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UNIVERSITY MASTER IN RESEARCH IN ENERGY EFFICIENCY AND SUSTAINABILITY IN INDUSTRY, TRANSPORTATION, BUILDING AND URBAN PLANNING

MASTER THESIS

INFLUENCE OF ZONING AND CONTROL OF INDIVIDUAL HEATING SYSTEMS ON COMFORT AND ENERGY CONSUMPTION OF RESIDENTIAL BUILDINGS

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SUMMARY

Thermal zoning control can be appropriate solution to simultaneously ensure thermal comfort and to reduce the energy consumption through differential heating/cooling. The topic of the master research project is Influence of zoning and control of individual heating systems on the comfort and the energy consumption of residential buildings. This work presents the study of a single family house located near Vitoria Gasteiz. The concept supports the increase in energy efficiency and indoor comfort for occupants by dividing the house for thermal zones.

The work proposes modeling of patterns using the building modelling software Design Builder. 49 scenarios – a thermal zones, which consist of basic zonal control, it is also called conventional system control. This zonal control consists of whole house thermostat setpoint located in the kitchen or in living room that allows to maintain the constant setpoint temperature. And zonal control: each zone or floor has individual thermostat setpoint. For some zonal control were applied TRVs or PTRV control on radiators. In total there are five zonal controls in this work. For all type of control systems different set-point temperature scenarios were: 18°C, 20°C, 22°C; the individual heating system and different type of boilers; and occupancy profiles were proposed.

After the simulations, the obtained results were compared, analyzed in detail and the energy and economic saving were determined. It is necessary to obtain the most energy and economy efficient option while maintaining comfortable indoor conditions. These results show that proposed scenarios could be an energy and cost-effective strategies at the same time providing the inner comfort. According to the results maximum energy saving of around 70% (corresponds to scenarios of zonal control Z5) and energy saving of about 50%-70% (coincides to Z4) are obtained. These zonal controls are equipped by TRVs. Concerning to heating system, condensing modulating boiler at set-point temperature of 18°C has highest energy saving of 93,5% for occupancy profile O1 (occupancy all day, set-point temperature 17°C for night, 4 person), although this set-point temperature is not considers as comfortable, but set-point temperatures of 20°C and 22°C are.

Keywords: Occupancy patterns, zonal heating control, heating energy consumption, control of the comfort in the buildings

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ACRONYMS AND ABBREVIATIONS

DWH – domestic hot water
HVAC - Heating, ventilation, and air conditioning
IEA – International Energy Agency
PTRV - programmable thermostatic radiator valves
STBC – Spanish technical building code
TRV - thermostatic radiator valve

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1. INTRODUCTION AND BACKGROUND

The energy problem was and remains the first of the top ten global concerns, therefore, plenty of researches are dedicated to identifying novel, efficient and affordable solutions to increase the total energy savings. Currently, one of the largest consumer energy sectors worldwide is the buildings sector. Buildings consume approximately 45% of primary energy resources globally |1|. The HVAC (Heating, Ventilation and Air Conditioning) and illumination systems in buildings are the main consumers of energy.

There are many ways to achieve energy savings in the buildings, one of them and considered in this study is the energy control and management, in some cases applying new technologies. It plays an important role in energy savings and can significantly reduce energy consumption. A literature review of different studies shows the achievement of the energy saving, the cost effectiveness, the indoor comfort by applying cooling and heating control which were classified for (a)conventional heating control with the whole house thermostat, room thermostat, thermostatic radiator valves (TRVs) **3.** *1*; (b)zonal heating control or multi-zone controls including TRVs, smart and programmable thermostats (PTRVs)…; such systems have concepts to control thermal comfort, illuminance, carbon dioxide concentration etc. **3. 2**; (c) novel advanced technologies and approaches to simultaneously provide energy efficiency and comfort etc. **3. 3**; (d)a hybrid control scheme (district heating system with distributed variable speed pumps) **3. 4**.

This study considers a review of over 100 documents regarding energy savings, achievement of comfort and reports 30 references, including residential, office, commercial buildings located in different parts of the world and with different climate conditions.

A comparative study of individual heating control system, thermal zoning and their influence on comfort and energy consumption is presented. The concept supports the increase in energy efficiency and indoor comfort for occupants by dividing the house in thermal zones controlled by temperature setpoint control.

The heating control has the potential to reduce the fuel used for space heating, which in 2019 accounts for 14.580 ktoe of total energy use in the Spanish residential sector |2|. Average consumption according to Type of Housing is 1,334 toe energy use for family houses and 0,649 toe – for flats |3|. Final energy consumption of the Basque Country in total is 5.284 ktoe and residential sector accounts for 581ktoe in 2017|4|. In **Figure 1 (a)** the energy consumption of each province of Basque Country is shown and **Figure 1 (b)** shows the energy consumption by type of energy in Basque Country. However, K. J. Lomas and al. studied the answer on the question ´´Do domestic heating controls save energy?´´ with a review of the systematic and critical international review of the evidence for the energy saving, cost effectiveness and usability of heating controls |5|. Eleven different types of standard, advanced and smart controls are assessed. Focusing in domestic, low-pressure hot water heating systems in temperate climates. The researchers came to the conclusion, for most control types, that, the quality of the evidence for energy savings was low, very low or non-existent. However, zonal controllers could be cost-effective compared to whole-house controllers. There was moderate quality evidence that smart thermostats do not save energy compared to standard thermostats and programmers and may, in fact, increase energy demand.

Final energy consumption of the Basque Country by types of energy.(ktoe)2017 (a)

Total	Coal and derivatives	Derivative of the oil	Natural Gas	Derivative energy	Renewable energy	Electric energy
5.284	37	2.323	1.326	16	342	1.240

Final energy consumption of the Basque Country by provinces.(ktoe) (b)

Araba/Álava	Bizkaia	Gipuzkoa
1.115	2.188	1.982

Figure 1. Final energy consumption of the Basque Country

In this study a three-level single family house near Vitoria Gasteiz is used as a case study. To achieve energy savings, as well as internal comfort in this house, it is proposed to study 49 scenarios, which will be obtained with help of Design Builder modeling, applying the individual heating system with different type of boilers and three different setpoint temperature (see detailed information in **4.3. 1**); with different zonal temperature control (see **4.3. 3**). Also, for scenarios taking into account the air temperature and 3 assumed occupancy schedules; heating operation for individual heating system and for the TRVs control are defined and shown in section **4.3. 2**.

After the simulations, the energy and cost-efficient results will be obtained, compared, analyzed in detail and the energy and economic saving will be determined.

It is expected to determine the most energy and economy efficient option or options while maintaining comfortable indoor conditions.

Previous studies can be found in this field. A group of researchers presented for an apartment in Beijing three kinds of heating modes A, B, C. Also mathematical model of the apartment was developed to study the heating energy consumption and thermal environment. Two of these modes had decrease of energy consumption for 4.24% and 14.73%, respectively |6|.

The effects of two different zoning controls of different types of apartment, occupancy patterns, building characteristics and location in Spain, have been assessed. The simulation of 336 scenarios using Design Builder software was assessed and cost-effective strategy aimed to reduce the energy consumption was analyzed in |7|. The obtained results have saving of around 20% for the most of scenarios. In |8| it is possible to observe the feasibility of individual natural gas fired boiler-based heating systems in the retrofitting of buildings constructed in the 50–60 s in Bilbao (northern Spain). 54 different scenarios are evaluated, which arise from the combination of 3 different envelope options, 2 types of heat production units, 3 heat production temperatures and 3 comfort temperature set-points. The cases are evaluated in terms of energy results, economic aspects, and the influence of user behaviour. The energy saving about 10% when condensing boilers are compared with high efficiency boilers. 5 -10% of energy saving in relation to hot water production temperature. And the greatest reduction of energy consumption up to 89% is related to the indoor occupants' behaviour.

In the future it is planned to suggest developments and their potential research significance related to the new thermal zoning method with more advanced thermostatic valves for example as smart and programmable thermostats: the battery operated PTRV (programmable thermostatic radiator valves) replacing normal TRV. PTRV have motorized valves to either enable or disable the hot water flow through the radiators according to a set-point temperature and time schedule. These can be set on the PTRVs themselves, via a central controller which communicates wirelessly with the PTRVs, or even remotely via a mobile phone or computer in some products. These options can be very efficient.

2. OBJECTIVES AND SCOPE OF WORK

The idea of this research project is to determinate or achieve the maximum cost effective and energy efficient, with comfortable indoor temperature conditions for the occupants option, among the proposed scenarios by using the energy performance simulation tools and applying the heating system with different types of boiler, thermal zone control and three different setpoint temperature for existing family house. For this, it is necessary to initially fulfill the investigative comparative analysis, investigate the impact of proposed thermal zones and control heating system on indoor comfort and energy consumption of the house. Afterwards select the solution by proposed scenarios.

Definition and planning:

Project scope: As said before the research project consists of 6 sections. The main structure can be summarized in the following parts:

- the introduction and background including the statistics data, short description of the project;
- the objectives, scope of work;
- a literature review of previous researches, articles of different kind of buildings – State of art;
- later the methodology used to conduct the work: description of materials and methods; evaluated scenarios, that is the main part of this work; case study, being considered the single family house; building energy simulation tools. Applying the various

strategies, we need to obtain, select the more cost efficient, energy efficient, with indoor comfort solution;

- Describe the obtained results and discusses
- make the conclusions regarding to selected strategy.

The GOAL of the work is to evaluate different solutions regarding to thermal comfort and energy efficiency in building, in order to identify the most interesting one(s).

3. STATE OF ART

3. 1. Conventional heating system

In |9|conventional control or CC with the whole house thermostat setpoint temperature was compared with zonal heating control systems including TRV and PRV. Consequently that CC systems have less effectiveness in energy saving comparing to zonal heating control systems which provides a reduction in annual gas demand for space heating of 12%. Also, the results of study |10|show misunderstanding of occupants the role of TRVs in the home heating system, since the setpoint temperatures in individual rooms with TRV were higher than the whole house thermostat setpoint temperature.

3. 2. Zonal heating control

Multi-zone control has a potential of energy saving. There are several papers that investigate zonal heating control systems or multi-zone controls. For example, J. Cockroft and al. directed to achieve potential energy saving by deployment of multi-zone controls for a variety of occupancy patterns in various existing UK houses (comparing the semi-detached-multi-zone and bungalow house-non-zoned) with the use of dynamic computer modelling and simulation, using the open source building performance simulation (BPS). They have identified that doors must be kept close for as much time as possible for achievement of energy saving, but there is the risk of not ensuring adequate ventilation for the occupied zones. Average energy saving by multi-zone control comparing to standard central heating control is 20% |11|.

Zonal control can include thermostatic radiator valves, a proportional-integral or a PI controller and MPC (model predictive control) controllers with or without battery energy storage system (BESS), differential pressure control valves (DPCVs); pressure independent balancing radiator valves (PIBRVs)etc. Such systems have concepts to control thermal comfort, illuminance and carbon dioxide concentration. Tomasz Cholewa, I. Balen, A. Siuta-Olcha in |12| present 16 multi-family buildings and quantifies the actual energy savings of four configurations of commonly used valves for hydraulic balance of the heating system such as thermostatic radiator valves (TRVs) (Group A buildings), differential pressure control valves (DPCVs) (Group B buildings), installation of TRVs and DPCVs (Group C buildings), pressure independent balancing radiator valves (PIBRVs)

(Group D buildings). The energy savings before and after modernization ranged between 14.6% and 23.8%.

3. 3. Novel advanced technologies

The development of new technologies has led to the investigation and application of more advanced methods and novel approaches for achieving energy efficiency and comfort in buildings. Researchers from Greece presented a novel intelligent coordinator control system based on hierarchical structure, with use soft computing techniques. The simulation results show that the control system successfully manages the users' preferences for thermal and illuminance comfort, indoor air quality and the energy conservation|13|. Some control methods were presented:

- The method to minimize energy costs in nearly zero-energy buildings (nZEB), considering two real buildings in Bucharest, Romania. Three heating and cooling controllers (thermostatic, PI and MPC) were simulated with or without battery energy storage system (BESS). Better results in terms of energy consumption reduction and total cost reduction was achieved by the lower thermal capacity building which responded faster at changes in the heating/cooling output and external influences like weather|14|;

- A novel approach - model predictive control (MPC) for optimal management of peak load, thermal comfort, energy storage and renewables in multi-zone buildings. Compared to current baseline operation MPC, is able to reduce average load by 23%, on average, in cooling mode, when no BES or PV is present|15|;

- A multi objective optimization approach allows to simultaneously provide energy efficiency and comfort. By simulation the research group achieve the reduce energy consumption in the order of 10% while also providing a comfortable work environment for the occupants|16|.

A novel heuristic reactive control strategy is developed to properly manage the thermal energy storage capacity, at both the short-term and the long-term, in a Canadian solar district heating system with significant results: despite a 10% increase in natural gas consumption, electricity use was decreased by 43%; reductions of 34% and 29% were achieved in terms of energy cost and GHG emissions., etc|17|.

3. 4. Hybrid control systems

A comparative analysis of hybrid control scheme |18|: district heating system (DHS) with distributed variable speed pumps (DVSPs) shows a great potential for energy saving and the annual average value of electricity consumption is 28.52% smaller than the conventional central circulating pumps (CCCP).

Also these type of new hybrid control system results in reduction of the boiler outlet pressure from 1.27 MPa to 0.81 MPa, which ensures safe operation of the heating network.

3. 5. Occupancy prediction

One of the central functions of a building is to provide a comfortable environment for its occupants. A review of some studies shows some methodologies for controlling occupant comfort (indoor air quality and lighting), as reinforcement learning (RL) method |19| with implementing cooperative multi-agent RL (MARL). Researchers conclude that RL technique has drawn only limited attention regarding indoor climate oriented smart building controls; MARL still needs to be examined and confirmed through large studies. It is important to include the occupant dimension into the control system, as occupants have a significant impact on energy consumption of buildings. A methodology, aimed at implementing an occupancy-based HVAC system operation schedule in office building - Zaanstad Town Hall (The Netherlands) is presented in article |20|. The process is based on the convenience of displacing groups of occupants with similar occupancy patterns to the same thermal zone. The savings related to the energy consumption of the HVAC system, as a result of the implementation of the strategy, in comparison to an occupancy-independent operation schedule amounted to 14%.

A critical review of studies which investigated occupant comfort in MURBs in relation to environmental and non-environmental variables is presented in |21| and various approaches used in assessing occupant comfort are compared. Results show that occupant comfort is affected by various indoor and outdoor environment conditions (affect on occupant health, their productivity in homes or their workplaces), building characteristics and occupant-related characteristics.

Some of these studies could reach good energy efficiency results providing comfortable conditions for the occupants. For example, Geun Young Yun explored by monitoring campaign the role of occupants' perceived control of thermal environments in thermal comfort in air-conditioned buildings. Seven air-conditioned buildings with operable windows were selected for field measurements in South Korea. Building energy simulations showed that a change in the perceived level of control over the thermal environment could reduce cooling energy consumption in buildings in the same time keeping the thermal comfort for the occupants|22|. Contrary, in the study presented in |23|, a comparison between the classic indoor control thermal comfort strategies (ON–OFF controller) and a PID-fuzzy controller shows although the PID-fuzzy controller results in lower costs of energy input; lead to less costs for the management of the equipment; but the over sizing of the power of the equipment doesn't justify the use of a such sophisticated regulator. And the ON–OFF systems seem to induce less energy consumptions in the cases of oversized heating system, they lead to poorer comfort conditions to people.

In |23| is presented machine learning (ML) to bridge the gap between controllable building parameters and thermal comfort, by conducting an extensive study on the efficacy of different ML techniques for modeling comfort levels. We show that neural networks are especially effective, and achieve 98.7% accuracy on average. We also show these networks can lead to linear models where thermal comfort score scales linearly with the HVAC setpoint, and that the linear models can be used to quickly and accurately find the optimal setpoint for the desired comfort level.

3. 6. Alternative achievement of energy saving and climate influence

The other way to reduce the energy consumption is applying passive methods, such as PCM-enhanced envelope with the highest value of energy savings (approximately 10 kWh) that was found in case of melting point value approximately 19 °C |24|; nearly zero-energy buildings (nZEBs) with real achieves up to a 90% reduction in heating and up to 50% in cooling energy|25|. Also increasing the indoor thermal mass by using brick veneer internal walls is shown to reduce the demand by approximately 10–15% depending on many factors as in which regional climate building is situated, etc.|26|.

Also impact of local climate and building characteristics play an important role in saving energy and can reduce or increase the energy consumption of building. The case of a severe cold climate of China (Inner Mongolia, North China with quite low temperature) published in |27| and analyzed the heating energy consumption, thermal comfort, occupancy behavior in 40 residential buildings using K-means clustering algorithm and DA method. The heating energy consumption intensity varied from 166 to 2429 kWh/m^2. The obvious regional differences showed divergence of the indoor thermal environment and the level of operation and management. In addition, occupant behaviors indeed influenced the indoor thermal environment, which reflected the latent influence on energy consumption. Finally, the combination of the K-means clustering, and DA method was a beneficial method because the final classification accuracy was up to 97.9%.

Quantitative analysis of the complex interplay between the impacts of local climates, building characteristics, and occupancy patterns on the annual and peak HVAC demand of residential buildings in Australia is presented in |28|. The climates range from tropical in the north of the country, to cold temperate in the south of the country. The results show the highest energy reductions are observed in the climates with high diurnal temperature variation, such as Melbourne (51%) and Hobart (54%). The effect of thermal inertia is less in the climates with low diurnal temperature variation such as Darwin (19%). Occupancy scenarios that include unoccupied periods result in lower annual HVAC demand, yet they increase the peak cooling and heating demand. This lead to high electricity demand of the building. Chenqiu Du together with collaborators explored the capacity for heating/cooling flexibility in residential buildings in the hot summer and cold winter zone in China, by investigating the year-round dynamic changes in the thermal adaptation of occupants|29|. Such implementation has been estimated with great energy saving potential (e.g. 34.4% in Nanjing). Some notices were observed:

- Clothing insulation and indoor air velocity showed different variations in the early-, mid- and late-winter/summer, even for the same temperature conditions, revealing the temporal differences in occupant thermal adaptation in response to the perceived outdoor climate and thermal experience.

- The human thermal adaptation was limited for very low and very high temperatures.

4. METODOLOGY USED IN THE DEVELOPMENT OF THE WORK

4. 1. DESCRIPTION OF THE MATERIALS AND METHODS

This study was carried out with comparative analysis of 49 scenarios using the Design Builder program. The real three-level house was modelled and simulated applying suggested heating system (applying different types of boilers), occupancy profiles, thermal envelop characteristics, zonal temperature control, climate. Specifically, the objectives of this study were to: 1) introduce fundamental basic concepts; reveal the essence of the work, the type of research or development and its limitations as well as the motivating intentions, outlining their original and innovative aspects; 2) summarize the various thermal zoning methods and practical applications of individual heating system design and building energy analysis; 3) investigate the impact of thermal zoning strategies on comfort and energy consumption during the building energy modeling process, also determinate or achieve the maximum cost-effective and energy efficient option ; and 4) suggest future developments and their potential research significance related to the new thermal zoning method.

This work is organized into six sections:

Section 1 provides an introduction and background, it describes the main aspects related to energy consumption in general, presentation of project: the ideas to be presented, the essence of the work, the type of research or development and its limitations as well as the motivating intentions, outlining its original and innovative aspects; some definitions, statistics.

Section 2 includes the objectives and scope of work.

Section 3 contains State of art - a literature review of previous researches, articles of different kind of buildings (residential, office, commercial located in different parts of the world, with the different climatic conditions), related to energy consumption and inner comfort.

Section 4 describes the overall methodology used to conduct this study: a) description of materials and methods; b) case study – The single family house situated near Vitoria Gasteiz. A building description, the location of house and climate of this region are described in this section; c) evaluated scenarios, regarding to: energy system - Individual heating system and setpoint temperature, applying different occupancy profiles and heating operation schedules; zonal control. And then model definition is described.

Section 5 Results, a comparative analysis of cost efficiency, energy efficiency, indoor comfort and contamination effects and discusses several promising research directions for thermal zoning methods in building energy simulation will be implemented. And finally, selection of the proposed solution will be done.

Finally, the conclusions drawn are described in Section 6.

4. 2. CASE STUDY – SINGLE FAMILY HOUSE

4.2. 1. Building description and location

Energy consumption of a housing depends on many factors as the climatic zone, location of the building, the constructive quality, the level of isolation, the grade of equipment, on the progress in generation of heat and/or cold, but especially on the habits of comfort of the users.

A detached existing, three-level house (see **Figure *2***) with total area 304,1 m^2 (occupied area about 180 m^2) and net volume of about 764,4 m^3 (occupied volume about 490 m^3) is selected to be a representative residential building located in the North of Spain, in Vitoria Gasteiz, Basque Country (latitude: 42,88°, longitude: -2,72°). The thermal characteristics of building: the opaque envelop of ground floor and first floor are made up of double hollow brick with a continuous thermal projected polyurethane insulation layer (U =0.368; 0.396 W/m^2 K), the opaque envelop of basement in contact with ground is made of concrete with internal thermal projected polyurethane layer (U = 0.443 W/m^2 K); the basement ground is concrete slab with projected polyurethane layer (U = 0.423 W/m^2 K) and polyethylene sheet. Internal horizontal partitions are reinforcement concrete (U = 2.649 W/m^2 K) (between thermally conditioned zones) and reinforcement concrete with projected polyurethane layer (U = 0.436 W/m^2 K) (between conditioned and non-conditioned zones). Internal vertical partitions between thermally conditioned zones are hollow brick; between conditioned and non-conditioned zones – hollow brick on both sides and projected polyurethane layer between them. The windows are low-e double glazed and are filled with air (U = 1.10 W/m^2 K), with aluminium frames. The summary of thermal envelop is described in **Table 1**.

Table 1. Summary of thermal envelop of family house.

Thermal envelop		U-value (W/ m2·K)	Insulation thickness (m)	Total thickness (m)
Windows Frame (30%)	Aluminium			
Glass (70%)	Low-e double glazed			
U-value window (W/ m2·K)		1.10		
Façade: Basement		0.443	0.05	0.155
Basement ground (habitable)		0.423	0.055	0.375
Basement ground (non habitable)		0.424	0.055	0.37
Façade: Ground floor		0.396	0.05	0.175
Façade: First floor		0.368	0.05	0.26
Horizontal partitions between thermally conditioned zones		2.649		0.29
Horizontal partitions between conditioned zones and non-conditioned zones		0.436	0.05	0.33
Roof		0.218	0.12	0.162

Vertical partition between thermally conditioned zones		2.085		0.1
Vertical partition between thermally conditioned &non conditioned zones		0.384	0.05	0.17

In **Figure 3** the plan views of the house and suggested scheme of installation of heating system are represented.

Figure 2. Single Family house.

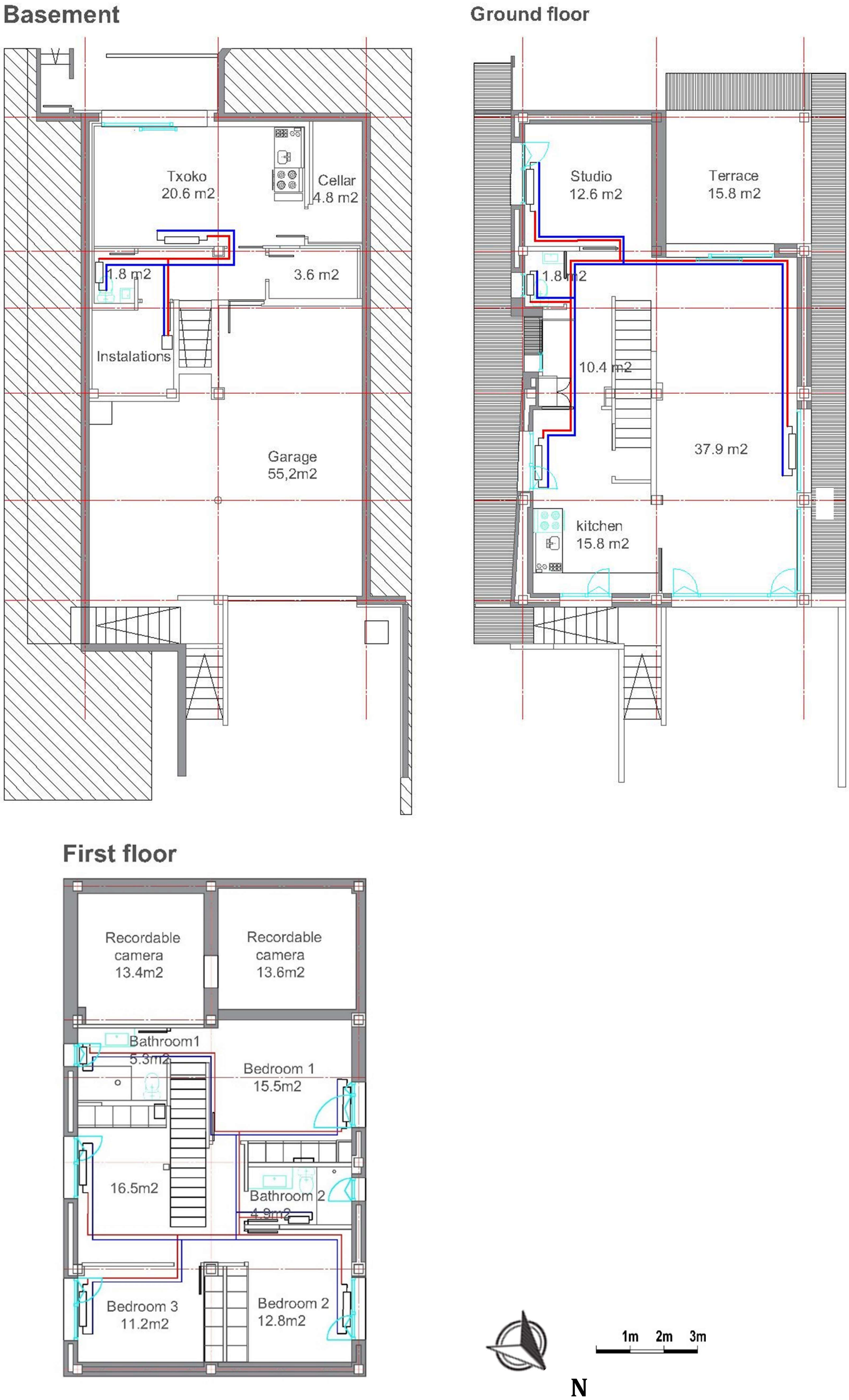


Figure 3. Plans of Basement, Ground floor and First floor. Scheme of installation heating system.

4.2. 2. CLIMATE OF VITORIA GASTEIZ

There are 6 climatic zones of winter severity in Spain (STBC) represented from letter α -the Canary Islands with mildest climate to E – Burgos with coldest climate (**Figure 4**).

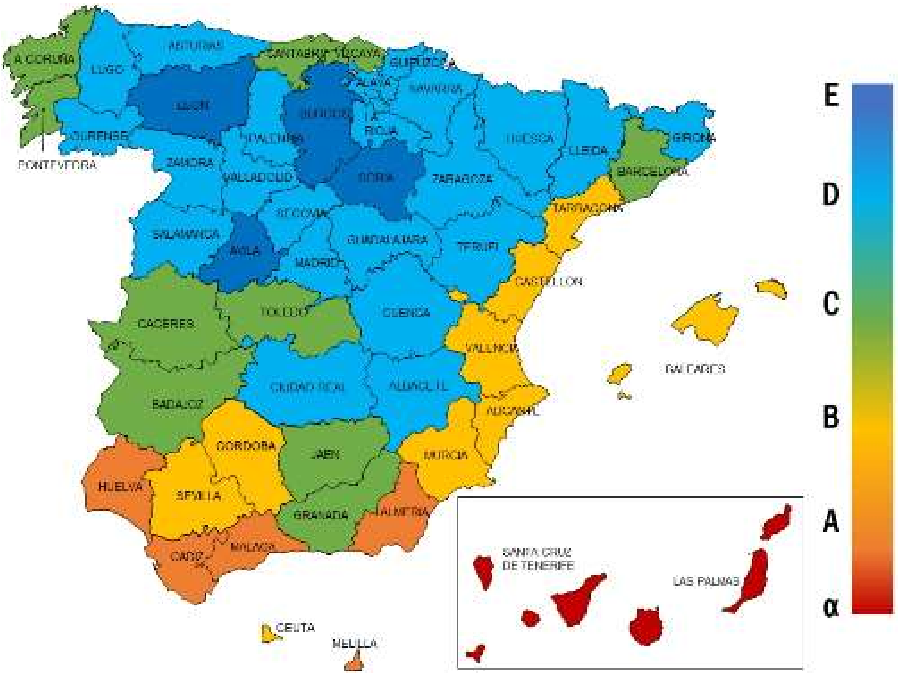


Figure 4. Map of climatic zones of Spain in winter.

Vitoria Gasteiz is situated in climatic zone C. This climate is moderated and warmly. It is a large number of rain in Vitoria, even in the driest month. In accordance with Köppen and Geiger climate qualifies as Cfb. (15). The average temperature - 16.0 °C. Average precipitations – 49.5 mm. The driest month is a July with 25 mm of precipitation.

With an average of 18.5 °C, August is the warmest month. The lowest average temperatures of the year take place in January, when it is about 6 °C. The biggest precipitation quantity happens in November, with a 70 mm of average.

4. 3. EVALUATED SCENARIOS

49 scenarios were simulated and evaluated by involving suggested heating control system (individual heating system), installing different types of boilers and setpoint temperature; zonal temperature control; occupancy profiles and heating operation (also taking in account the thermal envelope characteristics of the house **Table 1**).

Further, a detailed description of the scenarios will be presented. The summary of estimated scenarios is shown in **Table 2** and **APPENDIX I** represents the detailed description of each 49 scenario (from S0a to S16c).

Scenarios S0a, S0b and S0c represent the application of simple natural gas boiler (**B1**); where programable thermostat control located in living room (zonal control **Z1**) is assumed; the letter ´´a´´ indicates the occupancy schedule O1, while ´´b´´ and ´´c´´ indicate occupancy schedules O2 and O3 respectively (this kind of designation also applies to subsequent occupancy scenarios); and as a principal set point temperature 20°C is set. Scenario S1 represents the same characteristics as previous scenarios in only difference that programmable thermostat control is situated in the kitchen (zonal control **Z2**). For S2a-S2c; S3a-S3c; S4a-S4c represented the application of modulating natural gas boiler (**B2**), **Z1** zonal control and different set point temperatures 18°C, 20°C, 22°C respectively. All subsequent scenarios represent the application of modulating condensing natural gas boiler (**B3**) with the difference in application of zonal control: S5a-S5c (18°C), S6a-S6c (20°C), S7a-S7c (22°C) – zonal control Z1. S8a – S10c – zonal control **Z3** (thermostats installed in each zone/floor that is controlled individually). S11a – S13c – zonal control **Z4** (thermostat in living room in tandem with TRVs for radiators). S14a – S16c – zonal control **Z5** (one individual thermostat for each floor and the application of TRVs).

The H1, H2, H3, H4, H5, H6 indicate heating operation schedules based on occupancy profiles.

Table 2. Summary of estimated scenarios.

Individual heating system (boilers)	B1	B2	B3		
Setpoint temperature	18°C	20°C	22°C		
Occupancy	O1	O2	O3		
Zonal temperature control	Z1	Z2	Z3	Z4	Z5
Heating operation	H1	H2	H3		
Heating operation with TRVs	H4	H5	H6		

4.3. 1. INDIVIDUAL HEATING SYSTEM AND SETPOINT TEMPERATURE

Individual heating is found in 50% of Spain homes |30| and about 60% in Basque Country |31|.

For all scenarios was defined the Installation of individual gas heating system. For this heating system were applied scenarios with the different type of boilers: B1 - simple natural gas boiler; B2 - modulating natural gas boiler; B3 - modulating gas-fired condensing boiler (**Table 3**). One radiator is installed for each room or zone. And taking a different whole house indoor setpoint temperature of 18°C, 20°C, 22°C for heating and 25°C for cooling. The aim was to compare energy consumption for each setpoint temperature, to define the more comfortable and healthy for the occupants option and to observe the behavior of the occupants.

The simple boiler or non-condensing hot water boiler is the traditional commercial facility default option. This boiler does not allow combustion gases to condense in the heat exchanger, which is typically cast iron. It requires a return water temperature of around 60°C to ensure no condensation forms and that there is no thermal shock to the boiler. This type of boiler provides a combustion efficiency of around 80%. In this study was applied 85°C of water outlet temperature.

For the condensing boiler to operate at maximum efficiency, the secondary heat exchanger's surface needs to be equal to or below the dew point temperature of the fuel used. This is the temperature at which water droplets form. For natural gas boilers, the dew point is around 55°C. In other words, the water in the return pipe needs to be 55°C or lower or your boiler will not operate at maximum efficiency and potentially will not even condense. Therefore, was applied 55°C of water inlet temperature both for modulating boiler and modulating condensing boiler. But for the outlet of water 75°C. And the rated average water temperature for radiators is 75 °C.

Table 3. Temperature variable for different types of boilers

Type of boiler	**Heat production set point**	**Indoor temperature set point**		
Simple natural gas boiler (SB or B1)	60°C	18°C	20°C	22°C
Modulating natural gas boiler (MB or B2)	55°C	-	-	-
Modulating gas-fired condensing boiler (MCB or B3)	55°C	-	-	-

4.3. 2. OCCUPANCY PROFILE AND HEATING OPERATION

Three scenarios for occupancy profile and three scenarios for heating operation are defined. Occupancy Scenario O1 based on STBC (Spanish technical building code) and consists of 4-person house, where the occupants spend all day at home with the schedule of presence: 00:00 - 06:59 (night time) 07:00 - 14:59 & 15:00 - 22:59 & 23:00 - 23:59 (night time). Scenario O2 based on Scenario 1 in |27| also consists of family of 4 person (2 adults and 2 children) has full-time job schedule from 9.00 till 18.00 and spending weekends at home: 00.00-24.00. Third scenario O3 based on scenario 3 in |27| consists of 2-person house (a retired couple), who spend all day at home and only 2 hours outside home: 00.00-17.00 & 19.00-00.00. In **Figure 5** the detailed description is shown.

Heating operation scenario H1 based on occupancy scenario O1 and STBC with the heating operation schedule: 00:00 - 06:59 (night time) 07:00 - 14:59 & 15:00 - 22:59 & 23:00 - 23:59 (night time). At night time the indoor temperature always set on 17°C. Scenario H2 based on occupancy scenario O2 with full-time job schedule from 9.00 till 18.00 and for weekends heating operates from 00.00-24.00. Third scenario H3 based on occupancy scenario O3: 00.00-17.00 & 19.00-00.00. In **Figure 6** the detailed description is shown.

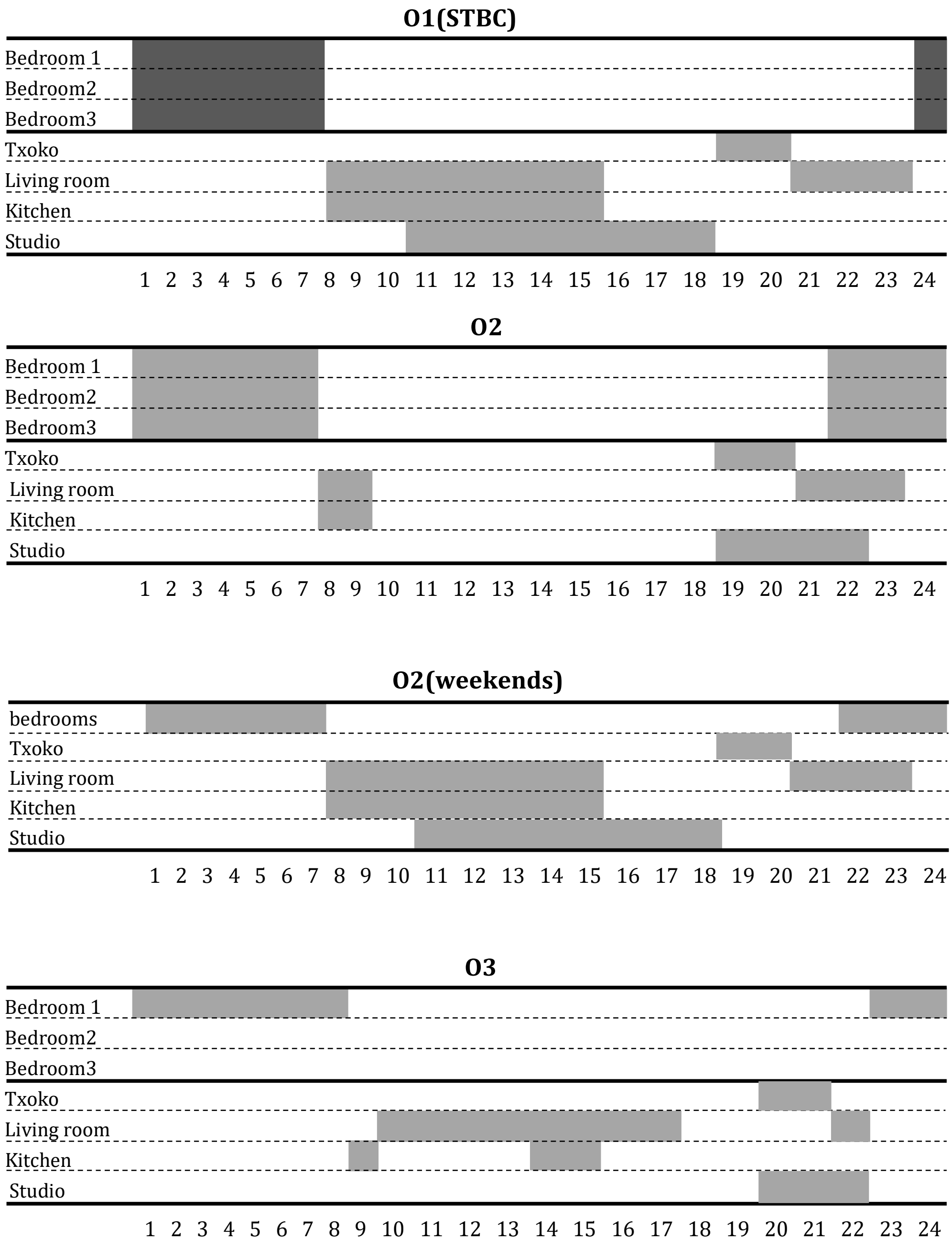


Figure 5. Occupancy scenarios representing daily and nocturn presence.

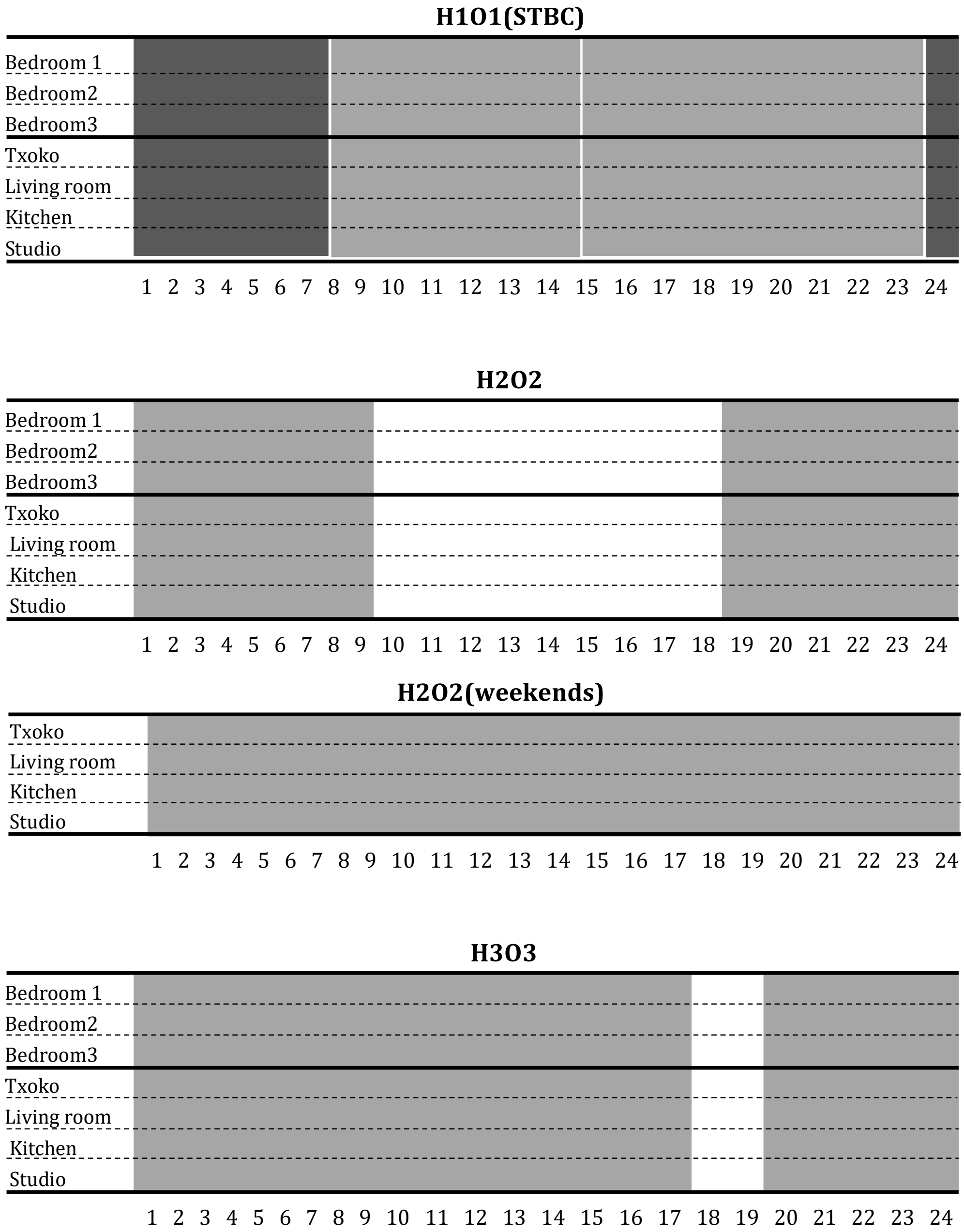


Figure 6. Heating operation scenarios.

These scenarios have a setpoint temperature of 17°C (night time) represented by dark grey color and 18°C° or 20C° or 22 C° (depending on applied scenario) represented by light grey color.

Also three heating operation schedules applying TRVs based on occupancy profile of previous viewed scenarios were defined: **H4O1** with schedule for each room: Bedrooms – 23.00-7.00(17°C), txoko – 18.00-20.00, livingroom –7.00-15.00 and 20.00-23.00, kitchen – 7.00-15.00, studio – 9.00-18.00, WC – 7.00-10.00 and 19.00-23.00; **H5O2:** Bedrooms – 21.00-7.00, txoko – 18.00-20.00, livingroom –7.00-9.00 and 18.00-23.00 for weekdays and 7.00-15.00 and 20.00 – 23.00 for weekends, kitchen –7.00-9.00 for weekdays and 7.00-15.00 for weekends, studio – 18.00-22.00 for weekdays and 10.00-18.00 for weekends, WC – 7.00-9.00 and 18.00-23.00; **H6O3:** Bedrooms – 22.00-8.00, txoko – 19.00 -21.00, livingroom - 8.00 -17.00 and 19.00-22.00, kitchen –

8.00-17.00, studio – 19.00 -22.00, WC – 7.00-10.00 and 19.00-23.00 **Figure 7** . And the corridor is defined as off /24 for all heating operations.

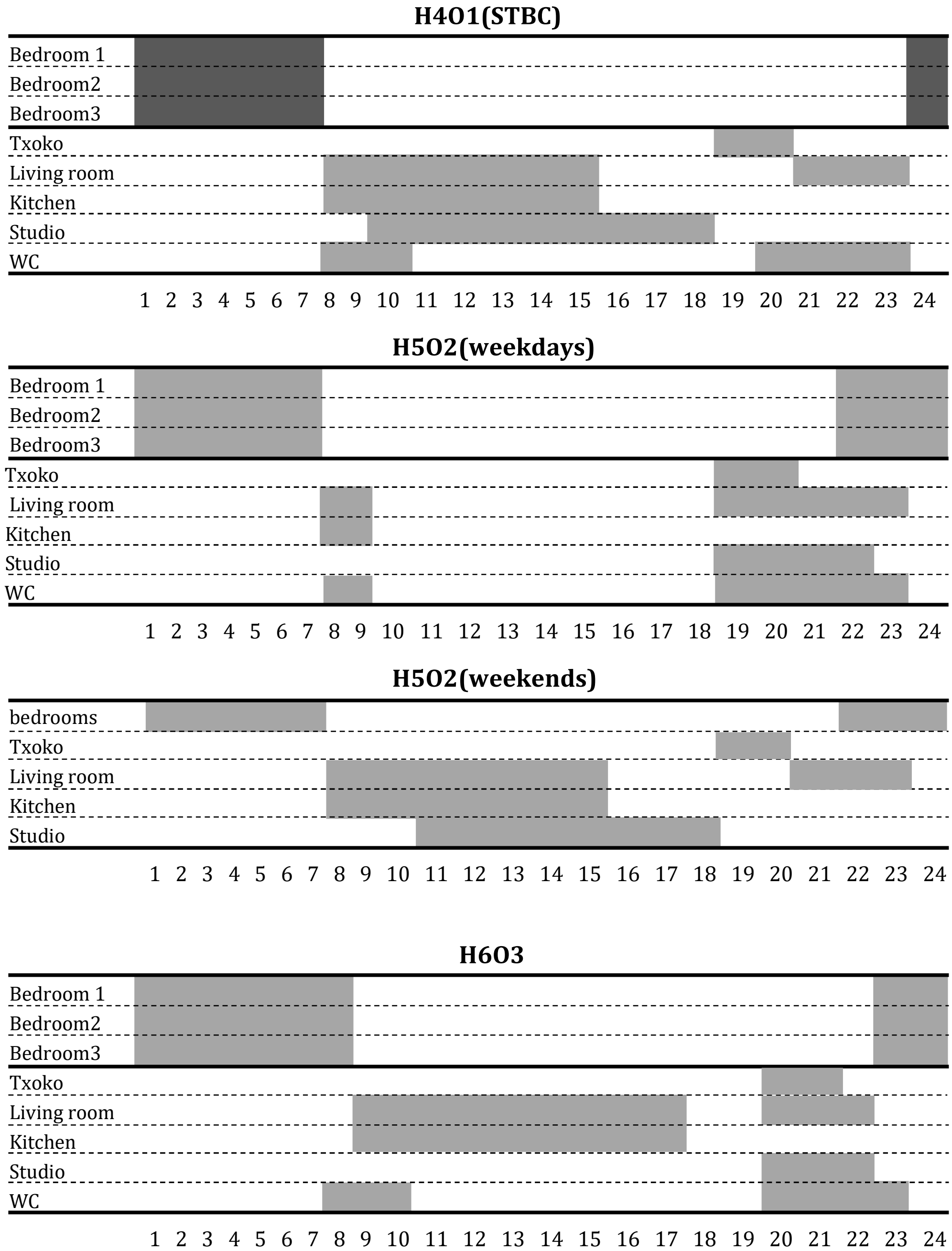


Figure 7. Heating operation scenarios for TRVs.

4.3. 3. ZONAL TEMPERATURE CONTROL

To see the influence of zoning on energy saving and inner comfort by considering the climatic conditions and building orientation 5 scenarios were defined.

In the case with only one thermostat in the home, the best location would be downstairs (ground floor) in the most used area which will usually be living room: Z1 (Zone 1) that includes entire house besides the non-residential rooms (**Figure 8 (b)**) with the whole house thermostat (or room thermostat) situated in living room; Z4 (Zone 4) compounds the room thermostat situated in living room and TRVs (thermostatic radiator valves) control for each radiator of whole house. And as alternative option to Z1 was applied: Z2 (Zone 2) with the whole house thermostat (room thermostat) situated in the kitchen (in this case the kitchen is oriented towards the south) (**Figure 8 (b)**). Although this location of thermostat is not the best option. The reason is to show the behaviour of thermostat in different inner conditions, depending on where the thermostat is situated.

This room thermostat prevents your home from getting warmer than necessary. It turns the heating on until the room reaches the temperature you have set, and then off until the temperature drops. In this research project were taken different setpoint temperatures of 18°C, 20°C, 22°C. It's also suggested to place thermostat up on the wall as conveniently as possible so you can still reach it. Having it higher up on the wall means it will take into consideration the heat rising to the upstairs a bit more. The overall best placement of a thermostat should be on an interior wall (one that is not touching the outside wall of your home). As well as an interior wall it should also be one that doesn't hit any of the above factors including direct sunlight, air vents, outside doorways, not in the kitchen, away from windows, and not in a hallway area.

A one-level house tends to be quite easy to maintain consistent heating and cooling as there is nowhere for the heat/cold to disappear upstairs. Contrary in a multi-level house in this case three-level house, this becomes even more difficult as heat rises so your upstairs will typically be much warmer than the downstairs. If you place it upstairs, the downstairs will be much colder than the rest of the home. The best setup would be to have different thermostats for each floor that heat and cool each separately: Z3 (Zone 3) consists of 3 heating subzones/floors, each floor controlled by an individual room thermostat (**Figure 9**). The downstairs thermostat will always be set lower than the subsequent upstairs thermostats as the upstairs will always be warmer. In the winter, a suggested guideline would be to set the downstairs at 2 degrees lower than the upstairs. That way the upstairs don't overheat making it the optimum comfort level.

And Z5 (Zone 5) as Z3 consists of 3 heating subzones/floors, each floor controlled by an individual room thermostat and the radiators are equipped with TRVs (Smart Radiator Thermostats). The rooms on each floor are assigned to the respective Zone Controller for that floor. When a Smart Radiator Thermostat on the upper floor needs heating, it informs the Thermostat that controls the upstairs Heating Zone.

TRVs allow to differently heat/cool any floor of a building and – for a given floor, any indoor area including various areas within an open space, according to their energy demand. Also allow to the rooms may be heated only at the times they are occupied and to the level needed; thus reducing the volume of the house that is being heated. TRVs offer a cheap and easy way of providing zoned temperature control within a building. In this project TRVs configured for a certain heating operation that shown in section **4.3. 2** (**Figure 7**).

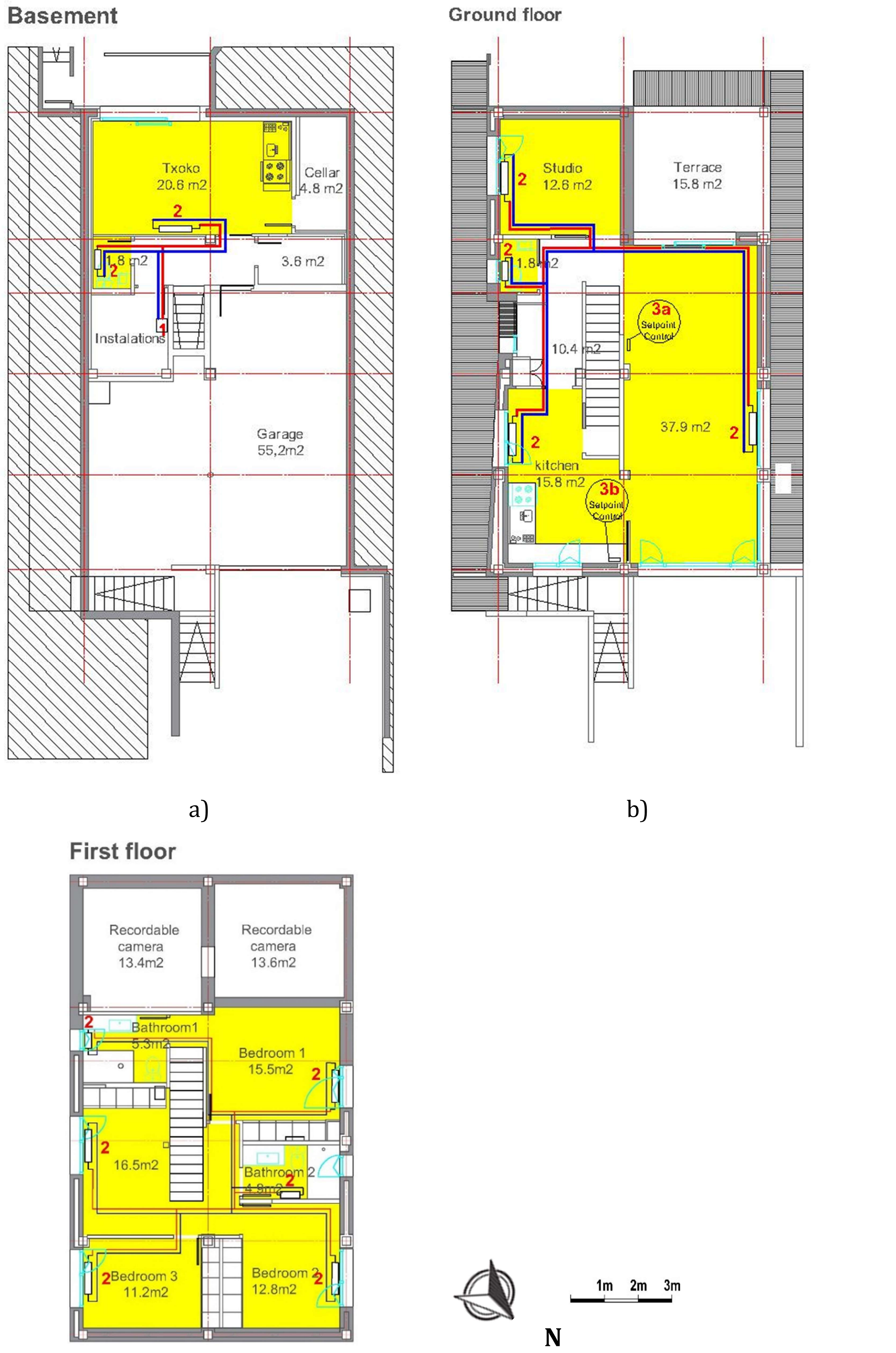


Figure 8. Scheme of installation heating system with zonal control; (1: boiler; 2: terminal units; 3: setpoint control: 3 a - setpoint control in the living room (Z1), 3b-Setpoint control in the kitchen (Z2)). Yellow color indicates the heated areas.

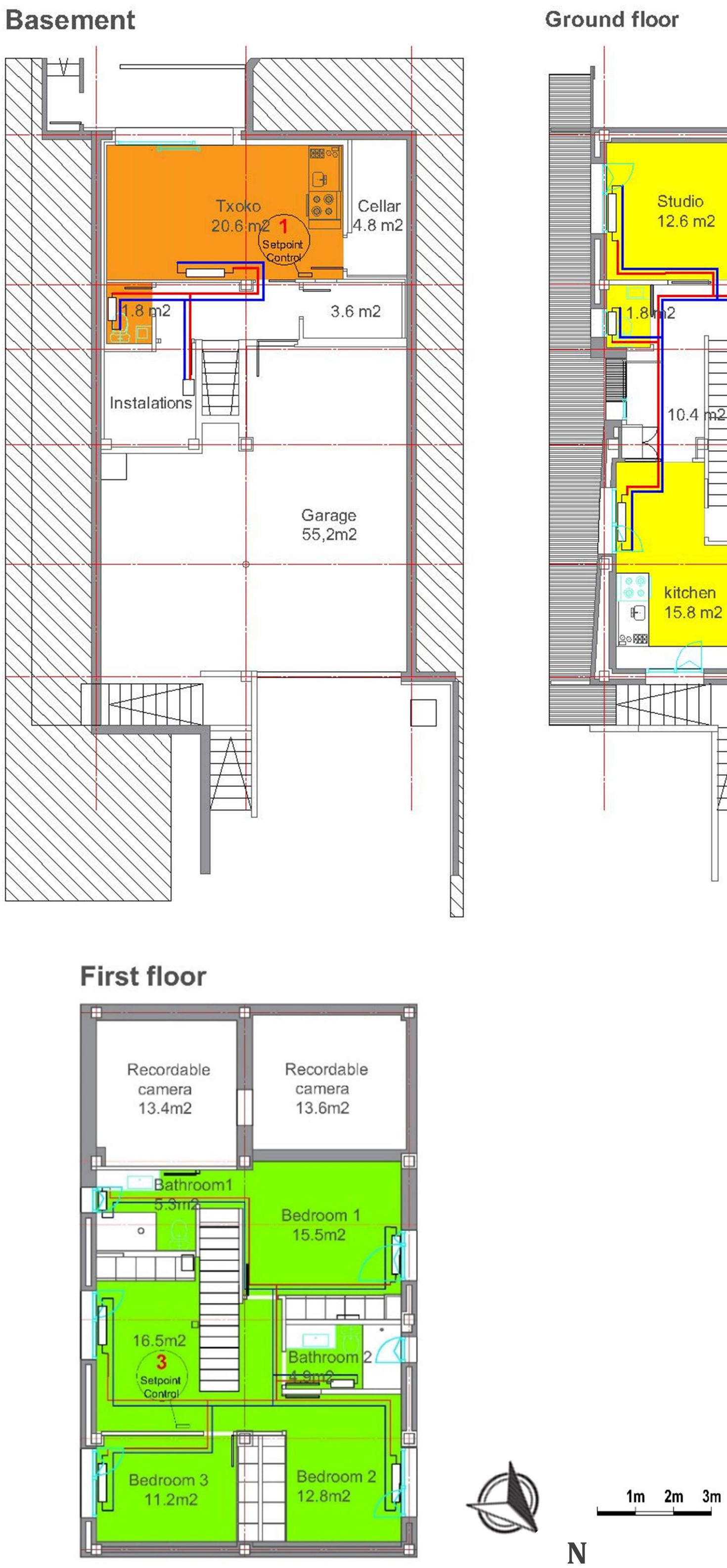


Figure 9. Scheme of installation heating system with zonal control(Z3).; 1: setpoint control in Txoko (1st floor); 2: setpoint control in living room (2nd floor); 3: setpoint control in corridor (3rd floor). Three types of color indicate the heated areas for each floor.

4. 4. MODEL DEFINITION

Building energy simulation programs can be useful tools in evaluating building energy performance, both at the design and operation stages; can help the better understanding the needs of society without consuming excess resources; can provide accurate predictions of building energy performance in building design and construction projects. After reviewing the presented review and comparison of various energy Simulation Software for buildings in |32|, were concluded that among the most complete simulation software tools the Design Builder Energy Plus is.

With the help of the Design Builder software, the model of real building was created (**Figure 10)**, including simulation of 49 assumed scenarios (**APPENDIX I**). Each simulation was carried out for one year. And the Residential-Dwelling template was set with occupancy density on 0,02 (people/m^2), corresponding to occupancy profile O1: 4 person, O2: 4 person, and 0,01 (people/m^2) - occupancy profile O3 for 2 person. For more detailed information of occupancy profile see section **4.3. 2**.

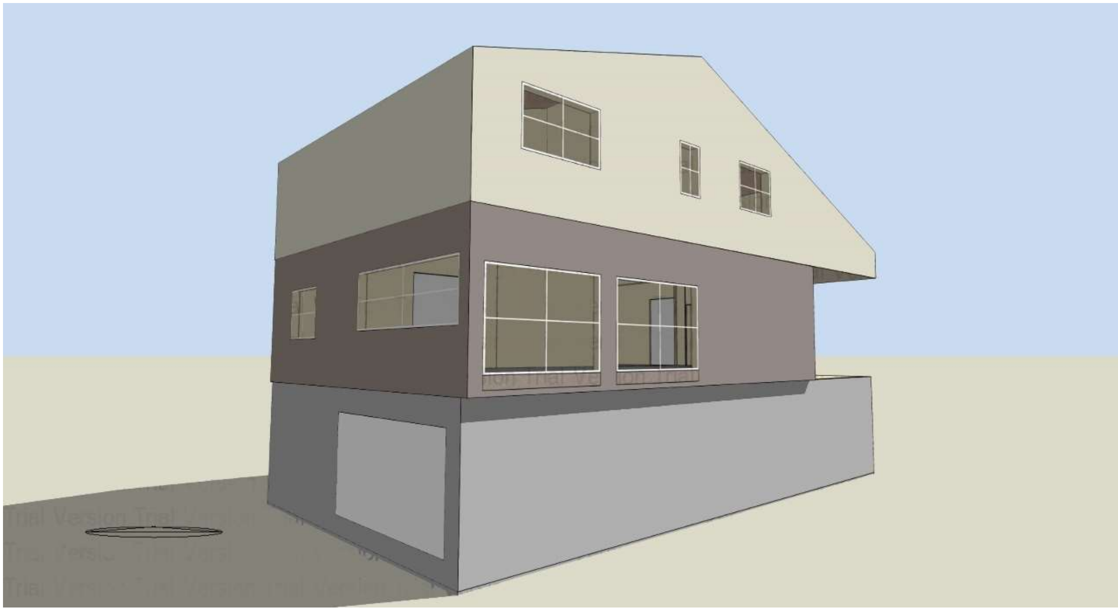


Figure 10. Model of the family house.

The individual heating system with the different types of boiler (simple - **B1** and modulating boiler – **B2**; modulating gas-fired condensing boiler – **B3**) for heating and DHW supply and hot water radiator network locating one auto-sized by program radiator in each room, including scenarios (Zonal control) with setpoint temperature manager situated in the kitchen (**Z1**) or living room (**Z2**), the setpoint temperature manager situated in each floor of house (**Z3**), heating control by TRVs for each radiator (**Z4**) and the setpoint temperature manager situated in each floor of house with heating control by TRVs for each radiator (**Z5**) was defined and presented in **4.3. 3.**

. The operation of TRVs was programmed according to three occupancy profiles Section **4.3. 2**. The average nominal supply temperature of water assumed for 75°C for radiators and for boilers: B1 - 60°C; B2 and B3 - 55°C. In this study we are not going to focus on DHW supply, but on space heating energy consumption. Thermal calculation was made for occupied area, that accounts about 179,4 m^2 (txoko, WC (basement), kitchen, living room, studio, WC (ground floor), bedrooms, WCs, corridor (first floor)). As fuel is used natural gas.

For 49 evaluated scenarios were applied three setpoint temperatures:

- **18°C** for scenarios S2a, S2b, S2c; S5a, S5b, S5c; S8a, S8b, S8c; S11a, S11b, S11c; S14a, S14b, S14c;
- **20°C** for scenarios S0 (a, b, c); S1; S3 (a, b, c); S6 (a, b, c); S9 (a, b, c); S12 (a, b, c); S15 (a, b, c);
- **22°C** for scenarios S4 (a, b, c); S7 (a, b, c); S10 (a, b, c); S13 (a, b, c); S16 (a, b, c);

And heating setback temperature set for 13°C. When the building system is off, the heating system in the building will come on to try and not go below of setback temperature.

Besides the energy performance of building, various analyses related to the environmental performance, including mechanical with 0,3 l/s-m^2 per area and natural ventilation with minimum fresh air 2,5 l/s person were applied, which are necessary to maintain adequate conditions of comfort in building. As well as comparing the environmental and energy impact of various materials, construction systems and different glazing systems used in the envelope of building (**Table 1**); detailed determination the lighting performance of the building, including distribution maps and tables of daylight factors, using the Natural lighting module.

5. RESULTS AND DISCUSSION

5. 1. Energy results

The results of yearly heating consumption of 49 scenarios were obtained **Figure 11**. This section presents these results, its comparative analysis, energy and economic assessment, discussion. And thereby defines the influence of zoning (zonal control) and heating system on energy consumption and indoor comfort. As well as achievement of more energy economic and comfortable in term of indoor environment option.

These results show the heating consumption of each considered scenario (fromS0a to S16c), dividing 49 scenarios by set temperatures: 18°C, 20°C, 22°C, with this sequence: from S2a – S14c for temperature of 18°C; from S0a – S15c for 20°C and from S4a – S16c for 22°C. The results are grouped together by zoning (zonal control: Z1 – zone controlled by programable thermostat, located in living room and in kitchen (Z2); Z3 – each floor/zone controlled by individual thermostat; Z4 - zone controlled by programable thermostat, located in living room and includes TRVs control in each radiator; Z5 - each floor/zone controlled by individual thermostat, involves TRVs control in each radiator). Moreover, the results are grouped together by type of boilers (B1-simple boiler, B2 – modulating boiler, B3 – modulating condensing boiler) and the occupancy profiles: O1 - occupancy schedule based on STBC, 4 person (indicated as letter ´´a´´), scenario O2 - fulltime job schedule, 4 person, O3 - fulltime schedule, except that people spend 2 hours outside home, 2 person, indicated as letters ´´b´´ and ´´c´´ respectively. The light blue color indicates the set point temperature of 18°C, blue color - 20°C and dark blue indicates the set point temperature of 22°C.

At first sight the big difference of energy consumption results between applied setpoint temperatures of 18°C, 20°C and 22°C. Further, the trend of decrease in energy consumption from scenarios Z1 to Z5 is follow. And it is evident that zonal controls Z4 and Z5 have significant reduction comparing to conventional control (Z1) especially where was applied temperature of 22°C. Concerning to occupancy scenarios, in case of temperature of 18°C there is no drastic difference in energy consumption results between O1, O2 and O3 scenarios. In case of temperatures 20°C observed the tendence of not significant increase from occupancy scenarios O1 to O3 for all zonal controls and as well as for setpoint temperature 22°C, in general. But in the latter case a quite big difference between occupancy scenarios is found (Z1, Z3).

The results grouped by type of boiler (B1, B2, B3) (**APPENDIX II**) and by type of zonal control (Z1-Z5) (**APPENDIX III**) are presented in detail.

Having obtained the energy results, it is very important to make the comparative analysis of them. This way can help to see the influence of energy system and zoning on heating consumption and on indoor comfort. As well as determinate energy and cost-efficient option.

Firstly, if we focus on set point temperatures, referring to **APPENDIX IV**, the graph in **Figure 12** shows the comparative analysis between evaluated scenarios in percentage and comparison of deportment of scenarios at different setpoint temperature. As in a previous figure the temperatures were indicated in different colors. The results, where was applied setpoint temperature of 22°C were taking as 100% for more clarity. Here, it is evident, the heating consumption applying temperature of 22°C is about 5-13 times higher than in case of 20°C, and about 10-25 times higher than in case of 18°C. This suggests that the set of temperature greatly affects energy consumption.

Afterwards, in **Figure 13** the comparison of results of three type of boilers for high rates, average rates and low rates of energy consumption is shown. It is possible to see that at temperature of 18°C the energy consumption in all types of boilers has approximately the same value. The same situation is observed at the temperature of 20°C. Whereas, at the temperature of 22°C in general the significant increase skips of consumption value is visible.

Further, referring to **APPENDIX III**, the comparative analysis and study of energy results of zonal control are described (**Figure 14**). Allowing to understand the effects of these zonal divisions on heating consumption and inner comfort. The first thing could be noticed as mentioned before, the significant decreasing in energy consumption of scenarios applying TRVs (zonal control Z4 and Z5).

Simulation results

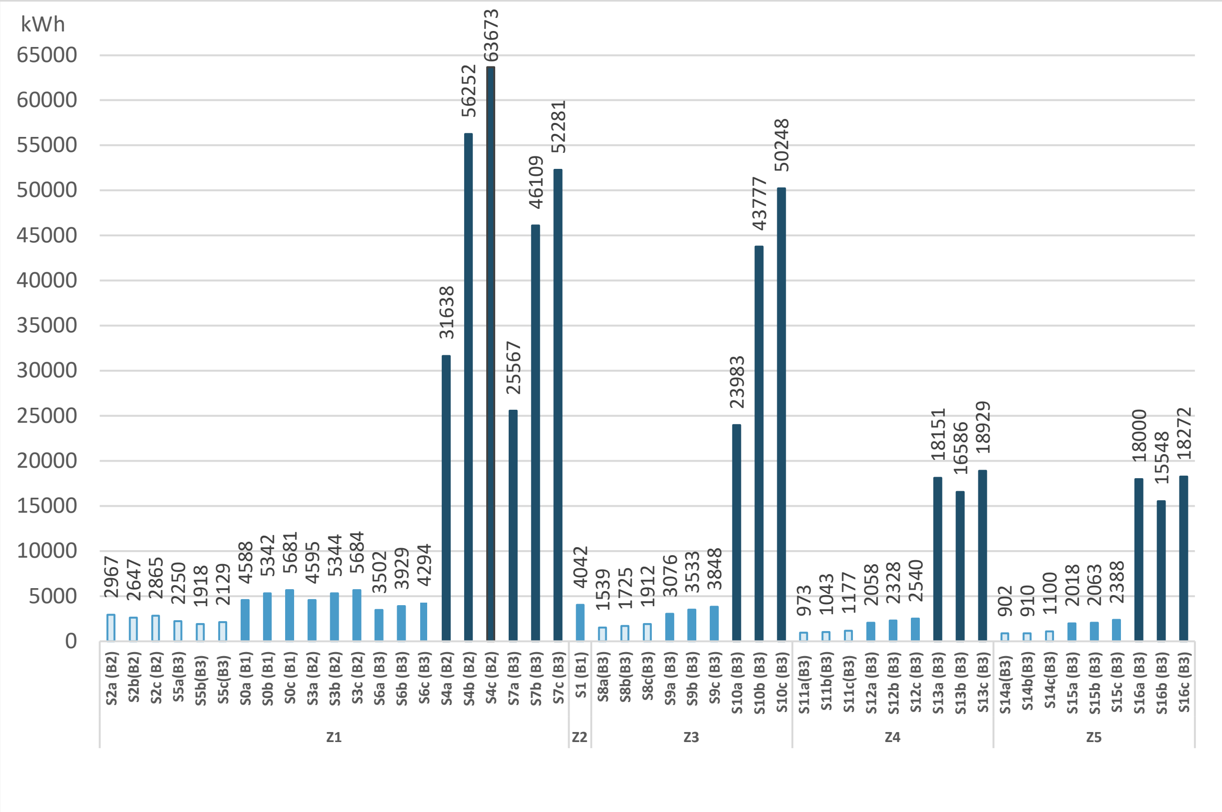


Figure 11. Annual heating consumption in the 49 scenarios estimated

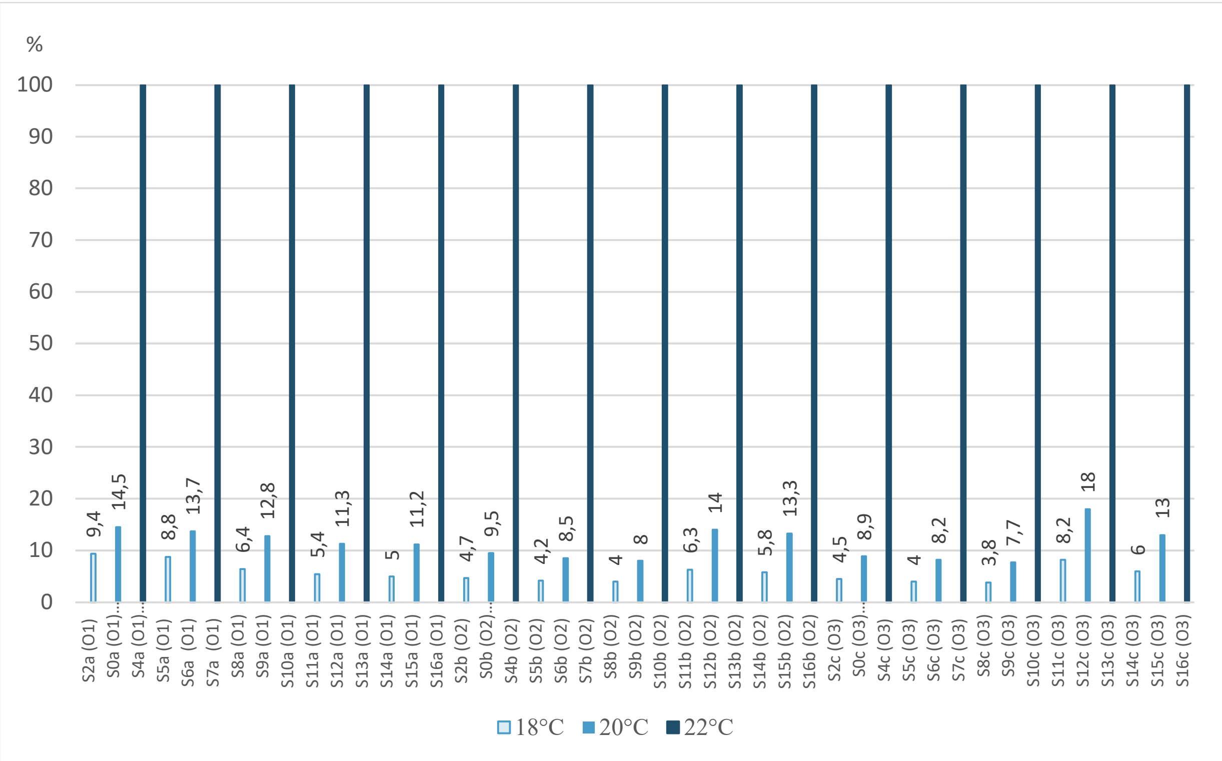


Figure 12. Comparison of energy results by applying the different setpoint temperature

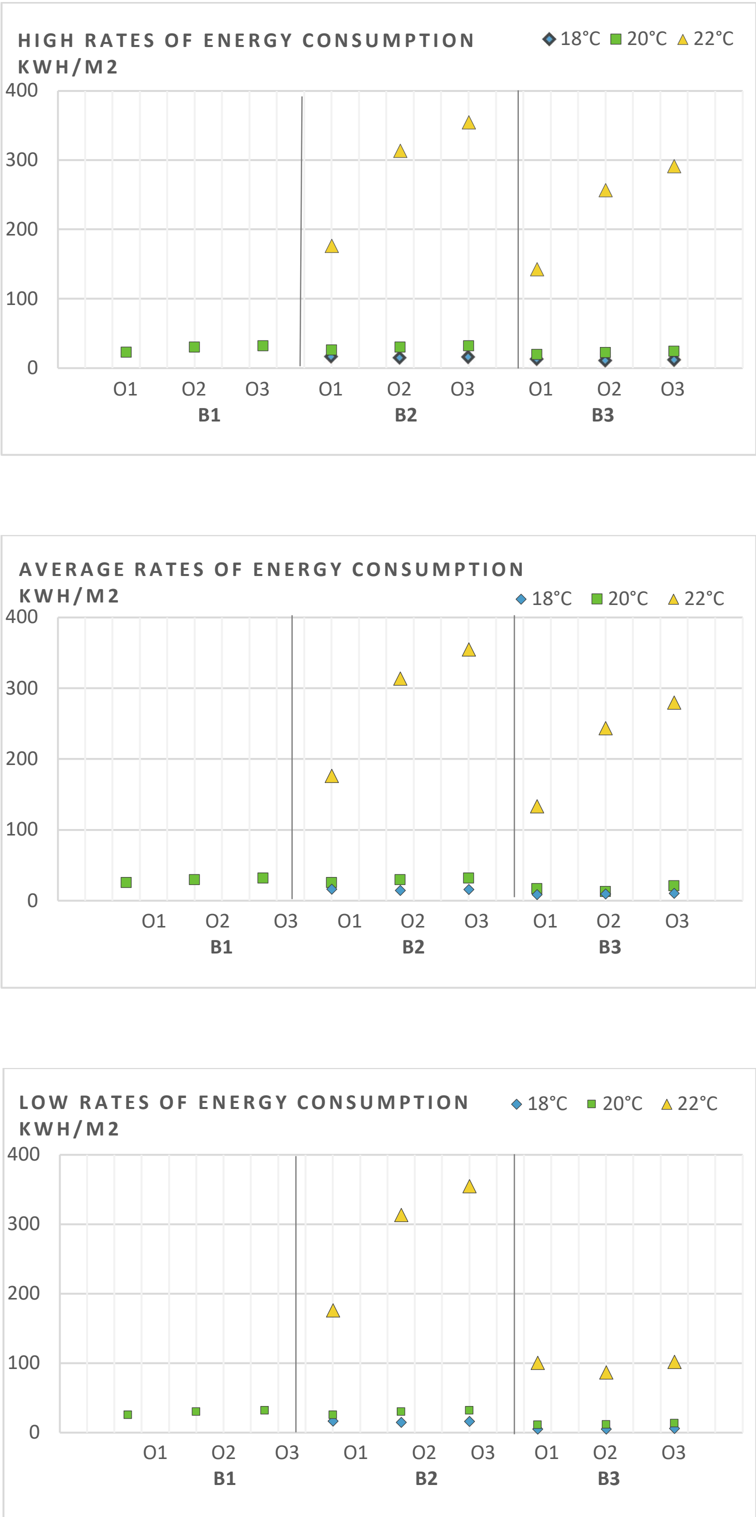


Figure 13. Annual energy consumption. Boiler´s comparison

Table 4. Summary of energy saving in kWh/m^2.year related to set point temperature.

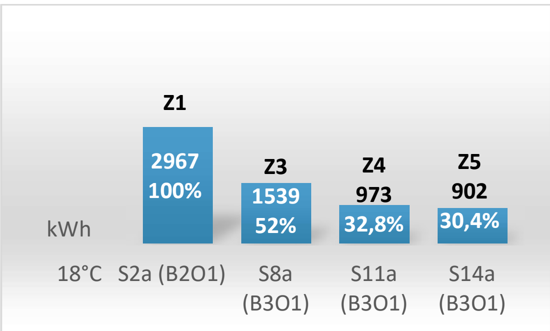
	B2			B3		
	01	02	03	01	02	03
22°C→20°C	150,7(85,5%)	283,8(90,5%)	323,2(91%)	123(86,3%)	235(91,5%)	267,5(91,8%)
22°C→18°C	159,8(90,6%)	299(95,3%)	339(95,5%)	130(90%)	246,3(95,8%)	279,5(96%)
20°C→18°C	9,1(35,5%)	15,1(50,7%)	15,7(49,5%)	7(36%)	11,2(51%)	12(50%)

Average rates of energy consumption.

	B2			B3		
	01	02	03	01	02	03
22°C→20°C	150,7(85,5%)	283,8(90,5%)	323,2(91%)	116,6(87,3%)	231(94,7%)	259(92,5%)
22°C→18°C	159,8(90,6%)	299(95,3%)	339(95,5%)	125(93,6%)	234,4(96%)	269,4(96%)
20°C→18°C	9,1(35,5%)	15,1(50,7%)	15,7(49,5%)	8,4(49,4%)	3,4(26%)	10,4(50,5%)

Low rates of energy consumption.

	B2			B3		
	01	02	03	01	02	03
22°C→20°C	150,7(85,5%)	283,8(90,5%)	323,2(91%)	89,1(88,8%)	75,2(86,7%)	88,5(87%)
22°C→18°C	159,8(90,6%)	299(95,3%)	339(95,5%)	95,3(95%)	81,6(94%)	95,7(94%)
20°C→18°C	9,1(35,5%)	15,1(50,7%)	15,7(49,5%)	6,2(55,4%)	6,4(55,6%)	7,2(54%)



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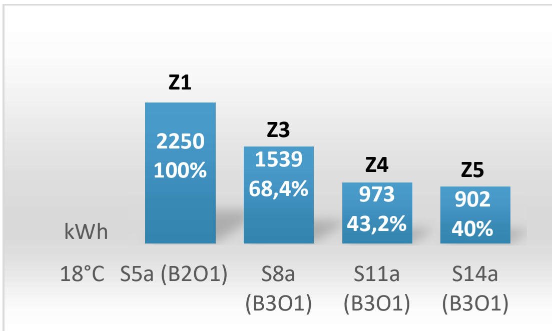

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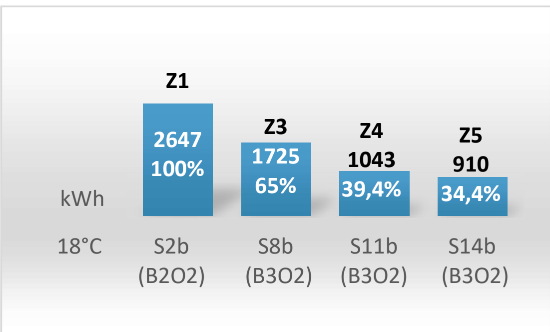

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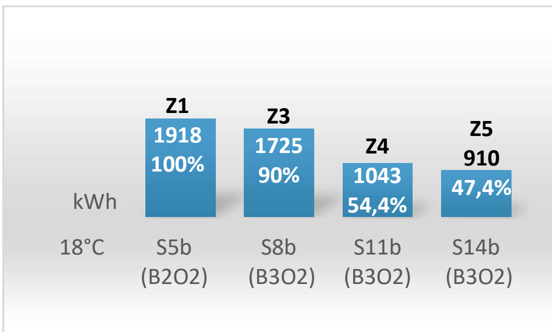

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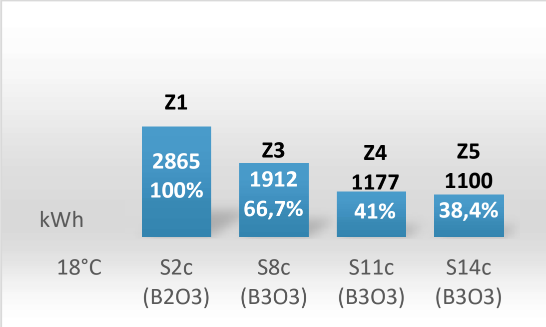

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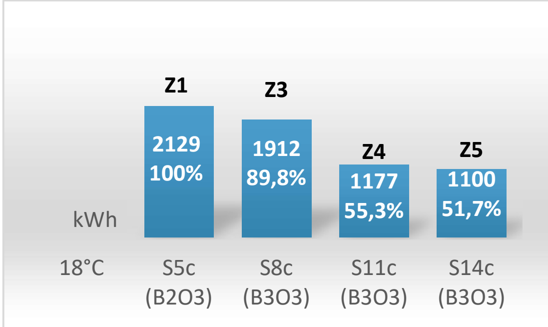

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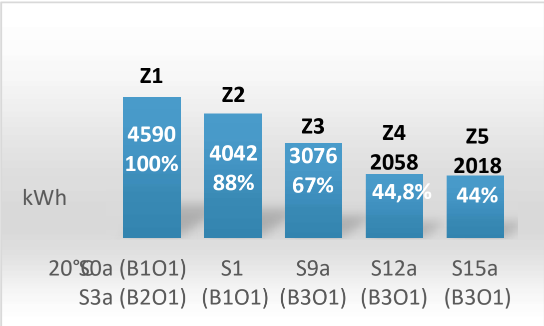

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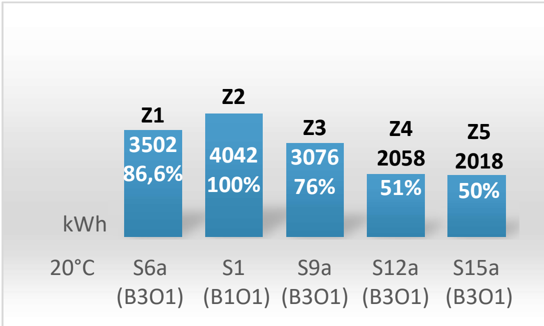

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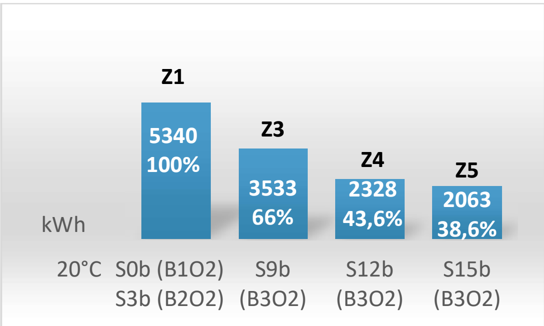

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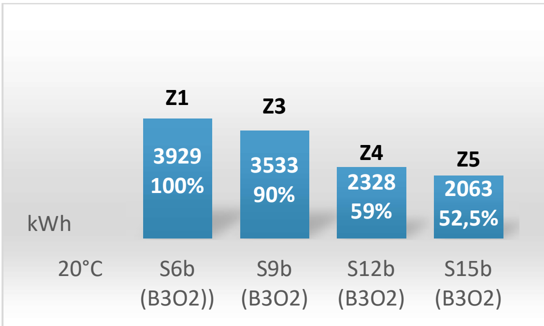

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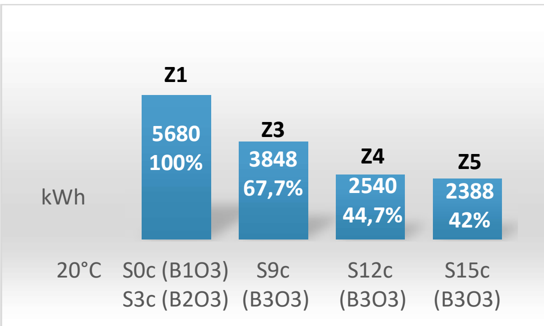

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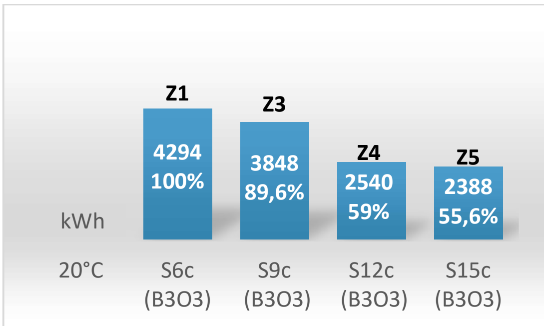

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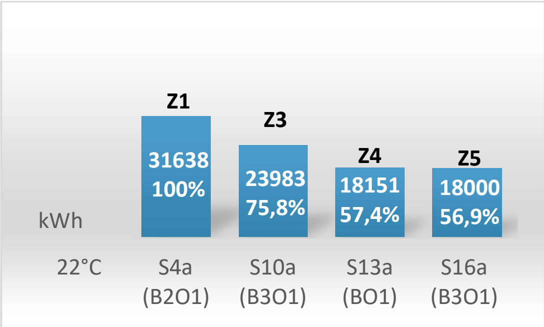

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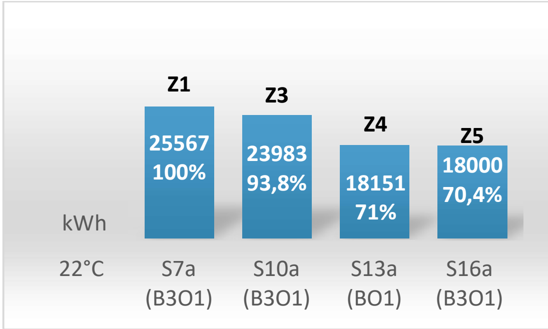

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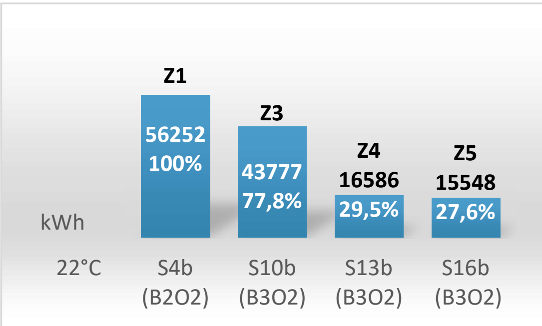

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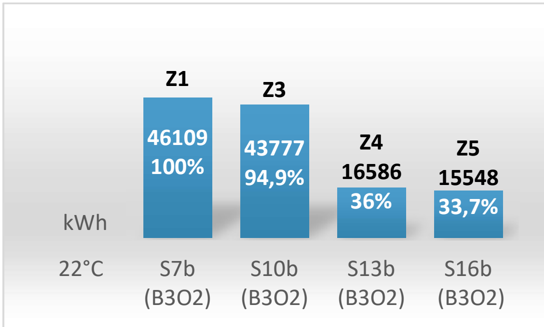

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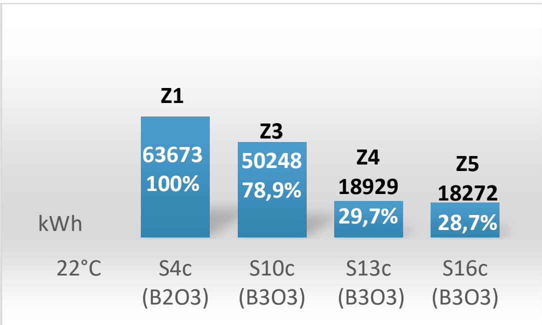

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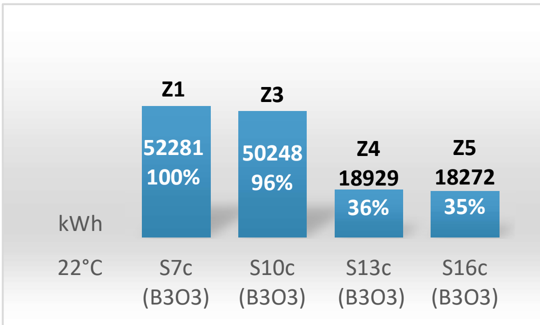


18)

Figure 14. Column chart 1-18. Comparison of energy results by zonal control

The next part of this study is to determinate the energy saving of evaluated scenarios. Thus, find out the more energy efficient option or options. Which is the purpose of this work.

In **Figure 15** the energy saving between different set point temperatures of all assumed scenarios represented, grouped by zones and occupancy profile. The temperature as in a previous graphs denoted with colors. The biggest energy saving of about 90- 95% is noticed between 18°C and 22°C for all zones.

In **Figure 16** the energy saving between occupancy scenarios are indicate. Depicted in three colors. The highest energy economy of about 50% seen between O1 and O3 in favor of last one (Z1 and Z3, at temperature 22°C). Therefore, meaningful effects on energy saving are evaluated for the 2 person occupancy profile, which also, corresponds to heating operation H3(O3) and to

H6(O3). Among these heating operations the H6(O3) considers as more efficient due to application of TRVs. These data were necessary, as they are directly related to internal comfort and energy consumption.

As seen before the greatest impact on energy consumption is related to the indoor temperature set-point. In **Table 4** the summary of energy saving related to set point temperature applying different types of boilers are presented, referring to **Figure 13**. It shows the high rates, average rates and low rates of energy saving between boilers. Thus, a maximum energy saving of about 75%-96% is appreciated when changing from a temperature set-point of 22°C to 20°C and when changing from 22°C to 18°C for B2, B3 boilers. This demonstrates the importance of user interaction comparing to other design aspects. Additionally, the mean value of energy saving between assumed type of boilers has also been represented in **Figure 17**.

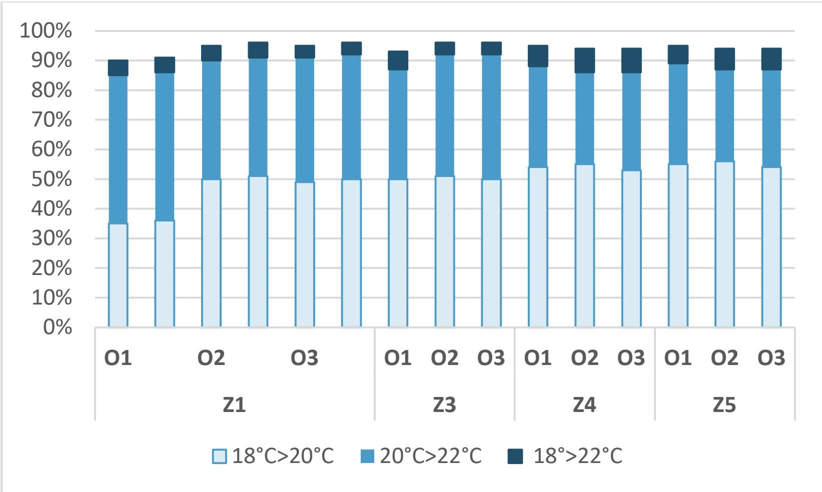


Figure 15. Annual energy saving comparing applied setpoint temperature.

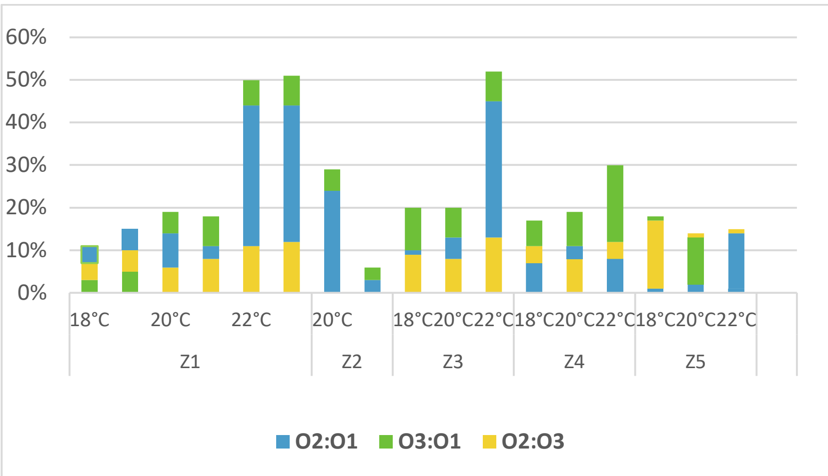


Figure 16. Annual energy saving comparing applied occupancy profiles.

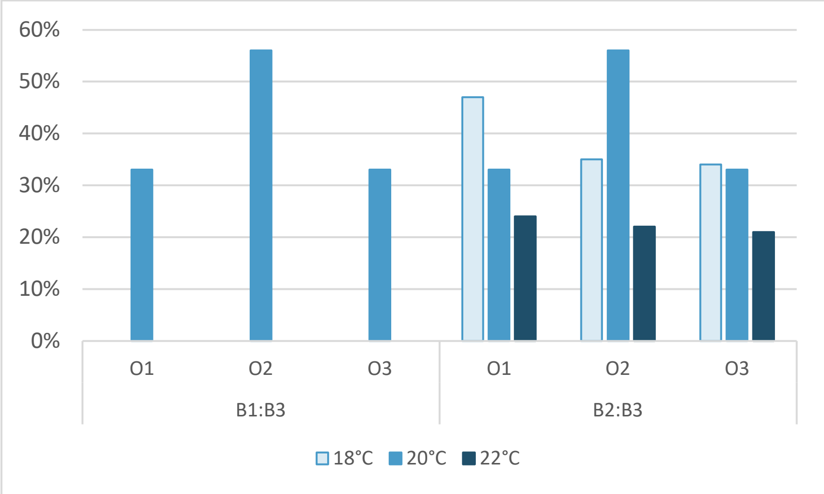
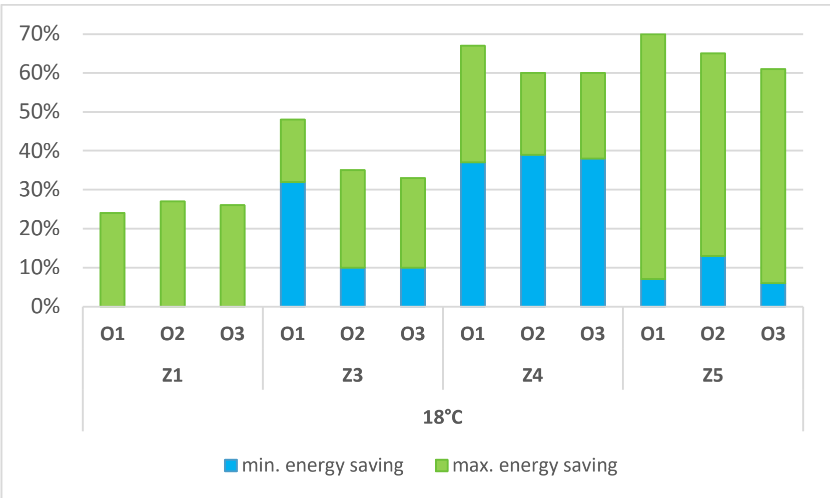
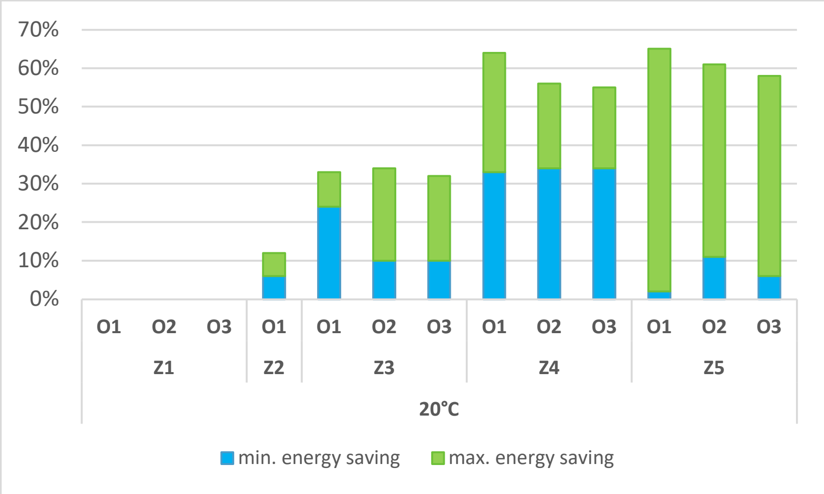


Figure 17. Summary of energy saving of different type of boilers. Average rates of energy consumption.

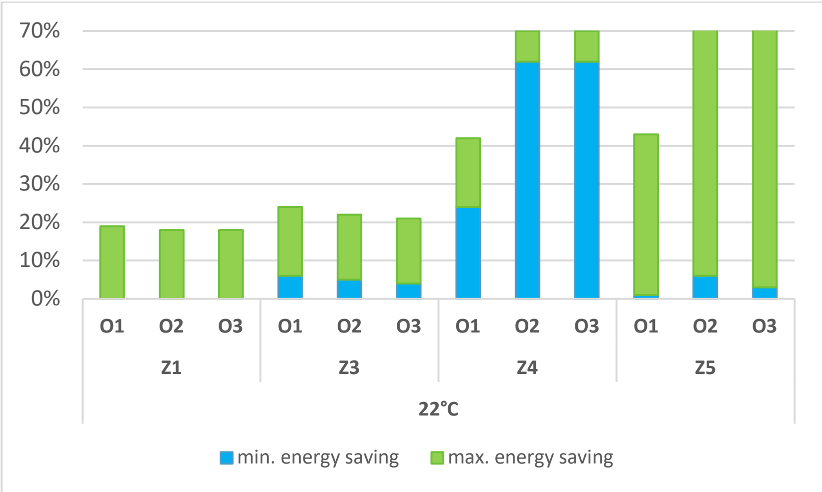
Finally, **Figure 18** represents the maximum and minimum energy saving related to each zonal control. In this figure the zonal controls were compared and energy savings in percentage between them were obtained. Here in case of 18°C, Z4 and Z5 have from approximately 60%-70% of maximum energy saving and Z1 and Z3 – 24%-48% of energy saving; in case of setpoint temperature 20°C, the Z4, Z5 have from 55%-65% of energy saving and Z2, Z3 – 12%-34%, thus, Z1 have no energy savings; and at the setpoint temperature of 22°C, can be observed the energy saving of about 70% for zone Z4 and zone Z5 and 18%-24% for Z1, Z3. The Z4 and Z5 have highest energy saving due to the application of TRVs. In turn, TRVs are self-regulate, changing the flow of hot water into a radiator, depending on heating operation schedules for each room (heating is on less hours in this case, whereas the operation schedule of whole house thermostat has almost all day and night heated), that provides additional energy saving. At the same time, the occupancy schedule coincides with heating operation for all scenarios. In other words, have the same hourly schedule.



a)



b)



c)

Figure 18. Annual energy saving related to zonal control.

5. 2. Analysis of indoor inironment

Regarding to indoor comfort

In general there are three factors that affect indoor comfort of building: Temperature (air temperature, mean radiant temperature, operative temperature), indoor air quality and control or zonal control considered in this project. Apart of this, the relative humidity, personal factors (metabolic rate of factor 1 and clothing insulation- winter clothing:1 clo, summer clothing: 0,5 clo), air velocity were taken in consideration in this study. In **Figure 19** some factors that affect inner comfort are analyzed.

In this figure, the mid winter day (15 january), setting for 20°C as inner operative temperature was taken as an example. Thus, it is possible to see the behavior of these factors for each zonal control.

After analyzing the factors mentioned before:

Temperature.

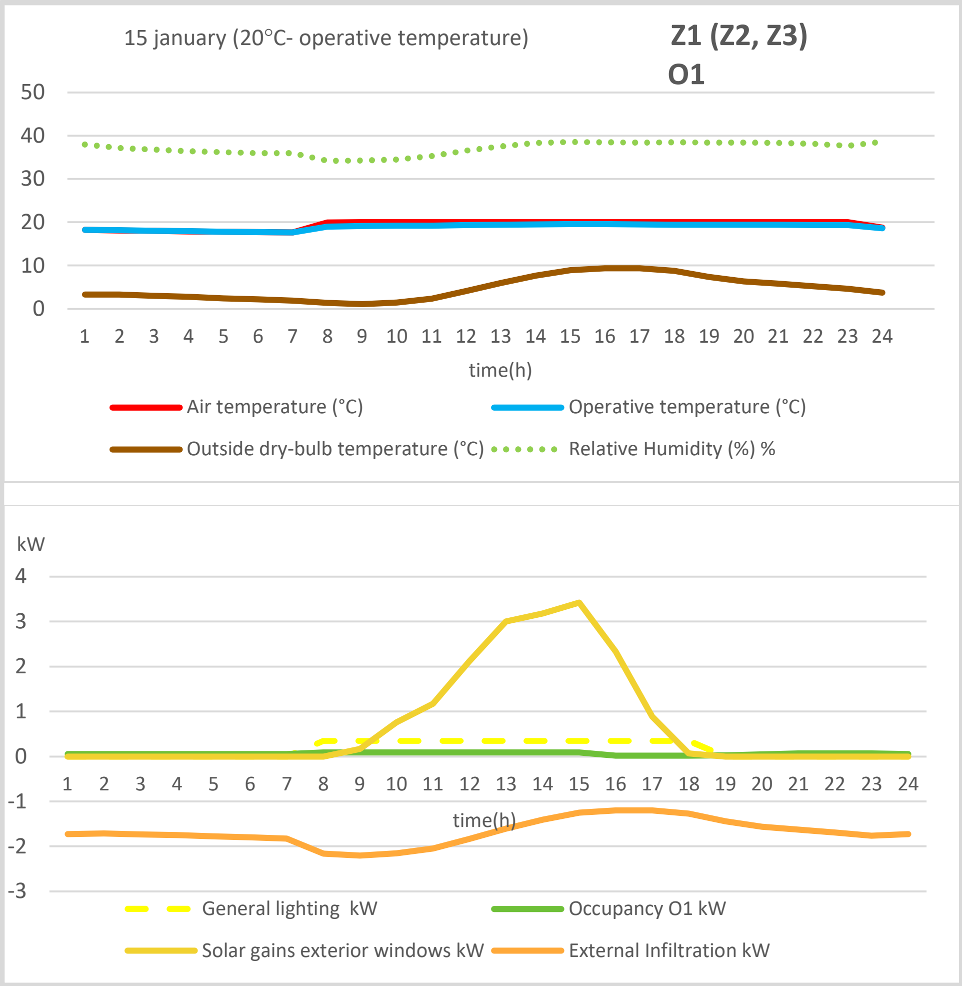
The most obvious factor affecting indoor comfort is for sure temperature. In this study taking in consideration an air temperature. An efficient Individual heating system will effectively heat the house to desired indoor temperature, for this it is important to conduct routine maintenance of the system. Also, the insulation plays an important role to keep heating system work efficiently. Insulation will better regulate your indoor temperature, improving comfort. To see the impact of heating system on indoor comfort were applied three types of set temperatures - 18°C, 20°C, 22°C (operative temperature) and humidity control ranges from 10-90%. And it is evident, the operative temperature together with occupancy profiles and heating operation have great impact on inner temperature (air temperature) maintaining the appropriate constant temperature. Therefore, we can see that air and operative temperatures have almost the same value during a day, in accordance with different type of occupancy schedules. As well as humidity strongly related to set temperature. Regarding to solar gains and general lighting, the graph shows the constant parameters for all zonal controls. But in case of scenario S1 – zonal control Z2 (thermostat control located in kitchen), due to the orientation of house toward south, solar gains, gains from kitchen equipment have greater effect on inner air temperature, help partially heat the room, so heating operation not reaches the set temperature. And, accordingly, it has less energy consumption.

Indoor air quality

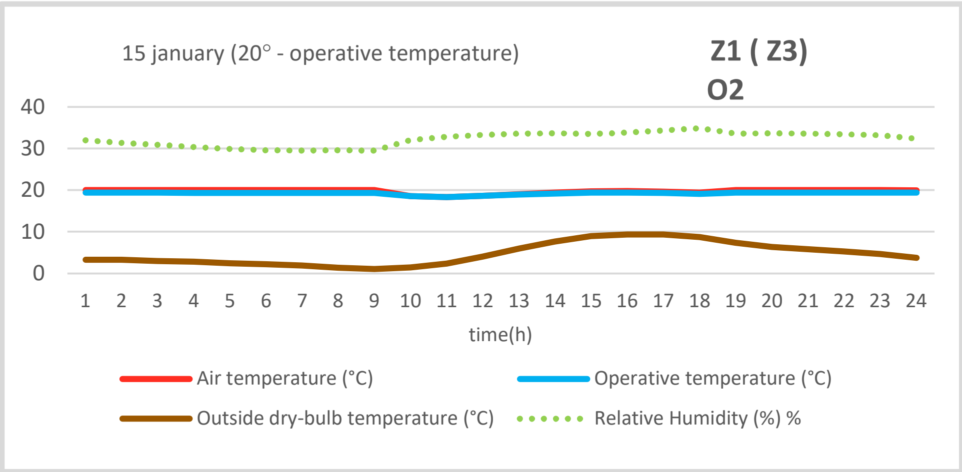
Dirty or stuffy air is not only unpleasant but also unhealthy for the occupants. It is recommended the airing of building. For this the simulation of the family house provides the mechanical and natural ventilation both applying the heating operation schedule, as well as infiltrations with constant rate 0,700 ac/h.

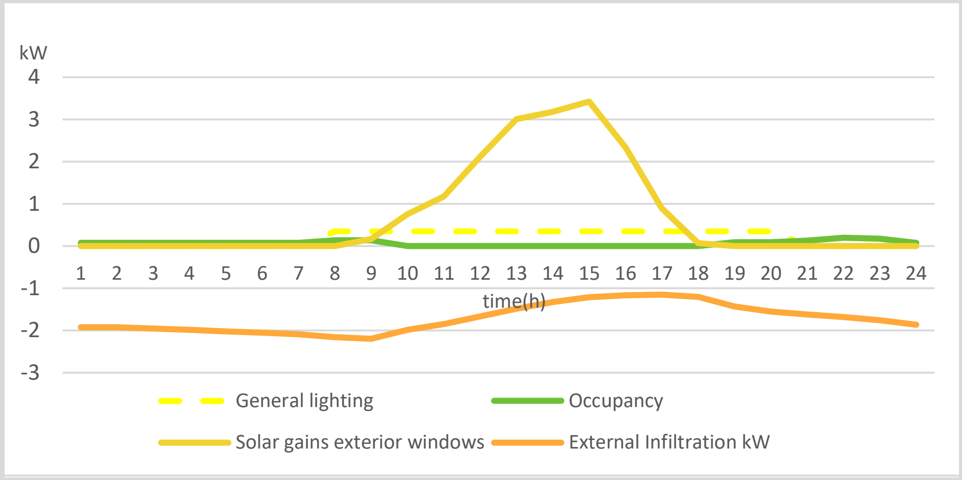
Control or zonal control

Part of indoor comfort is related to the control of individual heating system. A programmable thermostat and TRVs allow to control indoor temperature by setting desired or necessary temperature based on family´s daily routine and keep home comfortable throughout the day and save on energy cost.

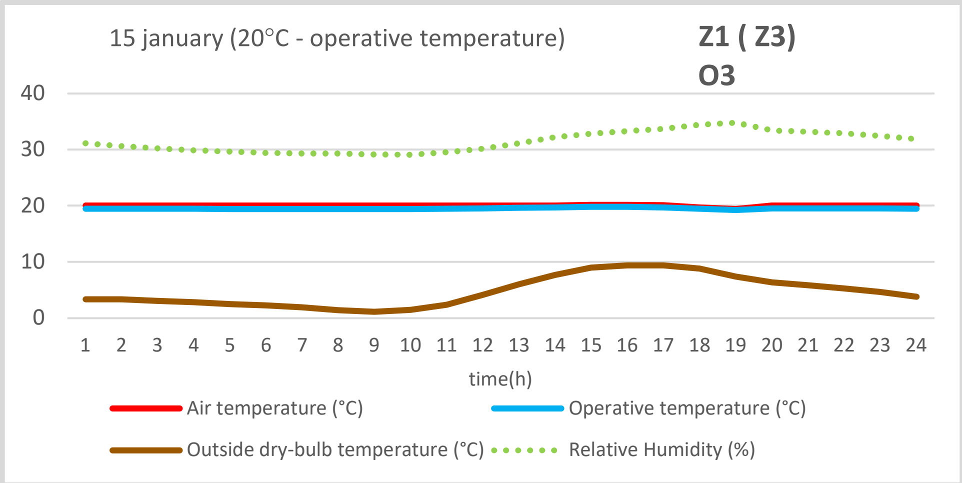

15 january (20°C- operative temperature)
Z1 (Z2, Z3)
O1
time(h)
Air temperature (°C)
Operative temperature (°C)
Outside dry-bulb temperature (°C)
Relative Humidity (%) %
kW
time(h)
General lighting kW
Occupancy O1 kW
Solar gains exterior windows kW
External Infiltration kW

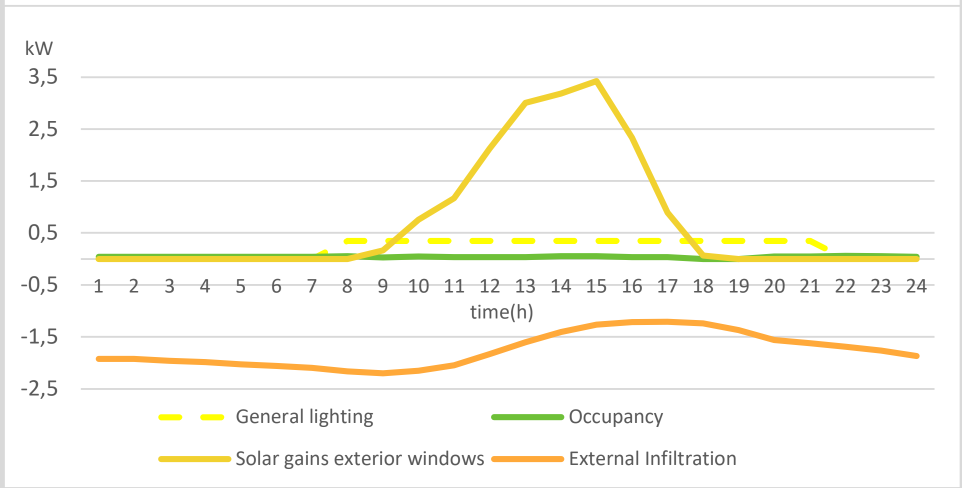
a)


15 january (20° - operative temperature)
Z1 (Z3)
O2
time(h)
Air temperature (°C)
Operative temperature (°C)
Outside dry-bulb temperature (°C)
Relative Humidity (%) %

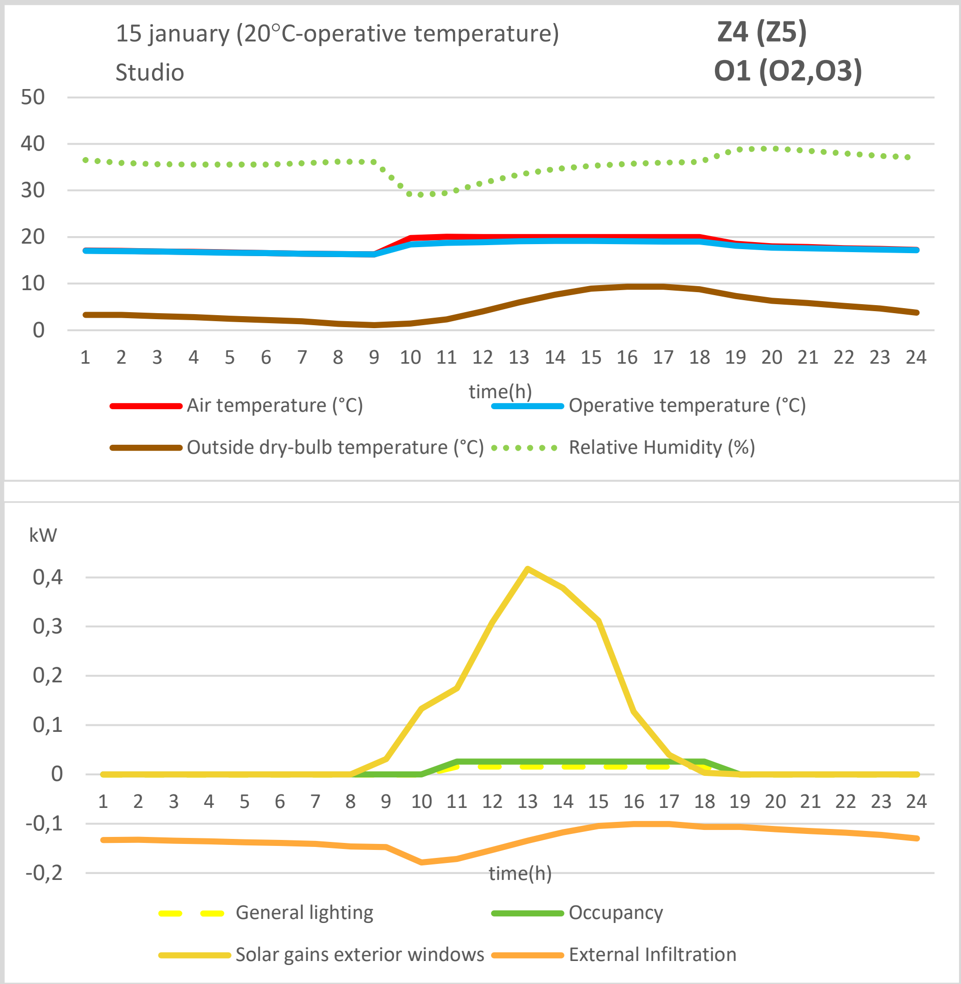

kW
time(h)
General lighting
Occupancy
Solar gains exterior windows
External Infiltration kW

b)

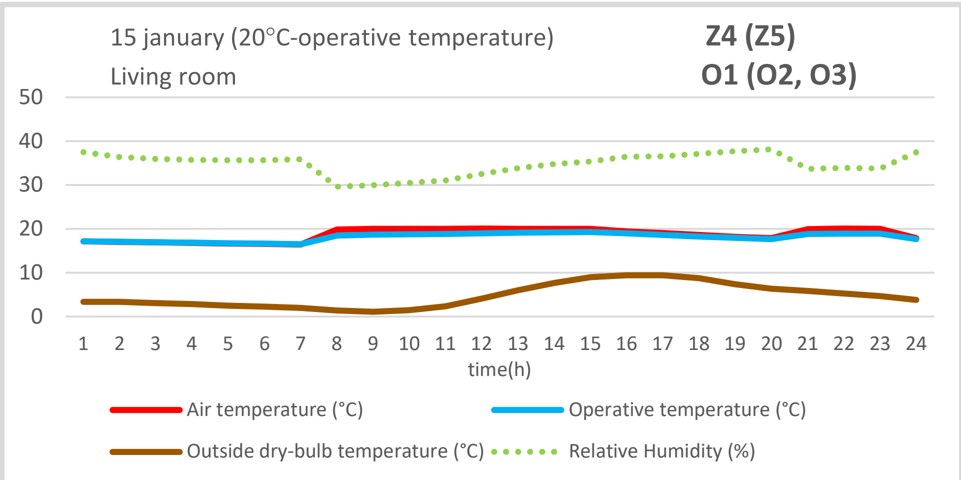

15 january (20°C - operative temperature)
Z1 (Z3)
O3
time(h)
Air temperature (°C)
Operative temperature (°C)
Outside dry-bulb temperature (°C)
Relative Humidity (%)

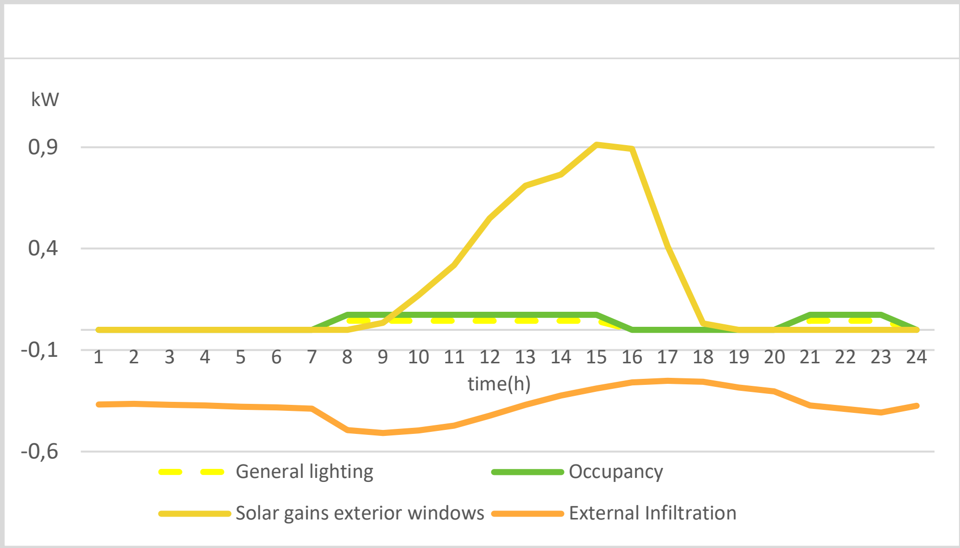

kW
time(h)
General lighting
Occupancy
Solar gains exterior windows
External Infiltration

c)

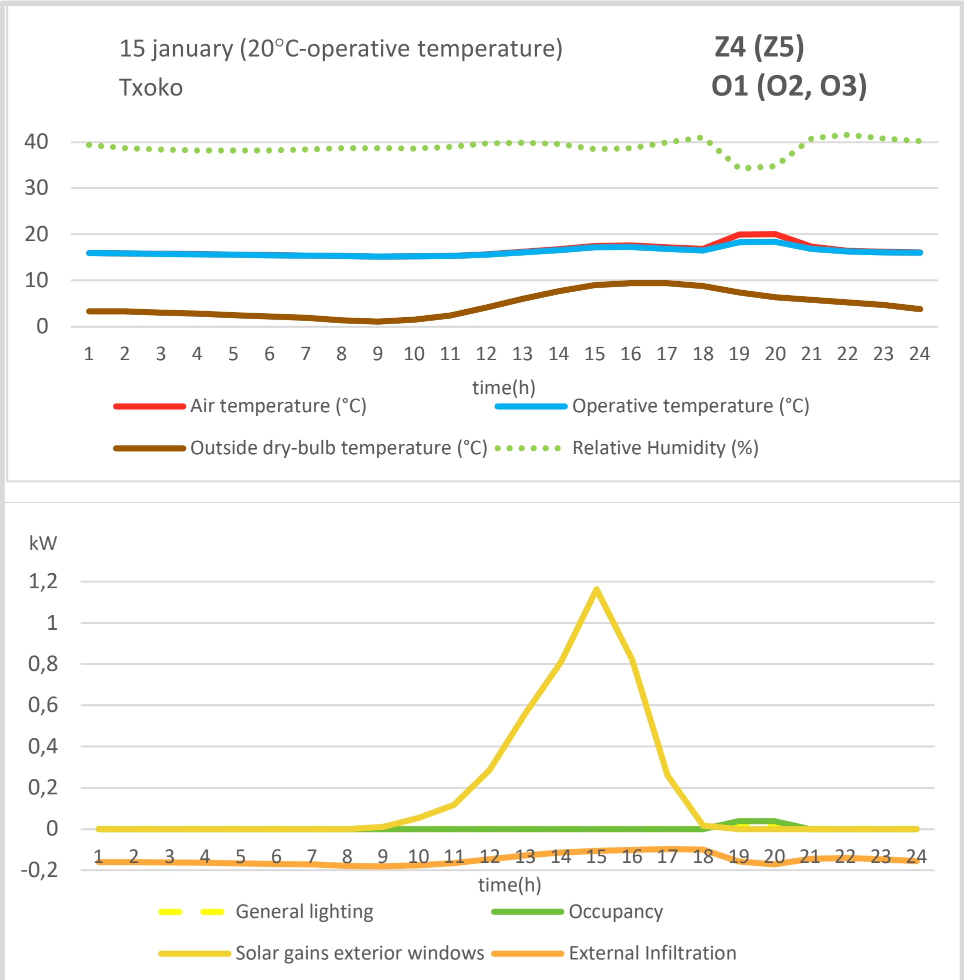

15 january (20°C-operative temperature)
Studio
Z4 (Z5)
O1 (O2,O3)
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time(h)
Air temperature (°C)
Operative temperature (°C)
Outside dry-bulb temperature (°C)
Relative Humidity (%)
kW
0,4
0,3
0,2
0,1
0
-0,1
-0,2
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time(h)
General lighting
Occupancy
Solar gains exterior windows
External Infiltration

d)

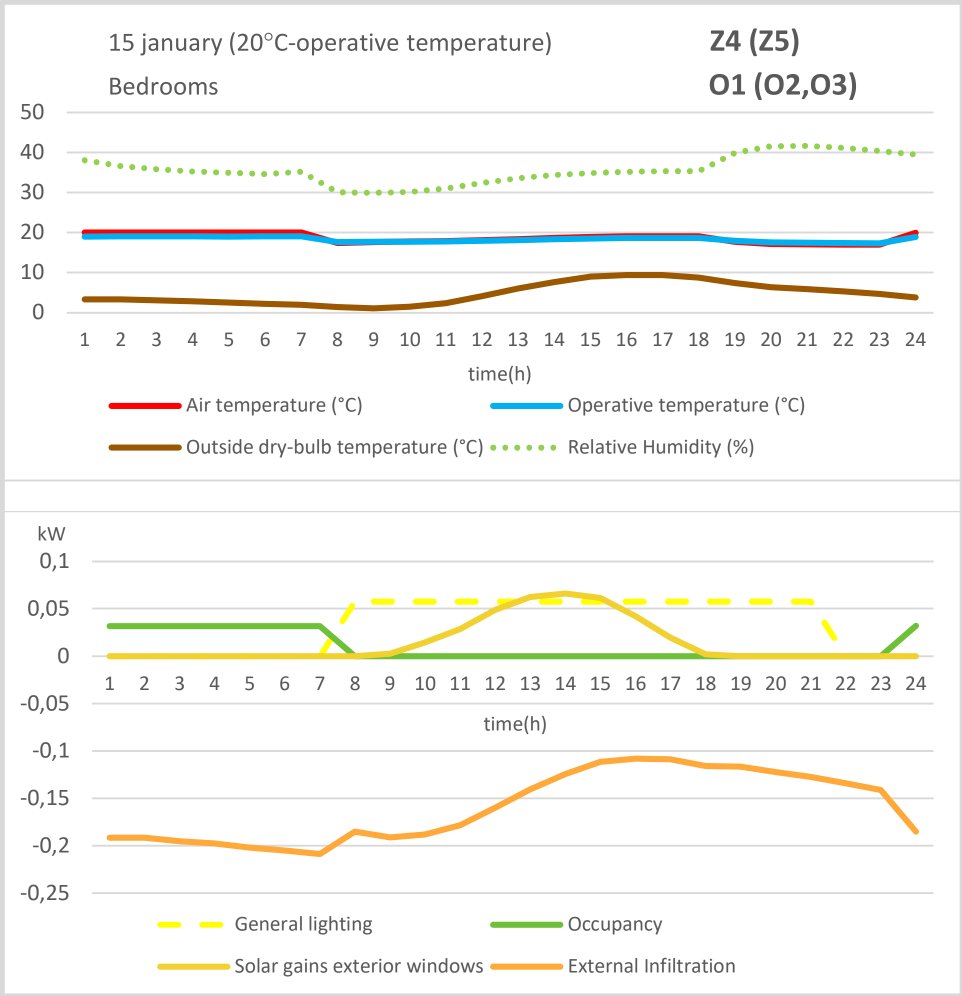

15 january (20°C-operative temperature)
Living room
Z4 (Z5)
O1 (O2, O3)
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time(h)
Air temperature (°C)
Operative temperature (°C)
Outside dry-bulb temperature (°C)
Relative Humidity (%)


kW
0,9
0,4
-0,1
-0,6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time(h)
General lighting
Occupancy
Solar gains exterior windows
External Infiltration

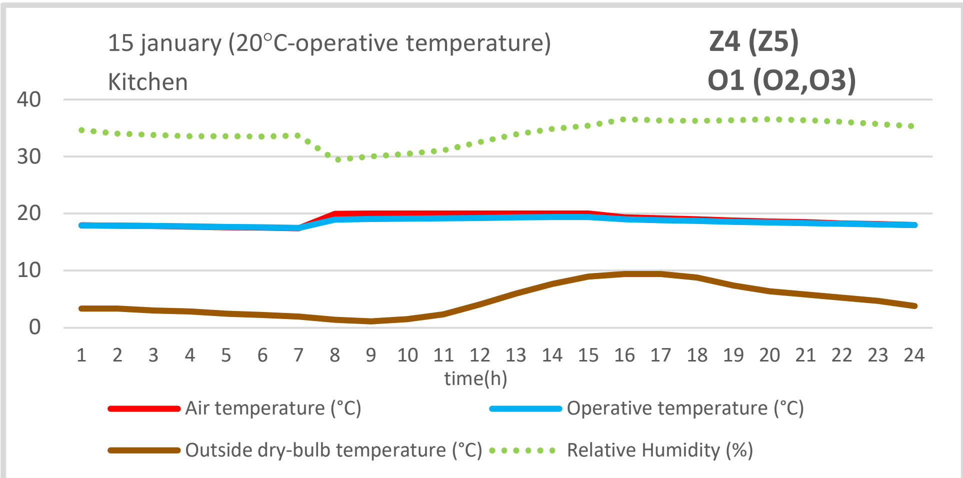
e)

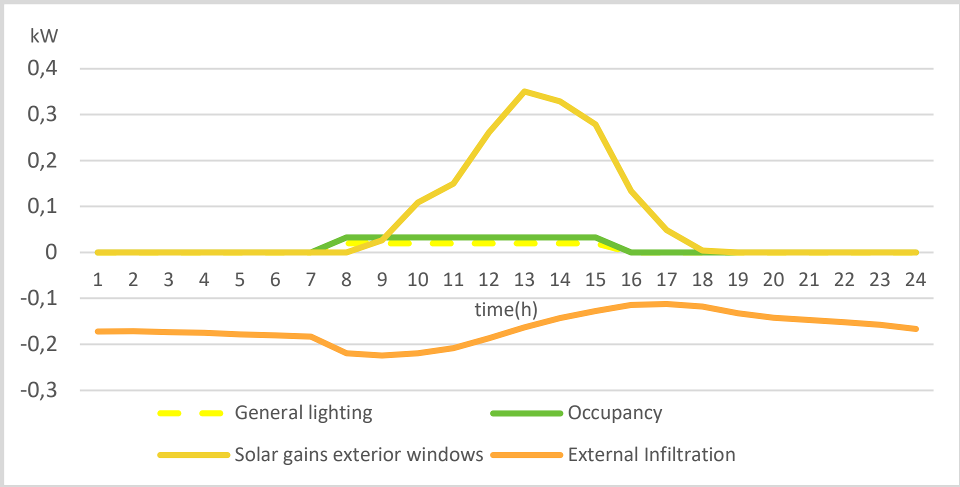

15 january (20°C-operative temperature)
Txoko
Z4 (Z5)
O1 (O2, O3)
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time(h)
Air temperature (°C)
Operative temperature (°C)
Outside dry-bulb temperature (°C)
Relative Humidity (%)
kW
1,2
1
0,8
0,6
0,4
0,2
0
-0,2
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time(h)
General lighting
Occupancy
Solar gains exterior windows
External Infiltration

f)

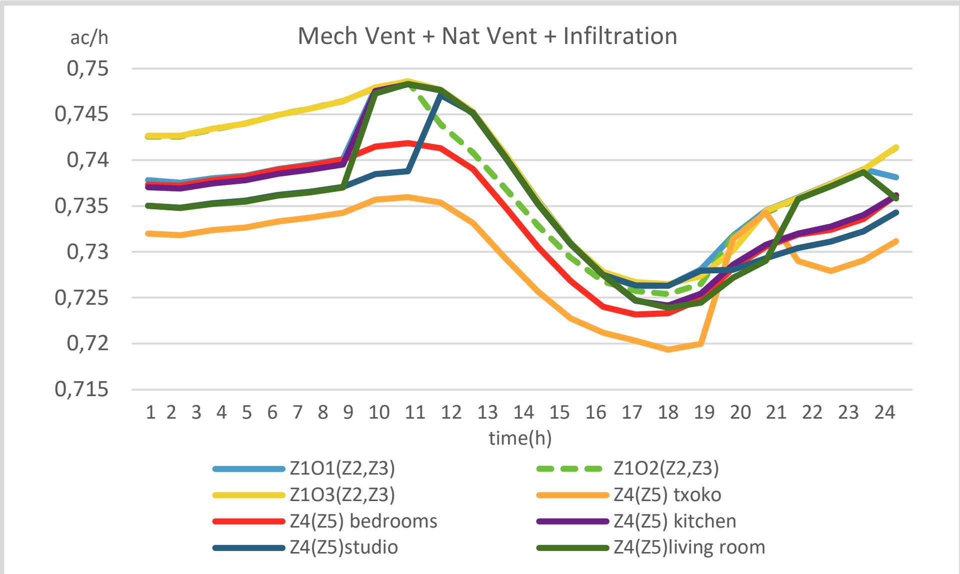

15 january (20°C-operative temperature)
Bedrooms
Z4 (Z5)
O1 (O2,O3)
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time(h)
Air temperature (°C)
Operative temperature (°C)
Outside dry-bulb temperature (°C)
Relative Humidity (%)
kW
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2
-0,25
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time(h)
General lighting
Occupancy
Solar gains exterior windows
External Infiltration

g)


15 january (20°C-operative temperature)
Kitchen
Z4 (Z5)
O1 (O2,O3)
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
time(h)
Air temperature (°C)
Operative temperature (°C)
Outside dry-bulb temperature (°C)
Relative Humidity (%)



h)

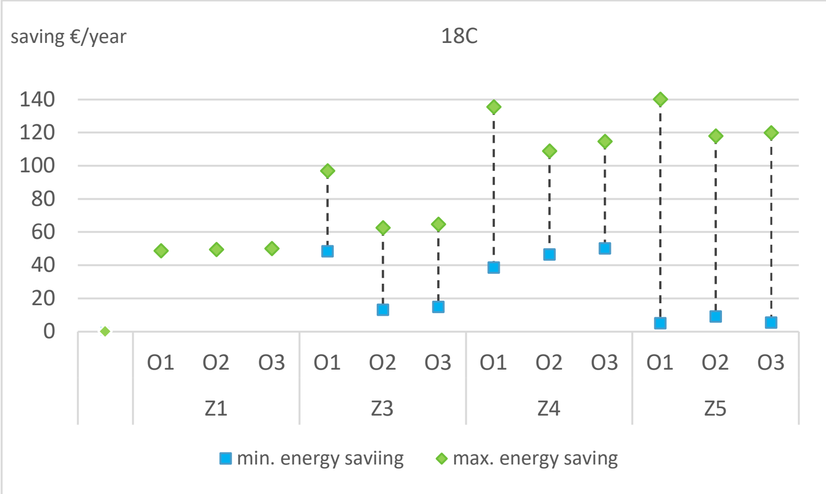


i)

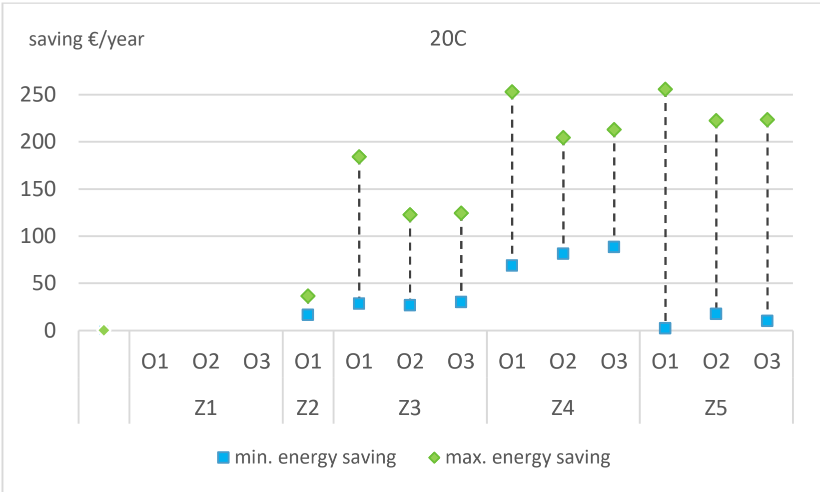
Figure 19. Factors affecting on internal environment

5. 3. Economic results

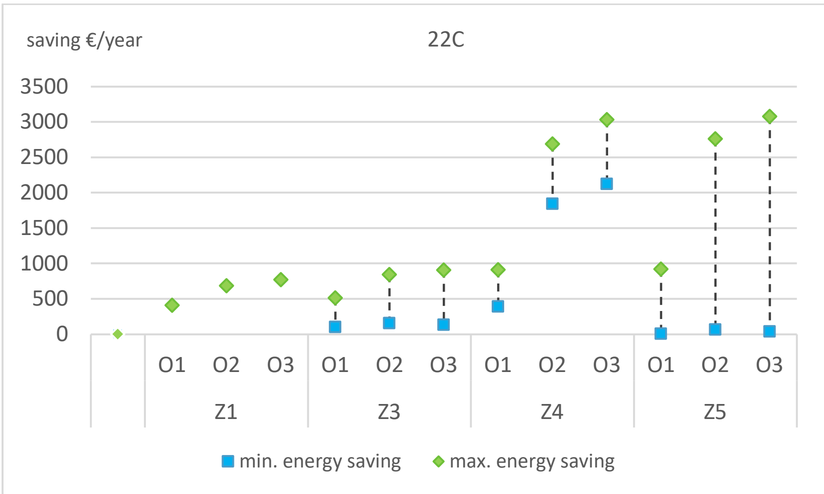
Referring to **Figure 18** the obtained energy saving were turned into economic saving presented in **Figure 20** as ranges from minimum to maximum yearly saving for the scenarios of each zonal control. It is clear that in most cases as in previous considerations the scenarios with Z4 and Z5 represent high economy both in cost and in energy.



a)



b)



c)

Figure 20. Economic saving for each scenario related to zonal control

6. CONCLUSIONS

In this master thesis has been studied how can affect the control of zoning in building and applied for this building individual heating system on energy consumption and indoor comfort for the occupants. A comparative analysis by simulation of 49 scenarios in real single family house situated near Vitoria Gazteiz is presented. For all evaluated scenarios was applied an individual gas heating system, applying 5 types of zonal control with a novel intelligent technologies as programmable thermostat, thermostatic radiator valves. These kind of technologies can achieve a significant energy saving and provide indoor environmental comfort. Afterwards, the energy and economic saving were obtained.

According to the results, their comparative analysis and savings obtained in previous section, the more efficient in term of energy saving options are defined. From them, the scenarios with zonal control where was applied temperature set-point 18 degrees resulted the most effective to reduce the energy consumption. Although this temperature cannot be considered as comfortable, but the setpoint temperature applied by STBC in this research project: 20°C for day-time and 17°C for night-time is. It is clear, that the higher is indoor temperature, the more comfortable a person should feel. However, very high indoor temperature can be harmful to human health.

The operation of heating systems plays a significant role. Condensing modulated gas-fired boiler (B3) offer higher saving than conventional boiler. It has the average rate of energy consumption amount of about 9,6 kWh/m^2 (at the setpoint temperature of 18°C); about 17 kWh/m^2 at the setpoint temperature of 20°C and about 220 kWh/m^2 for 22°C.

Focusing on occupancy profile, the scenarios with the application of O1 determinates as more energy efficient see **Figure 11**. As it provides the temperature set point for night time (17°C) lower than at day time. This occupancy schedule corresponds to Spanish Technical Building Code.

According to the results can conclude that the application of various zonal controls and application of individual heating system can significantly reduce energy consumption in the house and provide the necessary inner comfort conditions for occupants. Especially the significant energy economy noticeable in installing the one individual programmable thermostat control for each floor or zone comparing to thermostat control for entire house. But it turned out to be even more economical the zonal control with use of TRVs (zonal control Z4 and Z5). With their use the energy consumption is reduced for about 2 times. For example, for set-point temperature 18°C the average amount of energy consumption for both zonal controls is 937kWh (O1), 980kWh (O2), 1100kWh (O3); for 20°C 2040kWh(O1), 2200kWh(O2), 2460kWh(O3); for 22°C is 18000kWh(O1), 16000kWh(O2), 18500kWh(O3). A programmable thermostat in tandem with TRVs allow to control indoor temperature based on family´s daily routine and keep home comfortable throughout the day and save on energy cost.

In the future studies it is possible to consider some innovate control techniques as for example more advanced thermostats, that usually combining time and temperature programming and allow more complex profiles to be accommodated. The battery operated PTRV (programmable thermostatic radiator valves) can replace normal TRV, beside they have motorized valves to either enable or disable the hot water flow through the radiators according to a set-point temperature and time schedule. These can be set on the PTRVs themselves, via a central controller which communicates wirelessly with the PTRVs, or even remotely via a mobile phone or computer in some products. This could lead to some additional savings.

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APPENDIX I. Summary of 49 estimated scenarios

Scenario	Energy system				Temp. control		TVRs	SETPOINT (principal) TEMP			AIR TEMP			
	NG boiler	NG boiler (cond)	simple boiler	Modullating	1 (living room)	3 (one every floor		18°C	20°C	22°C		01	02	03
S0a														
S0b														
S0c														
S1					1(kitchen)									
S2a														
S2b														
S2c														
S3a														
S3b														

S3c														
S4a														
S4b														
S4c														
S5a														
S5b														
S5c														
S6a														
S6b														
S6c														
S7a														
S7b														
S7c														
S8a														
S8b														
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S10a														
S10b														
S10c														
S11a														
S11b														
S11c														
S12a														
S12b														

S12c															
S13a															
S13b															
S13c															
S14a															
S14b															
S14c															
S15a															
S15b															
S15c															
S16a															
S16b															
S16c															

APPENDIX II. Energy system – Individual heating system. Summary of yearly energy consumption by applying different types of boilers

	18°C					
№	**B1** (simple NG boiler) Scenario	kWh	**B2** (modulating NG boiler) Scenario	kWh	**B3** (modulating gas-fired condensing boiler) Scenario	kWh
1.			S2a (O1)	2967	S5a (O1)	2250
2.			S2b (O2)	2647	S5b (O2)	1918
3.			S2c (O3)	2865	S5c (O3)	2129
4.			x		S8a (O1)	1539
5.			x		S8b (O2)	1725
6.			x		S8c (O3)	1912

7.			x		S11a (01)	973
8.			x		S11b (02)	1043
9.			x		S11c (03)	1177
10.			x		S14a (01)	902
11.			x		S14b (02)	910
12.			x		S14c (03)	1100
	20°C					
	B1		**B2**		**B3**	
13.	S0a (01)	4588	S3a (01)	4595	S6a (01)	3502
14.	S0b (02)	5342	S3b (02)	5344	S6b (02)	3929
15.	S0c (03)	5681	S3c (03)	5684	S6c (03)	4294
16.	x		x		S9a (01)	3076
17.	x		x		S9b (02)	3533
18.	x		x		S9c (03)	3848
19.	x		x		S12a (01)	2058
20.	x		x		S12b (02)	2328
21.	x		x		S12c (03)	2540
22.	x		x		S15a (01)	2018
23.	x		x		S15b (02)	2063
24.	x		x		S15c (03)	2388
25.	S1 (01)	4042				
	22°C					
	B1		**B2**		**B3**	
26.			S4a (01)	31 638	S7a (01)	25 567

27.			S4b (O2)	56 252	S7b (O2)	46 109
28.			S4c (O3)	63 673	S7c (O3)	52 281
29.			x		S10a (O1)	23 983
30.			x		S10b (O2)	43 777
31.			x		S10c (O3)	50 248
32.			x		S13a (O1)	18 151
33.			x		S13b (O2)	16 586
34.			x		S13c (O3)	18 929
35.			x		S16a (O1)	18 000
36.			x		S16b (O2)	15 548
37.			x		S16c (O3)	18 272

APPENDIX III. Summary of yearly energy consumption by applying different zonal control

	18°C									
№	**Z1** (thermostat in Living room)		**Z2** (thermostat in kitchen)		**Z3**(one thermostat in each floor/zone)		**Z4**(thermostat in Living room with TRVs for each radiator)		**Z5**(one thermostat in each floor/zone and TRV for each radiator)	
	Scenario	kWh	Scenario	kWh	Scenario	kWh	Scenario	kWh	Scenario	kWh
1.	S2a (B2O1)	2967			S8a (B3O1)	1539	S11a (B3O1)	973	S14a (B3O1)	902
2.	S2b (B2O2)	2647			S8b (B3O2)	1725	S11b (B3O2)	1043	S14b (B3O2)	910
3.	S2c (B2O3)	2865			S8c (B3O3)	1912	S11c (B3O3)	1177	S14c (B3O3)	1100
4.	S5a (B3O1)	2250								

5.	S5b (B302)	1918								
6.	S5c (B303)	2129								
	20°C									
	Z1		**Z2**		**Z3**		**Z4**		**Z5**	
7.	S0a (B101)	4588	S1 (B101)	4042	S9a (B301)	3076	S12a (B301)	2058	S15a (B301)	2018
8.	S0b (B102)	5342			S9b (B302)	3533	S12b (B302)	2328	S15b (B302)	2063
9.	S0c (B103)	5681			S9c (B303)	3848	S12c (B303)	2540	S15c (B303)	2388
10.	S3a (B201)	4595								
11.	S3b (B202)	5344								
12.	S3c (B203)	5684								
13.	S6a (B301)	3502								
14.	S6b (B302)	3929								
15.	S6c (B303)	4294								
	22°C									
	Z1		**Z2**		**Z3**		**Z4**		**Z5**	
16.	S4a (B201)	31 638			S10a (B301)	23 983	S13a (B301)	18 151	S16a (B301)	18 000
17.	S4b (B202)	56 252			S10b (B302)	43 777	S13b (B302)	16 586	S16b (B302)	15 548
18.	S4c (B203)	63 673			S10c (B303)	50 248	S13c (B303)	18 929	S16c (B303)	18 272
19.	S7a (B301)	25 567								
20.	S7b (B302)	46 109								
21.	S7c (B303)	52 281								

APPENDIX IV. Annual results of occupancy scenarios by applying different setpoint

	18°C		20°C		22°C	
№	Scenario	kWh	Scenario	kWh	Scenario	kWh
1.	S2a (01)	2967	S3a (01)	4595	S4a (01)	31 638
2.	S5a (01)	2250	S6a (01)	3502	S7a (01)	25 567
3.	S8a (01)	1539	S9a (01)	3076	S10a (01)	23 983
4.	S11a (01)	973	S12a (01)	2058	S13a (01)	18 151
5.	S14a (01)	902	S15a (01)	2018	S16a (01)	18 000
6.			S0a (01)	4588		
7.			S1 (01)	4042		
8.	S2b (02)	2647	S3b (02)	5344	S4b (02)	56 252
9.	S5b (02)	1918	S6b (02)	3929	S7b (02)	46 109
10.	S8b (02)	1725	S9b (02)	3533	S10b (02)	43 777
11.	S11b (02)	1043	S12b (02)	2328	S13b (02)	16 586
12.	S14b (02)	910	S15b (02)	2063	S16b (02)	15 548
13.			S0b (02)	5342		
14.	S2c (03)	2865	S3c (03)	5684	S4c (03)	63 673
15.	S5c (03)	2129	S6c (03)	4294	S7c (03)	52 281
16.	S8c (03)	1912	S9c (03)	3848	S10c (03)	50 248
17.	S11c (03)	1177	S12c (03)	2540	S13c (03)	18 929
18.	S14c (03)	1100	S15c (03)	2388	S16c (03)	18 272
19.			S0c (03)	5681		