POLITECNICO DI TORINO

Dipartimento di Architettura e Design

Corso di Laurea Magistrale in
Architettura per il Progetto Sostenibile

TESI DI LAUREA MAGISTRALE

Occupant behaviour vs energy consumption in a residential building.
Survey analysis of occupant behaviour in Italian residential context and application of Home Automation scenarios to improve energy efficiency- CorTau House Case study

Autore:

Klaudia Izabela Penkala

Relatore:

Stefano Paolo Corgnati (DENERG, PoliTO)

Correlatori:

Valentina Fabi (DENERG, PoliTO)
Cristina Becchio (DENERG, PoliTO)

Settembre 2018

Acknoledgments

The present master thesis *"Occupant behaviour vs energy consumption in a residential building"* has been developed in order to fulfil the requirements to obtain the Master Degree in the field of Architecture at Politecnico di Torino, Department of Energy.

First of all, I would like to thank Valentina Fabi and Cristina Becchio, for their guidance, helpfulness and for their wise advises which helped me on my way to prepare this thesis.

Special thanks to Stefano Corgnati, who gave me the possibility to develop this thesis together with his team.

I would like to thank as well Giulia Crespi, Verena Barthemles and Maria Valentina Di Nicoli for their constant support and help.

Finally, since this thesis represents the end of a long period of studies, I would like to thank everyone who have always supported me in this study period giving me strength and motivation to achieve the goals. Especially I would like to thank Walter, who was always next to me and encourages me to believe in my capabilities, in every moment.

Executive summary

Energy-usage in buildings is one of the aspects that mostly influence greenhouse gas emissions and local air pollution in developed countries. Nowadays, in fact, the building sector consumes more than one-third of total primary energy in the world. Moreover, in the European Union countries, the residential sector is responsible for more than one-fourth of final energy consumption. One of the main factors that influences the energy consumption in the building sector is occupant behaviour. Occupants interact with the building systems in order to obtain satisfying comfort levels in the indoor environment by regulating lighting levels, heating/cooling set-points or windows and window blinds. Moreover, building occupants' daily activity profiles clearly shape the timing of energy demand in households. Existing literature has shown that occupant behaviour is one of the key driving factors of uncertainty in prediction of energy consumption, causing relevant discrepancies between real and simulated energy consumption, even among buildings with similar characteristics and same climatic conditions.

For this reason, a deep understanding and forecasting of occupants' behaviour and modelling energy-related occupants' activities throughout the day are crucial to evaluate their impact on the energy consumption and indoor quality performances. A way to investigate occupant behaviour, especially when it is not possible to monitor it directly, is the use of surveys, questionnaires and self-reporting.

In order to understand the occupant behaviour in the Italian residential context, a questionnaire survey was conducted in north-Italian dwellings at the beginning of summer 2018. The survey framework included questions about individual preferences for indoor environmental conditions, individual characteristics of the occupants (i.e. age, gender), social factors (i.e. education, job category, and household income), dwelling characteristics, and occupant interaction with the building systems and with windows. Furthermore, to shape energy-related activities profiles for weekdays and weekends, the respondents were asked to report their activities performed at home during the last full day, choosing for every 15-minutes intervals among the proposed activities, which were considered energy- or occupancy-related and therefore valuable for occupant behaviour analysis in residential buildings.
The survey results showed that occupant preferences about indoor climate conditions (i.e. air temperature) and interaction with building systems are variable and depend on many driving forces, as social drivers (i.e. household income, children presence), physiological drivers (i.e. age of the occupant) or building characteristics. Moreover, the results highlighted that occupants are often not aware about their influence on the energy consumption in the dwelling (i.e. significant part of the respondents tend to open windows when the heating or mechanical ventilation systems are active).

Nowadays, the answer to an energy-intensive occupant behaviour may be Home Automation. Automation, control and supervision systems may have a significant impact on the energy performance of a building and on the comfort of occupants and they may reduce energy consumption even up to 50%. Building automation could help reaching the nearly Zero Energy target in a building, or at least in decreasing building energy demand by balancing energy losses, internal gains and energy needs, with particular regard to the optimization of the balance between heating and cooling needs. The implementation of such systems allows obtaining a Smart Energy Home, which allows efficient energy management and where appropriate building automation systems work together in order to provide an effective control of lighting, heating, ventilation and air conditioning systems, which is essential to guarantee a healthy, safe working and productive indoor environment.

For this reason, the second part of the thesis aims to demonstrate how, through the implementation of building automation systems and a good occupant's interaction with them, it is possible to obtain considerable energy savings in the residential building.

This analysis was applied to a case study, the so-called "CorTau House", an nZEB located in Piedmont region, North of Italy. Basing on the case study parameters, there were defined all variables necessary to monitor in a Smart Home. After the definition of variables to monitor it was possible to speculate three possible Home Automation Scenarios (high, medium and low level of automation) for the CorTau House, all characterised by different costs and different level of occupants' freedom of interaction with the building systems and different control logics needed to combine an appropriate set of sensors and actuators. Moreover, with the use of the above-mentioned time use survey, compiled by CorTau House's occupants, it was possible to determine schedules different occupants' actions- occupancy profile, sleeping schedule and use of the lighting system schedule, with the division on different day of week (weekday and weekend). Thanks to above-mentioned schedules it was possible to develop control logics which not only are focused on the energy savings, but also are taking in consideration the preferences and habits of Cortau House's occupants. Finally, a literature review on sensors and actuators was carried out, analysing the current market offers, the availability and cost of the products availability for implementation

In conclusion, the thesis investigated home automation as a promising solution for improving building performances. Surely, energy demands may reduce not only thanks to the implementation of building automation systems, but also by encouraging a more aware occupants' interaction with the dwelling itself. Only with the combination of these two aspects, it is possible to truly achieve and operate Smart Energy Buildings with low energy needs and high performances.

The present master thesis is a continuation of the work developed during the *Laboratorio di Tesi: Metodologie e Misure per l'Ambiente Costruito*, which took place in the period from February 2017 to May 2017.

Keywords: occupant behaviour, energy consumption, italian residential buildings, household energy consumption, questionnaire survey, window opening, HVAC control, solar shading control, Home Automation, Smart Home

Acronyms

BACS Building Automation and Control Systems
COP Conference of the Parties
EPBD Energy Performance of Buildings Directive
GHG Greenhouse Gases
HVAC Heating, ventilation, and air conditioning
MS Member State(s)
IEQ Indoor Enviromental Quality
IPCC International Panel on Climate Change
nZEB nearly Zero Energy Building
OB Occupant Behaviour
PMV Predicted Mean Vote
PPD Predicted Percentage of Dissatisfied
TBM Technical Building Management
UNEP United Nations Environment Programme
UNFCCC United Nations Framework Convention on Climate Change
WMO World Meteorological Organization

Contents

Chapter 05

Conclusions

References

Attachments

CHAPTER NO. 1

Introduction

1.1. Climate Changes and International Energy Saving Policies

In the past, the climate changes has been driven only by natural causes. Our climate has changed over millions of years- from ice ages to tropical heat and back again. Natural changes over the past 10 000 years have generally been gradual. This has enabled people, plants and animals to adapt or migrate. However, some prehistoric climate changes may have been abrupt and are likely to have led to mass extinction of species. Over the past 150 years there has been a marked and growing increase in greenhouse gas producing activities such as industry, agriculture and transportation. These human-induced activities are increasing the level of greenhouse gases (GHG) in our atmosphere and are causing the Earth to heat up at an rate, which was noticed never before. CO_2 is the greenhouse gas most commonly produced by human activities and it is responsible for 64% of human-made global warming. Its concentration in the atmosphere is nowaday 40% higher than it was when industrialisation began (Fig. 1.01). Other greenhouse gases are emitted in smaller quantities, but they trap heat far even more effectively than CO_2, and in some cases are thousands of times stronger. Methane is responsible for 17% of man-made global warming, nitrous oxide for 6% [1].

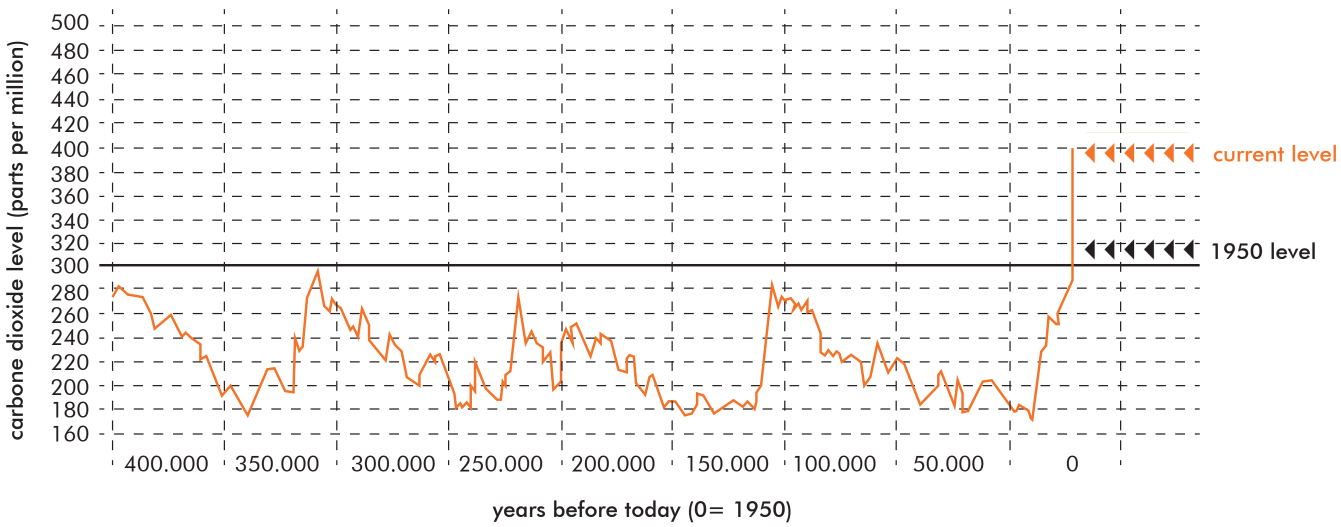


Fig. 1.01.: The relentless rise of carbon dioxide; source: https://climate.nasa.gov/climate_resources/24/graphic-the-relentless-rise-of-carbon-dioxide/

The UK was the world's first industrial-scale CO_2 emitter (cumulative carbon dioxide emissions has exceeded 10 000 Mt already in 1882) [2]. On the following maps (fig. 1.02) it is possibile to see the comparison of total world fossil fuel emission in 1960 and 2016. It is noticeable that emissions from most of growing economies have been increasing rapidly over the last few decades, the total emissions growed almost four times from 1960 to 2016. Focusing on the annual emissions in 2016, it is possible to see that many of low to middle income nations are now within the top global emitters. In fact, China is the country which emits the most of fossil fuels, followed in order by the US, EU-28, India, Russia, Indonesia, Brazil, Japan, Canada and Mexico. Most of nations that are already top emitters are likely to continue to increase emissions as they undergo development.

In contrast to CO_2 emissions growth in low to middle income economies, trends across many high income nations have stabilized, and in several cases decreased in recent decades. Despite this downward trend across some nations, emissions growth in transitioning economies dominates the global trend- as such, global annual emissions have continued to increase over this period [2].

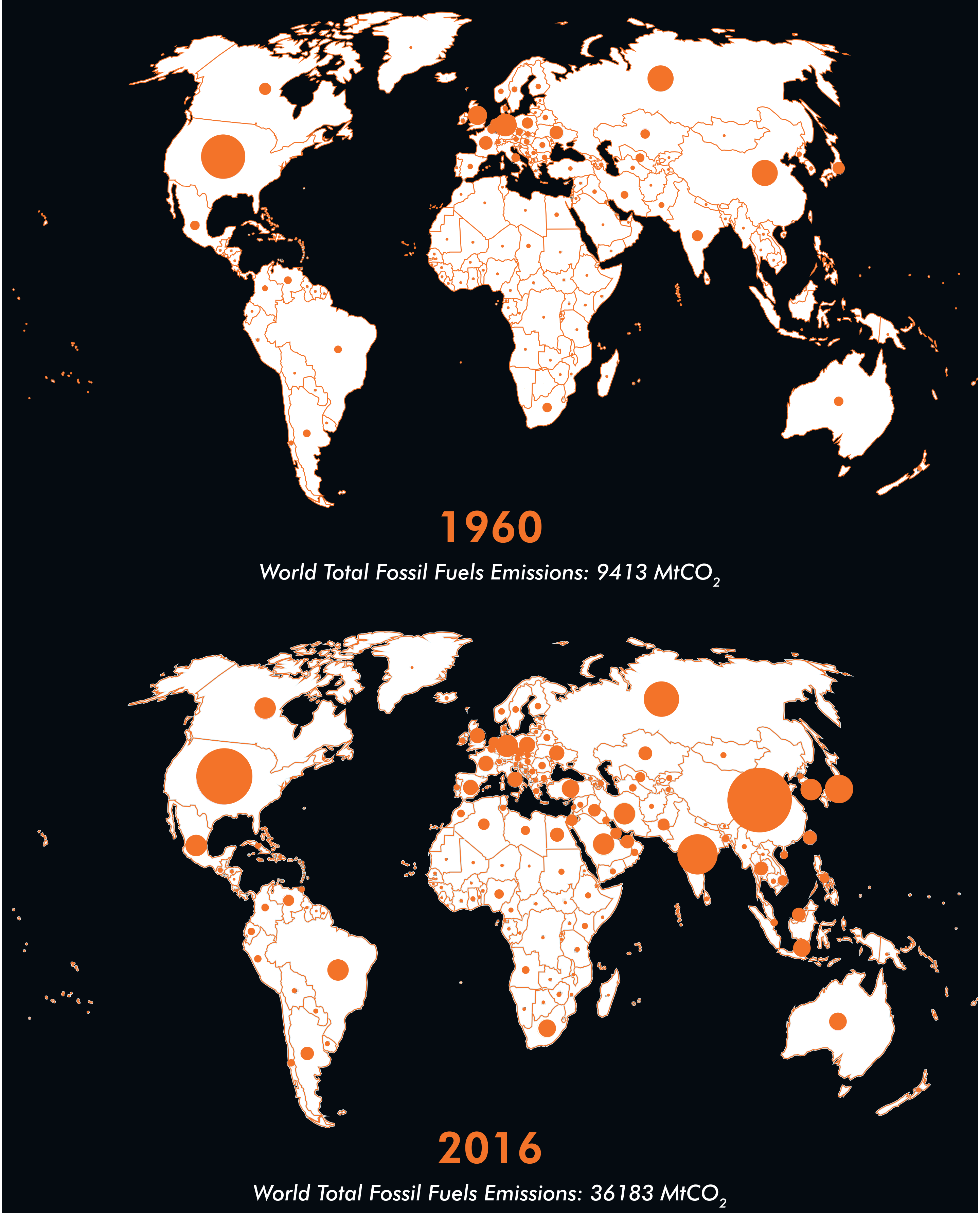


Fig.1.02.: *Total world fossil fuels emissions in 1960 and 2016; source: http://www.globalcarbonatlas.org/en/CO2-emissions*

As mentioned before, the industrialization has the big impact on climate changes. The current global average temperature is 0.85°C higher than it was in the late 19th century (Fig.1.03.). Each of the past three decades has been warmer than any preceding decade since records began in 1850 [3].

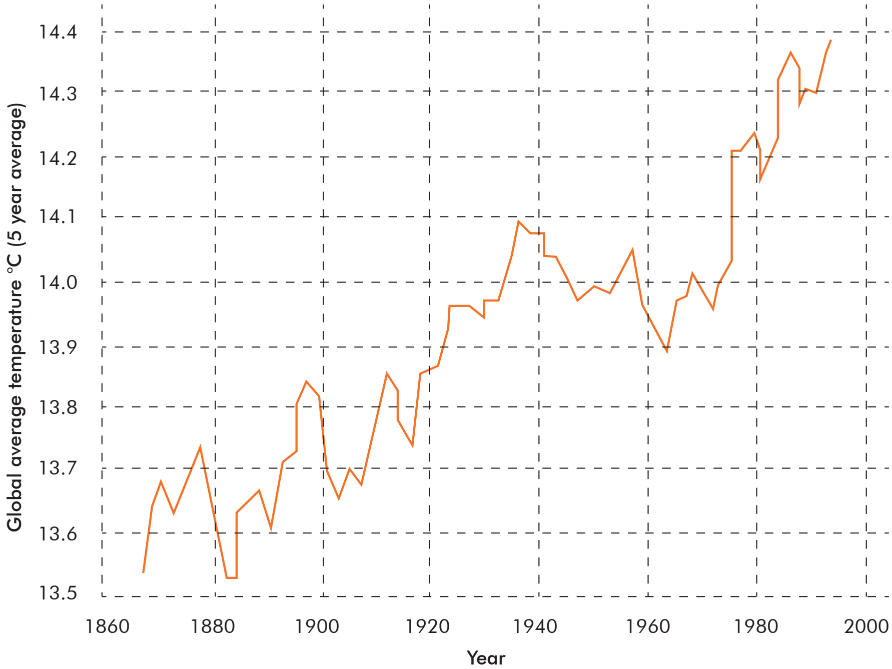


Fig. 1.03: Rising temperature over the years, source: http://www.bbc.co.uk/schools/gcsebitesize/science/aqa_pre_2011/rocks/fuelsrev6.shtml

Global warming is responsable for many wordlwide natural disasters. Temperatures are rising, rainfall patterns are shifting, see ice is melting (Fig.1.04), sea levels are getting higher and extreme weather resulting in hazards such as floods and droughts is becoming more common (Fig.1.05).

Fig. 1.04.: The loss of sea ice habitat from climate change is the biggest threat to the survival of polar bears, source: https://www.worldwildlife.org/species/polar-bear

Fig. 1.05.: Hurricane Sandy damage to Seaside, New Jersey, 30 October 2012; souce: https://www.worldwildlife.org/photos/hurricane-sandy-damage-to-seaside-new-jersey-30-october-2012

For those and many other reasons, climate change is nowaday an important issue and challenge for governor institutions. The important impact of the industrialization on the climate change was already identified in 19th century by some european researchers, among others: Fourier (1827), Tyndale (1859), and Arrhenius (1896). However, only in the late 1970s World Meteorological Organization (WMO) started to be concern about human activites, which are leading to CO_2 emissions, impact to serious warming of the lower atmosphere. The global awareness about this issue has start to grow in the 1980s, when North America suffered from intense heat waves and droughts. Those natual disasters pushed the political organizations to take actions. For this reason, in 1988, WMO and the United Nations Environment Programme (UNEP) established the International Panel on Climate Change (IPCC) to investigate and report on scientific evidence on climate change and

possible international responses to climate change. The IPCC has become central reference for debates and processes around the development of climate change policies. The first assessment report was published in 1990 and it drived to create the United Nations Framework Convention on Climate Change (UNFCCC) in 1991. This was signed by 166 countries over the world at the Earth Summit in Rio de Janeiro in 1992 and came into force in 1994. However, the UNFCCC didn't provide any targets for GHG emissions reduction, but have determined key points and principles, like:
- particular focus on developing countries, especially those which could suffer more from climate changes, like small islands;
- the need to monitor and limit their greenhouse gas emissions and for all the countries and for different national limits, taking account of countries' different responsibilities and capacities [4].

Subsequently, from 1994, the UNFCCC has started to organize cyclic international level meetings, called Confrence of the Parties (COP). At the begining it was organized every year, then every two years, every time in the different part of the world. One of the first important conferences was COP 3 (1997), where Kyoto Protocol was estabilished. Kyoto Protocol commited participating State Countries to reduce greenhouse gas emissions in developed countries in order to minimize the climate changes, in the period from 2008 to 2012, at least of 5,2% compared with the 1990 emissions level. However, The Kyoto Protocol allows some flexibilities in terms of the methods countries could use to meet their gas reduction commitments, for example:
- the countries could compensate the emission by increasing carbon sinks (forests, which are able to absorb CO_2 from the atmosphere);
- emissions trading – trading of emission allowances between countries [5];
To consider the Kyoto Protocol as valid, it was required that at least 55 nations, which together emit at least 55% of greenhouse gases, should sign the agreement (it entered into force in 2005 thanks to the insertion of Russia into the Treaty).

At the European Union level it is worth to mention the Energy & Climate Package (March 2007), called European 20-20-20 Targets. The 2020 package is a set of binding legislation to ensure the EU meets its climate and energy targets for the year 2020. Main goals of the Package were:
- to reduce by 20 % CO_2 emissions compared to the levels in 1990;
- al least 20 % of the energy, on the basis of the consumption should come from renewable sources;
- a 20 % increace in energy efficiency [6].

In the last decade the international organizations are always more focus on the sustainable building development. On of the global goals is to build nearly zero-energy buildings (nZEB). One of the main directives which is focused on this topic is The Energy Performance of Buildings Directive (EPBD), which is the European Union's main legislative instrument aiming to promote the improvement of the energy performance of buildings within the Community. In particular EPBD recast, published in 2010, was adopted by the European Parliament and the Council of the European Union in order to strengthen the energy performance requirements and to clarify and streamline some of the provisions from the 2002 Directive it replaces. According to the recast, until 2020, all new buildings should consume "nearly-zero energy". Moreover, all Member States should develop policies in order to stimulate the transformation of buildings that are refurbished into nearly zero-energy buildings [7].

Another important EU initiative was The Annex 66. The project was approved at the 74th Executive Committee Meeting of the IEA Energy in Buildings and Communities Programme, held in 2013 in Ireland. The Annex aimed to set up a standard occupant behavior definition platform, establish a quantitative simulation methodology to model occupant behavior in buildings, and understand the influence of occupant behaviour on building energy use and the indoor environment [8].

Those policies, agreement and norms are showing, that sustanaible solutions are gaing increasing intension all over the world. Thanks to implemented targets, many of countries was able to reduce CO_2 emissions significantly in the last years. However, the scale of the problem is still large and one of the biggest challenges nowaday is to involve developing countries into more sustainable development process.

1997

Kyoto Protocol (COP 3)

Internatonal agreement linked to the United Nations Framework Convention on Climate Change. It commits State Parties to reduce anthropogenic greenhouse gas emissions to minimize climate changes, in the period from 2008 to 2012, to a minimum of 5.2% compared with the 1990 emissions. To consider the treaty as valid, it was required that at least 55 nations, which produce together least 55% of emissions should sign the agreement; it entered into force in 2005 thanks to the insertion of Russia into the Treaty. [5]

2005

Annex 45

International project proposed to identify and to accelerate the use of appropriate energy efficient high-quality lighting technologies and their integration with other building systems. It assess and document the technical performance of existing innovative lighting technologies as well as future lighting technologies and their impact on other building equipment and systems. These novel lighting system concepts have to meet functional, aesthetic, and comfort requirements of building occupants. The Annex deals with four research areas:

- targets for Energy Performance and Human Well-Being;
- Innovative Technical Solutions;
- Energy-Efficient Controls and Integration;
- Information Dissemination [9].

2007

20-20-20 Targets

European policy which introduce goals for the year 2020 for different sectors. The main goals are:

- to reduce by 20 % CO_2 emissions compared to 1990 levels;
- at least 20 % of the energy, on the basis of the consumption should come from renewable sources;
- a 20 % increace in energy efficiency. [6]

2009

COP 15

The post-2012 agreement of European Union. It included the set of the global actions to prevent dangerous human-made interference with the global climate system. The key issues of the agreement were:

- to keep the global mean temperature increase below 2°C above the pre-industrial level;
- to stop rising GHG emissions by 2020 at the latest, to be reduced by at least 50% of 1990 levels by 2050, and to continue falling thereafter. Developed countries should cut their emissions by 80-95% below 1990 levels by 2050 [10].

2010

EPBD Recast

Adopted in order to strengthen the energy performance requirements at the EU level. Some of the objectives of the Directive was to:

- Until the 2020 all the building should be „nearly zero-energy";
- for buildings destined to be saled or rent, the energy performance certificates shall be stated;
- MS were obligated to prepare lists of national financial measures and instruments to improve the buildings energy efficiency [7].

2013

IEA EBC Annex 66

Approved at the 74th Executive Commitee Meeting of the IEA Energy in Buildings and Communities Programme. It estabilished a standard for Occupant Behaviour (OB) definition platform, with main objectives to:

- identify quantitative descriptions and classifications of OB;
- develop effective calculation methodologies of OB;
- implement OB models with building energy simulation tools;
- demonstrate the OB models in design, evaluation and operation and optimization by case studies [8].

2015

COP 21

A global agreement on the reduction of the climate change. The main key issue was to limit global warming to below 2°C compared to the level from the preindustrialization period. The agreement could be considered as valid only when at least 55 countries which together emit al least 55 % of GHG emissions will partecipate [11].

Fig. 1.06.: The summary of the international policies focused on the Climate Change

1.2. Residential buildings and the final energy consumption

Nowadays, the building sector consumes more than one-third of total primary energy in the world. Moreover, in the European Union countries, according to data provided by Eurostat, only residential sector is responsible for more than one-fourth final energy consumption (Fig. 1.07) [12].

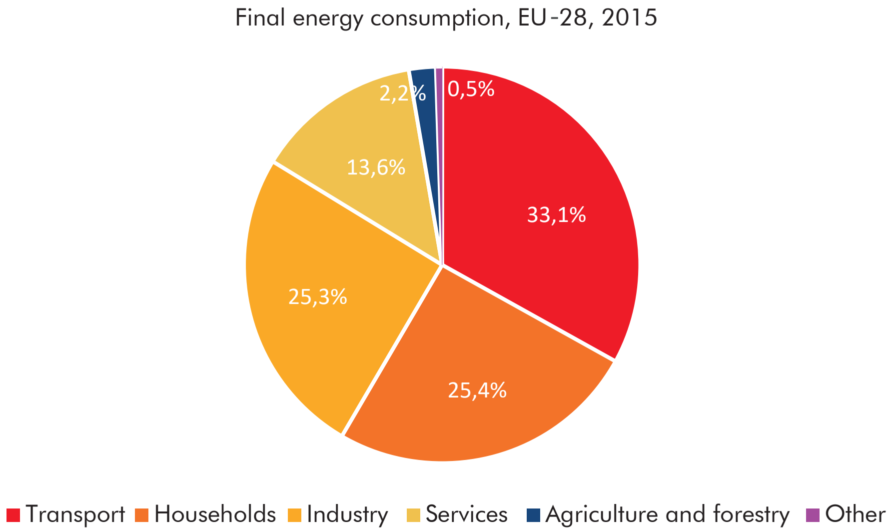


Fig. 1.07.: Final energy consumption for European Union countries in 2015, source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Consumption_of_energy

Final energy consumption in residential buildings highly depends on dwelling size and its location. Smaller dwellings usually require less energy as there is less conditioned and transfer area, and occupancy level is lower as well. Talking about location, the most important parameter is the climate of the location. For example, Pérez-Lombard et al (2007) [13] have found that the UK dwellings consume 28% of the total final energy use, meanwhile the Spanish dwellings only 15%, mainly due to more severe type of the climate and to the builing type- in the UK the detatched houses are predominant. The quantity and type of energy consumed in dwelling are primarly related to weather conditions, socio-economic level of the occupants, architectural design of dwelling and energy systems. Moreover, developed countries use significantly more energy than developing countries and it is expected that this tendency will continue to rise due to the installation of new appliances (like air conditions, computers, etc.). In the European Union, the highest part of energy consumption in dwellings is mainly due to HVAC system, especially to space heating- is responsabile for 65% of final energy consumption in the residential buildings [14].

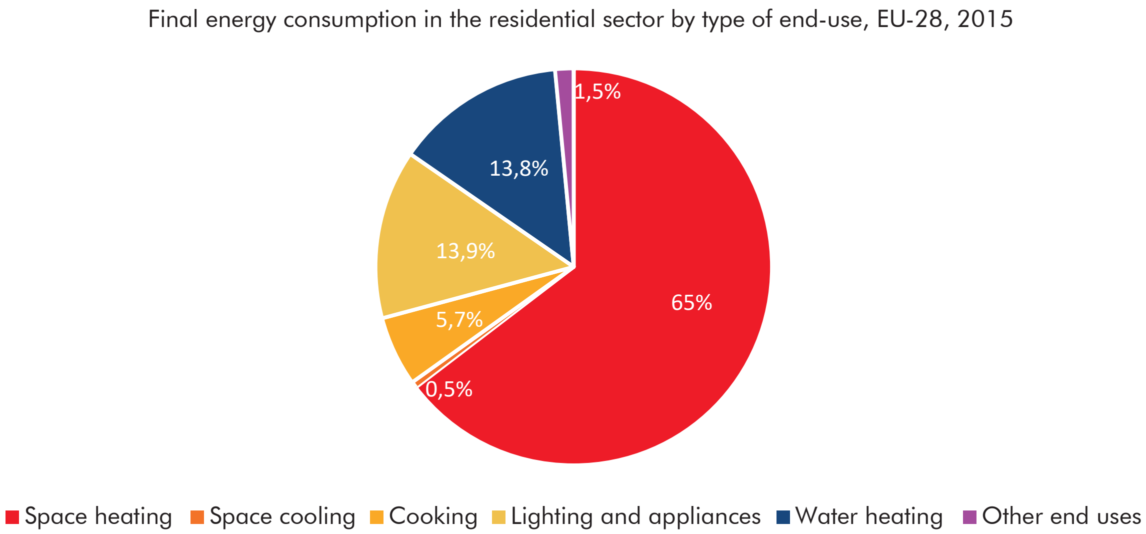


Fig. 1.08.: Final energy consumption in the residential sector by type of end-use for European Union countries in 2015, source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Final_energy_consumption_in_the_residential_sector_by_type_of_end-use,_EU-28,_2015.png&oldid=340063

The design standards for energy efficiency in buildings over the last years have more and more strict requirements regarding energy efficiency performance of buildings and appliances. During the last decade it is possible to notice important great improvements in building design (like green roofs, intelligent facades etc.), building technologies (automatization of lighting and shading systems etc.) and building operational strategies (occupancy driven HVAC control, etc.). However, overall building energy use does not decrease but rather in many cases rise up. Often, there is a great discrepancy between the designed and the real total energy use in buildings. The reasons for this discrepancy are usually not well known, but often it is more due to the occupants' behaviour and their lifestyle than the building design.

1.3. Influence of occupant behaviour on energy consumption in buildings

As mentioned before, occupant behaviour can influence significantly the energy consumption in the residential buildings. In fact, according to Annex 53 published by International Energy Agency (2016) [15], occupant behaviour, next to operation, maintenance and indoor environment conditions, is one of the main internal factors which are influencing the energy consumption in the buildings (Fig.1.09).

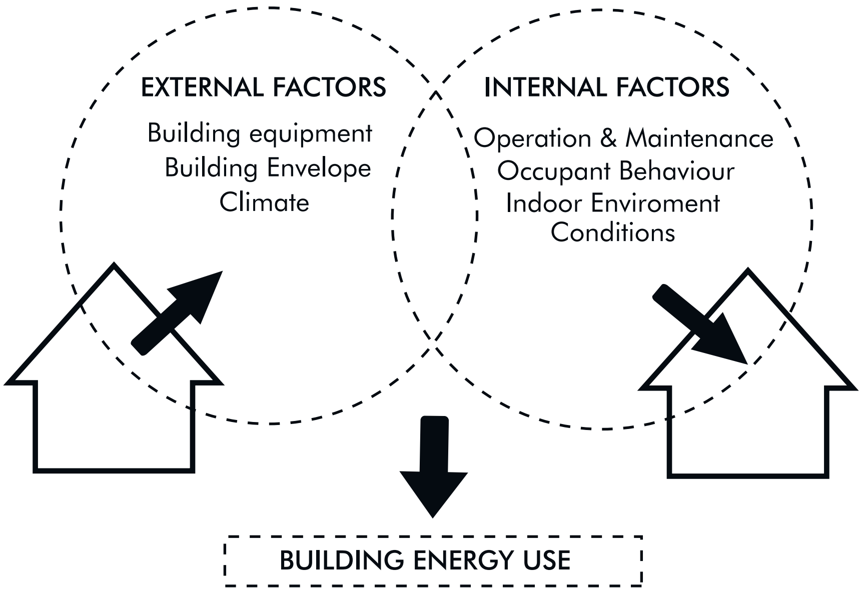


Fig. 1.09.: Influencing factors on total energy use in buildings, adapted from: IEA- ECBCS Annex 53

Many studies have already tried to investigate the behaviour of occupants in residential buildings. Many of them have found that variation in occupant behaviour may lead to big variations in the energy consumption in the residential buildings, even if dwellings have similar characteristics. For example, Seligman et al. [16] observed energy consumption in 28 identical detatched houses and they found that the largest differeneces in energy consumption was in proportion two to one. In another study, conducted by Bahaj and James [17], was found the consumption of electricity in nine similar social-housing units varied even up to 600% in some periods of the year. Another aspect of occupant behaviour, in the office buildins, was found by Masoso et al. (2010) [18], who have verified the "dark side" of the influence of occupant' behaviour. They have performed energy audits for the office buildings. They have found that more than 50% of energy was used during non-working hours than during official working hours due to occupant behaviour. The reasons were, among others, leaving light and equipment (computers) on at the end of the day and not enough good building zoning and controls.

However, not many studies have investigated the interactions of the occupant in real indoor environment in detail. In most buildings, occupant can behave with windows, heating or artificial light to obtain comfortable indoor environmental conditions. Good knowledge of occupant behaviour is crucial for an accurate prediction of building and effective operation of building systems.

Occupant behaviour- from drivers to energy use

Energy consumption in residential buildings is influenced by the occupant behaviour in many ways. Occupant behaviour is really complex and can be defined as *„observable actions or reactions of a person in response to external or internal stimuli, or respectively actions or reactions of a person to adapt to ambient environmental conditions (such as temperature, indoor air quality and sunlight), household and other activities."* [15]

According to study conducted by Fabi et al. (2011) [19] factors, which are influencing the occupant behaviour, both external and internal, could be named as the general term "drivers". They are leading the occupant to a reaction in the building and suggesting him to operate an action. These drivers include physical environmental conditions, psychological factors, physiological factor, social factors and contextual factors.

Second operator, which can influence the energy consumption is the occupant itself ("occupant stimoulus"). The occupant can react to those drivers in certain way (consciously or unconsciously) in order to improve restore the comfort conditions (i.e. thermal, indoor air quality or lighting).

Generally the behaviour of the occupants in the building can be separated in two main categories: the first one is how they occupy the building (when the building is occupied and how many people for every zone), which can be call *occupancy*. The second category is the occupants interaction with indoor climate; how the occupants interact with the building devices like windows, doors, blinds, air conditioning terminals, lights, thermostats and equipment like TVs, computers and so on. Usually the occupants have the possibility to adjust and control those devices, thus, those interactions are closely related to occupancy. For example, some devices like lights or ventilation can be turned on by the occupants when they are in the zone and switched off when they are out. Those actions can be defined as "action scenarios". More precisely, the occupant influence on the indoor environment can be grouped in three following groups:
- Occupant can modify the indoor environment in direct way by adjustment of heating and the ventilation systems, opening and closing windows and shading windows.
- In other hand, occupant can have an effect on indoor environment indirectly. His actions can be related to the change of internal heat gains/ energy use.
- Third type of influence affects indirectly indoor environment. Occupant can act in order to restore comfort by the adjustment of the occupant himself to the existing environmental conditions. The actions include the change of position (for example leaving the room), active body adaptation (i.e. the amount of clothes worn), and the thermo-regulation or passive body adaptation (i.e. drinking cold or hot liquids)

Action scenarios have an direct impact on indoor environmental quality and energy consumption. Both outputs have an effect on the drivers [19].

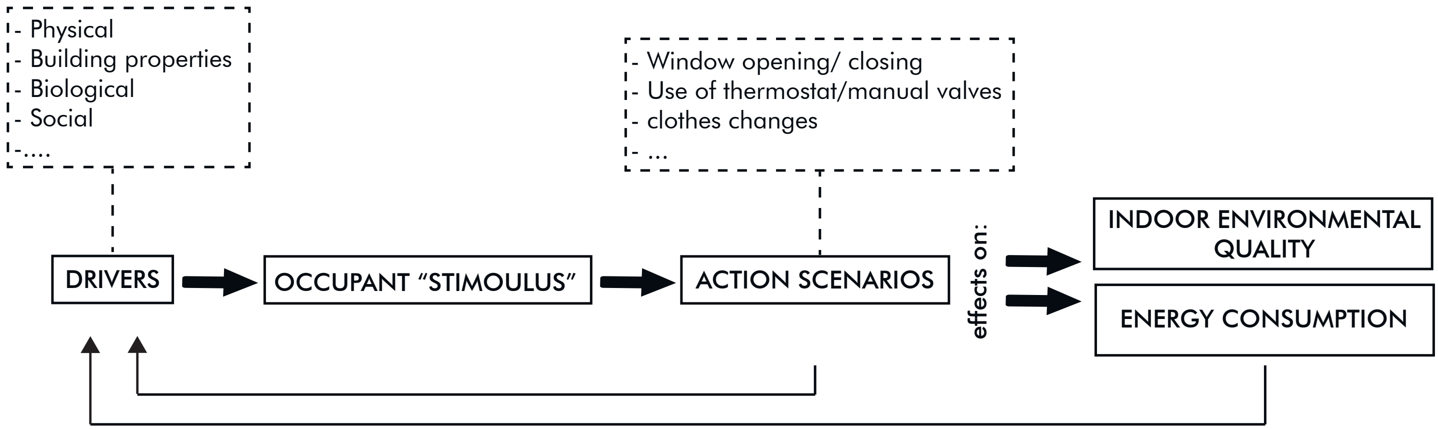


Fig. 1.10.: Flux diagram- from drivers to energy consumption and indoor environmental quality; adapted from: Fabi et al (2010)

1.4. Identification of driving forces

As mentioned before, the comfort is a state of mind that can vary from occupant to occupant due to personal (physiological, psychological) and social drivers, which directly affect occupant's energy use. Moreover, climatic parameters, economical parameters, regulations and policies, architecture and interior design of the space and building types can also directly influence energy behaviour of occupants. (Fig. 1.11)

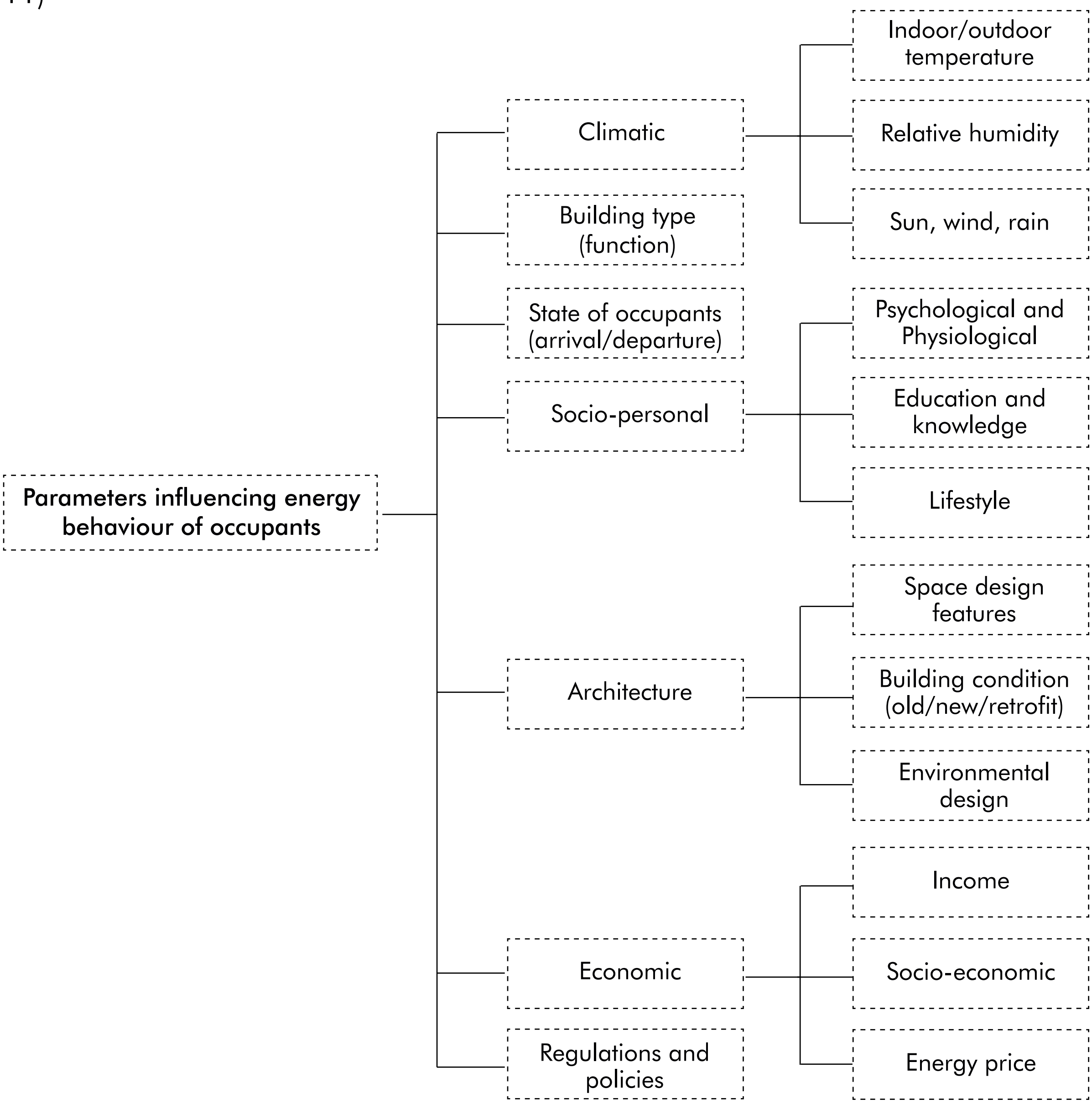


Fig. 1.11.: : Drivers influencing energy behaviour of occupants, source: Delzendeh et al., 2017

In the following part, basing on the existing reserearches, there are analysed the main drivers which are stimulating occupants to behave with window opening and closing and heating/cooling in residential buildings.

Identification of driving forces- window opening and closing

Window opening behaviour has an immediate impact on indoor air quality, indoor humidity and energy performance of building. In the domestic environment, window opening behaviour is the easiest way for occupants to control indoor thermal environment and to restore their comfort. Occupants usually open the window to cool the indoor environment when they feel hot indoors, but they will close the window if the indoor thermal environment are to cool and the window is still open. This would mean that occupants are not satisfied with the indoor conditions and at the same time they decide to take some actions (opening or closing window). When they feel comfortable with the indoor thermal conditions, they don't interact with the windows. [20]

As mentioned before, there are many factors which are influencing occupant behaviour (drivers). For window opening behaviour, one of the most important driver is the climatic condition.

Among all physical environmental drivers, one of the most influencing is the temperature (outdoor and outdoor). When the outdoor temperature is high, occupant is used to open window more often [21]. However, some researchers have observed that this tendency is changing when the outdoor temperature is perceived as too high. It may be due to the tendency to utilize split air-conditioners when outdoor air temperature is high. [22]
Another physical environmental parameter which has influence on occupant window opening behaviour is the presence of wind and rain. Windows are usually opened either to let fresh air into the room and thus improve the room air quality, or they are opened for cooling. Both reasons are dominated by internal parameters of the room, however more or less influenced by the difference between room and outside air temperature. But there are some occasions, when influences from the outside of the building become predominant concerning ventilation control by occupants. These are the occurrence of wind and rain.
Concerning wind, occupants are used to close the windows when the wish for fresh air or cooling, if the sensation of draft in the apartment is producing a predominant discomfort. This dipends strongly on wind direction, and generally increased at higher wind speeds. [23]

Another important influencing driver is architecture of the building. The orientation, type of the room and thermal mass play also an important role. Some studies have shown that windows in kitchen and living rooms are open for shorten periods than windows in bedrooms [24]. The effectiveness of natural ventilation strongly depends on properties of ventilation openings and their controllability, what is to facade design. The behaviour of occupants can be considered as a reaction to the controls provided by the specific design. For the facade design it is possible to distinguish two main factors influencing ventilation- the choice of the window opening type and the second is the size and placement of the openings on the facade. Type of the room influences how long the windows are opened. Several studies have demonstrated [25] that the most ventilated rooms are bedrooms, while the windows in the living rooms and kitchens are open usually for shorter periods.
Window opening behaviour can be also influenced by ventilation type. Nicol et al. (2004) [26] have found that the windows in the households without mechanical ventilation are kept open even four times longer than in flats with mechanical ventilation.

It is worth to highlight also the biological drivers. As found by some researchers, age of the occupants plays important role. Elderly people behave in different way than younger people- they tend to ventilate less than the young [27].

Several researches have investigated also the social aspects, as the drivers which are stimulating the windows opening behaviour. Among them, the most important is the lifestyle (like a presence in home or smoking behaviour). The longer the dwelling is occupied the more windows are kept opened. The smokers usually ventilate their houses more than two times longer than occupants without smoking habit. It is important also to consider household activities (i.e. cooking), when occupants are used to ventilate the apartment [27].

Indoor temperature is related with outdoor temperature, but also to the thermal comfort. Many studies have demonstrated that indoor climate preferences (i.e. temperature) is important driving force for the behaviour of the occupants. This driver is strongly correlated to the occupants' perception of comfort. [27]

Indraganti et al. (2014) [28] have found that also sociocultural aspect can influence the operation of window openings. They noticed that some occupants preferred to keep the windows shut to avoid vandalism (stone-pelting). Others preferred to keep windows closed for privacy reasons.

All driving forces which are influencing window opening and closing are presented toghether in the table below (Fig. 1.12.):

Climatic

Outdoor temperature
Indoor temperature
Wind speed
Presence of rain

Architecture (building properties)

Orientation
Type of the room
Thermal mass
Façade design- openings type/size
Ventilation type

Biological

Age of the occupants

Socio-personal

Indoor climate preferences (temperature)
Occupant presence
Smoking behaviour
Household activities

Sociocultural

Privacy
Vandalism

Fig. 1.12.: Summary of driving forces influencing window opening and closing behaviour

Occupants typically heat their apartment to keep warm in winter. Their preferred indoor temperature, however, can vary substantially from person to person. As demonstrated by Gram-Hanssen, (2010) [29] different user behaviour in identical houses may result even in a three times higher energy consumption for heating. In fact, Chen et al. (2015) [30] have found that only less than 40% attempt to the reduce frequency of use in order to save energy.

One of the factors determining the energy consumption for heating or cooling are climatic drivers. One of them is outdoor temperature. Already Vine (1987) [31] have found that homes in warmer climates turned the heater off and maintained lower winter settings than homes located in other climates. Besides outdoor temperature, outdoor humidity and the wind speed are also influencing the heating set point in dwellings. In fact, Fabi et al. (2013) [32] noticed that for occupants who frequently adjusted thermostat settings, indoor relative humidity drove them to turn up thermostatic radiator valve settings significantly.

The building properties have also the important impact on the occupant behaviour. Free-standing houses consume more energy than other types of dwellings. Guerra Santin et al. (2009) [27] have demonstrated that the detached houses consumes more than double energy than flats. Tachibana (2010) [33] also found that residents of apartments and condominiums are used more to turn off their heating systems, compared to those living in houses.
Some studies have also found that the room type has great influence on heating behaviour. Usually occupants prefer to set up higher temperatures in living rooms than kitchen or bedrooms [34, 35].

The type of heating system has been investigated as a driver as well. Centrally heated houses usually have higher temperatures than non-centrally heated [34].
Also the type of temperature control can have indirect influence on choices and the behaviour patterns. Guerra Santin et al. (2009) [27] have found that households with programmable thermostat were associated with higher indoor temperatures settings during the night and with more hours with radiators on. Also according to Lutzenhiser (2009) [36], manual control involves the deliberate cooling of people or the deliberate preparation of a cool space for people, while automatic cooling occurs regardless of occupancy or activity.

The biological aspects has been classified as a driver as well. The required indoor temperature often correlates with age of the occupant. Elderly people prefers higher indoor temperature settings that the young [37, 38]. Also the presence of children stimulate to set up higher indoor temperature [39]. Some researchers have reported that also the occupant gender can have influence on heating usage in residential buildings. Females prefer a higher set point, meanwhile males adjust the thermostat set point more often than females [40].

Several researchers have investigated also socio-personal drivers as decisive for heating adjustment. Indoor climate preferences is the main psychological driver related to the heating set-point adjustments. Moreover, some researchers have demonstrated thermal background has influence on heating adjustment. Schweiker et al. (2009) [41] conducted a survey in students' house in Japan and they have found that students originating from hot and dry as well as from moderate climates are normally used to a wider range of temperature and humidity and they are able to adapt easier than those from hot and humid climate. The number of occupants is also an important factor for energy use. There is linear correlation between household size and energy use [27]. Also the presence of occupants at home is crucial for energy use for heating. The continuous presence is correlated with an increase of energy use compared with a variable presence [29].

The influence of house ownership also has been evaluated in some studies. It was found that occupants who rent accommodation tend to spend more on heating [40].
Economic situation can also drive occupants to set up the heating. More heating leads to higher heating cost. Households with lower income tend to use less energy for keeping warm in the winter [34].

In the other study, it was found that a 1% increase in income results in 0.63% increase in energy use. Wilhite et al. (1996) [41] have compared the heating behaviour in Norwegian and Japanese dwellings and they have found that Japanese families were much more disciplined to in their heating setback habits. They had the habit of turning the heat down (or off) when they went to bed and off when they leave the house. This behaviour was, among others, probably related to the higher cost of energy (heating price).

Climatic	Architecture (building properties)
Outdoor temperature Indoor temperature Indoor relative humidity Climate Wind speed	Dwelling type Room type Type of heating system Type of temperature control

Biological	Socio-personal
Age of the occupants Gender of the occupants Health conditions	Indoor climate preferences (temperature) Number of occupants Occupant presence Ownership Children presence

Economic
Household income Heating price

Fig. 1.13.: Summary of driving forces influencing heating adjustment behaviour

1.5. Introduction to human comfort

It is possibile to think that energy-efficient buildings can be effective only when the occupants of the buildings feel comfortable. When the occupants are not satisfied with the environmental conditions, their behaviour can influence significantly the energy consumption of the building.

The comfortable conditions in the environments are established according to the study of the environmental well-being in a confined space. It can be defined environmental comfort, the conditions of well-being determined by the temperature, air humidity, noise level and illumination level of the indoor envirinment. The feeling of well-being perceived varies depending on the sensory perceptions, which can vary from person to person, and may depen on age, gender, psychic and physical state, metabolism, human sensitivity, etc. It is possible to distinguish four main types of comfort in the indoor environments:
- thermal comfort,
- visual comfort,
- aural comfort,
- indoor air quality.

Thermal comfort

Temperature is one of the most important components to the experience of comfort in an indoor environment. According to the ANSI/ASHRAE Standard 55-2010, thermal comfort is defined as *"that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation."* [42]. There are four main environmental parameters that affect thermal comfort:

- **Air dry bulb temperature (ta) [°C]**: temperature measured by dry bulb, it is temperature of the air surrounding the occupant.

- **Mean radiant temperature (tmr) [°C]**: the weighted average of all the temperatures from surfaces which are surrounding a particular point, with which it will exchange thermal radiation. When the point is exposed to the outside, this could also include the temperature of sky and solar radiation.

- **Relative air velocity (v) [m/s]**: Rate of air movement given distance over time. Typically, maximum limits are established in order to avoid draft. While draft might be a relevant concern in cold climates, it's quite irrelevant in warmer climates.

- **Relative air humidity (RH) [%]**: The percentage of water vapour containeg in one kilogram of the dry air. To consider RH are comfortable for the occupant, the optimal percentage should be between 40% and 60%, with max 10% of tollerance. When the RH is below 30% it may cause a sensation of discomfort like dryness of the mucous membranes; when the TH is above 70%, the moist indoor environment conditions may cause illnes of the occupants (like allergies), and moreover it can be dangerous for the building structure (like molds formation).

Moreover, there are two other important parameters, which are connected to the occupant, and which should be considered for thermal comfort:

- **Metabolism M [MET]**: the energy which is produced by human body. The human body transform potential chemical energy supplied by food into other forms of energy. The unit of metabolism is MET, and it varies according to the type of activity carried out by the occupant (Fig. 1.14). 1 MET=58,2 W/m^2 and corresponds to the metabolism of an awake human in rest conditions (sitting). The lowest level of metabolism is produced during sleeping (0,8 MET) and the highest level of metabolism is produced during demanding sports, when the value of 10 MET can be exceed.

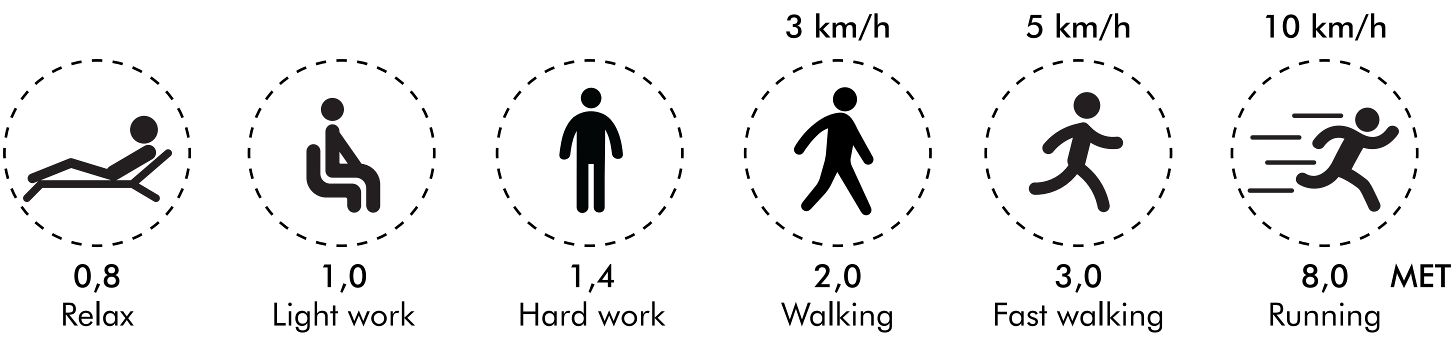


***Fig. 1.14.**: Metabolic rate for different activities*

- **Clothing insulation (clo)**: The amount of thermal insulation (clothes) the occupant is wearing; The unit of clothing insulation is CLO, where 1 CLO= 0,155 m^2K/W.

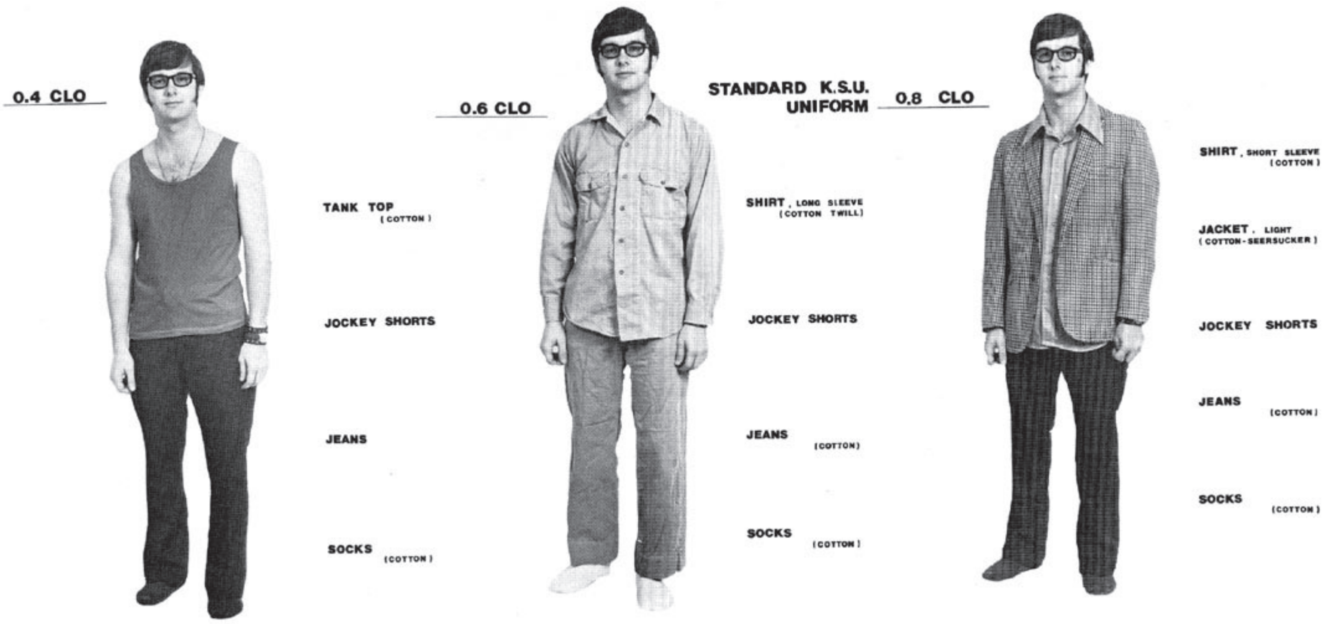


Fig. 1.15: Examples of CLO levels, source: http://www.webdelsol.com/DIAGRAM/1_1/clo_man.html

Fanger method

There are many method developed by reaserchers which are trying to decribe thermal comfort. One of the most famous and accepted methods was developed by Ole Fanger, which are known as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatified (PPD).

<u>The Predicted Mean Vote (PMV)</u>

The Predicted Mean Vote (PMV) defines a thermal scale with the range from Cold (-3) to Hot (+3), originally developed by Fanger and later adopted as an ISO standard. The original data was collected by probing a great number of people exposed to some different climate conditions and asking them to select a value on the proposed scale which the best described their comfort sensation. As a result of tests, a mathematical model of the correlation between all the environmental and physiological factors considered was then derived from the data. The results relate the size thermal comfort factors to each other through heat balance principles and produces the following psycho-physical ASHRAE scale:

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

Fig. 1.16.: Predicted Mean Vote sensation scale, source: P.O. Fanger, "Thermal Comfort. Analysis and Applications in Environmental Engineering", Robert E. Krieger Publishing Company, Malabar, Florida (1982)

According to ASHRAE 55, for an interior environment, the most recommended acceptable PMV range is between -0.5 and +0.5.

Predicted Percentage of Dissatisfied (PPD)

Predicted Percentage of Dissatisfied (PPD) is used to predict the percentage of occupants who can be dissatisfied with the indoor environment conditions. It is based on PMV, given that as PMV moves further from 0, or neutral, PPD increases. The maximum number of people dissatisfied with their comfort conditions is 100% and, as it is not possible to satisfy all of the people all of the time, the recommended acceptable PPD range for thermal comfort from ASHRAE 55 should less than 10% of occupant which are not satisfied of an internal environment conditions.

Adaptive method

Another method to define thermal comfort of occupants is adaptive method. This model add a more human behaviour to the mix. The method considers that, if changes occur in the thermal environment to produce discomfort, then people will generally change their behaviour and take actions to preserve their comfort conditions. Those actions could include taking off clothing, reducing activity levels or even opening a window. The main effect of this kind of model is to increase the range of conditions that designers can consider as comfortable for the occupant, especially in buildings ventilated in natural wasy (trough windows), where the occupants have a greater degree of control over their thermal environment. In fact, unlike the Fanger method, in order to consider adaptive comfort, the indoor environment (room) must have operable windows, no mechanical cooling system, and the occupants must be rest conditions (i.e. sedentary) with a metabolic rate between 1.0 and 1.3 MET. Moreover, occupants have the possibility to add or remove clothing to adapt to the present thermal conditions [43].

Visual comfort

Visual comfort is usually defined through a set of criteria based on the level of light in a room, the balance of contrasts, the colour „temperature" and the glare presence of absence. Lighting conditions may influence occupants' health and efficiency both in a straight line, since work efficiency depends on vision, and not directly, because lighting can straight attention, or affect motivation. The daylight and artificial light are two main sources of light. Illuminance level is usually measured in foot candles (fc, lm/ft^2) or lux (lx, in the metric SI system). The reccomended average indoor illuminance level in the residential buildings is 150 lx, but should vary depending on the room type and on the type of activities performed (Fig. 1.17)

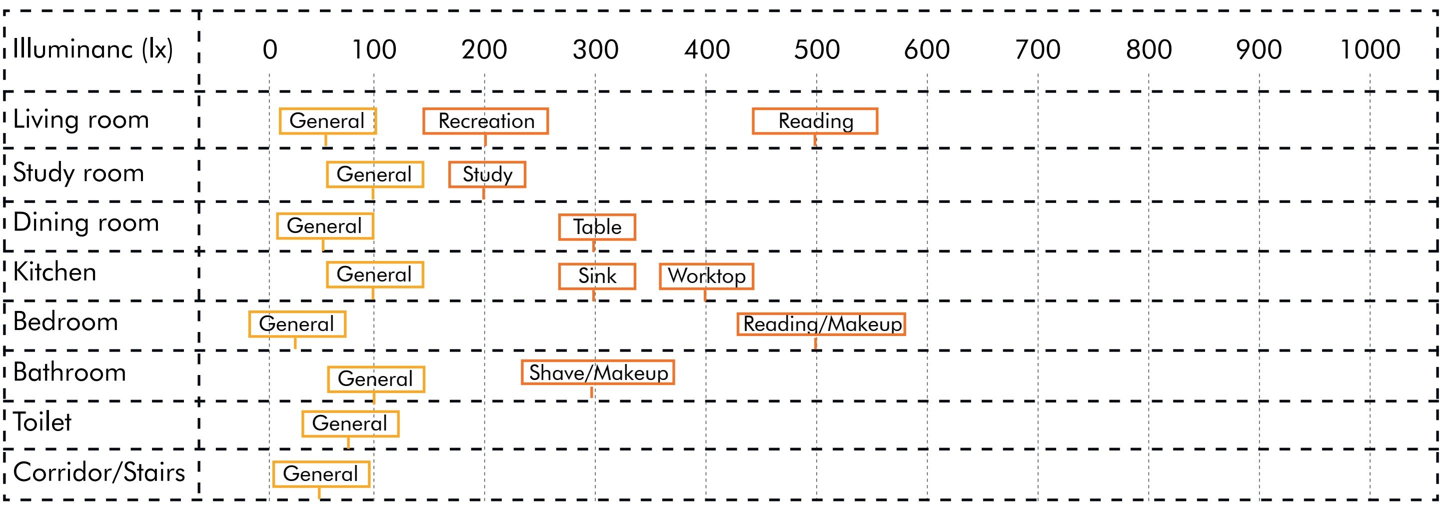


Fig. 1.17: Room activity and recommended illuminance levels; source: https://panasonic.net/ecosolutions/lighting/technology/knowledge/03/

Indoor Air Quality

The Indoor air quality (IAQ) referes to the quality of the air withing and around a building and it is related to the health and comfort of occupants. Indoor exposure to air pollutants causes very significant damage to health globally- nowadays it is big issue in the developed countries. Poor IAQ is related to the Sick Building Syndrome (SBS). This syndrom takes place when more than 20% of the occupants of a building are not satisfied about air quality.

There are different group of chemical and biological pollutants in indoor air. IAQ can be affected by gases (i.e. carbon monoxide, radon, volatile organic compounds), particulates, microbial contaminants (mold, bacteria), or any mass or energy stressor that can induce adverse health conditions (Fig.1.18). Source control, filtration and the use of ventilation (natural or mechanical) in order to dilute contaminants are the primary methods for improving indoor air quality in most buildings.

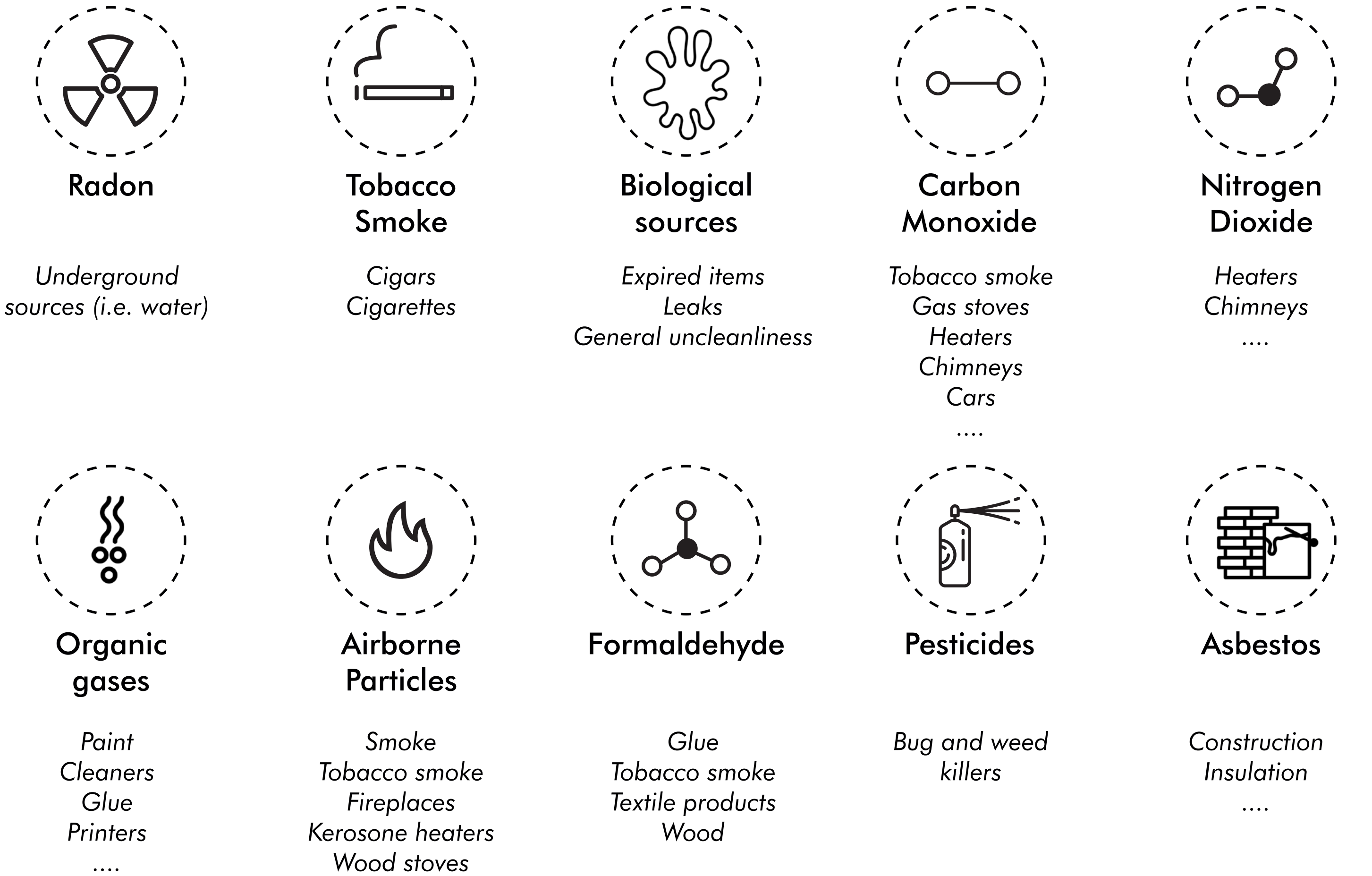


Fig. 1.18.: *Most common in-home sources of air pollution, source: http://info.tudi.com/blog/most-common-in-home-sources-of-air-pollution*

CHAPTER NO. 2

Smart Home and building automation

2.1. Definition of „Smart Home"

Smart homes and other smart technology, like smart grids and smart meters, are existing as concepts since many years, but are gaining increasing attention only in the last decade. Nowadays, smart homes are one of priorities for the European Union, included in Strategic Energy Technology Plan: „Create technologies and services for smart homes that provide smart solutions to energy consumers" [44].

There are many definitions of „Smart Home", not all of them overlap. Smart home can be defined as a residence which is supplied with a communications network, linking sensors, domestic appliances, and devices, that can be remotely monitored, accessed or controlled and which provide services that respond to the needs of its occupants. As defined by Balta-Ozkan et al. (2014) [45], the definition "smart home" reffers to any type of residential building, like a detached house, an apartment, or an -unit in a social housing development. Sensors can be used to detect the location of occupants, or to collect data about the building system states (i.e. temperature, energy usage, open windows). Domestic appliances refer to the equipment like refrigerators or washing machines.

Fig. 2.01.: Smart Home services

Smart Home can be managed trough many various devices, from big ones like furniture to small ones like temperature sensors. It is possible to distinguish a lot of different kinds of devices with different properties. They can vary in technical parameters, used software, feature, size and a lot more. Some of them have low computing power and memory capacity and run with battery like a sensor network node. Others have high energy consumption or need water to work, for example a washer. It's possible to group the main services into following categories [45,46] (Fig. 2.02):

- Energy efficiency control
- Security control surveillance
- Entertainment and communications
- Convenience and Comfort control
- Assisted living and e-health control:
  - eldercare;
  - healthcare;
  - childcare.

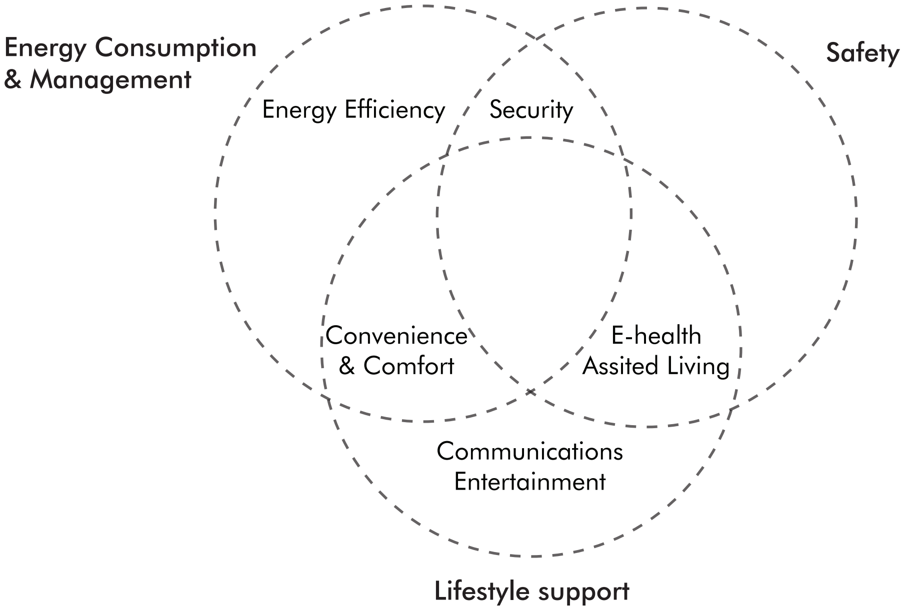


Fig. 2.02.: The main groups of services for an Smart Home

2.2. Smart Energy Home

In recent years, one of the main target of energy efficiency (EE) has been further the usage of more and more efficient devices. The Building Automation Controls (BACs) plays a fundamental role in the efficiency and sustainability of buildings. The performance of the buildings depends on their geometric and structural configuration, the installations and the occupants. Smart Home, as well as building automation systems, can have an impact on all these aspects. Previously, the management of plants and energy consumption were the only services offered by the Smart Home technology, for this reason referring to the „energy" type services, we could talk about Smart Energy Home. The term „Smart" has started to be associated with the possibility of managing the energy consumption of buildings and systems of Home Energy Management System (HEMS), i.e. devices with target of maximizing energy efficiency (in terms of energy usage) driving equipment and appliances. A Smart Energy Home system is characterized by two main targets: the improvement of comfort conditions within the indoor environment and the control of various devices and building systems for efficient energy management. This is done by identifying and reducing the energy waste, using energy only when and how much is needed, implementing an effective control system. An effective control of all heating, cooling and ventilation systems is essential to create a healthy and comfortable environment for the occupants. Although it may be obvious that new and technologically advanced buildings require a sophisticated control system, actually even the most traditional buildings can benefit from control systems. On the other hand, the use of sophisticated control systems is not the only way to reduce consumption. A more careful usage of the old systems that already provided in a building can be equally effective. This kind of approach could be adopted in those buildings which, for historical or cultural reasons, cannot benefit from more complex systems. The improvement of energy efficiency requires, first of all, the knowledge of energy consumption. An adequate monitoring and knowledge of their consumption would significantly reduce the energy usage of home devices.

It is possible to identify two specific „fields of application" of services related to a Smart Energy. On the one hand it is possible to act on the so-called „final usage of energy", i.e. the components responsible for energy use, on the other it is necessary to take into account and properly manage the parameters that qualify the quality of the indoor environment and the comfort of the occupants, like heating, cooling, lighting, ventilation systems, electrical equipment and drinking water. With regards to the comfort, it is possible to identify four main fields: the thermo-hygrometric comfort, visual comfort, air quality and acoustic comfort.

2.3. European Normative For Building Automation - EN 15232: 2007 Energy Performance of Buildings- impact of Building Automation, Controls and Building Management

The term „Building Automation and Control system (BACs)" refers to the centralised systems that are able to monitor, control and record the main functions of building services systems. By implementation of reliable BACs, building facilities can maintain the building environment more efficient and in consequence to reduce the building environment impact and energy costs. The core functions of BACs system are:
- to maintain control of the building's environment,
- to operate systems according to occupancy and energy demand,
- to monitor and correct the performance of systems,
- to sound allerts as required.

Thanks to BACs it is possible to monitor:
- mechanical system,
- plumbing,
- electrical systems,
- heating, ventilation and air-conditioning (HVAC).

Building Automation and Control systems (BACs) are defined by the norm EN 15232:2007. The norm allows to quantify and qualify the benefits of those systems. The standard is suitable both for existing buildings and for those in the process of designing or restructuring. In particular, for existing buildings, it defines the methods for the evaluation of energy savings, through implementation of management systems and control of building systems.
For this, the standard defines four different classes of energy efficiency- BACS (Building Automation and Control Systems). The classes of efficiency, from A to D, are as follow:

- Class A- High Energy Performance BACS and Technical Building Management (TBM);

- Class B- Advanced BACS and TBM;

- Class C- Standard BACS;

- Class D- Non energy efficient BACS - corresponds to traditional and technical system that provide no automation or energy efficiency.

The following table (Fig. 2.03) rapresents function list and assigment to energy performance classes source: table 1 EN 15232:2007 [D]:

	Heating/ Cooling control	Ventilation/ AC control	Lighting control	Sun protection
A	- Individual room control with communication between controllers - Indoor temperature control of distribution network water temperature - Total interlock between heating and cooling control	- Demand or presence dependent air flow control at room level - Variable set point with load dependant compensation of supply temperature control - Room or exhaust or supply air humidity control	- Automatic daylight control - Automatic occupancy detection manual on/ auto off - Automatic occupancy detection manual on/ dimmed - Automatic occupancy detection auto on/ auto off - Automatic occupancy detection auto on/ dimmed	- Combined light/blind/HVAC control
B	- Individual room control with communication between controllers - Indoor temperature control of distribution network water temperature - Partial interlock between heating and cooling control (dependent on HVAC system)	- Time dependent air flow control at room level - Variabile set point with outdoor temperature compensation of supply temperature control - Room or exhaust or supply air humidity control	- Manual daylight control - Automatic occupancy detection manual on/ auto off - Automatic occupancy detection auto on/ auto off - Automatic occupancy detection auto on/ dimmed	- Motorized operation with automatic blind control
C	- Individual room automatic control by thermostatic valves or electronic controller - Outside temperature compensated network water temperature - Partial interlock between heating ang cooling control (dependent on HVAC system)	- Time dependent air flow control at room level - Constant set point of supply temperature control - Supply air humidity limitation	- Manual daylight control - Manual on/ off switch + additional sweeping exinction signal - Manual on/off switch	- Motorized operation with manual blind control
D	- No automatic control - No control of distribution network water temperature - No interlock between heating and cooling control	- No air flow control at room level - No supply temperature control - No air humidity control	- Manual daylight control - Manual on/ off switch + additional sweeping exinction signal - Manual on/off switch	- Manual operation for blinds

Fig. 2.03: Function list and assignment to energy performance classes (section from table 1 of the EN 15232:2007 [D]); source: http://www04.abb.com/global/seitp/seitp202.nsf/0/d0bbe587cf46edc6c125777500401d30/$file/extract_from_ABB_brochure_2CDC-500060M0201_p_6_7.pdf

2.4. The ways to assess the interaction between occupants and systems

The correct prediction of the occupants' behaviour is crucial to evaluate their impact on the energy consumption and indoor quality performances.
It is possible obtain the informations about the occupant behaviour in multiple ways. The part below describes the most common ways and presents some examples of their use in the research field.

2.4.1. Review of human behavioural frameworks

There are several frameworks which are trying to describe human behaviour using a need-action-event cognitive process. Cognitive-behavioural frameworks consider users as reactive agents instead of passive receptors in the contextual environment. These models try to capture the stochastic nature of the human cognition process by describing the connection between the human 'inside world' inputs (drivers and needs) and the environmental 'outside world' outputs (actions and events) [47]. Some examples of cognitive-behavioural frameworks is described below:

Drivers – Needs – Actions – Systems' (DNAs) framework

An initial theory of the DNAs framework was proposed by Turner&Hong, then extended by Hong et al. (2015) [48]. Framework deals with energy-related behaviour, which refers both to individuals and groups of occupants and their interaction with building energy services systems, appliances and facilities to control the indoor environment. It also includes the movement and presence of the occupants in indoor environment. The scope of the framework was to provide an ontology of energy-related occupant behaviour in buildings to solve discrepancy issues for: i) oversimplifying or ignoring occupant behaviour in the building; ii) a broken interface between occupant behaviour and building system controls and, iii) a lack of reliable technology and system controls performance.
The impact of the behaviour of the occupant on building energy use was described using four key components: drivers behind the occupant behaviour, which are influencing the energy consumption, needs of the occupant to obtain desirable comfort conditions, actions which occupant takes in order to satisfy his needs; and systems with which occupant interacts to perform the actions which affect energy consumption. The DNAs framework facilitates the quantification of the impact of occupant behaviour on building energy consumption. The frameworks allows the incorporation of more accurate behavioural models into building simulation tools to obtain results on:
- the behavioural factors which are influencing energy consumption;
- the potential energy savings from improved occupant behaviour in buildings;
- the design of robust building operation scenarios, technologies, systems and retrofit strategies.

Occupant behaviour motivation survey framework (D'Oca et al., 2016)

D'Oca et al., (2016) [49] have provided standardized quantitative descriptions on the motivations driving occupant behaviour in office buildings. They have created a standardized tool to drive effective occupant behaviour data collection to enhance the state of the art on knowledge, methodologies and tools. They have found that research should focus on the rise and alternation of collective and social behaviours determined by geographical context, culture and norms, driving occupant motivations, which are crucial in fastening behavioural pattern and have consequences on building energy consumption and IEQ. The questionnaire should include at least 1000 interviewed.
The survey structure is based the DNAS ontology for energy-related occupant behaviour in buildings. The questionnaire is of a combination of key questions resulting from a comprehensive literature review of occupant behaviour questionnaire surveys, Humphreys' principle of occupant's interaction with control system in buildings, traditional and adaptive comfort theories merged with social science theories.

The questionnaire is based on the four following sections: i) comfort requirements, ii) habits, iii) intentions and iv) actual control of building systems. For each section, the survey provides additional informations about: i) context of the question, ii) focus area categories and iii) background references. (table xx)

Section	Context	Focus area	References
Comfort	physical environment	thermal comfort	Brager et al, 2004
		visual comfort	
		IAQ	
	physiological parameters	gender	Fanger, 1987
		age	
Habits	adaptive	past behaviour	Ackerly et al, 2012 Humphreys at al, 1995
	psychological	response automaticity	
	social	social norms	
	contextual	workstyle routine	
		employment role	
		country of orgin	
		environmental factors	
Intentions	awareness of consequences	perceived subjective norms	Onwezen at al, 2013 Ajzen et al, 2001 Harland et al, 2007 Stern et al, 1986
	situation responsability	perceived social norms	
	attitude	perceived willingness	
	efficacy	perceived effectiveness	
Control	knowledge	perceived control actual control	Brown et al, 2009
	ability	perceived access	
		perceived impediments	
	technology	perceived achievements	

Fig. 2.04: Structure of the OB Motivation Survey Framework, D'Oca et al., 2016

Moreover, for each of the focus area, the questionnaire includes survey questions and specifies and the scale or the options for the questionnaire responses. Some elements of the survey identify a specific action or motivation using qualitative responses (Fig. 2.04). For other questions, the generality was increased by aggregation of typical behaviours using the adoption of unpaired numerical scales. These elements constitutes the predictor variables for measuring the impact of motivational drivers over the likelihood of adopting motivation-driven rather than adaptive-unconscious interaction with the building control systems, having impact on energy and comfort requirements.

2.4.2. Review of occupant behaviour investigation methodologies

Monitoring studies

Trough monitoring of building systems it is possible to obtain informations about the relationship between monitored building systems states (like heating on/off or window open/closed), indoor and outdoor environmental variabiles, occupant behaviour and energy consumption of the building. There are two available aprroaches which can be use to obtain informations about energy-related occupant behaviour in buildings: field monitoring (objective) and questionnaires and self-reporting (more subjective).

Field monitoring

Field monitoring is the most direct and accurate method for occupant behaviour monitoring. In many existing studies, examination of occupant behaviour is often coupled with "primary indicators" like indoor and outdoor environmental conditions. The data can be collected through various sensors (i.e. thermometers, CO_2 sensors, lux meters, etc.) and also through weather stations. The methods of data collection usually include direct monitoring of the building control systems, using magnetic switches for windows, blinds and electric lighting, electromechanical sensors for shading systems, recording Thermostatic Radiator Valve (TRV) switches, AC thermostat set points, occupancy detectors such as motion detection sensors, intelligent control of building systems and real-time building visualization, security systems, PIR (passive infrared) sensors, and wireless electric outlet meters and many more. Occupant behaviour can also be monitored in indirect way by sensing "secondary" environmental variables, parameters or actions and then performing extrapolation information. Relevant secondary indicators may include for example the level of CO_2 or metering the building energy flows (i.e. thermal flow). Moreover, information about energy-related behaviours may be deduced by using data, which is already available such as occupancy derived from light switch sensors, computer switches, IT infrastructure and from equipment load profiles. Another common method to monitor control system state or occupancy movement and presence is use of imaging analysis like time-lapse photography taken from the outdoors (i.e. from the building façade) as well as camera-based and internal personal visual survey, such as personal building walkthroughs.

Questionnaires and self-reporting

The surveys, questionnaires and self-reporting (qualitative data collection methods) are another way to investigate the occupant interaction with the surrounding environment and building systems, collecting, through qualitative and quantitative variables, real and detailed information. It is possible to use the questionnaires when it is not possible to monitor directly (using data acquisition technologies). It is possible to distinguish paper questionnaires, web-based questionnaires, e-mail surveys or computer-assisted telephone interview. Questionnaire surveys usually are used to identify the most influencing factors which are affecting the occupant interactions with the building control systems, like: the use of heating and cooling, window opening/closing, mechanical ventilation, solar shading and blinds or electrical lighting. The surveys are usually performed by sending a letter with an invitation to the most representative group of people. Participants can be asked about their preferences for control system settings and repetitive behaviours in buildings. Collected data about occupant behaviour and preferences can be supplemented with informations about building characteristics, meteorological and census data. The following figure (Fig. 2.06) rapresents the most important pros and cons of diffrent types of qualitative data collection methods:

Qualitative Data Collection Methods		
Face-to-face Personal Interviews	Qualitative Surveys	
	Paper surveys or questionnaires	Web-based questionnaires
+ allows the interviewer to probe further, by asking follow-up questions and getting more information in the process; + the data can be more personalized; - limitations, such as language barriers, cultural differences, and geographical distances; - the person conducting the interview must have very good interviewing skills in order to elicit responses.	+ ideal for use in large populations or sample sizes of respondents; + the high amount of detail provided will aid analysis of data; - the large number of respondents (and data), combined with the high level and amount of detail provided in the answers, can make data analysis difficult to analyze and time-consuming.	+ quicker data collection; + the respondents can be invited to answer the questionnaire by sending them an email containing the URL of the site where the online questionnaire is available for answering; - limitation on the respondents, since the only ones to be able to answer are those who own a computer, have internet connection, and know their way around answering online surverys; - the lesser amount of detail provided means the researcher may end up with mostly surface data, and no depth or meaning, especially when the data is processed.

Fig. 2. 06: Pros and cons of qualitative data collection methods

Survey Occupants ASHRAE 55 (ANSI/ASHRAE STANDARD 55-2004)

ASHRAE 55 [42] is the standard, which has scope to make sure that any room, building, etc., is comfortable for a larger part of the occupants (at least 80%). For this reason, the standard consider a survey as an effective way to evaluate the environmental conditions. According to standard, a survey should be performed for every operating mode, in every design condition. This would require a survey check sheet to be provided by the team responsible for validating the thermal environment of the space. The sheet as a minimum should include the following data for the occupant to fill in:
- Occupant's name, date, and time;
- Approximate outside air temperature;
- Clear sky/overcast (if applicable);
- Seasonal conditions;
- Occupant's clothing;
- Occupant's activity level;
- Applicable equipment;
- General thermal comfort level;
- Occupant's location.

Moreover, in addition to the occupant's data, space shall be provided for the respondent to number the survey, summarize the results, and sign his/her name.

Surveys are commonly used in the research field. Some examples of using survey to understand occupant behaviour in buildings are described below:

Survey of occupant behaviour and control of indoor environment in Danish dwellings (Andersen et al., 2009) [50]

The researchers have conducted the questionnaire survey to understand the factors influencing the occupants' interaction with building control systems in Danish dwellings. Participating people were asked to answer to the questions on the present state of dwellings, their age and sex, perceived indoor environment at the time of the response and during the previous 14 days; and the questions regarding the behaviour during the previous 14 days. The questionnaire was performed in two sessions: in the summer and winter period. In summer period the people who have been called to participate at the survey was 974 but only 933 of the people completed the questionnaire. In winter period, an invitation mail was sent to 879 people, but only 636 people filled completely the questionnaire.
The researchers have tried to understand the effects on the state of the four control mechanism: window open/ closed, heating on/off, lighting on/off and solar shading in use or not. They were analysed separately using multiple logistic regression analysis.
It was found that window opening behaviour was strongly linked to the outdoor conditions. However, other factors had an important impact as well- such as solar radiation, floor area, ownership, gender of the occupant and the perception of environmental conditions. For example, females opened the window more often when they perceiving the environment as bright as compared with dark. For males, the window opening behaviour didn't have the strong correlation with perceived illumination.
For the use of heating it was found that it depends on the outdoor temperature and the presence of a wood burning stove. Moreover, other parameters like solar radiation, ownership and the perceived indoor environmental conditions (illumination and IAQ) also influenced the use of heating.
Considering the use of the lighting was mainly correlated to the solar radiation, perceived illumination and outdoor temperature. Moreover, the age of the occupants, their thermal sensation and gender can be considered as influencing the use of lighting.

Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing (Frontczak et al., 2012) [51]

The survey was the part of the research programme on a user-driven innovation aiming to develop control solutions for indoor environment which can maximize comfort of occupants. The invitation letter was send to seven representative groups of occupants, depending on the type of housing and on the ownership type. The questions included in the questionnaires were selected in accordance with the objective of the project and based on the previous stages: literature survey and preliminary studies among 5 families.
The questionnaire included 3 types of questions: i) socio-demographic (i.e. age, gender, income, current location); ii) regarding home of the occupant (i.e. window opening behaviour, adjusting heating, preferences for ways of controlling the indoor environment, self-estimated level of knowledge about how to use ventilation and heating systems in efficient way), iii) regarding work of the occupant (questions as under point regarding home).
The results have shown that the occupant were usually satisfied with the indoor environment. Manual control of the indoor environment was preferred by the occupants compared with automatic control, except for heating adjustment, where occupants accepted both types of control. Natural ventilation (window opening) was associated with fresh air supply. For many occupants the mechanical ventilation was not important at their homes. Moreover, respondents declared that are informed about the influence of their behaviour on the indoor environment quality. They also were convinced that are using the control systems in correct way.
Using the results of the questionnaires the researchers considered two potential solutions for controlling the indoor environment:

- Automatic control which can satisfy minimum acceptable conditions with the possibility of manual adjustment of conditions to occupants' needs;
- Manual control by building occupants.

Simulations

Simulation is the process which allows to create a model of a real or imagined system and conducting experiments with that model. The simulation experiments can help to understand the behaviour of the system or to evaluate strategies for the operation of the system. Assumptions are made about this system and mathematical algorithms and relationships are derived to describe these assumptions – this constitutes a "model" that can reveal how the system works. Simulations are deployed when the real system cannot be engaged, because it may not be accessible, or it may be dangerous or unacceptable to engage, or it is being designed but not yet built, or it may simply not exist. It can be used to demonstrate the eventual "real" effects of a system when subjected to alternative conditions and courses of action. [52]

Nowadays, there is available the wide range of simulation tools. Among them, the most common building simulation tools are Energy Plus, IDA Ice, ESP-r, TRNSYS, DeST, and DOE-2. However, programs vary in their approaches to modeling occupant behaviour, most are limited to static and simplified behaviour inputs and lack interoperability in model exchange or reuse, so they are still non enough sufficient for occupancy behaviour modeling.

CHAPTER NO. 3

Survey- „Occupant behaviour in residential buildings"

3.1. The aim of the survey

In the developed countries people spend almost 90% of their time indoors, more than half of that time they spent in homes. Occupants interact with the building systems in order to obtain satisfying comfort levels in the indoor environment by regulating lighting levels, heating/cooling set-points or windows and window blinds. Moreover, building occupants' daily activity profiles clearly shape the timing of energy demand in households. Existing literature has shown that occupant behaviour is one of the key driving factors of uncertainty in prediction of energy consumption, causing relevant discrepancies between real and simulated energy consumption, even among buildings with similar characteristics and same climatic conditions. The correct prediction of the occupant behaviour can reduce significantly the household energy consumption (households account for more than 25% of the energy consumption in the EU member states). A way to investigate occupant behaviour, especially when it is not possible to monitor it directly, is the use of surveys, questionnaires and self-reporting.

For this reason, the aim of this survey was to understand how occupants of north-Italian dwellings interact with building control systems, like window opening/closing behaviour, use of heating, cooling and mechanical ventilation, window blinds and artificial light. Moreover, the survey aimed also to developed energy-related daily activity profiles, which shape the timing of energy demand in households.

3.2. The structure of the survey

The question included in the questionnaire were selected in accordance with the objectives of the project to collect detailed information on the occupants. The survey was composed by seven parts:

1. Individual comfort attitudes and preferences.
2. Individual characteristics.
3. Social factors.
4. Dwelling characteristics.
5. Occupant interaction with building systems.
6. Occupant interaction with windows.
7. Activities performed at home on the last day.

The structure of the survey questionnaire was based on the interdisciplinary survey framework developed by Barthelmes et al. (2018) [53]. The researchers developed a theoretical model of occupant's window control behaviour with an extensive set of drivers, and presented how to develop such models, particulary with use of the Bayesian Networks based on extensive field measurements and contextual information from 47 Danish Dwellings.

1. Individual comfort attitudes and preferences

The first section of the survey adresses the occupants' individual comfort attitudes and their preferences. At the beggining, the respondents were asked to indicate how much important are for them indicated indoor environment conditions. Moreover, the preferences about the indoor environment parameters were elicited by asking the respondents how much they agree or disagree with comparative statements. Table 3.01. summarises the survey questions of the first section.

Table 3.01. Survey section 1: Individual preferences

Code	Survey question	Scale
2.	**How important are the following to you?**	
2.1.	Not being too cold or too warm	Very unimportant- very important - 7-point scale
2.2.	To have fresh air	Very unimportant- very important - 7-point scale
2.3.	To have good lighting condition	Very unimportant- very important - 7-point scale
2.4.	Absence of noise	Very unimportant- very important - 7-point scale
2.5.	Absence of drafts	Very unimportant- very important - 7-point scale
3.	**Please indicate how much do you agree or disagree with the following statements:**	
3.1.	„During the winter, I rather feel a little bit too cold in order to have a fresh air"	Strongly disagree- strongly agree - 5-point scale
3.2.	„I rather accept some noise from outdoors to have some fresh air"	Strongly disagree- strongly agree - 5-point scale
3.3.	„I rather feel a little bit too cold/ in order to save some energy costs"	Strongly disagree- strongly agree - 5-point scale
3.4.	„When I open windows I think about higher energy costs for heating"	Strongly disagree- strongly agree - 5-point scale
3.5.	„I rather accept a slightly bad indoor air quality in order to save some energy costs"	Strongly disagree- strongly agree - 5-point scale
3.6.	„My first priority is being comfortable with the temperature and air quality, I don't worry about energy costs"	Strongly disagree- strongly agree - 5-point scale
3.7.	„When I interact with windows and the thermostat, I think about my environmental impact"	Strongly disagree- strongly agree - 5-point scale
3.8.	„When I open the windows, I usually turn off the heating/ cooling or lower the thermostat settings"	Strongly disagree- strongly agree - 5-point scale

2. Individual characteristics

As already analysed in the sections before, many existing studies have found that physiological factors can influence significantly the occupants' perception of the indoor environment and comfort attitudes. For this reason, in the second section the respondents were asked about some of their individual characteristics, like their gender, age and their smoking habits. Table 3.02. summarises the survey questions of the second section.

Table 3.02. Survey section 2: Individual characteristics

Code	Survey question	Scale
4.	How old are you?	Numberic answer
5.	What is your gender?	Multiple choice
6.	Where do you live most of the time?	Multiple choice
7.	Do you have domestic animals?	Multiple choice
8.	Do you smoke?	Multiple choice
8.1.	Do you smoke also inside the home?	Multiple choice
8.2.	If you smoke inside the home, do you open windows to get rid off tobacco smoke pollution?	Multiple choice

3. Social factors

The third section is focused on social factors, which can influence the thermal sensation, occupant' preferences and energy consumption in the residential building- like household income, job category or level of education. The effect of the social and economic factors on thermal comfort and energy consumption will be then analyzed on the basis of the data colllected through the questions summarised in the Table 3.03.

Table 4.03. Survey section 3: Social factors

Code	Survey question	Scale
9.	What is your education?	Multiple choice
10.	What is your job category?	Multiple choice
11.	Please indicate the monthly household net income:	Multiple choice
12.	How many people live in your house?	Multiple choice
13.	Do you live with your family?	Multiple choice
14.	Do children also live in your house (up to 12 years old)?	Multiple choice
15.	Please indicate how many children live in your home:	Numberic answer
16.	Do you contribute personally to energy costs (bills)?	Multiple choice
17.	Who usually controls the temperature settings in your home?	Multiple choice
18.	Who usually opens the windows in your home?	Multiple choice
19.	Who usually closes the windows in your home?	Multiple choice

4. Dwelling characteristics

To understand better the occupant behaviour in residential buildings, it is important to collect informations about the dwelling characteristics. Some parameters (e.g. age of the building or set-point temperature) can infuence significantly the energy consumption. For this reason, the respondents were asked to indicate the informations about dwelling characteristics and about building systems present in the dwelling. The questions included in the fourth section are summarised in the table below (Table 3.04):

Table 3.04. Survey section 4: Dwelling characteristics

Code	Survey question	Scale
20.	Period of construction of the dwelling:	Multiple choice
20.1.	Have your building's energy performance ever improved? (ie. window replacement, insulation, boiler change...)	Multiple choice
21.	Type of the dwelling:	Multiple choice
22.	Dwelling area (m^2):	Multiple choice
23.	Ownership:	Multiple choice
24.	The configuration of the heating system:	Multiple choice
25.	The type of main heating system:	Multiple choice
26.	The type of heating terminals:	Multiple choice
27.	The type of heating source:	Multiple choice
28.	What is the set-point temperature usually set at the thermostat for heating (°C)?	text answer
29.	Do you have a cooling system?	Multiple choice
30.	The type of cooling system:	Multiple choice
31.	The type of cooling terminals:	Multiple choice
32.	What is the set-point temperature usually set at the thermostat for cooling (°C)?	Text answer
33.	Do you have any plants for the self-production of energy?	Multiple choice
34.	Do you have a wood burning stove?	Multiple choice
35.	Presence of a mechanical ventilation:	Multiple choice
36.	How many of these domestic appliances do you own and use at home?	Multiple choice

5. Occupant interaction with building systems

The aim of this section was to understand how the occupants interact with building systems, like thermostat, shading devices, artificial lights, mechanical ventilation and cooling. The questions included in the fifth section are summarised in the table below (Table 3.05):

Table 3.05. Survey section 5: Occupant interaction with building systems

Code	Survey question	Scale
37.	**How difficult or unhandy is it for you to use:**	
37.1.	Thermostat	Very difficult- very easy 7-point scale
37.2.	Windows	Very difficult- very easy 7-point scale
37.3.	Shading devices	Very difficult- very easy 7-point scale
38.	**How satisfied are you with the following control options in your home?**	
38.1.	Thermostat	Very unsatisfied- very satisfied 7-point scale
38.2.	Windows	Very unsatisfied- very satisfied 7-point scale
38.3.	Shading devices	Very unsatisfied- very satisfied 7-point scale
39.	If you had to give an overall assessment, how satisfied are you with the control systems in your home?	Very unsatisfied- very satisfied 7-point scale
40.	**Fill your typical schedule for the following actions during the weekdays (Monday-Friday):**	
40.1.	Presence within the building (choose the hours when you are usually at home):	Multiple choice- 24 hours
40.2.	Use of the lighting system (choose the hours when the lights are usually on):	Multiple choice- 24 hours
40.3.	Use of the heating system (choose the hours when the system is usually on):	Multiple choice- 24 hours
40.4.	Use of the cooling system (choose the hours when the system is usually on):	Multiple choice- 24 hours
41.	**Fill your typical schedule for the following actions during the weekends and holidays:**	
41.1.	Presence within the building (choose the hours when you are usually at home):	Multiple choice- 24 hours
41.2.	Use of the lighting system (choose the hours when the lights are usually on):	Multiple choice- 24 hours
41.3.	Use of the heating system (choose the hours when the system is usually on):	Multiple choice- 24 hours
41.4.	Use of the cooling system (choose the hours when the system is usually on):	Multiple choice- 24 hours
42.	**In the last 14 days, how often did you use the...**	
42.1.	Thermostat	Multiple choice
42.2.	Windows	Multiple choice
42.3.	Shading devices	Multiple choice
42.4.	Ventilation system	Multiple choice
42.5.	Cooling system	Multiple choice
43.	Do you open the windows even when the mechanical ventila-tion system is on?	Multiple choice
44.	Do you open the windows even when the heating device is on?	Multiple choice
45.	Do you open the windows even when the heating device is on?	Multiple choice

6. Occupant interaction with windows

The purpose of the sixth section was to understand the motivations of occupants or their usual habits when they interact with windows (window opening/closing) in relation to certain activities (e.g. during the cooking) and certain times of the days (e.g. leaving home). Table 3.06. summarises the survey questions of the sixth section:

Table 3.06. Survey section 6: Occupant interaction with windows

Code	Survey question	Scale
46.	**Please, indicate your typical motivations when you open the windows (indicate all that apply for every room):**	
46.1.	To let fresh air in	Multiple choice
46.2.	To get the bad smells out	Multiple choice
46.3.	To change the indoor temperature	Multiple choice
46.4.	To let more natural light in	Multiple choice
46.5.	To enjoy the outdoor environment	Multiple choice
46.6.	To prevent growth of moulds on surfaces	Multiple choice
46.7.	To get rid of tobacco smoke	Multiple choice
46.8.	To get the unpleasant odors from pets out	Multiple choice
47.	**I have specific habits related to window opening, in particular, I open windows:**	
47.1.	when I come back home	Multiple choice
47.2.	when I leave home	Multiple choice
47.3.	when I wake up	Multiple choice
47.4.	when I cook	Multiple choice
47.5.	after a shower	Multiple choice
47.6.	when I hang out the laundry	Multiple choice
48.	**Please, indicate your typical motivations when you close the windows (indicate all that apply for every room):**	
48.1.	It is getting too cold/hot	Multiple choice
48.2.	It is too windy	Multiple choice
48.3.	I'm leaving the room	Multiple choice
48.4.	To reduce the noise level from outdoors	Multiple choice
48.5.	It gets dark	Multiple choice
48.6.	To save energy (heating/cooling on)	Multiple choice
49.	**I have specific habits related to the window closing, in particular, I close windows:**	
49.1.	when I come back home	Multiple choice
49.2.	when I leave home	Multiple choice
49.3.	when I go to sleep	Multiple choice
49.3.	when I take a shower	Multiple choice

7. Activities performed at home on the last day

Occupant activities in the building throughout the day have an important impact on the energy consumption. For this reason, to define occupancy profiles and energy-related activities, in the last section of the survey the respondents were asked to report their activities performed at home on the last full day (from 4 am yesterday to 4 am today). The day was divided into 15-minutes intervals (in total 96 intervals). The time spent on a given activity in the course of a day therefore becomes the sum of 15-minute sequences, where these activities occur. The respondents could choose one of ten proposed activities for every interval that were considered energy- and occupancy-related and therefore valuable for occupant behaviour analysis in the residential building. The proposed set of the activities is based on the research of V.M.Barthelmes et al. (2018) [54], which was focused on the profiling occupant behaviour in danish dwellings using Time-Use Survey. The set of 10 activities was shown in Table 3.07. As the research is focused on the occupant behaviour in the residential buildings, all activities performed outside home are considered as „Not present at home".

Table 3.07. Survey section 7: Energy-related activites

Code	Activity
1.	Sleeping
2.	Toilette/bath
3.	Cooking/washing dishes
4.	Eating
5.	House cleaning/washing clothes
6.	Free/family time
7.	TV/IT entertainment
8.	Practical work
9.	Not present at home
10.	Other

3.3. Sampling and data processing

With common Internet access through various types of smart devices, online surveys reduce the cost and the time requirements of traditional paper surveys and give the opportunity to create large--scale database with limited cost. The online survey can be accessed through personal smart devices like smartphones, tablets or computers. For this reason an online platform was choosen for survey questionnaire distribution.

The survey was created through LimeSurvey Platform and was distribuited casualy using Social Media and e-mail invitations in the period from 15th July 2018 to 5th August 2018. The survey was available in two language versions- english and italian. A survey link was open 896 times and it was filled in 611 times (476 of survey questionnaires were completed) (Fig. 3.01). For the survey analysis only completed questionaires were take in consideration. Moreover, as the aim of the study was to understand the occupant behaviour of the Northern Italy population, respondents coming from other parts of Italy/from abroad (23 respondents) were also excluded.

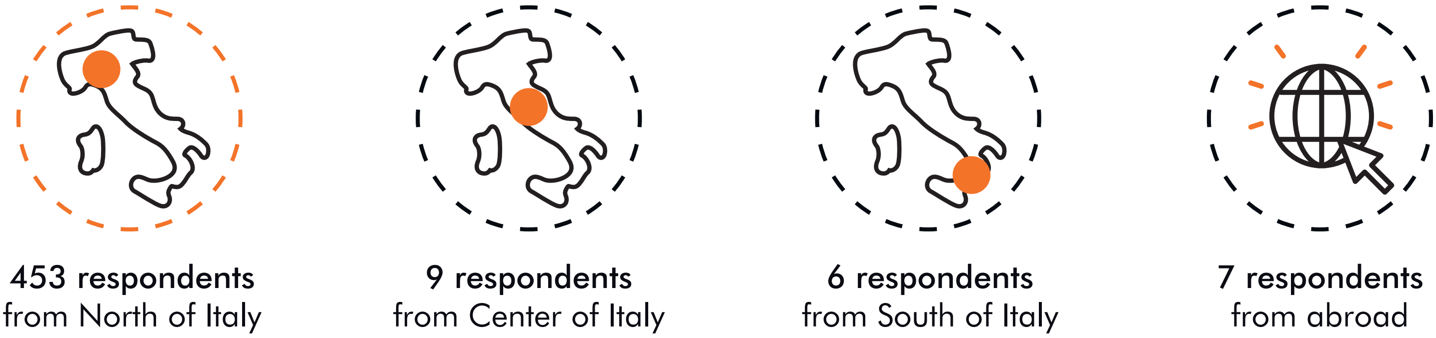


Fig. 3.01.: Orgin of the survey respondents

The main problem using online surveys is the limited demographic focus because people who usually participate in online surveys are most likely younger, as they are more familiar with use of the Internet and Social Media. In fact, it is noticeable that the highest rate of responders was between 13 and 29 years old (Fig.3.02.). The percentual of respondents age (fig.3.02.) does not correspond with the age of Northern Italy Population, according to the ISTAT data (Fig.3.03.), so obtained results can-not be considered as the sample of Northern Italy population.
For this reason, further analysis will focus on the on the limited range of population, between 13-59 years old (451 respondents).

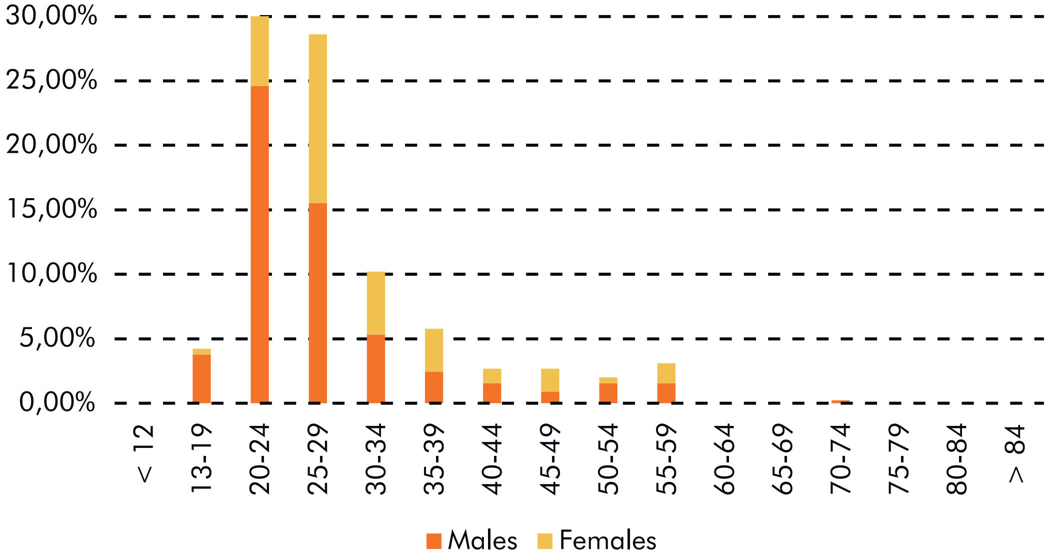


Fig. 3.02.: Age distribution of the survey respondents

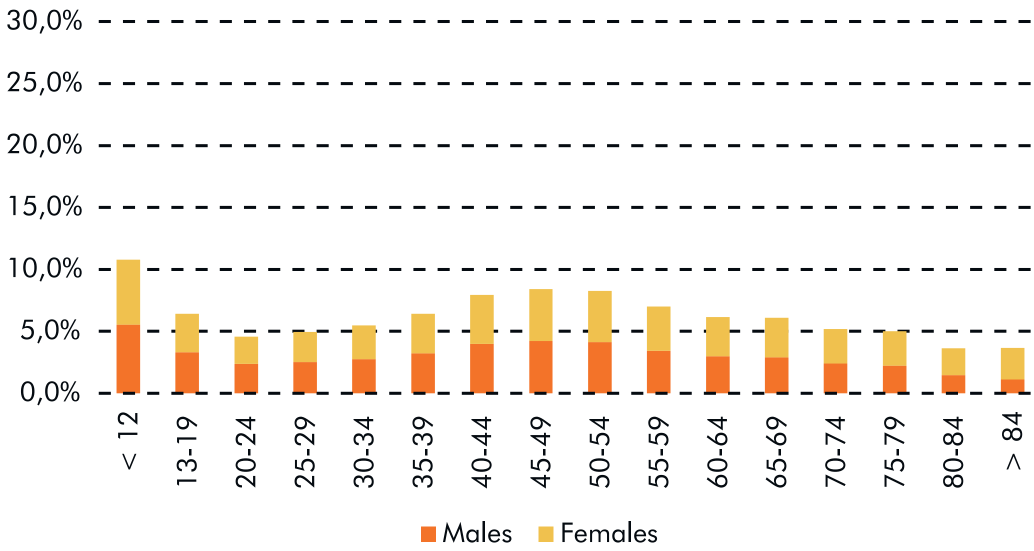
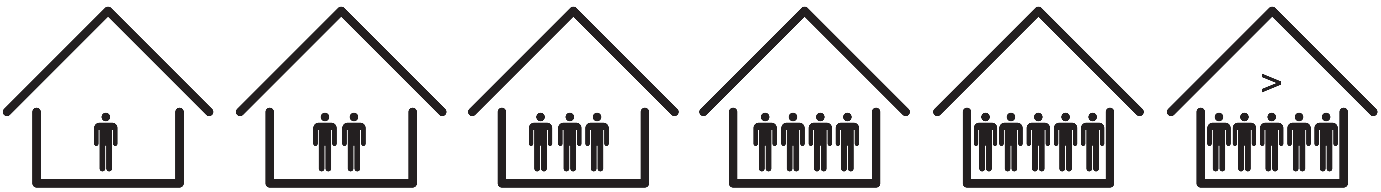


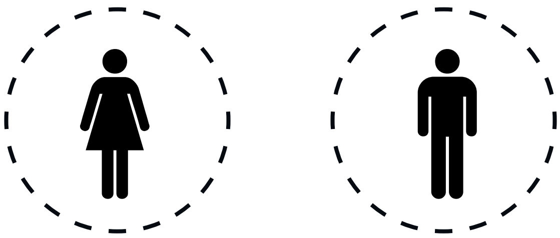
Fig. 3.03.: Age distribution of the Northern Italy Population, source: ISTAT

As regards the number of household members (Figure 3.04), the analysis yielded that respondents mostly lived in three- and four- member households, while a smaller fraction lived in households composed by one to two and more than four people. There was a quite balanced gender ratio of 57% male to 43% female among the surveyed occupants (Fig. 3.05).



22% 9% 25% 32% 9% 1%

Fig. 3.04.: Number of members in the households of the survey respondents



43% 57%

Fig. 3.05.: Respondents' gender ratio

3.4. Survey results

Individual preferences

This part of the survey aimed to investigate the indoor climate preferences of the occupants in the residential buildings. The respondents were firstly asked to indicate how important are for them to have certain indoor environmental climate conditions. The figure 3.06 clearly shows that the most of the occupants care about IEQ contitions. Most of the respondents choose „Slighlty important", „Important" or „Very important" answers for all the indicated indoor climate preferences. To understand better, what is the order of importance according to respondents, to the every answer was assigned the weight (Very unimportant= 0,25; Unimportant= 0,50; ...; Very important=1,75) and the answers were calculated with weighted arithmetic mean. There were no big deviations, but basing on the results of calculation it is possible to distinguish the following order of importance:

1. To have good lighting condition.
2. Not being too cold or too warm.
3. To have fresh air.
4. Absence of noise.
5. Absence of drafts.

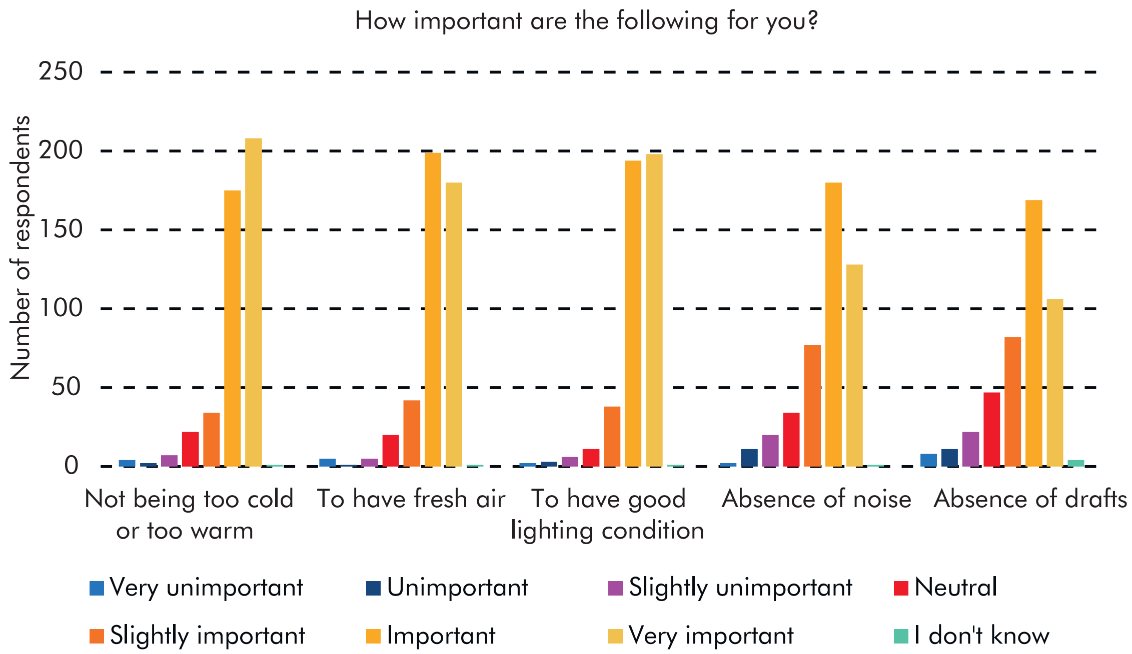


Fig. 3.06.: Respondents' preferences with regards to the indoor environmental conditions

Subsequently, the respondents were asked to indicate how much they agree or disagree with some comparative statements related to the IAQ, thermal comfort, noise levels and energy cost preferences which can have a significant influence on the interaction with window and/or thermostat. As it is possible to notice from the fig. 3.07, the respondents' preferences for indoor comfort conditions vary significantly.

Especially, it is possible to notice significant spread in the survey answers regarding thermal preferences that may influence thermostat/window control. For example, 56% of respondents stated to prefer to feel a little bit cold in order to save some energy money, but in the same time one-fourth of the respondents disagreed with the statement. With regard to the IAQ, the most of the respondents prefered to have fresh air rather than save some energy costs. Moreover, they most of them have also indicated to prefer to accept some noise from outdoors in order to have fresh air (58% of respondents, for 19% of respondents the statement was neutral).

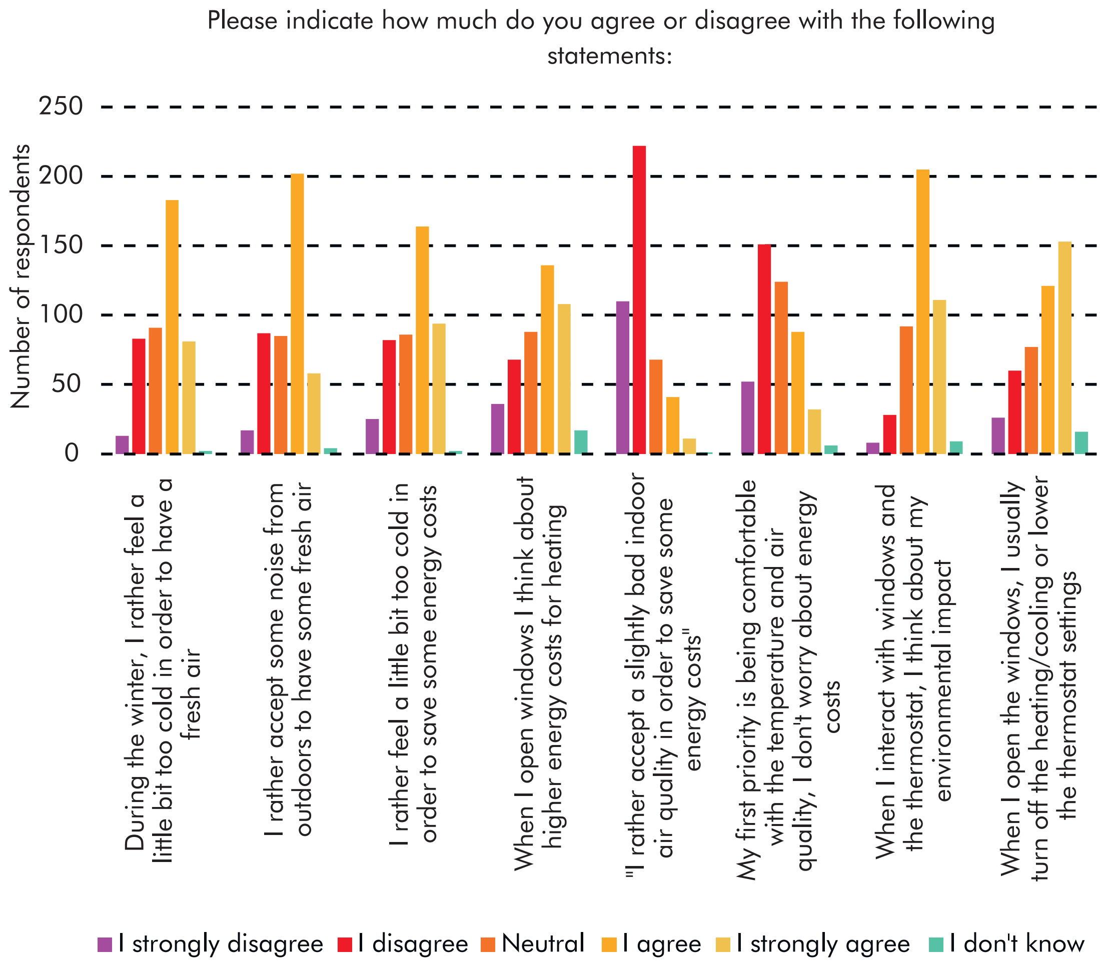


Fig. 3.07.: Respondents' preferences based on the questions 3.1.-3.8.

The differences in individual perception and preferences of the indoor environment may dipend on individual physiological characteristics. In this case it was found that the preferences higly depend on the age of the respondents. For example, with regards to the statement *„I rather feel a little bit too cold in order to save some energy costs"* (Fig. 3.07a), it was noticed that younger respondents agreed with this statement more often. With the increase of the age of the respondents, increases the percentage of respondent who don't agree with the statement.

I rather feel a little bit too cold in order to save some energy costs:			
Age range:	**13-29**	**30-44**	**45-59**
I agree:	72%	61%	44%
I disagree:	19%	21%	41%
Neutral:	9%	18%	14%

Fig. 3.07a.: The distribution of the responses for the question „I rather feel a little bit too cold in order to save some energy costs" according to age range

As already highlighted before, the economic level of occupants has significant effect in thermal sensation and on their preferences. For this reason, this section aimed to provide a deeper insight on energy-related social norms and economic situation in the households. As it is seen on the Figure 3.08, almost totality of the respondent had at least higher education level (95%) and among them 55% had an academic degree. Unfortunately, there is low respond rate of the respondents with the lower level of education (upper secondary school and vocational education), so education level will be not taken in consideration for the futher analysis of driving forces influencing the occupant behaviour. With regards to the economic level of the respondents, 26% of them didn't want to declare their monthy household net income. Among the respondents who have indicated the income, the most frequent income ranges of monthly household net income were between 1001-2000 and 2001-3000 Euro (Fig. 3.09).

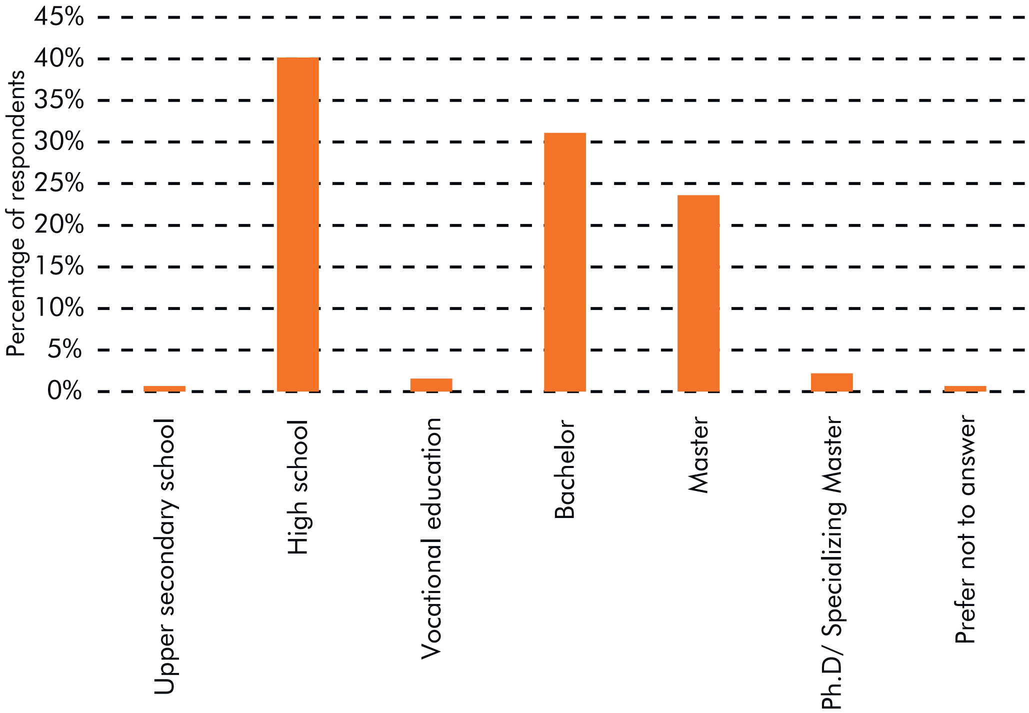


Fig. 3.08.: Respondents' education level

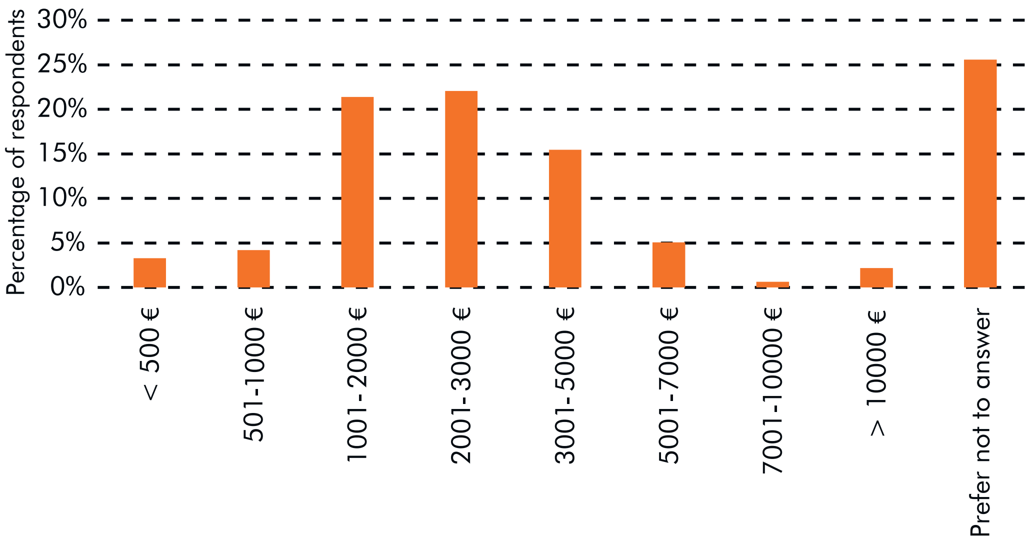


Fig. 3.09.: Monthly household net income

Subsequently, the respondents were asked to to indicate who usually control the temperature settings and open/close the windows in their homes. With regards to the temperature settings control (Fig. 3.10), The highest percentage of respondents (31%) have declared that they decide the temperature set-point together with the other members of the dwelling. However, also the significant percentage of respondents (23%) reported that whoever feels uncofortable change the temperature settings at their home.

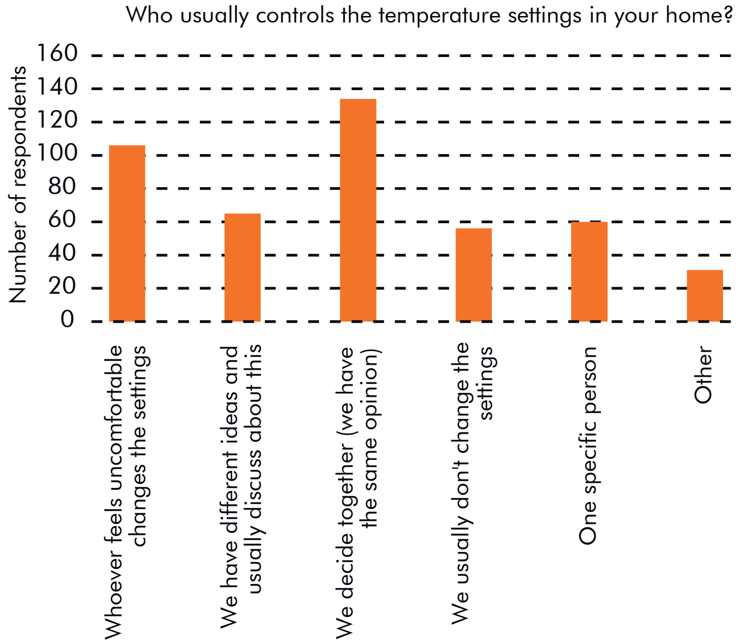


Fig. 3.10.: Survey responses to the question 17- „ Who usually controls the temperature settings in your home?"

With regards to the window opening and closing (Fig.3.11 and 3.12), in the most of the dwellings, the windows are operate much more freely than heating system.
The most of the respondents reported that windows are open or closed by whoever who feels uncomfortable (59% and 61%). The uncontrolled interaction of the dwelling occupants with the heating system and windows may lead to higher energy consumption (i.e. window opening when the heating system is working).

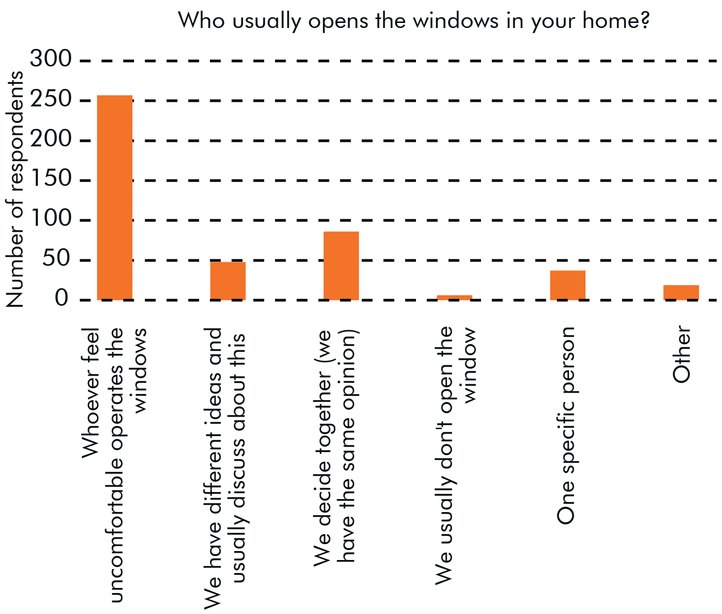


Fig. 3.11.: Survey responses to the question 18- „Who usually open the windows in your home?"

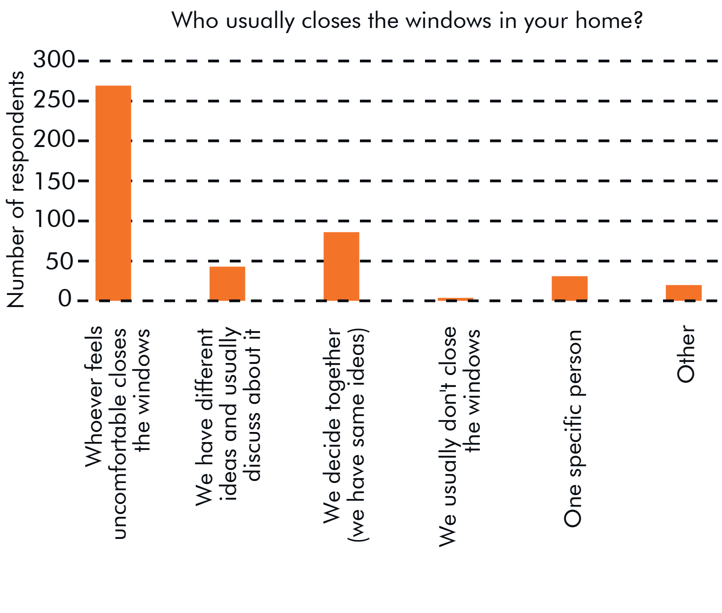


Fig. 3.12.: Survey responses to the question 19- „Who usually closes the windows in your home?"

In this section the respondents were asked to answer to the questions related to the dwelling, where they live per most of the time. However, the highest percentage of respondents were not able to indicate the period of the construction of the dwelling. With regards to the type of the dwelling (Fig.3.14), the majority of the respondents (almost 60 %) lived in an apartment in a block of flats, which include more than 6 apartments. This tendency corresponds to dwelling market in Turin, where the high-density blocks with more than 6 apartments are the most common. The respondents lived mostly in the dwellings with the area of 71-100 m² (Fig. 3.15) and 101-200 m² and more than 60% dwellings were owned by the respondents or their family (Fig. 3.16.)

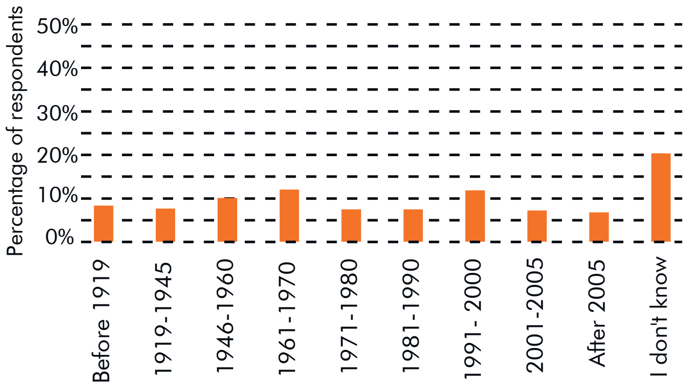


Fig. 3.13.: Period of the construction of the dwelling

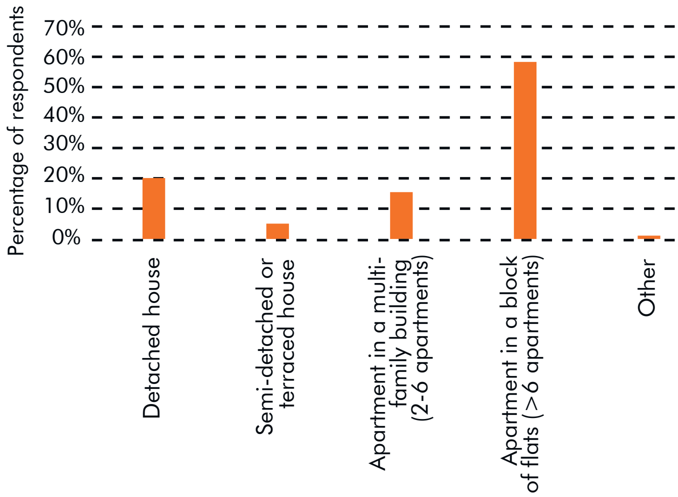


Fig. 3.14.: Type of the dwelling

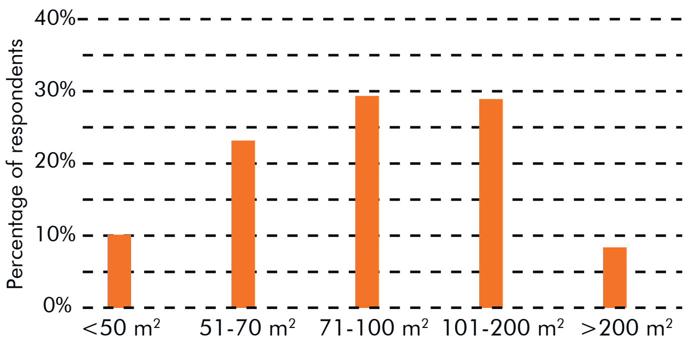


Fig. 3.15.: Dwelling area

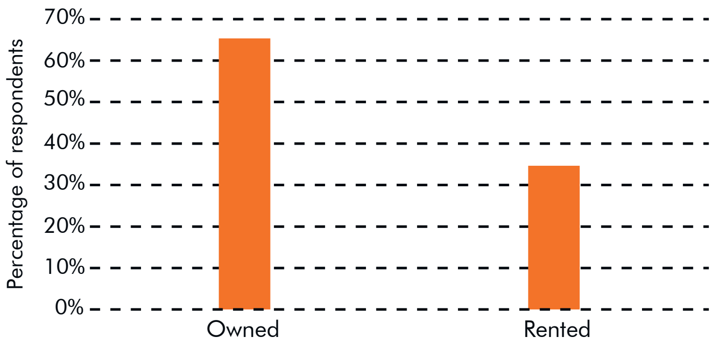


Fig. 3.16.: Type of the ownership

Heating system

To obtain complete informations about dwelling characteristics, the respondents were asked to provide informations regarding heating and cooling systems.
With regards to the heating system, 61% of respondents had the independent heating sytem and 39% of respondents were connected to the cental heating system (fig. 3.17). The main type of heating system (fig. 3.18) was traditional boiler (43%), the second in classification was condensing boiler (17%). The most frequent type of heating terminals (Fig. 3.19) were radiators (71%), and the most frequent type of the heating source was gas (Fig. 3.20).

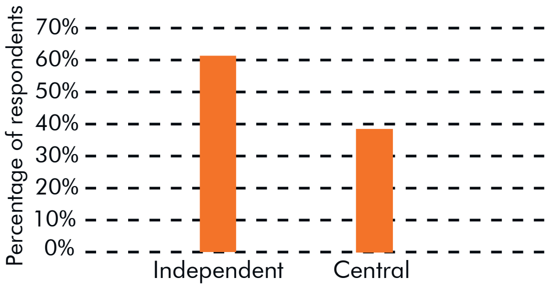


Fig. 3.17.: The configuration of the heating system

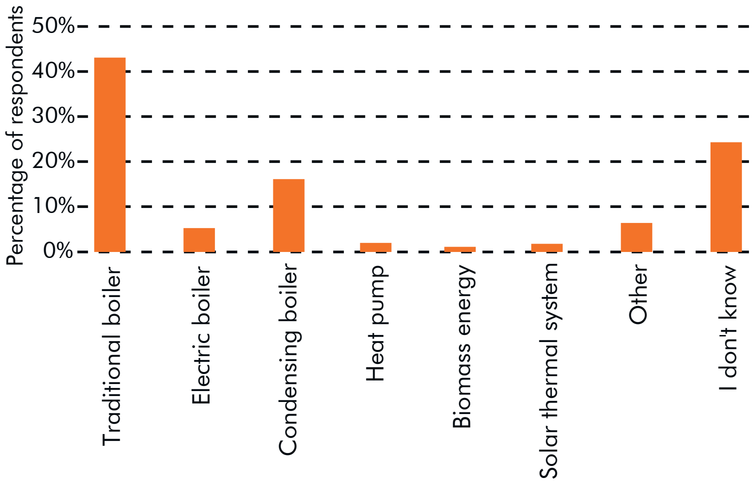


Fig. 3.18.: The type of main heating system

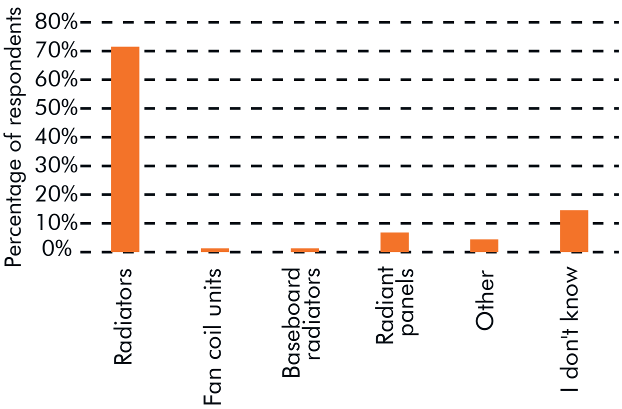


Fig. 3.19: The type of heating terminals

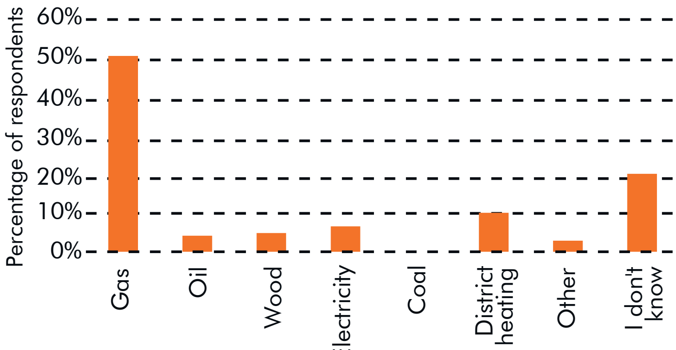


Fig. 3.20.: The type of the heating source

Cooling system

With regards to the cooling system, only 24% of respondents declared to have it at home. The most common type of cooling systems possessed by respondents were multi-split and mono-split air conditioners (Fig. 3.21). As the type of the cooling terminals, the most frequent (80%) were splits. (Fig. 3.22)

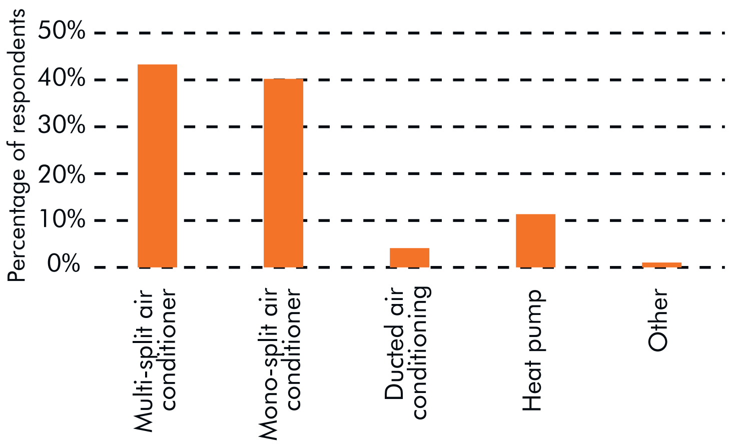


Fig. 3.21.: The type of cooling system

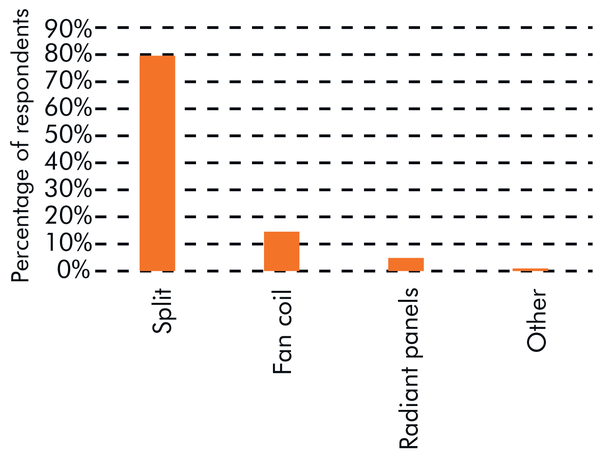


Fig. 3.22.: The type of cooling terminals

The temperture settings have an important impact not only on the energy consumption, but on the occupant well-being as well. The basic level of warmth recommended by the World Health Organization for a healthy and well-dressed person is 18°C during the winter period for an interior space. The temperature between 18°C and 21°C is considered as comfortable temperature for an interior space. Non adequate temperature may not only leads to the higher energy consumption, but also has big impact on the comfort of the occupant. The temperatures lower than 12°C and higher than 24°C during the winter may cause health problems (cardiovascular risk). For this reason, the respondents were asked to indicate the set-point for thermostat which they usually set during the winter and summer period. The most frequent temperature range during the winter period was between 19°C and 21°C, with the average temperature of 20,6°C (Fig. 3.23). However, significant part of respondents tend to overheat their dwellings- almost 25% of respondents set the temperature above 22°C.

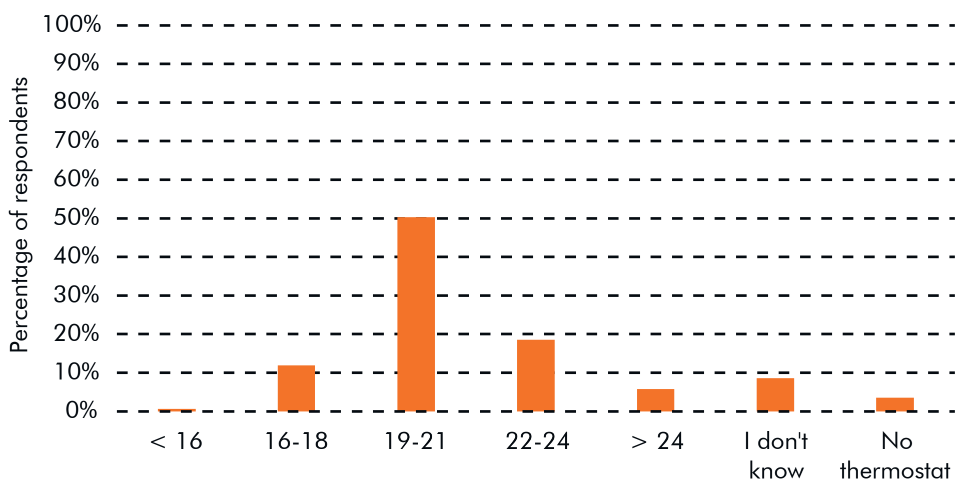


Fig. 3.23.: Thermostat set-point during the winter period

As analyzed previously (chapter 1.4), the temperature set-point may depend on many driving forces, like dwelling characteristics or social factors. For example, in this case was found that the average temperature set-point in the dwellings where the children lived was significantly higher (average T=21,5°C), compared to the dwellings where there was no presence of children (average T=20,4°C) (Fig. 3.24)

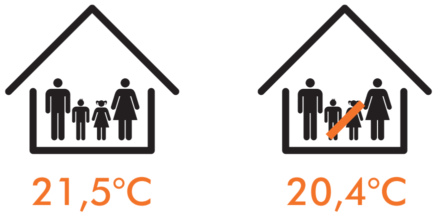


Fig. 3.24.: The average temperature set point in the dwellings with and without children

With regards to the composition of the dwelling members, it was found that another important driving force which may inluence the temperature set-point, is the number of household membres. Figure 3.25 shows that the temperature set-point increases with the number of occupants, with the difference of 0,7°C between the households with one member and the households with four members.

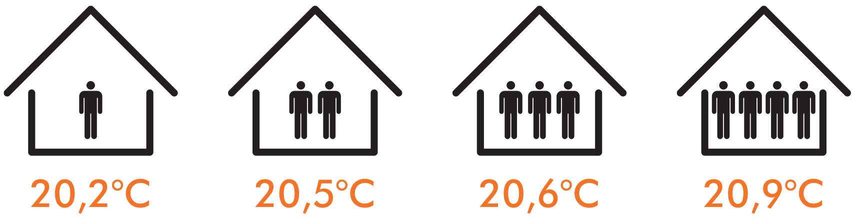


Fig. 3.25.: The average temperature set point in the dwellings according to the quantity of household members

Economic situation can also drive occupants to set up the heating. More heating leads to higher heating cost. It was already investigated by some researchers that households with lower income tend to use less energy for keeping warm in the winter [34]. This trend was confirmed in this study. As it may be seen on the Figure 3.26, the temperature increases significantly together with the economical level of the dwelling members. The temperature set-point may vary even up to 2,1°C.

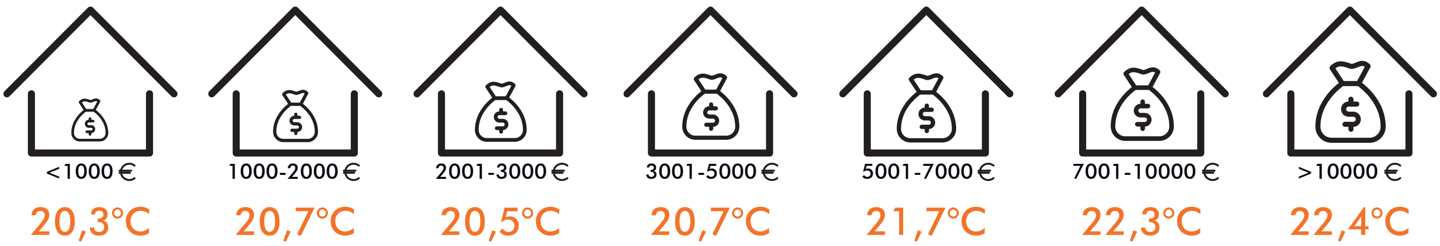


Fig. 3.26.: The average temperature set point in the dwellings according to the household income

The building properties have also the important impact on the occupant behaviour. In fact, in the present study was found that occupants who rent accommodation tend to spend more on heating. The deviation for the temperature set-point during the winter between rented and owned dwelling was 0,5°C (Fig. 3.27). The significant driving force for the temperature settings is also the configuration of the heating system (Fig. 3.28). It was found that centrally heated houses have higher temperatures settings than non-centrally heated (with the difference of 0,4°C). Moreover, 22% of respondents who lived in the dwellings with central heating system don't know what is the temperature set-point or do not have a thermostat to control temperature settings.

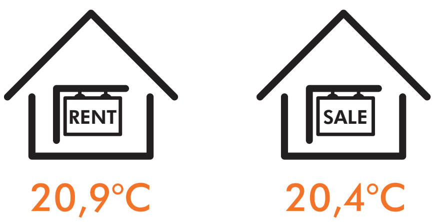


Fig. 3.27.: The average temperature set point in the rented and owned dwellings

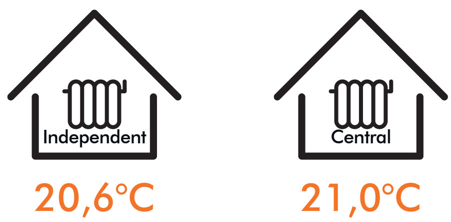


Fig. 3.28.: The average temperature set point in the dwellings according to the configuration of the heating system (independent and central)

With regards to the dwelling characteristics, the other parameters, like dwelling size or ownership, were examinated as well, but no significant deviations was found.

Occupant interaction with the building systems

Many studies have shown that the level of satisfaction of control options at home may directly influence perception and satisfaction of the home indoor environment. For this reason, this section of the survey addressed to obtain control-related informations. The respondents were asked if they had any difficulties in operating the control systems and subsequently how much they are satisfied or unsatisfied with the control options at their homes. With regards to the use of the windows, almost all of the respondents considered them to be easy or very easy to use. There is more spread in the answers regarding the use of the thermostat, however, 70 % of respondents reported that it is from slightly easy to very easy to use.

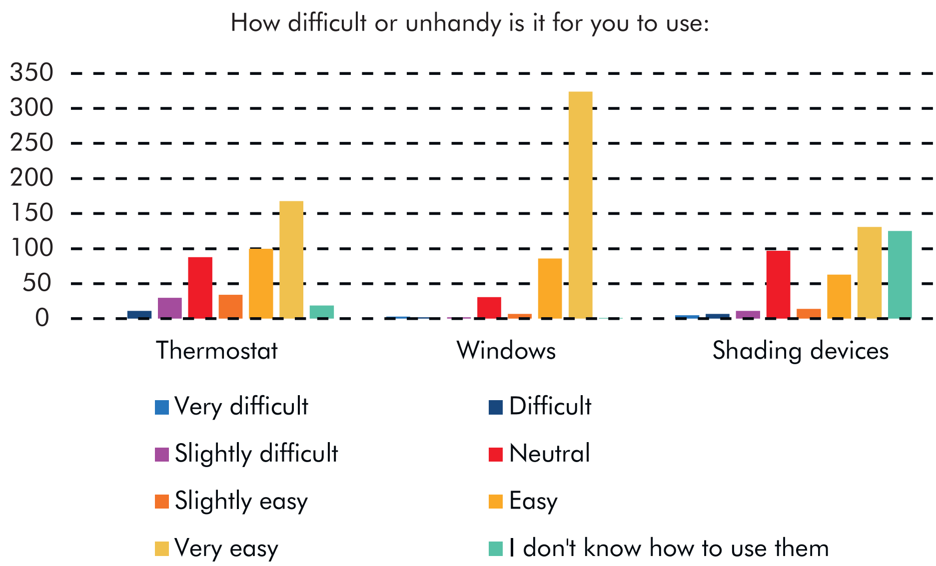


Fig. 3.29.: Survey responses to the question 37- „How difficult or unhandy is it for you to use Thermostat/Windows/Shading devices”

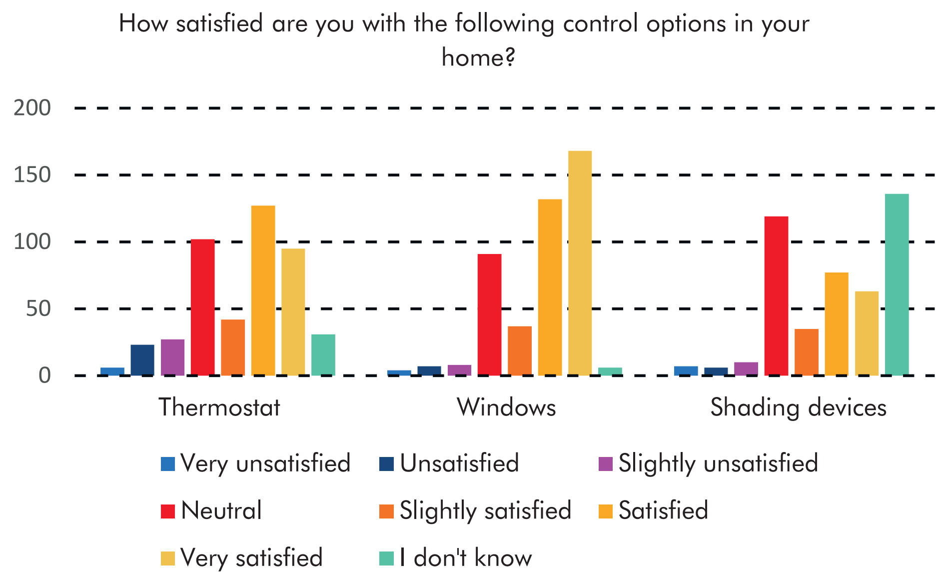


Fig. 3.30.: Respondents' satifsaction with control for thermostat, windows and shading devices

Figure below (fig.3.31) shows the satisfaction levels of the occupants with the control systems at their homes. 60% of respondents declared to be satisfied (from slightly satisfied to very satisfied) with the control systems.

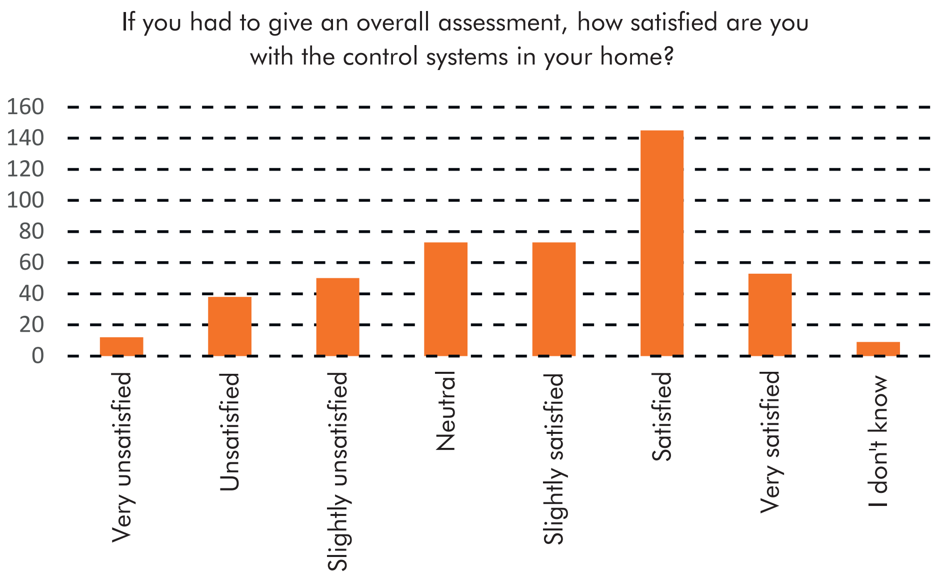


Fig. 3.31.: Overall respondents' satisfaction with the control systems in home

Additionally, the respondents were asked if they tend to open the windows when the building systems are on (mechanical ventilation, heating and cooling system- figure 3.32). Especially it is possible to notice significant respond rate of people who open window when mechanical ventilation and heating are on:

- 73% of respondents have reported that they open the windows when the mechanical ventilation is on (among them 31% of respondents answered „sometimes");
- 59% of respondents declared to open windows when the heating system is on (48% of them answered „sometimes").

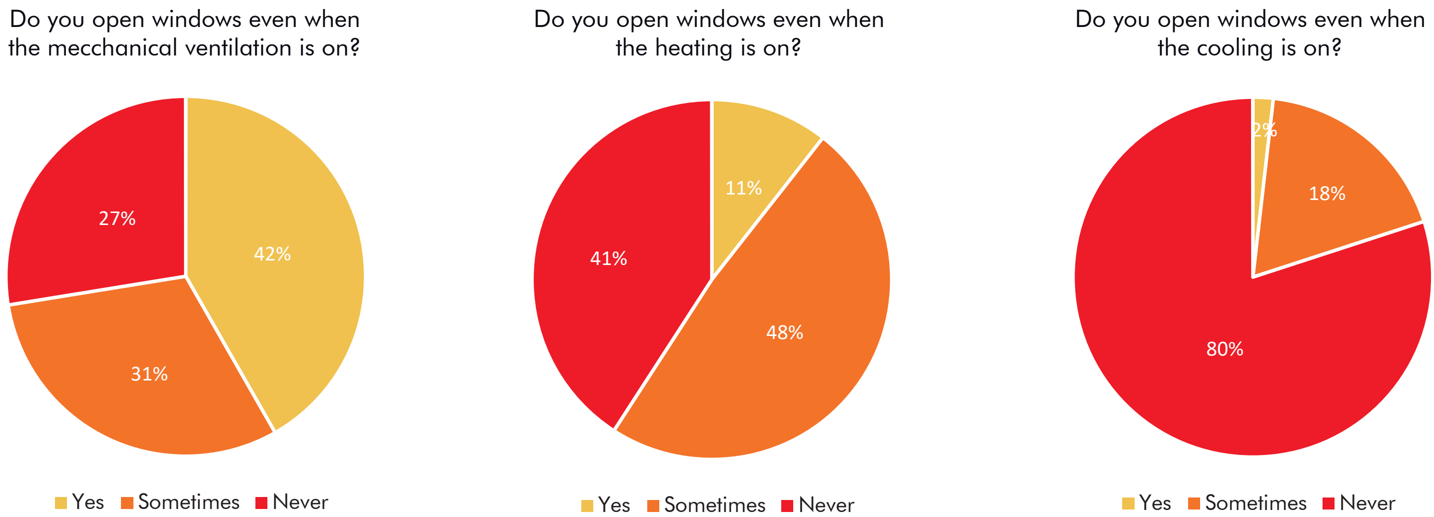
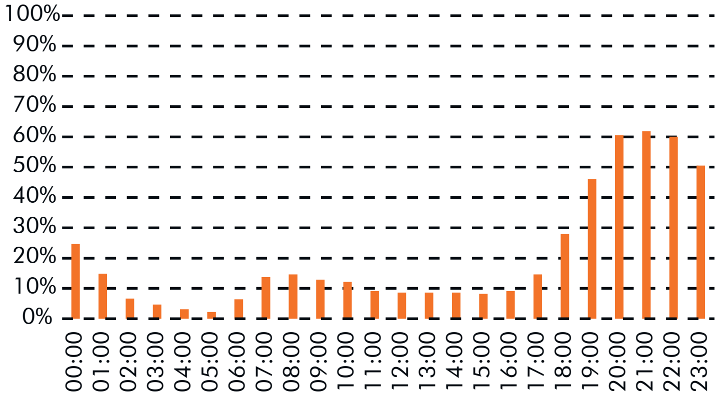


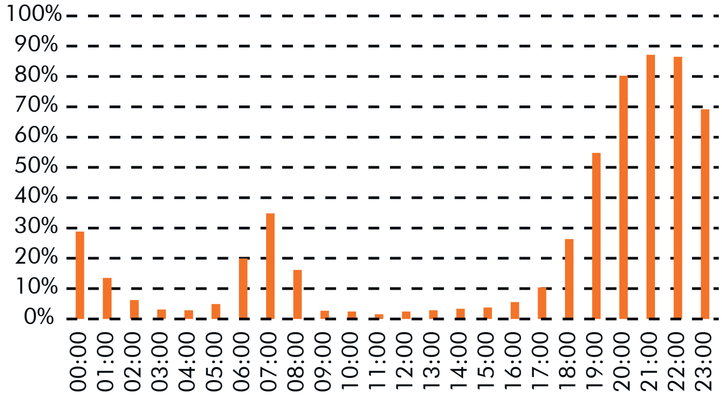
Fig. 3.32.: Survey responses to the questions 43-45- „Do you open windows even when the mechanical ventilation/heating/cooling system is on?"

Good knowledge of occupants' time preferences and habits with regards to the interaction with building systems is as well crucial for improvement of buildings' energy efficiency. For this reason, the respondents were asked to indicate at what time during the day they interact with the building systems like lighting, heating and cooling system. It may be seen that the interaction with building systems may vary signicantly depending on the day (i.e. it is possible to notice big discrepancies for the use of lighting system during the weekdays and weekends).

Use of lighting system (weekdays and weekends)

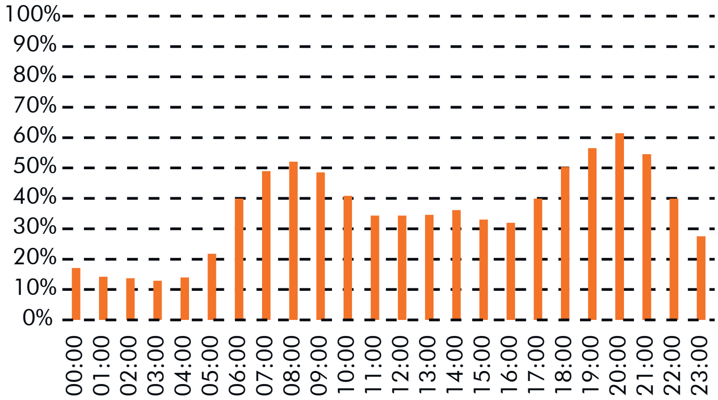


WEEKEND

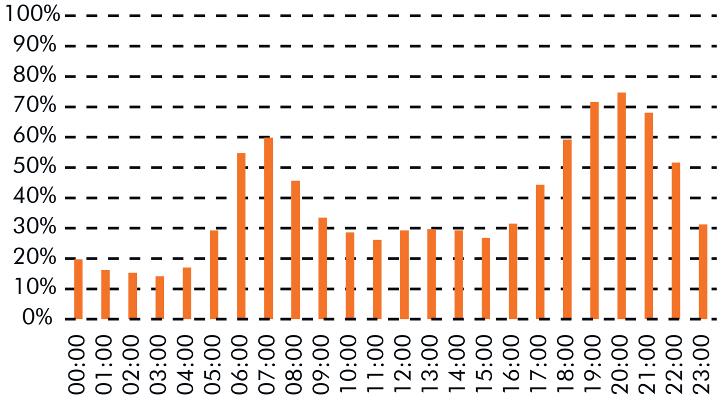


WEEKDAY

Use of heating system (weekdays and weekends)

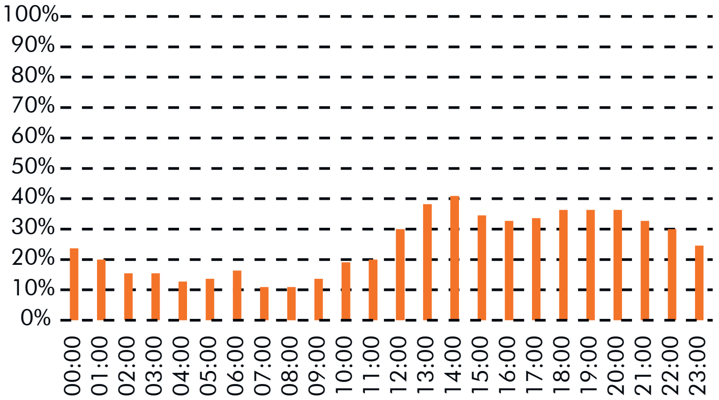


WEEKEND

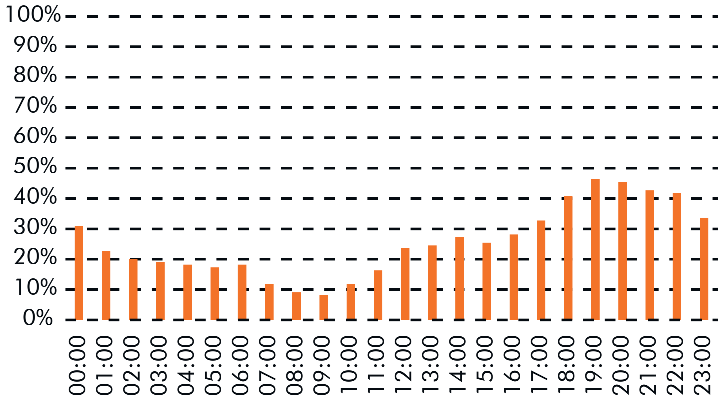


WEEKDAY

Use of cooling system (weekdays and weekends)



WEEKEND



WEEKDAY

Occupant interaction with windows can have important impact on the energy consumption. For this reason, the respondents were asked to indicate their motivations or usual habits when they interact with windows (window opening- fig. 3.33 and window closing- fig. 3.34). Figure 3.33 shows that most of the respondents open windows to let fresh air in (especially 94% of respondents open the windows in bedrooms). Other most frequent motivations were to get the bad smell out (especially in dining room and bathroom) and to change the indoor temperature (especially in bedroom). Moreover, re-pondents indicated that they open windows during the certain activities: 79% of respondents open the windows in kitchen during the cooking time, 75% of respondents declared to open windows when they wake up and 74% of the respondents open the windows after taking a shower.

For window closing behaviour, more than half of respondent indicate to close windows in all rooms then it is getting to cold or to hot and to save energy (when the heating/cooling device is on). Significant part of respondents close windows then it is too windy outside. Moreover, 62% of respondents tend to close windows when there is too much noise outdoors. Respondents indicate also that they close the windows during the certain activities- especially when they leave home.

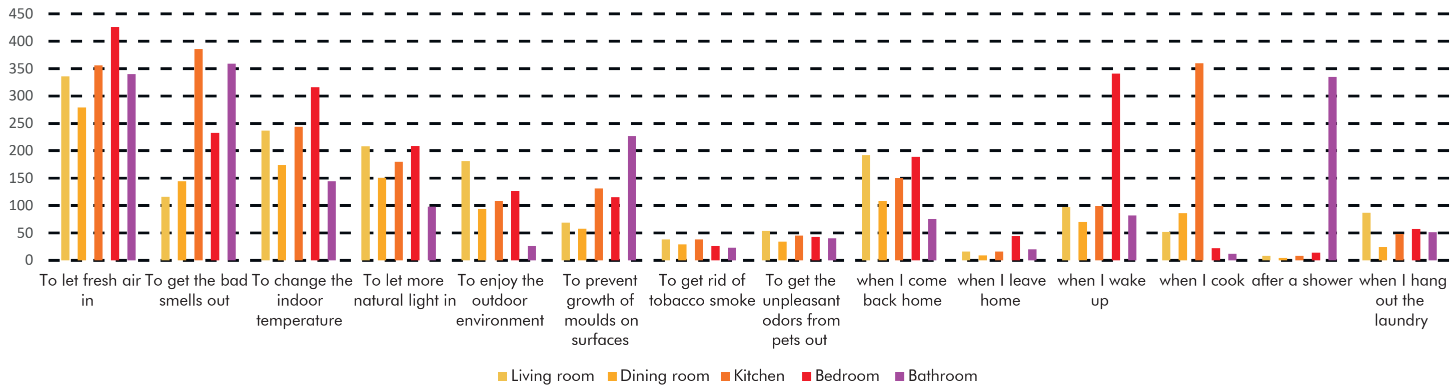


Fig. 3.33.: Survey responses to the question: „Why do you usually open windows and where?"

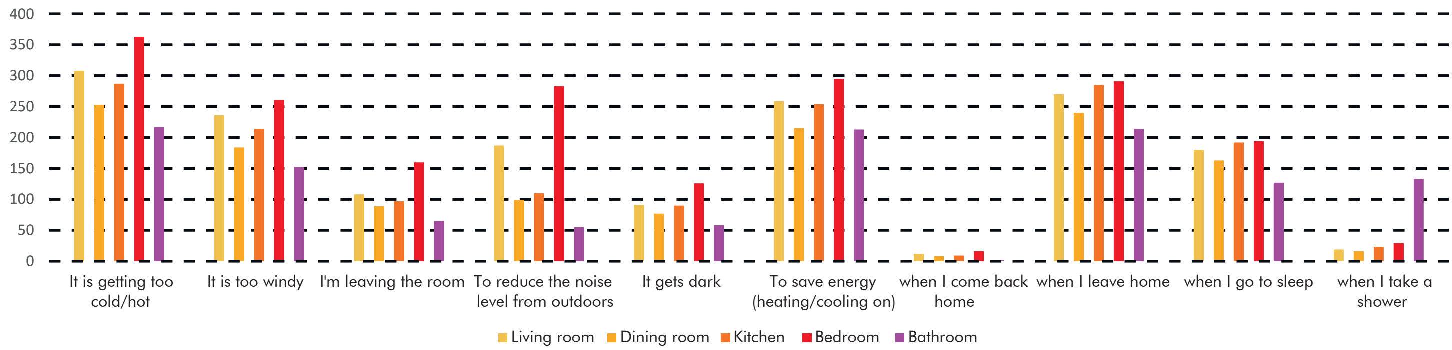


Fig. 3.34.: Survey responses to the question: „Why do you usually close windows and where?"

Moreover, important impact on the window opening behaviour has smoking habit. Among the respondents, who have declared to have smoking habit (21% of respondents smoke daily or some-times) and to smoke inside the home, 89% of them opens the windows always to get rid off tobacco smoke pollution, 11% of them open windows at least sometimes (Fig. 3.35).

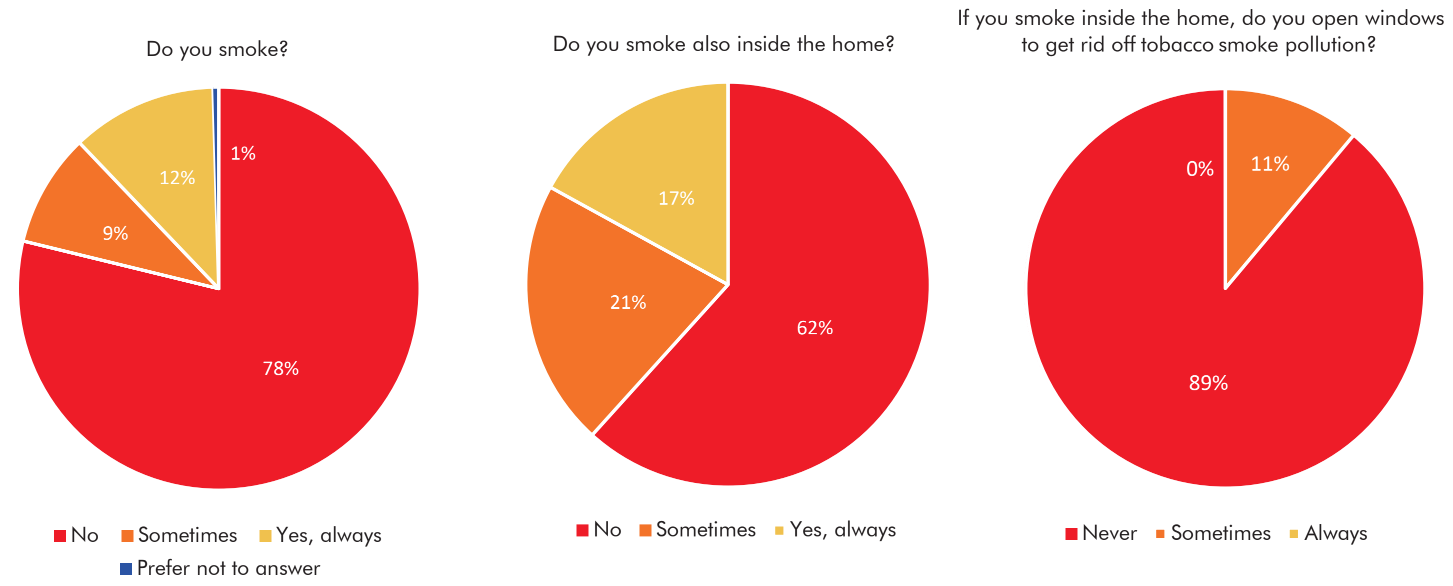


Fig. 3.35.: Smoking habit with relation to the window opening behaviour

Daily activity profiles (time-use survey)

Occupants' activities evidently shape the timing of building energy use throughout the day. Diary-based surveys on how occupants spend their time during the day can help to shape occupancy profiles and energy-related activities. Basing on the results from the last part of the survey (*„Activities performed at home on the last day"*), it was possible to define the daily activity profiles of the survey respondents in the Italian residential buildings. As energy-related activities can vary significantly during weekdays/weekend or in the different season of the year, the anwers of the survey respondents were divided according to the date when the survey was filled. In this way, two daily activity profiles were established- activity profile during the weekdays and weekends in the summer period.

In relation to weekdays activity profile (fig. 3.36), it is noticeable that sleeping is the dominant activity- 90 % of the survey respondents were asleep between 2:30 am and 6 am. During the week-days the respondents have spent a significant portion of their time outside the home. Most of the respondents were not present at the home from from 9 am to 6:30 pm, however a part of respondents were back home during the lunch time (between 1 pm and 2 pm). There are two evident peaks for „eating" activity during the lunch (around 1:30 pm) and dinner time (around 8:30 pm). It is possible to distinguish the peak for „TV/IT entertainment" activity in the evening hours- from 9 pm to 11 pm. The percentage of respondents who were doing „House cleaning/washing clothes" and „Practical work" activities were quite constant during all day.

In relation to weekend activity profile (fig. 3.37), it is possible to notice that the respondents have spent much more time at home comparing to weekdays. The highest percentage of people who were out of home (around 40 % of respondents) was noticed at 11:30 am and in the afternoon hours, from 3:30 pm to 7:00 pm. The „sleeping" activity duration was slighly longer than during the week-days- more than 90 % of respondents slept from 2 am to 7:00 am. During the weekend the occupants spent much more time on „Free/family time" activity- with the highest peak in the afternoon, from 3:30 to 5:30. Similary as during the weekdays, there are two significant peaks for „Eating" activity- from 12:30 am to 2:30 pm and from 7:30 pm to 9:30 pm. During the weekend, the respondents spent slightly more time on „Cooking/washing dished activities" than during the weekends- there are two pe-aks in the lunch/dinner time- from 12:30 am to 1:30 pm and from 7:30 pm to 8:30 pm. For the „TV/IT entertainment" activity the respondents had similar preferences as during the weekdays- more than 30 % of occupants have spent their time watching TV or navigating internet from 9:30 pm to 11:00 pm. „House cleaning/washing clothes" and „Practical work" activities were distributed during the day and there are no significant peaks which could indicate the preferable time for those activities.

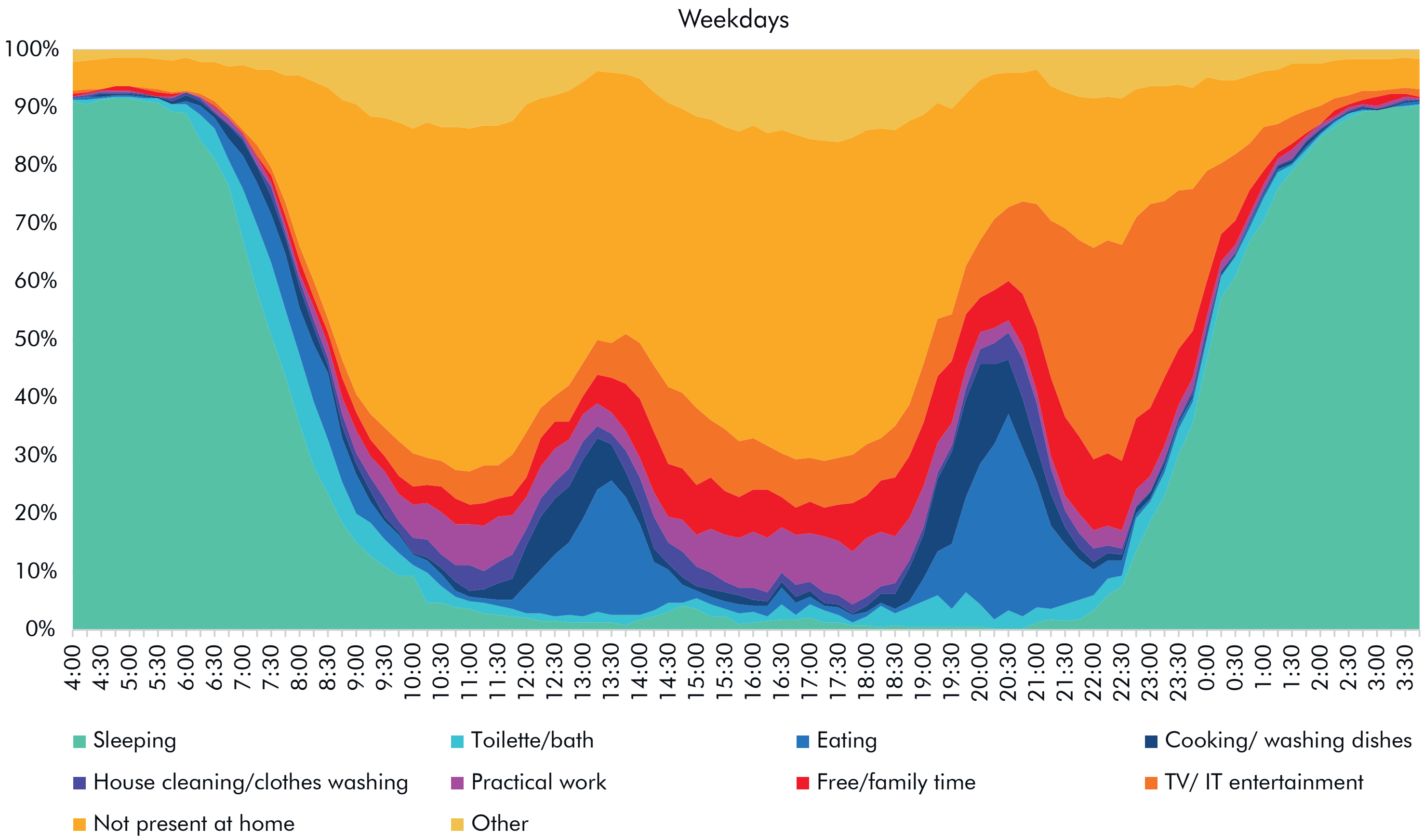


Fig. 3.36.: Daily activity profiles for weekdays

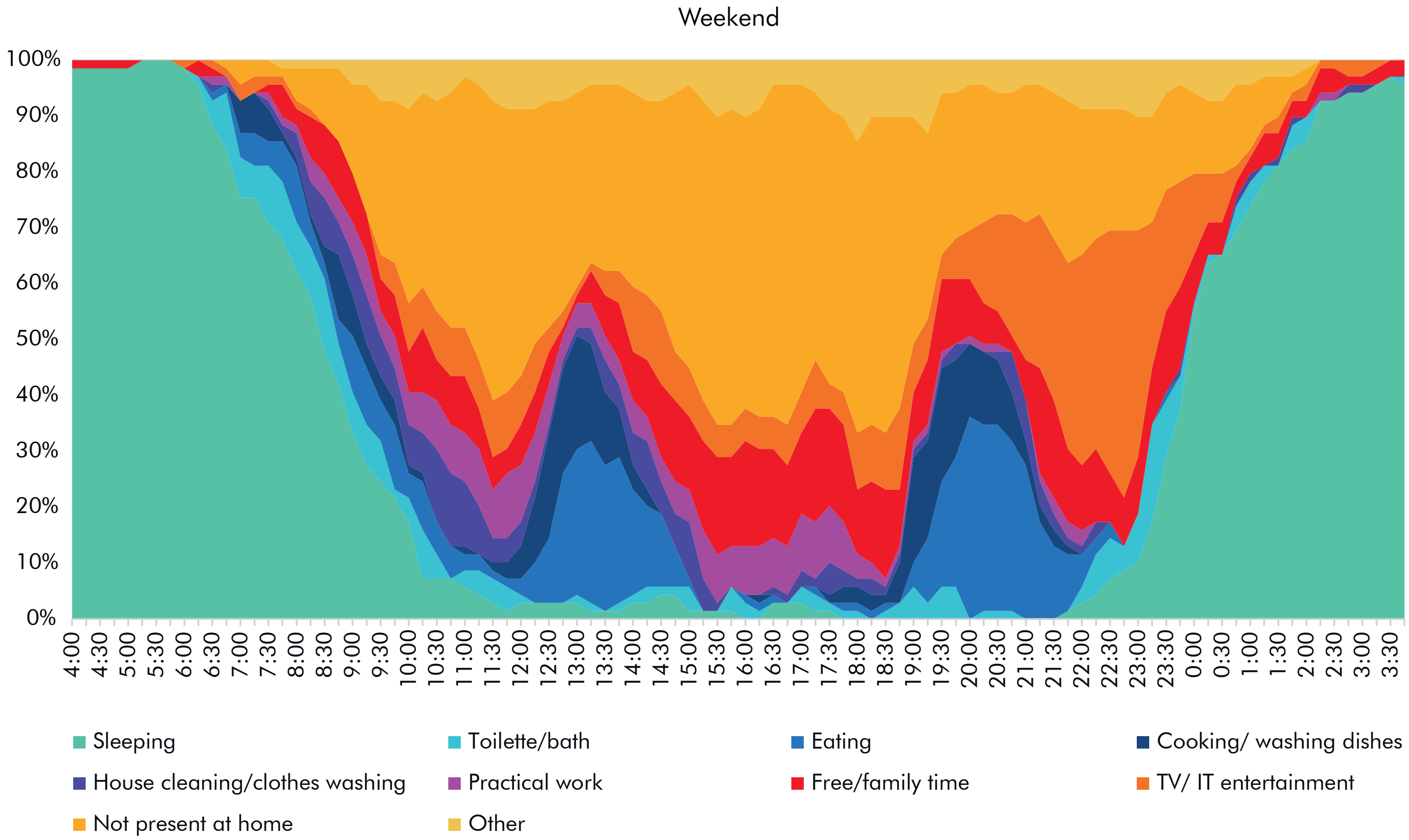


Fig. 3.37.: Daily activity profiles for weekends.

The following figure (fig. 3.38.) rapresents the average time which the respondents have spent on the 10 energy-related activities in 24 hours during the weekdays and weekend. The key results of these analysis were:
- longer sleeping times during weekends (8 h 16 min) with respect to weekdays (7 h 17 min);
- longer occupant presence within the residence during weekends (18 h 02 min) with respect to weekdays (16 h 25 min);
- occupants have more free/family time during the weekends (1 h 55 min) than during the weekdays (1 h 15 min);
- no significant difference in time spent for TV/IT entertainment activity during the weekends and weekends (2 h 06 min during the weekends and 2 h 11 min during the weekdays); similary for practical work activity (48 min during the weekends and 54 min during the weekdays);
- slightly longer time spent on cooking/washing dishes and eating activities during the weekends comparing to the weekdays (respectively 51 min vs 41 min for cooking/washing dishes activity and 1 h 32 min vs 1 h 16 min for eating activity);
- no significant difference for time spent for personal care activity during the weekends and weekdays (44 min and 42 min, respectively).

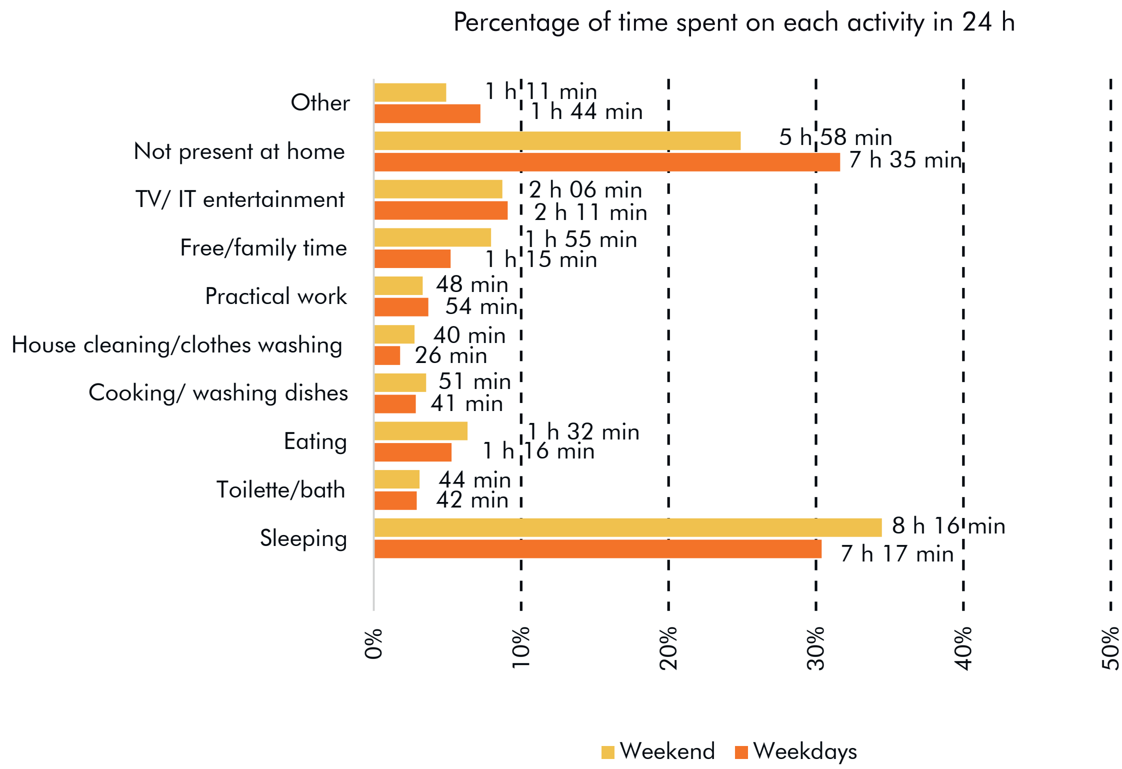


Fig. 3.38.: Daily time spent on the activities during weekends and weekdays during the summer period

Subsequently, basing on the general daily activity profiles, it is possible to distinguish daily profiles for single activities which can have the highest influence on the energy consumption. The following figures (from fig. 3.40 to fig. 3.42) rapresent the comparision between percentage of occupants who were performing certain energy-related activities during the day and hourly mean profile for households. The activities were compared to the hourly mean profile available in the *Report Ricerca di Sistema Elettrico,* developed by Politecnico di Torino and ENEA [55]. It was found that energy-related activities were in line with typical trends of hourly electricity profiles in an Italian household. As it is possible to notice from the fig. 3.40 to fig. 3.42, the peaks for the energy-related activities corresponds to the peaks of energy consumption of the example dwelling. It was especially found that cooking activities during the weekend may highly influence the overall energy consumption in a residential building during the lunch hours (12:00-14:00) and during the dinner hours (19:00-21:00).

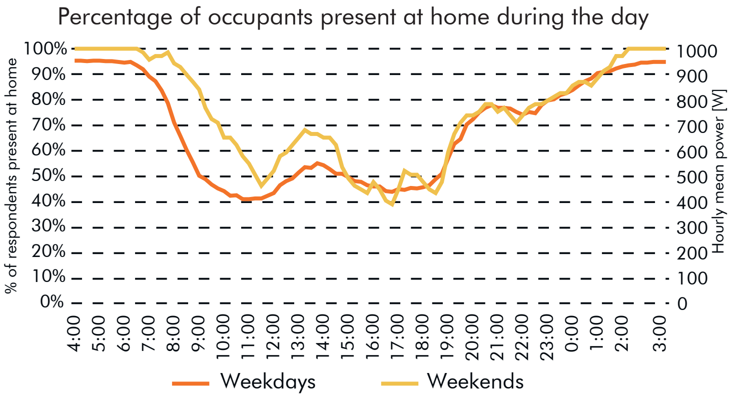


Fig. 3.39: Percentage of occupants present at home during the weekdays and weekends

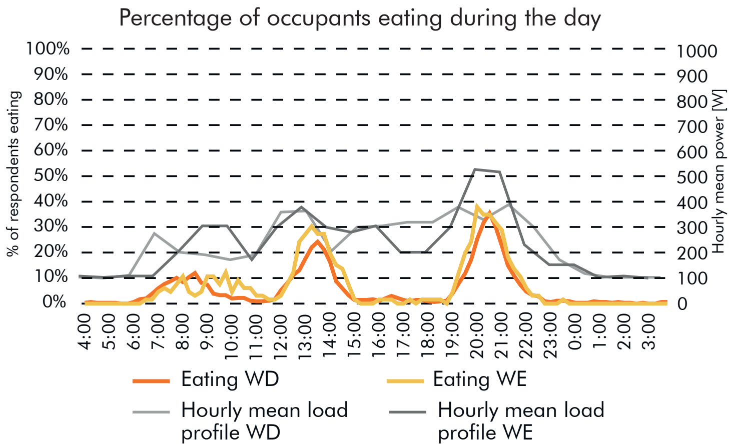


Fig. 3.40.: Percentage of occupants eating during the weekdays and weekends

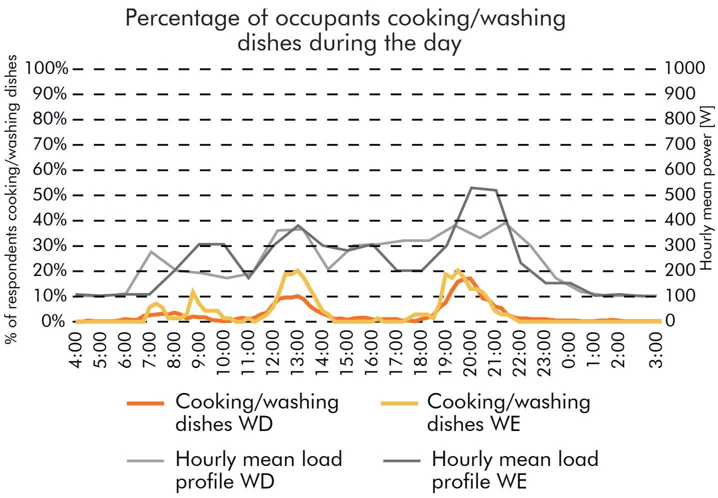


Fig. 3.41.: Percentage of occupants cooking/washing dishes during the day

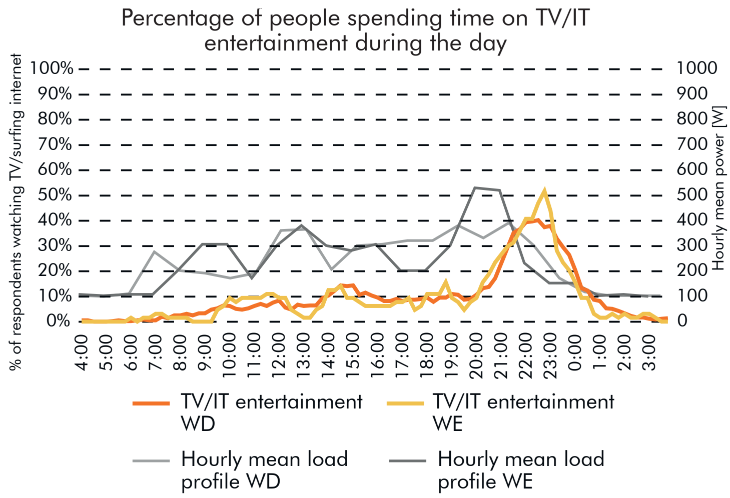


Fig. 3.42.: Percentage of occupants spending time on TV/IT entertainment during the weekdays and weekends

3.5. Conclusions

Occupant behaviour in residential buildings may significantly influence the overall energy consumption in the building. For this reason, a deep understanding and forecasting of occupants' behaviour and modelling energy-related occupants' activities throughout the day are crucial to evaluate their impact on the energy consumption and indoor quality performances.

In order to understand the occupant behaviour in the Italian residential context, a questionnaire survey was conducted in north-Italian dwellings at the beginning of summer 2018. The survey framework included questions about individual preferences for indoor environmental conditions, individual characteristics of the occupants (i.e. age, gender), social factors (i.e. education, job category, and household income), dwelling characteristics, and occupant interaction with the building systems and with windows. Furthermore, in order to shape energy-related activities, the respondents were asked to report their activities performed at home during the last full day, choosing for every 15-minutes intervals among the proposed activities.

The results of the questionnaire survey provided new insights on factors influencing occupant behaviour in north-Italian dwellings. The results have shown that occupants' preferences for indoor environmental conditions and their interaction with building systems may vary significantly from person to person and may depend on many driving forces, as social drivers (i.e. household income, children presence), physiological drivers (i.e. age of the occupant) or building characteristics (i.e. configuration of heating system). Especially, it was found that the occupants tend to overheat the dwellings during the winter and that the temperature set-point increases together with the number of dwelling member and when the children are present. Moreover, it was found that households with lower income tend to use less energy for keeping warm in the winter. The temperature set-point may depend as well on configuration of the heating system (central or independent) and may increase when the dwelling is rented.
Additionally, the results highlighted that occupants are often not aware about their influence on the energy consumption in the dwelling (i.e. significant part of the respondents tend to open windows when the heating or mechanical ventilation systems are active).
Finally, two energy-related activities profiles were established- the weekdays and weekends in the summer period. The daily profiles of ten energy- and occupancy-related activities were compared to the hourly mean power profile of an example Italian residential building. It was found that those activities (i.e. cooking) may have an important impact on the overall energy consumption in building. Moreover the daily activity profiles were different depending on the day of the week (weekdays and weekends). However, the energy-related activities vary depending on the day of the week, but may vary also depending on the season. For this reason, to obtain complete information, the survey questionnaire should be conducted the second time during the winter period, which would allow to shape energy-related activity profiles for weekdays and weekends during the winter.

Nowadays, the answer to an energy-intensive occupant behaviour may be Home Automation. Automation, control and supervision systems may have a significant impact on the energy performance of a building and on the comfort of occupants and they may reduce energy consumption even up to 50%. Building automation could help reaching the nearly Zero Energy target in a building, or at least in decreasing building energy demand by balancing energy losses, internal gains and energy needs, with particular regard to the optimization of the balance between heating and cooling needs. The implementation of such systems allows obtaining a Smart Energy Home, where appropriate building automation systems work together in order to provide an effective control of lighting, heating, ventilation and air conditioning systems, which is essential to guarantee a healthy, safe working and productive indoor environment. The automatic control should guarantee minimum acceptable conditions with the possibility of manual adjustment (override) of conditions to reach the occupants' needs.

For this reason, the next part of the thesis aims to demonstrate how, through the implementation of building automation systems and a good occupant's interaction with them, it is possible to obtain considerable energy savings in the residential building.

CHAPTER NO. 4

Application of Home Automation Scenarios to improve energy efficiency-CorTau House case study

4.1. Description of the case study

The so-called CorTau House is single-family detached house, built at the beginning of 2016. It is located in Livorno Ferraris, north of Italy, in Piedmont region. It is nZEB house, refurbishment of a "curmà", a traditional rural building, defused in Piedmont.
This building was chosen for the further analysis and its construction and energy characteristics are described in the sections below.

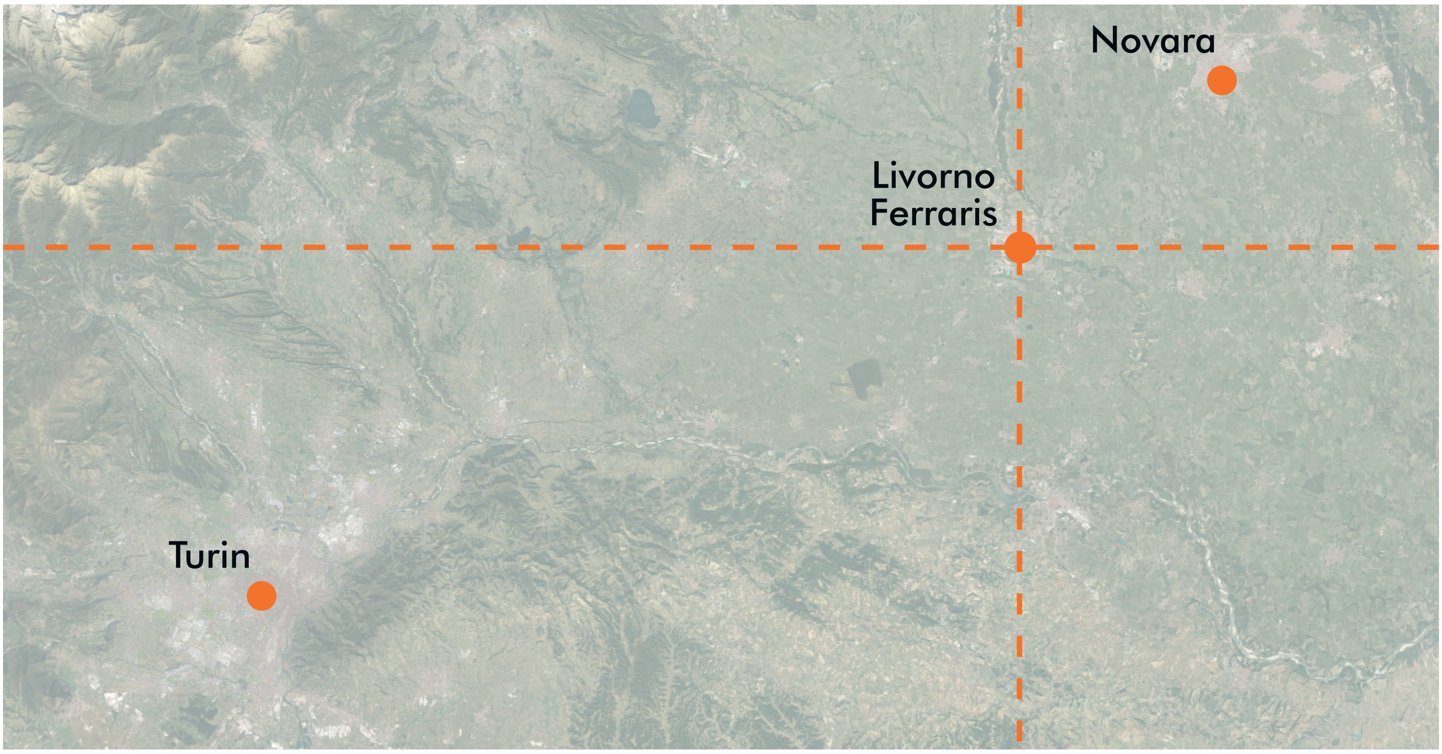


Fig. 4.01: The location of the case study

CorTau House general building characteristics

General informations	
Location	Livorno Ferraris, Piedmont, Italy
Latitude	45°17'6''00 N
Longitude	08°4'42''60
Altitude asl	188 m
Heating Degree Days	2549
Italian climate zone	E
Principal use	residential
Building typology	single-family house
Typology of intervention	energy retrofit of a traditional rural building

Geometrical data	
Number of floors above ground	1
Number of floors below ground	0
Gross floor area [m²]	163,6
Net conditioned floor area [m2]	131,4
Gross volume [m³]	490,8
Net conditioned volume [m³]	394,2
Average net interfloor height [m]	3,0
S/V [m^{-1}]	1,14
Glazing Percentage [%]	29%

CorTau House building envelope and HVAC system features

As mentioned before, the CorTau House is nZEB, which is typical model of all-electric building (the kitchen is furnished as well with electric appliances, like stove and oven). With regard to the building primary system, there is the controlled mechanical ventilation (CMV) sytem with heat recovery and dehumidifier which work together with radiant floors for space heating and cooling in all areas with the addiction of electric radiators in all the bathrooms. Space heating and cooling is provided by a water-to-water heat pump that supplies also domestic hot water (DHW) production. Space heating is also supported by electric radiators located only in bathrooms.

Tab. 5.03: *The Cortau House systems*

Building systems	
Ventilation	Controlled mechanical ventilation with heat recovery and deumidifier
Heating	water-to-water heat pump/ + electric radiators in the bathrooms
Cooling	water-to-water heat pump
Hot water (DHW)	water-to-water heat pump
Domestic appliances	all-electric

Cortau House plan

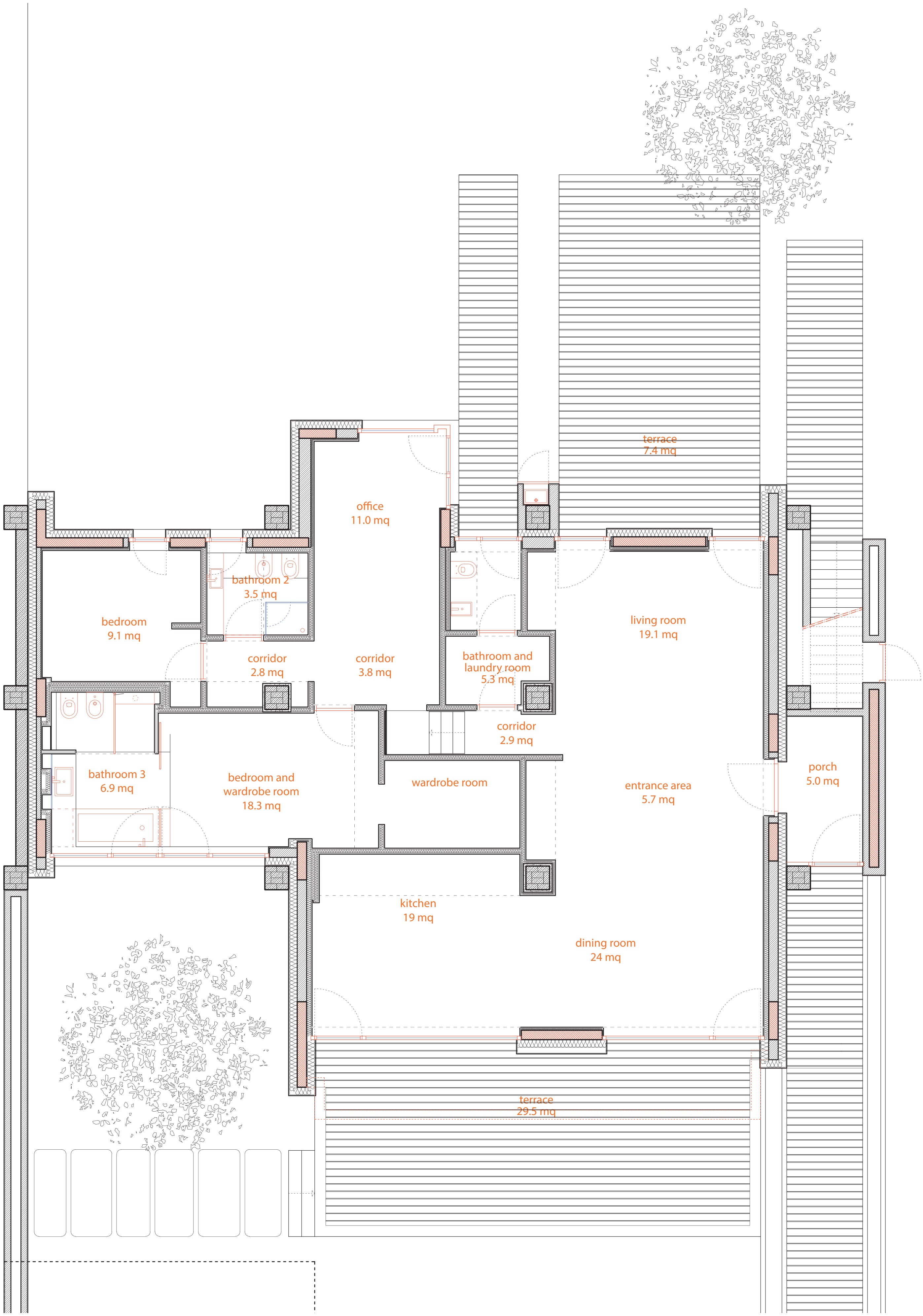


Fig. 4.02: *CorTau House floor plan*

Cortau House section

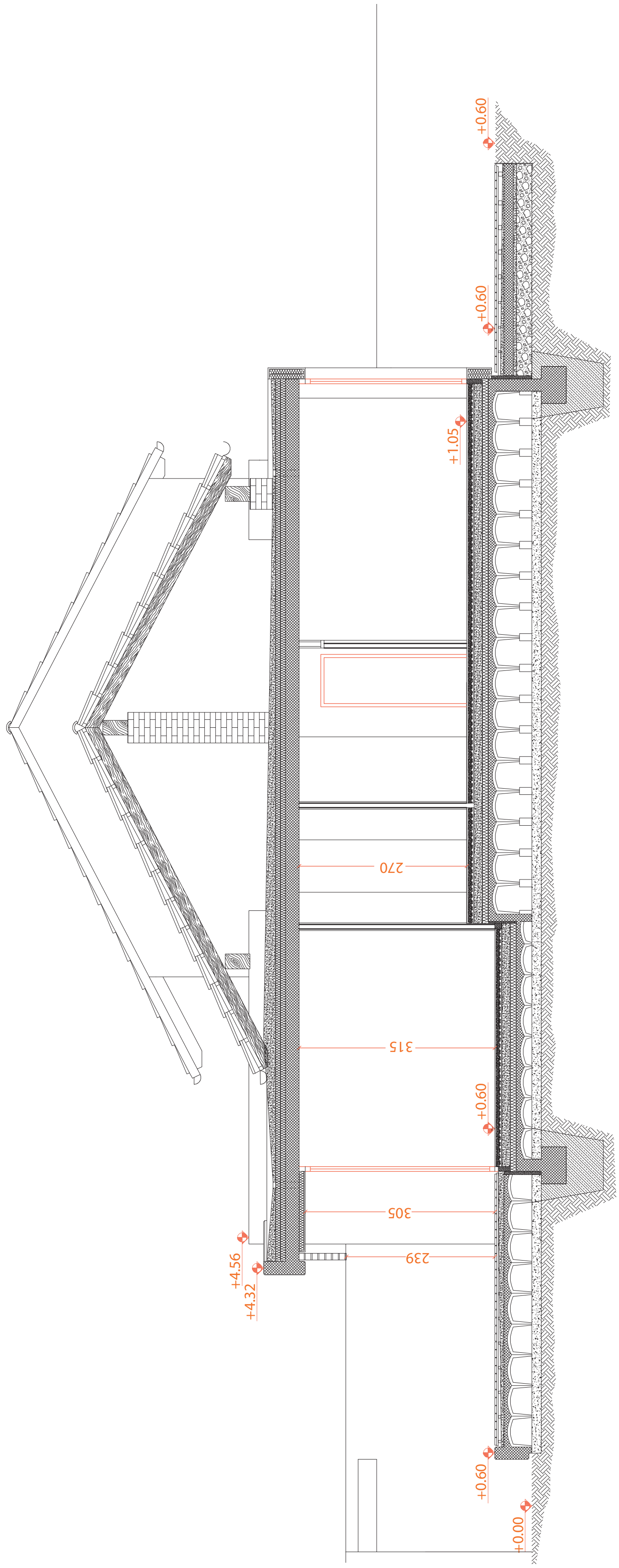


Fig. 4.03: CorTau House transverse section

4.2. Scenarios of Home Automation System for Cortau House

As resulted from the survey analysis „Occupant behaviour in residential buildings” in the north-italian context, the occupant behaviour can impact the energy consumption in buildings significantly. For this reason, the aim of this section was to speculate how it is possible to improve energy performance of the CorTau House by introduction of the Building Automation. However, a Smart Home completely automated, focused only on energy saving and which does not consider the occupant preferences and the perception of comfort is not the most appropriate solution. For this reason, the second part of the thesis aims to demonstrate how, through the implementation of building automation systems and a good occupant’s interaction with them, it is possible to obtain considerable energy savings in the residential building.

In the first part of this chapter there is defined the minimum set of variabiles to monitor (for environment and energy). Subsequently, three experimentation kits are defined, based on level of automation, every of them is characterized by different cost and different level of occupant interaction with the system.

The next part is focused on development of control and automation logics for a Smart Energy Home (basing on the automation levels marked out previously), which allow to obtain the energy savings thanks to management alone.

Finally, a literature review on sensors and actuators was carried out, analysing the current market offers.

4.2.1. Definition of variabiles to monitor

As mentioned before, the aim of this part is to identify the environmental and energy variables related to the occupants and that can influence energy consumption of the building. In particular, were taken in consideration variabiles which define indoor and outdoor environmental conditions, and energy variabiles (electric and thermal).

1- Indoor enviromental variabiles

A good indoor environment is associated with high indoor quality and thermal comfort. The indoor air quality and thermal comfort subsequently are significantly affected by the variabiles like the temperature, relative humidity or airflow pattern. Other variabiles, like level of indoor illuminance or sound level can also infuence the comfort of the occupant significantly. The minimum set of indoor environmental variabiles to monitor is defined below:

Indoor environmental variables

t_i- indoor air temperature [°C]	*Themal quality*
R.H.- Relative Humity [%]	*Hygrometric quality*
E- illuminance [lux]	*Light quality*
L_s- sound level [dB]	*Acoustique Quality*
CO_2- carbon dioxide level [ppm]	*Air Quality*

2-Outdoor enviromental variabiles

The optimal measurement set should also consider the outdoor envirnment variabiles, as they can have an important impact on the energy consumption. For example, the outdoor temperature can influence the heating/cooling behaviour or the occupants will prefer to use mechanical ventilation instead of natural ventilation when outside is too windy or when the outdoor air quality is bad.
The external environmental variabiles can be monitored near the building through one dedicated home weather station, or be collected by a standard weather station, which provides data aviabile online. The minimum set of outdoor environmental variabiles to monitor is defined below:

Outdoor environmental variables

t_{ext}- external air temperature
p_a- atmospheric pressure
v_a- air velocity
RH- Relative Humidity
VOC- outdoor Volatile Organic Compounds level [ppm]
I- Solar radiation
E- outdoor illuminance [lux]
L_s- outdoor sound level [dB]

3-Energy variabiles

The measurement of energy variabiles allows to obtain information that facilitate the management decisions of all building energy systems. These decisions affect the costs associated with energy demands, equipment costs and the global energy performance of building systems. At the lowest level, all types of measuring instruments provide output variables related to energy resources or energy carriers (energy, water, natural gas) required by a building. In addition to this basic level, much more sophisticated measuring instruments provide additional features such as measurement of electrical demand, measurement of power quality or detection of losses on the circuits. For electrical systems, measuring instruments can be installed both centrally to check the energy demand of the entire building and at the panel level (for example, to disaggregate the data related to the request for electricity for lighting or for a particular use associated with a circuit or, at a more detailed level, to measure the energy requirement of a single machine (i.e. a heat pump). For water, gas and other fluids associated with specific applications of the building, measuring instruments are installed on in-line circuits and can be characterized by different technologies. For the Cortau House it is neccessary to monitor electric and thermal energy and potable water. The main variabiles to monitor are listed below:

Electric energy

The most common measurment parameters are listed below, focusing on those whose offer the greatest potential energy efficiency improving:

- **electric current**- a flow of electric charge;
- **electric voltage-** the rate at which energy is drawn from a source that produces a flow of electricity in a circuit;
- **electric power-** rate, per unit time, at which electrical energy is transferred by an electric circuit
- **resistance-** measure of the difficulty to pass an electric current through that conductor.

Thermal energy

Space heating and cooling of Cortau House is provided by a water-to-water heat pump so for correct field measurements of energy used for heating/cooling it is neccessary to monitor:

- outlet temperature;
- return temperature;
- fluid flow and heat transfer.

4.2.2. Definition of automation levels

Considering the classification made above about the possible approaches to conducting the measurements, it is possible to think of a hierarchical order which, depending on the purpose, can maximize the advantages connected to monitoring and minimize the costs. For this reason, the variables necessary to monitor were reported in the following tables with division for three different experimentation scenarios characterized by the number of variables, cost, and services offered in the decreasing order (from high to low level of automation):

*Kit 1*_High Level of Automation- fully automated system, with minimal level of active involvment of the occupants
*Kit 2*_Medium Level of Automation- automated system with limited number of actuators, medium level of occupant interaction with the building systems.
*Kit 3*_Low Level of Automation- use of basic control system, high level of occupant interaction with building system

1- KIT I_High Level of Automation

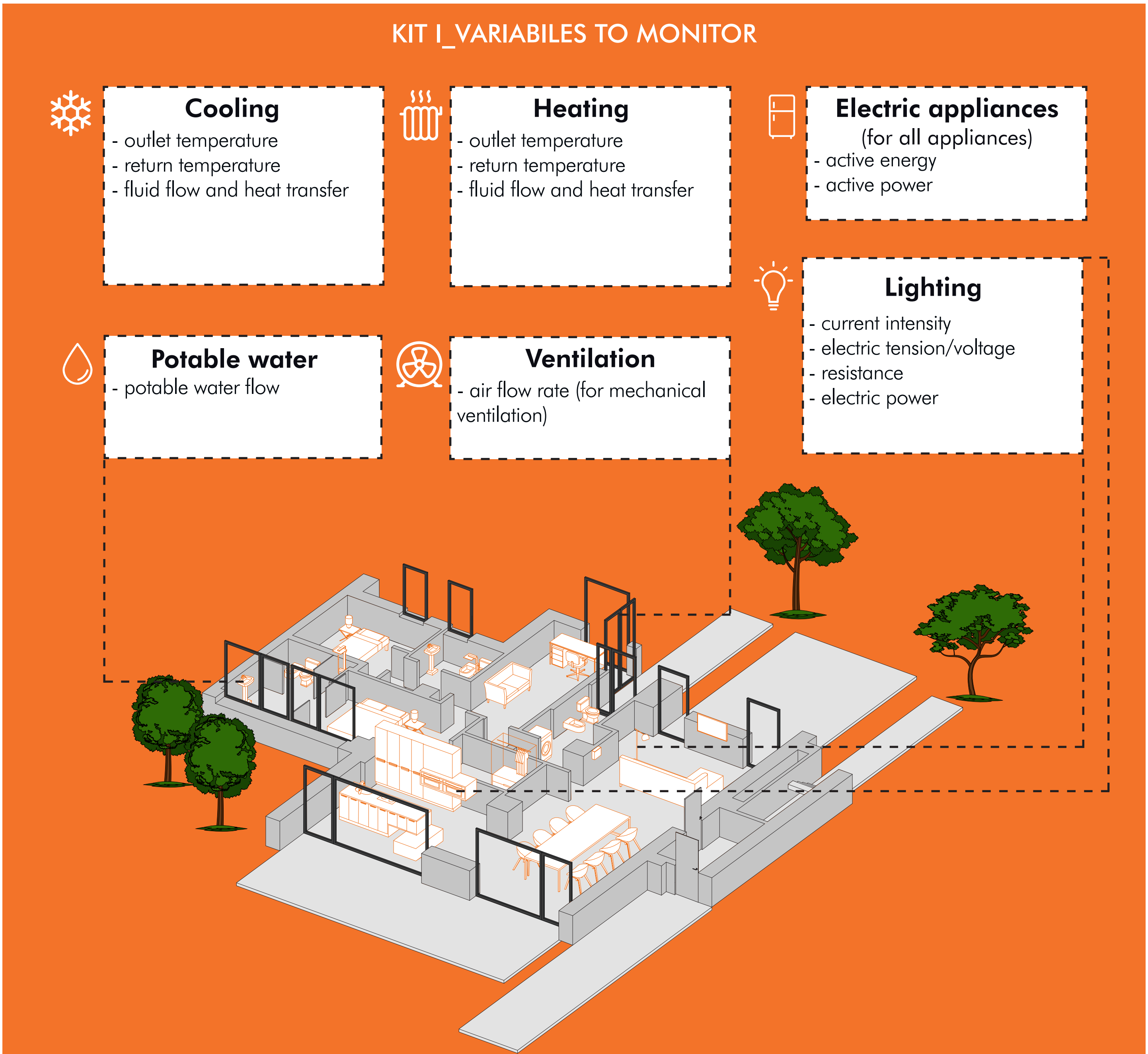


Fig. 4.04. Variabiles to monitor, High Level of Automation Kit (final energy consumption)

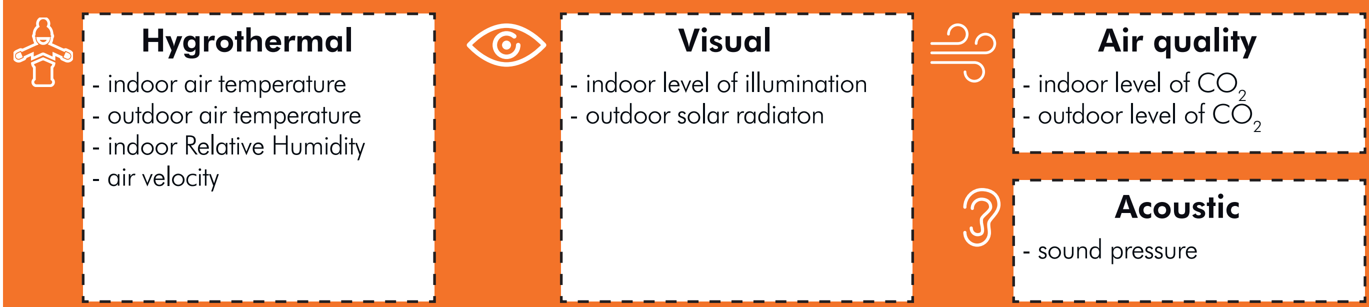


Fig. 4.05. Variabiles to monitor, High Level of Automation Kit (comfort)

KIT I_SENSORS TO USE

Cooling
- flow meter for heat pump
- heat meter

Heating
- flow meter for heat pump
- heat meter

Electric appliances
(for all appliances)
- Smart Plug

Potable water
- water flow probe

Ventilation
- air flow sensor

Lighting
- multimeter

Fig. 4.06. Sensors to use for final energy consumption control, High Level of Automation Kit

Hygrothermal
- thermocouple
- hygrometer
- anemometer

OR:
- indoor temperature sensor + home weather station (for outdoor temperatures)

Visual
- lux meter
- pyranometer

Air quality
- CO_2 meter
- VOC meter

Acoustic
- sound level meter

Fig. 4.07. Sensors to use for comfort control for the High Level of Automation Kit

Moreover, the sensors related to the occupant behaviour are taken into the consideration:
- sensors for the occupancy detection (passive infrared sensors),
- window sensors (control the windows state- open/closed).

KIT I_ACTUATORS TO USE

Cooling
- programmable thermostat,
- electric actuator + actuator head- Smart Valve (thermal electric actuator)

Heating
- programmable thermostat,
- electric actuator + actuator head- Smart Valve (thermal electric actuator)

Electric appliances
(for all appliances)
- Smart Plug
- relay- disconnect the line based on schedule or when there is overload

Potable water
no actuator

Ventilation
- heating/cooling turn on/off based on the state of the window
- inverter of VMC based on CO_2 level and number of occupants

Lighting
- lights switch on/off and dimmer based on the level of the indoor illuminance and occupation

Fig. 4.08. Actuators to use for final energy consumption control, High Level of Automation Kit

Hygrothermal
- electric linear actuator for windows

Visual
- electric linear actuator for window blinds

Air quality
- electric linear actuator for windows

Acoustic
- electric linear actuator for windows

Fig. 4.09. Actuators to use for comfort control, High Level of Automation Kit

2- KIT II_Medium Level of Automation

KIT II_VARIABILES TO MONITOR

Cooling
- outlet temperature
- return temperature
- fluid flow and heat transfer

Heating
- outlet temperature
- return temperature
- fluid flow and heat transfer

Electric appliances
(only for principal appliances)
- active energy
- active power

Lighting
- current intensity
- electric tension/voltage
- resistance
- electric power

Potable water
- potable water flow

Ventilation
- air flow rate (for mechanical ventilation)

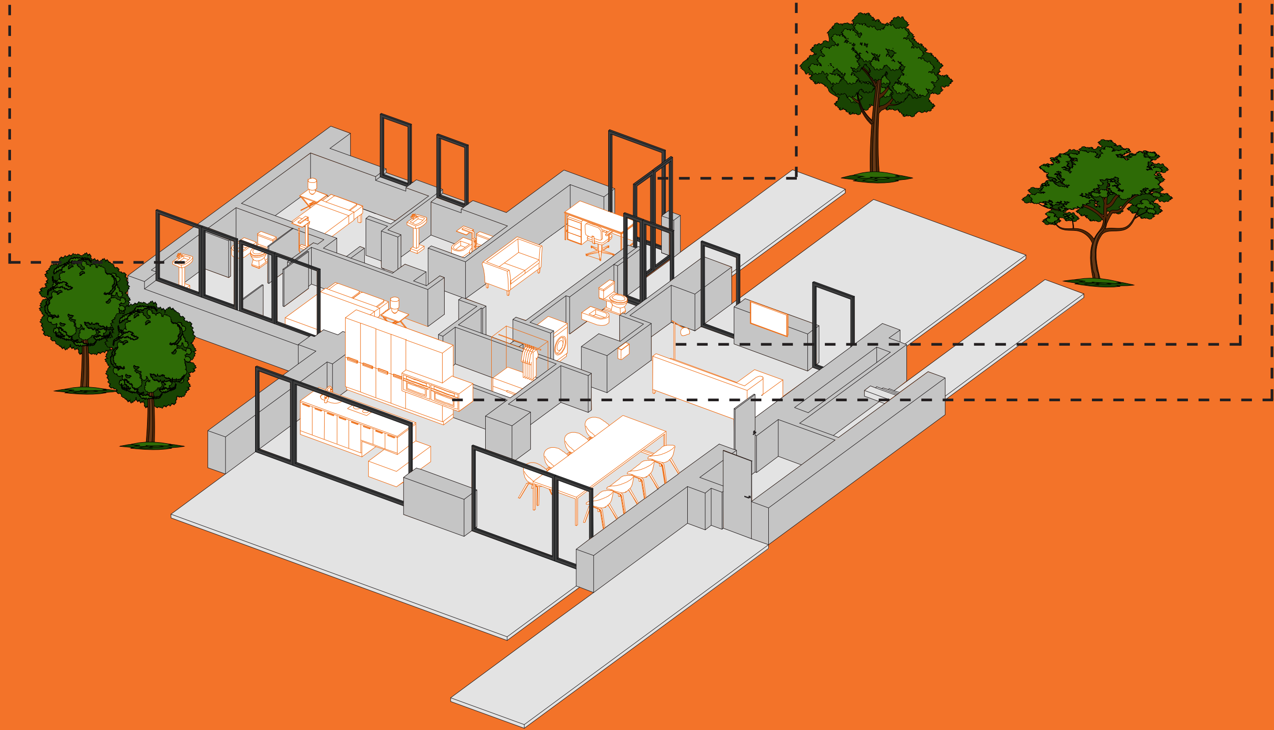


Fig. 4.10. Variabiles to monitor, Medium Level of Automation Kit (final energy consumption)

Hygrothermal
- indoor air temperature
- outdoor air temperature
- indoor Relative Humidity

Visual
- indoor level of illumination
- outdoor solar radiaton

Air quality
- indoor level of CO_2
- outdoor level of CO_2

Acoustic
- no variabiles to monitor

Fig. 4.11. Variabiles to monitor, Medium Level of Automation Kit (comfort)

KIT II_SENSORS TO USE

Cooling
- flow meter for heat pump
- heat meter

Heating
- flow meter for heat pump
- heat meter

Electric appliances
(only for principal appliances)
- Smart Plug

Potable water
- water flow probe

Ventilation
- air flow sensor

Lighting
- multimeter

Fig. 4.12. Sensors to use for final energy consumption control, Medium Level of Automation Kit

Hygrothermal
- thermocouple
- hygrometer

Visual
- lux meter
- pyranometer

Air quality
- CO_2 meter
- VOC meter

Acoustic
no sensor

Fig. 4.13. Sensors to use for comfort control for the Medium Level of Automation Kit

Moreover, the sensors related to the occupant behaviour are taken into the consideration:
- sensors for the occupancy detection (passive infrared sensors);
- window sensors (control the windows state- open/closed).

KIT II_ACTUATORS TO USE

Cooling
- programmable thermostat
- electric actuator + actuator head- Smart Valve (thermal electric actuator)

Heating
- programmable thermostat
- electric actuator + actuator head- Smart Valve (thermal electric actuator)

Electric appliances
(only for principal appliances)
- Smart Plug
- relay- disconect the line based on schedule or when there is overload

Potable water
no actuator

Ventilation
no actuator

Lighting
- lights switch on/off and dimmer based on the level of the indoor illuminance and occupation

Fig. 4.14. Actuators to use for final energy consumption control, Medium Level of Automation Kit

There are no actuators taken in consideration for comfort control. The system will send an information to the occupant if any action will be neccessary (i.e. window opening/closing).

3- KIT III_Low Level of Automation

KIT III_VARIABILES TO MONITOR

Cooling
- electricity consumption associated with the heat pump

Heating
- electricity consumption associated with the heat pump

Electric appliances
(only for washing machine)
- active energy
- active power

Lighting
- current intensity
- electric tension/voltage
(data from electricity meter)

Potable water
- potable water flow (from the counter)

Ventilation
no variabiles to monitor

Fig. 4.15. Variabiles to monitor, Low Level of Automation Kit (final energy consumption)

Hygrothermal
- indoor air temperature
- outdoor air temperature

Visual
- indoor level of illumination (only in significant points)

Air quality
no variabiles to monitor

Acoustic
no variabiles to monitor

Fig. 4.16. Variabiles to monitor, Low Level of Automation Kit (comfort)

KIT III_SENSORS TO USE

Cooling
- Smart Plug on the heat pump

Heating
- Smart Plug on the heat pump

Electric appliances
(only for washing machine)
- Smart Plug

Potable water
- water flow probe

Ventilation
no sensor

Lighting
- electricity meter

Fig. 4.17. Sensors to use for final energy consumption control, Medium Level of Automation Kit

Hygrothermal
- thermocouple (for indoor and outdoor temperature)

Visual
- electricity meter

Air quality
no sensor

Acoustic
no sensor

Fig. 4.18. Sensors to use for comfort control for the Low Level of Automation Kit

Moreover, the sensors related to the occupant behaviour are taken into the consideration:
- sensors for the occupancy detection (passive infrared sensors);

KIT III_ACTUATORS TO USE

Cooling
- programmable thermostat

Heating
- programmable thermostat

Electric appliances
(only for washing machine)
- Smart Plug

Potable water
no actuator

Ventilation
no actuator

Lighting
(only for significant points)
- lights switch on/off based on the level of the indoor illuminance and occupation

Fig. 4.19. Actuators to use for final energy consumption control for the Low Level of Automation Kit

Where actuators are not present (also for comfort control), the system will send an information to the occupant if any action will be neccessary (i.e. window opening/closing).

4.3. Development of control logics

As previously mentioned, the Building Automation systems available today apply logic of optimization of the control processes proceeding for individual applications: lighting, ventilation system, heating, cooling etc. The possible energy savings resulting from the optimization of the control is the sum of the savings obtained by the individual applications. In the physical world, however, building systems strongly interact with each other. If, for example, a window is opened to improve air quality, this will also determine a thermal flow that will influence the occupant's thermal comfort, and in particular the indoor air temperature.

In order to achieve energy savings that go beyond the sum of individual savings, it is therefore necessary to develop a system that can evaluate the interactions between the individual applications and evaluate a global action to optimize all building systems together. Obviously the control logics can also be set not only with the scope to obtain maximum energy efficiency of the building system, but also for example to improve air quality or thermal comfort.

The scope of the following part of research was to define the control logics to maximize the energy efficiency of the CorTau House, maintaining the comfort conditions, for three previously defined levels of automation, taking in the consideration the level of occupant interaction with the building systems:
- **High Level of Automation**- fully automated operation of the system (absence of occupant action);
- **Medium and Low Level of Automation-** operation of the system in interaction with the occupant's actions.

The first step to define the control logics was to specify all the possible actions arising from the systems that are taken into consideration, and to understand which parameters are influenced by those actions:
- Screening system adjustment (window blinds): thermal comfort, visual comfort;
- Switch off and adjustment of artificial lights: visual comfort;
- Window opening/closing: air quality, thermal comfort;
- Turning on, switching off and adjustment of the heating/cooling system: thermal comfort;
- Turning on, switching off and adjustment of the ventilation system: air quality, thermal comfort.

The physical parameters that define the comfort conditions, previously listed, are:

- **Air quality**: measurement of the ppm indoor level (CO_2 level). In order to maintain indoor air quality, the CO_2 level must never exceed the CO_2 limit set, $CO_2 > CO_{2\ lim}$ (CO_2 set point).
- **Thermal comfort**: measurement of the indoor temperature T_i. In order to maintain indoor thermal comfort it is necessary that T_i is never higher or lower than the T_i limit level established, $T_i < T_{i\ lim}$, $T_i > T_i$ lim (T_i set point)
- **Visual comfort**: measurement of the indoor illumination level lux). In order to maintain the indoor visual comfort , the indoor Lux level should be not lower or higher than Lux_i limit established, $E_i > E_{i\ lim}$, $E_i < E_{i\ lim}$ (Lux set point).

In the case when the predetermined limits are exceeded, the management actions of the various systems, controlled by the control logic, would begin to work with the aim to restore the comfort conditions.

The table below represents the summary of previously listed sensors and actuators with division for three different automation levels- low, medium and high, which are taken in consideration for control logics development (Fig. 4.20):

	High	Medium	Low
Indoor temperature (T_i)	●	●	●
Outdoor temperature (T_e)	●	○	○
Indoor CO_2 level (CO_{2i})	●	●	
Outdoor CO_2 level (CO_{2e})	●	○	
Indoor illuminance level (E_i)	●	●	●
Occupancy state (motion detection)	●	●	●
Window state (open/closed)	●	●	
Window blind state (open/closed)	●		
Heating/cooling flow rate (Φ_h ,Φ_c)	●	●	●
Ventilation flow rate	●	●	
Illumination flow rate (Φ_{ill})	●	●	●
Automatic window opening/closing	●		
Automatic window blind adjustment	●		
Automatic heating/cooling system control	●		
Automatic lighting control	●	●	●
Automatic ventilation system control	●		

○ *Informations obtained from Web services (i.e. Dark Sky)*

Fig. 4.20. List of sensor and actuators with division for three different automation levels

Where the automatic control of the building systems is not present, the occupants will receive alerts to control the building system states (i.e. „check if the window is open") and to take any action if necessary (i.e. „close the window").

Moreover, it is possible to manage the building systems with the use of predetermined schedules (i.e. day, hour). The necessary action will be taken by the system or occupant will be informed to take any action only when the day/time range corresponds with the previously determined schedules for different actions. For example, the system will open the window only when the occupant is present at home. With the use of the time use survey, compiled by CorTau House's occupants, it was possible to obtain schedules for different occupants' actions- occupancy profile (fig. 4.21), sleeping schedule (fig. 4.22) and use of the lighting system schedule (fig. 4.23), with the division on different day of week (weekday and weekend).

Occupancy schedules (weekdays and weekends)

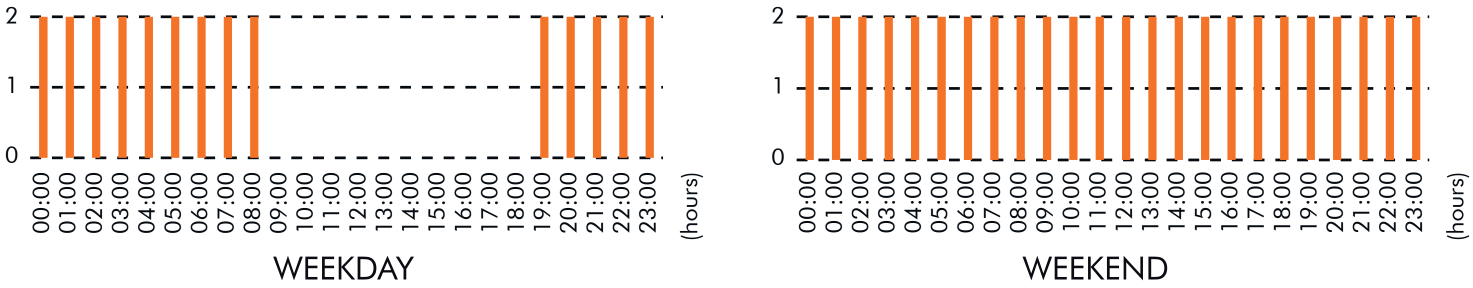


Fig. 4.21. CorTau House members' occupancy schedules

Sleeping schedules (weekdays and weekends)

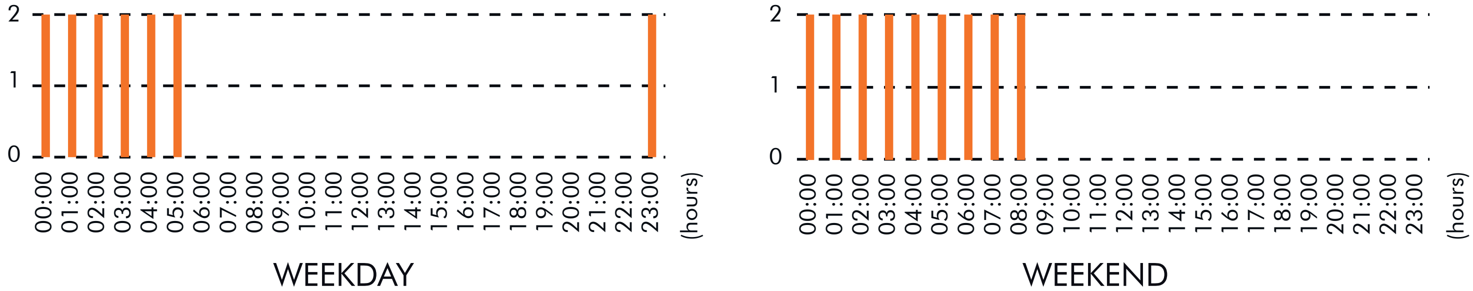


Fig. 4.22. CorTau House members' sleeping schedules

Use of lighting system schedules (weekdays and weekends)

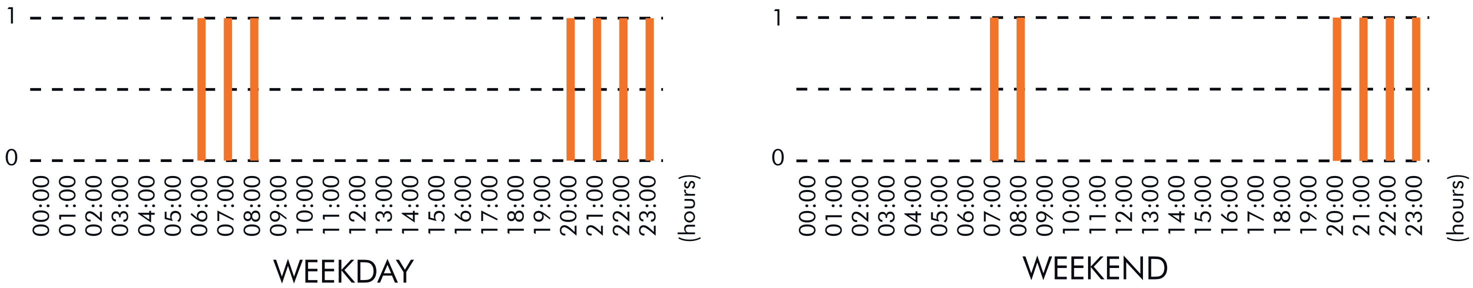


Fig. 4.23. CorTau House members' use of lighting system schedules

After the definition of the schedules, it is possible to speculate the set-point values the temperature during the winter and summer, indoor CO_2 level and indoor illuminance level, (E_i) in accordance to the period of the day (t threshold) and in accordance to the occupants' indoor climate preferences. The values come from the report of Politecnico di Torino *„Sviluppo di metodologie di aggregazione e benchmarking dei dati energetici di rete di edifici e modelli di feedback per il coinvolgimento degli utenti residenziali"* [54].

	Day	Time	T_i [°C] (heating)	T_i [°C] (cooling)	CO_{2i} [ppm]	E_i [lux]
Morning warmup	Weekday	04:00-05:00	24°C	22°C	800	0
	Weekend	07:00-08:00				
Occupied	Weekday	19:00-23:00	21°C	25°C	350	300
	Weekend	08:00-00:00				
Unoccupied	Weekday	08:00-19:00	18°C	27°C	800	100
	Weekend	-				
Night time setback	Weekday	23:00-04:00	16°C	30°C	1000	0
	Weekend	00:00-07:00				

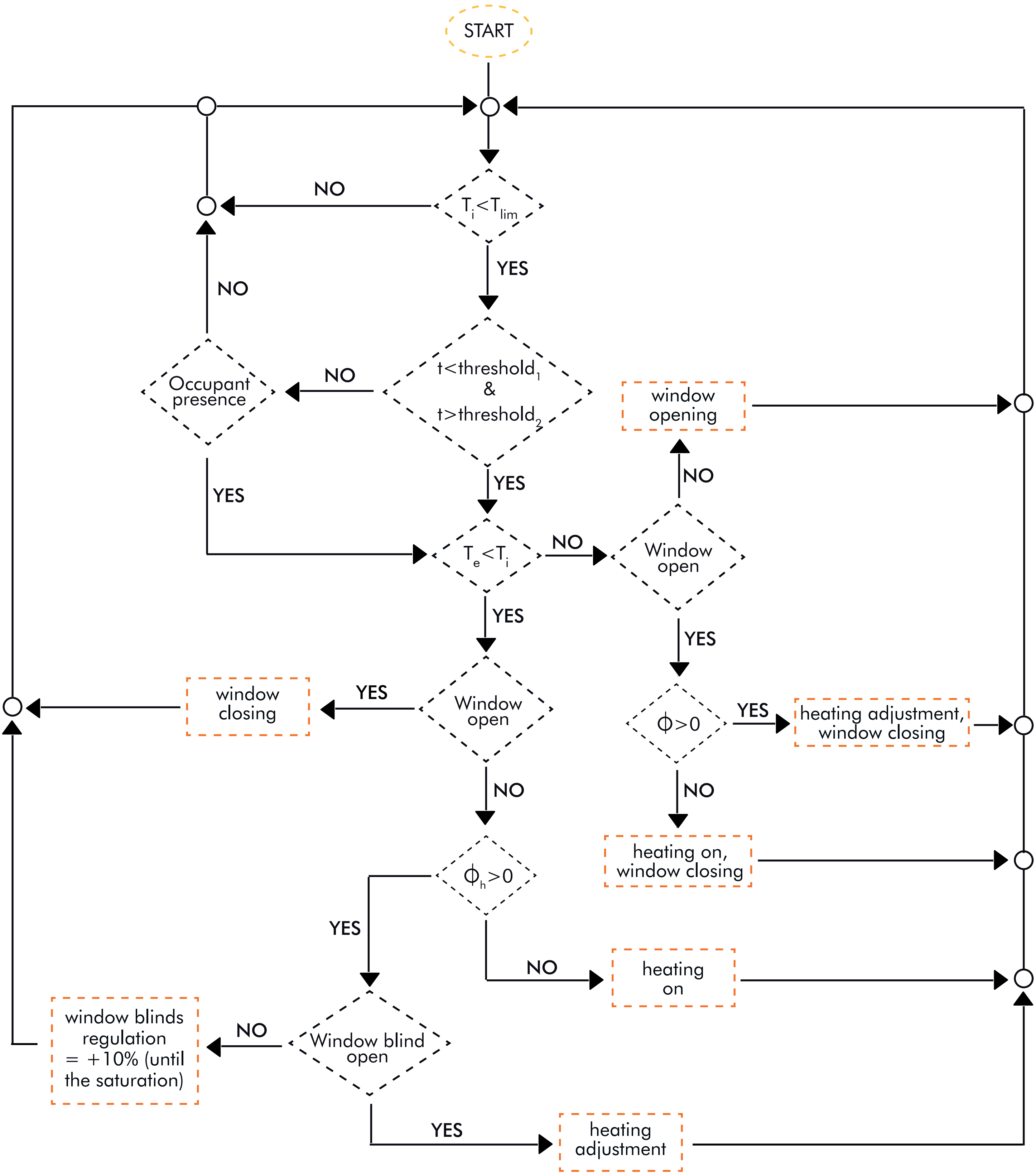
Fig. 4.24.

After establishing the variables to monitor and set-points in accordance to the period of the day, the following algorithms have been developed to regulate the actions of the system in case of exceeding each of the previously established limit values:

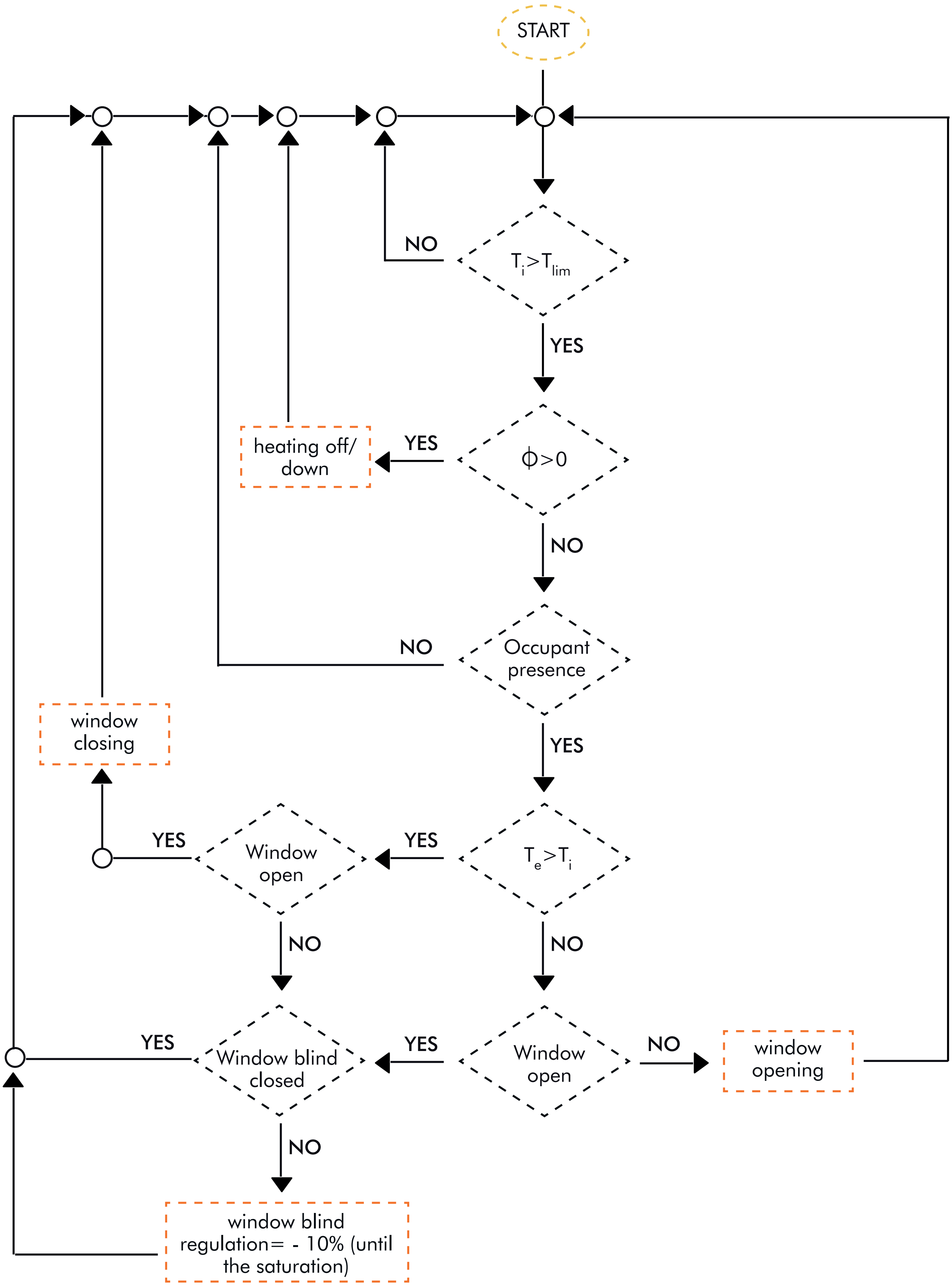
1. Algorithms to maintain the set-points for indoor temperature, in summer and winter.
2. Algorithms to keep the set-points for illuminance level.
3. Algorithms to maintain the set-point for air quality (high and medium level of automation).

1- Control logics for Scenario 1_High Level of Automation

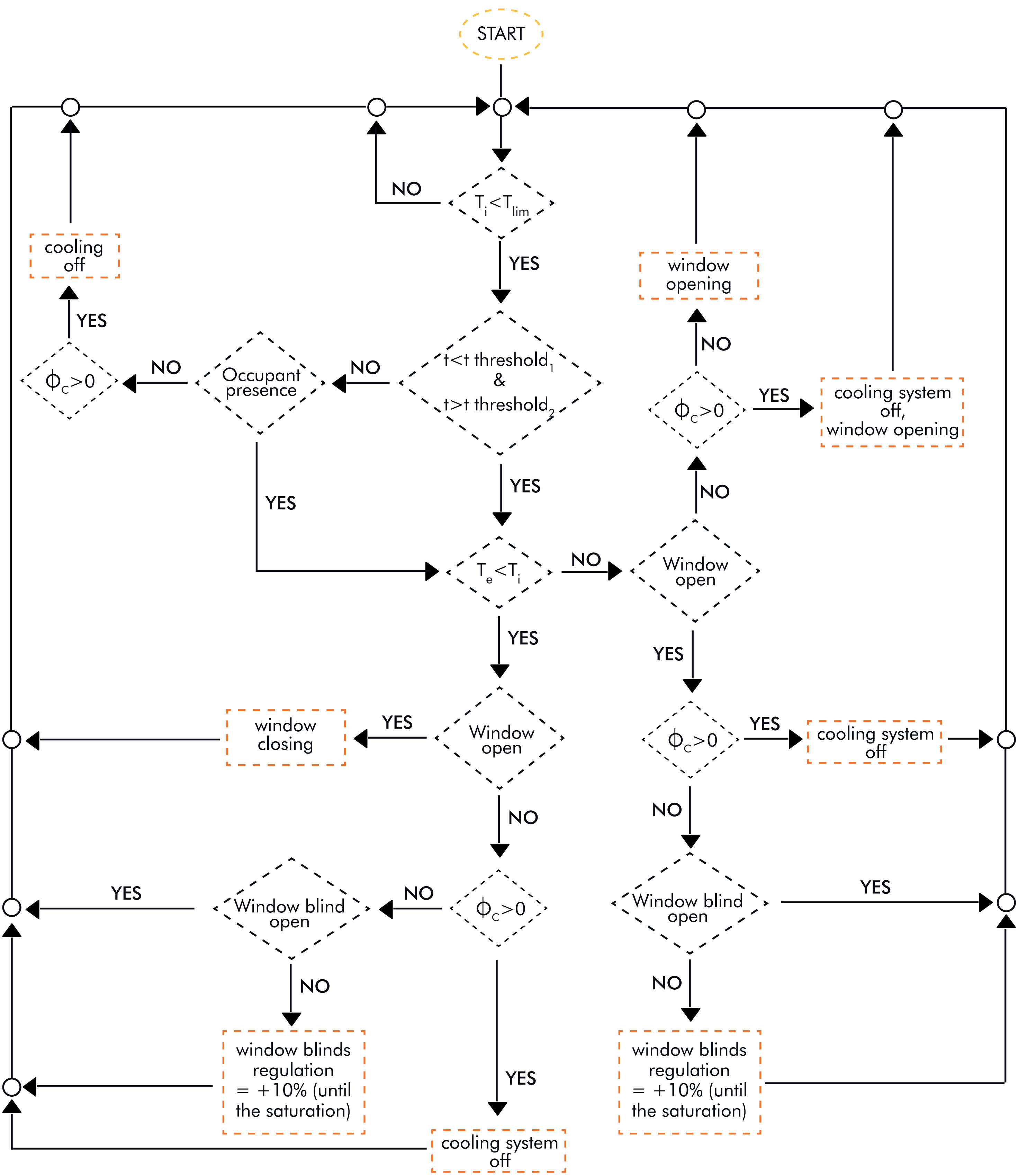
High Level o Automation- indoor temperature lower than limit temperature during the winter



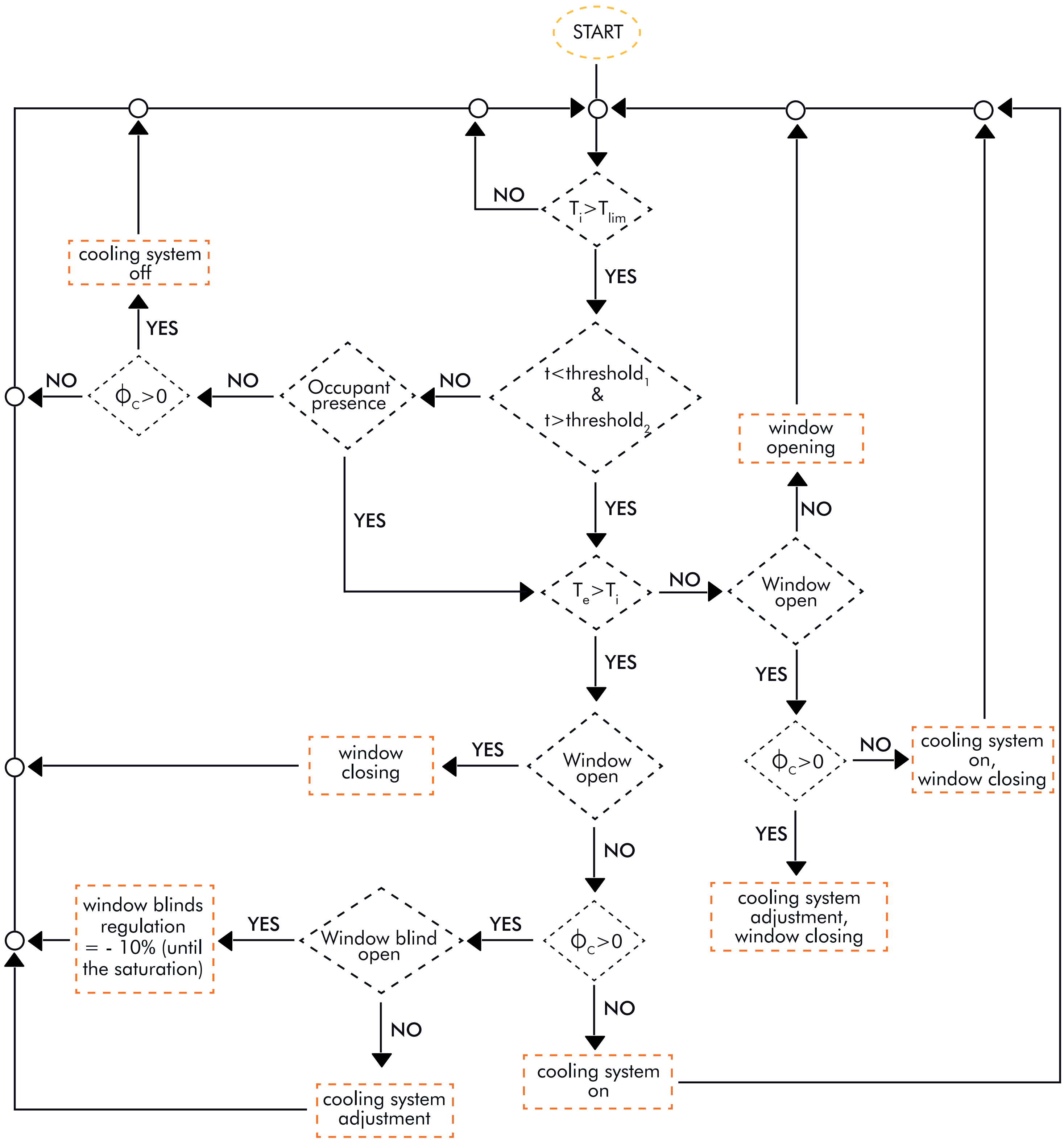
High Level Automation- indoor temperature <u>higher</u> than limit temperature during the winter



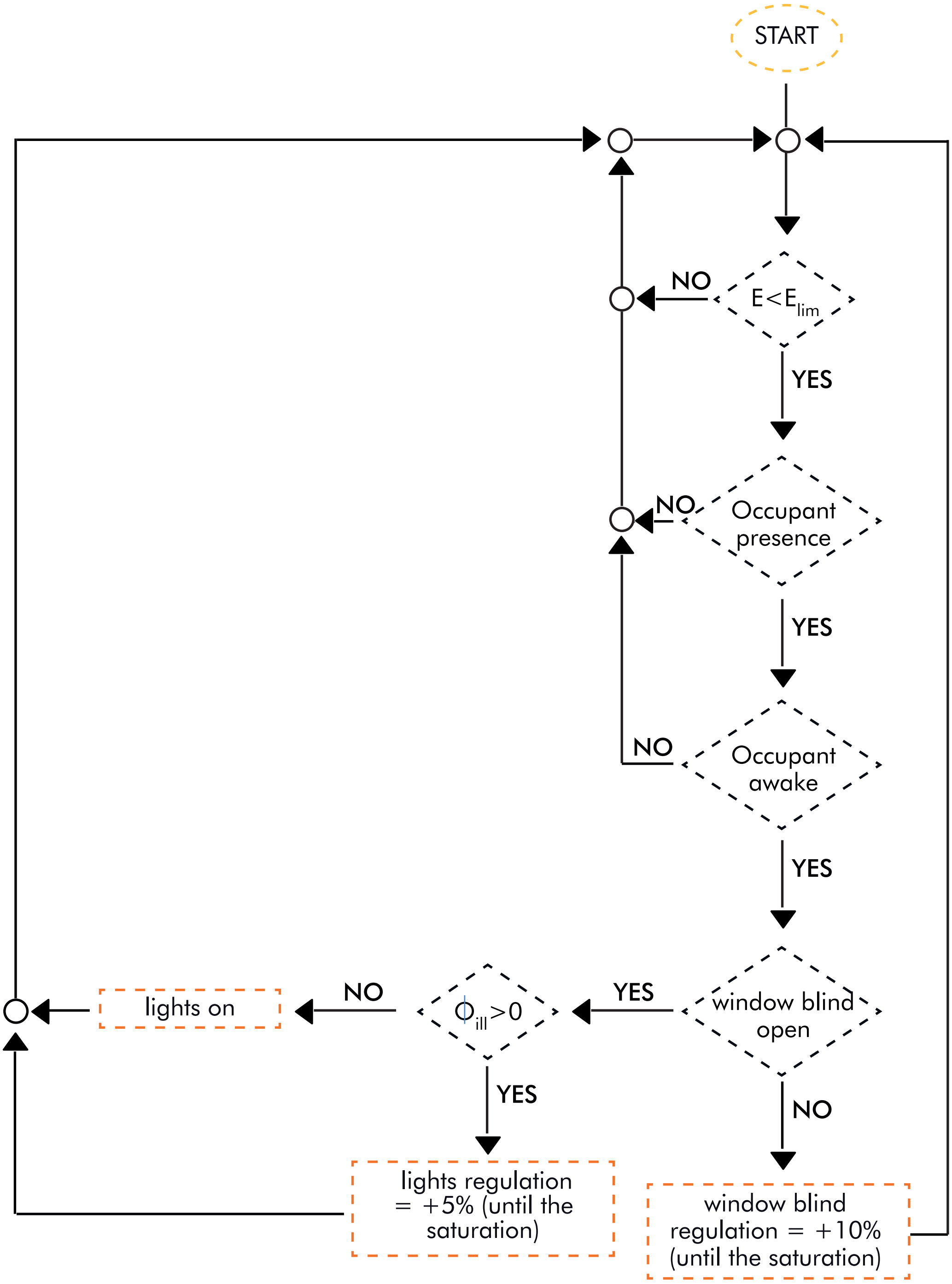
High Level Automation- indoor temperature lower than limit temperature during the summer



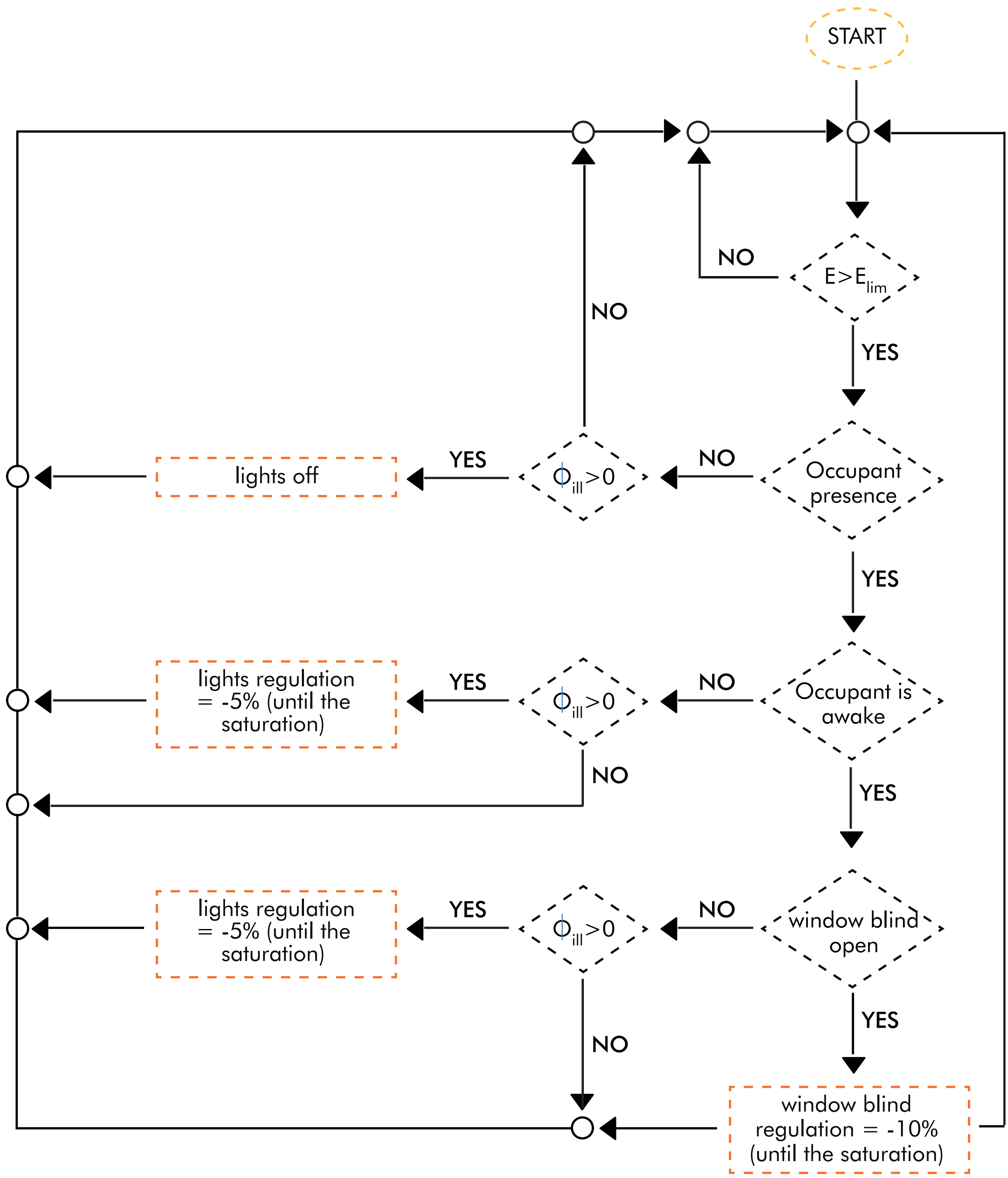
High Level Automation- indoor temperature ***higher*** *than limit temperature during the summer*



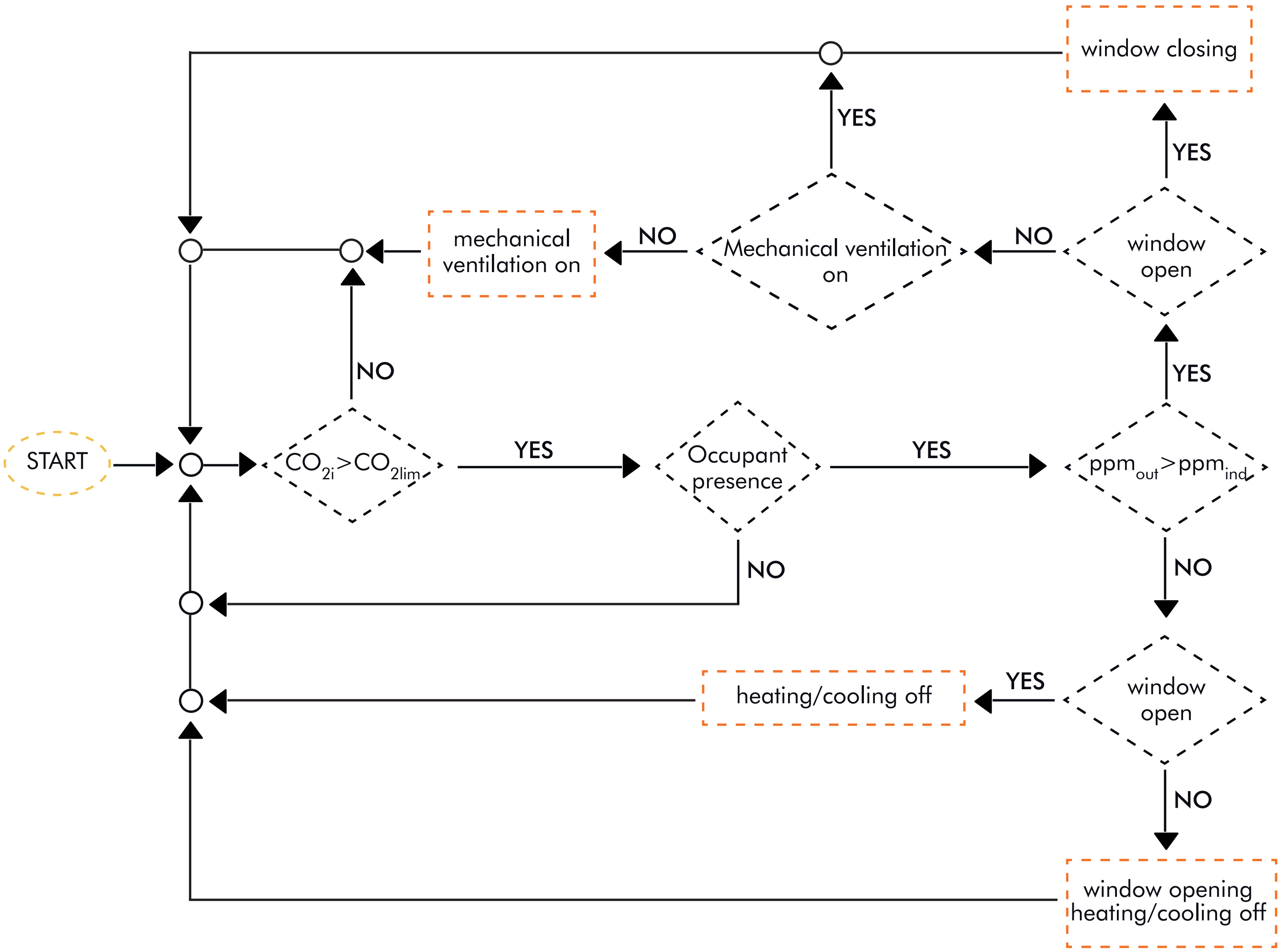
High Level of Automation- indoor illumination <u>lower</u> than limit illumintation



High Level Automation- indoor illumination <u>higher</u> than limit illumintation

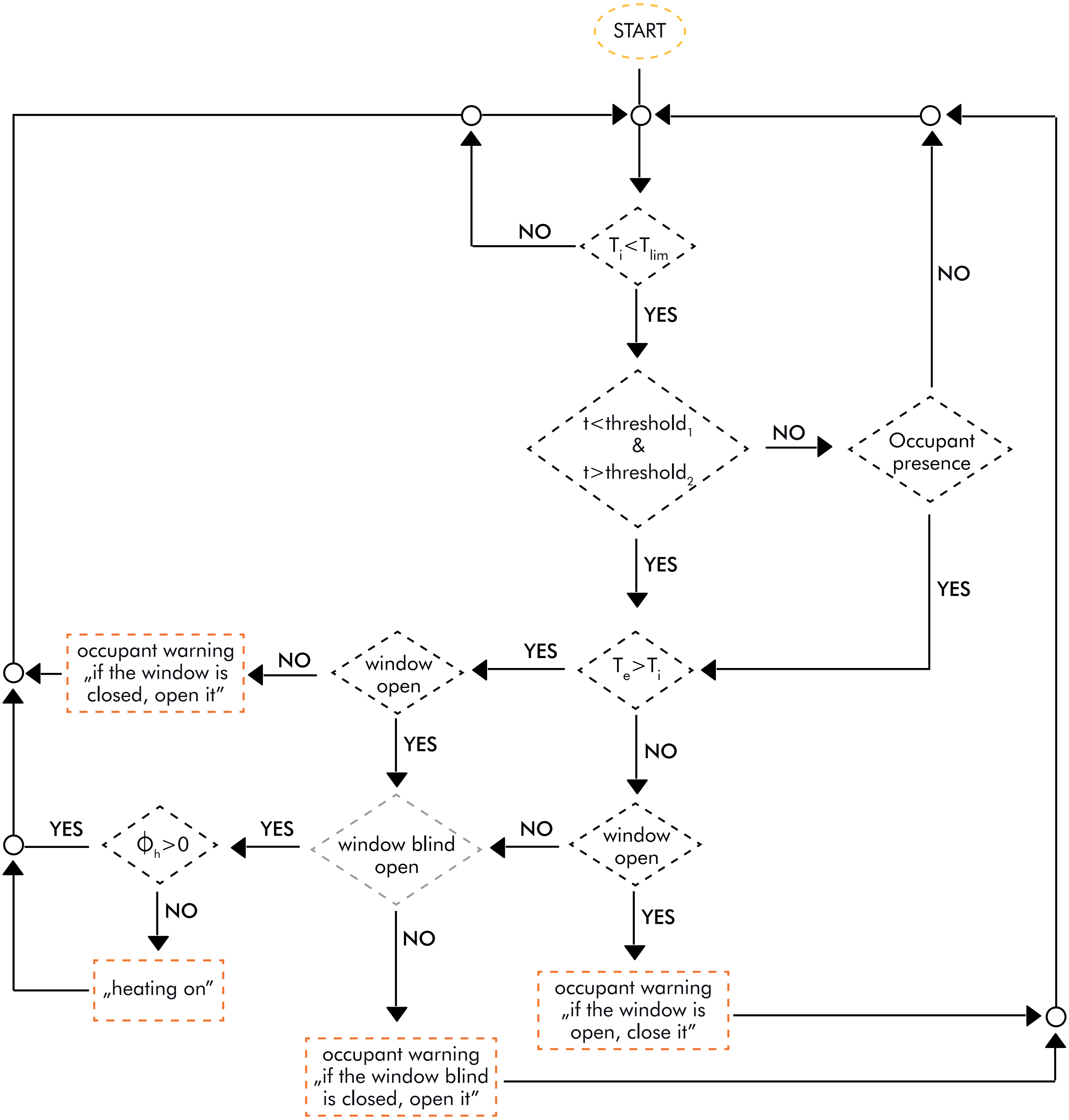


High Level of Automation- concentration of pollutant <u>higher</u> the limit value

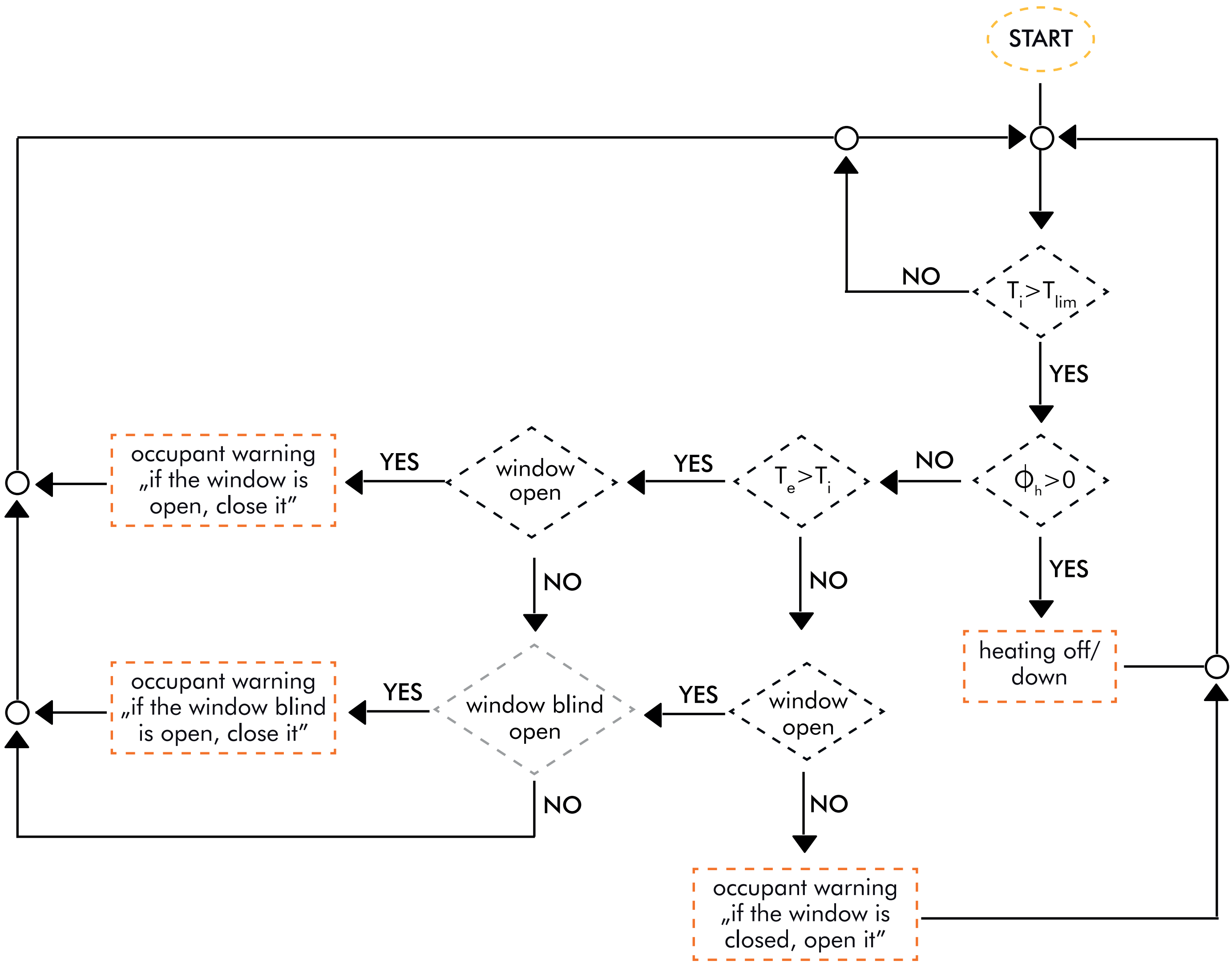


2- Control logics for Scenario 2_Medium Level of Automation

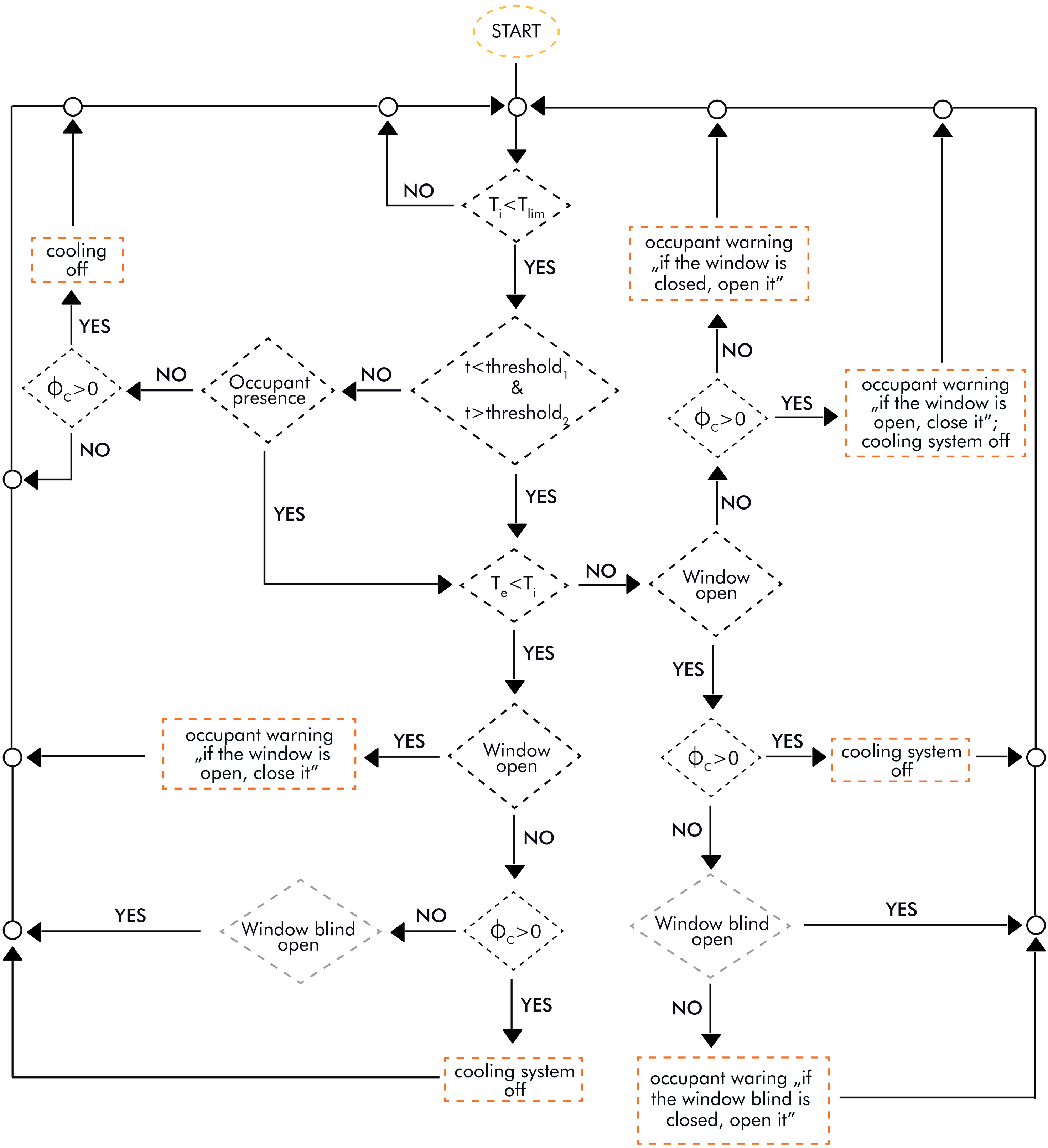
Medium Level Automation- indoor temperature lower than limit temperature during the winter



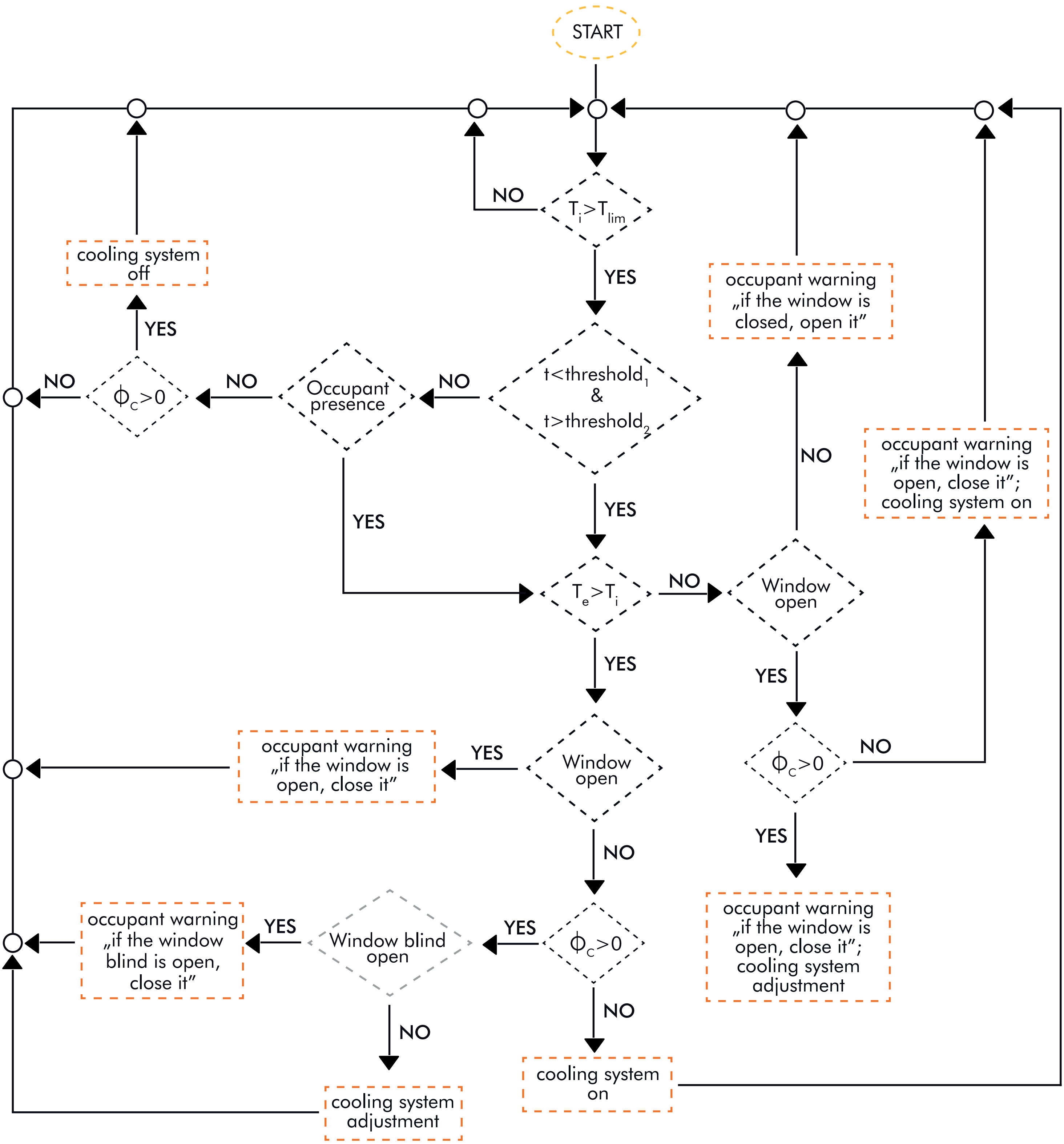
Medium Level Automation- indoor temperature higher than limit temperature during the winter



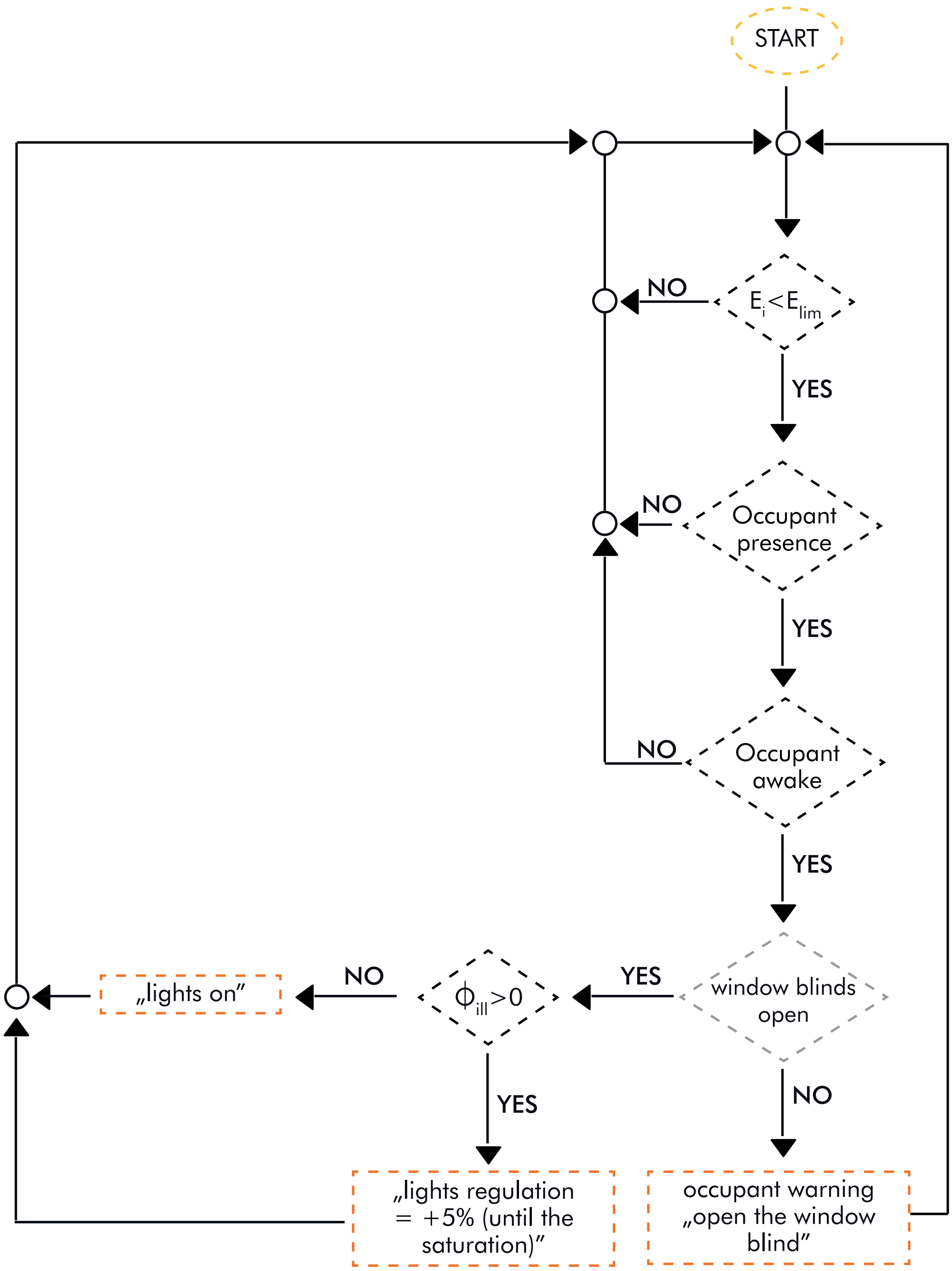
Medium Level Automation- indoor temperature lower than limit temperature during the summer



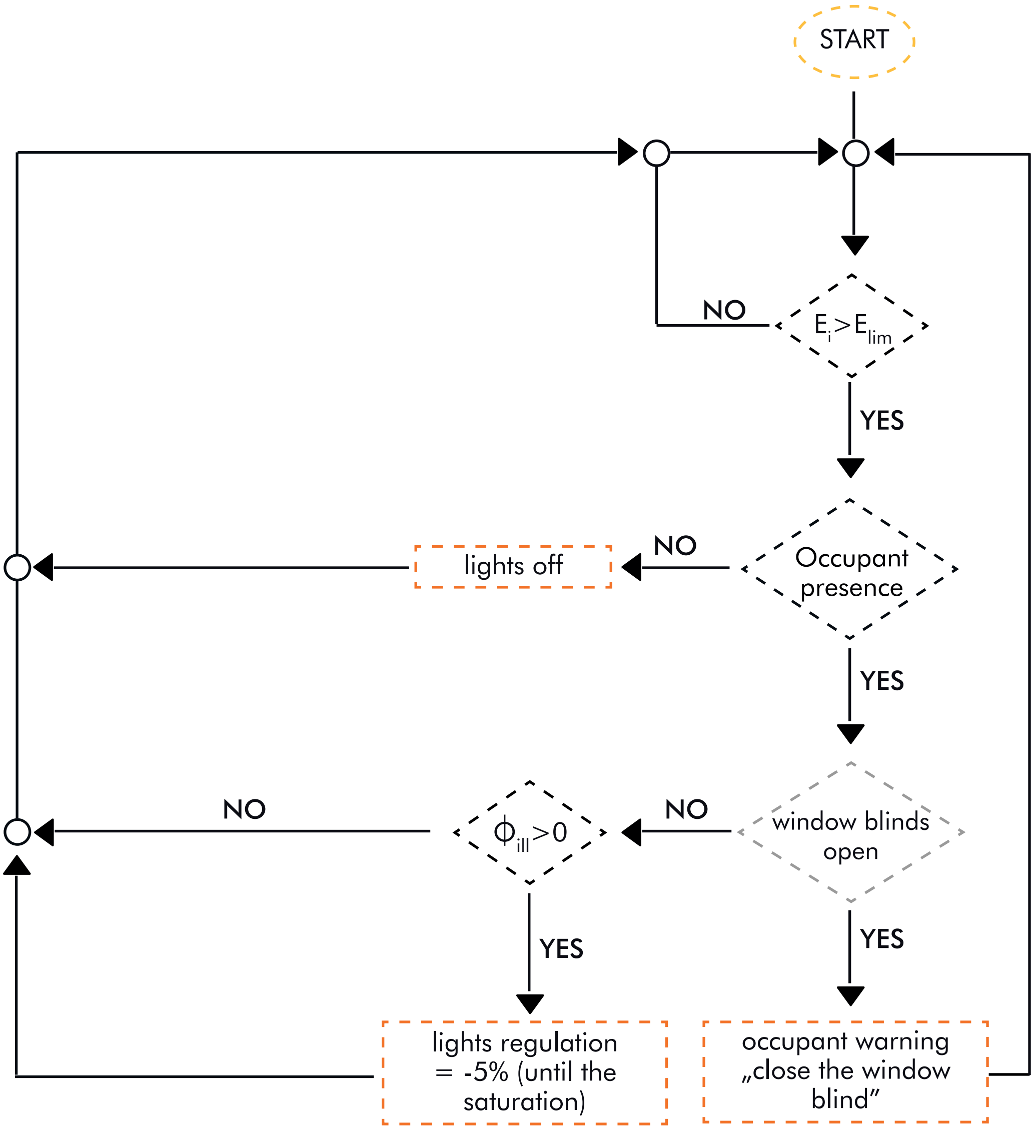
Medium Level Automation- indoor temperature higher than limit temperature during the summer



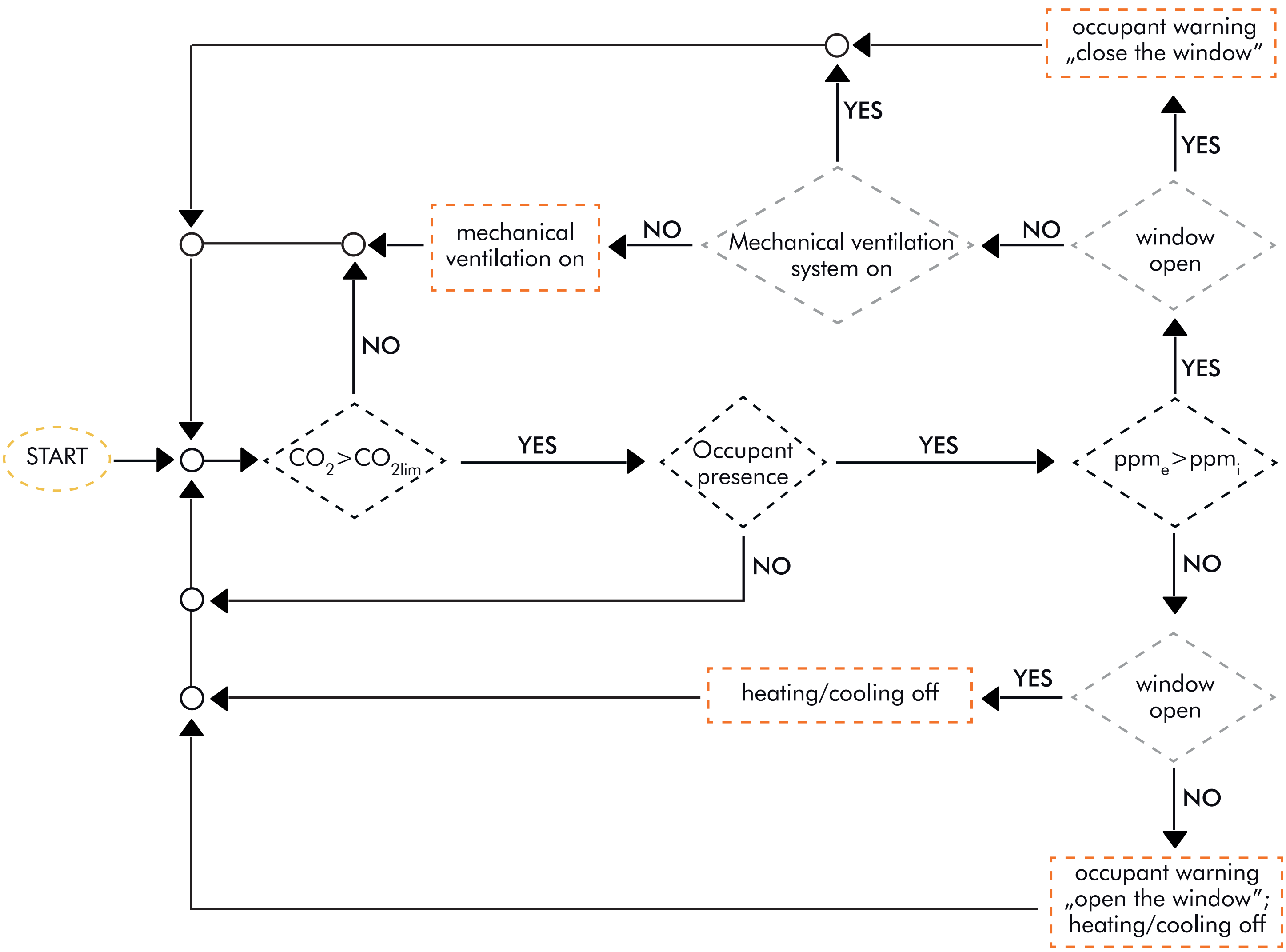
Medium Level Automation- indoor illumination lower than limit illumintation



Medium Level Automation- indoor illumination <u>higher</u> than limit illumintation

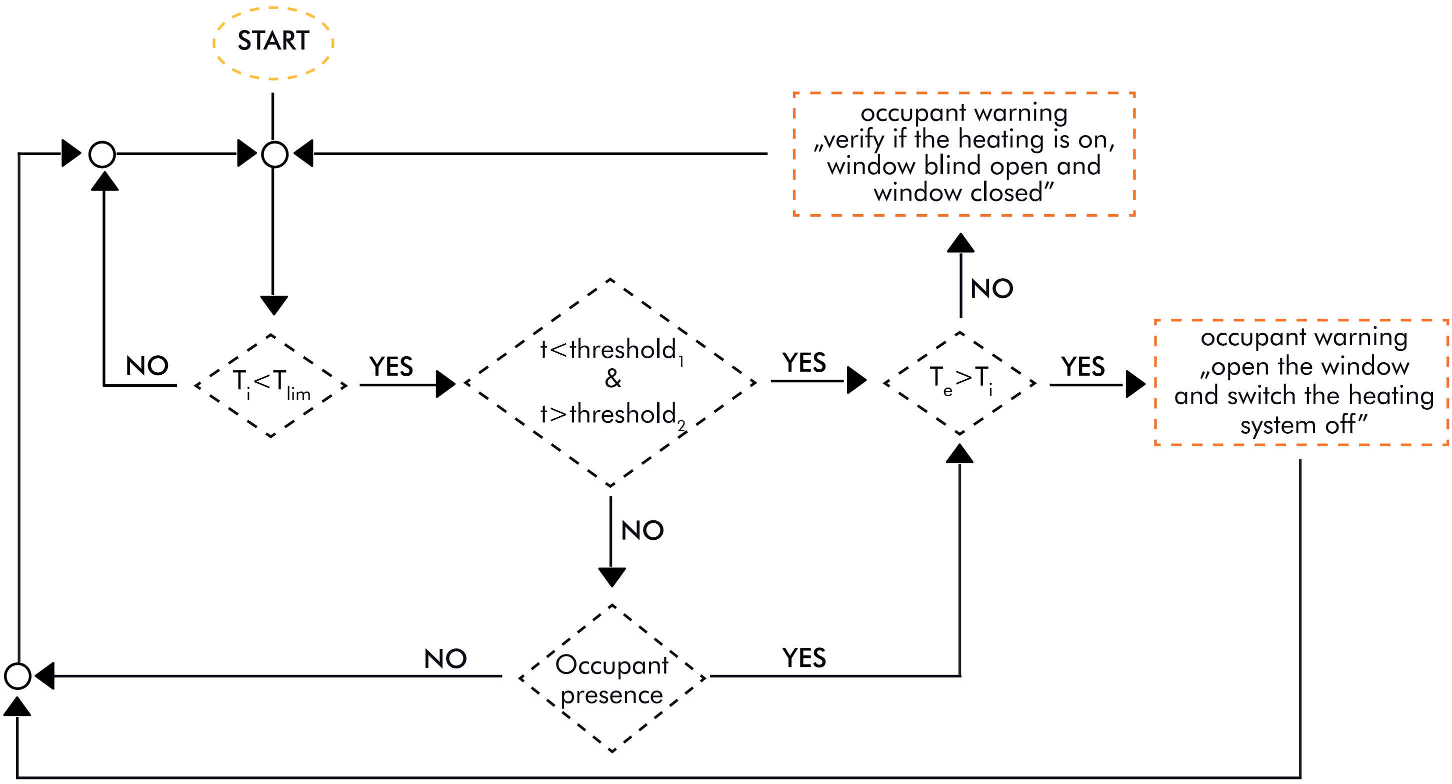


Medium Level Automation- concentration of pollutant higher the limit value

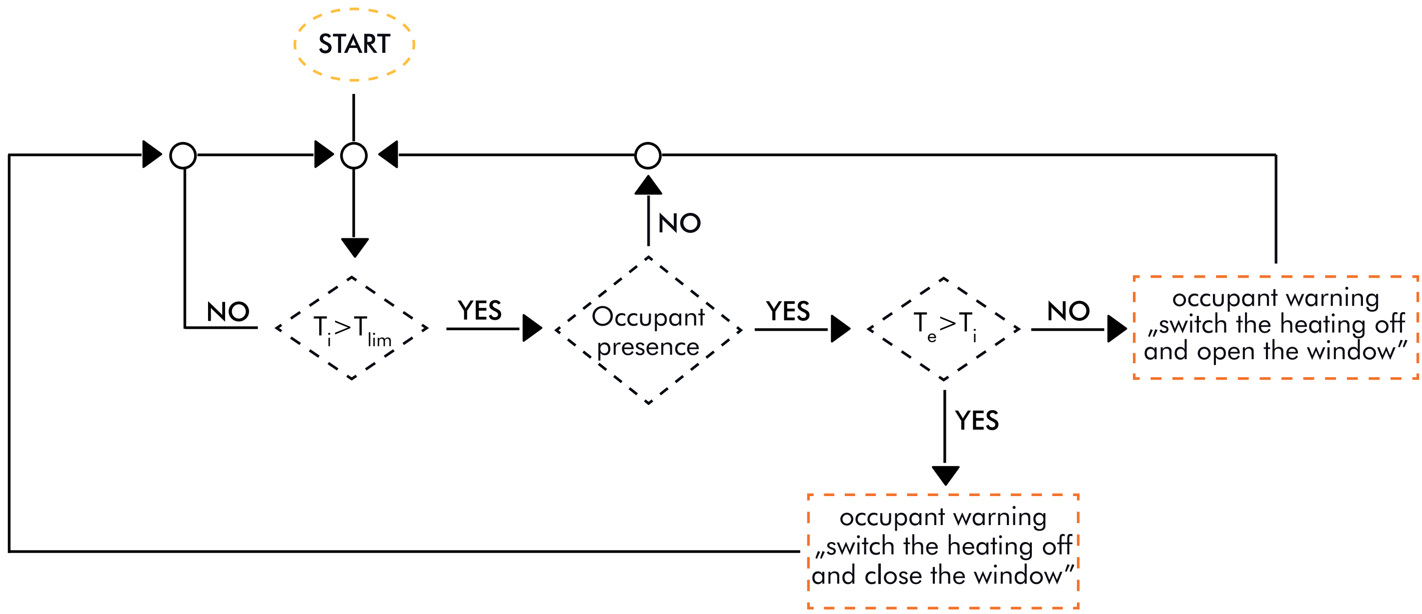


3- Control logics for Scenario 3_Low Level of Automation

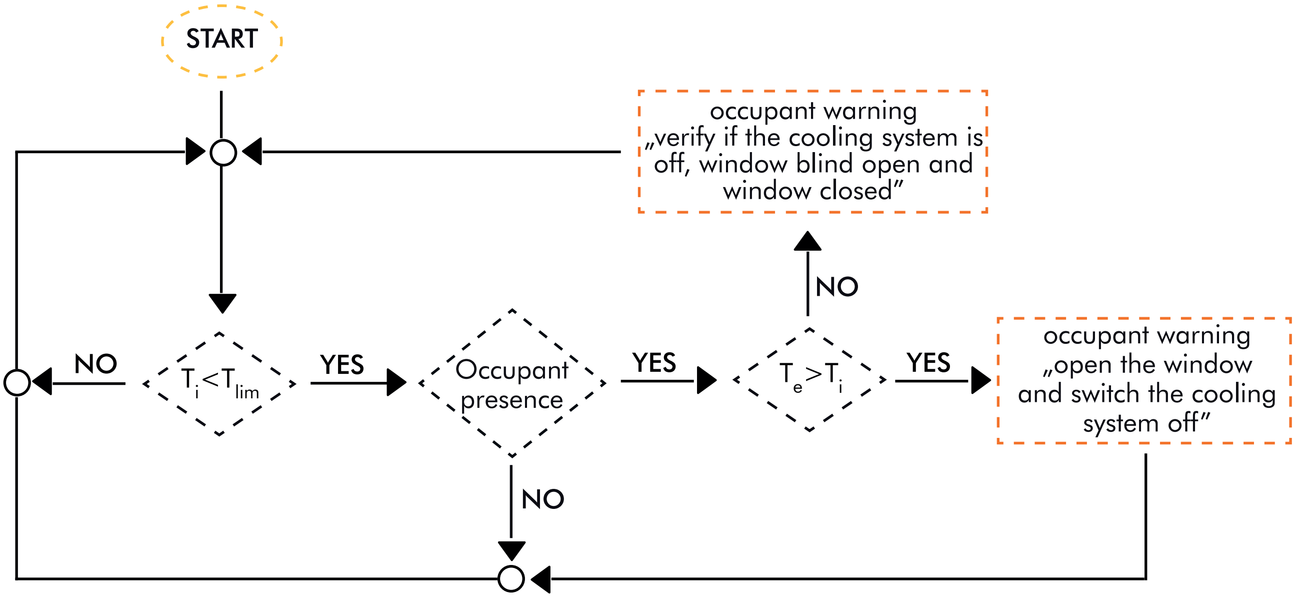
Low Level of Automation- indoor temperature lower than limit temperature during the winter



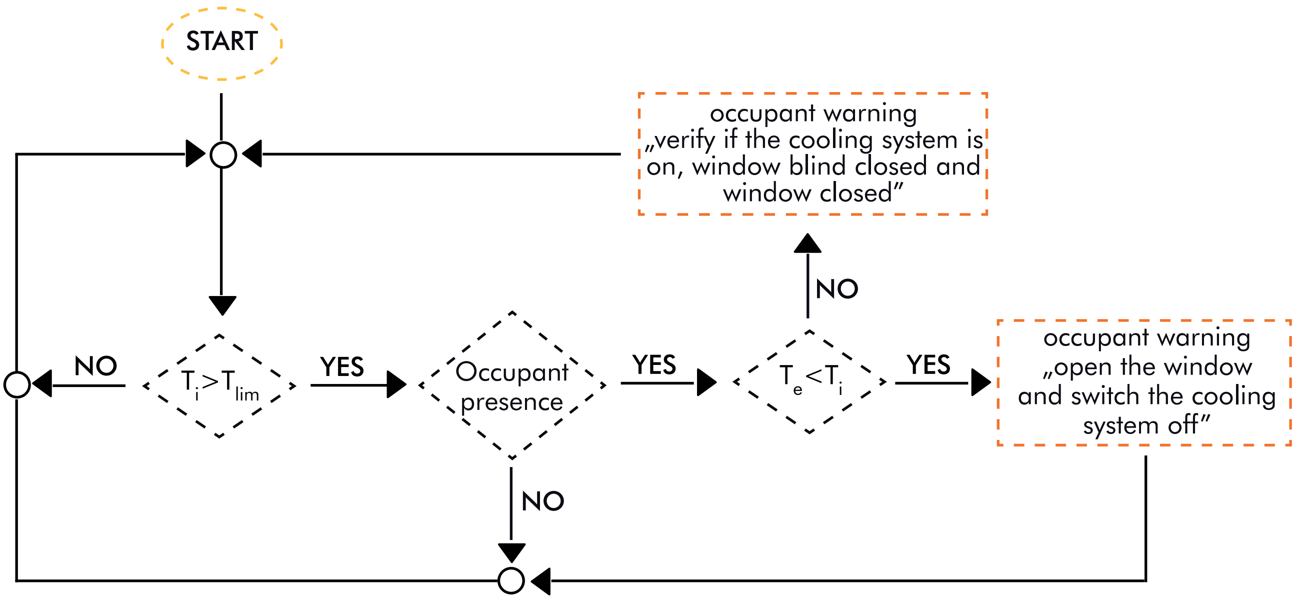
Low Level of Automation- indoor temperature higher than limit temperature during the winter



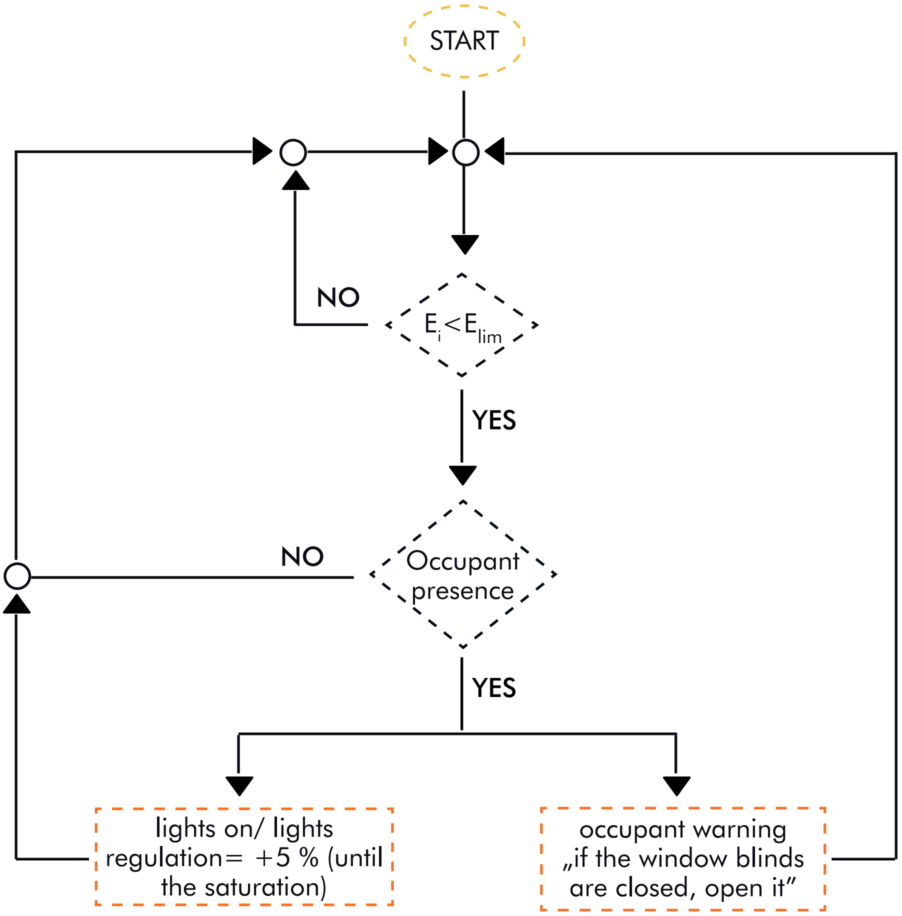
Low Level of Automation- indoor temperature lower than limit temperature during the summer



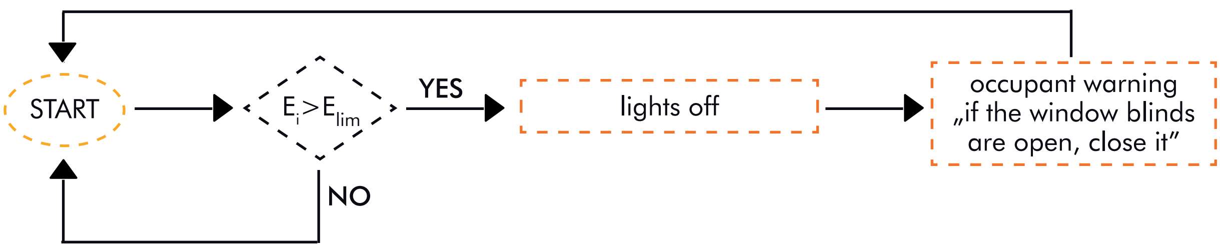
Low Level of Automation- indoor temperature higher than limit temperature during the summer



Low Level Automation- indoor illumination lower than limit illumintation



Low Level Automation- indoor illumination higher than limit illumintation



The development of the part focused on the control logics was based on the following literature:
- A. Capozzoli et al., "*Attività di monitoraggio energetico e ambientale, diagnostica ed Energy Engagement degli utenti degli use case*", Report Ricerca di Sistema Elettrico RdS/PAR2016/008 (2017) [55]

- C. Aghemo et al.,"*Managment and monitoring of public buildings through ITC based system: Control rules for energy saving with lighting and HVAC sevices*" [57]

4.4. Implementation of home automation ecosystem with commercial products and cost definition

The aim of this part was to study what home automation market offers nowadays and to investigate possible implementation of control system using comercial products according to classification made in previous section for 3 different levels of automation for Cortau House. As Cortau House is an existing building, completely wireless system was choosen, what allows to avoid invasive installation of actuators and sensors, which intervenes in the building structure. For buildings in the construction/renovation phase it would be more convenient to implement wired sensors and actuators, as usually they are cheaper and require less maintenance (i.e. it is not neccessary to change batteries periodically). It was also important to minimize the quantity of products, especially quantity of sensors, choosing sensors which can control few variabiles in the same time. Moreover, as home automation systems are still in development by companies, it is quite difficult to find a whole system to control every single parameter of the building produced by the same company. Different companies produce different sensors and actuators. In order to obtain maximum energy management efficiency it's important to include different ecosystems from different companies. A way to do it is use of an integrator system. One of examples of open source software which integrate plenty of products from different companies is Home Assistant. The use of the of this software was proposed for all three levels of automation:

System integration- Home Assistant

Home Assistant is free and simple software which can be installed on every PC or embedded board (like Raspberry Pi) without storing any of data in the cloud and which provides a great command set to perform intelligent logic to control every single aspect of the house. It's extremely modular and scalable, it includes every big company component, it's open source and free.

1- KIT I_High Level of Automation

For High Level of Automation kit there is considered minimum level of occupant interaction with buildings systems. All main building systems can be equipped with an actuator, which allows automatic control of buildins systems state (i.e. switch off/on lights, window opening/closing). For this level of automation top brands sensors and actuators are considered:

Smart Home Hub- Wink Hub 2

Wink is a brand of software and hardware products that connects with and controls smart home devices from a consolidated user interface. Wink collaborates with large range of brands like: Honeywell, Philips, Nest or Ecobee. The second generation Wink Hub supports most smart home devices with Bluetooth LE, Z-Wave® (Security Enabled Z-Wave Plus Device), ZigBee®, Wi-Fi®, Lutron® Clear Connect®, Thread (future), Kidde.

Sensors and actuators integrated with Wink Hub 2:

Wink door/window sensor

Controls door/window state (open/close). In case of Cortau House it could be used for windows control. The system can control heating, cooling and ventilation according to windows state.

Philips Dynalite Sensor

The Dynalite sensor combines motion detection, light level detection and IR receive in one unit. Each of these features can be operated at the same time, allowing automation scenarios such as turning on the lights when any motion is detected and then dimming the lighting level once the available sunlight has been measured. For high level automation control, HVAC systems can be also adjusted according to occupancy state.

Philips Hue white bulb A19

9,5 W bulbs, can be controlled remotely or through Philips Lighting Dimmer.

Philips Lighting Dimmer for Philips Hue

Smart Lighting Dimmer Switch for wall and ceiling lights. Allows to obtain all shades of white, from warm to cold white colour. Dimmable via smart device or dimmer switch.

Bali RTS Motorized Window Treatment

Motorized window blind, controlled remotely, with the possibility to schedule opening and closing times.

Honeywell smart multi-zone system:

Actual Courtau House heating/cooling system is divided into two zones: day zone and night zone. Improving Honeywell smart multi-zone system it would be possible to control home temperature room by room, up to 12 zones (for Cortau House case 7 zones are proposed). Honeywell system includes following actuators:

Wi-Fi Honeywell thermostat

Wi-Fi touchscreen controller, the intelligent heart of heating system which allows to program, adjust to zones and customize the room temperature.

HCC80R Honeywell Underfloor Heating Controller

A wireless underfloor heating controller which provides up to 8 zones of control.

MT8 Small Linear Thermoelectric Actuator (Smart Valve)

Smart-T small linear actuators are used in room and zone applications for time-controlled two-point and pulse-widthmodulated (PWM*) regulation of heating and cooling systems such as fan coil units, radiators, floor heating systems, chilled ceilings, and convectors.

Netatmo Weather Station

Netatmo Weather Station consist of 2 elements- indoor and outdoor module to measure various enviroment variabiles:
- indoor module- controls following indoor variabiles: temperature (0°C to 50°C), humidity (0 to 100%), CO_2 level (0 to 5000 ppm), sound level (35 dB to 120 dB);
- outdoor module- controls following outdoor variabiles: temperature (-40°C to 65°C), humidity (0 to 100%), atmospheric pressure (260 to 1160 mbar), CO_2 level (0 to 5000 ppm) and sound level (35 dB to 120 dB);

Additionaly there is possibility to extend the system with various accessories, like:
- The Smart Anemometer (wind gauge): measure the wind's speed and direction, including those of wind gusts.

DripView Smart Water sensor

DripView is a smart water sensor, which allows to control water consumption of any domestic appliance like washing machine, shower, toilet, ecc. A single sensor device is mounted on the top of existing water installation. A sensors allows also to detect leakages. DripView is an project of Aqubiq tech startup, formed as a spinout from the Technical University of Denmark (not in sale yet).

mydlink Home Smart Plug DSP-W215

The mydlink™ Home Smart Plug is a multi-purpose, compact smart home device that allows to monitor and control home's electronic appliances. Using the application, it is possible to turn appliances on or off, monitor energy usage of connected appliances, create on/off schedules and set up alerts.

Eco-worthy Stocke Linear Window Actuator

Stoke Linear Actuator 1500N 12V 5.7mm/S with mouting bracket. Allows remote window opening and closing.

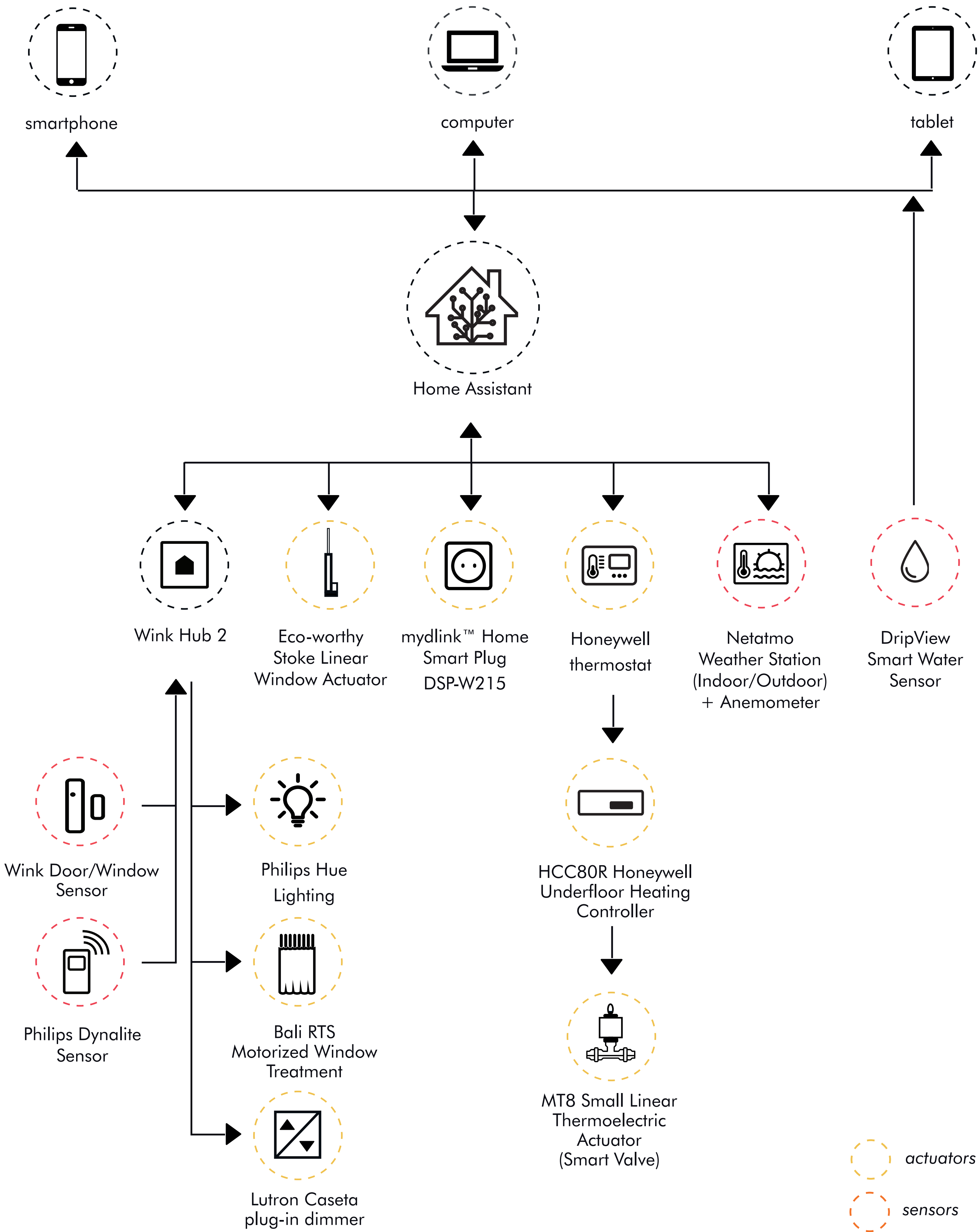


Fig. 4.24. Example of high level automation network for Cortau House with implementation of commercial products

Sensors/Actuators presented on the plan:

Symbol	Sensor/Actuator	Location details
● (dark red)	Wink Window Sensor	on the window frame
● (orange-yellow)	Philips Dynalite Sensor DUS360CS	mounted on the ceiling, max. detection area = 5,5 m x 7,0 m
● (orange)	Philips Dynalite Sensor DUS90AHB-DALI	mounted on the top of the wall, max. detection area = 1,75 x h
● (yellow)	Netatmo Weather Station (indoor module)	placed in the rooms where windows are presented, far from the windows
● (green)	Wi-Fi Honeywell thermostat	mounted on the wall, height= 1,50 m

Sensors/Actuators non presented on the plan:

Sensor/Actuator	Location details
Bali RTS Motorized Window Treatment	on the top of the window frame (indoor)
HCC80R Honeywell Underfloor Heating Controller	within or outside the distributor box
MT8 Small Linear Thermoelectric Actuator	on the valve of every circuit of heating/cooling system
Netatmo Weather Station (outdoor module)	outdoor (in the garden), at least 1 m distance from any indoor module
Netatmo Wind Gauge	on the top of the roof
DripView Smart Water sensor	mounted on top of existing water meter
Philips 929001173761 Hue Smart Wireless Dimmer Switch	mounted in the place of existing switches
mydlink Home Smart Plug DSP-W215	attached to every electrical socket
Eco-worthy Stocke Linear Window Actuator	between the window frames

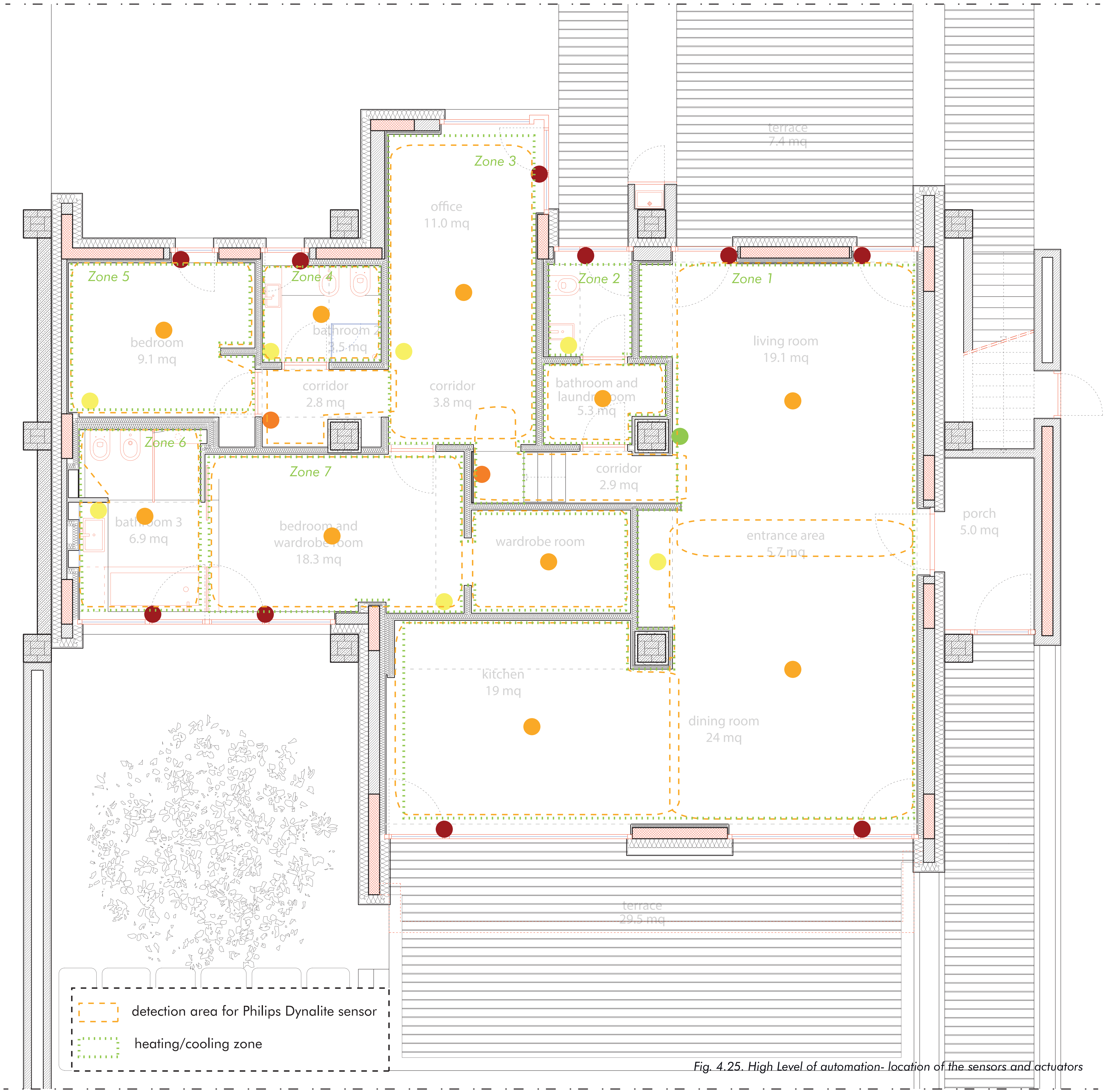


Fig. 4.25. High Level of automation- location of the sensors and actuators

Summary of quantity and costs of sensors and actuators for Kit I_High Level of Automation

Sensor/Actuator	Price/pc (EUR)	Quantity	Total price (EUR)
Wink Hub 2	75,98	1	75,98
Wink door/window sensor	25,00	10	250,00
Philips Dynalite Sensor DUS360CS	153,77	10	1537,7
Philips Dynalite Sensor DUS90AHB-DALI	206,95	2	413,90
Philips Hue White A19	10,77	12*	129,27
Bali RTS Motorized Window Treatment	49,13	15	736,95
Philips Lighting Dimmer	24,99	12*	299,80
Wi-Fi Honeywell thermostat ATP921R3118	241,00	1	241,00
HCC80R Honeywell Underfloor Heating Controller	312,60	1	312,60
MT8 Small Linear Thermoelectric Actuator (for every circuit)	40,18	16	642,88
Netatmo Weather Station (outdoor module)	59,99	1	59,99
Netatmo Weather Station (indoor module)	69,99	7	489,93
Netatmo Wind Gauge	99,99	1	99,99
DripView Smart Water sensor	not available	1	not available
mydlink Home Smart Plug DSP-W215	50,99	8*	407,92
Eco-worthy Stocke Linear Window Actuator	67,77	10	677,70

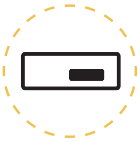
** estimated quantity*

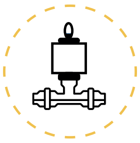
Total price of High Level Automation system: 6688,31
(without the price of DripView Water Sensor)

2- KIT II_Medium Level of Automation

For the Medium Level of Automation, there is considered higher level of occupant interaction comparing to Kit I. There is no sensor and actuator for window state control, so the system will send an information to the occupant is any action will be neccessary. The examples of products which can be used for Medium Level of Automation network are following:


Wi-Fi Honeywell thermostat


HCC80R Honeywell Underfloor Heating Controller


MT8 Small Linear Thermoelectric Actuator (Smart Valve)

For Medium Level of Automation Wink ecosystem is proposed as well. However, actuators are only limited to lighting dimmers. The system will send an information if any action will be neccessary- like windows opening/ closing or adjustment of window blinds.


Wink Hub 2


Philips Dynalite Sensor


Philips Hue white bulb A19


Philips Lighting Dimmer for Philips Hue

Xiaomi Corporation is quite new company, born in China (first realased product in 2011). In last years Xiaomi has expanded into developing a wider range of consumer electronics, including a smart home (IoT) device ecosystem. Nowadays, Xiaomi is rapidly exapanding to other countries, including european market. In Italy, the first store was opened in May 2018 in Milan. For medium level of automation kit following Xiaomi products were proposed:

Xiaomi Smart Multifunctional Gateway

The hub to connect all Xiaomi sensors and actuators.

Xiaomi mi smart WiFi socket

Xiaomi mi smart WiFi socket is a multi-purpose Smart Plug, which allows to monitor and control home's electronic appliances. Using the application, it is possible to turn appliances on or off, monitor energy usage of connected appliances, create on/off schedules and set up alerts.
10 A, max. 250 V

Xiaomi Mi Smart Temperature and Humidity Sensor

Detect in real time the temperature and humidity levels. Temperature range: from -20°C up to +60°C.

Xiaomi Mijia Honeywell Fire & CO_2 Detector

Detects smoke and CO_2 levels.

DarkSky Web Service

According to the list made previously (Medium Level of Automation- variabiles to monitor), some outdoor variabiles, like air temperature, solar radiation and level of CO_2, should be monitored as well in case of Kit II. However, to limit cost of the whole automation system, it is possible to obtain those meteorological parameters using one of the numerable web services. One example of web services is DarkSky Web Service, which is compatible with Home Assistant.

DripView Smart Water Sensor

The same as for Kit I, the DripView sensor is proposed to control the water consumption.

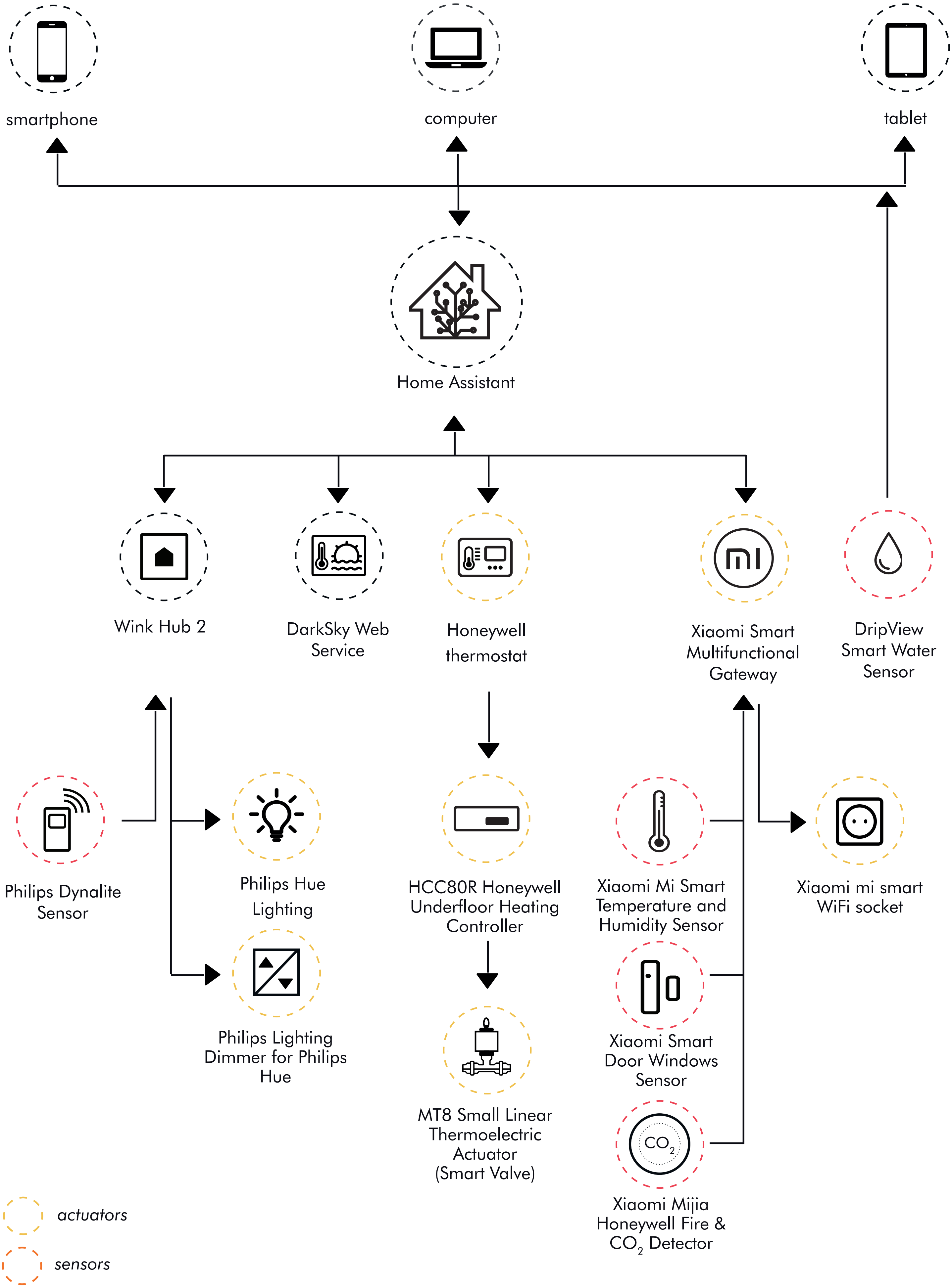


Fig. 4.26. Example of medium level automation network for Cortau House with implementation of commercial products

Sensors/Actuators presented on the plan:

Symbol	Sensor/Actuator	Location details
●	Xiaomi Smart Door Windows Sensor	on the window frame
●	Philips Dynalite Sensor DUS360CS	mounted on the ceiling, max. detection area = 5,5 m x 7,0 m
●	Philips Dynalite Sensor DUS90AHB-DALI	mounted on the top of the wall, max. detection area = 1,75 x h
●	Xiaomi Mi Smart Temperature and Humidity Sensor	placed on the wall in the rooms where windows are presented, far from the windows
●	Xiaomi Mijia Honeywell Fire & CO_2 Detector	in the center of the ceiling, only in rooms with higher level of occupancy
●	Wi-Fi Honeywell thermostat	mounted on the wall, height= 1,50 m

Sensors/Actuators non presented on the plan:

Sensor/Actuator	Location details
HCC80R Honeywell Underfloor Heating Controller	within or outside the distributor box
MT8 Small Linear Thermoelectric Actuator	on the valve of every circuit of heating/cooling system
DripView Smart Water sensor	mounted on top of existing water meter
Philips 929001173761 Hue Smart Wireless Dimmer Switch	mounted in the place of existing switches
Xiaomi mi smart Wi-Fi socket	attached to principal electrical sockets (washing machine, fridge, oven, dishwasher)

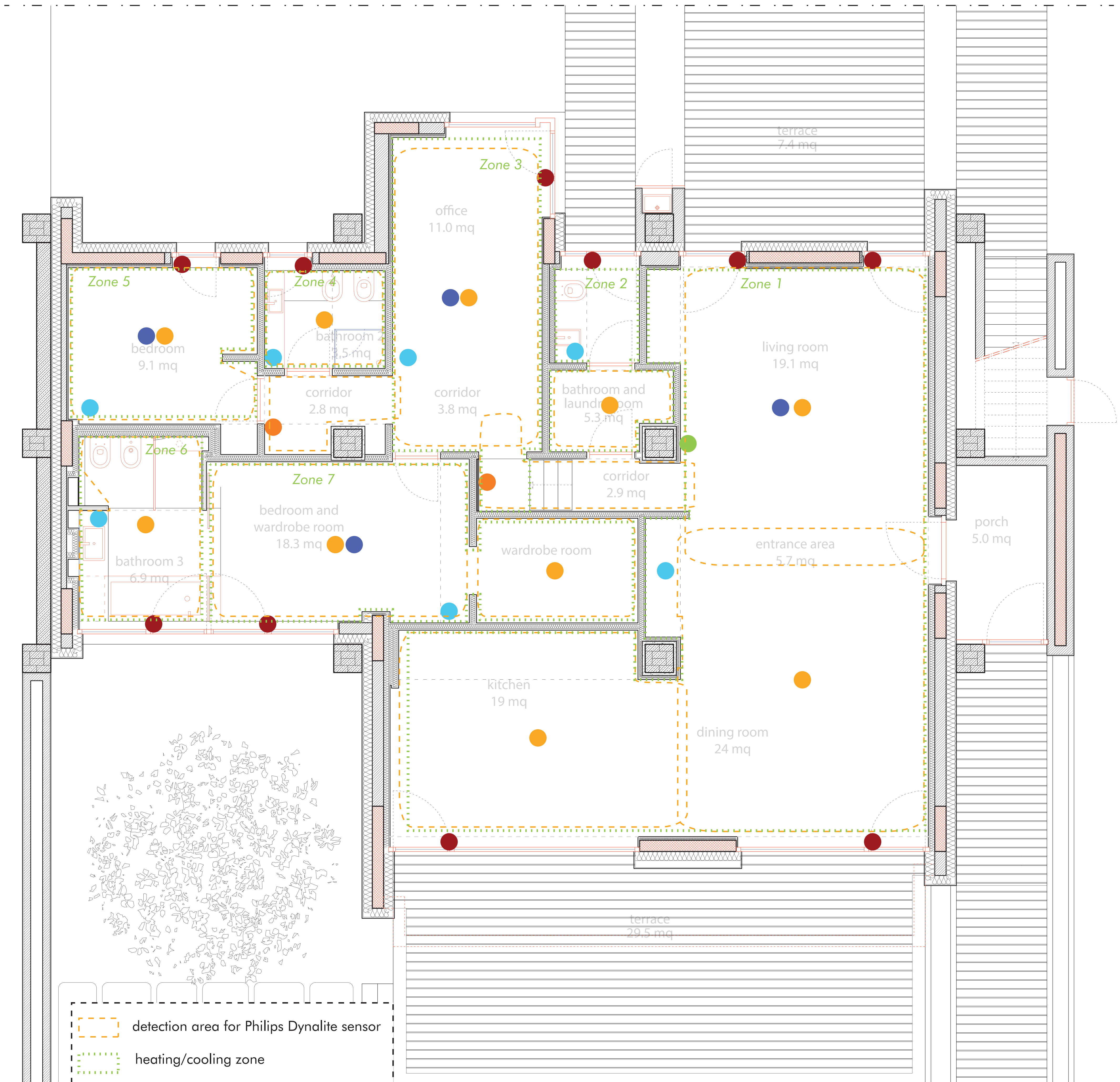


Fig. 4.27. Medium Level of automation- location of the sensors and actuators

Summary of quantity and costs of sensors and actuators for Kit II_Medium Level of Automation

Sensor/Actuator	Price/pc (EUR)	Quantity	Total price (EUR)
Wink Hub 2	75,98	1	75,98
Philips Dynalite Sensor DUS360CS	153,77	10	1537,7
Philips Dynalite Sensor DUS90AHB-DALI	206,95	2	413,90
Philips Hue White A19	10,77	12*	129,27
Philips Lighting Dimmer	24,99	12*	299,80
Wi-Fi Honeywell thermostat ATP921R3118	241,00	1	241,00
HCC80R Honeywell Underfloor Heating Controller	312,60	1	312,60
MT8 Small Linear Thermoelectric Actuator (for every circuit)	40,18	16	642,88
DripView Smart Water sensor	not available	1	not available
Xiaomi Smart Multifunctional Gateway	23,35	1	23,35
Xiaomi Mi Smart Temperature and Humidity Sensor	11,43	7	80,01
Xiaomi mi smart WiFi socket	20,82	4	83,28
Xiaomi Smart Door Windows Sensor	12,98	10	129,80
Xiaomi Mijia Honeywell Fire & CO_2 Detector	25,95	4	103,80

* *estimated quantity*

Total price of High Level Automation system: 4020,17
(without the price of DripView Water Sensor)

3- KIT III_Low Level of Automation

According to the classification made previously, for Low Level of Automation there is need to monitor only few variabiles and only in significant points. The proposed sensors (temperature, humidity, light intensity and motion detection) and actuators (Smart Sockets and Smart Bulbs) were all choosen from the Xiaomi company.

The informations about outdoor environmental variabiles (temperature) will be acquired trough DarkSky Web service, similary as in the case of Kit II.
The chosen products are following:

Xiaomi Smart Multifunctional Gateway

Xiaomi mi smart WiFi socket

Xiaomi Aqara Body & Light Intensity Sensor

Xiaomi Mi Smart Temperature and Humidity Sensor

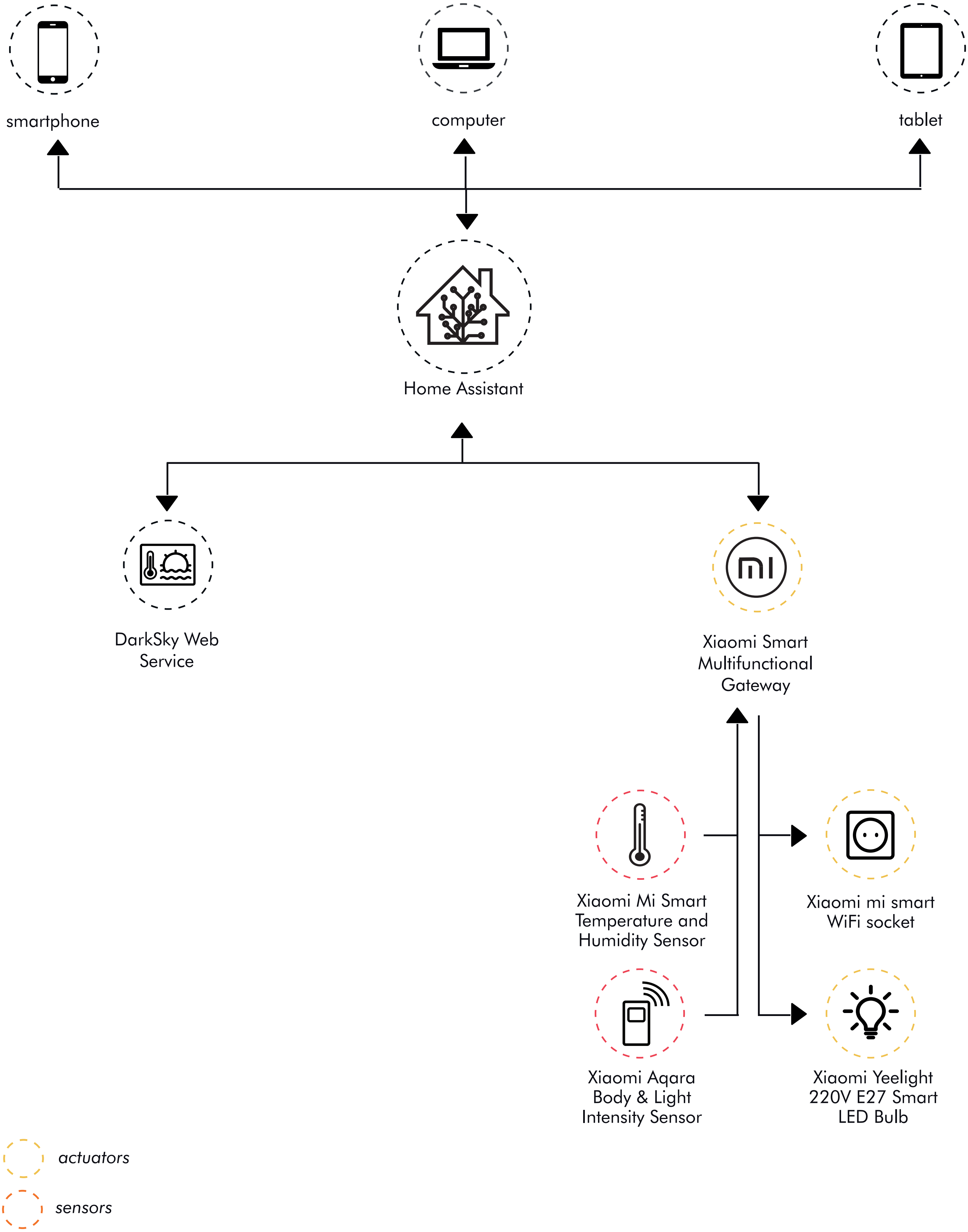


Fig. 4.28. Example of low level automation network for Cortau House with implementation of commercial products

Sensors/Actuators presented on the plan:

Symbol	Sensor/Actuator	Location details
(blue circle)	Xiaomi Mi Smart Temperature and Humidity Sensor	placed on the wall in the rooms where windows are presented, far from the windows
(purple circle)	Xiaomi Aqara Body & Light Intensity Sensor	placed on the wall, max. range = 7 m, 170 °

Sensors/Actuators non presented on the plan:

Sensor/Actuator	Location details
Xiaomi mi smart Wi-Fi socket	attached to electrical socket of washing machine
Xiaomi Smart Multifunctional Gateway	on the any not cluttered surface
Xiaomi Yeelight 220V E27 Smart LED Bulb	In place of existing light bulbs

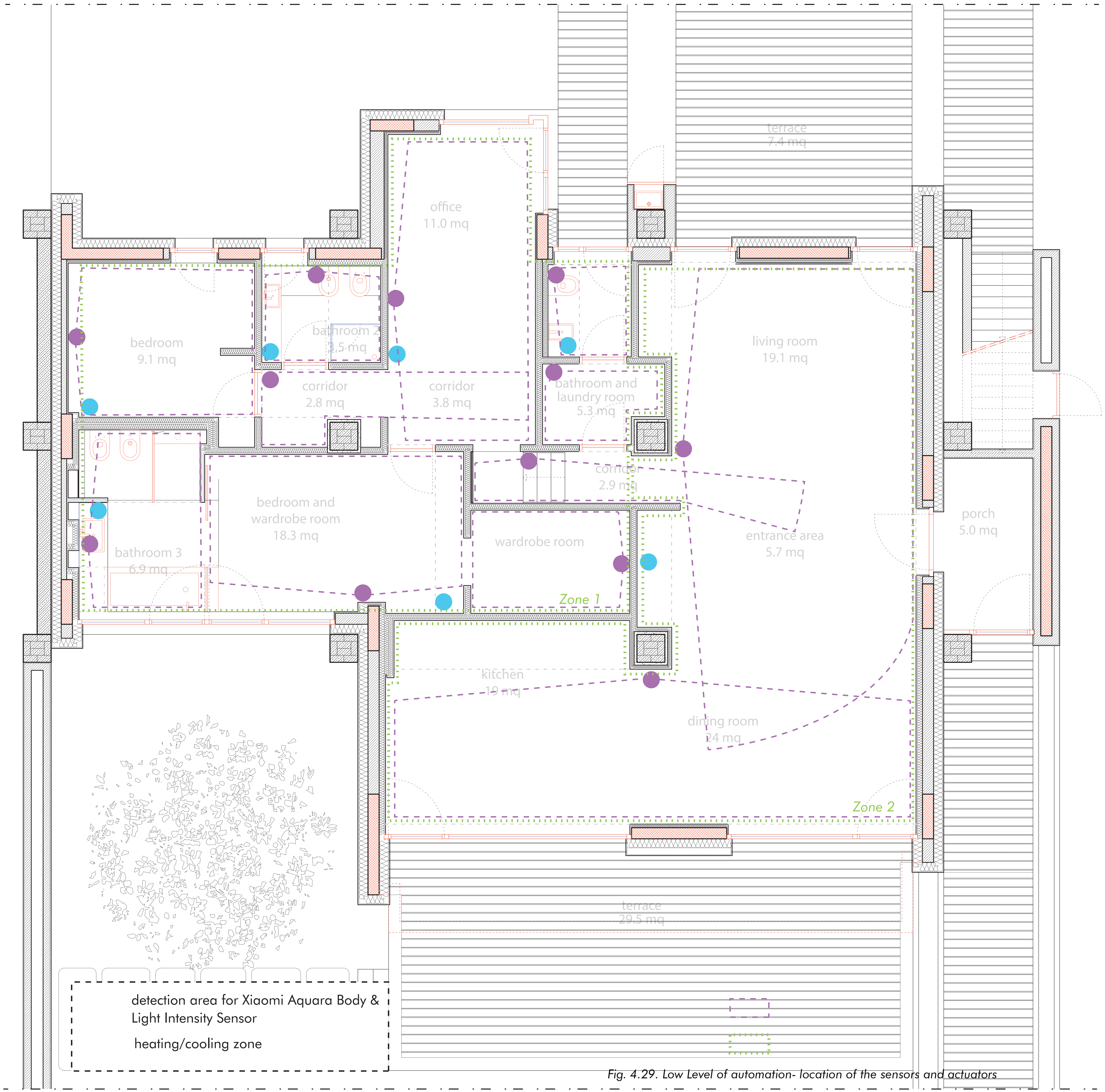


Fig. 4.29. Low Level of automation- location of the sensors and actuators

Summary of quantity and costs of sensors and actuators for Kit III_Low Level of Automation

Sensor/Actuator	Price/pc (EUR)	Quantity	Total price (EUR)
Xiaomi Smart Multifunctional Gateway	23,35	1	23,35
Xiaomi Mi Smart Temperature and Humidity Sensor	11,43	7	80,01
Xiaomi mi smart WiFi socket	20,82	1	20,82
Xiaomi Aqara Body & Light Intensity Sensor	16,34	11	179,74
Xiaomi Mijia Honeywell Fire & CO_2 Detector	25,95	4	103,80

Total price of High Level Automation system: 407,82
(without the price of DripView Water Sensor)

CHAPTER NO. 5

Conclusions

5.1. To sum up

The industrialization has the big impact on climate changes. Nowadays, building sectors are one of the main responsible for global CO2 emissions- it consumes more than one-third of total primary energy in the world. Moreover, in the European Union countries, only residential sector is responsible for more than one-fourth final energy consumption. One of the main internal factors influencing the energy consumption is the occupant behaviour. People usually spend most of their lifetime within the buildings and so they need to make the indoor environment comfortable by heating, cooling, ventilation and illumination, using a large amount of natural resources. As a consequence, building energy consumption will be increasingly dependent on the occupants' control of their indoor environmental conditions. For this reason, a deep understanding and forecasting of occupants' behaviour and modelling energy-related occupants' activities throughout the day are crucial to evaluate their impact on the energy consumption and indoor quality performances.

The most accurate way to obtain information about occupant behaviour is monitoring. Trough monitoring of building systems it is possible to obtain informations about the relationship between monitored building systems states (like heating on/off or window open/closed), indoor and outdoor environmental variables, occupant behaviour and energy consumption of the building. There are two available approaches which can be used to obtain information about energy-related occupant behaviour in buildings: field monitoring and questionnaires and self-reporting. When it is not possible monitor directly in the field or when it is necessary to analyse the occupant behaviour in wider scale, the most suitable way to acquire information are surveys.

In line with those considerations, the present master thesis aimed to investigate on the occupant behaviour in the north-Italian dwellings trough use of the survey questionnaires. The results of the questionnaire survey provided new insights on factors influencing occupant behaviour in north-Italian dwellings. What has emerged from the survey analysis is that occupants' preferences for indoor environmental conditions and their interaction with building systems vary significantly from person to person and may depend on many driving forces, as social drivers (i.e. household income, children presence), physiological drivers (i.e. age of the occupant) or building characteristics (i.e. configuration of heating system). Especially, it was found that the occupants tend to overheat the dwellings during the winter and that the temperature set-point increases together with the number of dwelling member and when the children are present. Moreover, it was found that households with lower income tend to use less energy for keeping warm in the winter. The temperature set-point may depend as well on configuration of the heating system (central or independent) and may increase when the dwelling is rented. Additionally, the results highlighted that occupants are often not aware about their influence on the energy consumption in the dwelling (i.e. significant part of the respondents tend to open windows when the heating or mechanical ventilation systems are active). Finally, two energy-related activities profiles were established- the weekdays and weekends in the summer period. The daily profiles of ten energy- and occupancy-related activities were compared to the hourly mean power profile of an example Italian residential building. It was found that those activities (i.e. cooking) may have an important impact on the overall energy consumption in building. Moreover the daily activity profiles were different depending on the day of the week (weekdays and weekends).

The answer to an energy-intensive occupant behaviour may be Home Automation. Automation, control and supervision systems may have a significant impact on the energy performance of a building and on the comfort of occupants and they may reduce energy consumption even up to 50%. Building automation could help reaching the nearly Zero Energy target in a building, or at least in decreasing building energy demand by balancing energy losses, internal gains and energy needs, with particular regard to the optimization of the balance between heating and cooling needs. The implementation of such systems allows obtaining a Smart Energy Home, where appropriate building automation systems work together in order to provide an effective control of lighting, heating, ventilation and air conditioning systems, which is essential to guarantee a healthy, safe working and productive indoor environment. The automatic control should guarantee minimum acceptable conditions with the possibility of manual adjustment (override) of conditions to reach the occupants' needs.

The analysis were applied to a Case Study, the so-called CorTau House. Basing on the case study parameters, it was possible to distinguish all variables necessary to monitor in a Smart Home. After the definition of variables to monitor it was possible to speculate three possible levels of home automation system (high, medium, low) for the CorTau House, all characterised by different costs and different level of occupant interaction with building systems.
Moreover, with the use of the above-mentioned time use survey, compiled by CorTau House's occupants, it was possible to determine schedules different occupants' actions- occupancy profile, sleeping schedule and use of the lighting system schedule, with the division on different day of week (weekday and weekend). Thanks to above-mentioned schedules it was possible to develop control logics which not only are focused on the energy savings, but also are taking in consideration the preferences and habits of Cortau House's occupants.
Finally, after the analysis of the current market offer in the field of home building automation it was found that the implementation of fully automated and integrated control systems is still quite difficult to implement and the price of this kind of investment may not be accessible for everyone. However, with implementation of basic network of sensors and actuators it is already possible to obtain a satisfactory control system.

In conclusion, the thesis investigated that home automation is a promising solution for improving building performances. Surely, energy demands may be reduced not only thanks to the implementation of building automation systems, but also by encouraging a more aware occupants' interaction with the dwelling itself. Only with the combination of these two aspects, it is possible to truly achieve and operate Smart Energy Buildings with low energy needs and high performances.

References

[1] *Causes of climate change*, https://ec.europa.eu/clima/change/causes_en
[2] *CO_2 and other Greenhouse Gas Emissions*, https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#empirical-view
[3] *Global warming*, http://www.bbc.co.uk/schools/gcsebitesize/science/aqa_pre_2011/rocks/fuelsrev6.shtml
[4] *A brief history of climate change policy,* https://www.soas.ac.uk/cedep-demos/000_P524_CCD_K3736-Demo/unit1/page_14.htm
[5] *The Kyoto Protocol, Essence and Goals*, https://www.mtholyoke.edu/~danov20d/site/goals.htm
[6] *2020 climate & energy package*, https://ec.europa.eu/clima/policies/strategies/2020_en
[7] *Directive 2010/31/EU on the energy performance of buildings (recast) - 19 May 2010,* http://www.buildup.eu/en/practices/publications/directive-201031eu-energy-performance-buildings-recast-19-may-2010
[8] *IEA-EBC Annex 66,* https://www.annex66.org/
[9] *IEA ECBS Annex 45 - Energy Efficient Electric Lighting for Buildings,* http://www.buildup.eu/en/explore/links/iea-ecbs-annex-45-energy-efficient-electric-lighting-buildings
[10] *Summary of the Copenhagen Climate change Conference,* http://enb.iisd.org/vol12/enb12459e.html
[11] *Paris COP 21: Key Issues for the New Climate Agreement,* https://www.climatecouncil.org.au/uploads/de494149f16b3b235d8fa74fb8a9c52d.pdf
[12] *Consumption of energy, Eurostat- Statistics Explained,* https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Consumption_of_energy
[13] L. Peréz-Lombard, J. Ortiz, C. Pout, *A review on buildings energy consumption information*, Energy and Buildings 40 (2008), 394-398
[14] *Energy consumption in households*, https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households
[15] *Total Energy Use in Buildings: Analysis and Evaluation Methods (Annex 53)*, Energy in Buildings and Communities Programme (2016)
[16] C. Seligman, J.M. Darly, L.J. Becker, *Behavioral approaches to residential energy conservation*, Energy and Buildings 1 (1997/98), 325-337
[17] A.S. Bahaj, P.A.B. James, *Urban energy generation: the added value of photovoltaics in social housing*, Renewable and Sustainable Energy Reviews 11 (2007), 2121-2136
[18] O.T. Masoso., L.J. Grobler, *The dark side of occupants' behaviour on building energy use*, Energy and Buildings 42 (2010), 173-177
[19] V. Fabi, S. P. Corgnati, R. V. Andersen, M. Filippi, B. W. Olesen, *Effect of occupant behaviour related influencing factors on final energy end uses in building*, Asociacìon y Técnicca Espagnola de Climatizacìon y Refrigeracìon (2011)
[20] Y. Jian, Y. Guo, J. Liu, Z. Bai, Q. Li, *Case study of window opening behavior using field measurement results*, BUILD SIMUL (2011) 4, 107-116
[21] F. Haldi, D. Robinson, *On the behaviour and adaptation of office occupants*, Building and Environment 43 (2008), 2163-2177
[22] S. Shi, B. Zhao, *Occupants' interactions with windows in 8 residential apartments in Beijing and Nanjing, China*, BUILD SIMUL (2016) 9, 221-231
[23] A. Roetzel, A. Tsangrassoulis, U. Dietrich, S. Busching, *A review of occupant control on natural ventilation*, Renewable and Sustainable Energy Reviews 14 (2010), 1001–1013
[24] C. Peng, D. Yan, R. Wu, C. Wang, X. Zhou, Y. Jiang, *Quantitative description and simulation of human behavior in residential buildings*, BUILD SIMUL (2012) 5, 85–94
[25] C. Dubrul, *Inhabitant Behaviour with Respect to Ventilation*, A Summary Report of IEA Annex VIII, in: AIVC Technical Note 23, Air Infiltration and Ventilation Centre (1988)
[26] J. F. Nicol, *Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans*, Proceedings of the seventh international IBPSA conference, Rio (2001), 1073-1078
[27] O. Guerra Santin, L. Itard, H. Visscher, *The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock*, Energy and Buildings 41 (2009), 1223–1232
[28] M. Indraganti, R. Ooka, H. B. Rijal, G. S. Brager, *Drivers and barriers to occupant adaptation in offices in India*, Architectural Science Review, 2015, Vol. 58, No. 1, 77–86.
[29] K. Gram-Hanssen, *Residential heat comfort practises: understanding users, Building Research & Information*, 38:2 (2010), 175-186.
[30] S. Chen, W. Yang, H. Yoshino, M. D. Levine, K. Newhouse, A. Hinge, *Definition of occupant behavior in residential buildings and its application to behavior analysis in case studies*, Energy and Buildings 104 (2015), 1–13
[31] E. Vine, *Saving Energy the easy way: an analysis of thermostat management*, Lawrence Berkeley Laboratory (1987)

[32] V. Fabi, R. V. Andersen, S. P. Corgnati, I*nfluence of occupant's heating set-point preferences on indoor environmental quality and heating demand in residential buildings*, HVAC&R Research, 19:5 (2013), 635-645
[33] D. L. O. Tachibana, *Residential Customer Characteristics Survey 2009*, Planning, Research & Evaluation Conservation Resources Division (2010)
[34] D. R. G. Hunt, M. I. Gidman, *A national field survey of house temperatures*, Buildings and Environment 17 (2) (1982), 107-124
[35] A. J. Summerfield, R. J. Lowe, H. R. Bruhns, J. A. Caeiro, J. P. Steadman, T. Oreszczyn, Milton Keynes, *Energy Park revisited: changes in internal temperatures and energy usage*, Energy and Buildings 39 (7) (2007), 783-791
[36] S. Lutzenhiser, J. Peters, M. Moezzi, J. Woods, *Beyond the Price Effect in Time-of-Use Programs: Results from a Municipal Utility Pilot, 2007-2008*, Lawrence Berkeley National Laboratory (2010)
[37] O. Guerra-Santin, L. Itard, *Occupants' behaviour: determintants and effects on residential heating consumption*, Building Research and Information 38 (3) (2010), 318-338
[38] H.-C. Liao, T.-F. Chang, *Space heating and water-heating energy demands of the aged in the US*, Energy Economics 24 (3) (2002), 267-284
[39] W. F. van Raaij, T. M.M. Verhallen, *A behavioral model of residential energy use*, Journal of Economic Psychology, 3(1) (1983), 39-63.
[40] R. V. Andersen, J. Toftum, K. K. Andersen, B. W. Olsen, *Survey of occupant behaviour and control of indoor environment in Danish Dwellings*, Energy and Buildings 41 (2009), 11–16
[41] H. Wilhite, H. Nakagami, T. Masuda, Y. Yamaga, H. Haneda, *A cross-cultural analysis of household energy use behaviour in Japan and Norway*, Energy Policy 24 (9) (1996), 795-803
[42] ANSI/ASHRAE Standard 55-2010, *Thermal Environmental Conditions for Human Occupancy*, Tullie Circle NE, Atlanta (2010)
[43] *Human Thermal Comfort Part-1*, https://knowledge.autodesk.com/search-result/caas/simplecontent/content/human-thermal-comfort-part-1.html
[44] *The Integrated Strategic Energy Technology (SET) Plan*, The EU's Energy Union strategy, 2015.
[45] N. Balta-Ozkan, B. Boteler, O. Amerighi, *European smart home market development: Public views on technical and economic aspects across the United Kingdom, Germany and Italy,* Energy Research & Social Science 3 (2014), 65–77
[46] V. Fabi, G. Spiglianti. S. P. Corgnati, *Insights on Smart Home Concept and Occupants' Interaction with Building Controls*, Energy Procedia 111 (2017), 759 – 769
[47] T. Hong, , S. D'Oca, W. J.N. Turner, S. C. Taylor Lange, *An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs framework*, Building and Environment 92, (2015), 764-777
[48] T. Hong, S. D'Oca, S. C. Taylor-Lange, W. J. N. Turner, Y. Chen, S. P. Corgnati, *An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAS framework using an XML schema*, Building and Environment 94 (2015), 196-205
[49] S. D'Oca, S. P. Corgnati, A. L. Pisello, T. Hong, *Introduction to an occupant behavior motivation survey framework*, Ernest Orlando Lawrence Berkeley National Laboratory, Energy Technologies Area (2016)
[50] R. V. Andersen, J. Toftum, K. K. Andersen, B. W. Olesen, *Survey of occupant behaviour and control of indoor environment in Danish dwellings*, Energy and Buildings 41, (2009), 11-16
[51] M. Frontczak, R. V. Andersen, P. Wargocki, *Questionnaire survey on factors influencing comfort with indoor envionmental quality in Danish housing*, Building and Environment 50 (2012), 56-64
[52] K. P. Lam, *Sustainability Performance Simulation Tools for Building Design,* In: Meyers R.A. (eds) Encyclopedia of Sustainability Science and Technology. Springer, New York, NY (2012)
[53] V. M. Barthelmes, R. K. Andersen, Y. Heo, H. Knudsen, V. Fabi, S. P. Corgnati, *Introducting thermal comfort attitudes, psychological, social and contextual drivers in occupant behaviour modelling with Bayesian Networks*, Proceedings of 10th Windsor Conference: Rethinking Comfort, Windsor, UK (2018)
[54] V. M. Barthelmes, R. Li, R. K. Andersen, W. Bahnfleth, S. P. Corgnati, C. Rode, *Profilig Occupant Behaviour in Danish Dwellings using Time Use Survey Data- Part I: Data Description and Activity Profiling*, 4th International Conference on Building Energy, Environment, COBEE2018-1-46, Melbourne, Australia (2018),
[55] A. Capozzoli, S.P. Corgnati, M. V. Di Nicoli, V. Fabi, M. S. Piscitelli, G. Spigliantini, *Attività di monitoraggio energetico e ambientale, diagnostica ed Energy Engagement degli utenti degli use case*, Report Ricerca di Sistema Elettrico RdS/PAR2016/008 (2017)
[56] A. Capozzoli, S. P. Corgnati, V. Fabi, F. Lauro, G. Spigliantini, *Sviluppo di metodologie di aggregazione e benchmarking dei dati energetici di rete di edifici e modelli di feedback per il coinvolgimento degli utenti residenziali*, Report Ricerca di Sistema Elettrico RdS/2015/021 (2016)
[57] C. Aghemo, J. Virgone, G.V. Fracastoro, A. Pellegrino, L. Blaso, J.Savoyat, Kevyn Johannes, *Managmentand monitoring of public buildings through ITC based system: Control rules for energy saving with lighting and HVAC sevices*, Frontiers of Architectural (2013), Elsevier

Attachments

Attachment 1
Survey „Occupant behaviour in residential buildings"- english version
Attachment 2
Paper „Effect of occupant behaviour on the energy consumption. Smart Homes and occupants' interaction with building control. Survey of data acquisition technologies for a Smart Home"

Attachment 1

Survey „Occupant behaviour in residential buildings"- english version

Attachment 2

Paper „Effect of occupant behaviour on the energy consumption. Smart Homes and occupants' interaction with building control. Survey of data acquisition technologies for a Smart Home"