually represented as a unique element.

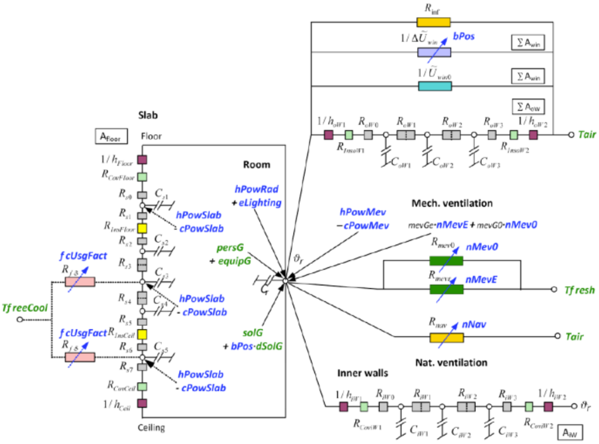

Figure 4.7. RC model used in Opticontrol project [19, 20]

- Experimental model

The experimental RC model can be obtained from the experimental study of the real building dynamics. Building thermal behaviour is monitored for a time under weather influences as outdoor temperature and solar radiation. The temperature of indoor air as well as the temperature of the walls surface provides data to analyse the system. Heat flux information through façade completes the dataset. The design must provide an initial RC topology that describes the dynamics using thermal capacitances and resistances. It is necessary to use a statistical program to recognize these parameters as Continuous Time Stochastic Modelling for R (CTSM-R) [21] used to estimate embedded parameters in a continuous time stochastic state space model under R environment. The Python GreyBox toolbox developed by De Coninck *et al.* [22] using JModelica also provides successful results assessing the quality of the obtained parameter values based on the prediction error with regard to a fitted output. A pseudo random activation of the HVAC system will improve the information obtained to represent the dynamics of the system. Van Dijk and Téllez propose in [23] the use of a Randomly Ordered Logarithmically distributed Binary Sequence (ROLBS) so as to create a power pattern in order to decouple the internal and external influences that appear in the system and to get adequate information for the recognition of the parameters in the process of creating a grey box RC-model that can be implemented in the MPC. Other patterns like Pseudo-Random Binary Signal (PRBS) proposed by Godfrey in [24] can also be used in order to excite the system and recognise the parameters of the model.

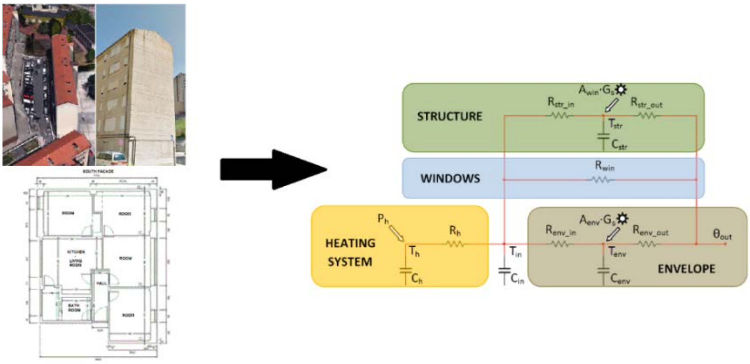

Figure 4.8. RC-model representation of a residential building obtained in an experimental way

- BRCM Toolbox, Zurich

BRCM Toolbox [25, 26] simplifies the complexity associated to the RC model creation. This MATLAB Toolbox defines the characteristics of the construction materials of the building and allows its graphical design. This toolbox determinates the relation between the different elements based in the graphic design of the space under study and creates a mathematical RC model in state-space in order to simplify the MPC implementation. Figure 4.9 represents the graphical design for a building plant and its spaces created with BRCM Toolbox.

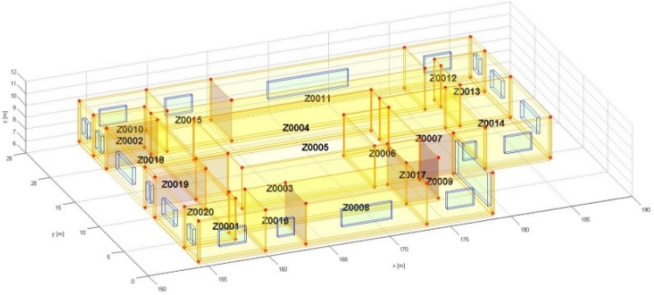

Figure 4.9 BRCM Toolbox visualization for a building floor [15]

- Building Energy Simulation model: TRNSYS, EnergyPlus model

Building Energy Simulation programs like TRNSYS or EnergyPlus are based in the study of energy consumption in buildings. Programs generate a black-box building model that relates different modules to describe the thermal dynamic behaviour of the modelled building. Using a graphic design module, programs can define different building zones, heating systems, perturbations and controls to simulate the behaviour of the building under the design conditions. Although it is not possible to incorporate the model provided by these programs to an MPC, they are normally used for model validation. They also may be used as a substitute of the real behaviour of the building contraposed with the state-space model of the MPC to study how the state-space model deviations affect the MPC control action. It must be said that BRCM Toolbox allows converting EnergyPlus input data files into BRCM thermal model input format, which can provide away to integrate these models into MPCs. This conversion, however is only valid for the thermal model data and it still has some limitations as described in

- State-space model of a Building Energy Simulation model

The Modelica library IDEAS [27, 16] can be used to develop a state-space representation of a Building Energy Simulation model, BES model, that include representations of the different air-spaces, walls, windows, floor, HVAC systems… The model describes the heat transfer relations among the elements, including the nonlinearities as other BES programs like the aforementioned TRNSYS or EnergyPlus do. Unlike these programs, Modelica makes possible to use the Dymola function `linearize2` to generate a state-space linear formulation that can be implemented under an MPC. Considering the description level associated to the BES models, the state number in the linearized state-space could be too high for an effective control with an MPC. Using model order reduction techniques state number can be reduced maintaining the system observable. BES model can also be linearized over different state vector points to reduce the nonlinearities effect away the linearization point.

State-space models can be used to implement the MPC. Nevertheless, differences between the model and the real behaviour of the building hinder a correct control action. The use of a state estimation filter like the aforementioned Kalman Filter (KF) [18] for linear system or the Extended Kalman Filter (EKF) for nonlinear system smoothes the error improving the control results. Some literature about it may be found in Maasoumy *et al.* [28] that discuss the building model uncertainty under the MPC.

4.2.2 State-space model representation in buildings, some particularities

State-space model is a mathematical model representation of the dynamics of a physical system based in a set of first order differential equations given in a matricidal form that related the system inputs, outputs and a set of state variables that describes the system. Its mathematical formulation, described in Equation 4.1, allows developing the system behaviour over the time and using mathematical resources to operate it. In particular, it allows raising a minimization problem about the system dynamics over the time to get the control action, which leads to MPC.

The characteristics of the building systems, which can be non-linear or deploy a large state number makes necessary the use of some mathematical proprieties in order to make the studio of the dynamic behaviour of the building and the minimization for obtaining the control action affordable.

4.2.2.1 State-space model: nonlinear systems

Usually, real systems cannot be represented by lineal models and require the addition of nonlinear terms to correctly describe their dynamics. Building models are not an exception. Nonlinearities can appear in perturbations as well as in the model itself. As indicated by Camacho and Bourdons [29], nonlinear models carry some difficulties for the MPC implementation as well as bigger challenges in the study of stability and robustness of these systems. The identification of nonlinear models is one of the problems due to its added complexity. Another crucial issue is the minimization of the cost function. The optimization problem is no longer convex, so that its resolution is more difficult than QP problems. Local minimums may occur bringing about quality and even stability problems. As a result, the computational resources and time necessary to solve the optimization problem increases. Literature proposes different ways to address this problem. Linearization around an operation point is one of the used techniques, in which the linear model can be recalculated for every step or when system is far from the linearization point. Literature provides other different methods to deal with non-linear systems as the conversion in (bi-)linear system by the BRCM Toolbox, the Hammerstein-Wiener (HW) modelling structures proposed by Yu *et al.* [30] or the use of different lineal model according with the system state

4.2.2.2 State-space rank reduction

Reduction of the state-system order is desirable in order to decrease computational time and need of resources. The implementation of MPC as a control paradigm requires great computational resources. Prediction horizon and time step in addition to the system state rank significantly condition the minimization system size. The evolution of computational capacity allows the resolution of problems that some years ago could hardly be resolved in an affordable time. However, some of the effects than previously were not taken into account by their complexity, are nowadays added to the model increasing its complexity. Some mathematical procedures such as the balanced model truncation [31] or the Hankel minimum degree approximation [32] provide resources to perform the state number reduction, ensuring the model maintains observable and controllable.

4.2.2.3 Observability and Controllability

In order to see what is going on inside the system under observation, the system must be observable. Based on Kalman definitions, a system is said to be observable if, for any possible sequence of state and external input vectors, the current state can be determined in finite time using only the outputs ($\boldsymbol{y}$ vector). In other words, it is possible to determinate the entire system behaviour from the output. For a linear time-invariant (LTI) system with $\mathrm{n_x}$ states as defined in Equation 4.2, it is possible to define an observability matrix $\mathcal{O}$, so that the system is observable if its row rank is $\mathrm{n_x}$.

$$\boldsymbol{\mathcal{O}} = \begin{bmatrix} \mathbf{C} \\ \mathbf{CA} \\ \mathbf{CA^2} \\ \vdots \\ \mathbf{CA^{n_x-1}} \end{bmatrix} \in \mathbb{R}^{\mathbf{n_y n_x \times n_x}} \tag{4.8}$$

A system is called state *controllable* for an $\mathrm{n_x}$ state system if for any pair of initial and final state vectors, a sequence of external inputs can transfer the system from the initial state to the final one in a finite time. For an LTI, that implies that the row rank of the controllability matrix $\mathcal{C}$ must be $\mathrm{n_x}$.

$$\boldsymbol{\mathcal{C}} = [\mathbf{B} \quad \mathbf{AB} \quad \mathbf{A^2B} \quad \cdots \quad \mathbf{A^{n_x-1}B}] \in \mathbb{R}^{\mathbf{n_x \times n_u n_x}} \tag{4.9}$$

A system is said to be output *controllable* for an n_x state and n_y input system when a sequence of inputs can transfer the output from any initial condition to any final condition in a finite time interval. For an LTI, that implies that the rank of the controllability matrix $\mathcal{P}$ must be n_y.

$$\boldsymbol{\mathcal{P}} = [\mathbf{CB} \quad \mathbf{CAB} \quad \mathbf{CA^2B} \quad \cdots \quad \mathbf{CA^{n_x-1}B} \quad \mathbf{D}] \in \mathbb{R}^{\mathbf{n_y \times n_u(n_x+1)}} \tag{4.10}$$

These characteristics ensure the correct use of the building reduced model when developing the system dynamics and allow knowing the system relevant states, which are crucial needs for the implementation of an MPC.

4.2.3 Perturbations

MPC must predict a future state set for the system based in the building dynamics and the predicted perturbations, external and controlled ones that affect the system. Perturbation denotes those stimuluses that influence the system. For the case under consideration, the climate control of a building, and leaving aside the control action, these perturbations can be grouped in two main categories:

4.2.3.1 Weather perturbations

Weather forecast provides predicted information about disturbances that affect the system, such as solar irradiation and outdoor temperature necessary to implement the MPC. Weather forecast accuracy is nowadays generally ensured for 3 days predictions, although small local variations can happen; according with literature MPC prediction horizon is normally defined between 8 and 48 hours. Nowadays, meteorological agencies can provide predictions for dry bulb (outdoor) temperature, wet bulb temperature, solar irradiance and cloud factor, which are the main factor that influences weather perturbations, also, it is possible to obtain predictions for humidity and wind speed. Local values may be obtained via Internet and included into the MPC dataset. This provides some of the necessary information to predict the system evolution and calculate the control action. Several researches have been performed to study the effect of the variations of the predicted weather parameters regard to the real one when implemented in MPC as the ones of the Opticontrol project [19, 20].

4.2.3.2 Perturbations associated to the building activity

Perturbations associated to the building activity such as human activity and appliance must be considered in the model. However, the thermal internal gains suppose the main perturbation focus of the system. Proposed values for these influences are defined in different normative [33, 34, 35, 36] and will be given in Chapter 6. Lighting effect is also another heating source although the use of new technologies as LEDs has decreased its power. Incoming solar radiation through windows and blind system is also a heating source and can determine the illumination use. Effects of failures in the prediction of internal gains and their consequences have been considered in some literature works as the one of Zhang *et al.* [37] where the treatment of uncertainty in weather and occupancy predictions is studied. Opticontrol project [19, 20] that since 2007 made an integral study about implementation of MPC in the building sector paid special attention to the treatment of these two perturbation sources, providing a very valuable literature font.

4.2.4 The optimization problem formulation

MPC implements a control action obtained from the minimization of the system cost function for the predictive horizon. Thus, the cost function can be considered the MPC core, being its main tasks to guarantee the system stability and to provide a control action according to a desired multiobjective performance.

Stability: According with Oldewurtel *et al.* [8], in order to guarantee the stability of a system under an MPC, the cost function is commonly chosen as a Lyapunov function. When considering systems with slow dynamics such as buildings, stability does not suppose a real issue and the election of the cost function can be based in the system performance.

Performance: The cost function is usually designed to provide a minimum value for different competitive parameters. In a building climate control these parameters are usually related to comfort criteria and energy use. Comfort criteria can try to minimize the deviation of the temperature with respect to the asked reference. Greater accuracy supposes an increment in the energy use, which is the other minimization parameter, as can be inferred from Equation 4.4.

In most of the studied cases, the cost function implemented for the control of a building climate system under MPC is quadratic, which ensures a constrained QP problem when the weight matrices are positive (semi-)definite. The cost function must balance a control solution according to the comfort and energy use (economic) criteria in agreement with the control policy defined by the weights.

The predictive behaviour of the minimization will anticipate not only changes in the perturbations that affect the building but also in the reference temperature and in the comfort band, changes in the weights to adequate the control action to the night electric rates should also be considered. Figure 4.10 shows the thermal behaviour of a dwelling under an MPC action. The system manages the night to day change in the reference temperature by anticipating the heating action. The power that the heating system can provide is also considered and the heating system with less nominal power anticipates its action more than the more powerful one. Early in the morning, both systems fulfil comfort conditions. Predictive behaviour may also be observed when reference temperature decreases. MPC anticipates this condition and reduces the energy use before that moment.

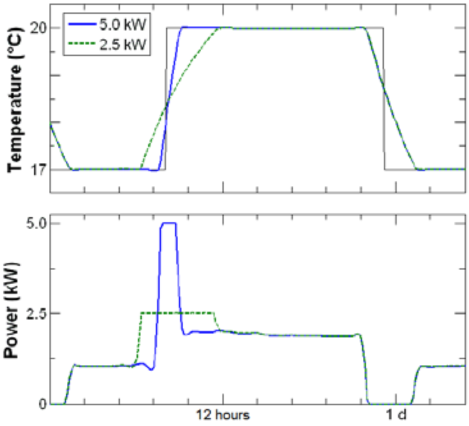

Figure 4.10. Thermal behaviour of a dwelling under an MPC for two different power sources. Control follows the reference temperature (black line) anticipating its action to the reference change

In some cases, in order to save energy it is also possible to avoid the use of the $(\omega - y)$ term in the cost function if the comfort restrictions are properly defined. The system will evolve freely inside the comfort band following the minimum energy use, what could be a good option for night time.

The model can restrict some of its states, outputs or control actions to non-continuous solutions as actuators with predefined positions or on-off equipment. In this case, minimization problem is considered a Mixed Integer Quadratic programming, which can be solved with the usual solver with greater time and computational resource consumption.

4.2.5 Constraints or Restrictions

The implementation of the minimization of the cost function of the MPC provides a natural way to incorporate the system restrictions to the control algorithm. This effect carries some advantages as an efficient management of the system near the constraints. The design of a building model requires the definition of different bound for both system response and HVAC actuators. For a general case, MPC must maintain the building inside a multivariable comfort band defined in different ways according with the applied normative. Operative temperature must maintain its value inside a comfort band to ensure the comfort of the building users. These temperature bounds will change accordingly with the season and may be relaxed out of use hours. In office buildings, humidity, air speed, solar radiation or ventilation rate values should also be maintained inside defined comfort bounds. The use of TABS or another radiant system requires the definition of the maximum and minimum surface temperature values for floor and ceiling to prevent overheating and avoid condensations.

HVAC system has also innate restrictions. The power the system can provide for heating and cooling is limited by the physical equipment that could be damaged if surpassed. When a system can be active, how much times a system is switched on and off or a minimum time for being active define other restrictions that the control must consider.

An efficient management of the system constraints can reduce energy use of the building. By removing the control reference for the operative temperature and constraining its values inside the comfort band, according with Equation 4.4, the temperature evolution will be only based in the minimization of the energy use.

4.2.6 Cost Function Weights

MPC is a multiobjetive control that through the minimization of a cost function as the one of the Equation 4.4 provides the climate system action. Cost function describes the different parameters that compete in the minimization.

In order to mix the different parameters of the cost function, function weights these parameters. This also provides a way to implement different policies by adjusting the corresponding weights of each parameter. **Q**, **R** matrices of Equation 4.4 must be positive definite or semidefinite and its values determinate the influence each term of the cost functions has in the minimization. A parameter must take small values when it has a high weight in order to reduce its influence in the minimization.

When the MPC controls the comfort parameters of a building, the weights relations can trade off the energy savings against maintaining the assigned value for the indoor temperature. Other aspects as the energy cost of different systems of the HVAC or even the CO_2 production associated to each system can also be considered.

Figure 4.11 provides a brief comparison of the MPC response in an office. *Power saving* configuration increases the values of matrix **R**, relative to the ones of matrix **Q** so that the power use increments the cost function value more than the temperature deviation from the setpoint. *Power saving* policies reduce the use of energy. *No discomfort* configuration penalizes the deviation from the set point more than the energy consumption. Comfort band, in black, represents the limits for the temperature. The design allows the control to transgress comfort limits for important energy savings.

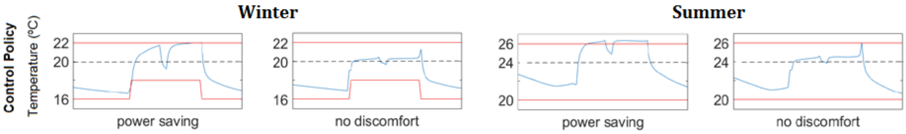

Figure 4.11. Influence of the weights in the cost function. Winter and summer responses for an energy saving and tracking setpoint policies. Figure also shows the comfort band temperatures for each season.

When considering different HVAC systems, which usually happen with TABS due to the need of ventilation, it is possible to penalize the use of one more than another by raising its weight in **R** matrix.

4.2.7 Horizon and time step length (variable horizon)

Definition of a correct prediction horizon is one of the factors that provide a successful implementation of an MPC in a building. Considering the slow dynamics of a building, slower when using TABS, it is necessary to expand the MPC calculus of predicted action in order to consider disturbance variances that can affect the system behaviour in a significant way. Typical values for prediction horizon can vary from 8 hour to 48 hours [19, 20]. Use of bigger prediction horizon will not carry any benefit to the control while the computational time is increased notoriously. Shorter horizon can provoke degradation in the control performance. Control must anticipate significant changes in the building activity as the work time begin and end in an office, significant temperature changes during the day, the thermal charge that constant human and building activity suppose. 48 hour horizon can be proposed when a prediction over the weekend is considered. The use of TABS and energy rate variable in time require a MPC horizon long enough to provide an appropriate response. MPC can also consider a time-variable predictive horizon. In this case, horizon length is consider another decision variable of the control

The time step between calculations may also be considered. Due to the slow building dynamics, it is not necessary to implement a fast time step. Literature studies normally propose values between 15 to 30 minutes. Bigger time step could distort the obtained results while shorter ones can require excessive computational resources if the prediction horizon is maintained. The time step must be long enough to allow the resolution of the minimization problem and to implement the control action during a representative time.

4.3 Summary

This Chapter has introduced Model Predictive Control (MPC) as the control of building climate system. A first part of the Chapter describes the MPC itself and then it continues studying the specific characteristics of the MPC when applied to building climate system. It defines how the building can be modelled, the minimization function, and the restrictions applied in buildings and the perturbations that affect the thermal behaviour: outdoor temperatures, solar irradiation and human activity. The weights of the parameters in the minimization function determine the policy that the control implements respect to the energy use.

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5.

Use of Model Predictive Control in aged buildings

English summary

By considering the energetic situation of Europe where a great percentage of the consumed energy is imported and the importance that the buildings use has in the consumption of that energy, the paper focused its study in a kind of building that abound in some neighbours of the European cities. Aged, low quality construction material residential blocks were developed in quick city expanse times, when energy savings were not a priority. The need for implement energy saving policies in building has been mainly focused in new construction building, laying aside this kind of old buildings. Need of energy savings consider rehabilitation techniques like insulation improvement or window change for this kind of aged buildings. The Chapter, studies the energy use reduction that

supposed the implementation of a model predictive control (MPC) respect the usually deployed *on-off* hysteresis control.

The simulation work is deployed under a real building RC model. The thermal behaviour of the original building, located in Otxarkoaga, Bilbao, was studied in order to know the effect of a future rehabilitation. The building was parametrized to a state-space representation that can be used under an MPC. A small description about the characteristics of an MPC is developed to understand the basics of the control taking into account the peculiarities of the building climatization sector. Results, similar to the ones provided in the original paper are presented in point 5.4. Section 5.4.1 describes the operation conditions of the heating system of one dwelling of the building under an MPC control. Section 5.4.2 studies the dependence of the system respect some MPC characteristic parameters as the time step, 5.4.2.1, or the weight relation, 5.4.2.2.

A comparison between two implementation of the MPC and two thermostatic controls is developed in point 5.4.3. Results show how the MPC simulations present better results than the hysteresis ones, reducing the consumption around 9 %. Simulation also shows how the MPC response varies with respect to its parameter and how when the MPC implements energy saving policy potential savings about 7 % appears.

Finally, the study shows in point 5.4.3.2 the benefits than an MPC can provide when implemented under a Time of Use (TOU) energy rate. Although no energy use reductions has been observed in the simulation, potential economic savings can reach to 19 % according with the results obtained.

5.

Model Predictive Control-aren erabilera eraikin zaharretan

Energia sektoreak gaur egun dituen joeren aurrean, gero eta gehiago dira energia politika eraginkorrak lortzeko ematen diren urratsak. Eraikinak, garraio eta industriarekin batera, energia erabiltzaile handienak dira gure gizartean. Horrela, Europan, kontsumitzen den energiaren erdia baino gehiago inportatzen da eta eraikinek energiaren %40a erabiltzen dute eta CO_2ko emisioen %36a sortzen dute. Egoera horri aurre egiteko, politika energetiko orokorrak sortzen eta inplementatzen ari dira. Horrela, eraikuntzarentzako diseinatutako material eta leihoen isolamenduak etengabeko hobetzen ari dira, berotze edo klimatizaziorako energiaren aurrezpena ahalbidetuz. Klimatizazio sistemen, berotze eta hozte ekipoen, eraginkortasuna handitu da. Energi berriztagarrien integrazioa edo kogenerazio moduko sistemek energiaren erabileraren hobekuntza suposatzen du, nahiz eta gaur egungo gure inguru hurbilenean hau inplementatzeko legedia egokiegia ez izan batzuen hustez. 3. Atalean ikusitako TABS-ek, energia aurrezpena ekartzeaz gain, eraikinaren inertzia termikoa erabiltzen dute gaueko energia merkeaz baliatzeko.

Hala ere, egungo hirietan oraindik ugariak dira kalitate eskaseko eraikuntza-materialekin eraikitako etxebizitza blokeak. Etxebizitza hauen kopurua kontutan hartuta, ikerketak egin dira hauen erantzun energetikoa zelan hobe daiteken aztertzeko. Leihoak aldatzea eta hormak isolatzea badira hartzen diren ekintza ohikoenak. Atal honetan, tipologia honetako etxe baten eredua hartuta, jokaera termikoa aztertuko da MPC baten gidaritzapean. Lortutako emaitzak, etxebizitzetan ohikoa den *on-off* termostatoarekin alderatzen dira MPCren erabilerak ekar ditzakeen hobekuntza energetikoak aztertzeko. Azterketa bibliografikoan ikusi da nola MPCa erabiliz egin diren ikerketa eta inplementazio gehienak zerbitzu-sektorearen eraikuntzetan gainean egin diren, eta etxebizitzetan egin direnean, kalitate hobeagoko eraikuntza berrietan egin diren.

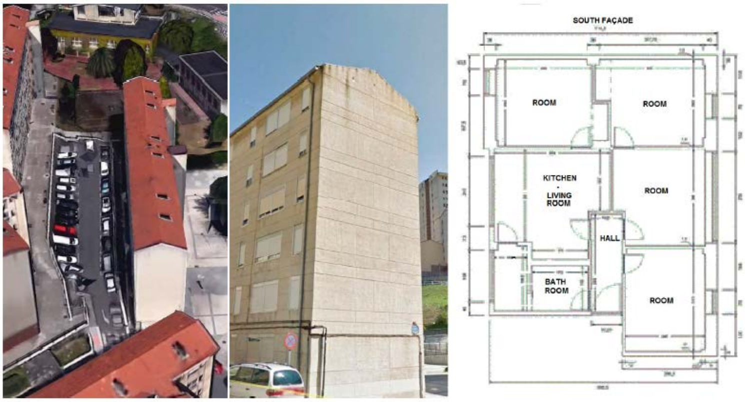
Hau horrela izanik, kapituluaren lehen atalean eraikinaren eraikuntza-ezaugarriak aztertuko dira. Bigarrenean, eraikinaren eredua lortzeko erabili den teknika esperimentala deskribatuko da. Ondoren, hirugarren atalean erabilitako MPCren ezaugarriak definituko dira. Azken atalean, simulazio bidez lorturiko emaitzak aztertuko dira.

5.1 Saiakuntza baldintzak

Ikerketarako aukeratutako etxebizitza, Otxarkoagan, Bilbon (43°15.5'N, 2°54'W) bloke sozial bateko etxebizitza bat da. Bilbok, Bizkaiko golkoaren hegoaldean kokatuta egonik, klima mesotermikoa du; tenperatura moderatua eta prezipitazio aldetik euritsua. Köppen-en sailkapenaren arabera, *Cfb* motakoa. Urtaro lehorrik gabeko klima epel hezea edo klima atlantikoa deitzen zaio ozeano Atlantikoak duen eragin nabarmenagatik. Gaueko eta eguneko tenperatura-bitarteak edota udako eta negukoak ez dira oso handiak. Hauek oso moderatuak dira itsasoaren eraginez, udak freskoak dira, nahiz eta batzuetan, tenperaturak 40 °C-tara heldu denbora tarte txikietan. Neguko tenperatura ere moderatua da eta urteko batez bestekoa 14.4 °C da. Urteko batez besteko prezipitazioa 1200 mm da eta itsasertzean egonik hezetasuna nabarmena da. Eguzki ordu dagokionez, eguzki ordu kopurua 1590 da, nahiz eta haietariko asko hodeitsuak dira. Udako solstizioan argitasunak 15 ordu inguru dauzka eta negukoan, berriz, 9.

Eraikina 60. hamarkadan eraiki zen ekialde-mendebalde kokapena du eta garai horietako eraikuntza motako adibide da. Hormigoizko egitura dauka, zutabeak fatxadan eta adreilu huts bikoitzak solairuen arteko itxituretan. Beranduago, adreilu huts sinpleko tabikea gehituz, fatxada bikoitzera aldatu zen isolamendu termikorik gabeko 2 zm huts ganbara utziaz.

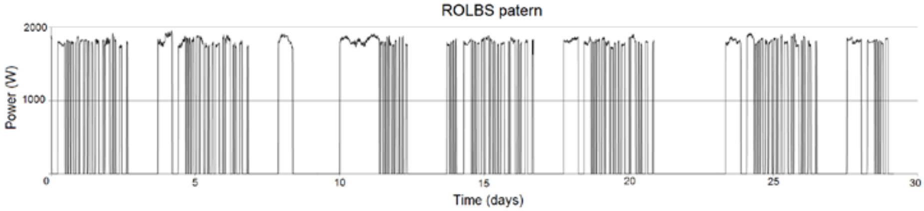
Etxebizitzak 50 m^2 ditu: hiru gela, egongela eta sukaldea. Bi leiho mota du. Ekialdekoek, sukaldekoek, zubi-termikoaren apurketarik gabeko aluminiozko markoa daukate. Besteek beira bikoitza dute, 6 mm aire ganbararekin. Adierazi bezala, materialen kalitatea eskasa da eta bero galerak handiak. 5.1 Irudian agertzen da eraikina eta horren planoa. Etxebizitzak berogailu sistema indibiduala dauka eta ez du hozte sistemarik.



5.1 Irudia. Ikertutako etxebizitzaren-eraikina Bilbon, 43°15.5'N, 2°54'W.

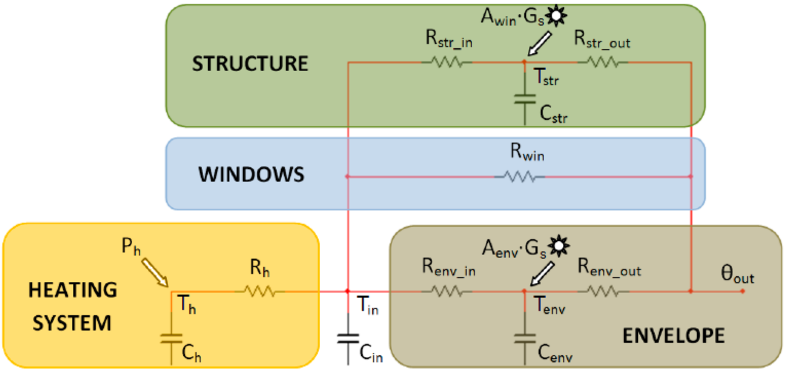
5.2 Ereduaren eraikuntza

Bilboko Etxebizitzak erakunde publikoak bere etxe multzoa sailkatzeko ikerketa bat agindu zuen tipologia desberdin definituz joera energetikoaren arabera. Sailkatu ondoren, joera energetikoa hobetzeko eta energia kontsumoa jaisteko hartu beharreko neurriak erabaki ziren. Ikerketaren oinarria, eraikuntza materialak ziren; material isolatzaileen erabilera edo leihoen aldaketa proposatzen zen. Proposatutako etxebizitza, 2012ko neguan modelizatu zen Garcia-Gafaro et al. deskribatutako prozedura jarraituz [1]. Eraikinaren portaera termikoa aztertzeko etxebizitza baten monitorizazioa egin zen hiru hilabetetan. Etxebizitza hutsik zegoela, hainbat geletan aire eta hormen gainazalaren tenperatura neurtu ziren, baita fatxadako bero galerak ere. Kanpoko tenperatura eta eguzki erradiazioa ere neurtu ziren denbora tarte horretan. Balioak minutuero hartu ziren eta batez bestekoa egin zen informazioa 10 minutuko denbora tarte batekin gordetzeko. Etxebizitzaren erantzun dinamikoaren analisia hobetzeko, bero sistema piztu zen 5.2 Irudian ikus daitekeen *Randomly Ordered Logarithmically distributed Binary Sequence* (ROLBS) [2] patroia jarraituz. Honek, sisteman agertzen diren barne eta etxebizitzarako kanpo eraginen efektuak banatzen ditu eta RC eredu grisa (*grey-box RC model*) egokia lortzea ahalbidetzen du.



5.2 Irudia. RC eredua lortzeko prozesuan barne eta kanpoko aldagaiak banatzeko erabilitako ROLBS patroia.

Behin neurketak eginda, etxebizitzaren joera termikoaren dinamika definituko duen RC eredua proposatzen da erresistentzia eta kapazitate termikoetan oinarrituta. Egindako monitorizazioaren balioak erabilita, ereduaren parametroak lortu dira Technical University of Denmark-en (DTU-n) garatutako *Continuous Time Stochastic Modelling package for R* (CTSM-R) gisako estatistika software erabilita. Parametro hauek kalkulatzeko *LOgical R-Determination* (LORD) [3] edo *GreyBox toolbox* [4] erabili daiteke. Erresistentzia eta kapazitate balioak lortuta, MPCan inplementa daitekeen *linear time invariant* (LTI) eredua garatzen da. Aztertu den kasurako, 4. mailako sistema bat proposatu da, non barne tenperatura, $\mathrm{T_{in}}$, gela guztien tenperaturaren batez bestekoa den. Etxebizitzarako proposatzen den ereduaren eskema 5.3 Irudian agertzen da. Lau elementu bidez karakterizatzen da sistema: egitura (str), leihoak (win), fatxada (env) eta berotze sistema (h). Eraikinaren elementuen tenperaturek definitzen dute sistema eta $\boldsymbol{k}$-une batentzako etxebizitzaren egoera definitzen dute: $\boldsymbol{x} = (\mathrm{T_{in}}\ \mathrm{T_{str}}\ \mathrm{T_{env}}\ \mathrm{T_h}\ )^{\mathrm{T}}$. Bero-sistemak, $\boldsymbol{u} = (\mathrm{P_h})$, etxebizitza girotzeko energia lortzen du eta aplikatuko den kontrol termikoaren eragilea izango da. Etxebizitzaren gainean eragiten duten perturbazioak $\boldsymbol{v} = (\mathrm{T_{out}}\ \ \mathrm{A_{win}G_s}\ \ \mathrm{A_{env}G_s})^{\mathrm{T}}$ kanpoko tenperatura, $\mathrm{T_{out}}$, eta eguzkiaren erradiazioa, $\mathrm{G_s}$, dira. Azken honen eragina leihoetan eta fatxadan $\mathrm{A_{win}G_s}$ eta $\mathrm{A_{env}G_s}$ gaien bidez ebaluatzen da, $\mathrm{A_{win}}$ eta $\mathrm{A_{env}}$ leihoen eta fatxadaren azalerak izanik.



5.3 Irudia. Etxebizitza karakterizatzeko erabilitako 4. mailako RC eredua.

Ts denbora tarterako diskretizatu ondoren, etxebizitza definitzen duen LTI eredua 5.1 Ekuazioaren bidez zehazten da egoera-espazioan:

$$\begin{gathered}\boldsymbol{x}_{k+1} = \mathbf{A}\boldsymbol{x}_k + \mathbf{B}_u\boldsymbol{u}_k\ + \mathbf{B}_v\boldsymbol{v}_k \\ \boldsymbol{y}_k = \mathbf{C}\boldsymbol{x}_k + \mathbf{D}_u\boldsymbol{u}_k\ + \mathbf{D}_v\boldsymbol{v}_k\end{gathered} \tag{5.1}$$

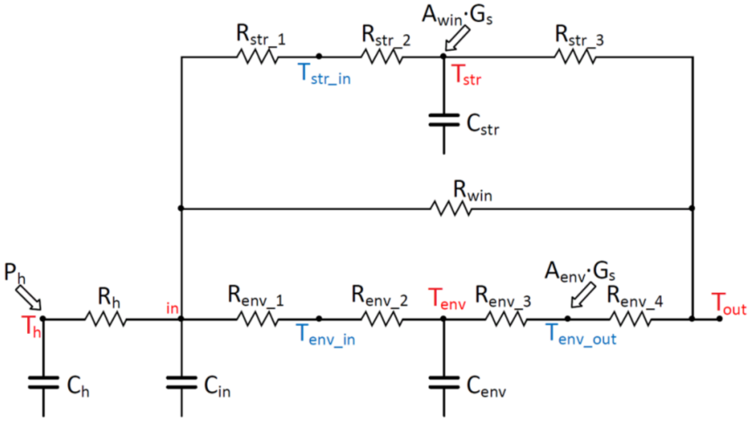
non matrizeek 4. kapituluan adierazitako nomenklatura jarraitzen duten.

Gogoratu behar da, $\boldsymbol{i}$-elementu batentzako horren egoera $\boldsymbol{k}$-unean ondoko adierazpen bidez definitzen dela:

$$C_i \mathrm{T}_i = \sum_j \frac{\mathrm{T}_j - \mathrm{T}_i}{R_{ij}} + \sum_l P_{il} \tag{5.2}$$

non T_i, $\boldsymbol{i}$-elementuaren tenperatura den $\boldsymbol{k}$-unean eta C_i elementu horri loturiko kapazitate termikoa. T_j, $\boldsymbol{i}$-elementuaren inguruan dauden $\boldsymbol{j}$-elementuen tenperaturak dira eta R_{ij}, $\boldsymbol{j}$ eta $\boldsymbol{i}$-elementuen artean dagoen erresistentzia termikoa da. P_{il}, $\boldsymbol{i}$-elementuaren gainean eragiten duten bero iturriak dira.

Adierazgarriak diren eragin fisikoak kontutan hartuz 4. mailako RC eredua definitu ondoren, eredua karakterizatu behar da erresistentzia eta kondentsadoreei balioak esleituz. Kasu honetan, eredua eta esperimentalki lorturiko balioak izango dira CTSM-R softwarearen informazio sarrerak. Hau egiteko, eredua matematikoki definitzen da 5.4 Irudiko eskema jarraituz. Horrela, fatxadaren tenperatura hainbat puntutan neurtutako kanpo eta barne tenperaturaren batez bestekoa eginik lortzen da. Ereduan, elementu hau bi erresistentzia eta kapazitate baten bidez adierazten da. Eraikinaren egitura eta barne hormak ere horrela definituko dira. Etxebizitza barneko airearen tenperatura gela desberdinen batez bestekoa da. Balio esperimentalak hartzean, gelen artean tenperatura aldeak ez zuen 1 °C gainditzen. Leihoak erresistentzia giza modelizatzen dira, kapazitate termikorik gabe. Eredurako proposatutako adierazpen zehatza 5.4 Irudian agertzen da.



5.4 Irudia. Parametroak antzemateko erabilitako topologia.

R_h barneko airearen eta berotze sistemaren arteko erresistentzia termikoa da. R_{env_2} eta R_{env_3} fatxadari lotutako erresistentziak dira, R_{env_1} eta R_{env_4} fatxadaren eta airearen artean agertzen diren erresistentzia termikoa dira, barneko eta kanpoko kasuentzat. Horien balioa, konbekzioarekin eta erradiazioarekin loturik egongo da. Egiturarentzat, antzeko notazioa erabili da; R_{str_1} airearen eta barneko hormen artean agertzen den erresistentzia da, eta R_{str_2}-k eta R_{str_3}-k egituraren eta barneko hormen erresistentzia termikoa karakterizatzen dute. R_{win} leihoen erresistentzia termikoa definitzen du. C_h, C_{in}, C_{env} eta C_{str} dagokien elementuei loturiko kapazitate termikoak dira. Behin parametro horien balioak zehaztuta, etxebizitzaren portaera dinamikoa definituta geratzen da. Parametroak lortzeko, T_h, T_{in} eta T_{out} balio esperimentalak erabiltzen dira. T_{str_in}, T_{env_in} eta T_{env_out} gainazalen tenperaturak dira eta esperimentalki ere lortu dira. Bukatzeko, parametroen kalkulurako eguzki erradiazioaren datuak, $A_{env}G_s$ eta $A_{env}G_s$, eta ROLBS seinalearen P_h berotze sistemaren potentziaren datuak ere erabili dira.

CTSM-R-ak osagai estokastikoak erabiltzen ditu antzemate prozesuaren doitasuna handitzeko. Osagai horien funtzioa, neurketa prozesuan egon daitezkeen akatsak antzemate prozesuan barneratzen da. Osagai estokastikoak sartuta, hauxe da sistema jarraituentzat antzemate prozesurako erabilitako egoeren espazio adierazpena hauxe da sistema jarraituarentzat

$$\begin{aligned} \dot{\boldsymbol{x}} &= \mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{u} + \boldsymbol{\sigma} d\omega \\ \boldsymbol{y} &= \mathbf{C}\boldsymbol{x} + \mathbf{D}\boldsymbol{u} + \boldsymbol{\sigma} e \end{aligned} \tag{5.3}$$

non matrizeek ohiko adierazpena duten. Kasu honetan kanpo-eragin guztiak ezagunak direnez, $\boldsymbol{u}$ bektorean batu dira. ω-k Weiner prozesu estandarra adierazten du eta e gehitutako zarata zuria da.

CTSM-Rren eredu matematiko honako erreferentzia hauetan deskribatzen da [5, 6, 7], non parametroak lortzeko eta egiaztatzeko erabiltzen diren tresneria estatistikoa azaltzen den. Antzemate prozesuarekin erlazionatutako parametroak [1]-ean lor daitezke. Parametroak lortu ondoren, sistemak 5.1 Ekuazioaren eta 5.3 Irudiaren itxura har dezan berridatzi da. Parametroak lortu ondoren eredua TRNSYSekin egiaztatu da, berau balioztatuz.

5.3 MPCren aplikazioa

Dokumentu honen 4. Atalean MPCri buruzko azterketa egin da. Atal honetan, berriz, kontrolaren aplikazioa aztertzen da etxebizitza baten berotze sisteman. 5.1 Ekuazioan sistemaren dinamika egoeren espazioan definitu da RC eredua erabiliz. Eguraldiaren aurreikuspena izanda beste eraginik kontutan hartu gabe, posible da MPCa inplementatzea etxebizitzaren ongizate termikoa kontrolatzeko; kasu honetan neguko barne tenperaturaren kontrola. Hau gauzatzeko, kontrolak berotze ekipoaren gainean eragiten du.

Kontrolaren ekintza diseinatzean, kostu funtzioa definitu behar da sistemarentzako: parametroak doituz, sistemak izango duen portaera zehaztu daiteke. Eraikinen ongizate kontrolean bi dira normalean lehian agertzen diren parametroak: alde batetik, ongizate termiko bera eta, beste aldetik, hori lortzeko erabili behar den energia edo horren kostua. Tenperatura eta beste parametroak erreferentziarekin erabat doitzea kostu handiegia suposa daiteke. Erabilitako energia larregi murrizteak, berriz, erabiltzaileen ezerosotasuna ekar dezake. Minimizazio funtzioan ponderatu behar dira parametro hauekin loturik dauden pisuak etxebizitzaren erantzun termikoa nahi den bezalakoa izan dadin.

Lehen ikusitako minimizazio funtzioak honela egokitu daitezke etxebizitza baten kasurako

$$\min_{u_0 \ldots u_{\mathrm{N}_p-1}} \sum_{k=0}^{\mathrm{N_p}-1} \left((\omega - \boldsymbol{y})_k^{\mathrm{T}} \mathbf{Q} (\omega - \boldsymbol{y})_k + u_k^{\mathrm{T}} \mathbf{R} u_k + \varepsilon_k^{\mathrm{T}} \mathbf{S} \varepsilon_k \right) \tag{5.4}$$

honako murrizketekin

$$0 < u < \mathrm{MaxPower} \tag{5.5}$$

$$\mathrm{T}_{\mathrm{min},k} - \varepsilon_k < \theta_{in,k} < \mathrm{T}_{\mathrm{max},k} + \varepsilon_k \tag{5.6}$$

5.5 Ekuazioak berotze sistemaren mugak ezartzen ditu, 5.6 Ekuazioak, berriz, ongizate termikoaren limiteak definitzen ditu. ε_k osagaia definitzen da minimizazio prozesuan tenperaturek definitzen duten ongizate banda lausotzeko eta, beharrezkoa denean, gainditu ahal izateko. Minimizazioan agertzen diren parametroak: tenperatura erreferentzia, pisuak eta murrizketak, denboran aldakorrak izan daitezke. Hau da predikzio horizontea ebaluatzen den bitartean haien balioa alda daitekeela suposatuko da. Minimizazioa askatzeko hainbat aukera daude. MatLab/Simulink ohiko hautaketa izan daiteke, nahiz eta, batzuetan CPLEX, GUROBI edo MOSEK, akademiarako doan dira hirurok, interesgarriagoak diren.

5.4 Emaitzak

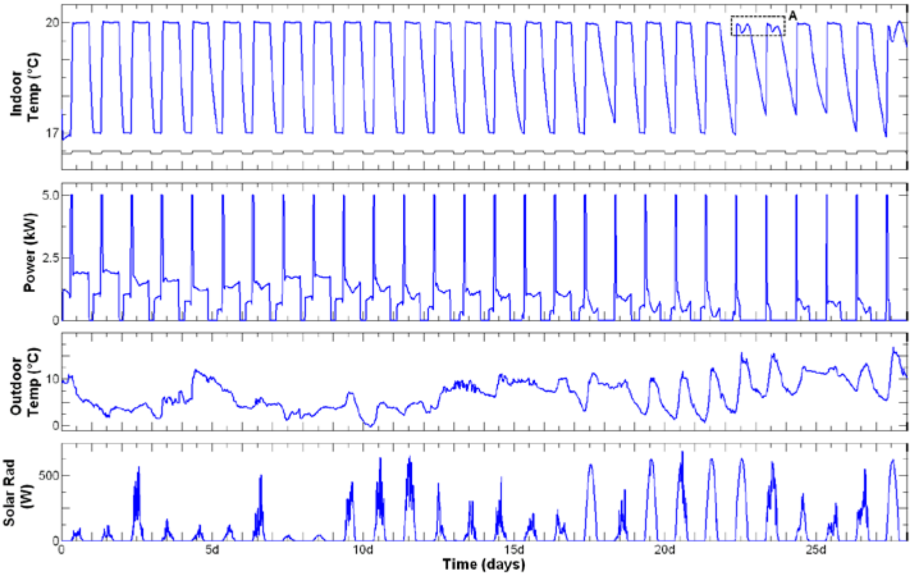
Etxebizitzak MPC kontrolpean duen portaera aztertzen da puntu honetan. Horretarako, 2012ko otsailean lortutako eguraldiaren informazioa erabili da, sistemaren perturbazio giza. Saiakuntzako balio horiek kanpoko tenperatura eta eguzki erradiazioa izan dira. Egin diren simulazioek, MPCak aurkeztutako eraikuntza-tipologiengan ekar ditzakeen abantailak aztertzen dira. Horretarako, MPCak etxebizitzaren tenperatura nola kontrola dezakeen aztertu da erreferentzia-tenperatura jakin bat jarraitzeko aginduz. Ondoren, parametro desberdinek kontrolean duten eragina aztertu da: horizonteen arteko erlazioak kontrolean duen eragina, pisuen arteko erlazioak kontsumoan duen eragina, iterazioen arteko denborak, denbora urratsak, eta kontrolean duen eragina. Ondoren, MPCak, kontrol termostatikoaren aurrean ekar ditzaken abantailak aztertzen da. Bukatzeko, denboraz diskriminatutako tarifazio baten aurrean MPCak dakartzan aurrezpen ekonomikoak aurkezten dira.

5.4.1 MPCaren portaera

Egindako den lehen azterketan, MPCak deskribatutako etxebizitzaren tenperatura kontrolatzeko gaitasuna aztertzen da. Honako ezaugarri nagusi hauek ditu etxebizitzaren ereduak: 50 m^2-ko planta, isolamendu berezirik gabe eta inertzia termiko baxua. Klimatizazio sistema 5 kW-ekoa da, berotze-ahalmena besterik ez duena. Aireztatze ahalmenik ez dago. Eredua era esperimentalez lortu da; beraz, ereduak, infiltrazioak eta beste galerak barneratzen ditu. Eguraldi-datuak, tenperatura eta eguzki erradiazioa, eredua definitzeko datuekin batera jaso dira eta etxebizitzan bertan, 2012-ko otsailean.

Azterketa honetarako, berotze ekipamenduari dagozkion bero kargak baino ez dira kontutan hartu, gizakiaren eta altzairuen eragina baztertuz. Tenperatura, orduaren arabera diskriminatzen da 5.1 Taulan agertzen den bezala. Egunez, tenperaturak 20 °C-koa izan behar du eta gauez 17 °C-taraino jaitsi daiteke. 2 °C-tako ongizate banda definitzen da balio hauen inguruan egunerako eta 1 °C-takoa gaberako. Asteburuetan, tenperatura konfigurazioa mantentzen da. MPCaren diseinuak, balizko energia aurrezpenaren minimizazioa lehenesten du proposaturiko erreferentzia-tenperaturaren jarraipena baino $\mathbf{R} \gg \mathbf{Q}$ eginez. Kontrolak erreferentzia-jarraipen politika lehenetsi nahi badu du, kostu-funtzioan, 5.4 Ekuazioan, $\mathbf{Q} \gg \mathbf{R}$ egingo du. Horrela, kontrolak proposatutako tenperaturak estuki jarraitu behar ditu.

20 ordutako predikzio horizontea aukeratu da kontrolarentzako: sistemak duen inertzia termikoa txikia denez, erantzuna aztertzeko behar besteko aurrerapena eskaintzen duelako. Hozketa-sistema falta denez, gauez gertatzen den bero galera era naturalean gertatzen da. Horrek ez du arazo berezirik sortzen, gauez beroa mantendu nahi delako, tenperatura 17 °C-z gainetik mantenduz. 5.5 Irudian, barne-tenperaturaren eboluzioa ikusten da, baita sisteman eragiten duten perturbazioak eta berotze sistemaren kontrol ekintza ere.



5.5 Irudia. Ereduan aplikatutako MPCaren erantzuna, Indoor Temp. Ereduan eragiten duten faktoreak: beroketa-sistemaren erantzuna, $\boldsymbol{u}$, kanpoko tenperatura eta eguzki erradiazioa. Irudiaren lerro beltzak, 20 eta 17 °C artean dagoen tenperatura erreferentzia aldaketa adierazten du.

5.1 Taula. Ongizate tenperatura eta ongizate termikoaren banda orduaren arabera.

Ordu tartea	Tenperatura (°C)	Ongizate banda (°C)
08:00 - 22:00	20	2
22:00 – 08:00	17	1

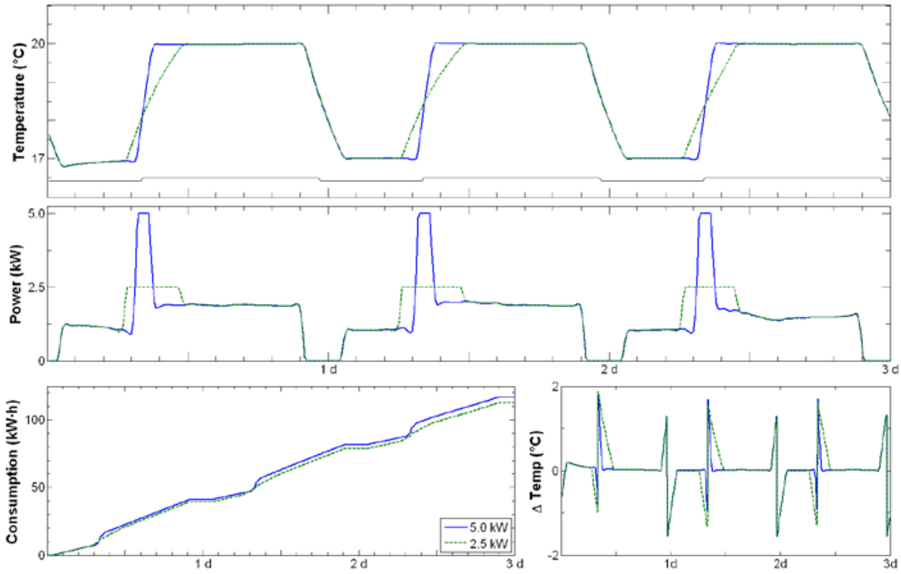
Kontrolak eskatutako joera jarraitzen du. 5.5 Irudian ikus daitekeenez, tenperaturak estuki jarraitzen duela agindutako erreferentzia, sisteman eragiten duten kanpoko tenperatura eta eguzki erradiazioa kontutan izanik. Tenperatura ongizate baldintzetara bideratzeko, berotze-sistemak potentzia osoa erabiltzen du goizeko lehen orduetan tenperatura ongizate ezarpenetara eramateko eta horren ostean, potentzia jaisten da tenperatura mantenduz. Hilabetearen bigarren zatian, eguzki erradiazioaren eta kanpo-tenperaturaren igoerek, behin erreferentzia lortuta, berotze-sistemaren beharra nabarmen gutxitzen da. Kontrolaren aurreikuspen-efektua 5.5 Irudiaren **A** laukian ikusten da: tenperatura igoeraren eta eguzki erradiazio handitzearen aurreikuspena kontutan hartuta, beroketa-sistema itzaltzen da. Horrek tenperatura jaitsiera dakar, beti ere ongizate banda barruan. Kanpo-tenperaturaren eta eguzki erradiazioaren eraginak handitzen direnean, tenperatura era naturalean heltzen da eskatutako erreferentziara. Bero-sistema itzali ezean, denbora tarte batean barne-tenperatura 20 °C-tan mantendu ahal izango litzateke, baina ondoren tenperaturak erreferentziazkoa gaindituko luke alferrikako energia-gastua sortuz. Tenperatura ongizate mugetatik kanpo eramateko arriskua egongo litzateke.

5.5 Irudiko hiru egunetako zoom bat agertzen da 5.6 Irudian. Bertan kontrolaren ekintza prediktiboa berriro argi agertzen da. Kontrolaren ekintza 5 kW eta 2.5 kW beroketa-sistementzat simulatu da. Kontrolaren ekintza erabat dator eskatutako erreferentziarekin beroketa-sistemen mugak kontutan hartuz.

Irudian oso argi agertzen da kontrolaren ekintzak nola aurre hartzen dion erreferentzia aldaketari, lerro beltza: erreferentzia aldaketa baino lehen tenperatura hasten da igotzen MPCren predikzio-ahalmenari esker, goizeko 08:00-tan tenperatura ongizate mugen barnean egonda. Antzeko zerbait gertatzen da gauez: erreferentzia-tenperaturaren aldaketa baino lehen itzaltzen da beroketa sistema nahiz eta tenperatura ongizate banda barnean mantentzen den. Bi potentzientzako betetzen dira azaldutako jokaerak, nahiz eta efektua argiagoa ikusten den 2.5 kW-ekoarentzat. Kontsumoa pixka bat altuagoa da beroketa sistemaren potentzia handitzen denean, nahiz eta sistemaren erantzuna arinagoa izan eta denbora gutxiago ematen duen erreferentziatik urrun. Azken irudiak erreferentziarekiko desbiderapenak azaltzen ditu. Ikusten denez, hauek erreferentzia aldaketan gertatzen dira eta barne tenperatura inoiz ez dago ongizate bandatatik kanpo.

5.4.2 MPCaren parametroak

Atal honetan, MPCaren konfigurazioan parte hartzen diren hainbat parametro aztertuko dira. Aztertuko den lehen parametroa denbora-urratsa edo *time step* izango da. Ondoren pisuen erlazio desberdinek ekartzen dituzten ondorioak aztertuko dira.

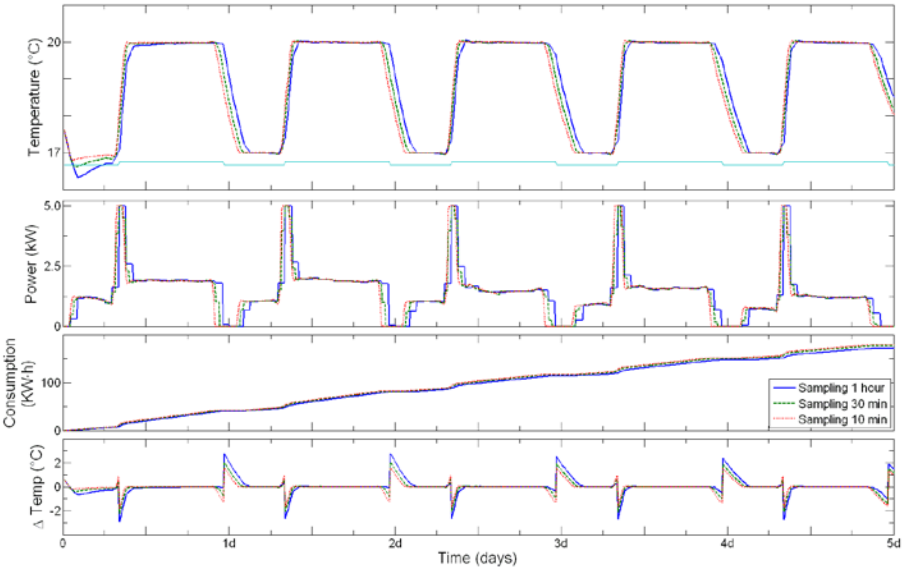


5.6 Irudia. Tenperaturaren eboluzioaren hiru egunetako zooma, non MPCaren efektu prediktiboa argi agertzen den. Barne tenperatura, bero-potentziaren ekintza, energia kontsumoa eta erreferentziarekiko desbiderapena agertzen da. Lerro grisak erreferentzien arteko aldaketak adierazten ditu.

5.4.2.1 Denbora-urratsaren eragina

MPC eraikin baten eredu diskretuaren gainean garatzen eta aplikatzen da 4. Atalean ikusi den bezala. Eraikinen dinamikak denbora konstante handia dutela esan daiteke. Horren ondorioz, eredu gainean eragingo duten eraginen laginketa eta ekintzaren kalkulua denboran zabal daiteke. Honek garrantzi handia izango du jakinda predikzio-horizontea kasu batzuetan bi egun baino gehiago heda daitekeela.

5.4 Ekuazioan ikusi da minimizaziorako erabili behar diren matrizeak nola hedatzen diren. Ereduak egoera kopuru handia izanez gero, denbora-urratsak kontrolaren bideragarritasuna baldintza dezake, behar diren konputazio ahaleginak direla eta. 5.7. Irudiak etxebizitzaren barne-tenperaturaren eboluzioa erakusten du hiru denbora-urrats desberdinentzako: Simulazioaren predikzio-horizontea hogei ordutakoa da eta denbora-urratsak 10 minutu, 30 minutu eta ordu betekoak. Argi ikusten denez denbora-urratsa 30 minuturaino luzatuz, kontrolak sistema ongizate baldintzen barnean mantentzen du. Hortik aurrera kontrolak ez du beraren lana ondo betetzen eta tenperatura ongizate parametrotik kanpo eramaten du. Konpromiso bilatu behar da konputazio lanak suposatzen esfortzua eta kontrolaren zehaztasun artean, MPCaren denbora-urratsaren ohiko balioak 10 eta 30 minutu artean egonik eraikinetan erabiltzen denean. Hala ere, bibliografiako hainbat lanek balio hori ordu betera luzatzen dute [8]. Hauetan ikertzen diren eraikinek eraikuntza-material kalitate hobeagokoak dituela ikusita, eraikuntzaren denbora konstantea kontutan hartu behar dela denbora-urratsa kalkulatzerakoan ondoriozta daiteke.



5.7. Irudia. Sistemaren eboluzioa sistemaren denbora-urratsak ordu bete, 30 minutu eta 10 minutu direnean. Berotze sistemaren jokaera, kontsumitutako energia eta erreferentziarekiko barne tenperaturak duen desbiderapena ere agertzen dira. Tenperaturaren erreferentzia aldaketa lerro grisaren bidez adierazita dago.

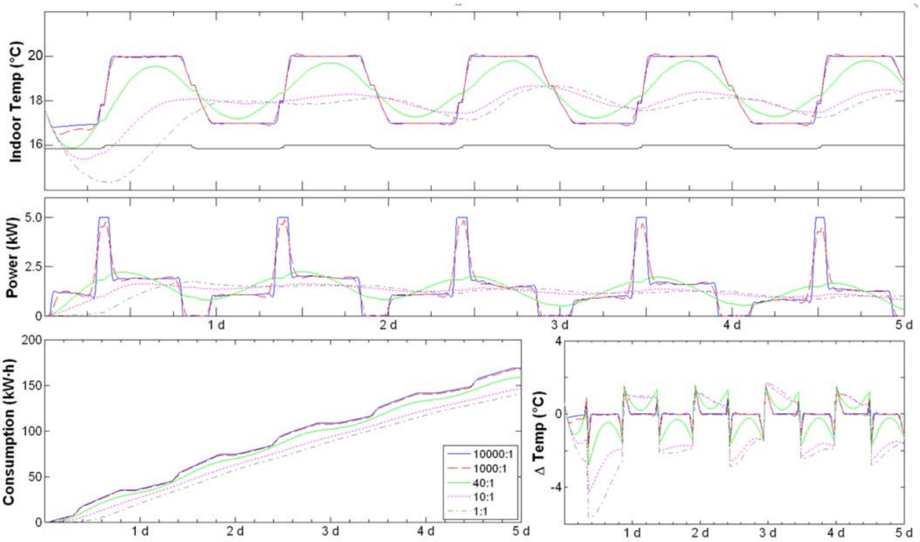
5.4.2.2 Pisuen arteko erlazioa

Bukatzeko, kostu funtzioan agertzen diren pisuen erlazio aldaketa kontrolean zer eragina duen ikusiko da. Orain arte erabilitako ereduaren gainean inplementatuko da MPCa. Erreferentziarekiko desbiderapena eta kontrol ekintza, energia gastua, ekuazio 5.4-an egokitzen dira pisu matrizeen bidez kontrolak nahi den klimatizazio politika gara dezan. **Q** pisua **R**rekiko handitzean, honekin loturik dagoen erreferentzia-tenperaturarekiko desbiderapena garrantzi handiago izango du minimizazioan, eta horren balioa txikiagotzeko joera areagotuko da. **Q** eta **R** positiboki definituta edo erdidefinituta izan behar dira minimizazioan askatu behar den problema QP izan dadin. Bi matrizeen arteko erlazioa finkatzerakoan, minimizatzen diren aldagaien unitateen proportzioa ere kontutan hartu beharko da. Aztertzen den kasuan **Q**-k °C gutxi batzuk ponderatuko ditu, **R**-k 0-tik 5000 W-raino doan potentzia ponderatzen duen bitartean. Simulazioaren emaitzak 5.2 Taulan agertzen dira, non aukeratutako pisuen erlazioarekin batera, erlazio bakoitzarentzat dagokion energia gastua eta ongizate termikoa adierazten den.

5.2 Taula. Energia kontsumoa eta ongizate eza hilabete batean pisu hainbat erlazioentzat **Q** eta **R**, minimizazio funtzioaren pisuak dira.

Pisuen erlazioa Q:R	Energia gastua (kW·h)	Ongizate ezaren orduak (hK)
10,000:1	636.68	0
1000:1	623.91	0
40:1	584.85	0
10:1	547.62	20.12
1:1	542.68	61.32

Nabaria da erlazio desberdinen artean agertzen den aldea. 10,000:1 eta 1000:1 erlazioetan, kontrolak erreferentzia era zehatzen jarraiarazten dio barne tenperatura, nahiz eta honek energia kontsumo handitzeak suposatzen duen. Kontrolak desbiderapena handiagoak onar ditzake energia kontsumoa jaitsiz. 40:1 erlazioarekin, sistema ongizate mugen barnean mantentzen da, nahiz eta erreferentzia zuzenean ez jarraitu. Kasu honetan, **Q**-ri dagokion gaiaren eragina galdu egin da eta kontrolak energia kontsumoa gutxitzeko minimizatzen du kostu funtzioa. Hasierako erlazioarekin alderatuta %8.5-eko beherapena suposatzen du kontsumoan, zeina oso adierazgarria da eraikinen arloan. 5.8 Irudiak era grafikoan adierazten du sistemaren eboluzioa. **Q** eta **R**-ren arteko erlazioa gehiago txikitzen bada, kontrolak ezin du ziurtatu ongizate termikoa. Energia aurrezpenak nabarmenak dira, baina kontrolak ez ditu muga baldintzak errespetatzen eta tenperatura ongizate bandatik kanpo ateratzen da.



5.8 Irudia. Barne tenperaturaren eboluzioa pisu erlazio desberdinentzat. Berotze sistemaren erabilera, kontsumitutako energia eta erreferentziarekiko desbiderapena ere agertzen dira.

Analisia errazteko, ongizate termiko eza definitzeko erabiliko den unitatea Kelvin ordua (Kh) izango da. Zein horrela defini daiteke: ongizate bandatik kanpo agertzen den tenperatura-desbiderapenaren denborarekiko integrazioa. Ongizate termiko ezaren balioaren ebaluazioa sistema diskretuentzako, ongizate bandatik kanpo agertzen den tenperatura-desbiderapenaren balioa bider sistema diskretuaren denbora-urratsa, Ts; hau, denbora-urrats guztientzako batuta. Hau da:

$$\mathrm{Kh} = \sum_i \left|\Delta T_{dev,i} Ts_i\right| \qquad i \in \{\text{occupation period}\} \tag{5.7}$$

non ΔT_{dev} ongizate bandarekiko agertzen den tenperatura-desbiderapena den.

5.4.3 Erabileraren adibideak

MPCaren ezaugarri adierazgarri batzuk aztertu ondoren, puntu honetan horren erabileraren bi adibide praktiko aztertuko dira. Lehenengo eta behin, MPCren erantzuna etxeetan sarritan erabiltzen den *on-off* kontrol termostatikoarekin alderatuko da. Bigarren ikerketa batean, MPCren erantzuna aztertuko da energia tarifa aldakor baten aurrean. Portaera honek garrantzi handia du bero iturri elektrikoak eta bero punpa elektrikoen erabilera ohikoa baita.

5.4.3.1 MPC vs kontrol termostatikoa

Etxebizitzetan, kontrol termostatikoa da gaur egun erabiliena, nahiz eta PID moduko inplementazioak ere egon daitezkeen. Kontrol termostatikoa, histeresi ziklo batean funtzionatzen duen *on-off* kontrola da. Histeresi banda, erreferentzia-tenperatura inguruan jartzen da eta sistema piztu eta itzaltzen da barne tenperatura bandaren mugak gainditzen dituenean: beroketa sistema pizten da tenperatura diseinuzko balio batetik jaisten denean eta ez da itzaliko histeresi-bandarako definituta dagoen goi tenperatura gainditu arte. Kontrol honen helburu bakarra tenperatura ongizate mugen barnean mantentzea da. Kontrolak ez du aurrezpen politikarik inplementatzen eta ez ditu kontutan hartzen eraikinaren dinamika ezta horren gainean etorkizunean egongo diren eraginak. Kontrol honen inplementazioa erraza da eta beraren forma sinpleenean, termostatoa baino ez du behar. Saiakera egiteko bi kontrol termostatiko definituko dira. Lehenak, erreferentzia-tenperatura estuki jarraituko du eta histeresi bandak 0.1 °C-ko zabalera izango du erreferentzia inguruan gau eta egunez. hys_HARD moduan definituko da erreferentzia jarraitzeko duen joeragatik. Kontrol honen inplementazioa ez da gauzatzen errealitatean histeresiak sortzen dituen etengabeko pizte-itzaltze dinamikagatik, baina baliagarria izango da konparaketa egiteko. Bigarren histeresi kontrola definituko da banda zabalago batekin. Kasu honetan, histeresi banda eta ongizate banda definizio bera izango dute. Erreferentzia balioaren inguruan 2 °C-ko desbiderapena onartuko da egunez eta 1 °C-koa gauez. 5.3 Taulan bi kontrolen definizioa agertzen dira

5.3 Taula. Histeresi-bandaren definizioa kontrol termostatikoan.

Histeresia	**Egunez**		**Gauez**	
	Goi-limitea	**Behe-limitea**	**Goi-limitea**	**Lower Limit**
hys_HARD	$T_{ref} + 0.1$ °C	$T_{ref} - 0.1$ °C	$T_{ref} + 0.1$ °C	$T_{ref} - 0.1$ °C
hys_SOFT	$T_{ref} + 2$ °C	$T_{ref} - 2$ °C	$T_{ref} + 1$ °C	$T_{ref} - 1$ °C

T_{ref} 20 °C-koa da egunez eta 17 °C-koa gauez.

Bi MPC alderatuko dira proposaturiko kontrol termostatikoarekin alderatzeko. Kontrolaren beste parametro berdinak mantenduz, minimizazio funtzioaren **Q**: **R** pisuen erlazioa aldatuko da kontrolak hainbat joera azal ditzan. 5.8 Irudian ikusita jarraituz, erreferentzia estuki jarraitzen duen MPC_HARD definituko da alde batetik eta bestetik, erlazioa gutxituz, energia erabilera gutxitzeko helburuarekin diseinatutako MPC_SOFT. Kasu honetan, kontrolak erreferentziatik urruntzeko eta ongizate bandan eboluzionatzeko askatasun handiagoa izango du tenperaturak. Erabilitako pisuen balioak 5.4 Taulan definituta daude.

5.4 Taula. MPC_HARD eta MPC_SOFT-entzat erabilitako pisuen balioak.

MPC	**$(\omega - \theta_{in})$**-rentzako pisua, **Q (1/K²)**	*u*-rentzako pisua, **R (1/W²)**
MPC_HARD	10,000	1
MPC_SOFT	40	1

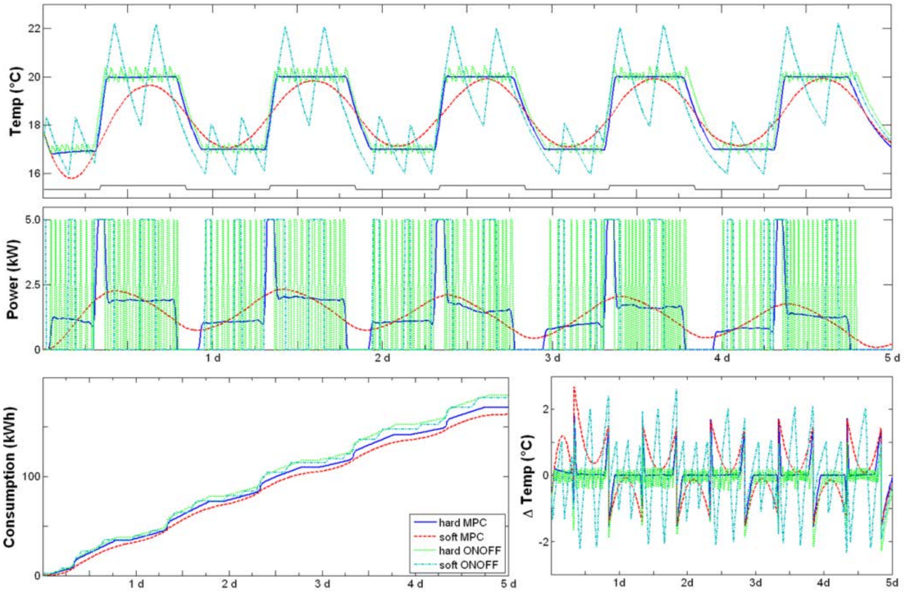
Q eta **R,** kostu funtzioan kontrola definitzeko erabilitako pisuak dira $(\omega\text{-}\theta_{in})$-rentzat, erreferentzia-tenperaturarekiko desbiderapenarentzat, *u*-rentzat, erabilitako energiarentzat.

Lau kontrolek tenperatura ongizate banda barnean mantentzen dute. Histeresi kontrolen kasuan, hau ziurtatzeko, erreferentzia aurreratzen da. 5.5 Taulan hilabete osorako lorturiko kontsumo datuak ikus daitezke, non MPCak erantzun hobea aurkezten duen.

5.5 Taula. Kontrol desberdinentzat otsailean erabilitako energia.

Kontrola	**Energiaren erabilera (kW·h)**
hys_HARD	700
hys_SOFT	692.12
MPC_HARD	639.07
MPC_SOFT	596.32

Energia kontsumo diferentzia nabarmena da. HARD kontrolak elkarren artean alderatzen baditugu, MPCak kontsumoa %9 jaisten du. Kontrolari ongizate bandan eboluzionatzeko askatasun handiago ematen badiogu, SOFT kontrola, hobekuntza %15-eraino igotzen da. Energia aurrezpen hauek, oso esanguratsuak dira eraikuntza arloan eta bat datoz bibliografiak erakusten dituen datuekin. Aurreko kasuan bezala, MPCren erantzuna aztertzen bada, SOFT kontrolaren energia erabilera gutxitzen duela ikus daiteke. 5.9 Irudiak lau kontrolen denborarekiko eboluzioa aurkezten du. Irudi honetan beste efektu nabargarria agertzen da; SOFT kontrolak berotze potentzia era uniformeagoan erabiltzen du. Berotze-ekipoak eten gabe lan egiten du kaltegarriak izan daitezkeen pizte-itzaltze beharrik gabe. Honetaz gain, kontrolaren diseinu-eskakizunak betetzeko ekipoak eman behar duen potentzia maximoa nabarmen gutxitzen da kasu honetan. Azkenik, 5.2 Taula eta 5.5 Taularen artean agertzen den kontsumo diferentzia predikzio-horizontearen luzerarekin loturik dago. Lehen kasuan 20 ordutako horizontea hartu da, bigarrenean hau 17 ordutara jaitsi den bitartean. Bi kasuetan tenperaturaren eboluzioa antzekoa da baina horizontea handitzean kontsumoaren hobekuntza ikus daiteke.



5.9 Irudia. MPC eta histeresi kontrolen arteko 5 egunetako alderaketa. Barne tenperatura, potentzia erabilera, metatutako energia kontsumoa eta erreferentziarekiko tenperatura-desbiderapena. Lerro grisak erreferentzia aldaketak adierazten ditu.

5.4.3.2 Faktore ekonomikoak

Azterketa bukatzeko, MPCren erabilerak eraikinetan izan dezakeen inpaktu ekonomikoa aztertzen da. Ezaguna da energia kontsumoak egunean zehar duen eboluzioa: momentu zehatz batzuetan kontsumo gailurrak agertzen da, beste batzuetan askoz baxuago mantentzen den bitartean. Horrek arazoak sor ditzake sareetan eta horren efektua lausotzeko ahaleginak egiten dira. Kontsumoa eraginkorrago izan dadin eta horren gailurrak txikitzeko asmoz, energia elektrikoa erabiltzen den orduarekin loturiko tarifak daude merkatuan, *Time of Use* (TOU) tarifak, non energia merkeago eskaintzen den erabilera txikiko orduetan. 5.6 Taulak, tarifa aldakorrarekin egingo den azterketan erabiliko diren TOU tarifa eta tarifa ez diskriminatzailea erakusten ditu.

5.6 Taula. Ikerketan erabiltzen diren indarrean dauden tarifa elektrikoak: TOU eta tarifa ez diskriminatzailea.

TOU Tarifa		**Tarifa ez diskriminatzailea**
Gailurra **12:00 a.m.–22:00 p.m.**	**Harana** **22:00 p.m.–12:00 a.m.**	
0.17977 €/kW·h	0.09572 €/kW·h	0.15207 €/kW·h

TOU tarifak MPCarengan duen efektua aztertzeko, adibideko etxebizitzaren modeloa erabiliko da. Nahiz eta honen efektua inertzia handiko eraikinetan nabarmenago izan, TABS duten eraikinetan adibidez, interesgarritzat hartzen da tipologia honetako eraikinetan izan dezakeen efektua aztertzea. MPCak TOU tarifa erabiltzean, beraren aurreikuspen ahalmena erabiltzen du tarifan dagoen energia kostu-aldaketa ikusteko eta kostu-funtzio bidez beroketa sistemaren ekintza optimizatzeko. Energia kostu hau denboran aldakorra izango da eta kostu funtzioan u bektorea biderkatu beharko du. Horrela, MPCren minimizazio prozesua hurrengo adierazpenaren bidez defini daiteke:

$$\min_{u_0 \ldots u_{\mathrm{N}-1}} \sum_{k=0}^{\mathrm{N_p}-1} \left((\omega - y)_k^{\mathrm{T}} \mathbf{Q} (\omega - y)_k + u_k^{\mathrm{T}} \mathbf{S}(\mathbf{t}) \mathbf{R} u_k + \varepsilon_k^{\mathrm{T}} \mathbf{S} \varepsilon_k \right) \tag{5.8}$$

Dagozkion murrizketekin:

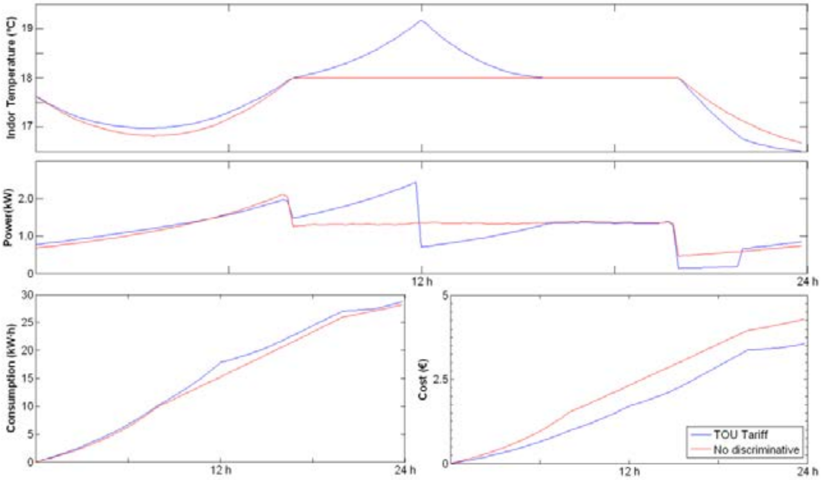
$$0 \leq \boldsymbol{u} \leq 5\ \mathrm{kW} \tag{5.9}$$

$$\mathbf{T}(\mathrm{t})_{\mathrm{ongizate\_min}} \leq \boldsymbol{y} \leq \mathbf{T}(\mathrm{t})_{\mathrm{ongizate\_max}} \tag{5.10}$$

$\mathbf{S}(\mathbf{t}) \in \mathbb{R}^{\mathbf{n}_u \times \mathbf{n}_u}$ denborarekiko aldakorra den matrizea energia kostuarekin loturik dagoen ponderazioa agertzen da. Normalean kostu ekonomikoen balioak agertzen dira $\mathbf{S}(\mathbf{t})$-n. $\mathbf{Q}$-k eta $\mathbf{R}$-k orain arte izan duten zentzua mantentzen dute eta denboran zehar aldakorrak izan daitezke.

Kostu funtzioaren pisuak, predikzio horizontean aldakorrak izan daitezke. Gauza bera gertatzen da erreferentziaa-tenperatura eta ongizate bandarekin. Hau dela eta, MPCa inplementatzeko CPLEX ebazlea erabili da YALMIP interpretatzailearekin.

Energia aurrezteko politika bera inplementatu da TOU tarifa eta tarifa ez diskriminatzailea erabilita, non $\mathbf{S}(\mathbf{t})$ matrizearen parametroak egokitu diren 5.6 Taularen balioen arabera. 5.10 Irudiak simulazioan lortutako emaitzak erakusten ditu. Kontrolak, energia aurrezteko politika jarraituz, tenperatura ongizate bandaren beheko limitetaraino eramaten ditu. Grafikoak erakusten du nola kontrolak egokitzen duen energia erabilera tarifaren arabera. Tarifa ez- diskriminatzailearekin sistemak orain ikusitako moduko joera aurkezten du. TOU tarifarekin ordez, goizeko 12:00ak baino lehenago kontsumoa handitzen da eta gelaren tenperatura igotzen da energia metatzeko prezio merkea aprobetxatuz. Gaueko 22:00ak baino lehen antzeko zerbait gertatzen da. TOU kontrolak kontsumoa murrizten du energia garestia ez erabiltzeko. 20:00etan kontsumoa handitzen da energia merkeago erabiliz aurreztearren galdutako beroa berreskuratzeko. Grafikoan ikusten denez, TOU tarifaren kontsumoa pixka bat handiagoa da tarifa ez-diskriminatzailearekin alderatzen bada. MPCak, TOU tarifa erabilita, energia erabileraren patroiak energia merkearen unetara mugitzen ditu. Hala ere, azken grafikoan ikusten den bezala, energia kontsumoari loturiko kostu ekonomikoa nabarmen gutxitzen da. Grafikoaren hasieran dagoen tenperatura jausia, sistemaren hasieraketari dagokio.



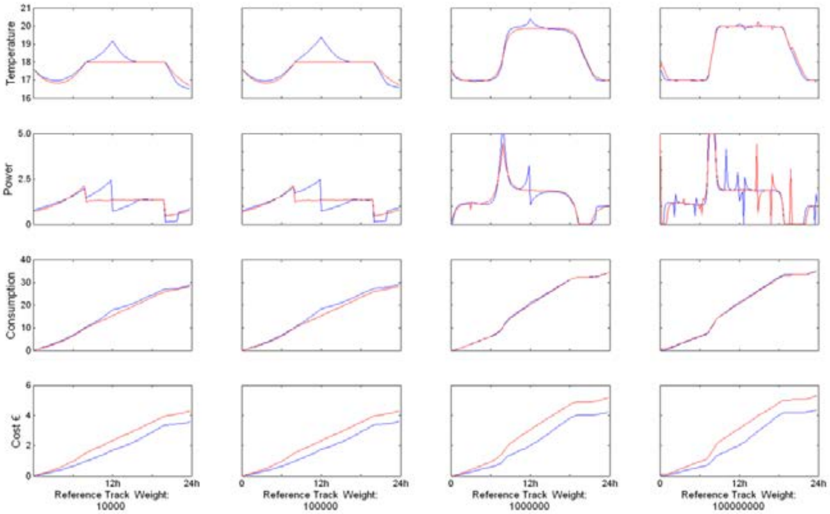
5.10 Irudia. Egun bateko eboluzioa TOU tarifa eta tarifa ez diskriminatzailea erabilita.

Antzeko emaitza lortzen da 5.11 Irudian eta 5.7 Taulan pisuen erlazioa aldatzen denean. Kontrolak sortutako energia erabilera antzekoa da bi tarifentzat (TOUk apur bat gehiago erabiltzen du). Hala ere, kostu ekonomikoa txikiagoa da TOU tarifarekin. erreferentzia jarraitzeko politikak inplementatzen direnean, kontsumoa berdinduz doa, nahiz eta kostu ekonomikoan aldeak mantentzen diren.

5.7 Taulan aurrezpen ekonomikoak aurkezten dira pisu-erlazio desberdinentzat. Bigarren zutabeak TOU tarifak eta tarifa ez-diskriminatzaileak alderatzen ditu. Hirugarren zutabean, kontsumo desplazamendua zenbatekoa den ezagutzeko, MPCan aurreko kontrolei, behin kontrolaren ekintza kalkulatuta, TOU tarifa aplikatzen zaie.

5.7 Taula. Otsailean lortutako aurrezpen ekonomikoak TOU tarifarekin eta tarifa ez-diskriminatzailearekin **Q** eta **R** erlazioa aldatuz.

Erreferentzia jarraitzeko pisua	**Aurrezpen ekonomikoak % (TOU *vs.* Ez-diskriminatzailea)**	**Aurrezpen ekonomikoak % (TOU *vs.* Ez-diskriminatzailea TOU Tarifarekin)**
10,000	~%19	~%4.2
100,000	~%18	~%4.25
1.0×10^6	~%20	~%4.2
1.0×10^8	~%19	~%0.5



5.11 Irudia. **Q** eta **R** pisu-erlazio aldaketak inplementatzen dituen bi MPCen egun bateko eboluzioen alderaketa. Urdinak TOU tarifa erabiltzen du eta gorriak tarifa ez diskriminatzailea. Grafikoan Barneko tenperatura (°C), Potentzia erabilera (kW), kontsumitutako energia (kW·h) eta kostu ekonomikoa (€) adierazten dira.

5.5 Zenbait ondorioak

Atal honetan aurkeztu nahi izan da MPCak eraikuntzaren klimatizazioaren esparruan ekar ditzakeen onurak aurreko lan batzuen laburpen eta dibulgazio gisa. Eraikin baten eredua termikoa izanik, posiblea da eguraldiaren aurreikuspena eta erabilera patroiak jakinda MPC erabiltzea eraikinak ongizate baldintzak bete ditzan energia edo kostu ekonomikoaren aurrezpenak lortuz. Aurrezpen horiek, %15eraino hel daitezke, artikuluan eta bibliografian ikusten daitekeenez, zeina balio handia den aplikatutako esparruan.

MPCren parametro desberdinen eragina aztertu dira, kontrola doitzean duten eragina aztertzeko. Horrela, energia aurrezteko politika finkatzeko minimizazio funtzioan pisuek duten eragina ikusi da: Barne tenperaturaren eboluzio malguak ongizate banda barnean %7.5eko aurrezpenak ekar ditzake erreferentzia-tenperatura estuki jarraitzen duen politika baten aurrean.

Bukatzeko, MPCren erabilerak ekar ditzakeen aurrezpen ekonomikoak aurkeztu dira. TOU tarifa erabiltzen denean, energia merkea kontsumi daiteke eta eraikinaren inertzia termikoarekin erabilita hori disipatu energia garestiaren unetan. Energia aurrezpen nabariak lortzen ez badira ere, aurrezpen ekonomikoak %20koak izan daitezke inertzia termiko txikia duen eraikinetan, aurrezpenak handituz inertzia termikoa handitzen denean.

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6.

Factors that influence the control

English summary

This charter studies some fundamental factors that influence the control design in the next chapter where an enhanced blind system control that used predictive information of the MPC a of the HVAC of an office is proposed.

Section 6.1 reviews the normative that regulates the thermal comfort inside offices. ISO 7730 [1] and ASHRAE 55 [2] were developed in parallel; even so, the comfort levels proposed by ASHRAE 55 show a slightly lower temperature levels than those proposed in ISO 7730. European regulation EN 15251 [3] does not deepen the thermal comfort and refers to ISO 7730 normative. This section considers the parameters that influence the thermal comfort sensation. Metabolic rate and clothing insulation depends on user conditions. Air and radiation temperatures, which determinate the operative and effective temperature, air speed and humidity are factors that depend on the environment. In a first consideration, humidity range can be ensured by an external system, a dehumidifier for example, which left the temperature as the main control comfort parameter. Normative gives some comfort definitions. PPV/PMD is the one usually proposed by normative although Kelvin·hour (Kh) is also considered in normative and commonly appears in literature. Normative collects different factors that provoke thermal discomfort. Among them, the radiant temperature asymmetry, the vertical air temperature difference, draft, floor surface temperature or temperature variations with the time are collected in section 6.1.2. In its last part of this section, the PhD Thesis document introduces the adaptive comfort concept, which is added to the normative in an informative way. This concept is based on the study defined in the work ASHRAE RP-884 [4]. CBE Thermal Comfort Tool [5] gives software that calculates the thermal comfort using PPV/PMD [6] and adaptive comfort definitions.

Section 6.2 introduced different considerations about the climate and weather. This subject has a great importance for the HVAC control under an MPC, due to the big influence of the outdoor temperature and solar radiation have in the comfort conditions. ASHRAE HOF [7] provides climate information from 6443 station around the world. Chapter 7 proposes a novel blind system control to reduce the energy use in office buildings. This is the reason to introduce the solar radiation considerations that allow determining its predicted value for its use in that study. The last part of this section is a study of the Typical Year Data Sets, TMY [8]. These data collections compile 68 meteorological parameters from the last years in order to provide the most common values in that period. This global database provides information for simulations in building behaviour and is used in programs like TRNSYS or EnergyPlus. However, it must be consider that this information is not useful for design works due to the lack of extreme conditions.

Section 6.3, the last section of this Chapter, compiles the information about windows and blind system provides by some normative. ASHRAE HOF, ISO 9050 [9] and ISO 10292 [10] study the transfer of solar radiation through glass and window system of some glass layers giving expressions to calculate the percentage of transferred solar energy, g-value. ASHRAE HOF, ISO 15099 [11] and EN 13363 [12, 13] characterize the blind systems providing information about its g-value. Specifically, EN 13363 provides expressions for the estimation of the g-value for the integrated window-blind system that will be used in Chapter 7.

6.

Kontrolengan eragina izango duten hainbat faktore

6.1 Ongizate termikoa

Bai bulego eraikin erraldoietan bai etxebizitza txikienean, klimatizazio instalazio baten helburu nagusia erabiltzaileen konfort termikoa ziurtatzea da. Hau lortzeko, espazioak betetzen dituen baldintza termikoak, zein erabiltzaileren metabolismo fisikoa, eta janzkera kontutan hartu behar dira. Hortaz gain, ikusi den bezala, konfort pertzepzio hau lortzeak operazio-kostua duela esan behar da, zein ahalik eta txikien izatea den helburua.

Gaur egun, ingurumen termiko moderatuak aztertzen dituzten arau teknikoak bi dira, paraleloan garatu direnak: ISO 7730:2005 [1] eta ASHRAE 55:2013 [2]. EN 15251:2007 [3] arau europarrak zeharka tratatzen du ongizate termikoa eta ISO 7730 aipatu ohi du. Bi arauak bakoitzari dagokion esparru geografikoan aplikatu beharrekoak dira. Gizakiaren egoera baldintza gordinetan beste dokumentu batzuetan aztertzen da: ISO 7243:1989 [14], ISO 7933:2004 [15] eta ISO 11079:2007 [16]. Arau horietan, ongizate termikoaren kalkulu analitikoa eta definizioa bilatzen da, giza eta barne inguruneen faktore termikoak definitzen dira barne espazio batean erabiltzaile gehienentzako onargarriak diren ingurumen baldintza termikoak ziurtatzeko. Ongizate termiko eza sor dezaketen iturriak identifikatzen dira haiek ekiditeko. Arauetan aipatzen den bezala, ongizate faktoreak aplikatzerakoan hainbat faktore hartu behar dira kontutan, hala nola sexua, desberdintasun geografiko eta kulturalak, edo erabiltzaileen janzteko ohiturak eta gorputz-metabolismoa. Puntu honetan ISO 7730 eta ASHRAE 55 arauek ezartzen dituzten parametroak aztertuko dira. Era orokorrean, bi arauak antzekoak direla esan daiteke, nahiz eta ASRHAE 55-k proposatzen dituen ongizate mailetan tenperatura apur bat baxuagoa izan.

Hainbat dira ongizate termikoa ziurtatzeko kontutan hartu behar diren parametroak. Alde batetik, erabiltzailearekin loturik dauden metabolismo fisikoa eta janzkeraren isolamendua aipatu behar dira. Bi arautegiek, parametro horientzako antzeko sailkapena proposatzen dute. Metabolismoari dagokionez, parametroa egoera sedentario batetik jarduera lehiakorra arte sailkatuta dago. Janzkerari dagokionez, horrek sortzen duen isolatze efektu termikoa ebaluatzen da. Janzkera kode eta ohiturak hartu behar dira kontutan erosotasun termikoengan eta energia gastuan duten eraginagatik, bai neguan zein udan. Adibidez, orain dela urte batzuk Japongo korporazio batzuek lausotu zuten janzkera kodea energia aurrezteko, udan gorbata galaraziz; zuzendariek eman behar izan zuten adibidea.

Kontutan hartu beharreko beste parametroak aztergai den barne-espazioarekin lotuta daude: airearen tenperatura, batez besteko erradiazio tenperatura, airearen abiadura eta hezetasuna. Gai horiek eta horien eragina ondoren azaltzen dira:

Airearen tenperatura (T_a): Honekin, espazioaren tenperaturaren batez bestekoa izendatzen da. Ongizate parametroak kontutan harturik, oinei, bularrari eta buruari dagozkien datuak hartzen dira.

Erradiazio tenperatura ($\overline{T}_r$): Espazioa mugatzen duten elementuen batez besteko tenperatura da. Erradiazioak ongizate termikoan duen eragina aztertzeko erabiltzen da.

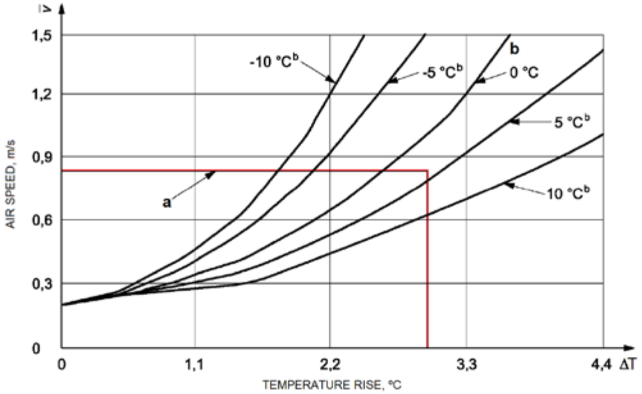
Espazio edo ingurune baten bero trukaketaren tenperatura zehazteko, bi tenperatura horiek batera kontutan hartzen dira. ISO-k tenperatura operatiboa definitzen du eta ASHRAE-k, berriz, tenperatura eraginkorra definitzen dituzte.

> Tenperatura operatiboa: Balizko ingurune beltz baten eta horren barruko airearen tenperatura uniformea, kontutan harturik ingurune horretan legokeen erabiltzaileak dituen bero galerak aztertzen ari den inguruneak direla.
>
> Tenperatura eraginkorra: %50 hezetasun erlatiboa, 0.1 m/s-ko airearen abiadura

eta $\overline{T}_r = T_a$ duen balizko ingurune baten tenperatura non erabiltzaile bat dagoen 1.0 met metabolismo jarduerarekin eta 0.6 clo arropa mailarekin, ingurune horretan erabiltzaileak lituzkeen bero galerak, momentu horretan dituen arropekin eta aktibitate fisikoarekin direla dituenak.

Airearen abiadura: Airearen abiadura handitzen denean, pertsona eta ingurunearen arteko bero-trukaketa ere handituko da bero-galerak areagotzean. Abiadura minimo bat definituta ez badago ere, airearen abiadura handituz, sentsazio termikoa txikituko da. Udan onuragarria izan daitekeen eragin honek, leihoak irekitzea edo haizagailuak erabiltzea, ezerosotasuna sor dezake handiegia bada. 6.1 Irudiak, 26 °C-ko tenperaturatik abiatuta, abiadura noraino handi daitekeen adierazten du **a**-lauki gorri baten bidez. Agertzen diren lerroek azala eta airearen arteko bero transferentzia bera dute, eta lerro bakoitzean, erradiazio eta airearen tenperaturaren aldea (T_r-T_{air}) konstante mantentzen da. Egoera sedentariorentzako tenperatura aldaketak eta airearen abiadurak onartzen duten balioak $\Delta T < 3$ °C, $v < 0.82$ m/s dira. 6.1 Irudian ikusten den bezala, airearen abiadura altuak eraginkorragoa izango da airearen tenperatura, erradiazioarena baino baxuagoa denean.

Hezetasuna: Aireak duen ur lurrun kopurua da. Hori adierazteko, horren balio absolutua edo erlatiboa erabil daiteke. Hezetasunak gisa-gorputzaren lurrunketa bidezko bero-galerengan du eragina. ISO 7730-ren arabera, ingurumen termiko moderatuetan (< 26 °C) eta metabolismo murriztutako ekintzetarako hezetasunaren eragina mugatua da sentsazio termikoengan. Aipatutako baldintzapean, hezetasun erlatiboaren %10-ko hazkundeak, tenperatura operatiboaren 0.3 °C-ko hazkunde parekoa da. Tenperatura edo metabolismo altuagoentzat, eragina handiago izan daiteke. Tenperatura aldaketa iragankorra denean, hezetasunaren eragina ere handitzen da. Hala ere, hezetasunaren eragina ez da sentsazio termikora mugatzen. Ongizatea zentzu zabalean hartuz, larruaren ihartasun zein begien narritadurarekin lotura eduki dezake hezetasun-mailak.



6.1 Irudia. ASHRAE 55-en eta ISO 7730-ren irudia. Behar den airearen abiadura erradiazioaren eta aire tenperaturaren igoera konpentsatzeko. a laukiak. Hasierako tenperatura 26 °C-koa da

6.1.1 Ongizate egoera kuantifikatzeko PMV/PPD metodoa

Espazio baten ongizate termikoaren maila kuantifikatzeko irizpideak finkatzea beharrezkoa da. Ikusi da ASHRAE 55 eta ISO 7730 arauak direla kontzeptu hau tratatzen duten arau garrantzitsuenak. Bi arau hauek, balantze termikoan oinarritzen diren *Predicted Mean Vote* (PMV) eta *Predicted Percentage of Dissatisfied* (PPD) erabiltzen dute espazioen ongizate termikoa definitzeko. PMVk pertsona talde handi batek egoera termiko bati buruzko sentsazio termikoaren batez besteko adierazpena da. Fanger-ek [6, 17] PPV/PPD eredua definitu zuen bero balantze ekuazioak eta ikerketa enpirikoak erabiliz eta zazpi posizioko eskala definituz hotz handitik (-3) bero handira (+3), 6.1 Taulan ikus daitekeen bezala.

6.1 Taula. Zazpi mailetako bero pertzepzio taula

PPV	Pertzepzio
+3	Bero handia
+2	Beroa
+1	Epela
0	Neutroa
-1	Apur bat hotza
-2	Hotza
-3	Hotz handia

Fanger-ek proposaturiko PPV/PPD ereduaren [6] ekuazioak ISO 7730 arauan eta agertzen dira eta horiek kontutan hartzen dituzte lehen definitutako parametroak ongizate termikoa (PMV) ebaluatzeko: janzkera, metabolismoa, airearen tenperatura, erradiazio tenperatura, hezetasuna eta airearen abiadura. Balio hori, Predicted Percentage of Dissatisfiedrekin (PPD) erlaziona daiteke erabiltzaileen zer ehunekoa dagoen ezerosotasun-termiko egoeran. Egoera onargarri batentzat, jendearen %80 eroso egon beharko luke. Arauek balio horiek kalkulatzeko kode informatikoa aurkezten badute ere, *CBE Thermal Comfort Tool* for ASHRAE 55-k [5], beste programa batzuk bezala, kalkulu hori zuzenean burutzen du 6.2 Irudian ikus daitekeen bezala.

Hauek dira ISO 7730-ek PMVa kalkulatzeko proposatzen dituen ekuazioak:

$$\begin{gathered} \mathrm{PMV} = [0.303\exp(-0.036\mathrm{M}) + 0.028] \cdot \\ \{(\mathrm{M}-\mathrm{W}) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (\mathrm{M}-\mathrm{W}) - \mathrm{p_a}] \\ -0.42 \cdot [(\mathrm{M}-\mathrm{W}) - 58.15] - 1.7 \cdot 10^{-5} \cdot \mathrm{M} \cdot (5867 - \mathrm{p_a}) \\ -0.0014 \cdot \mathrm{M} \cdot (34 - \mathrm{T_a}) \\ -3.96 \cdot 10^{-8} \cdot \mathrm{f_{cl}} \cdot [(\mathrm{T_{cl}} + 273)^4 - (\overline{\mathrm{T}}_\mathrm{r} + 273)^4] - \mathrm{f_{cl}} \cdot \mathrm{h_c} \cdot (\mathrm{T_{cl}} - \mathrm{T_a})\} \end{gathered} \tag{6.1}$$

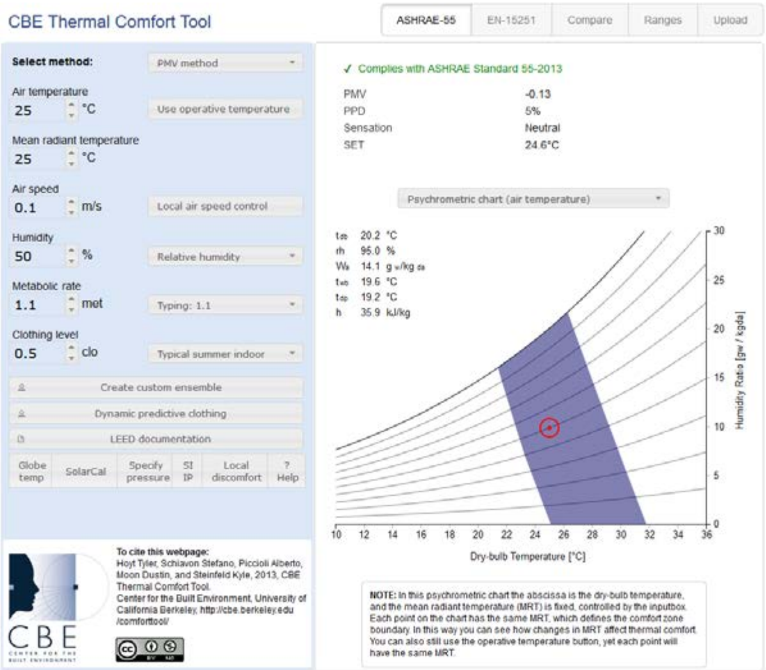
non:

$$\begin{gathered} \mathrm{T_{cl}} = 35.7 - 0.028 \cdot (\mathrm{M}-\mathrm{W}) \\ -\mathrm{I_{cl}} \cdot \{3.96 \cdot 10^{-8} \cdot \mathrm{f_{cl}} \cdot [(\mathrm{T_{cl}} + 273)^4 - (\overline{\mathrm{T}}_\mathrm{r} + 273)^4]\mathrm{f_{cl}} \cdot \mathrm{h_c} \cdot (\mathrm{T_{cl}} - \mathrm{T_a})\} \end{gathered} \tag{6.2}$$

$$h_c = \begin{cases} 2.38 \cdot |T_{cl} - T_a|^{0.25} & 2.38 \cdot |T_{cl} - T_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} - \text{rentzat} \\ 12.1 \cdot \sqrt{v_{ar}} & 2.38 \cdot |T_{cl} - T_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} - \text{rentzat} \end{cases} \tag{6.3}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 \cdot I_{cl} & I_{cl} \leq 0.078\ \mathrm{m^2K/W} \\ 1.05 + 0.645 \cdot I_{cl} & I_{cl} > 0.078\ \mathrm{m^2K/W} \end{cases} \tag{6.4}$$

M	Tasa metabolikoa den (W/m^2)
W	Potentzia mekaniko efektiboa den (W/m^2)
I_{cl}	Arroparen isolatze ahalmena (m^{2}K/W)
f_{cl}	Arroparen azalera faktorea
T_a	Airearen tenperatura (°C)
$\overline{T}_r$	Batez besteko tenperatura erradiatzailea (°C)
v_{ar}	Airearen abiadura erlatiboa (m/s)
p_a	Ur lurrunaren presio partziala (Pa)
h_c	Konbekzio bidezko bero-transferentzia koefizientea (W/(m^{2}K))
T_{cl}	Arroparen gainazalaren tenperatura (°C)



Select method: PMV method

Air temperature 25 °C

Mean radiant temperature 25 °C

Air speed 0.1 m/s

Humidity 50 % Relative humidity

Metabolic rate 1.1 met Typing: 1.1

Clothing level 0.5 clo Typical summer indoor

✓ Complies with ASHRAE Standard 55-2013

PMV	-0.13
PPD	5%
Sensation	Neutral
SET	24.6°C

t_{db}	20.2	°C
rh	95.0	%
W_a	14.1	g_w/kg_{da}
t_{wb}	19.6	°C
t_{dp}	19.2	°C
h	35.9	kJ/kg

NOTE: In this psychrometric chart the abscissa is the dry-bulb temperature, and the mean radiant temperature (MRT) is fixed, controlled by the inputbox. Each point on the chart has the same MRT, which defines the comfort zone boundary. In this way you can see how changes in MRT affect thermal comfort. You can also still use the operative temperature button, yet each point will have the same MRT.

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Center for the Built Environment, University of California Berkeley, http://cbe.berkeley.edu/comforttool/

6.2 Irudia. *CBE Thermal Comfort Tool*-ek egindako PMVren eta PPDren kalkulua. Egoera termikoa ASHRAE kartan ere kokatzen du

Arauek, metabolismoa eta arroparako unitateak estandarizatzen dituzte unitate metaboliko bat 1 met = 58.2 W/m^2 eta arropa unitatea 1 clo = 0.155 m^{2}K/W definituz.

Ongizatea definitzeko, 6.1 Taulako PMV -2 eta +2 balio tartea erabili beharko litzateke, eta kasu honetan, oinarrizko parametroen balio tartea 6.2 Taulan adierazitakoak lirateke.

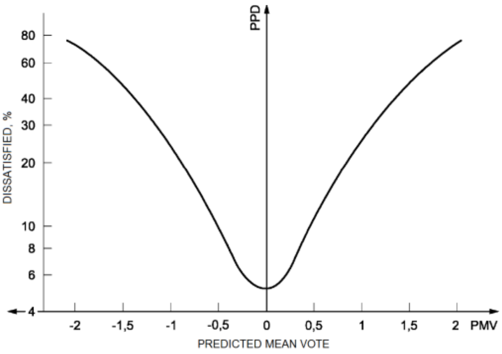
6.2 Taula. PMVren oinarrizko parametroen balio onargarriak

Parametro	Balio tartea
M	46 – 232 W/m^2 (0.8 – 4 met)
I_{cl}	0 – 0.31 m^{2}K/W (0 – 2 clo)
T_a	10 – 30 °C
$\overline{T}_r$	10 – 40 °C
v_{ar}	0 – 1 m/s
p_a	0 – 2700 Pa

PMV-ren kalkuluak espazio baten ongizate irizpideak kalkulatzeko baliagarria izan daiteke. PMV = 0 finkatzean, arropa, aktibitate metabolikoa eta ingurumen baldintzak egokitzen dira sentsazio termikoa finkatzeko. PMV-k egoera termikoari buruzko batez besteko balio adierazten du. PPD-ak inguru termiko baten aurreikuspena egiten du, deseroso legokeen jendearen ehunekoa kuantifikatuz. 6.1 Taularen *hotz handia*, *hotza*, *beroa* eta *bero handia* sentitzen dutenak dira ezeroso moduan hartzen direnak. PPD-aren balioa kalkulatzeko, 6.5 Ekuazioa erabiltzen da, sarrera PMV balioa izanik.

$$\mathrm{PPD} = 100 - 95 \cdot \exp(-0.03353 \cdot \mathrm{PMV}^4 - 0.2179 \cdot \mathrm{PMV}^2) \tag{6.5}$$

6.5 Ekuazioan ikusten den bezala, egoerarik onenean ere, jendearen %5 gutxienez deseroso egongo da. Honekin jendearen arteko desberdintasunak hartzen dira kontutan. Adierazpen hau, 6.3 Irudian agertzen den grafikoaren bidez adierazten da sarritan.



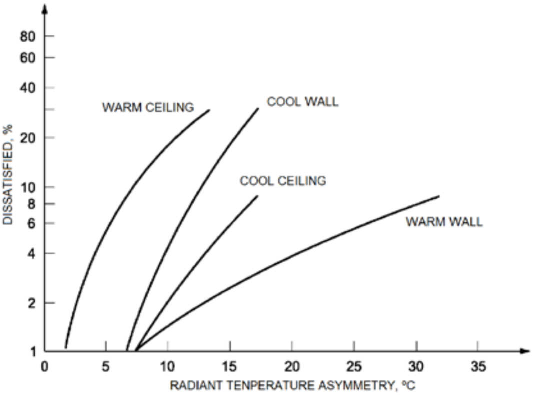
6.3 Irudia. PMVren eta PPDren arteko erlazioa

6.1.2 Ezerosotasun termiko lokala

Ongizate termiko gainean eragiten duten faktoreak aztertu ondoren, ezerosotasun termikoengan era lokalean eragin dezaketen faktoreak aztertu dira. Aipaturiko ASHRAE 55 eta ISO 7730 arauek antzeko faktore multzoa aurkezten dute. Faktore hauek janzkera arina eta egoera sedentario baldintzapean aplikatzen da. Orokorrean, metabolismo handia edo arropa gehiago denean jendearen sentikortasun termikoa jaisten da.

6.1.2.1 Erradiazio-tenperaturaren asimetria

Espazio batean egon daitekeen gainazalen arteko tenperatura ezberdintasunek eta eguzki-erradiazioak eragina dute ongizate termikoan. Gorputzak sentikortasun berezia du sabai beroei, naiz eta horma eta leiho hotzek ere ezerosotasuna sor dezaketen. ISO 7730 arauak, espresio analitikoak eta haien aplikazio esparrua ematen ditu ezerosotasun hau ebaluatzeko. 6.4 Irudian erradiazio-tenperaturaren asimetriagatik sortzen den ezerosotasuna agertzen da ohiko lau kasuentzat.

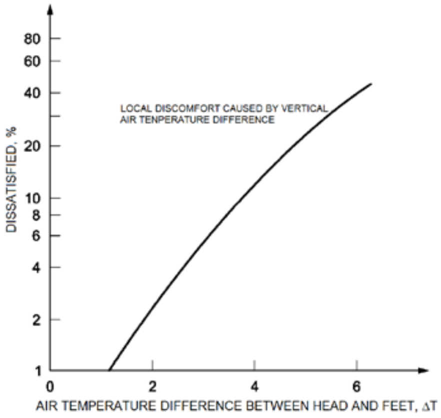


6.4 Irudia. ASHRAE 55 eta ISO 7730ren irudia. Erradiazio asimetriak sortutako ezerosotasun lokala

6.1.2.2 Tenperatura diferentzia bertikala

Oinen eta buruaren artean agertzen den desberdintasunak ondoeza sor dezake espazio baten erabiltzaileen artean. ASHRAE 55 eta ISO 7730 arauek 6.5 Irudiaren bidez termikoki ase gabe (PD – percentage dissatisfied) dagoen jendearen proportzioa. Balio honentzako, ISO 7730-ek honako ekuazio hau proposatzen du, non $\Delta T_{a,v}$ buru eta oinen arteko tenperatura diferentzia adierazten duen eta $\Delta T_{a,v} < 8$ °C izan behar duen

$$\mathrm{PD} = \frac{100}{1 + \exp(5.76 - 0.856\Delta T_{a,v})} \tag{6.6}$$



6.5 Irudia. ASHRAE 55 eta ISO 7730-ren irudia. Oinak eta buruen arteko tenperatura aldeak sortzen duen ezerosotasun termikoa

6.1.2.3 Aire korronteak

Klimatizazio ekipoek sortzen duten aire mugimenduak ongizate termikoa hobe badezake ere, ezerosotasun iturria izan daiteke. ASHRAE 55-ren arabera, erabiltzaileak ongizate egoeran daudenean, airearen abiadurak ez du 0.15 m/s gainditu behar, nahiz eta erabiltzaileek airearen abiaduraren kontrol lokala dutenean, abiadura handi daiteke.

ISO 7730 arauak ondoko adierazpen matematikoa ematen du aire-korronteengatik deseroso egongo den erabiltzaile portzentaia kalkulatzeko, aire-korronteen tasa (DR – *draught rate*) kalkulatzeko:

$$\mathrm{DR} = (34 - \mathrm{T}_{a,l})(\bar{v}_{a,l} - 0.05)^{0.62}(0.37\bar{v}_{a,l}\mathrm{Tu} + 3.14) \tag{6.7}$$

non

$\mathrm{T}_{a,l}$ airearen tenperatura, 20 eta 26 °C artekoa.
$\bar{v}_{a,l}$ airearen batez besteko abiadura m/s-tan, $\bar{v}_{a,l} < 0.5$ m/s.
Tu turbulentzia lokala da ehunekotan, %10 eta %60 artekoa.

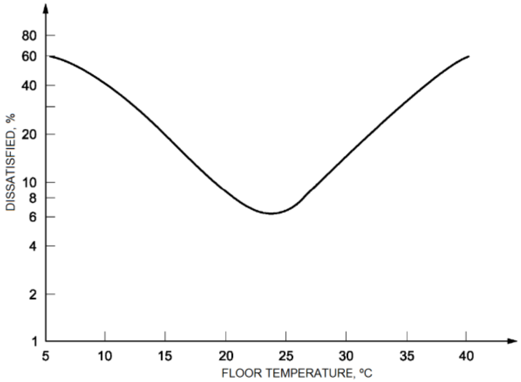
DR > %100 bada, DR = %100 erabili behar da, eta $\bar{v}_{a,l} < 0.05$ m/s bada, $\bar{v}_{a,l} = 0.05$ m/s erabili behar da.

6.1.2.4 Zoru hotz eta beroak

Berriro ere, bi arauek era berean aurkezten dute puntu hau. Zorua hotzegi edo beroegi badago, ezerosotasuna ager daiteke erabiltzaileen artean. Zoru hotz eta beroek sortzen duten ezerosotasuna definitzeko ISO 7730-ak ondoko adierazpena proposatzen du, T_f zoruaren tenperatura izanik. Horren adierazpen grafikoa 6.6 Irudian agertzen da.

$$PD = 100 - 94 \cdot \exp(-1.387 + 0.118 \cdot T_f - 0.0025 \cdot T_f^2) \tag{6.8}$$

Beste ezerosotasun iturriekin bezala, adierazpen hau era grafikoan agertzen da arauetan. Kasu honetarako, deseroso daudenen kopurua ez luke %10 gainditu beharko.



6.6 Irudia. ASHRAE 55 eta ISO 7730-ren irudia. Zoru bero eta hotzek sortutako ezerosotasun termikoa

Balio hauek kontutan hartu behar dira zoru erradiatzaileekin lan egitean: TABS, elektrikoa... EN 1264:2009-ak [18] zoru erradiatzaileentzako ematen duen tenperatura-tartea 17 eta 29 °C-koa da erabiltzen diren zonaldeentzako. Tenperatura 33 °C-raino igo daiteke sukalde eta bainuetan eta 35 °C-raino perimetroko zonaldeetan.

ASHRAE 55-k, 6.3 Taularen bidez, erosotasun termiko mota bakoitzagatik ager daitezkeen balio maximoak ematen ditu.

6.3 Taula. ASHRAE 55. Ezerosoen ehunekoa ongizate eza lokalaren eraginengatik

Aire korronteak	Tenperatura diferentzia bertikala	Zoru hotz eta beroak	Erradiazio asimetria
< %20	< %5	< %10	< %5

6.1.3 Giro termiko ez egonkorrak

Deskribatutako ezerosotasun faktoreak egoera egonkorrean kontutan hartzekoak dira. Espazio baten egoera termikoa, aldiz aldakorra da pairatzen diren perturbazioengatik. Hau dela eta, ongizate egoeran fluktuazioak egon daitezke erabiltzaileek honen gaineko kontrola ez badute. Hiru tenperatura aldaketa mota hartzen dute kontutan arautegi biek:

Aldaketa ziklikoak: Gailurren arteko tenperatura aldaketa 1 K baino txikiagoa bada, aldaketek ez dute eraginik ongizate termikoan. ASHRAE 55-ak, multzo honetan sailkatzeko aldaketak 15 minutuko denbora tartean izan behar direla esaten du.

Ranpak: Tenperatura aldaketa monotono eta ez ziklikoak dira. Aldaketa 2 K/h baino txikiagoak direnean, ISO 7730-k egoera egonkorra har daitekeela esaten du. ASHRAE 55-k 2.2 K/h proposatzen du, 15 minututan 1.1 K baino ezin duela aldatu jakinda.

Fluktuazio iragankorrak: Berehala nabaritzen diren tenperatura aldaketak dira. Hauek zuzenean eragiten dute ongizate termikoengan. Kontsigna aldaketa da honen adibidea.

6.1.4 Epe luzerako ongizate termiko orokorraren baldintzen ebaluazioa

Espazio batek jarduera jarraitua izan behar badu, ongizate-neurketek denboran zabaldu behar dute. Epe luzerako ebaluazioa urtaro edo urte osorako egindakoak dira. Arau bakoitzak hainbat aukera aurkezten ditu. Aukera hauek, PMV edo tenperatura operatiboa (batzuetan ponderazio faktore bat erabilita) aurredefinitutako konfort zonalde batetik zenbat denbora kanpo dagoenekin oinarrituta daude. ASHRAE 55-ak, hala ere, erabiltzaileengan oinarritutako analisia ere proposatzen du. Neurketa mota hau egiterakoan, arauek onartzen dute tenperatura konfort mugetatik kanpo egotea hainbat unetan.

Lan honen alde esperimentalean konfort termiko ebaluazioa Kelvin·ordu-tan (Kh) emango da. Hau horrela egiteko arrazoia praktikoa da. PMV kalkulatzeko behar diren hainbat datu hartu barik, tenperaturan oinarritzen dira ikerketak. Lan ordutan lortutako konfort desbideraketak txikiak izanik eta aplikatzen den MPC-ak lortzen duen erregulazioa dela eta, posiblea da horrela planteatzea. Konfort lokaleko hainbat baldintza hartu dira kontutan. TABS moduko klimatizazio sistemen erabilera, zoruaren eta sabaiaren tenperaturen kontrola behartzen du gainberotze eta kondentsazioak ekiditeko. MPC-arekin posiblea da ere denbora tarte batean egongo den tenperatura aldaketa maximoa definitzea denboran zehar sor daitekeen ezerosotasun termikoa ekiditeko. Hala ere, eraikinaren ereduaren akatsak eta aurreikusitako perturbazioetan egon daitezken desbideraketak ereduengan portaera estokastikoa sor dezakete.

6.1.5 Ongizate adaptatiboa

Ongizate adaptatiboa, eraikin kanpoko eguraldiak barneko ongizate termikoan eragina duela oinarritzen da. Janzkera, klimatizazio kontrolak eskura edukitzeak edo aurreko egunetako eguraldiak erabiltzaileen nahi termikoengan eragina dutela suposatzen du eredu honek. Horrela, erabiltzaileek haien joera edo nahi termikoak egokitzen dituzte, pairatzen duten ingurumen termikoaren arabera. Eredu hau era naturalean haizeztatutako eraikinetan erabiltzen da (EN 15251-ean era mistoa erabiltzen duten eraikinetan erabil daiteke). Ongizate adaptatiboaren teoria, ASHRAE RP-884 [4] ikerketetan oinarritzen da. de Dear *et al.* [19] adaptazio termikorako hiru multzo definitzen ditu: portaeran oinarritutakoak, fisiologikoak eta psikologikoak. Azken honek sentikortasun termikoaren aldaketa sortarazten du, zeinak PMV-ren aurreikuspenen eta landa behaketen arteko desbideraketak azaltzen dituen. ASHRAE 55-ak kontzeptu hau arauan gehitzen du informazio gisa. 6.7 Irudiak metodo adaptatiboa erabiliz egoera termiko bat definitzen du, karta adaptatiboan kokatuz.

Select method: Adaptive method

Air temperature: 25 °C

Mean radiant temperature: 25 °C

Prevailing mean outdoor temperature: 29 °C

Air speed: 0.3 m/s (59 fpm)

✓ Complies with ASHRAE Standard 55-2013

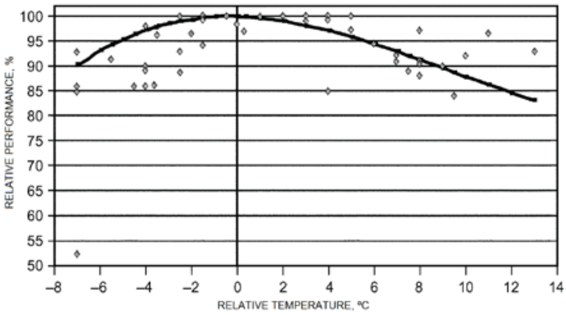
80% acceptability limits — Operative temperature: 23.3 to 30.3°C
 └ Status — Comfortable
90% acceptability limits — Operative temperature: 24.3 to 29.3°C
 └ Status — Comfortable

To cite this webpage:
Hoyt Tyler, Schiavon Stefano, Piccioli Alberto, Moon Dustin, and Steinfeld Kyle, 2013, CBE Thermal Comfort Tool.
Center for the Built Environment, University of California Berkeley, http://cbe.berkeley.edu/comforttool/

NOTE: Method is applicable only for occupant-controlled naturally conditioned spaces that meet all of the following criteria: (a) There is no mechanical cooling system installed. No heating system is in operation; (b) Metabolic rates ranging from 1.0 to 1.3 met, and (c) Occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5-1.0 clo.

6.7 Irudia. *CBE Thermal Comfort Tool*-ek egoera termikoa kalkulatzen metodo adaptatibo bidez

Azkenik, ongizate termikoak eraikinarenen aktibitatean duen eragina aipatu behar da. ASHRAE HOF-k [7] ongizate termiko eta bulego-lanaren eraginkortasuna aztertzen duten hainbat ikerketen bidez, bi parametroak erlazionatzen ditu. 6.8 Irudiak ikerketa hauen emaitzak erakusten ditu. Sakabanaketa handia egon arren, joera argia ikusten da: 8 °C-ko aldea agertzen denean, egindako lanaren eraginkortasuna, ingurumen optimoan egiten denaren %91-era jaisten da.



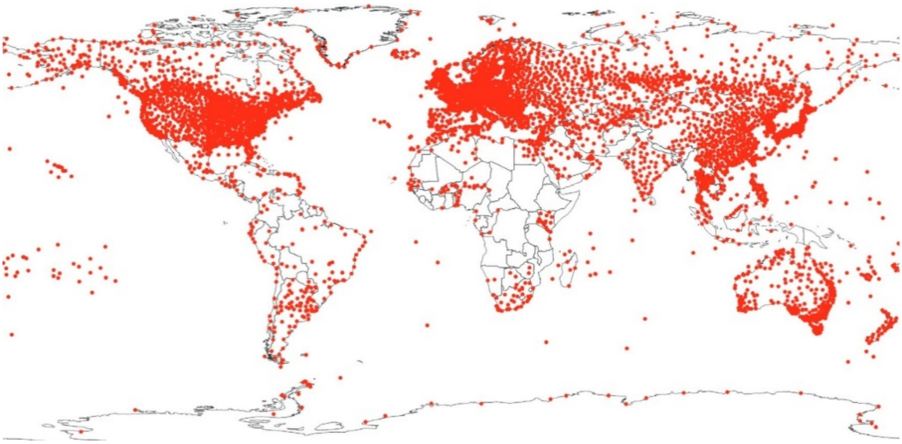
6.8 Irudia. Bulegoen eraginkortasun erlatiboa. Lanaren eraginkortasuna ongizate-tenperatura egokiarekin alderatuta

6.2 Eguraldi eta klimaren informazioa

Jada aztertu den moduan, kanpoko tenperatura, haizearen abiadura, eguzki-erradiazioa, hezetasuna eta, oro har, faktore meteorologikoek eragin nabaria dute eraikin baten konfort termikoa ziurtatu behar denean. Eraikuntza tradizionalean, faktore hauek kontutan izan dira materialak aukeratzerakoan, espazioen distribuzioan edo eraikinen koloreetan. Horrela, eskura ziren materialak erabiliz, isolatze termiko, aireztatzea, eguzki edota lurraren energia era egokian aprobetxatzea, eta eguzkitiko energia islatzea edo absorbatzea lortzen zen. Nahiz eta eraikuntza materialak eta sistemak aldatu, parametro hauek kontutan hartu beharrekoak dira, eraikuntzaren eraginkortasun energetikoa helburua denean. Neguko eta udako tenperaturak, eguzkiaren irradiazioak, hodeien ohiko estaldurak, hezetasunak edo haizeak, eraikinaren eraikuntza eta klimatizazio sistemen dimentsioak baldintzatuko dituzte.

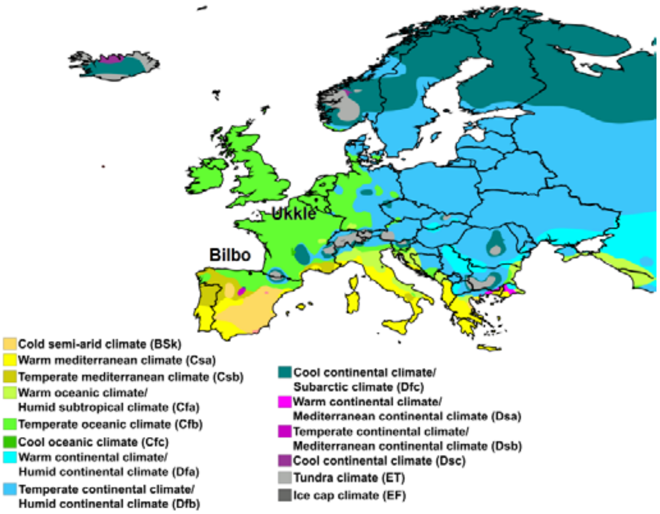
Beharrezkoa da, eguraldi eta klimaren informazio egokia edukitzea eraikinen ongizate termikoa era egokian ziurtatzeko. Ezagutza hau ez da unekoa soilik izango, igarotako denbora tarte adierazgarria kontutan hartu behar da, gerta daitezkeen egoera puntualei dagokien garrantzia emateko eta urtez urte ematen diren aldaketa joerak aztertzeko. Horrela izanik, eguraldi eta klima kontzeptuak desberdindu behar dira. NASA-ren arabera, eguraldiak atmosferaren jokamoldea adierazten du; besteak beste, tartean tenperatura, hezetasuna, euria, hodeien estaldura, argitasuna, ikusmena, haizea eta presio atmosferikoa faktoreak daude. Parametro hauek unetik, unera aldatzen dira eta eguraldiak haien joera aztertzen du epe motzean: minutuko denbora tartea edo urtarokoa hartuz. Honen azterketaren bidez, hurrengo egunaren tenperatura edota euriaren aukera igarri daiteke. Klimak, aldiz, epe luzeko eguraldi patroiak aztertzen ditu, 30 urtekoak normalean, zonalde eta urte sasoi jakin batean agertzen diren joerak aztertzeko: belaunaldi batetik bestera elurteen gutxitzea edo uden tenperatura igoera adibidez. Honen garrantzia agerikoa da: urtaroen hasiera eta bukaerak nekazaritza eta iparraldeetako izotz-urtzea, hainbat garraio bideen desagertzea eta beste batzuen sorrera baldintzen baitu. Ez da kasualitatea Ameriketako Estatu Batuetako meteorologia agentzia, *National Oceanic and Atmospheric Administration* (NOAA), Merkataritza Departamentuaren menpe egotea.

ASHRAE HOF-k munduan zehar sakabanatutako 6443 estazio meteorologikoen (2013an) epe luzeko informazio hau biltzen du [7, 20]. Aipatu den bezala, informazio klimatologiko honek garrantzia du eraikinen klimatizazio arloan sistema eta ekipoen diseinuan, banaketan eta instalazioan. Emandako informazioa, beste esparruetara heda daiteke, hala nola, nekazaritza edo energia sorrerara. Informazio horren artean, hilabete bakoitzaren erraboil lehor, erraboil hezea eta ihintz puntuaren tenperaturen batez besteko balioak daude; haizearen abiadura eta norabidea, tenperatura maximo eta minimoaren aldeak eta eguzki-erradiazio normala eta difusoa ere agertzen dira. Beroketa eta hezetasuna gehitzeko diseinu baldintzak; hozketa, hezetasuna gutxitzeko eta entalpiaren diseinu-baldintzak urteko diseinuko muturreko baldintzekin agertzen dira ere. Informazio guzti honi dagokion diseinua, Thevenard-ek garatutako ASHRAE RP1435-n [21] agertzen da. 6.9 Irudian, lan hori klima-informazioaz hornitu duten munduan zehar sakabanatutako estazioen kokapena agertzen da.

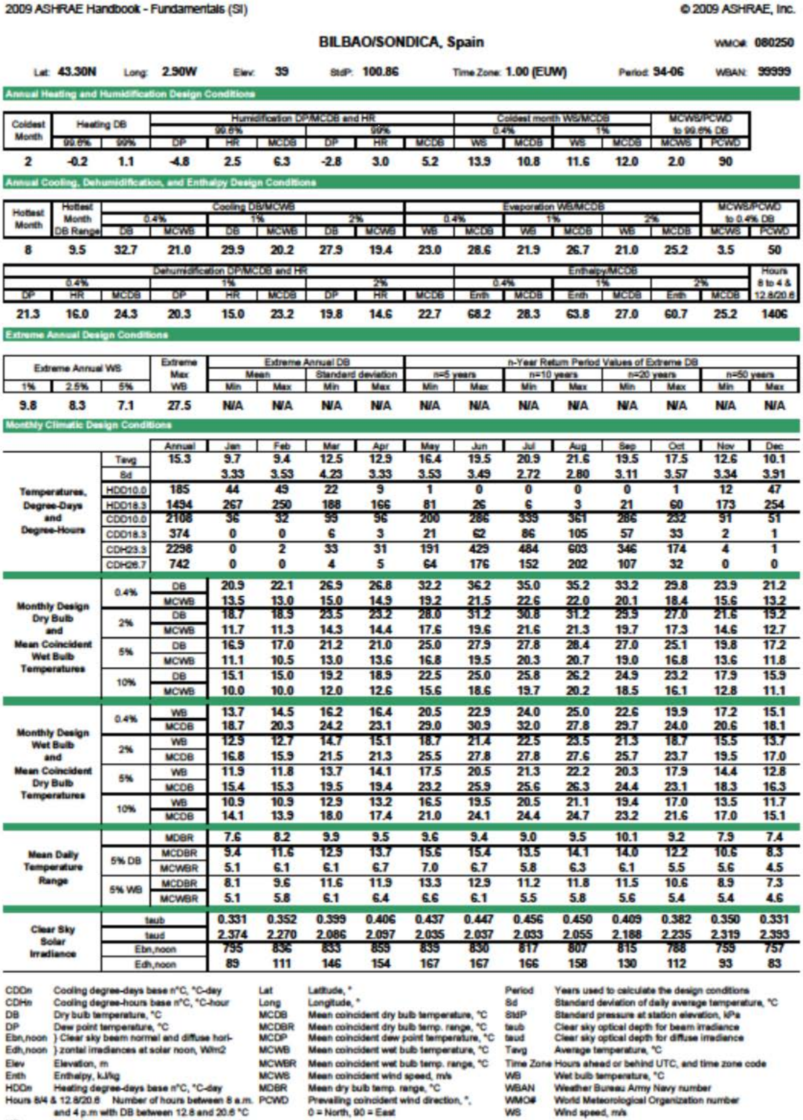


6.9 Irudia. Munduan zehar banatutako 6443 estazioak

Haien artean, kontrol simulazio kasuak egiteko erabili diren tokiak daude, Bilbo eta Ukkle. Bi estazio hauek, klima ozeaniko epelaren eraginpean daude, *Cfb*, Köppenen klima-sailkapenaren arabera, eta haien kokapena gaur egungo Europako klima azaltzen duen 6.10 Irudian agertzen da. Kokapen hauentzako ASHRAE HOF-ek (2009) eskaintzen duen informazioa klimatikoa 6.11 eta 6.12 Irudietan ikus daiteke.



6.10 Irudia. Bilboren eta Ukkleren kokapena Köppenen klima-sailkapen Europako mapan



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BILBAO/SONDICA, Spain

WMO# **080250**

Lat: **43.30N** Long: **2.90W** Elev: **39** StdP: **100.86** Time Zone: **1.00 (EUW)** Period: **94-06** WBAN: **99999**

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB	
			99.6%			99%			0.4%		1%			
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
2	-0.2	1.1	-4.8	2.5	6.3	-2.8	3.0	5.2	13.9	10.8	11.6	12.0	2.0	90

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
8	9.5	32.7	21.0	29.9	20.2	27.9	19.4	23.0	28.6	21.9	26.7	21.0	25.2	3.5	50

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 & 12.8/20.6
0.4%			1%			2%			0.4%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
21.3	16.0	24.3	20.3	15.0	23.2	19.8	14.6	22.7	68.2	28.3	63.8	27.0	60.7	25.2	1406

Extreme Annual Design Conditions

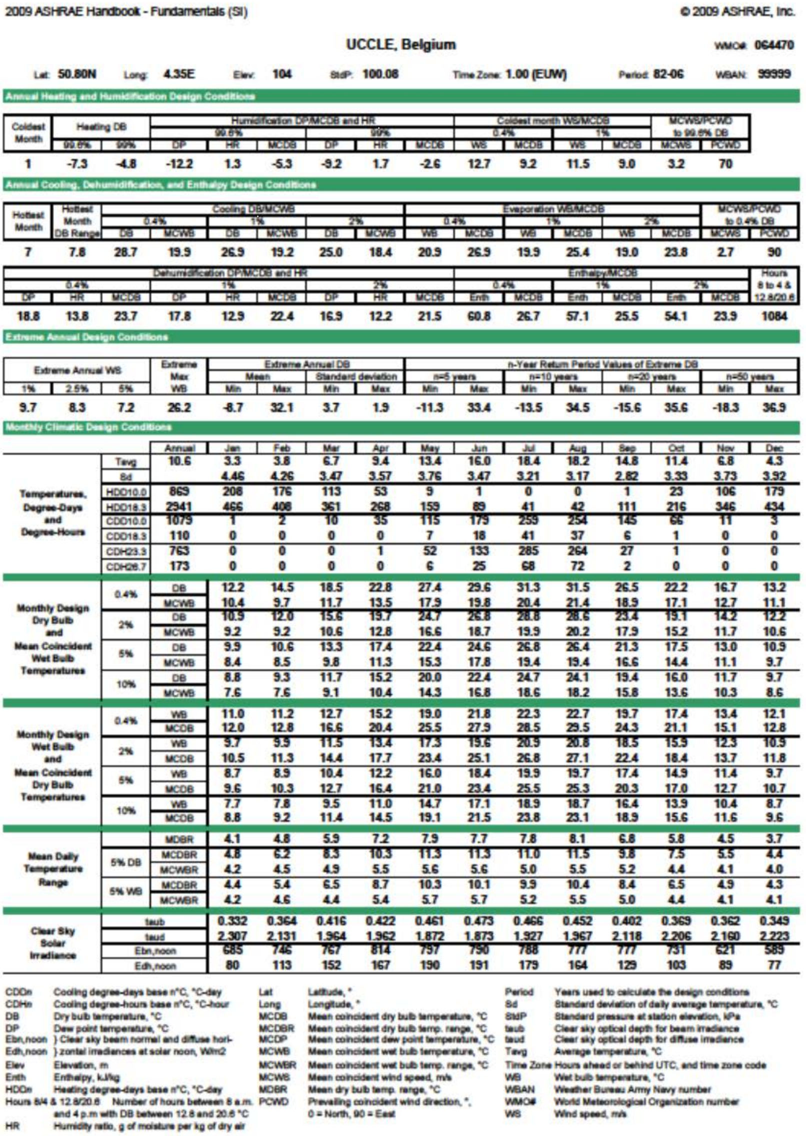
Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
9.8	8.3	7.1	27.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Monthly Climatic Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperatures, Degree-Days and Degree-Hours		Tavg	15.3	9.7	9.4	12.5	12.9	16.4	19.5	20.9	21.6	19.5	17.5	12.6	10.1
		Sd		3.33	3.53	4.23	3.33	3.53	3.49	2.72	2.80	3.11	3.57	3.34	3.91
		HDD10.0	185	44	49	22	9	1	0	0	0	0	1	12	47
		HDD18.3	1494	267	250	188	166	81	26	6	3	21	60	173	254
		CDD10.0	2108	36	32	99	96	200	286	339	361	286	232	91	51
		CDD18.3	374	0	0	6	3	21	62	86	105	57	33	2	1
		CDH23.3	2298	0	2	33	31	191	429	484	603	346	174	4	1
		CDH26.7	742	0	0	4	5	64	176	152	202	107	32	0	0
Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures	0.4%	DB		20.9	22.1	26.9	26.8	32.2	36.2	35.0	35.2	33.2	29.8	23.9	21.2
		MCWB		13.5	13.0	15.0	14.9	19.2	21.5	22.6	22.0	20.1	18.4	15.6	13.2
	2%	DB		18.7	18.9	23.5	23.2	28.0	31.2	30.8	31.2	29.9	27.0	21.6	19.2
		MCWB		11.7	11.3	14.3	14.4	17.6	19.6	21.6	21.3	19.7	17.3	14.6	12.7
	5%	DB		16.9	17.0	21.2	21.0	25.0	27.9	27.8	28.4	27.0	25.1	19.8	17.2
		MCWB		11.1	10.5	13.0	13.6	16.8	19.5	20.3	20.7	19.0	16.8	13.6	11.8
	10%	DB		15.1	15.0	19.2	18.9	22.5	25.0	25.8	26.2	24.9	23.2	17.9	15.9
		MCWB		10.0	10.0	12.0	12.6	15.6	18.6	19.7	20.2	18.5	16.1	12.8	11.1
Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures	0.4%	WB		13.7	14.5	16.2	16.4	20.5	22.9	24.0	25.0	22.6	19.9	17.2	15.1
		MCDB		18.7	20.3	24.2	23.1	29.0	30.9	32.0	27.8	29.7	24.0	20.6	18.1
	2%	WB		12.9	12.7	14.7	15.1	18.7	21.4	22.5	23.5	21.3	18.7	15.5	13.7
		MCDB		16.8	15.9	21.5	21.3	25.5	27.8	27.8	27.6	25.7	23.7	19.5	17.0
	5%	WB		11.9	11.8	13.7	14.1	17.5	20.5	21.3	22.2	20.3	17.9	14.4	12.8
		MCDB		15.4	15.3	19.5	19.4	23.2	25.9	25.6	26.3	24.4	23.1	18.3	16.3
	10%	WB		10.9	10.9	12.9	13.2	16.5	19.5	20.5	21.1	19.4	17.0	13.5	11.7
		MCDB		14.1	13.9	18.0	17.4	21.0	24.1	24.4	24.7	23.2	21.6	17.0	15.1
Mean Daily Temperature Range		MDBR		7.6	8.2	9.9	9.5	9.6	9.4	9.0	9.5	10.1	9.2	7.9	7.4
	5% DB	MCDBR		9.4	11.6	12.9	13.7	15.6	15.4	13.5	14.1	14.0	12.2	10.6	8.3
		MCWBR		5.1	6.1	6.1	6.7	7.0	6.7	5.8	6.3	6.1	5.5	5.6	4.5
	5% WB	MCDBR		8.1	9.6	11.6	11.9	13.3	12.9	11.2	11.8	11.5	10.6	8.9	7.3
		MCWBR		5.1	5.8	6.1	6.4	6.6	6.1	5.5	5.8	5.6	5.4	5.4	4.6
Clear Sky Solar Irradiance	taub			0.331	0.352	0.399	0.406	0.437	0.447	0.456	0.450	0.409	0.382	0.350	0.331
	taud			2.374	2.270	2.086	2.097	2.035	2.037	2.033	2.055	2.188	2.235	2.319	2.393
	Ebn,noon			795	836	833	859	839	830	817	807	815	788	759	757
	Edh,noon			89	111	146	154	167	167	166	158	130	112	93	83

CDDn	Cooling degree-days base n°C, °C-day	Lat	Latitude, °	Period	Years used to calculate the design conditions
CDHn	Cooling degree-hours base n°C, °C-hour	Long	Longitude, °	Sd	Standard deviation of daily average temperature, °C
DB	Dry bulb temperature, °C	MCDB	Mean coincident dry bulb temperature, °C	StdP	Standard pressure at station elevation, kPa
DP	Dew point temperature, °C	MCDBR	Mean coincident dry bulb temp. range, °C	taub	Clear sky optical depth for beam irradiance
Ebn,noon	} Clear sky beam normal and diffuse hori-	MCDP	Mean coincident dew point temperature, °C	taud	Clear sky optical depth for diffuse irradiance
Edh,noon	} zontal irradiances at solar noon, W/m2	MCWB	Mean coincident wet bulb temperature, °C	Tavg	Average temperature, °C
Elev	Elevation, m	MCWBR	Mean coincident wet bulb temp. range, °C	Time Zone	Hours ahead or behind UTC, and time zone code
Enth	Enthalpy, kJ/kg	MCWS	Mean coincident wind speed, m/s	WB	Wet bulb temperature, °C
HDDn	Heating degree-days base n°C, °C-day	MDBR	Mean dry bulb temp. range, °C	WBAN	Weather Bureau Army Navy number
Hours 8/4 & 12.8/20.6	Number of hours between 8 a.m. and 4 p.m with DB between 12.8 and 20.6 °C	PCWD	Prevailing coincident wind direction, °, 0 = North, 90 = East	WMO#	World Meteorological Organization number
				WS	Wind speed, m/s
HR	Humidity ratio, g of moisture per kg of dry air				

6.11 Irudia. Bilboko diseinu-baldintza klimatikoak ASHRAE HOF (2009) agertzen diren moduan



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UCCLE, Belgium

WMO# 064470

Lat: 50.80N Long: 4.35E Elev: 104 StdP: 100.08 Time Zone: 1.00 (EUW) Period: 82-06 WBAN: 99999

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB	
			99.6%			99%			0.4%		1%			
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
1	-7.3	-4.8	-12.2	1.3	-5.3	-9.2	1.7	-2.6	12.7	9.2	11.5	9.0	3.2	70

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
7	7.8	28.7	19.9	26.9	19.2	25.0	18.4	20.9	26.9	19.9	25.4	19.0	23.8	2.7	90

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 & 12.8/20.6
0.4%			1%			2%			0.4%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
18.8	13.8	23.7	17.8	12.9	22.4	16.9	12.2	21.5	60.8	26.7	57.1	25.5	54.1	23.9	1084

Extreme Annual Design Conditions

Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
9.7	8.3	7.2	26.2	-8.7	32.1	3.7	1.9	-11.3	33.4	-13.5	34.5	-15.6	35.6	-18.3	36.9

Monthly Climatic Design Conditions

			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperatures, Degree-Days and Degree-Hours		Tavg	10.6	3.3	3.8	6.7	9.4	13.4	16.0	18.4	18.2	14.8	11.4	6.8	4.3
		Sd		4.46	4.26	3.47	3.57	3.76	3.47	3.21	3.17	2.82	3.33	3.73	3.92
		HDD10.0	869	208	176	113	53	9	1	0	0	1	23	106	179
		HDD18.3	2941	466	408	361	268	159	89	41	42	111	216	346	434
		CDD10.0	1079	1	2	10	35	115	179	259	254	145	66	11	3
		CDD18.3	110	0	0	0	0	7	18	41	37	6	1	0	0
		CDH23.3	763	0	0	0	1	52	133	285	264	27	1	0	0
		CDH26.7	173	0	0	0	0	6	25	68	72	2	0	0	0
Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures	0.4%	DB		12.2	14.5	18.5	22.8	27.4	29.6	31.3	31.5	26.5	22.2	16.7	13.2
		MCWB		10.4	9.7	11.7	13.5	17.9	19.8	20.4	21.4	18.9	17.1	12.7	11.1
	2%	DB		10.9	12.0	15.6	19.7	24.7	26.8	28.8	28.6	23.4	19.1	14.2	12.2
		MCWB		9.2	9.2	10.6	12.8	16.6	18.7	19.9	20.2	17.9	15.2	11.7	10.6
	5%	DB		9.9	10.6	13.3	17.4	22.4	24.6	26.8	26.4	21.3	17.5	13.0	10.9
		MCWB		8.4	8.5	9.8	11.3	15.3	17.8	19.4	19.4	16.6	14.4	11.1	9.7
	10%	DB		8.8	9.3	11.7	15.2	20.0	22.4	24.7	24.1	19.4	16.0	11.7	9.7
		MCWB		7.6	7.6	9.1	10.4	14.3	16.8	18.6	18.2	15.8	13.6	10.3	8.6
Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures	0.4%	WB		11.0	11.2	12.7	15.2	19.0	21.8	22.3	22.7	19.7	17.4	13.4	12.1
		MCDB		12.0	12.8	16.6	20.4	25.5	27.9	28.5	29.5	24.3	21.1	15.1	12.8
	2%	WB		9.7	9.9	11.5	13.4	17.3	19.6	20.9	20.8	18.5	15.9	12.3	10.9
		MCDB		10.5	11.3	14.4	17.7	23.4	25.1	26.8	27.1	22.4	18.4	13.7	11.8
	5%	WB		8.7	8.9	10.4	12.2	16.0	18.4	19.9	19.7	17.4	14.9	11.4	9.7
		MCDB		9.6	10.3	12.7	16.4	21.0	23.4	25.5	25.3	20.3	17.0	12.7	10.7
	10%	WB		7.7	7.8	9.5	11.0	14.7	17.1	18.9	18.7	16.4	13.9	10.4	8.7
		MCDB		8.8	9.2	11.4	14.5	19.1	21.5	23.8	23.1	18.9	15.6	11.6	9.6
Mean Daily Temperature Range		MDBR		4.1	4.8	5.9	7.2	7.9	7.7	7.8	8.1	6.8	5.8	4.5	3.7
	5% DB	MCDBR		4.8	6.2	8.3	10.3	11.3	11.3	11.0	11.5	9.8	7.5	5.5	4.4
		MCWBR		4.2	4.5	4.9	5.5	5.6	5.6	5.0	5.5	5.2	4.4	4.1	4.0
	5% WB	MCDBR		4.4	5.4	6.5	8.7	10.3	10.1	9.9	10.4	8.4	6.5	4.9	4.3
		MCWBR		4.2	4.6	4.4	5.4	5.7	5.7	5.2	5.5	5.0	4.4	4.1	4.1
Clear Sky Solar Irradiance		taub		0.332	0.364	0.416	0.422	0.461	0.473	0.466	0.452	0.402	0.369	0.362	0.349
		taud		2.307	2.131	1.964	1.962	1.872	1.873	1.927	1.967	2.118	2.206	2.160	2.223
		Ebn,noon		685	746	767	814	797	790	788	777	777	731	621	589
		Edh,noon		80	113	152	167	190	191	179	164	129	103	89	77

CDDn	Cooling degree-days base n°C, °C-day
CDHn	Cooling degree-hours base n°C, °C-hour
DB	Dry bulb temperature, °C
DP	Dew point temperature, °C
Ebn,noon	} Clear sky beam normal and diffuse hori-
Edh,noon	} zontal irradiances at solar noon, W/m2
Elev	Elevation, m
Enth	Enthalpy, kJ/kg
HDDn	Heating degree-days base n°C, °C-day
Hours 8/4 & 12.8/20.6	Number of hours between 8 a.m. and 4 p.m with DB between 12.8 and 20.6 °C
HR	Humidity ratio, g of moisture per kg of dry air
Lat	Latitude, °
Long	Longitude, °
MCDB	Mean coincident dry bulb temperature, °C
MCDBR	Mean coincident dry bulb temp. range, °C
MCDP	Mean coincident dew point temperature, °C
MCWB	Mean coincident wet bulb temperature, °C
MCWBR	Mean coincident wet bulb temp. range, °C
MCWS	Mean coincident wind speed, m/s
MDBR	Mean dry bulb temp. range, °C
PCWD	Prevailing coincident wind direction, °, 0 = North, 90 = East
Period	Years used to calculate the design conditions
Sd	Standard deviation of daily average temperature, °C
StdP	Standard pressure at station elevation, kPa
taub	Clear sky optical depth for beam irradiance
taud	Clear sky optical depth for diffuse irradiance
Tavg	Average temperature, °C
Time Zone	Hours ahead or behind UTC, and time zone code
WB	Wet bulb temperature, °C
WBAN	Weather Bureau Army Navy number
WMO#	World Meteorological Organization number
WS	Wind speed, m/s

6.12 Irudia. Ukkleko diseinu-baldintza klimatikoak ASHRAE HOF (2009) agertzen diren moduan

6.2.1 Eguzki-erradiazioa

Eguzki-erradiazioa ongizate termikoan eragin garrantzitsua duen faktoreetariko bat da. Bero iturri gisa, ingurumenak berotzeko erabil daiteke, baina horren eragina gutxitu behar da HVAC sistemak hotza iragatzen duenean. 7. Atalean, errezel sistema bat diseinatuko da bulego batean eguzki-energia era eraginkorrenean aprobetxatzeko. Hori dela eta, puntu honetan da eguzki-erradiazioaren karakterizazioan sakontzen da eta errezel sistemen ezaugarrietan, berriz, hurrengo puntuan.

6.2.1.1 Eguzki-erradiazioa oskarbian. Parametroak

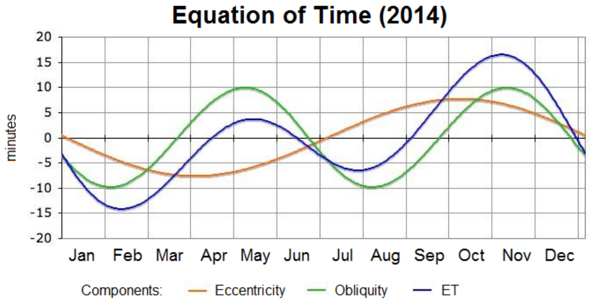
Kokapen jakin baten ordu zehatz batean eguzki-erradiazioa kalkulatzeko, hainbat parametro definitu eta lortu behar dira. Eguzkiaren kokalekua almanaka astronomikoen edo nautikoen bidez kalkula badaiteke ere, kasu honetan modu laburbildua proposatzen da. Ondoren, lurrera heltzen den eguzki-erradiazioa kalkulatzeko behar diren parametroak azaltzen dira.

Eguzki-konstantea eta lurrez kanpoko eguzki-erradiazioa: Dokumentu honen 3. Atalean azaldu den bezala, gorputz guztiek energia igortzen dute tenperatura jakin batean egoteagatik. Eguzkia, gorputz beltzak har daiteke, bere gainazaleko tenperatura 5772 K delarik. Balio horrekin eta lurrarekiko batez besteko distantzia hartuta erraz kalkula daiteke lurrera heltzen den energia, hau da eguzki-konstantea $\mathrm{E_{sc}} \sim 1367\ \mathrm{W/m^2}$. Lurra eta eguzkiaren arteko distantzia aldakorra dela jakinda, balio hori hobe daiteke lurretik kanpoko eguzki-erradiazioaren, $\mathrm{E_{sc}}$, formula erabiliz

$$\mathrm{E_o} = \mathrm{E_{sc}}\left[1 + 0.033 \cdot \cos\left(360° \frac{\mathrm{n} - 3}{365}\right)\right] \tag{6.9}$$

Formula hori hurbilketa bat da; bertan n neurketa egiten den urteko eguna da eta kosinuaren angelua gradu sexagesimaletan emanda dago.

Denbora-ekuazioa eta Eguzki-denbora: Une bakoitzean heltzen den eguzki-erradiazioa kalkulatzeko eguzkiaren kokapen erlatiboa ezagutu behar da. Eguzkiaren inguruan lurrak deskribatzen duen ibilbidea eliptikoa da, eta Kepler-en bigarren legearen arabera, horrek lurrak eguzkiarekiko duen bira abiadura aldatzen duela suposatzen du. Abiadura aldaketa horrengatik, eguzkia ez da egunero helduko haren tokiko meridianora, eguerdira edo altuera maximora, une berean. Beste aldetik, lurraren bira ardatza ez da ekliptikarekiko perpendikularra, 23.45° inguruko zeihartasun angelua du. Denbora-Ekuazioak edo *Equation of Time*-k (ET), eguzkiaren posizioa ezagutzeko hainbat minututakoa izan daitekeen desbideraketa efektu horiek deskribatzen ditu. ASHRAE HOF-ek, Iqubal-en lanean [22] agertzen den formularen erabilera proposatzen du. Astronomi- edo nabigazio-almanakek eguneroko denbora-desbideraketaren informazioa ere ematen dute. 6.13 Irudiak era grafikoan adierazten du fenomeno hori, orbita-abiadura konstante ez izateagatik sortzen diren aurrerapenak eta atzerapenak azalduz. Urte batetik bestera, ET-k aldaketa txikiak erakusten ditu. Grafikoan ikusten den bezala, ET-ren balioak minututan daude.



6.13 Irudia. Denbora ekuazioaren eboluzioa urtean zehar

Mugimendu erlatiboa kontutan izanda, eguzkiak lurra inguratzen du egunean zehar. Behin erreferentzia puntu bat finkatuta, Greenwich, posiblea da jakitea eguzkia non dagoen une jakin batean. Astronomi- edo nabigazio-almanakek, beste balio batzuen artean, Greenwich-entzako orduz orduko eguzkiaren posizioa, longitudea, zehazten dute (GHA). Eguna 24 ordutan banatzen da eguzkiaren abiadura "konstante" mantenduz (ET gogoratu behar da). Lurra 24 meridianotan banatzen bada, eguzkiaren mugimendu erlatiboak ordu batean 15°-ko arkua deskribatzen du. Behatzen den tokiaren longitudea eta ordutegi desfasea ezagutzen badira, behatze puntuarekiko eguzkiak duen posizio angeluarra eta ordua erlatiboak zehaztu daitezke: ordu angelua, *hour angle* (H) eta ageriko eguzki denbora, *Apparent Solar Time* (AST).

$$\mathrm{AST} = \mathrm{LST} + \frac{\mathrm{L} - \mathrm{LSM}}{15} + \frac{\mathrm{ET}}{60} \tag{6.10}$$

$$\mathrm{H} = 15(\mathrm{AST} - 12) \tag{6.11}$$

non LST ordutegi lokala ordu zonaldean, L longitudea eta LSM ordu lokala ematen duen meridianoa diren. Ekuazioan agertzen den "15" osagaiak, denbora eta longitudearen arteko erlazioa finkatzen du: 1 ordu = 15°. Agertzen den "12"a, Greenwich eta ordu aldaketa zonaldeen arteko ordu diferentzia da.

Deklinazioa (δ), eguzkia kokatzeko behar den bigarren aldagaia da. Lurraren ardatza, eguzkiaren inguruan egiten duen ibilbidearekiko, ekliptikarekiko, makurtuta dago. Ekliptika eta ekuatorearen artean 23.45° angelua dago. Honek urtaroak sortarazten ditu. Eguzkiaren deklinazioa, ekuatorearekiko duen posizioa da. ASHRAE HOF-ek honako adierazpen hau proposatzen du deklinazioaren balioa kalkulatzeko, duen zehaztasuna ingeniaritzako aplikaziotarako nahikoa dela jakinda. Hala ere, behar izanez gero, almanakek, orduko balio zehatza ematen dute.

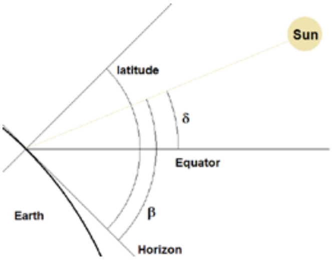
$$\delta = 23.45\sin\left(360°\frac{\mathrm{n}+284}{365}\right) \tag{6.12}$$

6.14 Irudiak deklinazio (δ), latitudea (l) eta eguzkiaren altuera (β) tokiko meridianoan nola erlazionatuta dauden erakusten du eta 6.13 Ekuazioak horren adierazpena ematen du. Eguzkiaren altuera, horizontearekiko osatzen duen gorapen-angelua da.

$$\beta = 90° - |l - \delta| \tag{6.13}$$

Eguzkia tokiko meridianoan ez dagoenean, altuera kalkulatzeko H kontutan hartu behar da eta 6.14 Ekuazioko adierazpenaren bidez lortzen da

$$\sin\beta = \cos l \cdot \cos\delta \cdot \cos\mathrm{H} + \sin l \cdot \sin\delta \tag{6.14}$$



6.14. Irudia. Eguzkiaren deklinazioa ($\boldsymbol{\delta}$) tokiko meridianoan

Eguzkiaren kokapena: Orain arte kokapena definitzeko garapena, Greenwich-ekikoa izan da. Toki jakin bateko eguzki-erradiazioa neurtzeko, eguzkiaren kokapena era lokalean eman behar da. Eguzkiaren kokapena era lokalean finkatzeko bi koordenatu erabiliko dira; bat horizontearekiko **altuera** (β) izango da, bestea **azimuta** (Z). Azimuta plano horizontalean neurtzen da eta eguzkiaren proiekzioa horizontalean hegoarekin osatzen duen angelua da, eguzkiaren posizioak toki horretan duen tokiko meridianoarekiko desbideraketa da. Trigonometria erabiliz, sinuaren eta kosinuren emaitza bi angeluei dagokie. Eguzkiaren azimutaren balioa 6.15 eta 6.16 Ekuazioak erabiliz lortzen da.

$$\sin Z = \frac{\sin\mathrm{H} \cdot \cos\delta}{\cos\beta} \tag{6.15}$$

$$\cos Z = \frac{\cos\mathrm{H} \cdot \cos\delta \cdot \sin l - \sin\delta \cdot \cos l}{\cos\beta} \tag{6.16}$$

Behatze tokiaren kokapena ezagututa, posiblea da aurreko bi ekuazioak batu daitezke azimuta koadrante eran lortzeko.

$$\mathrm{ctan}Z = \frac{\tan\delta \cdot \cos l}{\sin\mathrm{H}} + \frac{\sin l}{\tan\mathrm{H}} \tag{6.17}$$

$\cos l$ eta $\sin\mathrm{H}$ beti positiboak direnez, $\mathrm{ctan}Z$ positiboa bada, Z ipar-hemisferioari dagokio (0-90°) eta negatiboa, berriz, hegoaldea. H da Ekialdea edo Mendebaldea zehazten dituena.

Aire masa: Eguzki-erradiazioa atmosfera zeharkatzean sakabanaketa eta zurgaketa prozesuak pairatzen behar ditu. Horien eragina, soilik eguzkiaren altueraren menpekotasuna du eta Kasten eta Young [23] adierazpena proposatu zuten lurreko puntu baten eta eguzkiaren artean zegoen m aire masa portzentajerentzako. Balio horrek une jakin batean erradiazio bidean dagoen aire masa, eguzkia justu gainean egongo litzatekeenarekin alderatzen du.

$$\mathrm{m} = \frac{1}{\sin\beta + 0.50572(6.07995 + \beta)^{-1.6364}} \tag{6.18}$$

6.2.1.2 Eguzki-erradiazioa oskarbian. Kalkulua

Eguzki-erradiazioak bi osagai nagusi ditu: zuzena eta difusoa. Osagai zuzena, eguzki diskotik zuzenean heltzen diren izpiez osatzen da. Difusoa, berriz, zeruko beste tokitik, zeru domotik, heltzen den erradiazioa da. Bi osagai hauek, gainazal horizontal batentzako, 6.19 eta 6.20 Ekuazioen bidez definitzen dira [7] arabera:

$$\mathrm{E_b} = \mathrm{E_o}e^{-\tau_b m^{a_b}} \tag{6.19}$$

$$\mathrm{E_d} = \mathrm{E_o}e^{-\tau_d m^{a_d}} \tag{6.20}$$

non

$\mathrm{E_b}$	eguzki energiaren osagai zuzena
$\mathrm{E_d}$	eguzki energiaren osagai difusoa
$\mathrm{E_o}$	lurretik kanpoko eguzki-erradiazioa
m	aire masa
τ_b eta τ_d	sakonera-optiko difusoak,
a_b eta a_d	aire masaren osagai zuzena eta difusoa

τ_b eta τ_d lekuaren araberakoak dira eta urtean zehar aldakorrak. Altueraren, airearen ur kopuruaren eta aerosolen gisako faktoreen funtzio dira. Haien balioa 6.11 eta 6.12 Irudiei dagokien tokiko ezaugarrien tauletan agertzen dira. a_b eta a_d koefizienteak τ_b eta τ_d-kin erlazionatuta daude 6.21 eta 6.22 Ekuazio bidez

$$a_b = 1.454 - 0.406\tau_b - 0.268\tau_d + 0.021\tau_b\tau_d \tag{6.21}$$

$$a_d = 0.507 + 0.205\tau_b - 0.080\tau_d - 0.190\tau_b\tau_d \tag{6.22}$$

ASHRAE HOF-ek 2013 arte erabiltzen ziren ekuazioak, bertsio horretan egokitu ziren. Gueymardek eta Thevenardek aldaketa [24]-n azaltzen dute.

Eguzki-erradiazioaren eragina jasotzen duten gainazalek ez dute zertan horizontalak izan beharrik. Atal honetan, edozein orientazioa duen gainazal batek jasotzen duen irradiazioa azaltzen da. Hau egiteko, lehenik eta behin gainazalaren orientazioa bi magnitude bidez definitu behar da. Σ, gainazalak duen inklinazio-angelua da eta 0°-tik, horizontala, 90°-ra, bertikala, aldatzen da. Gainazaleko azimuta, ψ, hegoaldeko proiekzioak eta gainazalaren normalak osatzen duten angelua da. Hau behin definituta, gainazal-eguzki azimuta, γ, zehaz daiteke

$$\gamma = Z - \psi \tag{6.23}$$

Intzidentzia-angelua, θ, eguzki-erradiazioak eta gainazalaren perpendikularrak osatzen duten angelua da eta gainazalari helduko zaion erradiazio-intentsitatearekin loturik dago.

$$\cos\theta = \cos\beta \cdot \cos\gamma \cdot \sin\Sigma + \sin\beta \cdot \cos\Sigma \tag{6.24}$$

Gainazalari heltzen zaion eguzki-erradiazioa, E_t, hiru osagaietan bana daiteke. Osagai zuzenarekiko eta zeruko difusoarekiko normalean txikia izango den beste osagaia ere kontutan hartzen da, lurrean islatutako erradiazio difusoa, E_r. Era sinplean, horrela adieraz daiteke gainazal batek jasotzen duen erradiazioa

$$E_t = E_{t,b} + E_{t,d} + E_{t,r} \tag{6.25}$$

non $E_{t,b}$ osagai zuzena, $E_{t,d}$ osagai difusoa eta $E_{t,r}$ lurrean islatutako osagaiak diren. *Osagai zuzena*, $E_{t,b}$, honako adierazpen honen bidez lor daiteke intzidentzia angelua, $\theta > 0$ denean; beste kasuetan $E_{t,b} = 0$ da.

$$E_{t,b} = E_b\cos\theta \tag{6.26}$$

Osagai difusorako, $E_{t,d}$, [7]-k proposatzen duen adierazpena Stephensonen [25] eta Threlkelden [26] plaka bertikal batentzako egin zituzten saiakuntzetantan oinarrituta dago. Hortik, honako adierazpena lortzen da Σ inklinazio angelua duen gainazal batentzat.

$$E_{t,d} = E_d(Y \cdot \sin\Sigma + \cos\Sigma) \tag{6.27}$$

non $\cos\Sigma$ osagaia berdin zero da $\Sigma > 90°$ denean eta Y-ren balioa 6.28 Ekuazioarekin definitzen den θ intzidentzia angeluaren arabera.

$$Y = \max(0.45\,, 0.55 + 0.43\cos\theta + 0.313\cos^2\theta) \tag{6.28}$$

Azkenik, *lurrean islatutako osagaia*, $E_{t,r}$, 6.29 Ekuazioaren bidez defini daiteke

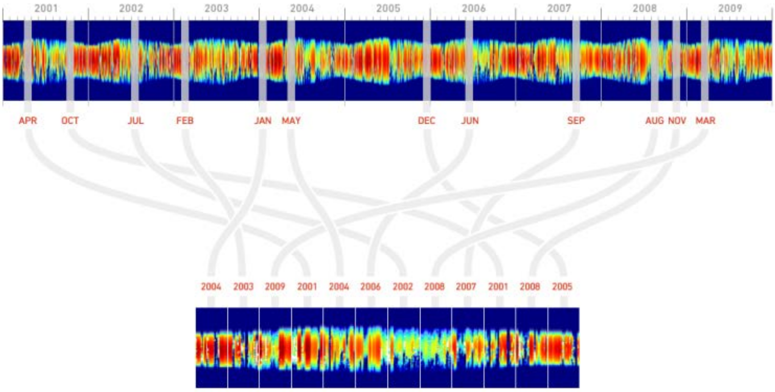
$$E_{t,r} = (E_b \sin\beta + E_d)\rho_g \frac{1 - \cos\Sigma}{2} \tag{6.29}$$

non β eguzkiaren altuera eta ρ_g lurraren islapena diren. $\rho_g = 0.2$ balioa hartzen da hurbilpentzat hainbat gainazalen batez besteko efektua hartuz. [7]-k beste gainazal batzuentzako islapen balioa estimatuak ere ematen ditu. Eguzkitiko islapen osagai honen balioa normalean aurreko biena baino nabarmenki txikiagoa izan ohi da.

Eguzki-erradiazioaren azterketa dokumentu honetan duen garrantzia nabaria da. Hurrengo atalean, errezel-sistema bat integratuko da bulego eraikin baten klimatizazio kontrolean. Ukkleko estazio meteorologikoak emandako datuak kontrol ereduan integratzen dira, haien artean eguzki-erradiazioarenak. Hurrengo Atalean ikusiko da bezala, estazioak eguzki-erradiazioa karakterizatzeko osagai zuzen eta difusoaren balioak ematen dituela denboran zehar.

6.2.2 Informazio Meteorologikoa: Ohiko Urtearen Informazio Bilduma (*Typical Year Data Sets* – TMY)

Urte Tipikoaren Informazio Bilduma, TMY, lokalizazio geografiko zehatz batean hartutako meteorologia-datuen konpilazioa da. Urteetan toki horrek pairatzen dituen baldintzak jasotzen eta prozesatzen dira. Bildutako informazioa urte kopuru luzean zabaltzen da, azken 15 edo 30 urteak hartzen dira kontutan, erregistratuta dagoen informazioaren arabera. Informazioa orduero gordetzen da urtean zehar eta hilabeteka aztertzen da. Azterketa metodoa, Sandia National Laboratories-etan proposatu zuten Hall *et al.*-ek [8] 1978an TMY-ren hasierako bertsioa sortzean. Azterketa metodoa, gaur egungo TMY3 bertsiora hobetu da. Hilabete bakoitzarentzat, urte guztien informazioa hartu da eta 10 parametro aukeratzen dira bakoitzari pisu bat ezartzen zaiolarik. Parametroak honako hauek dira: bulbo hezearen eta lehorraren tenperatura maximo, minimo eta batez bestekoa; haizearen batez besteko abiadura eta abiadura maximoa, eta eguzki-erradiazio globala eta zuzena. Hauek aztertuta, hilabete ohikoena hartzen da TMY-ren hilabete adierazgarri moduan. Horrela lortutako hilabeteak biltzen dira ohiko urtean, urte desberdinen hilabeteen arteko aldeak leunduz, TMY-a sortzeko. Egoera bereziak pairatzen duten urteen azterketa ezohiko jokaera izan duten hilabeteak ezabatuz normalizatzen da. 1982 eta 1991 urtetako Mexiko eta Filipinetako sumendien erupzioek, bi urte horien hainbat hilabetetako informazioa baztertzera behartu zuten. Era berean, Otsailaren 29a ez da TMY-an sartzen. 6.15 Irudian, ohiko urtearen eraketaren grafikoa aurkezten da.



6.15 Irudia. Ohiko Urtearen (TMY-ren) eraketa (solargis.com).

Lokalizazio bakoitzarentzat, informazioa ".csv" fitxategi batean gordetzen da. Estazioa identifikatu ondoren, horren posizioa ematen da. Parametro meteorologikoen TMY-aren orduko informazioa honen ostean agertzen da matrize bat osatuz. TMY3 bertsioan, tokia definitzen duten 68 parametro agertzen dira. Taularen sarrera bakoitzarentzat ematen den informazioa honako parametro hauek osatzen dute: ordua eta eguna, eguzki-erradiazioaren hainbat definizio, argitasuna, hodeien estaldura, bulbo hezeen eta lehorren tenperaturak, hezetasuna, presioa, haizea, ikusmena, hodeien altuera, egin dezakeen euria, egiten duen euria eta aerosolak. Informazioa osatzean ez da muturreko baliorik hartzen, beraz, ez da eraikinen diseinurako informazio egokia. Hala ere erabat egokia da simulazioetarako eta horrela erabiliko da dokumentu honen hurrengo atalean: Ukkleko estazioaren TMYren tenperatura eta eguzki-erradiazioaren balioak hartuko dira, bulego eraikin batek pairatzen dituen baldintza meteorologikoak simulatzeko. Horrela klimatizazioa kontrolatzen duen sistemaren joera azter daiteke eraikinaren eredu bat erabiliz.

6.3 Leiho eta Errezela sistema

Eguzki-erradiazioaren karakterizazioa aztertu ondoren, eraikinetan honek duen eragina aztertuko da. Energia iturri izanik, horren efektua fatxada barnera hedatzen da ingurumena berotuz. Aurreko kapituluetan aztertu da nola karakterizatzen den eguzki-erradiazioaren portaera RC ereduan. Fatxadaren zonalde opakoetan, energia bero-eroapenez transferitzen da materiala bera berotzen den bitartean, zonalde gardenetan, leihoetan, aldiz, erradiazioak beira zeharkatzen du eta barne-ingurumenean eragin zuzena du. Kasu honetan, RC ereduan definitzean aipatutakoa gogoratuz, efektu kapazitiborik ez da kontutan hartuko eta zeharkatzen duen eguzki-energia beiraren transmitantzia edo islapen moduko faktoreen menpe dago. Hoztaz gain, leihoek duten argiztapen efektua ez da ahaztu behar. Errezel sistemaren erabilera, heltzen den erradiazioaren eta argitasunaren eragina egokitzeko baliagarria da. Eguzki-erradiazioaren kontrolak eragina du ingurumenak jasan behar duen karga termikoan. Karga hau neguan handi daiteke errezelak irekiz eta, neurri batean txikituko da udan ixtean, klimatizazio beharra gutxituz.

6.3.1 Leihoak

Leihoen betebehar esparru zabala dute eraikinetan; argitasun eta bero-iturria izateaz gain, aireztatzea baimentzen du eta efektu psikologiko positiboa sor dezake ingurumenaren eta erabiltzaileen artean. Atal honetan, eguzki-erradiazioak leihoen sekzio gardenean zehar duen portaera deskribatzen da, 7. Atalean aplikatzean hobeto ulertzeko. Leiho baten beiran zehar transferitzen den energia, lehen hurbilketa batean, 6.30 Ekuazioak erakusten dituen bi osagaietan bana daiteke

$$\dot{Q} = UA(T_{out} - T_{in}) + gAE_t \tag{6.30}$$

U bero transferentzia koefiziente orokorra da. A azalera, T_{out} eta T_{in} kanpo- eta barne-tenperaturak, g-faktorea, eguzki-energiaren irabazpen-koefizientea eta, berriz, E_t eguzkitiko irradiazioa. Ekuazioaren lehen gaiak tenperatura diferentziak sortutako bero transferentziarekin erlazionatuta dago. Bero transferentzia koefiziente orokorrak, U-k, osagai honen bero-transferentzia karakterizatzen du. Bigarren gaia, berriz, beira zeharkatzen duen eguzki-erradiazioarekin du lotura. g-balioak leihora heltzen den irradiazioarekiko leihoa zeharkatzen duen zatia adierazten du. E_t balioak lehen aipatutako erradiazio zuzena eta difusoak zenbatzen ditu.

Arreta 7. Ataleko azterketara zuzenduz, 6.30 Ekuazioaren bigarren osagaia baino ez da aztertuko, eguzki-erradiazioari dagokiona. Bero-transferentzia erak aztertzean, eguzkiak erradiatutako energia maiztasun banda-batean zabaltzen dela ikusi da.

Erradiazioa gainazal batera heltzen denean, islatu daiteke, absorbatu edo transmititu ondoko ekuazioa betez

$$\rho + \alpha + \tau = 1 \tag{6.31}$$

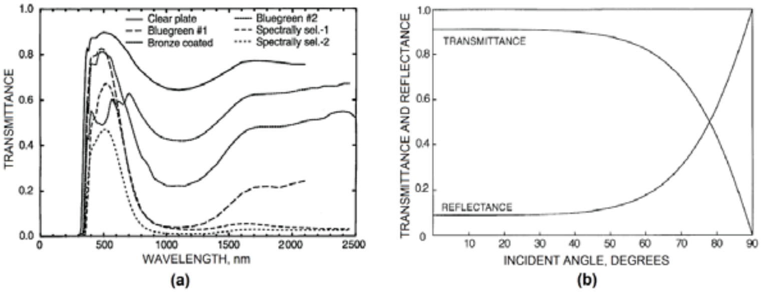
non ρ islapena, α absortibitatea eta τ transmitantzia heltzen den fluxuaren frakzioak diren.

Horrela, posible da beiraren ezaugarriak aldatzea erradiazioarekiko nahi den jokamoldea izan dadin. Beirari islapen geruza bat gehitu daiteke edo islapen eta absortibitatea handitzeko eta transmitantzia gutxitzeko tindatu. Portaera hau, ez da berdina izango espektro guztiarentzat eta beirak jasotzen duen tratamenduaren arabera lortutako transmitantzia desberdina da.

Atmosferak energia altuko erradiazioa, izpi ultramoreak, ia erabat xurgatzen du. Leiho baten beiran zehar ez da argi ikusgaiaz gain, maiztasun baxuko erradiazioa ere pasatzen da. ASHRAE HOF-ek, erradiazio espektroa bi zatitan banatzen da; 0.3 µm-tik 3.5 µm-ra doan espektro tarteari uhin-luzera motzekoa edo eguzki-erradiazioa esaten zaio eta tarte honetan eguzki-erradiazioaren %99-a dago (ISO 9050-ak [9] 2.5 µm-ra jaisten du tartea), ikusgaia barne. 3.5 µm-tik 50 µm-ra doanari uhin-luzera luzekoa edo erradiazio termikoa deritzo eta ingurugiro-tenperaturan dauden gorputzen erradiazio-emisioa tarte honetan kokatzen da.

Eguzki-erradiazioaren eragina gutxitzeko, trataera berezia eman dakioke beirari. Horrela, eguraldi hotzeko zonaldeetan erradiazio solarraren transmitantzia ahalik eta handiena bilatzen da espektro osoan energia aprobetxatzeko. Eguraldi beroko zonaldeetan, aldiz, ikusgaitik kanpoko erradiazioaren transferentzia ekiditen da islapen edo absortibitatea handituz infragorri esparruan. 6.16 Irudiak tratamenduaren araberako beiraren transmitantzia erakusten du. Irudiak ondo erakusten du nola ikusgaia eta gero transmitantzia jausten den.

Eguzki-erradiazioaren intzidentzia-angeluak ere eragina du transmititutako irradiazioan. Intzidentzia angelua 50 ° izan arte, transmitantzia konstantetzat har daiteke, baina angelu balio altuagoentzat hasiko da jausten. Hainbat latitudeetan, hau interesgarria izan daiteke eguzkiaren udako eta neguko altuerak tarte horretan kokatzen badira. Udan eguzkiaren altuera handitzean, intzidentzia angelua ere handituko litzateke, transmitantziaren balioa gutxituz. 6.16 Irudiak joera hau erakusten du.



6.16 Irudia. (ASHRAE HOF). **(a)** Beiren espektro-transmitantzia argi intzidentzia normalaren funtzioan. **(b)** Islapen eta transmitantziaren aldaketa intzidentzia-angeluaren arabera

1200 °C baino tenperatura baxuagoan igorritako erradiazio luzearentzat beirak opakoak dira, normalean. Berotegi efektua, ezaugarri honetan oinarritzen da. Gela batean igorritako erradiazioa ez da leihotik zuzenean aterako eguzki-erradiazioa sartu ahala. Beirak erradiazio hori xurgatuko du eta beraren bi aldetatik igortzen du erradiazio zati bat berreskuratzen. Beira geruza bat baino gehiago dagoenean efektu hau biderkatu egiten da. 6.17 Irudiak infragorrientzako beiraren opakotasuna eta plastikoaren gardentasuna erakusten ditu.

6.17 Irudia. Beiraren opakotasuna (ezkerrean) eta plastiko poltsa baten gardentasuna (eskuinean) infragorrientzat (Internet).

Aipaturiko efektu hauek kontutan hartuta, beiraren g-faktorea kalkulatu daiteke. g-balioa edo eguzki-faktorea (g-*value* edo *solar factor*) amerikako *solar heat gain coefficient* (SHGC) parekoa da. SHGC-k normalean leiho osoa neurtzen du marketeria barne, baina beira soilik neurtzen duenean g-balioaren esanahia du. Faktore horien adierazpenak ASHRAE HOF-en eta ISO 9050-ean [9] agertzen dira.

ASHRAE HOF-ek hainbat geruzatako leihoarentzat proposatutako adierazpena

$$\mathrm{g-value} = \mathrm{SHGC}(\theta) = \tau^{f}(\theta) + \sum_{k=1}^{\mathrm{L}} \mathrm{N}_k \alpha_k^{f}(\theta) \tag{6.32}$$

τ^f	leihoaren aurrealdeko transmitantzia
L	Beira geruza kopurua
α_k^f	k geruzaren absortibitatea
N_k	k geruzan barrurantz doan fluxuaren frakzioa

dira, eta N_k-ren adierazpena honako hau da

$$\mathrm{N}_k = \mathrm{U} \sum_{\mathrm{j}=k}^{1} \mathrm{R}_{\mathrm{j}-1,\mathrm{j}} \tag{6.33}$$

Hau da, *k*-geruzatik kanporantz dauden geruzen erresistentzia termikoa bider leihoaren U-faktorea. Balio hori sinplifikazio bat da, bero-transferentzia koefizienteek eta U-*k* geruzaren tenperaturarekiko menpekotasuna baitute. Azalpen gehiagorentzako, Finlayson eta Arasteh-en [27], LBL-ren [28] eta Wright-en [29] lanetara zuzentzen du testuak.

ISO 9050:2003-ak adierazpen konplexuagoa proposatzen du 6.34 Ekuazioaren adierazpena horrela garatuz intzidentzia normalarentzat

$$\mathrm{g-value} = \tau_e + \mathrm{q_i} \tag{6.34}$$

τ_e eguzkitiko transmitantzia zuzena da eta $\mathrm{q_i}$, berriz, barruranzko bero-transferentzia faktorea. τ_e kalkulatzeko, S_λ distribuzio espektralak erabiltzen dira

$$\tau_e = \frac{\sum_{\lambda=0.3\mu m}^{2.5\mu m} \tau(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=0.3\mu m}^{2.5\mu m} S_\lambda \Delta\lambda} \tag{6.35}$$

non

S_λ	distribuzio espektral erlatiboak, ISO 9845:1:1992 [30]
$\tau(\lambda)$	beiraren espektro-transmitantzia
$\Delta\lambda$	uhin-luzera tarteak

$\mathrm{q_i}$ gaia hiru beira edo gehiago aztertzen direnean horrela idatz daiteke

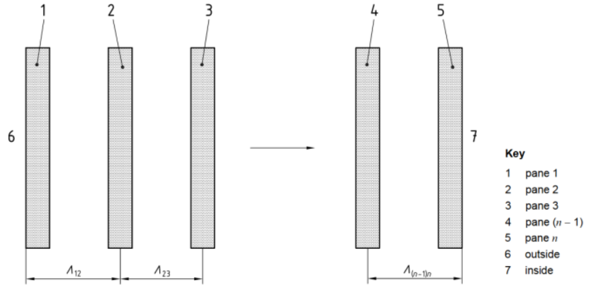
$$\mathrm{q_i} = \frac{\dfrac{\alpha_{e1}+\alpha_{e2}+\alpha_{e3}+\cdots+\alpha_{en}}{h_e} + \dfrac{\alpha_{e2}+\alpha_{e3}+\cdots+\alpha_{en}}{\Lambda_{12}} + \dfrac{\alpha_{e3}+\cdots+\alpha_{en}}{\Lambda_{23}} + \cdots + \dfrac{\alpha_{en}}{\Lambda_{(n-1)n}}}{\dfrac{1}{h_i}+\dfrac{1}{h_e}+\dfrac{1}{\Lambda_{12}}+\dfrac{1}{\Lambda_{23}}+\cdots+\dfrac{1}{\Lambda_{(n-1)n}}} \tag{6.36}$$

α_{e1}	n-geruzetako leihoaren kanpoko (lehen) geruzaren eguzki-absortibitatea zuzena
α_{e2}	n-geruzetako leihoaren bigarren geruzaren eguzki-absortibitatea zuzena
α_{en}	n-geruzetako leihoaren n-geruzaren eguzki-absortibitatea zuzena
h_e, h_i	Kanporantz eta barneranzko bero-transferentzia koefizienteak
Λ_{12}	Bero eroapena lehen geruzaren kanpoko gainazaletik bigarren geruzaren erdiraino
Λ_{23}	Bero eroapena bigarren geruzaren erditik hirugarren geruzaren erdiraino
$\Lambda_{(n-1)n}$	Bero eroapena (n-1)-geruzaren erditik n-geruzaren kanpoko gainazaleraino

6.18 Irudiak leihoaren geometria erakusten du eta geruzen arteko bero-koefizienteak. Batez besteko ohiko balditzen pean, honako hauek dira h_e eta h_i balioak: h_e = 23 W/(m^{2}K) eta h_i = (3.6+4.4ε_i/0.837) W/(m^{2}K). ε_i, ISO 10292:1994-ak [10] definitutako emisibitate zuzendua den. Bero eroapen balioen, Λ-en, kalkulua ISO 10292-ak finkatzen duen eran egin behar da. α_{ei} absortibitate balioak kalkulatzeko era ISO 9050-ean agertzen da. Leihoak transferitutako irradiazioa

$$\phi_{ei} = \mathrm{g}\phi_e \tag{6.37}$$

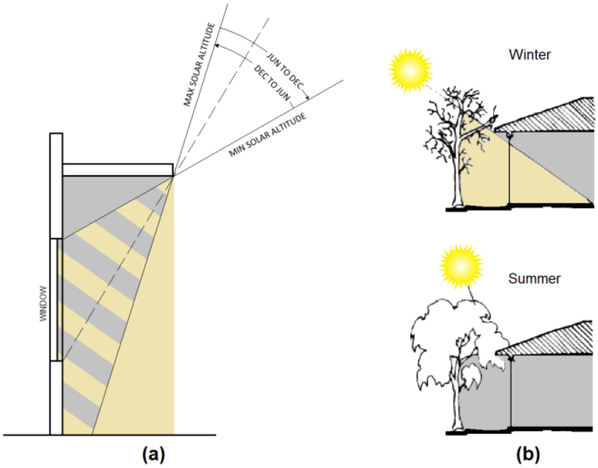
ϕ_e eguzkitiko-erradiazioa eta g leihoaren $g - \text{value}$ izanik.



6.18 Irudia. *n*-geruzen geometria eta bero eroapen koefizienteen azalpena

6.3.2 Errezela sistemak

Eguzki-erradiazioa bero-karga garrantzitsua izan daiteke ingurumen batean. Efektu honek, klima batzuetan neguko beroketan eragin ona badu ere, udan energia erabilera handi dezake klimatizazio beharrengatik. Eguzki-erradiazioaren eragina gutxitzeko erarik eraginkorrena, horren bidea oztopatzea da ingurumenera heldu aurretik. Jada aztertu diren beiren propietate egokien aukeraketa edo geruza plastikoak gehitzea konponbide egokia badira ere, irtenbide arkitektonikoak erabil daitezke, 6.19 Irudiko erlaitza edo begetazioa bezala. Errezelak ere erabil daitezke.



6.19 Irudia. Elementu arkitektonikoen erabilera. Erlaitzen erabilera(a). Eguzkiaren altuera aldaketagatik eguzki-erradiazioa neguan sartzen da baina ez udan. Begetazioaren erabilera (b)

Errezelen erabilerak, intimitatea ziurtatzeaz gain, leihoa zeharkatzen duen irradiazio eta argitasun kontrola ahalbidetzen du. Klems-en [31] eta Wright *et al.*-en [32] ikerketak leiho sistema konplexuak aztertzeko prozedura proposatzen dute, errezelak ere aztertuz. ASHRAE HOF-ek, ISO 15099:2003-ak [11], EN 13363-1:2009-ak [13] eta EN 13363-2:2008-ak [12] ere, errezelen sistemei buruzko azterketak egiten dituzte.

Era sinplifikatuan, errezelaren efektua barneko eguzki-erradiazioaren ahultze koefizientearen, *indoor solar attenuation coefficient* (IAC), bidez defini daiteke

$$\phi_{ei} = \mathrm{g} \cdot \mathrm{IAC} \cdot \phi_e \tag{6.38}$$

non erradiazio zuzenaren eta difusoaren eraginak kontutan hartu diren. 6.38 Ekuazioak erakusten duen bezala, errezelen eragina beirak duenari gehitzen zaio. Normalean bi errezel mota erabiltzen dira; listoi erakoak listoi horizontal edo bertikalez osaturik daude eta leihoaren kanpoaldean, barnealdean edo beira geruzen artean jar daitezke. Bai bibliografia zientifikoan, bai arautegian ere, errezel motak ondo definituta daude.

Sareta motakoa da 7. Ataleko ikerketan erabili den errezela launa. Ehunezkoak izan ohi dira eta harien islatzailetasunak, koloreak eta harien arteko zabalerak zehazten dituzte haien ezaugarriak. Efektu hauek aspaldi aztertu dira eta haien arabera egiten da 6.20 Irudiko sailkapena. Honetan, irekidura faktorearen eta hariaren kolorearen funtzioan bederatzi talde sortzen dira. Irekiera txitxia denean, argitasuna sumatuko da, baina objektuak ez dira ikusiko. Irekiera handia denean, ikusgarritasun orokorra ona da. Ohiko baldintzen pean, era honetako errezelen IAC-ak ez du intzidentzia-angeluaren menpekotasun nabarmenik. ASHRAE HOF-ek leiho eta errezel konbinazio ohikoenentzat balioak ematen ditu. Kotey *et al.*-ek [33] errezel biribilkarien IAC lortzeko ereduei buruzko azalpenak ematen ditu.

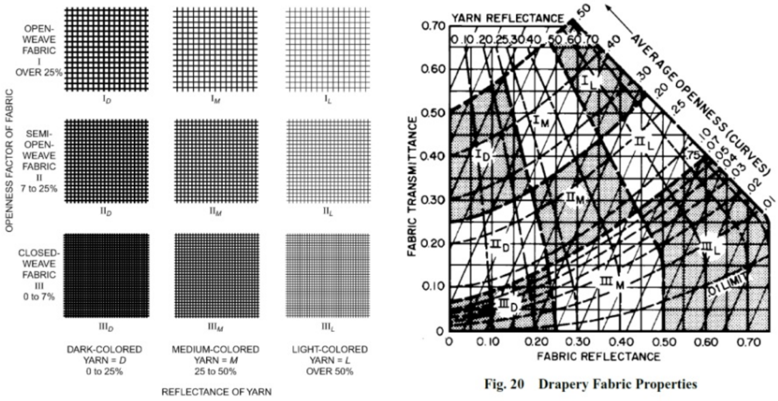


Fig. 20 Drapery Fabric Properties

6.20 Irudia. (ASHRAE HOF) Errezelaren sailkapenaren adibidea irekidura eta hariaren islapen faktorea kontutan harturik (ezkerrean). Transmisio eta islapen faktoreak irekidura eta hariaren islapen faktoreen funtzioan (eskuinean).

EN 13363-1:2006+A1-ek eta EN 13363-1:2006+A1:2008/AC-k ez dituzte leihoak eta errezelak banatzen, sistema oso gisa lantzen dute metodo sinplifikatu bat erabiliz. Arauak aplikazio eremuak mugatzen dituzte, faktoreen balio maximo eta minimoak zehaztuz: errezelaren transmitantzia $0 \leq \tau_{\mathrm{e,B}} \leq 0.5$, islapena $0.1 \leq \rho_{\mathrm{e,B}} \leq 0.8$ eta leiho osoaren transmitantzia $0.15 \leq \tau \leq 0.85$. Arauak, kanpo-, barne- eta beiren arteko sistemak aztertzen ditu horien g balio orokorra zehaztuz. 6.21 Irudian arauak aurkeztutako sistemak agertzen dira. Kanpoko eguzki-babesa duen sistemaren adierazpena honako hau da

$$\mathrm{g}_t = \tau_{\mathrm{e,B}}\mathrm{g} + \alpha_{\mathrm{e,B}}\frac{G}{G_2} + \tau_{\mathrm{e,B}}(1-\mathrm{g})\frac{G}{G_1} \tag{6.39}$$

non

$\alpha_{\mathrm{e,B}} = 1 - \tau_{\mathrm{e,B}} - \rho_{\mathrm{e,B}}$
$G_1 = 5\ \mathrm{W/(m^2K)}$
$G_2 = 10\ \mathrm{W/(m^2K)}$
$G = \left(\frac{1}{U_{\mathrm{g}}} + \frac{1}{G_1} + \frac{1}{G_2}\right)^{-1}$

Barneko eguzki-babesa duen sistemarentzako, arauak honako adierazpen hau ematen du

$$\mathrm{g}_t = \mathrm{g}\left(1 - \mathrm{g}\rho_{\mathrm{e,B}} - \alpha_{\mathrm{e,B}}\frac{G}{G_2}\right) \tag{6.40}$$

non

$\alpha_{\mathrm{e,B}} = 1 - \tau_{\mathrm{e,B}} - \rho_{\mathrm{e,B}}$
$G_2 = 30\ \mathrm{W/(m^2K)}$
$G = \left(\frac{1}{U_{\mathrm{g}}} + \frac{1}{G_2}\right)^{-1}$

Azkenik, beira arteko eguzki-babez sistemarentzako emandako adierazpena honako hau da

$$\mathrm{g}_t = \tau_{\mathrm{e,B}}\mathrm{g} + \mathrm{g}\big(\alpha_{\mathrm{e,B}} + (1-\mathrm{g})\rho_{\mathrm{e,B}}\big)\frac{G}{G_3} \tag{6.41}$$

non

$\alpha_{\mathrm{e,B}} = 1 - \tau_{\mathrm{e,B}} - \rho_{\mathrm{e,B}}$
$G_2 = 3\ \mathrm{W/(m^2K)}$
$G = \left(\frac{1}{U_{\mathrm{g}}} + \frac{1}{G_3}\right)^{-1}$

Eguzki-erradiazio zuzenaren transmitantzia-faktorea, $\tau_{\mathrm{e,B}}$, honako adierazpen hauek zehazten dute:

Kanpo eguzki-babesa sistementzako

$$\tau_{\mathrm{e,t}} = \frac{\tau_{\mathrm{e}}\tau_{\mathrm{e,B}}}{1-\rho_{\mathrm{e}}\rho'_{\mathrm{e,B}}} \tag{6.42}$$

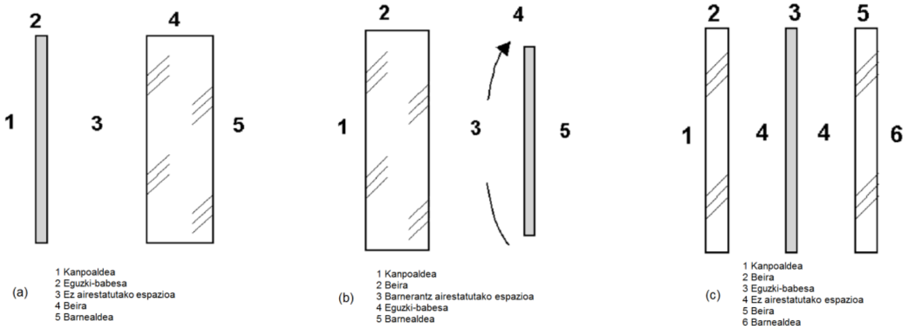
Barne eguzki-babesa sistementzako

$$\tau_{\mathrm{e,t}} = \frac{\tau_{\mathrm{e}}\tau_{\mathrm{e,B}}}{1-\rho'_{\mathrm{e}}\rho_{\mathrm{e,B}}} \tag{6.43}$$

non

τ_{e}	beiraren eguzki-transmisio faktorea
ρ_{e}	kanpoko beira-geruzaren kanpokoaldeko gainazalaren eguzki-islapen faktorea
ρ'_{e}	kanpoko beira-geruzaren barnealdeko gainazalaren eguzki-islapen faktorea
$\tau_{\mathrm{e,B}}$	Eguzki-babesaren eguzki-transmisioaren faktorea
$\rho_{\mathrm{e,B}}$	eguzki-erradiazioari aurre egiten dion eguzki-babesaren aurrealdeko eguzki-islapen faktorea
$\rho'_{\mathrm{e,B}}$	eguzki-erradiazioari aurre egiten dion eguzki-babesaren atzealdearen eguzki-islapen faktorea

7. Atalean garatutako errezel sistema sareta motakoa denez, EN 13363-2-k listoizko eta veneziar erako sistementzako egiten duen azterketa sakona azalpen honen kanpo uzten da.



6.21 Irudia. (EN 13363-2) Leiho eta errezel sistema ezberdinentzako, transmitantzia kalkulua.

6.4 Laburpena

Atal honetan, bulego-eraikinaren klimatizazio kontrola ulertzeko beharrezkoak diren hainbat kontzeptu azaldu dira. Lehen eta behin, ongizate-irizpideak eta horiek finkatzeko arau desberdinek finkatutako parametroak finkatu dira. Horrela, posible izango da MPC-ak bete behar dituen ongizate- eta diseinu- baldintzak definitzea. Honen ondoren, eguraldiaren iragarpenak MPC-an izango duen garrantzia ezagututa, balio hauen azterketa txiki bat egin da, bereziki eguzki-erradiazioarena. Ohiko urte meteorologikoa (TMY) izan da Ukkeleko bulegoaren simulazioa balioz hornitzeko erabili den datu-base meteorologikoa. Baldintza horietan modeloaren egitura aztertu da. Bukatzeko leiho eta errezel sistemak aztertu dira haiekin loturik dauden parametro nagusiak hobeto ulertzeko.

Puntu hauen azterketa, munduan zehar ohikoenak diren arauak eta aholkuak jarraituz egin da.

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7.

Use of an enhanced blind system control to reduce the energy use in an office building

7.1 Introduction

In building sector, office building presents one of the biggest potential for saving energy. This kind of building has some specific proprieties that characterise the use of its climate system, HVAC. As it has been seen in Chapter 3, an important number of companies have constructed new emblematic buildings to represent them. One of the most remarked characteristic of these buildings is their sustainable design; which involves water recovery, improved lighting and high efficiency energy use. Considering that climate systems is one of the mayor energy consumer in the building activity, any improvement carried out in this field will substantially affect global efficiency of the building.

Modern office buildings share some specific that influence the HVAC behaviour. The use of the building is restricted to some time slots in which the indoor climate must be ensured certain comfort limits. Building users usually have no control over the climate control and when they have some, it is only in a moderate way. Air system is normally needed to ensure ventilation although it can also have climate use. Humidity control is usually included in the HVAC to ensure a correct relative humidity. This factor has only moderate influence in the two studied cases in Bilbao and Ukkel due to their moderate Atlantic climate, *Cfb*. Office wardrobe protocol is also standardized by society habits.

The use of TABS provides important energetic savings that can be translated into economic benefits. The integration of the heating system in the building structure is a strategic decision that conditions the behaviour of the building climate system. The large surface used for heat interchange, the surface of the office floor, converts a low exergy system like TABS in a very attractive energy option, especially combined with geothermal or solar systems. The integration of the TABS in the building structure highly increases its thermal inertia what provides a way to reduce the undesired energy use peaks that appears in the global energy use by sifting the energy consumption to a low cost energy rates.

Two-office module is a usually studied office model as can be deduced from many literature works as the ones of Olesen [1], Sourbron [2], Saelens [3] and Li [4]. This model was widely studied in the PhD of Verhelst [5] and Sourbron [6] in order to study the effect of the GEOTABS [7] and the MPC in a modern high quality office building. This study continues the already done work by developing an improved blind system control (BSC) [8] that benefits from solar radiation energy in winter to heat the office while preventing its passage in summer reducing the cooling energy use.

7.2 Two-Office module

The use of two-office model as a repetitive module of an office building allows simulating the behaviour of the building under some desired conditions. In this section the module and its operative conditions are described.

7.2.1 Module design

The office module object of the study is considered part of an office building with a north-south orientation, good quality construction materials and important window surface with shading system. The HVAC systems consists of a main TABS, Concrete Core Activation (CCA) system that is supported by an air handling unit (AHU) that is also used to provide ventilation. The building offices are north-south oriented and the module is composed of three spaces, two office zones and a corridor for separation and access. The climate control provides an individual regulation of the temperature of each room. A cross section of the module is represented in Figure 7.1. TABS is only developed in the offices where there is rising floor, while central corridor has been designed with suspended celling. Outer wall has been designed with 0.1 m mineral wool insulation. Design characteristics appear in the Sourbron PhD document [6] and are represented in the Tables 7.1 and 7.2. Table 7.1 presents the geometric characteristics of the module spaces while Table 7.2 shows a summary of the characteristic values of the façade of the module.

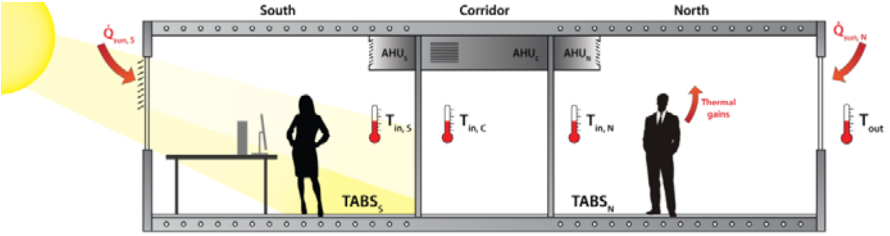


Figure 7.1. Cross representation of the modelled two office zones and corridor module

Table 7.1. Module characteristics

Two Zone Building Parameters	Unit	Value
Area of the South or North zone	m^2	12
Area of the corridor	m^2	4.32
Heated volume	m^3	96.3
Heated area	m^2	28.3
Transmission area	m^2	8.6
U-value external wall	$W/(m^2 \cdot K)$	0.41
U-value total façade	$W/(m^2 \cdot K)$	0.85
Percentage of glazing	%	50

Table 7.2. Technical characteristics of wall layouts and windows

Wall	*d* (m)	*U* ($W/m^2 \cdot K$)
Outer wall	Plaster-Concrete block-Mineral wool-Brick 0.01-0.14-0.1-0.09	0.41
Internal wall	Gypsum board-Mineral wool-Gypsum board 0.012-0.05-0.012	0.79
Floor/Ceiling	Floor tiles-Air layer-Screed-Reinforced concrete with CCA-Plaster 0.04-0.41-0.05-0.2-0.01	1.38
Suspended ceiling	Ceiling tiles-Air layer-Reinforced concrete-Screed-Air layer-Floor tiles 0.01-0.2-0.2-0.05-0.41-0.04	1.11
Window	***U* ($W/m^2 \cdot K$)**	***g*-value**
Window glass	1.10	0.40
Window frame (15%)	2.00	-
Window total	1.29	0.36
Solar shading	-	0.25

There are some other factors that define the operation of the module:

Ventilation: Hygienic ventilation is ensured using the AHU with a reposition rate of 36 m^3/h person according to the specifications of EN 15251:2007 [9]. This system will also ensure a correct humidification and heating or cooling support for the TABS in temperature control.

Solar shading system: Due to the orientation of the module, it is necessary to provide a solar shading device to reduce the solar radiation in the south oriented office. The shading device lowers when solar radiation excess $\dot{Q}_{sol}$ > 250 W/m^2 and rises when $\dot{Q}_{sol}$ < 150 W/m^2 [6]. The undefined radiation range between these two values allows implementing different control policies in order to reduce the amount of consumed energy. A first design uses a hysteresis control between the bound values that in this work is changed by an improved control that uses the predictive capacities of the main climate control, an MPC, to reduce the heating and cooling energy use. Blind system (BS) is implemented in both north and south offices, although its use is not necessary in the north office, it has been implemented in order to observe its behaviour. Elected BS is dark-coloured yarn closed-weave fabric as can be seen in Figure 7.2. The system decreases the solar transmittance having g-value = 0.25 and it has no intermediate positions between open and close states. The windows are three-layer glass with a global g-value of 0.36, as represented in Table 7.2.

Figure 7.2. Blind system opacity effect during solar eclipse of 20 March of 2015 in Leuven, Belgium

The climate system: The HVAC is composed by two different climate systems in order to ensure the thermal comfort of the users:

- Thermally Activated Building System (TABS) is the main option for heating and cooling operations in the offices. In order to take advantage of the thermal inertia of the building structure, water pipes are embedded in the concrete, which stores and provides the energy for climate control to the office zones via convection and radiation. Considering the typical heat pump and direct cooling configurations, Sourbron defines in [33] the maximum heating values between 79 and 86 W/m² for heating and between 42 and 65 W/m² for cooling. The model under study supposes a power of 50 W/m² for both heating and cooling, which provides 600 W power for one office zone. This system is not implemented in the corridor. The climate control prioritizes its use and cooling or heating mode is determined by season considerations and will never be activated together. No considerations about the heating or cooling equipment have been done although the use of an electric or gas heat pump and a gas boiler can be a typical choice for heating, while a heat exchanger, a chiller or a reversed heat pump could be the cooling option.
- An auxiliary Air–Handling Unit (AHU), necessary for ventilation and air conditioning, fulfils additional power request. The system adjusts the indoor temperature when the TABS is not able to provide enough heating or cooling power or its response is not quick enough to maintain the comfort conditions. The AHU can contribute with an additional 850 W for heating and cooling in each office zone and 360 W in the corridor.

Occupation: Offices are supposed to be occupied on weekdays from 08:00 to 18:00 hours with a stop from 12:00 to 13:00 for lunchtime. Internal gains are considered for human activity, $\dot{Q}_{people}$, office appliance, $\dot{Q}_{appl}$, and illumination, $\dot{Q}_{light}$, for that time according with the values provides in ASHRAE Handbook Fundamentals (ASHRAE HOF) [10] revised by the results of the works of Hosni *et al.* [11] and Hosni and Beck [12] for an occupancy of one person/10 m². The aforementioned work of Verhelst shows the time distribution of these loads during a weekday as represented in Figure 7.3. Small residual gains are considered during no-office hours. Table 7.3 shows a description of these internal gains.

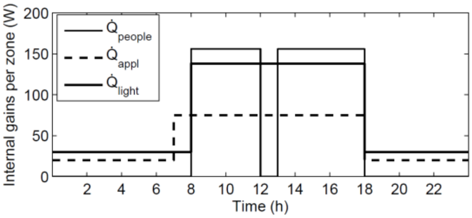


Figure 7.3. Internal gains during a weekday in an office zone

Table 7.3. Operative parameters of the office module

Parameter	Value
Occupancy rate	1 person per 10 m^2
Sensible heat gains from people	7.5 W/m^2
Latent heat gains from people	5.5 W/m^2
Appliances heat gains	7.8 W/m^2
Lighting heat gains	7.5 W/m^2
Zone thermal capacitance	5 times the air thermal capacitance.
Convective heat transfer values of floor and ceiling	correlations of Awbi and Hatton [13]
Radiative heat transfer coefficient	5.6 W/m^2
Infiltration rate	0.05 ACH during AHU-operation, 0.2 ACH no-oper
Ventilation rate	36 m^3/h pers (EN15251 [9] [Class II])

7.2.2 Weather information

The weather information has been widely discussed in Chapter 6, due to the availability of the weather information of the Ukkel meteorological station, the office building is considered to be in Brussels region; moderate Atlantic climate and latitude about 51° north. Information of the Typical Meteorological Year, TMY3, is used to provide the simulations the necessary data of the weather perturbations that affect the building. Two main effects are considered, outdoor temperature and solar irradiation.

Outdoor temperature: affects the heat loses or gains through the building façade, which are minimized by the use of a thick mineral wool layer. The temperature pattern is represented in Figure 7.4 (a), where the seasonal variation is clearly observed. Climate can be considered moderate, with no extreme temperatures.

Solar radiation: Its incidence over the façade must be considered a heat source. The heat will propagate through wall and heat the indoor environment. The incidence over the windows implies the transference of the window's g-value fraction of the incident radiation that will affect inner walls, floor and appliances. The use of a BS reduces even more the solar radiation effect. The solar radiation has been considered as the sum of the effect of the direct and diffuse radiations. Figure 7.4 (b) and (c) show the incident solar irradiation pattern for north and south oriented offices. Figures show the amplitude difference between both orientations, the slight value in the north orientation that minimizes the need of a BS. The effect of a ledge for the south orientation is also observed; it reduces the incident radiation in summer, when the Sun increases its relative height. In this case, the use of a BS is necessary.

There exists other meteorological parameters that affect the building behaviour as the outside wind effect that varies the façade convection coefficient and consequently its U-value or the humidity, no too extreme in this climate. These effects have not been reflected in the model under the consideration that they are much less representative than the outdoor temperature and solar radiation.

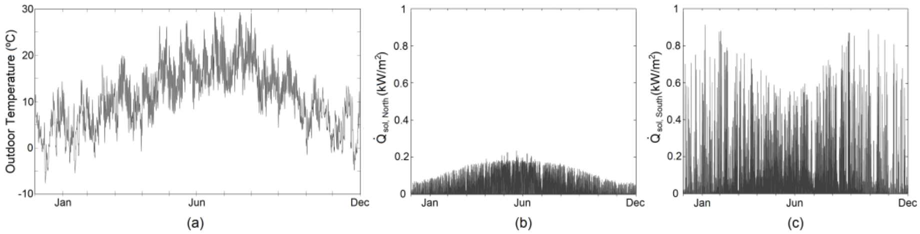


Figure 7.4. Weather condition evolution during the year. Outdoor temperature (a) and solar irradiation in North (b) and South (c) offices (kW/m^2)

7.2.3 Comfort parameters

Chapter 6 described the parameters that affected the thermal comfort in a building. Considering the typical office activity, metabolism and costume parameters can be supposed to be as defined. The use of TABS limits velocity of the indoor air. The need of use of the AHU is reduced and consequently the velocity of the air associated to this system decreases. The big heat exchange surface and the low temperature difference also induce slower air movements. Under a moderate climate, humidity control is not critical and if necessary, it can be slightly corrected without affecting in a substantial way the comfort parameters or the energy consumption.

Once the influence of these parameters is weighted under the conditions of the study, it is possible to design temperature as the main comfort parameter for office users and focus the control action on maintaining it inside a comfort band.

The thermal discomfort is evaluated in Kelvin·hours (Kh) that can be defined as the hours that the users stay out the comfort range multiplied by the temperature deviation out of the range. This is one of the options that both ISO 7730:2005 [14] and ASHRAE 55 [15] provide for comfort evaluation and it has been implemented as described in Equation 7.1 when the deviation is larger than 0.1 K. The simplicity of this method as well as the results of the control action, which show only very small deviation from the comfort range, justifies this decision over other options. PMV/PPD is other equally valid common comfort definition.

$$\text{Kh} = \sum_{i} \left| \Delta T_{dev,i} Ts_i \right| \qquad i \in \{occupation\ period\} \tag{7.1}$$

where ΔT_{dev} is the temperature deviation from the defined comfort band and Ts the time step.

In order to improve energy savings, winter temperature ranges have been slightly reduced, which can be compensated increasing clotting factor. Temperature reference and the comfort band defined around it depend on the outdoor conditions that are given by the season, which also determinates the TABS configuration. When the TABS is configured for heating, the reference temperature for offices during the day is 20 °C, with a comfort band of 2 °C below and above the reference. In order to reduce the energy use, there is no temperature reference during night and weekend time and the lower limit of the comfort band drops to 16 °C in these periods. Due to its predictive nature, MPC has no problem to recover the comfort band around the temperature reference at the beginning of the working day. Assuming adapted wardrobe protocol, during the cooling season; in summer, the values for the reference temperature during the day is raised to 24 °C and the upper and lower bounds of the comfort band are raised to 26 °C and 20 °C respectively. For the corridor, due to the thermal isolation from the exterior provided by the office zones, no temperature reference is fixed the comfort band delimits the comfort situation. Comfort definition also considers parameters like temperature variation velocity or surface temperature of the TABS that must be inside the ranges defined in Chapter 6. Table 7.4 defines the temperature values during office-hours for heating and cooling situations.

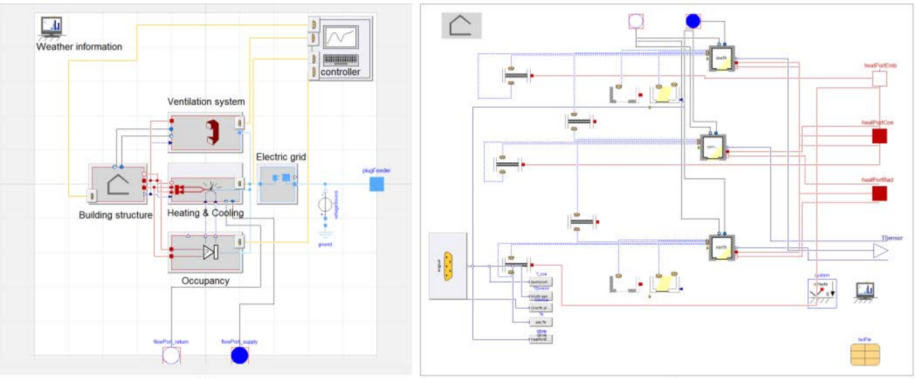
Table 7.4. Reference values and comfort band limits for temperature (in °C). Office hours are considered from 08:00 to 18:00

Comfort Definitions	**Heating**		**Cooling**	
	Office Hours	**Night/Weekend**	**Office Hours**	**Night/Weekend**
Upper temperature	22	22	26	26
Reference	20	no ref	24	no ref
Lower temperature	18	16	20	20

7.3 Model creation

Once the office module and operation parameters are defined, it is possible to create a model of the office module in order to implement the control action over an MPC. As described in Chapter 4, it is possible to create a white-box model of the module using a building energy simulation program as TRNSYS or EnergyPlus. The use of Modelica and the library IDEAS allows the creation of a white –box model of the module based on the physics of its components interactions the specifications of Tables 7.1 to 7.3. Modelica provides a graphical interface that allows the connexion of predefined elements in order to calculate the interactions among them. Figure 7.5 (a) provides a Modelica global representation of the office module divided in different component; the building structure, ventilation system, heating and cooling system, weather and occupancy information… Figure 7.5 (b) shows the inner part of the building structure module where the interrelation of the three spaces and the effects of the outdoor temperature and solar radiation appears. Each component has associated a code that defines its behaviour and relation with other elements.

Picard *et al.* [16] describe the linearization of the model of the building energy simulation created using Modelica to an RC model. The deep of the modelling description provokes the appearance of a 50 states state-space model when the linearization is done. This 50 states state-space model describes the system in matrix notation using a RC representation. This model, validated using TRNSYS, characterizes the office module dynamics as represented in Equation 7.2 for a continuous system.



(a) (b)

Figure 7.5. Modelica representation of office module (a) and building structure (b)

The discussion about the dimensions of the components appears in Chapter 4. The states represent the temperatures of the different elements of the module, being the temperatures of the office zones and corridor the main control objective. The other states are assigned to the TABS, the wall between office zones and corridor and the temperature of the external façades and windows. The independent treatment of both office zones and the corridor results in a relatively high number of 50 states. In particular, four states characterize the behaviour of each TABS defining the temperature of the concrete and its covering. The façade and the inner partition walls are determined by four further states in each room. No capacity has been considered for windows, whose behaviour is defined by their thermal resistance and g factor. As described in [16], the non-linearity of the transmittance of solar radiation under varying incidence angles is treated as an input to the linearized model. The walls between different office modules and TABS embedded into the floor and ceiling are assumed adiabatic. The model also includes the action of the HVAC system, TABS and AHU, as well as the influence of external perturbations like the weather, the human activity and the use of office devices.

$$\begin{aligned} \dot{\boldsymbol{x}} &= \mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{u} \\ \boldsymbol{y} &= \mathbf{C}\boldsymbol{x} + \mathbf{D}\boldsymbol{u} \end{aligned} \tag{7.2}$$

The thermal behaviour of the office module is controlled by an MPC that actuates over the TABS and AHU. In order to implement the system under the MPC, the disturbances that affect the office module are divided in two groups; the action of the climate control, $\boldsymbol{u}$, and the effect of the weather parameter and internal gains, $\boldsymbol{v}$. Solar radiation effect over the windows appears as a nonlinear term, $\boldsymbol{u}_{\mathrm{BS}}\boldsymbol{v}$, due to effect of the control associated to the BS.

$$\begin{aligned}\dot{\boldsymbol{x}} &= \mathbf{A}\boldsymbol{x} + \mathbf{B}_u\boldsymbol{u} + \mathbf{B}_v\boldsymbol{v} + \mathbf{B}_{uv}\boldsymbol{u}_{\mathrm{BS}}\boldsymbol{v} \\ \boldsymbol{y} &= \mathbf{C}\boldsymbol{x} + \mathbf{D}_u\boldsymbol{u} + \mathbf{D}_v\boldsymbol{v} + \mathbf{D}_{uv}\boldsymbol{u}_{\mathrm{BS}}\boldsymbol{v}\end{aligned} \tag{7.3}$$

where $\boldsymbol{x} \in \mathbb{R}^{\mathrm{n}_x}$ is the state vector and n_x the number of states, $\boldsymbol{u} \in \mathbb{R}^{\mathrm{n}_u}$ is the control action of the HVAC system with n_u actuators (2 TABS and 3 AHU) and $\boldsymbol{v} \in \mathbb{R}^{\mathrm{n}_v}$ is the vector that represents the n_v disturbances in the system: outdoor temperature, solar radiation for north and south orientation, internal gains associated to human activity in the office, the appliance use and the lighting. Vector $\boldsymbol{y} \in \mathbb{R}^{\mathrm{n}_y}$ contains the n_y values observed in the system. $\mathbf{A}$, $\mathbf{B}_u$, $\mathbf{B}_v$, $\mathbf{B}_{uv}$, $\mathbf{C}$, $\mathbf{D}_u$, $\mathbf{D}_v$, $\mathbf{D}_{uv}$ are the matrices that define the system. $\mathbf{A} \in \mathbb{R}^{\mathrm{n}_x \times \mathrm{n}_x}$ defines system dynamics, $\mathbf{B}_u \in \mathbb{R}^{\mathrm{n}_x \times \mathrm{n}_u}$ represents the effect of the control action on the system, $\mathbf{B}_v \in \mathbb{R}^{\mathrm{n}_x \times \mathrm{n}_v}$ determines the effect of the disturbances on the system and $\mathbf{B}_{uv} \in \mathbb{R}^{\mathrm{n}_x \times \mathrm{n}_{\mathrm{BS}}}$ determines the influence of the solar radiation among the windows where n_{BS} is the BS number. $\boldsymbol{u}_{\mathrm{BS}} \in \mathbb{R}^{\mathrm{n}_{\mathrm{BS}} \times \mathrm{n}_v}$ is the matrix associated with the action of the BSC. $\mathbf{C} \in \mathbb{R}^{\mathrm{n}_y \times \mathrm{n}_x}$, $\mathbf{D}_u \in \mathbb{R}^{\mathrm{n}_y \times \mathrm{n}_u}$, $\mathbf{D}_v \in \mathbb{R}^{\mathrm{n}_y \times \mathrm{n}_v}$ and $\mathbf{D}_{uv} \in \mathbb{R}^{\mathrm{n}_y \times \mathrm{n}_{\mathrm{BS}}}$ give the values of the system states making it observable. The action of the solar radiation is decoupled; the effect of the solar radiation over the façade is represented in $\mathbf{B}_v$ matrix, meanwhile the nonlinear term $\mathbf{B}_{uv}\boldsymbol{u}_{\mathrm{BS}}\boldsymbol{v}$ determines the effect of the solar radiation through the windows and BS in the office spaces. The discrete-reduced state-space model also maintains this representation. In order to correctly evaluate the effect of the solar radiation, it is necessary to decouple the solar action over the façade, $\mathbf{B}_v\boldsymbol{v}$ and through the windows and BS, $\mathbf{B}_{uv}\boldsymbol{u}_{\mathrm{BS}}\boldsymbol{v}$ before discretize or reduce the order of the system. These actions convert the linearized grey-box system model into a black-box one where the terms inside the matrices have not physical meaning.

The implementation of the MPC requires a discrete state-space representation of the model that will use a fifteen minutes time step, Ts. The discretization and linearization of the system around the operation point causes the loss of the simplicity of the sparse matrices in the continuous-time domain. This generates a rise in computation time and complexity associated to the control. In order to reduce the complexity of the system and to decrease the computational effort, the system dimension is reduced to a more manageable 25 states. The state reduction implies the loss of the physical meaning of the states, so $\boldsymbol{y}$, the output vector, is necessary to recover the information needed for the evaluation of the results.

The reduction of the number of states of the state-space model is performed using a balanced model truncation via square root method as described by Safonov and Chiang in [17]. Although in this case, the number of states is reduced to 25, once observability and controllability is ensured, it is possible to decrease the state number without losing the meaning of the system by reducing the number of the largest singular values that represent the system.

7.4 Climate control of the office module

This point describes the two controls present in the office module, the main control of the HVAC, an MPC that actuates over the TABS and AHU to ensure the comfort inside the offices and corridor and the control of the BS that controls the solar radiation through the window system. A novel control algorithm that takes into account predicted information of the MPC is proposed for the BS. Figure 7.6 shows a scheme of the MPC control action over a building. The BSC receives predicted energy use information to manage this system independently of the MPC. Two state estimation Kalman filters have been added in order to reduce the deviations of incorrect weather forecast and inaccurate building model.

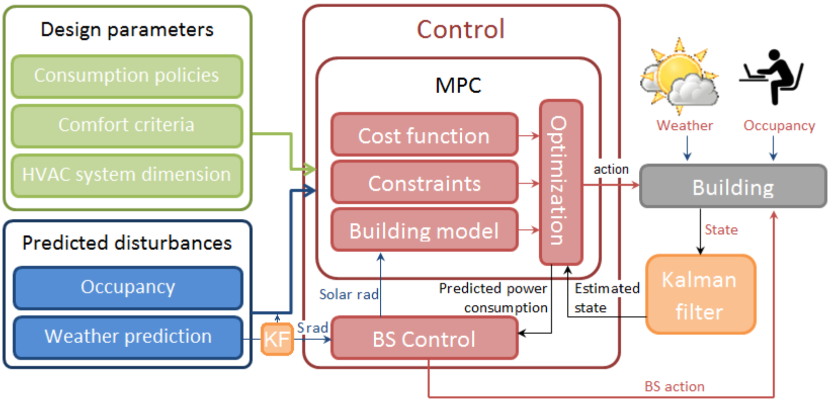


Figure 7.6. Model Predictive Control (MPC) scheme of the control for the Heating, Ventilating and Air-Conditioning (HVAC) system of a building with the proposed enhanced Blind System Control

7.4.1 Main Control of the Heating, Ventilating and Air-Conditioning System: Model Predictive Control (MPC)

This point defines the operative mode of the HVAC system under the MPC as well as the parameters that characterize the MPC and the restrictions it must fulfil. The system time step is fixed to 15 minutes while the prediction horizon of the MPC is 12.5 hours. When larger prediction horizon has been considered, control does not improve the comfort or energy consumption results in a significant mode. Multi-objective behaviour if the MPC must guarantee the comfort conditions while minimizing the energy use

TABS seasonal use: To avoid an undesired frequent switching between hot and cold activation of the TABS, the control defines a seasonal TABS action. Based on the meteorological forecast of a characteristic Belgian TMY for outside temperature and solar irradiance, the TABS is designated for cooling from spring to the middle of autumn and for heating during the rest of the year. In addition to meeting the needs of ventilation and humidity, the AHU will satisfy the need for additional heating or cooling power necessary to maintain the thermal comfort.

Minimization function and constraints: As mentioned in the introduction, the use of an MPC can realise an improvement of 15% or more in energy savings compared to other controls such as Rule Based Control, RBC, that are widely used in HVAC control. The MPC uses measured and predicted disturbances that influence the system to calculate the control action. The minimization of a cost function for the $\boldsymbol{u}$ vector is a typical constrained quadratic programming problem represented by Equation 7.4 with a prediction horizon, $\mathrm{N_p}$, subject to the constraints given by Equations 7.5 to 7.9. The solution of the minimization provides the minimum action the HVAC system needs to guarantee the thermal comfort in the building.

$$\min_{\boldsymbol{u}_0 \dots \boldsymbol{u}_{\mathrm{N_p}-1}} \sum_{\mathrm{k}=0}^{\mathrm{N_p}-1} \left(\left(\boldsymbol{\omega} - \boldsymbol{y}_{office}\right)_{\mathrm{k}}^{\mathrm{T}} \mathbf{Q} \left(\boldsymbol{\omega} - \boldsymbol{y}_{office}\right)_{\mathrm{k}} + \boldsymbol{u}_{\mathrm{k}}^{\mathrm{T}} \mathbf{R} \boldsymbol{u}_{\mathrm{k}} + \boldsymbol{\varepsilon}_{\mathrm{k}}^{\mathrm{T}} \mathbf{S} \boldsymbol{\varepsilon}_{\mathrm{k}} \right) \tag{7.4}$$

where $\boldsymbol{y}_{office} = (\mathrm{T_{north}}, \mathrm{T_{corridor}}, \mathrm{T_{south}})^{\mathrm{T}} \subset \boldsymbol{y}$ is the vector that stores the indoor temperatures of the office zones and corridor, which is a subset of vector $\boldsymbol{y}$, outputs of the system, $\boldsymbol{\omega}$ is the vector of temperature references for office zones and corridor. $\boldsymbol{u}$ is the vector that provides the control actions (energy use). $\mathbf{Q} \in \mathbb{R}^{\mathrm{n}_{y\_\mathrm{office}} \times \mathrm{n}_{y\_\mathrm{office}}}$, with $\mathrm{n}_{y\_\mathrm{office}}$ the number of controlled temperatures, and $\mathbf{R} \in \mathbb{R}^{\mathrm{n}_u \times \mathrm{n}_u}$ are diagonal positive semidefinite matrices that weigh the deviation from the reference temperature and the energy use in the minimization, and k is the evaluated time moment of the prediction horizon. $\mathbf{S} \in \mathbb{R}^{\mathbf{n}_{\boldsymbol{\varepsilon}} \times \mathbf{n}_{\boldsymbol{\varepsilon}}}$ is the weight matrix associated to the $\boldsymbol{\varepsilon}$ parameter, its values being significantly larger than the ones of $\mathbf{Q}$ and $\mathbf{R}$.

The system is subject to the following constraints:

$$\mathbf{MinPower}_{\mathrm{k}} < \boldsymbol{u}_{\mathrm{k}} < \mathbf{MaxPower}_{\mathrm{k}} \tag{7.5}$$

$$\mathbf{T}_{\mathrm{min,k}} - \boldsymbol{\varepsilon}_{\mathrm{k}} < \boldsymbol{y}_{office,\mathrm{k}} < \mathbf{T}_{\mathrm{max,k}} + \boldsymbol{\varepsilon}_{\mathrm{k}} \tag{7.6}$$

$$\boldsymbol{\varepsilon}_{\mathrm{k}} > 0 \tag{7.7}$$

$$\mathbf{T}_{\mathrm{surfmin,k}} < \boldsymbol{y}_{\mathrm{surf,k}} < \mathbf{T}_{\mathrm{surfmax,k}} \tag{7.8}$$

$$\left|\Delta \boldsymbol{y}_{office,\mathrm{k}}\right| < \Delta \mathbf{T}_{\mathrm{max,k}}; \qquad \mathrm{k} \in \{occupation\ period\} \tag{7.9}$$

where **MinPower** and **MaxPower** determine the minimum and maximum power values the HVAC system can supply for heating and cooling. It is defined according to the seasonal use. $\boldsymbol{y}_{\mathrm{in}}$ denotes the temperature in the office zones and corridor limited by the boundary values of the comfort band $\mathbf{T}_{\mathrm{min}}$ and $\mathbf{T}_{\mathrm{max}}$. $\boldsymbol{y}_{\mathrm{surf}}$ is the temperature of the surface of the ceiling and floor where $\mathbf{T}_{\mathrm{surfmin}}$ and $\mathbf{T}_{\mathrm{surfmax}}$ delimit its range of values to avoid overheating and condensation of moisture at inner surfaces. $\boldsymbol{\varepsilon}_{\mathrm{k}}$ is a highly weighted relaxation variable of the minimization that allows the temperature to trespass the comfort limits. The last condition, Equation 7.9, limits the temperature variation velocity during office hours. This restriction is important for those energy saving policies that do not fix or fix in a very slightly way the temperature reference and allow a free temperature evolution inside the comfort band. As the system prioritizes the use of the TABS over the AHU, the system is subject to one last constraint: the use of the AHU is restricted to office hours.

The MPC calculates the optimal action over the prediction horizon using the weights associated to the variables, the reference for the indoor temperature and the defined constrains. The minimization problem defined in Equation 7.4 is the core of the MPC and provides a control vector for the time horizon that will fulfil the desired conditions under the predicted disturbances. For each iteration, the control action only implements the first element discarding the rest, recalculating the next series of control actions in the next iteration. In the case investigated, CPLEX [18] is used as solver with YALMIP [19] to construct the problem. YALMIP provides high freedom in the design of the minimization problem as well as an improved efficiency in computational resources. As a design choice, the control prioritizes the use of the TABS above the AHU using the weights inside the $\mathbf{R}$ diagonal matrix, Equation 7.4. These weights ideally reflect the real operating cost associated to both systems. The relationship between the weights associated to the energy use, $\mathbf{R}$, and those related to the deviation of the indoor temperature from the reference temperatures, $\mathbf{Q}$, defines different energy use policies, allowing a deviation from the reference temperature when it can provide important energy savings.

7.4.2 Blind System

The main task of the BS is to reduce excessive solar radiation passing through the windows, which reduces the thermal gains and provide visual comfort. This effect can also be obtained treating the windows glass is removed when the BS is rolled up, so the radiation can be used to improve the thermal gains when it is required. The BS is an inner dark-coloured yarn closed-weave fabric with a transmittance value so that according with Equation 6.43 (EN 13363-1:2006+A1 [20]), total transference factor through the blind system, $\boldsymbol{u}_{\mathrm{BS}}$, in Equation 7.10 is 0.25.

$$S\_rad_{inside} = g_{window} \cdot \boldsymbol{u}_{\mathrm{BS}} \cdot S\_rad \tag{7.10}$$

where S_rad, a term of the perturbation vector $\boldsymbol{v}$, is the incident solar radiation, S_rad_{inside} is the solar radiation crossing the complete window system, g_{window} is the g-value of window and $\boldsymbol{u}_{\mathrm{BS}} \in \{0.25, 1\}$ is the action of the BSC and its value when closed (0.25) was defined in Equation 6.40.

$$\boldsymbol{u}_{\mathrm{BS,close}} = 1 - g_{window}\rho_{\mathrm{e,B}} - \alpha_{\mathrm{e,B}}\frac{G}{G_2} \tag{7.11}$$

Table 7.5 shows the behaviour of the BS according to the incident solar radiation and the amount of radiation that cross the window-BS set. It can be seen that for incident radiation values between 150 and 250 W/m², the BS action is not defined and must be elected by the BSC.

Table 7.5. BS state related to the incident solar radiation (*S_rad*) and solar radiation value through BS & window

Incident Solar Radiation	BS State	Solar Radiation after window & BS
Solar radiation > 250 W/m²	CLOSED	$g_{window}\cdot 0.25\cdot S\_rad$
150 W/m² < Solar radiation < 250 W/m²	BSC defined	$g_{window}\cdot \boldsymbol{u}_{\mathrm{BS}}\cdot S\_rad$
Solar radiation < 150 W/m²	OPEN	$g_{window}\cdot S\_rad$

Previous studies filled that uncertainty with an *on-off* hysteresis control. This study proposes a novel BSC for that undefined range and compares the obtained results. The enhanced BSC will use the predicted results of the main MPC. As the prediction horizon period is too long for the BSC, two-hour ahead-predicted results will be used, which is substantially shorter than the prediction horizon of the MPC, but long enough to be significant. Predicted energy use is the main indicator to determine the BS control action. If there is net heat use for the next two hours, the BSC will open the blinds, closing them when the prediction is cold use. The design of the enhanced BSC considers also the following assumptions:

- The BS stays closed if the incident irradiance is higher than 250 W/m². It will be open when the incident radiation is lower than 150 W/m².
- The BS action does not influence the illumination comfort of the office and there are no extra energy expenses when the blind system is closed. This simplification is also made by the hysteresis control.
- In order to increase the user global comfort minimizing the action of the BS, when the predicted average power use in the TABS/AHU system for the next two hours is below a predefined threshold, the BS state remains unchanged.

Proposed Enhanced Blind System Control

The design of an improved BSC system for the two-office zones module enhances the global control behaviour of the climate system, both economically and energetically as well as from a comfort perspective.

Interaction between MPC and enhanced BS: Figure 7.7 shows the interaction of the novel enhanced BSC with the main MPC in one time step. The MPC evaluates the system for a control action during the prediction horizon using the values of the solar radiation among others. The BSC receives the information of the predicted solar radiation for the prediction horizon and the values of the control action of the previous iteration to decide about the need of heating or cooling of the office. The BSC evaluates the solar irradiance at each time step of the prediction horizon. For the undefined range, the controller must determine the BS state for that step and give the MPC the value of $\boldsymbol{u}_{\mathrm{BS}}$ in order to recalculate the value of the solar irradiance through the BS. The BSC computes the predicted energy needs for the next two hours; the BS will be open in case of a net heating power demand, and closed if there is a demand for cooling power in order to assist the action of the main HVAC system. The MPC receives the information of the predicted solar radiation through the BS for the prediction horizon and using these values, calculates the control action for the HVAC to ensure comfort conditions and minimize energy use. In order to avoid consecutive opening and closing of the blinds that can disturb the office users' comfort, a small hysteresis band is imposed on the energy-use variable, during which the BS state is not changed.

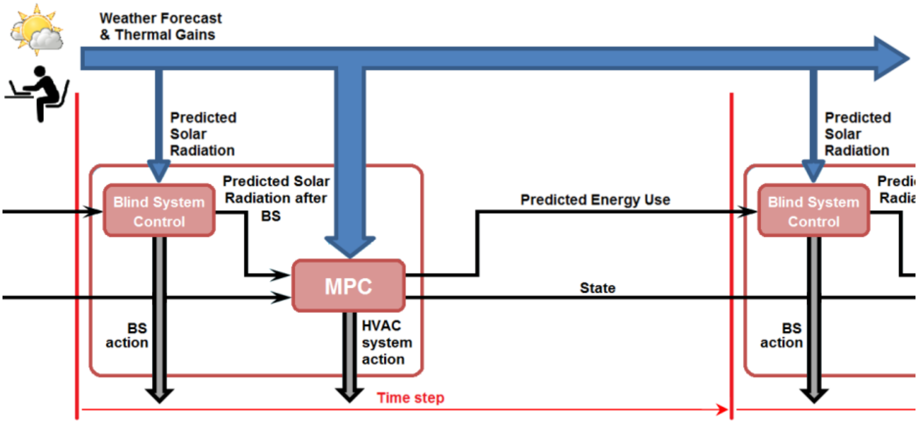


Figure 7.7. Scheme of the interaction of the enhanced BSC with the main MPC control for one time step

BSC Algorithm: Figure 7.8 shows a flow chart of the enhanced BSC. For each iteration of the prediction horizon, the BSC predicts the state of the BS and calculates $\boldsymbol{u}_{\mathrm{BS}} \cdot S\_rad$ in order to evaluate the effect of the solar radiation through the window and BS system in Equation 7.3 and use it to obtain the control action.

Under these operation parameters, BSC takes an active part in the energy saving process, allowing radiation entering in winter to provide heating power and avoiding it in summer to save cooling energy.

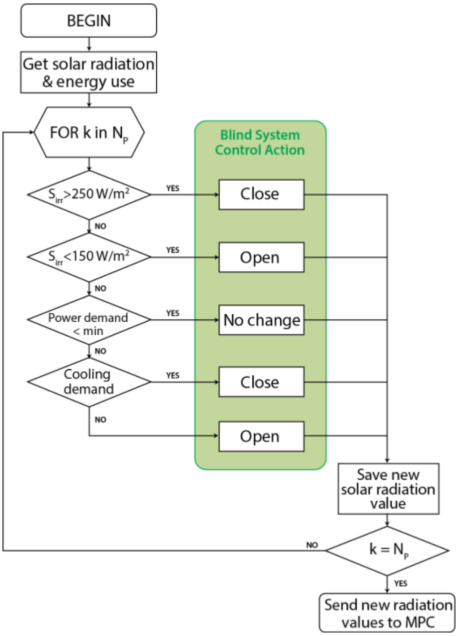


Figure 7.8. Flow chart representation of the proposed enhanced BSC

7.5 Performance comparison

It is necessary to compare the proposed enhanced BSC with other sun shading elements in order to consider the possible benefits it can suppose. Under similar evaluation conditions and using an MPC as main HVAC control, simulations for four BS scenarios will be compared. In all the cases, weather and internal gain data is the same. The main climate controller is an MPC that maintains the same definition of all of its parameters for the four scenarios; prediction horizon and time step, weights of minimization function, comfort definition, system maximum and minimum power. Solar radiation through the window and BS is the unique value that changes due to the effect of the use of different BSC.

7.5.1 Scenario definition

These are the four scenarios proposed to evaluate the performance of the BS:

(1) No BS: This scenario is used as a reference. There is no BS to mitigate the influence of the solar radiation, so the MPC has to manage the HVAC to dissipate the energy of the solar radiation. This scenario should provide the worst situation with respect to energy use in summer. In winter, this would provide more heat gains improving the results, as long as this does not imply the need for cooling.

(2) Hysteresis BSC: This is a usually proposed control as shown in the already presented literature. The control action is defined by a hysteresis control when the solar radiation value is inside the limits defined in Table 7.5. The control action is open or closed. It is presumed that the performance of this control can be improved.

(3) MPC integrated BSC: In this case, the MPC internalizes the BS. The minimization function, considers the action of the solar radiation as another minimization parameter when it is between the already defined maximum and minimum radiation values. The predictive capacity of the MPC ensures an appropriate control and, in order to improve the control response; the BS is not limited to open or closed positions, being able to stay in any other intermediate position. Considering the nature of the MPC, which minimizes the objective function for the whole prediction horizon, the effect of the absence of solar radiation at night can distort the results for the hours near the sunset, which could affect the total energy use.

(4) Enhanced BSC: This is the improved control proposed in this paper. It takes information about the predicted energy use for the future two hours and uses this information to define an open or closed state for the controllable radiation band. This control is supposed to give upgraded results improving the behaviour of the hysteresis one.

The orientation of the offices introduces an important distinction between the solar radiation values: as will be seen, while the BS is nearly unnecessary in the north office during the whole year, its use in the south one is mandatory to reduce the amount of solar radiation that gets into the south office zone in summer.

7.5.2 Performance parameters

The study focuses in the two main parameters the climate control must to govern; energy use and thermal comfort. Although in winter some energy use reduction can be achieved by a correct use of the BS, the main impact appears in summer when the BS reduces the effect of the solar radiation effect decreasing the use of cooling energy. Thermal comfort has been already discussed in point 7.2.3. Comparison of the time out of the comfort limits is evaluated in Kh according with 7.1. It must be consider that both parameters are competitive each other, a reduction in the energy use, can suppose a more oscillating temperature response that can go out the comfort limits. A more strict reference-follow policy is implemented, the energy use increases.

7.5.3 Results

This Section shows the results obtained in the module of office zones under the different control schemes. The control must maintain the office module inside the thermal comfort conditions while using the minimum amount of energy. The study focuses on the savings that the use of a suitable BSC adds to the general MPC.

7.5.3.1 Enhanced BSC Results

A first simulation, Figure 7.9, provides a year-long representation of the behaviour of the climate system in the two office zones and corridor using the enhanced control for the BS (scenario 4). The results show the global behaviour of the system during the whole year; no BSC, hysteresis BSC and MPC integrated BSC lead to results similar to those in Figure 7.9, although an increase in energy use and thermal discomfort appears. It is possible to see how the control maintains the indoor temperature inside the defined comfort band. The inertia of the TABS and the thermal gains of the offices, human use and office devices, cause variations with respect to the reference temperature. In some occasions, the temperature exceeds the lower comfort limit due to the relaxation in the design of the comfort constraint when offices are out of use.

The energy use for both TABS and AHU also appears in Figure 7.9. Recall that the use of TABS is limited to heating in winter and to cooling in summer as the figure shows; while the AHU is designed to provide support action for heating or cooling as can be observed in Figure 7.9 (b) column. It may therefore be observed from the accumulated energy use that the cold consumption exceeds the heat consumption, such that an adequate use of the BS will provide significant energy savings. The south office has higher solar exposure than the north one, which increases the cooling energy use. The temperature in the corridor remains quite stable, because of the regulating effect provided by the adjacent offices and the absence of significant heat gains. Therefore, it has been found that the BSC action is mainly focused on the south office.

Figure 7.10 zooms into the control response of Figure 7.9. A representative zoom of a week is shown for the TABS heating and cooling configuration for the south office. This shows the evolution of the temperature and the energy use of TABS and AHU. Control is fitted in order to improve the energy savings so the value of the weight matrix $\mathbf{Q}$, associated to the energy use, has larger eigenvalues than the values of matrix $\mathbf{R}$, associated to the reference tracking, in Equation 7.4, which entails that the control will not strictly follow the temperature reference. It is also possible to observe the effect of the $\boldsymbol{\varepsilon}$ parameter: the MPC allows the temperature to exceed the comfort band in some occasions in order to decrease the energy use. This is merely a design choice. The behaviour of the TABS and the delay associated to the heat transfer through the concrete can be observed. The thermal energy is mostly stored in the TABS at night to be used during the office hours. This delay also shows the predictive behaviour of the MPC. While TABS are in heating configuration, the AHU system is mainly used to correct the temperature deviations in cooling configuration as it provides additional cooling power when required. A temperature decrease appears at lunchtime. The lack of internal gains associated to occupancy and office appliances combined with the ventilation heat losses cause this to happen in both cooling and heating configurations. The lower graphs show the behaviour of the control under a no discomfort policy as compared to the power saving policy. Weights associated to the reference track and $\boldsymbol{\varepsilon}$ parameter in Equation 7.4 have been increased, putting a higher penalty on discomfort. Using the parameters of the study, it is possible to maintain the temperature inside the comfort limits at the expense of increased energy use.

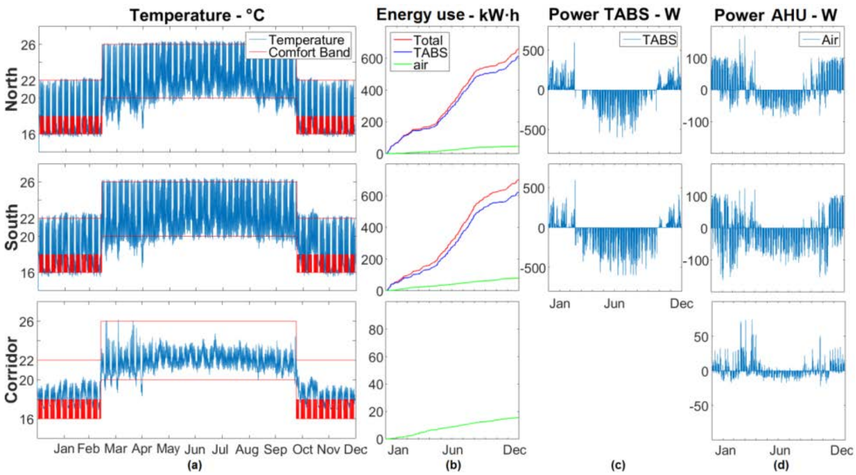


Figure 7.9. Enhanced BSC study: zone temperature evolution (a), accumulated energy use (b) and developed power in TABS (c) and in AHU (d)

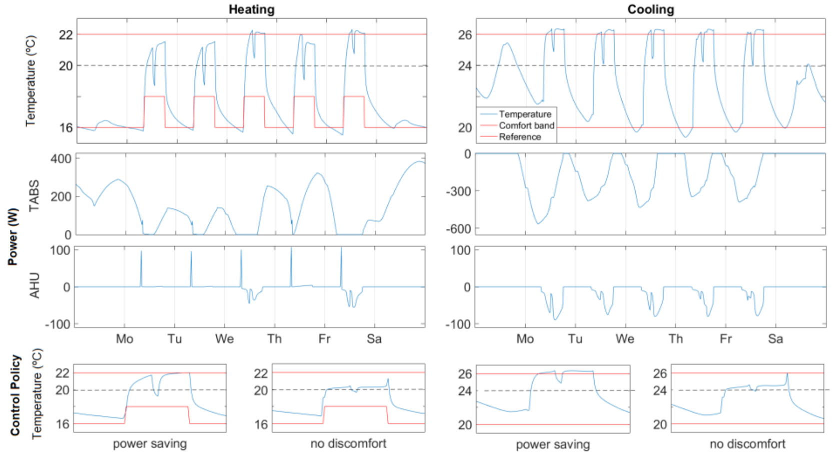


Figure 7.10. One-week response of the control for heating and cooling configurations. Temperature evolution, and TABS and AHU system power use are shown. One-day temperature evolution for the selected configuration, power saving, against a *no discomfort* policy is also presented at the bottom

Figure 7.11 shows other aspects of the behaviour of the enhanced BSC. The action of the BS control can be observed in Figure 8a, which represents its state evolution over time. The other columns show the accumulated thermal discomfort in Kh.

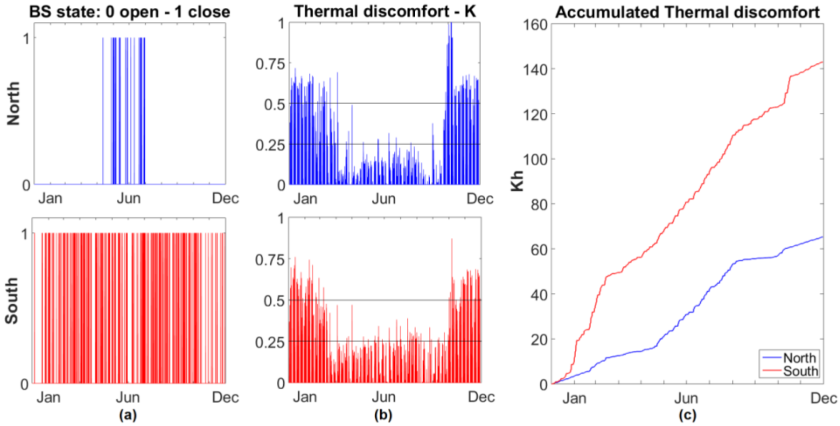


Figure 7.11. Enhanced BSC study. BS state (a), thermal discomfort (b) and accumulated thermal discomfort (c) for north and south offices

The thermal discomfort in Kh is defined as the integration over time of the temperature surpassing outside the comfort band during occupation hours. In [21], Gyalistras *et al.* suggested values near 70 Kelvin hours per annum (Kh/a) as a good indicator for thermal discomfort. Only deviations larger than 0.1 K are considered when evaluating the discomfort, as suggested in [21]. Taking into account the distribution of the thermal discomfort over the year, Figure 7.11 (b), it can be seen that in the south office the temperature is only out of the comfort band during 0.65% of the office-time for a deviation higher than 0.5 K and it never surpasses 1 K. As result of these considerations, the outcomes for the control action are considered satisfactory, especially knowing that the MPC design allows to exceed of the comfort band as denoted by Equation 7.4.

7.5.3.2 Comparison between BSC

Disregarding the values associated to each scenario, all of them show the same pattern for the results as correspond for the same main PC where the unique change is the solar radiation that reaches the offices. Figure 7.12 presents a comparison between the enhanced BSC and the other three BSC scenarios defined in Section 7.5.1: hysteresis BSC, the MPC integrated control and no BS control. The response patterns of Figure 7.9 and Figure 7.10 are similar for all these controls, so the comparison is based on the accumulated energy use as well as the accumulated thermal discomfort in Kh for the four cases over a whole year.

The graphics in Figure 7.12 (a) show that the enhanced BSC provides the lowest energy use and the highest comfort (Figure 7.12 (b)) for the south oriented office zone, whereas the north office zone presents similar results for all four BSCs (Figure 7.12 (c,d)). Besides, according to Figure 7.12 (a), major savings are accumulated during the cooling period, when the solar radiation maximizes its influence. In particular, the novel enhanced BSC presents an overall energy use, which is 15% lower than the hysteresis BSC, and similar energy use results to the MPC integrated BSC. Regarding thermal discomfort, it can be observed in Figure 7.12 (d) that there is no substantial difference between BSC actions in north orientation. For South orientation, the enhanced BSC and MPC integrated BSC show similar results, which are better than the hysteresis one in Figure 7.12 (b).

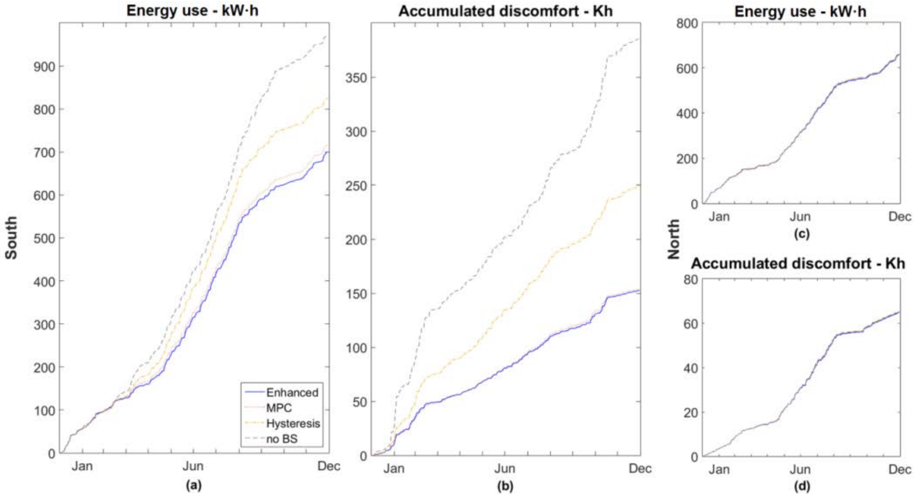


Figure 7.12. Accumulated energy use (a,c) and thermal discomfort (b,d) in north and south office orientations for the studied controls

7.5.3.3 Enhanced BSC Results. Interpretation and Discussion

The simulation results indicate that most of the energy savings associated to the use of the enhanced BSC occur in the south office during the summer period. The large influence that internal gains exert on the environment induces a heavy use of the cooling system. The effect of solar radiation, which can be observed comparing the results between north and south offices, increases the use of the cooling system. Therefore, a more active well-fitted BSC yields important savings in the energy use as Table 7.6 shows. Due to the low solar radiation that the north office receives, the BSC has no relevance in the energy use. However, in the south oriented office the heating effect of solar radiation causes a substantial decrease in the energy use of 20% during the winter period, compared to the north office. Analysing the summer period, this passive heating effect increases the energy use for cooling. The maximum energy use occurs when no BS is present. The use of a hysteresis BSC reduces this energy use to 85% of the reference case. The integration of the BSC in the MPC or the use of the enhanced BSC reduces the energy use down to 74% and 72% of the reference case, respectively. Considering a whole year, the use of the enhanced BSC in the south office reduces the energy use to values close to those of the north office, so that the control avoids the undesired heating effect of solar radiation in summer. This provides energy savings of 30% with respect to a no BS situation or 15% with respect to the hysteresis BS. When comparing with the MPC integrated control, there is only a small difference, but it must be considered that MPC requires a more complex hardware implementation than the enhance BSC.

Table 7.6. Accumulated energy use of the HVAC system for different BSC. Energy use percentage is referenced to the scenario without BS

Scenario		**Accumulated Energy Use kW·h**					
		Total	**Winter**	**Summer**	**Energy Use (%)**	**Total TABS**	**Total AHU**
North	enhanced	659.0	257.8	401.0	99.54	613.2	45.8
	MPC	660.5	258.2	402.3	99.79	614.7	45.8
	hysteresis	664.1	256.5	407.5	100.32	618.0	46.1
	No_BS	662.0	253.0	408.9	100	615.8	46.2
South	enhanced	699.8	197.3	502.4	71.97	621.2	78.6
	MPC	716.8	198.5	518.2	73.73	637.4	79.4
	hysteresis	824.8	190.8	633.9	84.83	715.7	109.2
	No_BS	972.3	198.6	773.6	100	820.9	151.4

The priority in the use of TABS over the AHU is defined in the MPC assuming different operative costs per unit of cooling or heating power. Using the enhanced BSC, the energy-use of TABS to AHU ratio is near 8, while this ratio decreases to 6.5 for the hysteresis control and 5.5 when no BS is present.

Results presented in Figure 7.12 and Table 7.7 give an idea about the thermal comfort provided to the users of the offices. Under the same study conditions, except for the parameters directly related to the BS, all other parameters of the MPC remain the same for all simulations. The enhanced BSC obtains the highest comfort. As in the previous comparison, MPC integrated BSC results are close to the ones of the enhanced BSC, while the usually proposed hysteresis shows worse behaviour. Results for the case without BS are the worst due to the increment of the energy use needed to maintain thermal comfort.

Table 7.7. Accumulated thermal discomfort in the south oriented office zone for the whole year and fraction of office time out of the comfort band for different temperature deviations

Scenario	**Thermal Discomfort Kh/a**	**Deviation > 0.25 K (%)**	**Deviation > 0.5 K (%)**	**Deviation > 1 K (%)**
Enhanced	142.92	6.34	0.65	0
MPC integrated	154.04	6.48	0.71	0
Hysteresis	249.01	15.11	2.66	0
No_BS	385.12	21.28	9.19	1.39

In the south office, the BS mitigates the influence of solar radiation on thermal discomfort reducing discomfort when enhanced BS or MPC integrated BS is used.

Figure 7.10 shows how to implement a *no discomfort* policy in which the temperature reference track and **ε** value weight are prioritized over energy use. The comfort is increased however also the energy use increases as can be deduced from Equation 7.4.

The use of the enhanced BSC provides significantly better results than those obtained with the usually proposed hysteresis BSC when evaluating both energy use and thermal comfort. Compared to the BS integration in the MPC, it shows similar results in thermal comfort and energy use, but the enhanced BSC simplifies the computational effort and the hardware complexity associated to the BS positioning. For a whole year calculation, an i7-6700 16 GB RAM desktop computer takes 8 h (24 h in the case of an i7-3520M 4 GB RAM laptop) for enhanced and hysteresis control calculation increasing this with about half an hour for the integrated MPC. The use of discrete BS positions in an integrated MPC, as the ones proposed in the literature, requires the use of integer programming that can increase the computation time more than an order of magnitude.

7.6 Conclusions

The climatization of office buildings represents an important fraction of the total energy use in our society. Besides conditioning the indoor air quality, the system must provide thermal comfort to the users. The use of an MPC gives rise to energy savings of about 15% with respect to traditional control policies.

The power dissipation of electronic devices in present-day offices provides heat gains, which together with human activity and solar radiation introduces heat sources that will significantly increase the temperature in the office zones. Although all these energy sources, considered in the HVAC control, reduce the heat power consumption during winter, they substantially increase the cooling needs in summer. This study investigates an office module, designed with high quality building materials and a solar BS, allowing decreasing the total use of energy of an MPC controlled HVAC system by simulations. The simulations for a novel enhanced BS algorithm decoupled from the MPC, but considering its predicted energy use values, provide a potential energy use reduction for the HVAC system of 15% in south office in comparison with a usually proposed hysteresis control. The evaluation of the predicted energy need provides a good indicator to determine the state of the BS.

The proposed control shows similar results for energy use and thermal comfort to an MPC that integrates the BS under similar conditions, which in some of its variants has been successfully studied. Therefore, the obtained results can be considered significant. The use of a decoupled control reduces computational requirements in the MPC minimization; meanwhile *on-off* BS hardware is potentially simpler than multistate one.

Unlike the outside temperature or the heat gains associated with occupancy, the strong effect of solar radiation on thermal comfort, mostly in summer, can be counteracted. The development of an appropriate BSC provides an opportunity to significantly decrease the energy use, which justifies this study and the use of an advanced control strategy. The enhanced BSC also improves the distribution of the energy use over the two HVAC systems, TABS and AHU, which should entail a cost reduction by favouring the system with lower running costs.

The comparison among the different BSCs has been carried out considering perfectly known predictions for the disturbances. Deviations between the predicted and real values of solar radiation can introduce errors in the behaviour of the BSC. Therefore, once the control feasibility has been validated when comparing with other BSCs, future studies should contemplate the implementation under real conditions, taking into account on-line weather forecast predictions. In this case, a state estimation Kalman filter should be used to reduce the errors in the predictions. The study of the proposed BSC in other weather conditions or other qualities of the construction materials can also continue this research work.

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8.

Summary and Conclusions

The building sector presents one of the highest energy consumption in developed societies. Among building energy uses, indoor environment climatization is the most significant component of household energy demand, and can vary substantially from year to year depending on climatic variations. The increasing concern about environment, the energetic dependence of Europe, and why not, economic factors make it desirable a rationalization of the energy use and its reduction whenever possible as long as it does not affect the comfort conditions of the building users.

Although the quality of building materials has been significantly improved, there is still a significant amount of aged building with a heavy lack of insulation in the cities. Improving insulation can upgrade the thermal behaviour, which can also be done using an enhanced control.

The use of an advanced control such as the MPC can provide important energy savings according to the results of literature and the ones of this study. Many characteristics convert MPC in an appropriate control for building climate systems. The use of the weather forecast and the building occupancy information to advance the control action provides the MCP a great advantage regarding to error-based controls as the PID or hysteresis *on-off* controls. The multi-objective characteristic of the MPC allows developing different control policies to manage the relation between thermal comfort and energy use. The elements considered in the minimization function and their weights defines the implemented policy, which can include parameters as the amount of energy used, the cost of the used energy or the CO_2 emissions associated to that energy use. The deviation regarding a comfort band or a temperature references can also be included in the cost function. The MPC uses a minimization function that handles in a native way the restrictions associated to the problem. In a building climate control, it is possible to define physical restrictions as the nominal power the equipment can supply as well as the comfort definitions or the temperatures of the floor and ceiling in the TABS. The main problem the MPC presents for its implementation in the buildings' climate control systems is the definition of an accurate model of the building. Considering that the model of the building is an active part in the minimization, deviations between the model and the real behaviour of the building can be an error source in the control.

The use of TABS provides a climatization system with high thermal inertia, slow response that requires a correct control system. This thermal energy distribution system provides some advantages that increase the efficiency of the HVAC. As a large surface radiant system, it is possible to implement low temperature heating and high temperature cooling, which reduces in a significant way the energy loss and consumption; in addition, it allows the integration of renewable low-temperature energy sources which results in systems such as the GEOTABS.

The use of a blind system in a South oriented room (North hemisphere) provides significant benefits during summer season, reducing the solar radiation that arrives to the room and therefore the amount of cooling energy necessary to maintain the thermal comfort in that room.

Based on the results obtained from the studied cases, it is possible to propose some conclusions that, although based on simulations, are consistent with those obtained over real buildings or other simulation studies.

The characterization of TABS or CCA system as a RC model provides a way to introduce this element into a building state-space representation. Using statistical software as CSTM-R or modules as Grey-Box toolbox is possible to obtain a thermal resistor and capacitance description for the TABS dynamics. Although obtaining an adequate characterization is not so trivial, it is possible to identify a low order representation for the TABS dynamics. Chapter 3 describes how to obtain the RC model characterization for a concrete TABS slab using experimental or simulation data. The results were proven to be successful by using a new data set.

As Chapter 6 describes, thermal comfort depends on different parameters. For the objective of the studies undertaken in this PhD thesis, temperature is the determinant factor, neglecting factors like humidity, air displacement or factors associated to the human behaviour. Under those conditions, it is possible to define a temperature range that determines the comfort zone. Varying the control parameters, weights of the minimization function in an MPC, define different control policies may be defined so as to prioritize energy savings or temperature stability over the other fulfilling comfort conditions.

The MPC may be used to maintain the comfort conditions in an aged building with low quality construction materials. As Chapter 5 shows, this kind of buildings, with reduced thermal inertia compared with more modern, better construction quality ones also obtains the benefits associated with an MPC implementation over the typically used thermostatic *on-off* control. The use of an MPC can provide potential savings between 10 % and 15 % of the heating energy when comfort conditions are maintained during all of the day. Chapter 5 also shows how implementing an energy saving policy by adapting the weights in the minimization function allows the control to reduce the energy use by an additional 7.5 % maintaining the thermal comfort conditions regard other MPC designs more focused in a strict tracking of a comfort-defined temperature of reference.

Under the consideration that the heating/cooling energy is provided by an electric heat pump, it is possible to observe the effect that the use of a TOU energy rate provokes when used under an MPC. Last part of Chapter 5 shows how the MPC can provide important advantages when used under this kind of energy rate. The control can shift the use of energy toward cheaper rates. This does not necessary suppose a reduction of the global energy consumption but can provide important economic savings.

MPC action displaces the energy use to reduce the consumption peaks that appear in some moments of the day or under some special circumstances. This allows the reduction of the nominal power of the installed equipment and in the case of electrical power; it can provide more homogeneous distribution of the use of energy in a building zone.

Office buildings usually develop more sophisticate climate system than those used in domestic environment. According with literature, the use of an MPC to control the HVAC system of a building can reduce the energy use a 15 %. Two-office module is a usually studied office model. Good construction materials, North-South orientation, TABS and AHU system to provide adequate comfort environment are some of its characteristics. Chapter 7 studies this office building module characterizing it in a state space representation that can be controlled by an MPC.

Implementation of TABS allows the use of the building structure as a low exergy thermal store that can reduce the economic expenses of the HVAC operation by storing night low rate energy to use it during the day or can use the cooler temperature of the night to naturally refrigerate the concrete structure during summer. Although this question is not considered in ISO 11855-6, which provides information about the control of embedded radiant heating and cooling systems, in order to avoid energy loses by dispelling the energy accumulated in the structure, it is necessary to prevent the change between heating and cooling working modes. In this way the MPC allows the heating and cooling action in a seasonal mode. The large surface of the TABS allows decreasing the temperature difference in the heat interchange between the element surface and the environment, which reduce the energy losses and increases the comfort. The high radiant component associated to the TABS, reduce the need of climate all the air volume, which makes this system appropriate for tall ceilings.

Power dissipation of the office devices, human activity and solar radiation introduce heat gains that significantly increase the temperature in the office zones. Although these energy charges can suppose a reduction of the energy consumption in winter, they substantially increase the cooling needs in summer. Considering an adequate use of the infrastructures of the office zone, the only factor that can be regulated to reduce the energy use is the incident solar radiation though the windows. The use of ledge like architectonical solutions reduces the effect of the solar radiation; even so, the use of an adjustable blink system improves this effect.

Until the development of this investigation, the studies about the two offices module had been focused in the main control of the HVAC, letting the blind system out of it. These studies usually proposed an *on-off* hysteresis control to regulate the blind system. The study of the Chapter 7 gives a new direction to the blind system control. By considering the HVAC system controlled by an MPC, an enhanced control of the blind system that takes advantage of the predicted energy use values of the MPC shows promising results regard to the energy consumption.

Chapter 7 provides a comparative test with other blind system control schemes considering similar parameters for the HVAC system's MPC. This enhanced blind system control, which is regulated only under *on-off* positions, shows similar energy savings than those provided by the integration of one multi state blind system under the HVAC system's MPC rule. When comparing it with the usually proposed blind system *on-off* hysteresis control, results over a year show potential energy savings about 15 % in the south office mainly based in the reduction of cooling need. Due to the low radiation incidence in north office, the study shows that the use of a blind system is not necessary in this zone.

The study also shows how the thermal comfort would be improved when the proposed enhanced blind system control is considered. Under a Kelvin hour per annum (Kh/a) comfort units, the estimated thermal discomfort for office hours is nearly halved, showing a more reduced temperature deviation from the comfort band.

Finally, another effect has also been observed in this study. The ratio of energy use between the main TABS and the secondary AHU system increases for the TABS when the enhanced blind system is implemented, which is supposed to carry benefits in the operation cost as well as in the control of the whole system.

8.1 Future lines of research

As in other life situations, sometimes it is necessary to make a stop in the way and do a recompilation about the progress done. This thesis document, in fact, makes a recompilation about the experience of these last years. A lot of things can be added or studied in each of the proposed subjects; real implementations *and* more accurate studies *and* the study under other localization's weather conditions *and*… A long *and* that had to be stopped in order to write this document but can be retaken with renewed strength when this process is finished. Some of the subjects that can be added to the research done should depend on aspects such as the minimization of the system not only respect to the energy use but also, CO_2 emissions, primary energy use or economic factors. This could provide a correlation in order to study how economic and ecologic factors interact.

The capacity of energy storage of the concrete may also be studied. Although comparing with its electric equivalent the thermal State of Charge of the concrete shows some implementation difficulties, this parameter could help to improve the energy management of TABS.

The blind system control could be tested under a sunnier and darker environment to obtain a broader idea about its effectiveness. The use of a multistate blind system has not been introduced in the study neither the considerations about the influence of the blind system in the light use, due to the important reduction in the consumption that provides last generation bulbs.

A comparison of the response of the MPC in the aged residential block with the response of a rehabilitated one could provide information about the compatibility of both energy use improvement methods. Classical rehabilitation can suppose the addition of insulation materials to the indoor side of the façade or the replacement of the old high U-factor windows by new low U-factor ones.

Considering larger buildings, it could be possible to study the way to take advance of the thermal inertia of the building structure to decouple the action of the HVAC system over different rooms forcing the control action in different moments, so it should possible to decrease the nominal power requirements for the climate equipment.

8.

Laburpena eta ondorioak

Eraikinak dira gizarte garatuetan energia kontsumoaren eragileetatik handienetariko bat. Energia erabilera horren zati handi bat, barne ingurumenaren ongizate termikoa ziurtatzeko erabiltzen da. Ingurumenaren egoerari buruz dagoen kezkak, Europak duen energia dependentziak eta, zergatik ez, hainbat faktore ekonomikok energia erabileraren arrazionalizatzea eta gutxitzea eskatzen dute eraikinen erabiltzaileen ongizate baldintzak kaltetu barik.

Eraikinen materialen kalitatea nabarmenki hobetu bada ere, hirietan badira oraindik isolamendu kalitate urria duten eraikin zaharkituak. Isolamenduaren hobekuntzak eraikinaren joera termikoa hobetuko du. Helburu hau, kontrol aurreratu baten bidez ere lor daiteke.

Bibliografiak eta ikerketa honen emaitzak adierazten duten arabera, MPC bezalako kontrol aurreratuen erabilerak energia aurrezpen nabarmenak lor ditzake. MPCaren hainbat ezaugarrik eraikinen klimatizazio sistementzako egokia bihurtzen dute.

Eguraldiaren aurreikuspenak eta eraikinen okupazio eta erabileraren informazioak kontrolaren ekintza aurreratzea ahalbidetzen dute. Ezaugarri honek akatsetan oinarritutako kontrolekiko abantaila handia ematen dio MPCari, adibidez PIDekiko edo *on-off* histeresi kontrolekiko. MPCaren helburu-aniztasun ezaugarriak bideragarri egiten du ongizate termiko eta energia erabilera kudeatzeko politika desberdinen garapena. Inplementatuko den kontrol politika, MPCaren minimizazio funtzioan zehazten da hor agertzen diren parametro eta funtzioan duten pisuen bidez. Parametro hauek erabilitako energia, horren kostua edo energiarekin loturik dauden CO_2 emisioak izan daitezke besteak beste. Erreferentzia tenperatura batekiko edota ongizate banda batekiko desbideraketa ere sar daiteke kostu-funtzioan. Modeloan agertzen diren mugak berezko eran integratzen dira MPCaren minimizazioan. Eraikin baten klimatizazio kontrolaren muga fisikoak defini daitezke, ekipoen potentzia nominala bezala. Ongizate termikoaren definizioak edota TABSen zoru- eta sabai-tenperaturak definitzen dituzten mugak ere ager daitezke minimizazioan. Eraikinen klimatizazio sistemen kontrolaren arloan MPCak inplementatzeko agertzen den arazorik handiena eraikinaren eredua sortzea da. Eredua minimizazioaren zati eraginkorra da; eta eredu eta eraikinaren joeran agertzen diren ezberdintasunak akats iturri izan daitezke kontrolean.

TABS-en erabilerak inertzia handia sortarazten dute klimatizazio sisteman, hau da, sistemak erantzun motela izango du, zeinak kontrol era egokia beharko duen. Banaketa termikorako era honek HVAC sistemaren efizientzia handitzen duten hainbat abantailak dakarzkio. Azalera handiko sistema igorlea izanik, posiblea da tenperatura baxuko beroketa eta tenperatura altuko hozketa inplementatzea. Ezaugarri honek, era nabarmenean gutxitzen ditu energia galerak eta kontsumoa. Era berean, GEOTABS moduko tenperatura baxuko energia-iturri berriztagarriekin konbinatzea ahalbidetzen du.

Udan hegoalderantz norabideratutako gela batean (ipar hemisferioan), errezel-sistema erabiltzeak onura adierazgarriak dakartza. Honek, gelara heltzen den eguzki-erradiazioa gutxitzen du eta, honen ondorioz, gela horretan ongizate termikoa mantentzeko behar den hozte-energia.

Aztertutako kasuen emaitzek hurrengo ondorioak aurkeztea ahalbidetzen dute. Nahiz eta simulazioetan oinarrituta egon, lortu diren emaitzak bat datoz eraikin errealetan eta simulazioetan oinarritutako argitalpen askoek lortzen dituztenekin.

TABS edo CCA sistemen karakterizazioak RC-eredu eran, integrazioa eraikin baten egoera-espazioaren ereduan ahalbidetzen du. CSTM-R estatistikako software edo Grey-Box toolbox moduluak erabilita, posiblea da lortzea TABS dinamika definitzen duen erresistentzian eta kapazitate termikoetan oinarritutako deskripzioa. 3. Atalak, hormigoizko bloke baten RC ereduaren karakterizazioa nola lor daitekeen datu esperimental edo simulazioak erabiliz deskribatu du. Lortutako emaitzak datu multzo berriekin egiaztatu ziren.

6. Atalaren arabera, ongizate termikoak hainbat parametroen menpekotasuna dauka. PHD tesi honen ikerketan, tenperatura da ongizatea definitzen duen parametro nagusia.

Hezetasuna, airearen mugimendua, giza jarduera eta arropa ez dira kontutan hartzen, haien balioak beste era batean egonkortzen direla suposatuz. Baldintza hauen pean, ongizatea mugatzen duen tenperatura tartea definitzea posiblea da. Kontrol parametroak egokituz, MPC-aren minimizazio funtzioaren pisuak, energia aurrezpena edo tenperaturaren egonkortasuna lehenesten dituzten politikak aukeratzea posible da.

MPCa erabilgarria da ongizate baldintzak mantentzeko kalitate gutxiko eraikin zaharkituetan. 5. Atalak erakusten duen bezala, eraikin mota honek kalitate oneko eraikin berriekin alderatuta inertzia termiko txikiago duela. Hala ere, MPCaren ezaugarriak etxebizitzetan erabiltzen den ohiko termostato kontrolen aurrean hobeki moldatzen dira. MPCaren erabilerak, berotzeko energiaren % 10 eta %15 arteko aurrezpen potentziala aurkezten du ongizate baldintzak egun osoan zehar mantentzen direnean. 5. Atalak MPCaren minimizazio funtzioan pisuek duten eragina ere aurkezten du. Pisuak egokituz, posible da energia aurrezpenari zuzendutako politika definitzea, % 7.5 arteko energia aurrezpena lor daitekeen ongizate baldintzak betez.

Berotze- eta hozte-energia bero punpa elektriko baten bidez lortzen bada, posiblea da TOU tarifen erabilera MPCan duen eragina ikustea posiblea da. 5. Atalaren azken zatiak MPCak energia-kontsumoa une merkeagorantz nola desplazatzen duen ikus daiteke. Honek, operazioaren kostu ekonomikoen murrizketa dakar nahiz eta energia aurrezpenik ez egon.

MPCak energiaren erabilera desplazatzen du eguneko zenbat unetan edo momentu berezietan, kontsumo gailurrak lausotuz. Honek instalatutako potentzia nominalaren jaitsiera ahalbidetzen du, baita energia kontsumo homogeneoagoa eraikinaren zonalde batean.

Bulego eraikinek, normalean etxebizitzek erabiltzen dutena baino klimatizazio sistema sofistikatuagoa erabiltzen dute. Bibliografiaren arabera, MPC baten erabilerak energiaren gastua % 15-a gutxitu dezake. Bi bulegoetako modulua ohiko aztergaia da eta sistemen eraginkortasuna konparatzeko erabiltzen da: gohi-kalitateko eraikuntza materialak, Ipar-Hegoa orientazioa, TABS eta AHU sistemak ongizate termikoa egokitzeko. 7. Atalak modulu hau aztertzen du, MPC bidez kontrolagarria den espazio-egoeran definituz.

TABS-en inplementazioak, eraikinaren estruktura exergia baxuko biltegi bezala erabiltzea ahalbidetzen du. Honek, HVAC-en operazio-kostuak jaitsi ditzake gabeko tarifa merkeko energia metatuz hurrengo egunean erabiltzeko. Gabeko ingurune tenperatura hotzago izanik, udan hozketa naturala erabil daiteke hormigoizko estruktura hozteko. Bero eta hozketa igorleen kontrolari buruz ISO 11855-6-ak aipatzen ez badu ere, TABS-ak erabiltzen direnean beroketa eta hozketa lan-moduen arteko aldaketak ekidin behar dira estrukturan metatutako energia alferrik ez disipatzeko. Horrela, MPC-aren lan-modua urtaroaren arabera definitzen da. TABS-en gainazal operatibo handiak, gainazalaren eta ingurumenaren bero-trukaketako tenperaturaren jaitsiera txikitzea ahalbidetzen du. Honek bero galerak gutxitzen ditu eta ongizate termikoa handitzen du.

TABS-ei loturiko irradiazio-osagaia (sistema igorlea da), gela baten aire bolumen osoa erabat ez berotzea ahalbidetzen du. Ezaugarri hau kontutan hartzekoa da gelaren sabaia altua denean.

Bulego-altzariek disipatzen duten beroa, giza jarduera eta eguzki erradiazioak bulegoen tenperatura nabarmenki igotzen duten bero iturriak dira. Neguan bero iturri hauek energia erabileraren jaitsiera sor badezakete ere, udan hozketaren beharrak handituko dituzte. Behin bulegoko klimatizazio sistemak era egokian doituta, leihoetatik heltzen den eguzki erradiazioa da doi daitekeen parametro bakarra barneko bero kargak eta energia kontsumoa murrizteko. Erlaitza bezalako konponbide arkitektonikoen erabilerak eguzki erradiazioaren efektua gutxitzen du; are gehiago, errezel-sistema doigarria erabilerak efektu hori hobetzen du.

Ikerketa lan hau burutu arte, bi bulegoko moduluaren ikerketak HVAC sistemaren kontrolera bideratutzen ziren, errezelen-sistema zeharka integratuz. Ikerketek, *on-off* histeresi kontrola proposatzen zuten errezel-sistema doitzeko. 7. Atalean burutzen den azterketak bide berria irekitzen dio errezel-sistemari. HVAC sistema MPC baten bidez kontrolatuta dagoela kontutan hartuta, MPC-an aurreikusitako balioak erabiltzen duen errezel kontrol-sistema aurreratua proposatzen da. Errezel kontrol honek, MPC-ak ematen dituen energia erabileraren balioak erabiltzen ditu eta emaitzek energia aurrezpen nabarmenak erakusten ditu.

7. Atalak alderaketa burutzen du errezel kontrol eskemen artean. HVACen MPCaren parametroak konstante mantentzen dira. Proposatutako errezel sistema aurreratuak, *irekia-itxia* posizioak besterik onartzen ez dituenak, MPCan erabat integratuta dagoen eta errezelen kokapen sistema jarraitua duen kontrolak beste energia-aurrezpen lortu du. Normalean erabiltzen den *on-off* histeresi kontrolarekin alderatzean, kontrol aurreratuak erakusten duen energia-aurrezpena % 15 da hegoaldeko bulegoan. Aurrezpena, hozte beharren murrizpenaren ondorio da. Iparraldeko bulegoan, irradiazio gutxiago jasotzen da. Ikerketak erakusten du errezel-sistemaren erabilera ez dela beharrezkoa.

Azterketaren emaitzek erakusten dute proposatutako errezel-sistema aurreratuak ongizate termikoa hobetzen duela. Kelvin ordu urteko, *Kelvin hour per annum* (Kh/a), ongizate unitateetan, lan orduetan lortutako ondoeza termikoa balioa erdira jaisten da eta ongizate bandarekiko dagoen tenperatura desbideraketa ere txikiagoa da.

Bukatzeko, beste ondorio bat lortu da ikerketan. TABS sistema nagusia eta AHU laguntzailearen artean erabilitako energia proportzioa TABSaren alde egiten du proposatutako errezel sistema aurreratua erabiltzean. Honek operazio kostuari onurak ekartzen dizkiola suposa daiteke.

8.1 Etorkizuneko lan-ildoak

Bizitzan sarritan gertatzen den bezala, ikerketan ere beharrezkoa da bidean etenaldi bat egitea eta egindako bidea aztertzea. Tesi honek, berez, azken urtetan egindako hainbat lanen bilduma da. Aztertutako esparruei buruzko ikerkuntza sakon daiteke; benetako modeloen gaineko inplementazioak *eta* ikerketa zehatzagoak *eta* hainbat eguraldi baldintza pean *eta*... Dokumentu hau idaztean momentu batean gelditu beharra *eta* luzera... berriro har daitekeena indar berrituekin tesi prozesua bukatzean. Badira ikerketari gehitu daitezkeen hainbat gai xehetasunetan sakonduz. Hauen artean, minimizazio funtzioaren parametroena egon daiteke. Erabilitako energiaz gain, kostu ekonomikoak, CO_2 sorrera edota lehen-mailako energia sar daitezke minimizazioan. Hau ikertuta, faktore ekonomiko eta ekologikoen artean balizko erlazioa aurkituko litzateke.

Bero-energia gordetzeko hormigoiak duen ahalmena ere iker daiteke. Hormigoiaren kargaren egoera, *State of Charge*, termikoaren ezagutza interesgarria izan daiteke TABSen kudeaketan, nahiz eta horren inplementazioak zailtasun batzuk dituen horren baliokide elektrikoarekin aurkeztean.

Errezel-sistemaren kontrola, ingurumen eguzkitsuagoetan eta ilunagoetan probatu beharko litzateke bere eraginkortasuna neurtzeko. Egoera anitzeko errezel-sistem ez da ikerketan sartu, ezta errezel-sistemak argiztapen energian duen eragina ere. Azken hau ez da kontutan hartu azken belaunaldiko argi bulboek duten eraginkortasun handia dela eta.

Eraikin zaharkitu baten eta birgaitutako baten MPCaren erantzuna alderatuz, birgaitzea eta energiaren erabilera hobetzeko bi metodo hauek batera inplementatzeko bideragarritasuna aztertu ahal izango litzateke. Ohiko bergaiketak, fatxadaren barnealdea isolatuz edo U-faktore handiko leiho zaharren U-faktore txikiago duten beste batzuengatik ordezkatuz burutzen da.

Eraikin handiak aztertzean, posiblea da eraikinaren klimatizazio-instalazioaren potentzia nominala murriztea eraikinaren inertzia termikoa erabiliz. HVAC sistemak une ezberdinean eragin dezake gela bakoitzean kontrolaren ekintza denboran.

List of publications/Argitalpenen zerrenda

This section shows some of the publication of the author.
Puntu honetan, egilearen argitalpenak jasotzen dira.

JCR indexed journal publications/Argitalpenak JCR-n indexatutako aldizkarietan:

Carrascal-Lecumberri, E.; Garrido, I.; van der Heijde, B.; Garrido, A.J.; Sala, J.M.; Helsen, L. Energy Conservation in an Office Building using an Enhanced Blind System Control. Energies, 2017, vol 10

Carrascal, E.; Garrido, I.; Garrido, A.J.; Sala, J.M. Optimization of the Heating System Use in Aged Public Buildings via Model Predictive Control. Energies, 2016, vol 9

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