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Faculty of Engineering
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Performance Assessment of Heating Solutions for Dutch Residential Houses

Evaluation of IR-panels systems and comparison with heat pumps and low-temperature heating

Polito Supervisor:

Prof. Ing. Vincenzo Corrado

TU/e Supervisors:

Prof. Dr. Ir. Jan Hensen

Dr. Ir. Pieter-Jan Hoes

Candidate:

Filippo Biliotti

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Summary

Nowadays thermal comfort research is driven from the urgency of decarbonizing the built environment. Carbon-free heating solutions, like infrared (IR)-panels, are therefore proposed for residential houses on the market. These systems are claimed to be affordable, sustainable, and capable of reaching good comfort levels. This research, through the application of a case study building, evaluates the available method to assess thermal comfort in residential environments equipped with IR-panels, enlightens their accuracy with radiant solutions, and investigates their weaknesses. Then, is evaluated an IR-panels heating system, assessing its performances in terms of efficiency, comfort level, and cost, with particular attention to local discomforts. This system is evaluated in its actual configuration (as implemented in a residential house in the Netherlands) and with the implementation of new control strategies based on the adaptive theories analysed. Finally, it is done a comparison of the IR-panels' performances, with the one of another all-electric solution, a heat pump heating system combined with radiant floors, implemented into the same case study building. The research's outcomes for the IR-panels verify good overall comfort levels, but the available methodologies proposed to assess thermal comfort may overlook some critical condition of discomfort. Indeed, with IR-panels active, it is likely to be exposed to high radiant asymmetry, even if the overall comfort sensation assessed is within the limitation. IR panels heating systems seem now not capable of reaching the performances guaranteed from heat pumps, especially in terms of energy consumption, however this does not exclude that they can be a comfortable-affordable solution for applications as small apartments, rather than family houses like the case study building.

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1. Introduction

1.1. Context

It is a nowadays common understanding that the built environment is one of the main responsible for the CO2 emission in the global atmosphere as, e.g., in Europe buildings account the 30-40% of the total primary energy consumption [1], therefore research has seen an intensification of effort since this has become a sensitive matter. The task is to heat the built environment in the most sustainable way possible, trying to reach the desired comfort level with higher standards of efficiency and energy consumption. In this direction, one of the newest technologies on the market are infrared (IR) panel heating systems. Supporters claim the IR-panels to be affordable, comfortable, and sustainable, while opponents say that the benefits claimed are hardly verified. Nowadays, relatively little research has been done into this topic, and most reports compare IR systems with conventional natural gas heating, and not with other electrical alternatives. It is easy to understand the need to compare the infrared panels with another solution all-electric. Regarding this, solutions like heat pumps heating systems, are not only meeting this requirement but also are one of the most used solutions, which makes them the perfect target for the comparison.

Currently TU/e and other partners are involved in the *HERSCHEL project (Harnessing Effective Radiation Solution with Comfortable Heated Energy Levels)*, in which the performance of an IR-panels heating system is evaluated. The project partners are TU/e, ONexus, JADS and Beligreen, united in the aim to develop a predictive comfort model for a heating solution with IR-panels.

This research is related to the HERSCHEL project, sharing information needed and data collected from the HERSCHEL-case study building where the panels have been installed.

1.2. Infrared Heating: An Overview

Infrared radiation panels convert electricity into radiant heat, transferring the heat to a target via the emission of infrared radiation [1]. The applicability of this system is vast, depending on the technology used and the type of environment. As well for domestic solution, this system is applied in health and medical application, or industries' process. Unlike other systems, they do not heat the air but directly objects and people, which, on the other hand, will themselves emit radiation and heat back the surrounding environment. Usually, there is a specific range within which is felt the heat (approximately 3 meters) [2] outside which the heat won't be perceived. As well for objects outside the range, also parts of the body which are not directly hit by the radiation wave will not be heated. This technology works differently from the most common solutions available on the market (e.g. convective solutions), and it is claimed that the results would be a considerably less energy consumption. The whole point of this consideration lays in the assumption that heating the air of a room would require much more energy than heating directly the occupants and surrounding objects, but still, this matter need to be investigated properly and this is just one of the aim of this project. Literature also claim that electric heating is not affordable/suitable solution for domestic heating, however they do offer an efficient and quick response, almost instantaneous, as they do not need to pre-heat the air [1].

The radiation produced from the panels will heat objects and not the air, so it is important to verify that the difference between the air temperature and the mean radiant temperature must be not too high, resulting otherwise in an unpleasant condition. As a matter of fact, with this system, subjects are likely expose to possible local thermal discomfort condition which will require specific attention, such as:

- Asymmetry in radiant temperature;
- Vertical gradient temperature;
- Draft risk;

These systems can be classified by the wavelength of the peak of the infrared radiation, through which can be defined short, medium or far/dark. Infrared panels are available on the market with different fuel option; however, the electric solution does not require any pipe work, and this is a big advantage for installation or fuel storage facilities. Usually those type of panel, use a tungsten wire filament material which is coiled to enhance the surface area. A common material combined with these systems is ceramic, 90% absorbent of the radiation and then used to direct it towards object.

Resuming the main benefits claimed we find low energy consumption, high efficiency, competitive price for the whole system, and a straightforward installation, other than being silent and requiring not much space to be placed or maintenance. Nevertheless, the electric solution of these systems guarantees a 100% efficiency but, once more, very little literature exists for the characterization of electric infrared heaters, especially when it comes to domestic applications, where it is evident that an accepted methodology for evaluating the performances of IR heating device still needs to be defined [1].

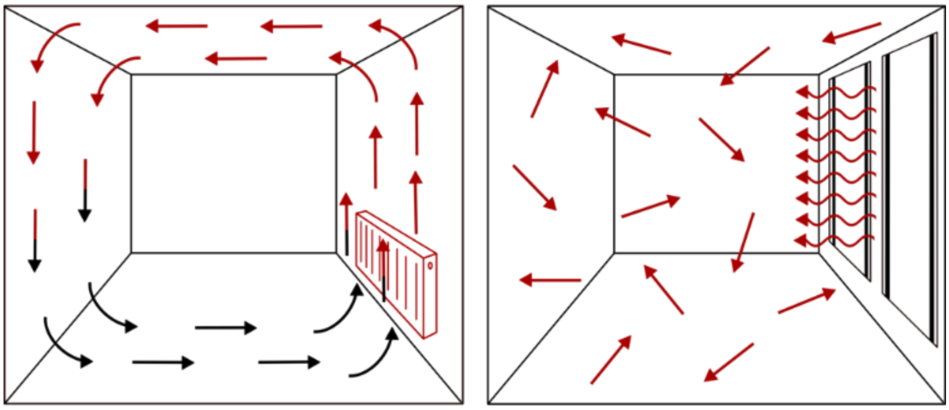

Fig. 1: Different heating solutions: on the left convective, on the right infrared-radiant

1.3. Objective, Research Questions and Report Structure

The objective of the research is to evaluate electric infrared panels as a sustainable solution to heat residential environment in the Netherlands and compare it with another common heating solution: an electric heat pump with floor heating. The IR systems is evaluated in its actual available system configuration, as it is implemented in the HERSCHEL case study building, and with the implementation of new thermal comfort theories, derived from the literature research. The evaluation will be based mainly on the comfort level assessed, and the energy consumption. Assessing thermal comfort is a complex matter when it comes to residential environments and, when it comes to infrared panels, an accepted methodology to adopt still needs to be defined. For this reason, another aim of the research is to investigate whether the available methods to assess thermal comfort can be considered reliable, and in which conditions. Also, from the evaluation of the heating system, is possible to investigate more type of control derived from the implementation of different adaptive setpoint temperature, so to enlighten their possible benefits or weaknesses.

The methodology applied approaching to the problem has been developed over some “research questions”, which answers, placed in their logical order in the process, will bring step by step closer to the final goal (detailed methodology applied in Chapter 3). The research questions help define the structure of the report, which is basically composed by three stages, with the related questions reported below.

1) *Assessing Thermal Comfort: How to assess thermal comfort in residential houses? What methods are available/commonly used? Are the existing comfort models working for IR systems?*
2) *Modelling IR-panels in Building Performance Simulation (BPS) Model: Which are Infrared Panel’s special features? What are the most important parameters to consider? How evaluate these characteristics in a BPS model? How to validate the model?*
3) *Performance comparison: Which are the most relevant performance indicators? Comparing IR systems with heat pumps, which one is more suitable and when? How many different scenarios could these considerations be extended to?*

The structure of the report sees the Chapter 2 dedicated to state of the art in assessing thermal comfort, which gives an overview of the available method and the direction pointed from research around the topic, while in chapter 3 is described the methodology adopted for the research. In chapter 4 is provided a detailed overview of the case study building, of which the energy simulation model is described in chapter 5. Chapter 6 is dedicated instead to the heat pump model, while in the 7th are shown the simulation’s results. Finally, chapter 8 is dedicated to the discussion of the research outcomes.

2. Thermal Comfort in Residential Buildings: State of the Art

2.1. From Fanger's PMV to Adaptive Models

Thermal comfort is defined as *"that condition of mind which express satisfaction with the thermal environment"* [3], and it's the result of the combination of different factors related to the environment itself, but also occupants. The interaction of these two, environmental and personal factors, will affect the occupants' state of mind in terms of whether they feel satisfied or not from the thermal condition. In this context, the thermal environment is considered by different parameters, like air temperature, mean radiant temperature, air velocity and partial pressure of water vapour, while metabolic rate and clothing insulation are representative of the occupants. It is from these theories that evolved Fanger's Predicted Mean Vote (PMV), which stands among the most acknowledged thermal comfort model. Developed in the late 1960s using principles of heat balance and climate chamber experiments, was further included in many different standards, most remarkably ISO 7730 (1984) and ASHRAE 55-1992. Well-established that satisfying the heat balance comfort equation is a condition for comfort, PMV represent "*the difference between the internal heat production and the heat loss to the actual environment for a man kept at the comfort value for skin temperature and sweat production at the activity level"* [3]. Quantifying the sensation with an adapted ASHRAE-7 point psycho-physical scale, where a vote of 0 stands for thermal neutrality and so for comfort condition, Fanger was able not just to obtain a method that allows predicting what vote could arise from a group of people, but also to determine the relationship between PMV and the predicted percentage of dissatisfied (PPD). Assuming the impossibility to satisfy the totality of persons and examining local discomfort condition, with these two indexes not only the thermal sensation for moderate thermal environments' occupants become predictable, but also guidelines are given to define the PPD ranges whether the environment thermal conditions are acceptable or not.

Without specifying the applicability ranges for the model's parameters, PMV is revealed not capable of expressing the effects of the changes in time. Firmly established that this model applies to stationary condition in temperate environment, many studies, conducted since its introduction, have enhanced PMV inadequacy, or at least its limits, for certain conditions. Humphreys and Nicole found that more the thermal condition is far from neutral state, the less reliable is the index, while Becker and Paciuk [4], discussing the relation between PMV and PPD, found that it's not symmetrical around the thermoneutrality as expected, especially on the warm side and for residential buildings. After field studies, conducted both on naturally ventilated and air-conditioned buildings, De Dear and Brager assumed that for the first group the neutral temperatures significantly differed from the predicted (overestimated up to 2,1 °C and underestimated up to 3,4°C); they consequently established the non-applicability of the model for naturally ventilated buildings and concluded that this is due to the model's partial accounting of personal adaptation to the indoor environment. Other studies showed also that occupants of air-conditioned buildings are twice as sensitive to changes in temperatures as occupants of naturally conditioned buildings and that are less incline to adapt to that changes. On the contrary, other than being more tolerant to a wider range of temperature, occupants of naturally conditioned buildings are also more active in thermoregulatory adaptation trough changes in activity level and clothing [4].

Despite all criticism, the PMV-model has many strengths, it is starting from these that many proposals of modifications trayed to overcome the previously mentioned limitation. The limits of the theory emerged later, with the necessity of analysing dynamic environments, and lies in the assumption of steady-state condition. That hypothesis later has been understood not representative of the real state in buildings, and this difference is enhanced focusing on residentials. It is in these type of buildings that there are multiple zones with different thermal comfort requirements and where occupant's activities are less predictable or, more in general, subjects have more ways to adapt to the environment than e.g. in offices [1, 2]. The adaptation process was first defined by de Dear and Brager (1998) and later become the object of many researches. It can be distinguished in different forms each one is connected and will affect one another:

- *Psychological;* connected to experiences, habituations.
- *Physiological;* divided into two categories: genetic adaptation and acclimatization.
- *Behavioural thermoregulation;* involving all activities, both conscious or unconscious, that modify heat and mass fluxes regulating body's thermal balance.

Still focusing on residential buildings, we can safely assume that nearly all kind of adaptation applies to the case: changing activity, adapting clothing, opening windows, etc., consequently, for the calculation of the indoor comfort temperature, adaptation's effect should be considered. Furthermore, since outdoor climate affects indoor comfort as humans have become an integral component of the system, the outdoor temperature needs to be defined by the required number of parameters: Morgan and de Dear showed how even the weather of past days influences clothing and occupant's perception of comfort temperature [5]. In trying to define guidelines to determine thermal comfort for Dutch buildings, Van der Linden et al. defined, for two macro-type of buildings (alpha and beta) the Adaptive Temperature Limits (ATL) method [6], which gives operative temperature limits as a function of outdoor parameters, however, it is suggested to manage this method with care because when we focus on residential buildings, we could have some zones that may require special corrections or adjustment. Peeters et al. agreed on dividing residential buildings into three different zones: bedroom, bathroom and other (kitchen, living room or studio), and for all the three, a different comfort temperature calculation method is proposed [2]. It was with de Dear and Brager [3] that modifications were included in ANSI/ASHRAE 55: two adaptive thermal model are proposed, one for centrally conditioned and one for naturally ventilated buildings, based on the average outdoor temperature. Later, the theory it has been extended also to mix-mode buildings.

Firmly established the necessity to embrace adaptive model, where indoor design temperature or acceptable ranges are related to the outdoor conditions and occupant's adaptation, what emerge is the lower need of prescriptive standard if occupants can control the indoor climate individually. In this way, persons are more tolerant of deviation from the optimum conditions and, having a higher degree of experienced control, are more active in their adaptation.

2.2. Adaptive Models: Research into the Available

Being adaptation "*gradual lessening of the human response to repeated environmental stimulation",* adaptive models are based on the idea that outdoor climate influences indoor comfort and on occupants' adaptive opportunities related to the available options of personal control on the indoor environment [4]. During the last decades adaptive theories have been implemented in other standards, like ASHRAE 55 or ISO 7730, however, research is still trying to define the applicability condition for the different models, how they work and in which condition. In the next chapters, chasing the definition of an efficient comfort model for residential buildings, is proposed an overview of the main available and most used methods.

2.2.1. ASHRAE 55-17: Thermal Environmental Conditions for Humans

ASHRAE 55 [3] is an American National Standard that established the ranges of indoor environmental conditions to achieve acceptable thermal comfort for occupants in buildings. First published in 1966, has been updated multiple times in the years, last time in 2017. Based on Fanger's theory and using the PMV and PPD indexes has seen introduced in the '13 review the *prevailing mean outdoor temperature* as the input variable for the adaptive model. With the latest '17 update, new elements have been included to consider occupants' adaptation: a new requirement to calculate the change to thermal comfort resulting from direct solar radiation. In this standard, the acceptable ranges, which are the implementation of the adaptive concept, are related to the acceptability percentage and doesn't specifically apply to some type of buildings, even though restrictions are given since the adaptive model requires the absence of mechanical cooling or heating system.

In the standard different methods are described: graphical and simplified method or analytical, both with different applicability limits, note that for naturally ventilated buildings only the analytical can be applied. Fanger's theory prescribe the evaluation of the thermal comfort sensations due to the definition of 6 input parameters:

M : Metabolic rate [Met – W/m^2]

I_{cl} : Clothing insulation [clo]

t_a : Air temperature [°C]

t_r : Radiant temperature [°C]

V_a : Average air velocity [m/s]

RH : Relative Humidity [%]

It is possible for all the six parameters to vary with time and the first two factors are the once relative to the occupants. Metabolic rate is usually defined in tables for typical activities, the standard gives also calculation guidelines for occupants' activities that vary with time. Clothing insulation can be determined in different ways: as the sum of the insulation value of the single cloths, or with a table who describe the fluctuation of the value concerning outdoor temperature, adjustment related to the activity are also prescribed. When direct beam solar radiation falls on an occupant, the mean radiant temperature $\widetilde{T_r}$ shall account for long and short wave mean radiant temperature, and the standard gives a specific prescription for that case. Local thermal discomforts are also considered, and specific ranges for radiant temperature asymmetry, vertical air gradient and floor surface temperatures are given.

Following the adaptive method, the problem is reduced to a graphical check of the acceptability ranges for the prevailing mean outdoor temperature ($\overline{t_{pma(out)}}$) and operative indoor temperature (t_o). The ranges are classified into two categories regarding the expected percentage of acceptability, namely 80% and 90%, note that the standard prescribes to use the first once.

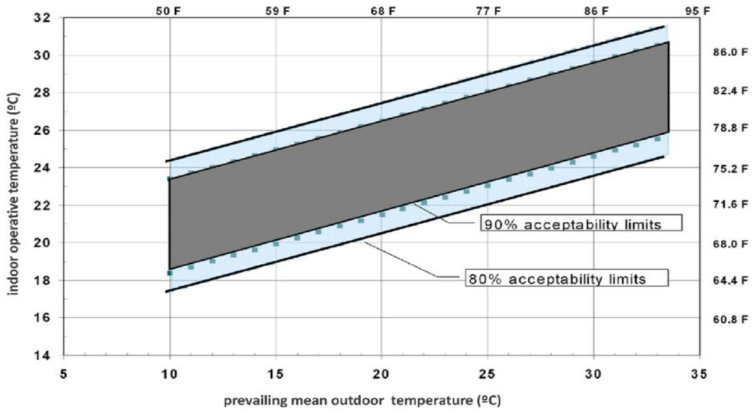

Fig. 2: Acceptable operative temperature ranges, ASHRAE 55-17

<u>Limit and applicability:</u>

- 1.0 Met < M < 2.0 Met, for naturally ventilated buildings the upper limit is 1,3 Met.
- I_{cl} < 1,5 Clo, does not apply when clothing is highly impermeable. For naturally ventilated buildings the range is between 0,5 and 1,0 Clo, people must be able to adapt their cloth
- V_a > 0,2 m/s (40 fpm) and elevated air speed in general require specific prescription
- 10 °C < $\overline{t_{pma(out)}}$ < 33,5 °C, if it is outside this range is prescribed to install a mechanical system

Operative temperatures shall be derived directly from figure 2, or through these equations, which will provide the acceptable ranges:

$$\begin{cases} Upper\ 80\%\ accept.\ limit\ (°C) = 0.31\ \overline{t_{pma(out)}} + 21.3 \\ Lower\ 80\%\ accept.\ limit\ (°C) = 0.31\ \overline{t_{pma(out)}} + 14.3 \end{cases} \qquad \textit{Eq. 1}$$

If t_o > 25°C, the upper limit can be increased with a Δt_o given by tables.

The standard gives also specific indication for the accounting of the $\overline{t_{pma(out)}}$, it has to:

- Base on no more than 30 sequential days prior to the day in question
- Be the arithmetic mean of all the mean daily outdoor air temperatures ($\overline{t_{dma(out)}}$) of all the sequential days
- $\overline{t_{dma(out)}}$ shall be the arithmetic mean of all the outdoor dry-bulb temperature observed in the daily 24 hours

- ➢ Weighting methods are permitted, providing that the weighting curve decreases toward more distant days (see Eq. (2))

When the purpose of the study is a dynamic thermal simulation, the preferred expression for $\overline{t_{pma(out)}}$ is an exponentially weighted, running mean of a sequence of mean daily temperatures prior the day in question, where days in the more remote past have less influence on occupants':

$$\overline{t_{pma(out)}} = (1-\alpha)[t_{e(d-1)} + \alpha t_{e(d-2)} + \alpha^2 t_{e(d-3)} + \alpha^3 t_{e(d-4)} + \cdots \quad \textit{Eq. 2}$$

Here α is a constant between 0 and 1, that rules running mean's reactions to changes of the outdoor climate condition, recommended values are between 0,9 and 0,6, corresponding respectively to a slow and fast response. The Eq. (2) is reducible to this more convenient form:

$$\overline{t_{pma(out)}} = (1-\alpha)t_{e(n-1)} + \alpha t_{rm(n-1)} \quad \textit{Eq. 3}$$

Where $t_{e(n-1)}$ represents the mean daily outdoor temperature and $t_{rm(n-1)}$ is the running mean temperature for the day before the day in question.

It is important to specify that effects regarding local discomfort, clothing insulation, metabolic rate, humidity and air speed, are all already accounted in this method, but, concerning the aim of this project and the necessity to evaluate properly which could be IR-panel's special features, those elements will be discussed further. Special attention needs to be paid over the solar radiation, which calculation is described peculiarly from the standard's "Annex C", giving specific prescriptions to the account of it. A clear limit that emerge is that these prescriptions don't apply to naturally ventilated buildings as the adaptive approach provides just a simplified method built on the concept of operative temperature and prevailing mean outdoor temperature, where radiation is already accounted and doesn't foresee a specific computation. This lack has been discussed over the last years and has been object of much research, but the question is still not clearly expressed. Halawa E. et al. [7] in their work concluded that the existing comfort standards "*do not clearly factor in the effect of mean radiant temperature*", enhancing the necessity to express a more direct connection between radiation and the adaptive model equation. They also established that "ignoring" radiant asymmetry's effect could be a critic condition when the adaptive model prescribes higher acceptable indoor temperatures.

<u>Resume of ASHRAE 55's main features:</u>

- ➢ Suitable for naturally ventilated buildings (No mechanical cooling system installed or heating operating)
- ➢ Specific prescription for direct-beam solar radiation or elevated air speed not provided for naturally ventilated buildings
- ➢ Adaptive model based on acceptability ranges for prevailing mean outdoor temperature and indoor temperature

- Running mean of external temperature as input for the adaptive model (Operative temperature ranges given as function of a running mean outdoor temperature)
- Possibility to express the running mean outdoor temperature as exponentially weighted on the past days
- Local discomforts already accounted for the adaptive model

2.2.2. UTCI: Universal Thermal Climate Index

UTCI represents "*a state-of-the-art human thermal climate index in the form of a multi-node thermo-physiological model"* [8]. This is the result of the European COST (Cooperation in Science and Technical Development) Action 730 project which was originally conceived by the ISB Commission. They intended to define a universal index in its utility and application for the assessment of the outdoor thermal environment in the major human biometeorological fields: applicable for a whole-body calculation, but also local skin, valid in all climates or seasons and reliable in all thermal condition. After an evaluation of the accessible model of human thermoregulation, the advanced multi-node "Fiala" had been selected as a base [9]. That intend the human organism as separated into two interacting systems of thermoregulation: the active and the passive once, it also predicts human perceptual responses dynamically from physiological states. The two systems are expanded with a clothing model, which adjust to the ambient temperature, being the clothing insulation heavily influenced by fluctuations of air velocity, activity, and so physiological response.

UTCI output is an equivalent perceived temperature defined trough an interaction of air temperature, radiative temperature, humidity (expressed as water vapour pressure) and air velocity, that is defined as the "*air temperature of the reference condition causing the same model response as actual conditions",* different values of UTCI are categorized in terms of thermal stress and so regarding environment's impact on a person.

$$UTCI = f(t_a; t_r; v_a; RH) = \ t_a + Offset(t_a; t_r; v_a; RH) \qquad \text{Eq. 4}$$

As introduced, this model considers the behavioural adaptation of clothing insulation and their distribution over the body in order to contemplate possible different insulation values on the vary model's segments. In this context, clothing insulation was decided to be considered as a function of just air temperature in a non-linear way and where a critical role is played by the reduction of the thermal clothing resistances and permeability due to air movement (a significant difference was the "typical" walking speed, conventionally fixed at 4 km/h, which corresponds to a metabolic rate of 2,3 Met). Chasing the determination of the equivalent perceived temperature, first needs to be defined a reference environment with 50% relative humidity, still air and radiant temperature equal to air temperature, to which other climate conditions will be compared to [10]. The equal dynamic physiological conditions are based on the response predicted by the model for the actual reference environment and, from a dynamic multidimensional response (skin wetness, core temperature etc.), the outcome is going to be a single-dimensional strain value. Note that the "*offset*" to t_a is derived from the comparison of the actual model response to the response under the reference conditions [11] To assess finally the associated response is used a ten points scale which describes a wide thermal stress range from extreme cold to ultimate hot. Considering then the computational time needed for the calculation of the equivalent temperature (representing the UTCI value) shortcuts, such as look-up tables and pre-calculated index for relevant combinations of climate parameters, are provided and the same goes for the procedures to translate climate data into correct input factors. Of these parameters, the most articulate procedure had to be formulated around the mean radiant temperature, leaving to that the largest uncertainty.

Blazejczyk et al. compared UTCI with other selected bioclimatic indices using different datasets of meteorological conditions. Comparing it with simple meteorological parameters, like air temperature or mean radiant temperature, the correlation reasonably worked only with the first, showing a slope coefficient of the regression line of 0,7. This indicates that UTCI changes relatively at different rates than the air temperature, in various ranges of ambient conditions, while a weaker relationship was found with mean radiant temperature [12]. They continued that for simple indices, like WBGT (Wet-bulb-globe-temperature) or Humidex, regarding warm conditions, correlation with UTCI is still very poor. On the contrary, a significantly better fit was met for two simple indices, like Apparent Temperature (AT) or Effective Temperature (ET), which can be applied under a wider range of conditions. The most similarity has been found matching UTCI with other indices derived from human heat balance models: Physiological Equivalent Temperature (PET), Perceived Temperature (PT) or Standard Effective Temperature (SET*), where the latter had the best result in terms of relation coefficients. The study continued comparing UTCI with non-thermal indices like PMV, the results derived from the correlation factors showed good relationships between these, even though it’s not based on the principle of equivalent temperature. When an experiment was conducted in Warsaw (Poland) in 2007 [11], trying to analyse urban areas and their specific condition, it was found that UTCI values were extremely sensitive to the temporal changes of mean radiant temperature and air speed which only ET and SET* were displaying. Always Blazejczyk et al. concluded that UTCI, with its sensitiveness to alteration in ambient stimuli (air temperature, solar radiation, humidity, wind speed), represents the temporal variability of thermal conditions better than the other indices they considered.

Since its introduction UTCI have been object of many researches around its field of applicability and in 2015 Vatani et al. investigated that for a case study in Shahroud, Iran [13]. They have been conducting measurements and analysis over 200 people, brick industries’ workers, for outdoor but also indoor environments, chasing to define relationship between the index and different parameters regarding the workplace: environmental and physiological. The results enhanced the already proved strong relation between UTCI and WBGT but, in contrast from what showed by Blazecjzyk et al.[12], the relation found was weaker for outdoor than indoor environment. A more significant correlation was found bonding UTCI with air velocity, more precisely, this index is less applicable for assessing environment with high air velocity, independently from being outdoor or indoor. They concluded that UTCI is generally appropriate to use in conditions with low humidity and air movement, but further research is needed to firmly assess its full applicability in occupational heat stress issues. Langner et al. tried to characterize indoor thermal environments trough UTCI with a focus on the heat stress [14] with a study over different type of buildings in Berlin, both residential and offices, with different locations around the city, year of construction and envelop characteristics. They derived the index from measured air temperature and humidity, and accordingly with the used method, assumption over the mean radiant temperature and air velocity were made: for the indoor reference climate the mean radiant temperature was set equal to the air temperature and air velocity to 0,1 m/s which, being below the range of validity for the calculation of the index, was brought to 0,3 m/s. The study has been conducted with the specified assumptions over the reference conditions, also regarding the activity level (2,3 Met for indoor occupants), it was concluded that thus the index would be incorrect. The assumed air velocity will result to higher heat strass than the UTCI estimation, while the assumption over the activity will typically bring to an overestimation of the index. Finally, the most uncertainties lie over the mean radiant temperature which, being set equal to air temperature, will generally bring to underestimated UTCI values. Brode et al., deriving the operational procedure for determining it, showed how the index increase linearly with radiation, 3°C per 10°C increment in radiant temperature, while regression equation confirmed that UTCI agrees perfectly with the reference condition of air temperature equal to mean radiant temperature [11]. Fig. 3 shown below is representative of the UTCI offset from air temperature as function of the magnitude of heat radiation expressed as (Tr – Ta) for different air temperatures (Ta) with wind and humidity according to the reference condition [15]

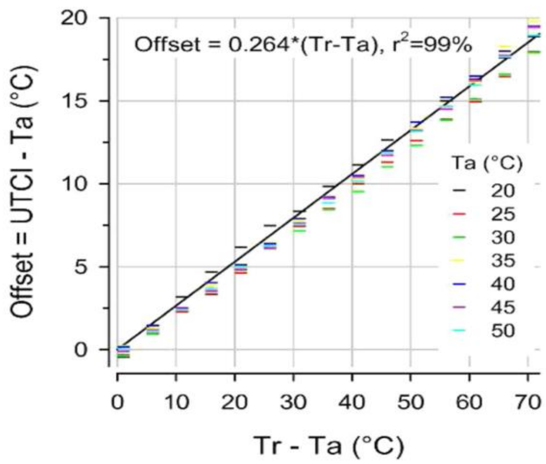

Fig. 3: UTCI offset related to the intensity of heat radiation (Tr – Ta) for different air temperatures

In conclusion, this index still lacks a validate procedure for the thermal comfort assessment in indoor environments.

<u>Resume of UTCI's main features:</u>

- Indoor environment's suitability not acknowledged
- 4 environmental input parameters: $(t_a; t_r; v_a; RH)$
- Strong correlation with WBGT
- Uncertainties over the preliminary assumptions for the reference environment about the air velocity and the mean radiant temperature

- Preliminary assumption for the reference environment: RH = 50%, $v_a = 0{,}5\ m/s$, M=2,3 Met
- Computational code available for the calculation of the index
- Clothing insulation expressed as linear function of air temperature
- Linear dependency between UTCI's offset from air temperature and the difference between air temperature and mean radiant temperature
- Dynamic algorithm for the calculation of the clothing insulation

2.2.3. European Standard: EN 16978-1

The European Standardization Organization, formerly Comité Européen de Normalisation (CEN), developed this standard, which was first published in 2007, then a revision namely prEN16798-1 came out in 2015, which then have been approved and assessed as European standard EN 16798-1 in 2019. The aim was to specify criteria for the assessment of energy performance of buildings, giving optimal input parameters thus to consider simultaneously thermal, acoustic, visual comfort and air quality, and not prescribe design methods. Following prescriptions given from other standards, e.g. ASHRAE 55, it also considers occupants' adaptations and expectations to the thermal environment, either it would be naturally or mechanically ventilated, residential or a workplace, even if its applicability fits mainly in non-industrial non-domestic buildings, like offices, schools, hospitals, restaurants etc. This is due to workplaces being the central concern of much of the research on which this Standard is based, but this is not to be intended as a limitation since it doesn't invalidate its use with other buildings, tough caution is suggested [16]. Differently from other standards, this one does not classify buildings according to the type of control (e.g. type of ventilation) but rather in terms of the type of building and occupants' expectations. For a given category different limitations are associated: for mechanically cooled buildings categories give limitations to PMV's ranges, while for free-running buildings is considered only the operative temperature. This standard also does not incorporate specific criteria for local discomfort.

For naturally ventilated buildings with no cooling system (free-running mode) the comfort temperature is defined by the mean outdoor temperature and for each category of buildings the allowable range is given, note that ranges have been modified with the latest draft review and are reported below in Eq. 5, Eq. 6 and Eq. 7.

$$Upper\ Limit : \begin{cases} Category\ III\ (°C) = 0.33 f(t_{out}) + 18.8 + 4 & (10°C \le f(t_{out}) \le 30°C) \\ Category\ II\ (°C) = 0.33 f(t_{out}) + 18.8 + 3 & (10°C \le f(t_{out}) \le 30°C) \\ Category\ I\ (°C) = 0.33 f(t_{out}) + 18.8 + 2 & (10°C \le f(t_{out}) \le 30°C) \end{cases} \quad \textit{Eq. 5}$$

$$Optimal\ comfort\ temperature\ (°C) : 0.33 + 18.8 \quad \textit{Eq. 6}$$

$$Lower\ Limit : \begin{cases} Category\ III\ (°C) = 0.33 f(t_{out}) + 18.8 - 3 & (10°C \le f(t_{out}) \le 30°C) \\ Category\ II\ (°C) = 0.33 f(t_{out}) + 18.8 - 4 & (10°C \le f(t_{out}) \le 30°C) \\ Category\ I\ (°C) = 0.33 f(t_{out}) + 18.8 - 5 & (10°C \le f(t_{out}) \le 30°C) \end{cases} \quad \textit{Eq. 7}$$

Where $f(t_{out})$ is the running mean external temperature which can be derived from Eq. 2.

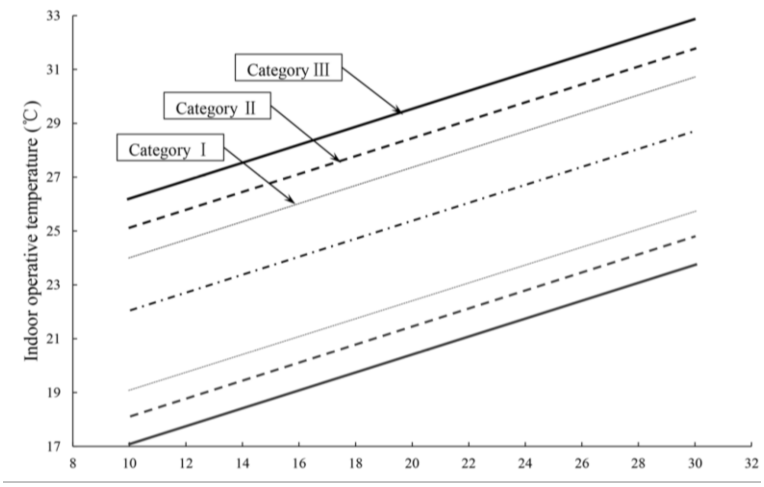

Fig. 4: Acceptable operative temperature ranges prEN 16798-1

Resume of En 16798-1's main features:

- Ideal application for offices, schools, and non-industrial or non-domestic buildings in general
- Running mean external temperature as input parameter for the characterization of the operative temperature
- Different operative temperature's acceptability ranges given for each category of buildings
- Classification of buildings regarding occupants' expectation.
- No specific criteria for local discomfort
- Requirements for the comfort temperature

2.2.4. Isso 74: Dutch Adaptive Thermal Comfort Guidelines

In 2004 the first adaptive thermal comfort prescriptions were introduced in the Netherlands as a national guideline which in 2014 have been updated with a combination of elements from the traditional version and new adaptive features. Since their first guideline was published in the late '70s based on Fanger's PMV, Netherlands had a history of its own regarding standardization: they have got through the Weighted Temperature Exceeding Hours method (GTO or Gewogen Temperatuur Overschrij- ding in Dutch) and the Adaptive Temperature Limits method (ATG or Adaptieve Temper- atuur Grenswaarde in Dutch), which is internationally known as ISSO 74. This was founded on the adaptive approach for naturally ventilated buildings, where the indoor comfort temperature is derived from the running mean external temperature directly and it applies to buildings services, offices and related non-residential buildings [17]. The principal news introduced with the latest review is the approach to the building, which is not intended as a whole but is divided into different "spaces", and the database from where has been developed the adaptive equation, which has been switched from the ASHRAE'S RP-884 T to the SCATs European field study. More than that, also temperature's limitations were divided into four categories (A, B, C and D), differently defined for each class of building (α and β, regarding the type of operating control system), while the outdoor temperature has been determined accordingly with the EN 16978-1 [18]. It is relevant though to clarify the concept behind the alpha and beta distinguish: the first refers to free-running situations, mostly summer with operable windows and other adaptive opportunities, while the latter refers always to the same conditions, but with a controlled cooling system. Nevertheless, considering the new approach to the building, the spaces in which would be divided will refer to the above-mentioned categories. Finally, requirements regarding local discomfort like draughts and radiant asymmetry are provided, as well for long term evaluation or transient conditions.

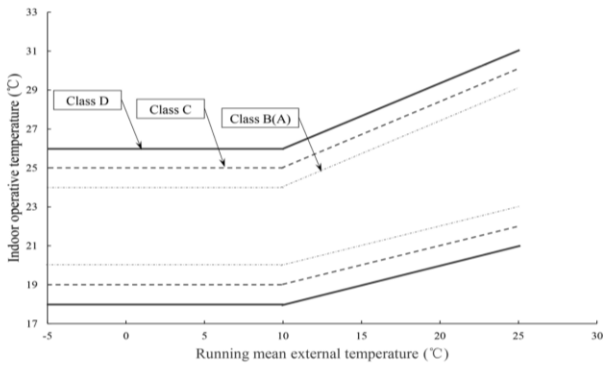

Fig. 5: Acceptable operative temperature ranges ISSO 74 – 2014 review

Boerstra et al. [17] described peculiarly the guideline, identifying the most significant steps:

1) Determine the type building's spaces: α or β
2) Determine the classification level: A, B, C or D

Then, temperatures requirements for each thermal comfort classes are derived from the following equation, based on the weighted running mean outdoor temperature ($f(t_{out})$) in accordance with EN 16978-1.

$$ALPHA: Upper\ limit \begin{cases} Class\ D\ (°C) \begin{cases} 0.33f(t_{out}) + 18.8 + 4 & (10\ °C \leq f(t_{out}) \leq 25°C) \\ = 26 & (-5\ °C \leq f(t_{out}) < 10°C) \end{cases} \\ Class\ C\ (°C) \begin{cases} 0.33f(t_{out}) + 18.8 + 3 & (10\ °C \leq f(t_{out}) \leq 25°C) \\ = 25 & (-5\ °C \leq f(t_{out}) < 10°C) \end{cases} \\ Class\ B(A)\ (°C) \begin{cases} 0.33f(t_{out}) + 18.8 + 2 & (10\ °C \leq f(t_{out}) \leq 25°C) \\ = 24°C & (-5\ °C \leq f(t_{out}) < 10°C) \end{cases} \end{cases} \quad Eq.\ 8$$

$$ALPHA: Lower\ limit \begin{cases} Class\ B(A)\ (°C) \begin{cases} 0.2f(t_{out}) + 18 & (10\ °C \leq f(t_{out}) \leq 25°C) \\ = 20 & (-5\ °C \leq f(t_{out}) < 10°C) \end{cases} \\ Class\ C\ (°C) \begin{cases} 0.2f(t_{out}) + 17 & (10\ °C \leq f(t_{out}) \leq 25°C) \\ = 19 & (-5\ °C \leq f(t_{out}) < 10°C) \end{cases} \\ Class\ D\ (°C) \begin{cases} 0.2f(t_{out}) + 16 & (10\ °C \leq f(t_{out}) \leq 25°C) \\ = 18°C & (-5\ °C \leq f(t_{out}) < 10°C) \end{cases} \end{cases} \quad Eq.\ 9$$

$$BETA: Upper\ limit \begin{cases} Class\ D\ (°C) \begin{cases} = 26 & (-5\ °C \le f(t_{out}) < 10°C) \\ 0.33f(t_{out}) + 18.8 + 4 & (10\ °C \le f(t_{out}) \le 16°C) \\ = 28 & (16°C < f(t_{out}) \le 25°) \end{cases} \\ Class\ C\ (°C) \begin{cases} = 25 & (-5\ °C \le f(t_{out}) < 10°C) \\ 0.33f(t_{out}) + 18.8 + 3 & (10\ °C \le f(t_{out}) \le 16°C) \\ = 27 & (16°C < f(t_{out}) \le 25°) \end{cases} \\ Class\ B(A)\ (°C) \begin{cases} = 24 & (-5\ °C \le f(t_{out}) < 10°C) \\ 0.33f(t_{out}) + 18.8 + 2 & (10\ °C \le f(t_{out}) \le 16°C) \\ = 26 & (16°C < f(t_{out}) \le 25°) \end{cases} \end{cases} \quad Eq.10$$

$$BETA: Lower\ limit \begin{cases} Class\ B(A)\ (°C) \begin{cases} 0.2f(t_{out}) + 18 & (10\ °C \le f(t_{out}) \le 25°C) \\ = 20 & (-5\ °C \le f(t_{out}) < 10°C) \end{cases} \\ Class\ C\ (°C) \begin{cases} 0.2f(t_{out}) + 17 & (10\ °C \le f(t_{out}) \le 25°C) \\ = 19 & (-5\ °C \le f(t_{out}) < 10°C) \end{cases} \\ Class\ D\ (°C) \begin{cases} 0.2f(t_{out}) + 16 & (10\ °C \le f(t_{out}) \le 25°C) \\ = 18°C & (-5\ °C \le f(t_{out}) < 10°C) \end{cases} \end{cases} \quad Eq.\ 11$$

Resume of ISSO 74’s main features:

- Applies to office buildings, schools, and similar non-residential buildings, explicitly not intended to assess thermal comfort in dwellings or comparable situations
- Running mean external temperature as input parameter for the characterization of the operative temperature
- Requirements for the comfort temperature
- Different operative temperature’s acceptability ranges given for each category of buildings
- Buildings divided categories and classes regarding the type of control and performance level
- Requirements for local thermal discomfort provided

2.2.5. Temperature Characterization for Residential Buildings

Since adaptive theories have been developed research has been focusing on trying to incorporate adaptation to the outdoor climate into the comfort model and into the definition of parameters which can best represent this relationship. Established the past days’ weather’s influences over the actual thermal sensation and restricting the research on residential buildings it has been understood that the available multitude of adaptations forms which apply to this situation makes the task even harder. It is in dwellings and similar in fact, that changing activity, adapt clothing or opening windows are everlasting operations. Nevertheless, the various zone of building responds to different needs and have specific requirements related with the area’s (room’s) destination.

Peeters et al. [19] indeed, establish that the domestic scene is far from “steady state” condition and adaptation is a constant activity, considering also the perception of the thermal environment being influenced not only by today’s outdoor temperature but also from the once from the past days. To incorporate that into the calculation of the thermal comfort they believe that the outdoor temperature must be characterized by a parameter that consider a precise amount of detail. It is then from Van der Linden et al. [20] work, a new guideline for The Netherlands, that is derived the definition of an adapted version of the running mean outdoor temperature ($T_{e,ref}$), expressed in a simpler form than in de Dear and Brager's publication.

$$T_{e,ref} = \frac{T_{today} + 0.8\,T_{today-1} + 0.4\,T_{today-2} + 0.2\,T_{today-2}}{2.4} \quad \textit{Eq. 12}$$

Peeters et al. [19] then distinguished residential buildings in three zones: bedrooms, bathrooms and others (kitchens, living rooms, studios etc.).

Bathrooms' lower limit is defined as "*the coldest temperature that is acceptable to a nude, wet body"* but, once dry or dressed, occupants must still feel pleasant. The comfort temperature derived for this zone is a compromise which have been defined with the following equation:

$$Bathrooms\ comfort\ temperature\colon \begin{cases} T_n = 0.122\,T_{e,ref} + 22.65°C & (T_{e,ref} < 11°C) \\ T_n = 0.306\,T_{e,ref} + 20.32°C & (T_{e,ref} \geq 11°C) \end{cases} \quad \textit{Eq. 13}$$

When focusing on bedrooms it was observed that physiological and behavioural adaptation are limited during sleep (Maeyens et al., Parmeggiani) also, after researches conducted by Humphreys, was showed that a good quality sleep could be obtained even with temperature around 12°C [2], although World Health Organization fixed the lower limit to 16°C due avoiding respiratory disease.

$$Bedrooms\ comfort\ temperature\colon \begin{cases} T_n = 16°C & (T_{e,ref} < 0°C) \\ T_n = 0.23\,T_{e,ref} + 16°C & (0 \leq T_{e,ref} < 12.6°C) \\ T_n = 0.77\,T_{e,ref} + 9.18°C & (12.6 \leq T_{e,ref} < 21.8°C) \\ T_n = 26°C & (T_{e,ref} > 21.8°C) \end{cases} \quad \textit{Eq. 14}$$

Rooms like kitchen, living room, or study have metabolic levels similar to those we find in offices, or at least comparable since the activity range is between 0.8 and 1.4 Met. After the evaluation of many surveys and researches Peeters et al. [2] concluded that for this type of spaces the comfort temperature is defined as it follows:

$$Other\ rooms\ comf.temperature\colon \begin{cases} T_n = 0.06\,T_{e,ref} + 20.4°C & (T_{e,ref} < 12.5°C) \\ T_n = 0.36\,T_{e,ref} + 16.63°C & (T_{e,ref} \geq 12.5°C) \end{cases} \quad \textit{Eq. 15}$$

Along with the assessment of residential buildings as dynamic system goes the acceptance that the above neutral temperature will not be met continuously, and this needs to be implemented properly in BES-programme. Since the parameters that influence occupants' response to the environment will be fluctuating with time, the same will happen to the indoor temperature, which will have to corresponds to a value close, regarding a certain range, the optimal temperature derived from the comfort equation. Peeters et al. [2] defined the peak to peak temperature variation for a certain time interval as it follows:

$$\Delta T_{ptp}^{x} < a \quad \textit{Eq. 16}$$

Where x and α are two constants, note that the numerical result could be affected by the simulation time step defined, i.e. if the time step increases, temperature variation within a smaller period won't be considered (even if it's known that increasing the time step would negatively influence the quality of the simulation). The temperature ranges are, as well the neutral temperature which they include, also influenced by occupants' adaptation. Research has shown how those ranges are not symmetrically distributed around the comfort temperature and how this is affected by different seasons. This dependency has been observed but not officially proven yet since research is still going on, that is why the comfort band around neutral temperature is supposed having a constant width. They concluded defining comfort temperature's ranges with the following equations for the upper and lower limit (where "w" is the width and "α" a constant < 1):

$$\begin{cases} T_{upper} = T_n + w\alpha \\ T_{lower} = T_n - w(1-\alpha) \end{cases} \qquad \textit{Eq. 17}$$

2.3. Discussion and Comparison of the Reviewed Methods

The analysis conducted in the preview's chapters examined the principal and currently most used methods to assess thermal comfort. Firmly established that research is still going on this subject, it emerges clearly that thermal comfort needs peculiar attention to the specific features that every single situation requires. Especially when focusing on residential buildings, where occupants are constantly free to adapt clothing, activity or opening windows, the thermal sensation will be strongly influenced by personal behaviour. Reason why, it is enhanced the need to found theories on a consistent number of surveys and data.

Adaptive theories, defining wider ranges for optimal environmental conditions, are currently the most trusted approach to assess comfort in dwellings and similar, though research is still debating on the methodology, limits and parameters accounted. In trying to relate the outdoor condition with the indoor environment is common acceptance the use of an exponentially weighted running mean outdoor temperate as the input parameter to derive the comfort condition. This works for the ASHRAE 55, the EN 16978-1 and the ISSO 74; only the UTCI index is derived from a computation that needs the air temperature, mean radiant temperature, relative humidity, and wind velocity as inputs. The output for the first three indexes is the operative temperature, while for the UTCI is the homonym index (actually saying that the operative temperature is the output is not 100% correct, as the method requires a double check on that temperature and the running mean outdoor temperature). Each of the methods evaluated presents many strengths though, for most of the indexes their applicability into residential environments still needs to be proven and only the ASHRAE standard officially does it. For residential spaces has become crucial the occupants' adaptation, which influences, as long with the different requirements that dwelling's rooms need, has brought to the definition of special comfort temperatures for each type of room (bedroom, bathroom, other) [19].

ADAPTIVE MODEL	LIMITATION AND APPLICABILITY		
	Activity	Outdoor Temperautre	Cloth. Insulation
ASHRAE 55-17	1.0 Met < M < 1.3 Met	10 °C < T out < 33,5 °C	0.5 Clo < I_{cl} < 1.0 Clo
UTCI	2.3 Met	/	Funciotn of air temp.
EN 16978-1	Sedentary	10 °C < T out < 30 °C	/
ISSO 74	/	/	/

Tab. 1: Models evaluation – Limits and Applicability

ADAPTIVE MODEL	LIMITATION AND APPLICABILITY						
	Ventilation System			Operation		Building Type	
	Naturally	Mixed	Mechanical	Cooling	Free Running	Residential	Workplace
ASHRAE 55-17	OK	NO	NO	NO	OK	OK	OK
UTCI	INDOOR APPLICABILITY NOT ACKNOWLEDGE YET						
EN 16978-1	OK	OK	NO	NO	OK	OK*	OK
ISSO 74	OK	OK	OK	OK	OK	NO	OK

Tab. 2: Models evaluation – Limits and Applicability

ADAPTIVE MODEL	INPUT	Local Discomfort	OUTPUT
ASHRAE 55-17	Run. Mean Outdoor temp.	Already accounted	Operative temperature
UTCI	Ta - Rel. Hum. - Tmr. - Va	/	UTCI Index
EN 16978-1	Run. Mean Outdoor temp.	Not Included Criteria	Operative temperature
ISSO 74	Run. Mean Outdoor temp.	Specific Requiremetns	Operative temperature

Tab. 3: Models evaluation – Parameters Accounted

What emerges is that research is making significant steps towards the definition of efficient adaptive methods for the assessing of thermal comfort, it is clear though that there are still inadequacies and grey areas to clarify. When we address to the ASHRAE adaptive approach, local discomfort's effects are already considered within the operative ranges. That has been identified as a significant lack, especially when focusing on the aim of this project, whose purpose is to investigate infrared heating system, where radiant asymmetry is already been accounted as the most likely local discomfort to occur. What is expected is that conventional operative ranges will not exactly be representative of the actual thermal sensation. That is likely to happen, just as one of the most common assumptions around infrared heating panel was proposed: comfort could be reached at lower air temperature since objects are heated directly and not through a "fluid" (air) - just like the hit surface become warmer, the once which is not is left cold. EN 16978-1, on the other hand, is proposed to establish input parameters for optimal energy performance and does not include any prescription for local discomfort. One of the most innovative approaches is the one adopted by the Dutch National Standard ISSO 74, defined by Boerstra et al. as "*a new hybrid thermal comfort guideline",* where the new elements of the adaptive procedure are combined with the heat balance's static strengths [17]. It is true though that this does not specifically apply to residential buildings but, the additional requirements for local discomfort, the accounting of personal control, as long with the above-mentioned innovations make this one of the most reliable thermal comfort standards to apply in the Netherlands.

2.4. Mean Radiant Temperature and Local Discomfort

The evaluation of the mean radiant temperature becomes crucial in assessing thermal comfort, even more when it comes to infrared radiant heating systems. In this chapter are presented the available mean radiant temperature calculation algorithm proposed by EnergyPlus, the energy simulation software used in this research, and the most common guideline proposed for the detailed evaluation of the radiant asymmetry, the local discomfort which is assumed most likely to occur with this heating system.

2.4.1. EnergyPlus - MRT Calculation Algorithms

EnergyPlus (the energy simulation software used for this research) provides three different calculation methods for the accounting of the mean radiant temperature. The first one is an averaged method which does an average of the zones surface's temperatures, calculated assuming to be in the exact centre of the room, while the other two account in different ways of weighting factors: one, called "surface weighted", does an average of the zone average mean radiant temperature and a specific surface's temperature, while the other accounts of all the angle factors between a person and all the surfaces around. The surface weighted method intends to represent the condition in which an occupant gets closer to a particular surface, so that his radiant field is affected equally by that surface and the average of all the others. This is a simplified method, which limitations are overcome by the angle factor method which, despite the necessity of a meticulous calculation process required for evaluating all the angle factors, gives a precise evaluation of mean radiant temperature perceived.

EnergyPlus' Mean Radiant Temperature available calculation algorithms:

- *Zone Averaged Method:* $MRT = Av.\ Zone\ MRT$
- *Surface Weighted Method:* $MRT = \frac{T_{surf} + Av.\ Zone\ MRT}{2}$
- *Angle Factor Method:* $MRT = \sum F_i \times T_{surf,i}$

Using the different calculation method, it is possible to assess different operative temperature, that will be used to evaluate the comfort level. The comfort can so be evaluated in a more general way, as an average for the zone, or for a specific position of an occupant in the room. It is important to acknowledge that, within this research, it is assessed that the Zone Averaged Method and the Angle Factors once (defined for a seated person in the centre of a room), despite a negligible divergence, are giving the same output as values of the mean radiant temperature. For this reason, the angle factor method will be used only to investigate specific position where is assumed likely to encounter local discomfort and, their calculation, is done accordingly with what described in the chapter 9 of the ASHRAE Fundamentals Handbook [21].

2.4.2. Radiant Asymmetry

Within the possible local discomforts, due to the infrared radiant system itself, radiant asymmetry is the most likely to encounter. Even though local discomforts are already accounted for the ASHREA 55 Adaptive approach applied, it is decided to evaluate the possibility of these phenomena, accordingly with what described in the same standard's "Annex I".

The radiation field about the human body may be affected by the influence of the surrounding surfaces' temperature, direct sun light or, like what can happen with infrared panels, emitted radiation field of equipment and heating system. In general, people are more sensitive to asymmetric radiation due to warm ceiling than others, and this just enhanced the possibility of encounter discomfort since the IR-panels are installed right on the ceiling. Following the standard's prescriptions, the PPD limit for radiant asymmetry should be 5%, defined accordingly with figure 33. Though for this research will be used as limit the one proposed in the standard ISO 7730 where different limits are given for different building classes, and the Class C limit is then chose, with PPD limit for radiant asymmetry due to warm ceiling of 10% which occurs for a radiant asymmetry of 7°C. Note that when comes to evaluate this type of local discomfort for the heat pump's model, it is checked the radiant asymmetry due to cool ceiling, with a limit of 10% PPD that occurs with a radian asymmetry of 18°C.

As described in the ASHREA 55 standard, radiant asymmetry is defined as "the difference between the plane radiant temperature (T_{pr}) in opposite directions. The vertical radiant temperature asymmetry is with T_{pr} evaluated in upward and downward directions. While the horizontal once is the maximum asymmetry registered in all the horizontal directions". This parameter must be accounted at waist level, 0,6 – 1,1 meters for seated or standing person [21].

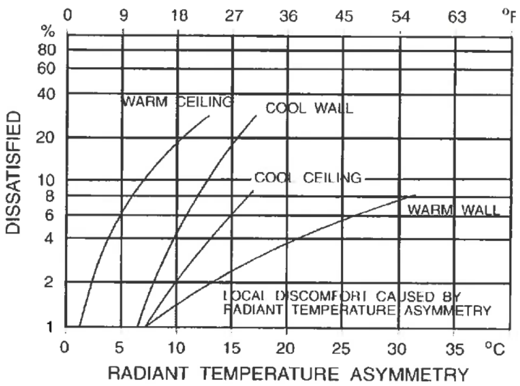

Fig. 6: PPD due to local thermal discomfort caused by radiant asymmetry

Defined the radiant asymmetry with ΔT_{pr}, accordingly with ASHRARE handbook, the relative equations to determine it are:

- $\Delta T_{pr} = T_{pr,i} - T_{pr,j}$ *Eq. 18*
- $T_{pr} = \sqrt[4]{\sum_{i=1}^{n} F_i T_i^4}$ *Eq. 19*

3. Methodology

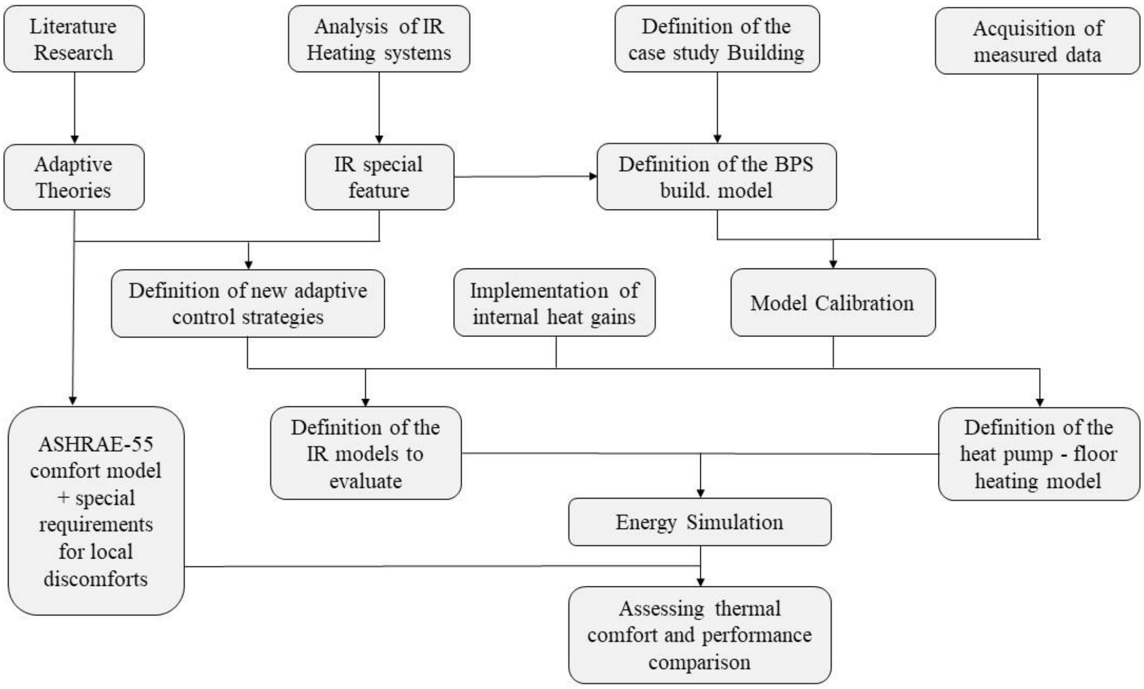

Fig. 7: Methodology resume flow chart

3.1. Literature Research and Preliminary Studies

A literature research is initially needed to define the state of the art for assessing thermal comfort. What emerge, is that even one of the most common method available, like Fanger's PMV/PPD (ISO 7730), has the limit to reduce thermal comfort to a steady-state heat balance equation, therefore research have been focusing on "Adaptive Models" [22] [23]. These models are based on the idea that the outdoor climate influences indoor comfort because humans can adapt to different temperatures as they are an integral component of the system. Assessed that, it is common understanding the importance to define the right amount of input details to account for adaptation and, regarding that, different solutions are proposed, willing to define an optimum setpoint temperature for residential environments and the variables to characterize it. Also, since due to the system itself (IR-panels), it is likely to encounter local discomfort as radiant asymmetry, the comfort model must account also for these situations. Nowadays research is still trying to define the applicability condition for the different models, how they work and in which cases, though ASHRAE 55-17 has been found a consistent guideline to apply an adaptive approach for residential houses, so it is the one that is used within this research. A specific attention will be placed to the evaluation of the mean radiant temperature and to the radiant asymmetry. Remembering that the adaptive approach already accounts for local discomforts, it may be possible that the guideline overlooks unpleasant conditions due to the differences of temperature perceived with the IR-panels operating. For this reason, the ASHRAE Handbook of Fundamentals guideline is applied to account for that discomfort.

3.2. Experimental Method - Building Performance Energy Simulation

Once defined the method to assess thermal comfort and the specific requirements needed, the work proceeded with the definition of the case study building where the IR-panels have been installed, and where measurements were collected during the months of March and April 2020. The characterization of the thermal environment goes through the definition of the building in its geometry, construction elements, heating system, and all the details required to give a peculiar representation of the subject, also, the data about the measurements are acquired. These steps are compulsory for the experimental process, which will see the use of a Building Performance Simulation (BPS) model, so to perform energy simulations that will give full information about the system's efficiency and comfort level assessed. The data measured are used for the validation of the model, which process is shown in detail in the next paragraphs. The model built will see the implementation of the IR-panels heating systems, in its actual configuration, and with new control strategies based on the adaptive theories evaluated. Also, the same building model is used to produce the target of the comparison for the IR-panels, with the implementation of a heat pump heating system combined with floor heating.

3.2.1. Developing the BPS Model

To build a virtual building model it has been used DesignBuilder, a third-party user interface for EnergyPlus (the energy simulation software used for this research). Designbuilder is so a user-friendly GUI (Graphic User Interface) to EnergyPlus, where model can be built in a simpler straightforward process and other than that, can also be directly used for thermal simulation. Here, it is characterized the thermal environment and is created the element representative of the IR-panel. For modelling the infrared panel attached to the ceiling, it is defined a "sub-surface" which will locally modify the composition of the ceiling element where the panel will be placed. To guarantee the element's layers continuity, the sub-surface discretized will include the floor slab as well, so to replace the portion of the ceiling where the new surface is applied. With this kind of element, it is possible through DesignBuilder to define an "Internal Source" which represent the emittent wire coiled filament which produce the radiation and so the heat (full detail of the panel composition at §5.2).

The house during the measurements was empty, not even furnished, so no occupancy profile or internal heat gains due to equipment will be considered in this stage of the research as preliminary input.

Once built the model of the building, characterized all the construction elements, the different zones, and the more general parameters, it is possible to generate an IDF file, to which access with EnergyPlus thus to implement all the functionality not available on DesignBuilder. It is then to this file that are added the advanced settings: properties like the HVAC system, for which has been found a consistent solution in the EnergyPlus' sub-model "Low Temperature Radiant Electric". To implement the properties required for the characterization of the system's control, is used an EnergyPlus feature: the Energy Management Systems (EMS) [24]. EMS is an EnergyPlus feature that allows to modify within the simulation the model itself (full detail at § 5.3.3.2). Within this research, EMS is also used to implement in the models different control type required for their characterization.

3.2.2. Model Calibration

The model produced needs then to be validated with the data measured and, the whole process of reaching the optimal fit, is called "model calibration", which, since the methodology is using measurements to fit the model, it can be defined *Inverse modelling* [25]. The objective of the calibration is to find an optimal fit for the model, so that the simulated output will tend to the measurements and that the virtual model will replicate what happens in the actual physic building. Finally, the model could be used to implement the desired new settings and to run other simulations. Note that to replicate the real conditions verified in the building it is implemented a weather file, built with the data measured on the site (see § 4.3). Once defined the initial model, named "Model Zero", the process of calibration has focused on a few parameters pre-defined as the target of the calibration itself, trying to fit the model so that the simulation output will meet the measured data within a certain "confidence degree" [26].

The method applied for the calibration consists in focusing on just one ambient, the living room, and then fit the model to meet the desired criteria. First, have been chosen different temperatures, of the air and surfaces, which will be the targets of the calibration. Once adjusted the model regarding the living room's output, it is supposed to be calibrated in its totality, thing that will be checked with the same methodology but focusing on other zones. The parameter considered for the calibration of the model based on the living room are so defined:

- Mean air temperature: *T air*
- North wall's surface temperature: *T wall*
- Ground's surface temperature: *T ground*
- Ceiling's surface temperature: *T ceiling*
- Front window's surface temperature: *T win. F.*
- Back window's surface temperature: *T win. B.*

To evaluate the accuracy level of the model, the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (Cv(RMSE)) were calculated for each parameter and then limits were found consistent with the ASHRAE 14 guideline [27][26].

$$NMBE(\%) = \frac{1}{\overline{X_{meas}}} \frac{\sum_1^n (X_{meas} - X_{sim})}{n} \, 100\% \qquad \textit{Eq. 20}$$

$$RMSE = \sqrt{\frac{\sum_1^n (X_{meas} - X_{sim})^2}{n-1}} \qquad \textit{Eq. 21}$$

$$Cv(RMSE)(\%) = \frac{RMSE}{X_{meas}} 100\% \qquad Eq.\ 22$$

ASHRAE Guid. 14 Limits		
Values Type	NMBE	Cv(RMSE)
Monthly	± 5 %	15 %
Hourly	± 10 %	30 %

Tab. 4: ASHRAE Guideline 14 limits for uncertainty indices and evaluation of degree of confidence

Note that the guideline's limits are addressed to simulation over a whole year run period, thing that has not been possible considering the amount of baseline data acquired. Though for the calibration will be execute simulations with a time step of 10 minutes controlled with the hourly limits, which will guarantee a solid approach.

3.2.3. Internal Heat Gains

To recreate a proper domestic environment, it is required to implement into the model people occupancy profiles, with related equipment's and lighting's heat gains (in the "Annex C" are showed in detail all the information regarding the heat gains: schedule and values). As people are integral part of the thermal environment, they contribute to the total heat gains with their presence and activity so, through the specific object on EnergyPlus, the relative properties are defined for the different zones of the building. Within this object, not only is possible to define the occupancy profile, but it can also provide information that are compulsory to assess the thermal comfort of a group of occupants [24], like the comfort model itself, or the mean radiant temperature calculation method, since the accounting of that becomes a crucial point with a radiant heating system.

Building's occupancy profiles describe how those are used, and for the base case, the default setting proposed by the simulation software are assumed. Then, these are checked and modified so to meet the literature and standard's applicability prescriptions of the method. Based on the dimension of the house, the case study building is assumed inhabited by 4 people: 2 adults and 2 children and, from the destination of the different zones, are assumed the maximum occupant number. The occupancy profile then is modified by a specific schedule that can vary within weekdays and weekends, other than during the hours of the day, and the number of occupants is so modified per each zone with fractions of the total number of persons assumed. The activity level instead, directly determines the amount of heat gains per person in the zone under design conditions. That is defined accordingly with the 2005 ASHRAE Handbook of Fundamentals where, assuming the average body surface equal to 1,8 m^2, the Watts per person are defined for different domestic activities, accounting the total heat gain per person including convective, radiant, and latent component. The values are checked with the ASHRAE 55 applicability limits, and an internal EnergyPlus algorithm then determines what fraction of the total is sensible and which is latent, then the sensible percentage is separated into radiant and convective regarding the input value for "Fraction Radiant", which amount is assumed of 30%. The last important parameter required to define into the People object so to assess thermal comfort is the air velocity which, in accordance to the limitation of the ASHRAE standard and following the indication of the same Handbook, is set to 0,136 m/s.

Following the same guideline, the occupant' clothing insulation value must be between 0,5 and 1 Clo, with people able to adapt their clothing with the passing of time. It is a common acceptance to use 0,5 Clo for summer design days, while 1 Clo for winter, though this simplified assumption may bring to incorrect assessment of thermal comfort, since is reasonable to believe that the clothing value cannot be constant for a such a continuous amount of time. To overcome this limit, EnergyPlus provide a dynamic calculation algorithm for the clothing insulation, proposed by ASHRAE 55. This model varies the clothing insulation as a function of the outdoor temperature registered at 06:00, and in figure 32 below is showed the algorithm's function.

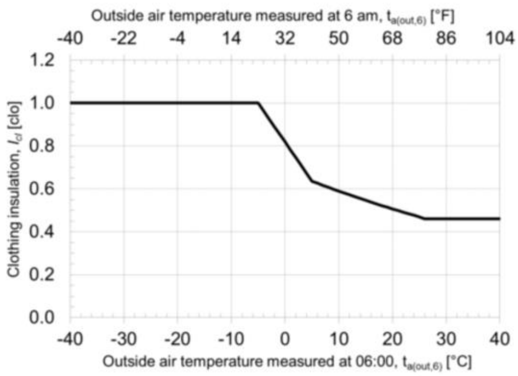

Fig. 8

To complete the definition of the internal heat gains that affect a domestic environment, need to be defined the lights and equipment present in the building. Just like for the activity levels, values and calculation methods for these elements are provided within the standard's guideline. As done for the activity levels, the assumed values for these objects and relative schedule type, are by default proposed by the simulation software, which have been checked and found consistent with the standard's prescriptions. In "Annex C" are showed the schedule details. At these stage, with the model characterized in all its properties (geometry, construction elements, HVAC properties, environmental factors, and internal gains), that is ready to perform energy simulation which will produce the results and data needed for the performance comparison and the research purposes.

3.2.4. Implementation of Adaptive Control Strategies

To investigate more deeply the possible performances and efficiency of the heating system, trough the EMS are implemented into the model different control strategies for the panels. These control strategies are the results of the literature research, where to incorporate the adaptation into the definition of the setpoint temperature, are used and tested different approaches, of which tab. 4 gives a resume.

IR-Panels Control Strategies

N°	Name	Control Parameter	Control Type	SetPoint Temp. (Tsp)	Heating Program	Released Power
1	IR_C1	Air Temp	On/Off	20 °C	ON If Tair < 19,5 °C OFF if Tair ≥ 20,2 °C	Full Capacity
2	IR_C2_1	Op. Temp	On/Off	20,5 °C	ON If Top < Tsp - 0,5°C OFF if Top ≥ Tsp + 0,5°C	Full Capacity
3	IR_C2_2	Op. Temp	Ideal	20,5 °C	Constant Tsp	Linearly with ΔT
4	IR_C3_1	Op. Temp	On/Off	Adapt. ASHRAE 55	ON If Top < Tsp - 0,5°C OFF if Top ≥ Tsp + 0,5°C	Full Capacity
5	IR_C3_2	Op. Temp	Ideal	Adapt. ASHRAE 55	Constant Tsp	Linearly with ΔT
6	IR_C4_1	Op. Temp	On/Off	Adapt. Residential	ON If Top < Tsp - 0,5°C OFF if Top ≥ Tsp + 0,5°C	Full Capacity
7	IR_C4_2	Op. Temp	Ideal	Adapt. Residential	Constant Tsp	Linearly with ΔT

Tab. 5

Two different control parameters are tested for the panel's thermostat: the zone mean air temperature, and the operative once. For both different setpoint temperature and control type are evaluated. The first strategies, IR_C1, represents the actual calibrated model, with an on/off control type based on the mean air temperature, representative of the current system's characteristics with a static setpoint of 20°C. The strategies from number 2 to 7, are all with the operative temperature as control type, and can be divided in three groups. The first, with the strategies 2 and 3, has a constant setpoint temperature of 20,5°C (it is been increased from 20°C to 20,5°C since now it is accounting the operative temperature and not any more the mean air temperature). The difference between the two is just in how the power is released from the system, indeed the number 2 has an On/Off control, like the actual system, while the number 3 has an ideal control, which release power linearly with the difference between the setpoint and actual temperature. Same criteria is adopted for the next two groups, where the strategies 4 and 5 are sharing the same adaptive approach, the ASHRAE 55 once, while the group with strategies 6 and 7 is based on the temperature characterization proposed by Peeters et al. [19]. The adaptive approach proposed by ASHRAE, sees the setpoint temperature derived from Eq. 1 (see § 2.2.1), defined as function of the $\overline{t_{pma(out)}}$ as it follows in Eq. 23.

$$Tsp = 0.31\,\overline{t_{pma(out)}} + 17.8 \quad \textit{Eq. 23}$$

Differently from the ASHRAE standard, the setpoint temperatures defined from Peeters are given as function of $T_{e,ref}$, defined with Eq. 12, while the setpoint temperatures is implemented with Eq. 13-14-15, using a different once for bathrooms, bedrooms, and all the other zones (see §2.2.5). It is important to acknowledge that, for the ASHRAE standard, the adaptive method can be applied for 10°C $\leq \overline{t_{pma(out)}} \leq$ 33,5 °C, thing that would make impossible to use the method since the measured data are showing temperature also around 3 – 4 °C. For this research purposes, it is then decided to extend the limits so to be able to apply the method described previously.

The IR models are used to run yearly simulation, then the focus is directed on the winter and heating season, which is the one relevant for the evaluation of the system. The same simulations are run for the heat pump model, so to produce the comparison data on which found the final evaluation. To guarantee a solid approach, and to make the model "comparable", the characteristics of the heat pump models need to be alike the IR once. For these reasons, are produced three different heat pump models (description of the system at § 6), characterized with the same setpoint temperature implemented into the IR-models. It is so defined a model with a constant setpoint operative temperature, another with the once defined with the ASHRAE approach, and the last one with a different temperature characterization done for each zone destination (resume in tab 5).

Heat Pump Control Strategies

N°	Name	Control Parameter	Setpoint Temp. (Tsp)	Heating Program
8	HP_C1	Op. Temp	20,5 °C	Constant Tsp
9	HP_C2	Op. Temp	Adapt. ASHRAE55	Constant Tsp
10	HP_C3	Op. Temp	Adapt. Residential	Constant Tsp

Tab. 6

3.3. Evaluation of the Model

The model's simulation output, produced by the energy simulations, are so collected and evaluated. Their performances are analysed in terms of comfort level assessed (with the ASHRAE 55 adaptive approach), percentage of unmet time, local discomfort due to radiant asymmetry, and energy consumption. To give a clear and complete evaluation of the thermal comfort, it is decided to analyse some considerable positions where is most likely to encounter condition of discomfort. The zone considered is the living room, where having big windows facing both the east and west side, plus the presence of 5 IR-panels operating, is definitely the zone with the highest chance to present local discomfort due to radiant asymmetry or critic thermal comfort condition. A detailed overview of the position evaluated, with the angle factors calculation, is proposed in the "Annex D". The results so obtained, will help understand whether the ASHRAE comfort model, has or not weaknesses or criticism if applied in condition like the once verified with IR-panels heating systems.

The IR-panels models are evaluated in their performances, comparing them between each other and with the heat pump models. The definition of the setpoint temperature and the control type, are the common criteria to consider in the evaluation of all the models, it is then straightforward that for a direct comparison it is require to combine the models in groups as it follows:

A. IR_C2_1 / IR_C2_2 / HP_C1
B. IR_C3_1 / IR_C3_2 / HP_C2
C. IR_C4_1 / IR_C4_2 / HP_C3

Note that the strategy IR_C1, representative of the actual heating system, is still part of the comparison and compulsory for the evaluation of the IR-panels, but its different control type makes it not directly comparable with the heat pump's models. Within the IR-panels models' evaluation, is possible to investigate the possible benefits that an Ideal control type could bring over an On/Off once.

Evaluating the models is also possible to investigate which adaptive setpoint temperature brings more benefits in terms of comfort and energy consumption, if the one proposed in the ASHRAE 55 standard, or the one defined accordingly with Peeters et al. [19].

4. Description of the Case Study Building and Measurements

Fig. 9: Picture of the building

4.1. Case Study Building

The case study building, where the heating system have been installed and where during the months of March and April measurements have been conducted, is a terraced house located in Vankelswaard (NL). It develops over 3 levels: day area on the ground floor, three bedrooms and bathroom on the first, unoccupied attic at the top. The house during the measurements was empty, also unfurnished and even the floors had not a proper wear layer. The house was built in 1964 and recently renovated with new windows and thermal insulation for the external walls of which unfortunately, the thermal resistance has not been possible to acknowledge. Below the general information received:

- Glazing HR++, U = 1.1 W/ m^2K
- Ground floor slab: Rd = 3.8 W/ m^2K
- Roof: Rc = 4 W/ m^2K
- Windows and doors with wooden frames HR ++.
- Concrete floor slabs not grounded.
- Ceiling's external layer of plaster.

The ambient of the house, and so the zone later define in the BPS model, are the following:

- Ground Floor:
    - Hall (7.4 m^2)
    - Living room (30,2 m^2)
    - Toilet 1 (1,3 m^2)
    - Kitchen (7,2 m^2)

- First Floor:
    - Bedroom Eas (14,5 m^2)
    - Bedroom Back (13,4 m^2)
    - Bedroom Small/Studio (4,7 m^2)
    - Toilet 2 (2,4 m^2)
    - Bathroom (5,5 m^2)
    - Wardrobe (1,7 mq)
- Attic:
    - Unoccupied attic (19 m^2)

In the “Annex A” are reported the building’s plans to which refer the zones defined above, while pictures of the house can be found in the “Annex B”.

4.2. IR-Panel Heating System

The infrared panels installed on the ceilings in the house as heating system are of two different kind, defined regarding their nominal power and dimensions as following:

- Type “A”: Dimension (0,6 x 0,6) m, Power 240 W
- Type “B”: Dimension (0,9 x 0,6) m, Power 350 W

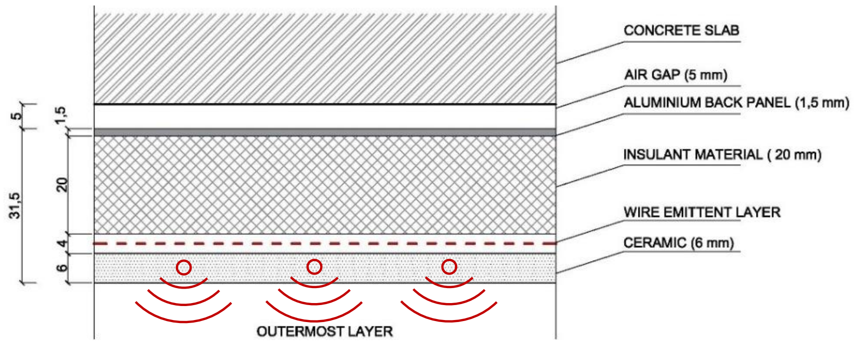

Fig. 10: Composition of the infrared pane – Drawing out of scale, unit in millimetre

Five panels of type “A” have been used to heat the living room, one type “B” for the bedroom front, while two of type “A” have been installed in the bedroom back (in the “Annex A” is showed the position). The system has been working 24/7 during the considered days and each zone had its own dedicated thermostat with a constant setpoint air temperature. Once installed, the panel will be separated from the ceiling slab by a little air gap, while its composition consists of an aluminium back panel which hold an high performance insulation layer of 2 cm, then there are the wire coiled cables and finally, the outermost layer of ceramic.

Resuming the panel installed in the house:

- Livingroom. 5 panels type A

- Bedroom Front: 1 panel type B
- Bedroom Back: 2 panels type A

Note that further in the research, once completed the calibration, will be considered more panels in other zones (like described in the Annex A) so to run simulation for the entire building with occupancy profile and finally evaluate the system applied to a real applications.

4.3. Measurements and Data Collected

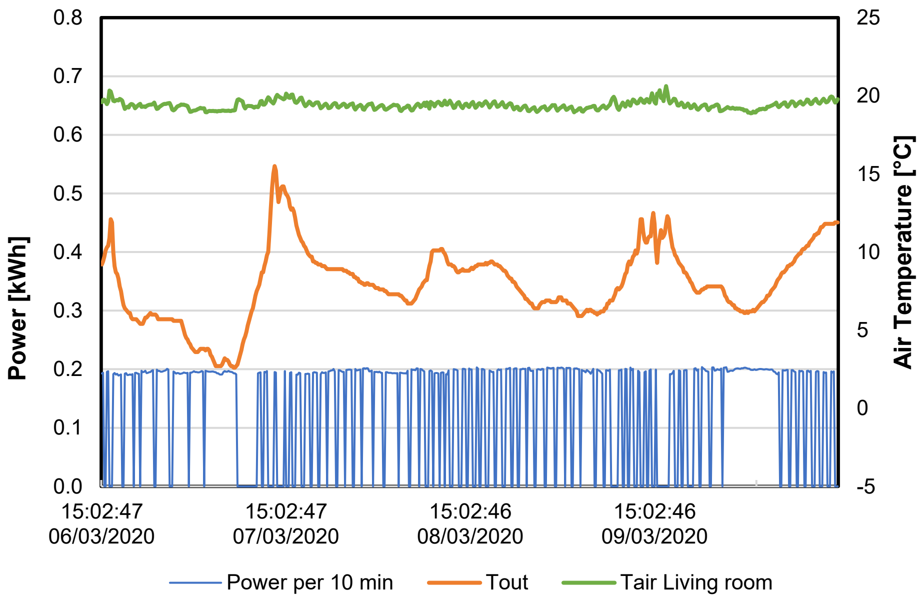

Fig. 11: Some of the data registered into the HERSCHEL-case study building and received for the research

In the house, for the months of March and April 2020, data have been collected with different sensors installed. Also, the infrared panels supplied have been installed and used for heating some of the rooms. Unfortunately, it has not been possible to collect information about the solar radiation on the site, though the parameter registered and provided are the following:

- Site:
  - Air Temperature
  - Relative Humidity
  - Solar Irradiance (From Vertigo Station – TU/e)
- Thermal environment:
  - Air Temperature
  - Relative Humidity
  - Surfaces Temperature

- Air Speed
- Wet-bulb globe temperature
- Electric power used

The site parameters have been used to defined a weather data to be used in simulations, thus to recreate the exact thermal conditions verified, while the different temperatures registered into the building will be the comparison data for the calibration of the model. The sensors installed in the building, have been one place in the centre of each surface for which the temperature has been provided. Also, to record the zone's mean air temperature it has been used just one sensor positioned in the centre of the room. This is not the perfect method, since having the chance to use more sensors around the room, and then doing the average of the temperature registered, it would have brought to a more accurate measure, though the measures provided have been found sufficient and adequate for the research's purposes.

5. Developing and Calibrating the IR-panels BPS Model

5.1. Geometry and Construction Elements

The geometry of the model and all the construction elements that compose the building, are defined in the Annex A. It is reminded that in this stage of the work, the model is built with the software DesignBuilder.

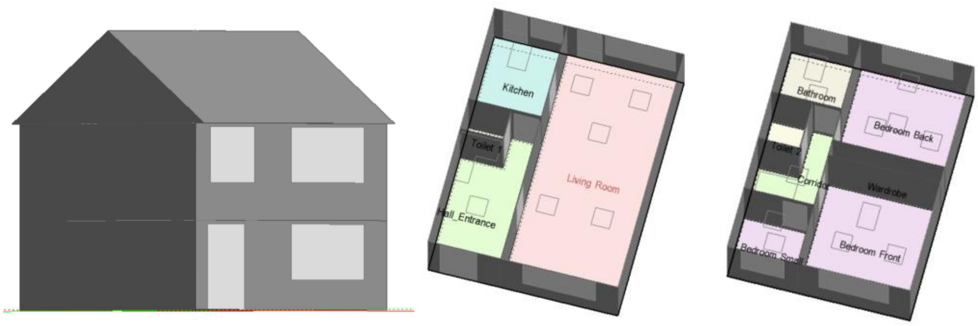

Fig. 12: Screenshots of DesignBuilder model - from the left: whole building, ground floor, first floor

5.2. Preliminary Assumptions and First Input

The house during the measurements was empty, not even furnished, so no occupancy profile or internal heat gains due to equipment will be considered in this stage of the research. Also, some input like ventilation/infiltration rate will be initially assumed and then verified and reviewed within the comparison of simulated data and measured once. These more general input can be easily placed from DesignBuilder and will be resumed as it follows.

- No occupancy
- No lights or equipment (no internal gains)

- No shading system
- Ventilation rate to be defined within the calibration

5.3. IR-Panel Heating System

5.3.1. Discretization of the Element

Acknowledging the composition of the panel from § 4.2, it is straightforward defined the element. Note that being the back panel made of aluminium, a material with such high thermal conductivity, it was needed to avoid that layer from being modelled because that was causing fatal errors into the simulations. This correction will not cause any problem or affect in any relevant way the results. The position of the panels is described in the "Annex A".

- <u>IR - Internal floor slab</u>:

  Composition from the innermost layer (from the floor of the upper level):
  - Floor Slab: Cast concrete (200 mm; λ = 1,13 W/mK)
  - Plaster (10 mm; λ = 0,42 W/mK)
  - Air Gap (5 mm; -)
  - High performance insulant material (20 mm; λ = 0,02 W/mK)
  - Internal source
  - Ceramic (20 mm; λ = 1,3 W/mK)

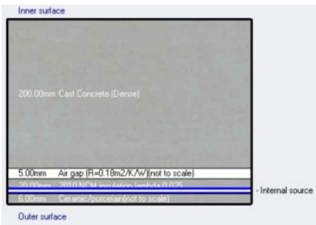

Fig. 13: Cross-section: Sub-surface - Internal Floor with IR panel

To implement into the IR-panel element the heating properties it is used EnergyPlus, in particular the EMS feature, which are described in the detail in the next chapters.

5.3.2. EnergyPlus Advanced Model Settings

EnergyPlus is a thermal load simulation program that, among many features available, after having defined peculiarly the thermal environment and all the detail necessary, is able to calculate heating and cooling loads required to reach the setpoint fixed, energy consumption and many different simulation's outputs. EnergyPlus reads input and writes output to .txt file and provides a spreadsheet-like interface: EP-Launch. With EnergyPlus we can operate on IDF files: a file produced with DesignBuilder, which contains all the necessary details to characterize the building model. It is then to this file that are added the advanced settings referring to all the elements not available on DesignBuilder, this can be done editing the .txt file or via EP-Launch. It is with software that properties like the HVAC system, and more advanced controls are implemented in the model. Also, it will be used to run the simulations that will give the final outputs for this project results.

Within this research, all the calculation algorithms used and provided by EnergyPlus are not described in detail, though a report is done for all the relevant and more specific elements. More information can be found in the “EnergyPlus Documentation Guide” [24].

5.3.3. IR Panels: Heating System Properties

On EnergyPlus are now not available any pre-set HVAC system sub-models to recreate an infrared heating system, though it has been possible to implement into the model the required properties. First it was defined the sub-model that best represent the electric infrared panels.

EnergyPlus provide a list of “Low Temperature Radiant System Model” and one of that consist in an electric solution [24]: ZoneHVAC:LowTemperatureRadiant:Electric is the name of the object.

5.3.3.1. HVAC Object: ZoneHVAC:LowTemperatureRadiant:Electric

This low temperature radiant system it is the one chose to model the infrared panels, and is a component intended to replicate into simulation any radiant system with electric resistance heating used to supply energy. The system is not controlled by a zone thermostat, and all the controls are defined within this only object’s syntax. The heat is supplied by varying the electrical power supplied to the unit: if not modified from other settings, by default the program will vary the power linearly to difference from the actual zone temperature and the setpoint temperature. For each panel installed in the house, it has been created an object with the intent to model all the panels in the building. To this object, more advanced controls will be implemented through the *Energy Management Systems* feature that will be described in the next chapter.

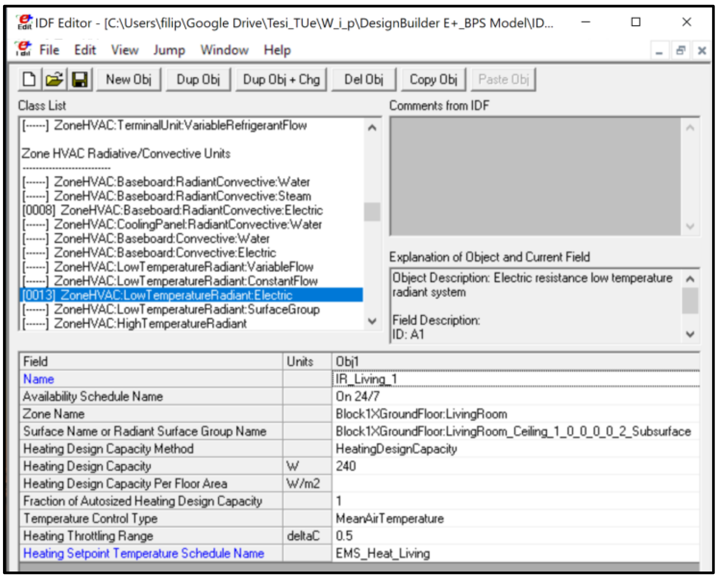

Fig. 14: EP-Launch screenshot: HVAC properties input

In Fig. 14 above is showed the input interface for the object. Among the different things to define we find:

- Zone served from the object
- Surface to which apply the HVAC properties
- Heating design capacity
- Temperature control type and setpoint value
- Throttling range

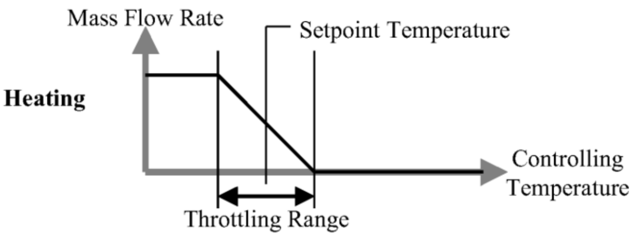

Fig. 15: Low Radiant Heating System: default heating flow rate [25]

5.3.3.2. Energy Management System (EMS)

Energy Management Systems (EMS) [24] is an EnergyPlus feature that allows to modify within the simulation the model itself. It provides a tool that allows to develop custom control and modelling routines for the BPS model so to modify it. As described in the EMS Application Guide provided by EnergyPlus, EMS provides a high-level control to override selected aspects of the simulations. To describe the control is used a programming language called EnergyPlus Runtime Language (Erl), through which the program interprets and executes the instructions.

EMS architecture is essentially composed by the following objects:

- *Sensors:* with this object is defined a variable of the simulation that will be registered from the program. That is use as input from the EMS program, while it can be obtained as an output from the model, or as a data acquired from an external file (e.g. spreadsheets or .txt). We can define, regarding the time step simulation, the exact moment when this variable needs to be registered, that settings is to relate to the "*EnergyPlus Model Calling Point*".
- *Actuators:* with this object is defined the objective of the EMS, so the object that needs to be modified. Actuators, like Sensors, available for the simulation or editing, depend on the model that we are working with, since the different output or settings that characterize the model will allowed to access their limited related settings.
- *Program:* this is the central processor of the EMS and primary container for the Erl language. Within this object we can literally write the program lines to give the instructions for the simulations.

Within this research, EMS is used to implement in the model the different IR-panels control type, and to the heat pumps model as well, so to apply the adaptive comfort theories pre-defined.

5.4. Model "Zero"

The first uncertainties to be cleared around the preliminary assumptions are to address to the air movement inside the building. Considering only the natural ventilation, it is decided to try different values that combine both infiltration and ventilation rates in a single parameter:

A. 1,5 ac/h
B. 1 ac/h
C. 0,5 ac/h

Note that the different simulations in the next tables and figures are named from the letters that refer to air changes value.

The base model that will give the first output will be named "Model Zero" and the main input, implemented to replicate the real thermal environment, can be resume as it follows:

- Heating setpoint: constant, 20° C – control type: air temperature
- Partition that divides the dwellings assumed as adiabatic
- Heating availability schedule: always, 24/7
- Run period: from the 7th to the 28th of March
- Time step: 10 minutes (like the time step of the measured data)
- Weather data built with outdoor temperature and relative humidity registered on the site, while solar irradiance from the TU/e Vertigo Station.
- Ground floor's panel active: 5 type A in the living room
- First floor's panels active: 1 type B in the bedroom front, 2 type A in the bedroom back

- No Occupancy – No equipment

It is important to acknowledge that the HVAC properties implemented to the model are attended to release the power linearly to the difference between the zone mean air temperature and the heating setpoint temperature. As showed in fig. 16 below, the panels active in the building are the once in the living room, bedroom front and back.

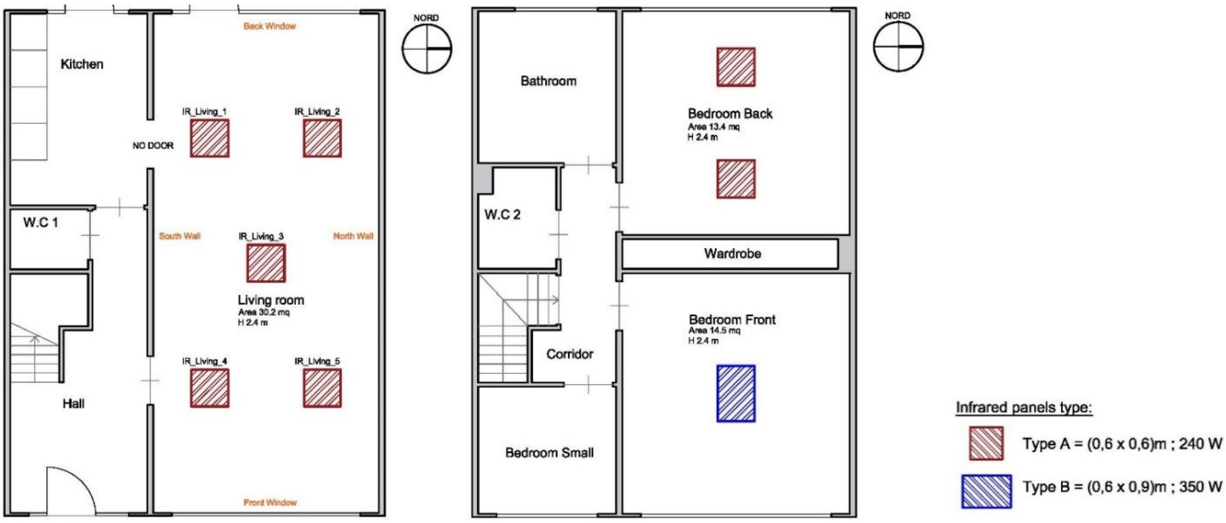

Fig. 16: Position of the active panels: on the left the ground floor, on the right the first one

The first simulation's output for the Model Zero enlightened the necessity of reviewing the way that the power is released from the infrared panel. It is clear indeed that the real system literally works like ruled from an On/Off controller, and once it is turned on, the power is released with full capacity, not linearly like the default settings of the sub-model used to discretize the system on EnergyPlus. Even though the Cv(RMSE) calculated for the different parameters chosen as target for the calibration are showing good indicators values (see table 5 and 6) for the Model Zero, the need for this modification is strictly required to represent properly the real thermal environment. To give a clearer overview of these first outcomes, in fig. 17 and 18 below are showed the simulation's results of the mean air temperature and power usage for different values of air changes per hour. The output are compared with measured data and from the power's graph (fig. 18) it is straightforward to understand the need of the On/Off control, while it is only after the implementation of this one, that is more evident which is the most accurate value to define the air movement in the building.

Note that to give a clearer lecture of the simulations output, the figures are showing results only for the coldest day registered during the run period: March the 7th.

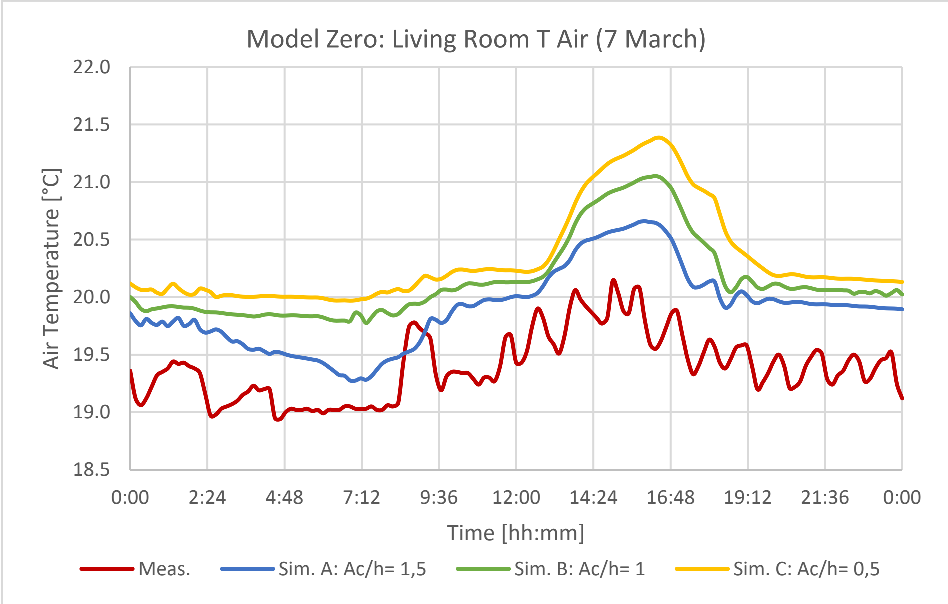

Fig. 17: Model Zero - Living room mean air temperature

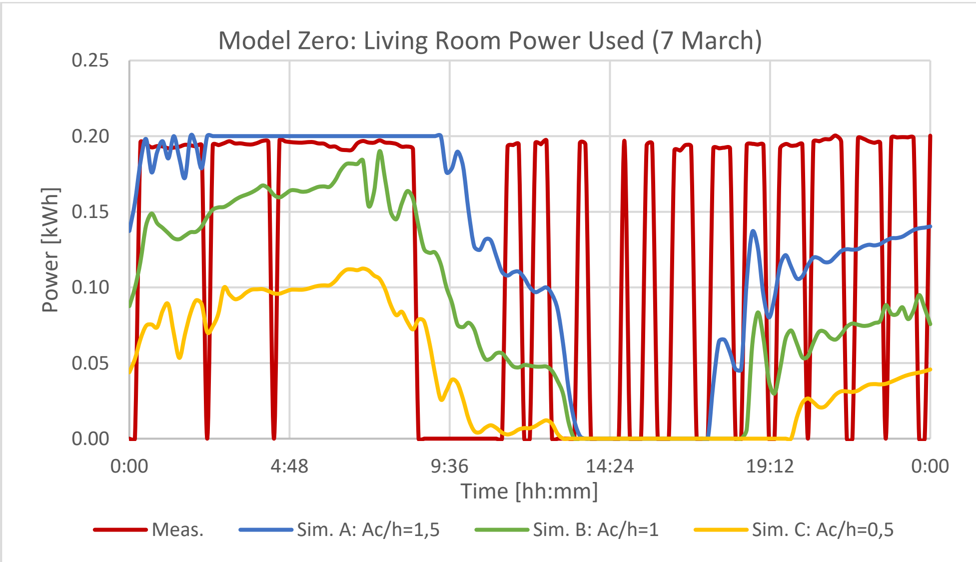

Fig. 18: Model Zero - Living room power usage

Model Zero Accuracy level: Living room Air temp

Simulation	A	B	C
Air chang. / Hour	1,5 Ac/h	1 Ac/h	0,5 Ac/h
NMBE(T)	-4%	-6%	-8%
RSME(T)	1.28	1.52	1.98
Cv(RMSE)	**7%**	**8%**	**10%**

Tab. 7: Model Zero Accuracy level, based on living room air temperature for different values of ventilation

Model Accuracy Level: Model Zero - Simulation B (Ac/h=1)						
Run Period 7-28 March / Time step 10 min						
Living Room	**T Air**	**T Wall**	**T Win. B.**	**T Win. F.**	**T Ceiling**	**T Ground**
NMBE(T)	-6%	-4%	-5%	1%	-1%	-8%
RSME(T)	1.52	1.00	4.40	2.50	0.86	1.00
Cv(RMSE)	**8%**	**5%**	**22%**	**12%**	**4%**	**5%**

Tab. 8: Model Zero Accuracy Level Indicators

5.5. Implementation of the On/Off Control and Final Adjustments

To identify the model after the implementation of the on/off control that is named "Model 1". The new control is accomplished vie the EMS on EnergyPlus. Since the sub-model chosen for discretizing the system (ZoneHVAC:LowTemperatureRadiant:Electric) doesn't provide a direct way to control directly the power release we want the system to release full power once it turns on), the goal is reached with a few simple program lines reported below, that modify the IR-panels thermostat control, using as *Sensors* the zone's mean air temperature:

- **On/Off Control Program Lines:**

  IF Zone Air Temperature < 19,5 °C then SETPOINT = 50°C

  ELSEIF Zone Air Temperature ≥ 20,2°C then SETPOINT = 0°C

In this way the IR-panels release immediately the power with full capacity, since the big difference from the zone air temperature and the setpoint temperature is such that all the capacity is required to reach it.

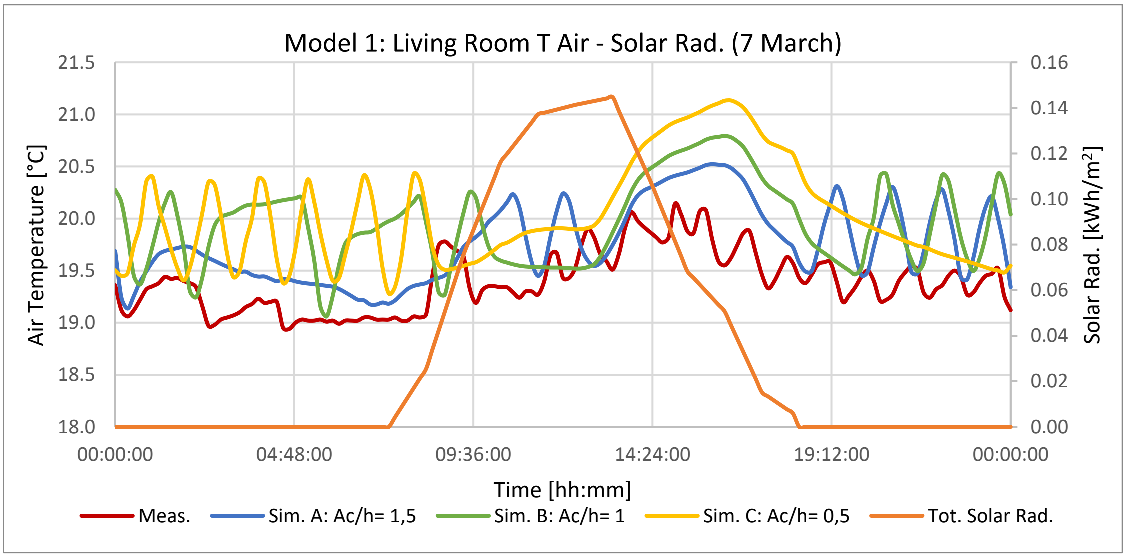

Fig. 19: Model 1 - Living room mean air temperature with the implementation of the On/Off control

Model Accuracy Level: Model 1 - On/Off - Simulation B (Ac/h= 1)						
Run Period 7-28 March / Time step 10 min						
LIVING ROOM:	**T Air**	**T Wall**	**T Win. B.**	**T Win. F.**	**T Ceiling**	**T Ground**
NMBE(T)	-5%	-9%	-9%	2%	0%	-7%
RSME(T)	1.41	2.09	4.11	2.52	0.81	2.09
Cv(RMSE)	**7%**	**10%**	**21%**	**12%**	**4%**	**10%**

Tab. 9: Model 1 Accuracy Level Indicators – implementation of the On/Off control

From table 9 we can see that implementing the On/Off control brought to improving the accuracy level of some indicators, like the mean air temperature, while others as "T Wall" or "T Ground" have diverged from the target. It is important to understand that even if the indicators are showing a divergence from the calibration, the implementation of the on/off control is compulsory for the characterization of the system, and so the model itself.

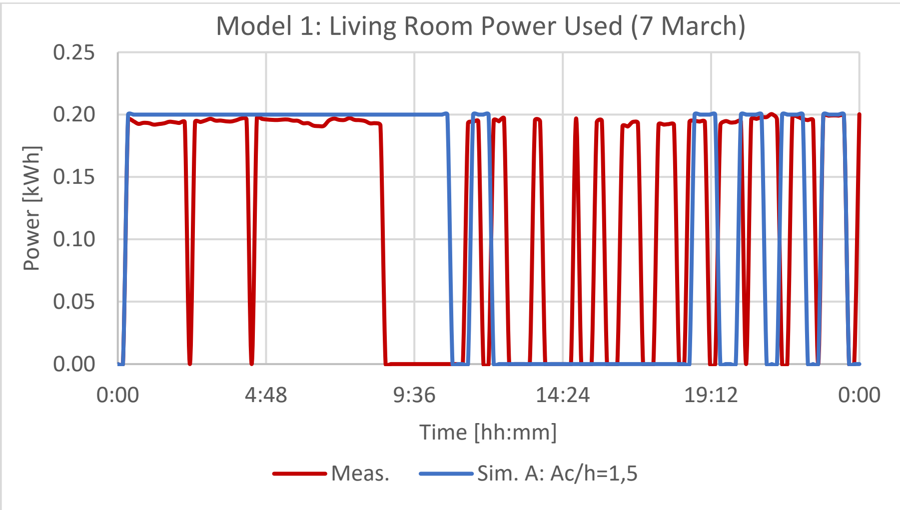

Fig. 20: Model 1- Simulation A - Living room power usage

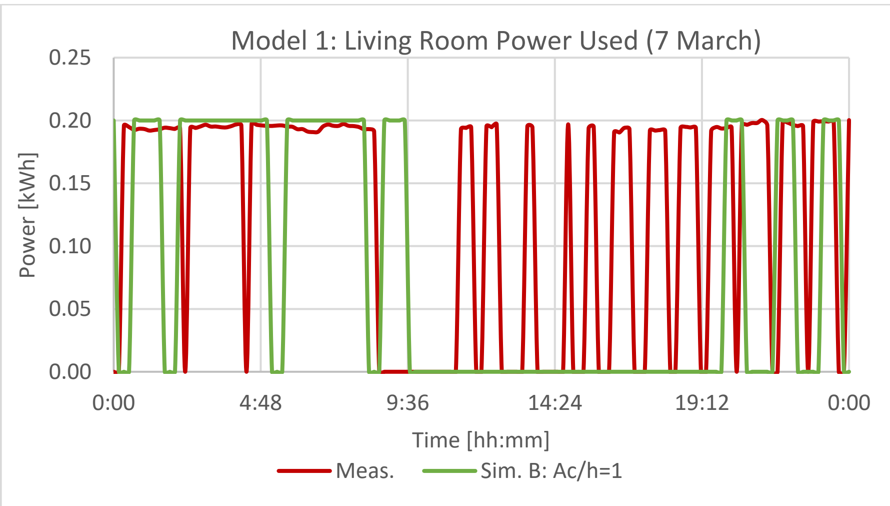

Fig. 21: Model 1 - Simulation B - Living room power usage

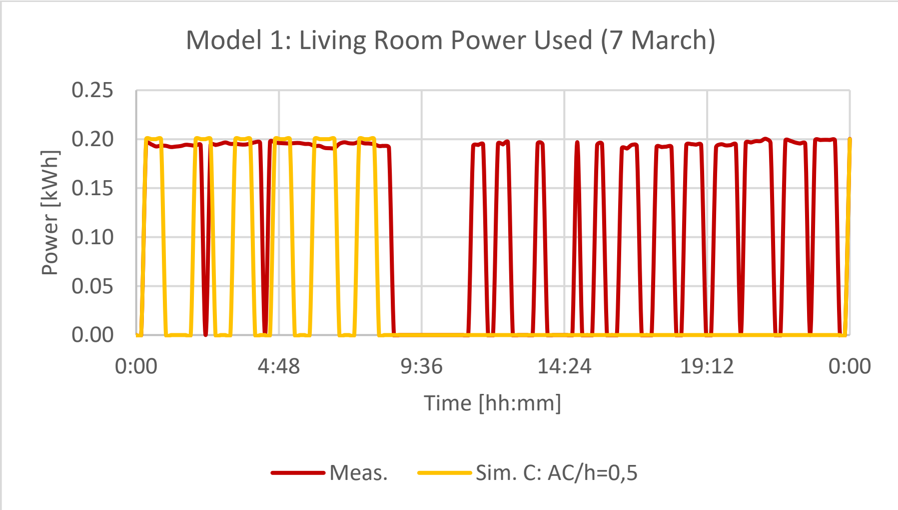

Fig. 22: Model 1 – Simulation C - Living room power usage

The general accuracy level of the Model 1, regarding the mean air temperature, remains almost the same of the Model Zero, though from the figure 20-21-22, with the power usage compared with the measured once for different values of ventilation, it gets clearer that the correct value is the one used in the simulation B (1 ac/h). Figure 20 is showing that, for simulation A (1,5 ac/h), the panels are not turning off even during the warmer hours of the day (from noon until the end of the afternoon), while instead happens in the measured data. Also, the setpoint temperature of 20°C, it is rarely met within the simulation (see fig. 19). Considering also that that happens coincidently with the solar radiation peak, it is then accepted that 1,5 ac/h is a too high value for the ventilation rate. Similar consideration but with opposite direction can be done for what is showed in figure 22, where the value of 0,5 ac/h of the simulation C is too small for the ventilation, indeed the panels are turning on not often as they should, even in the colder hours. In conclusion, the value that is accepted for the air movement inside the house is 1 air change per hour, verified with the simulation B and, from now on, it is used to reach the final calibration of the model.

Model 1 Accuracy Level: Living room Air temp

Simulation	A	B	C
Air chang. / Hour	1,5 Ac/h	1 Ac/h	0,5 Ac/h
NMBE(T)	-4%	-5%	-7%
RSME(T)	1.23	1.41	1.85
Cv(RMSE)	**6%**	**7%**	**10%**

Tab. 10: Model 1 - Air temperature accuracy level for different values of ventilation

It needs to be explained though that, even if the Simulation A, is showing the best value as accuracy level indicator (see table 10), it should not be the one chosen for the calibration of the model. Reasons for this belief lay in the observation that the accuracy indicators may have a better "numerical" result, but the outputs are showing important differences in how the model responds. Simulation B, on the other hand, meet considerably better than the others the power usage measured and its fluctuations with time, which is an important aspect to consider into the characterization of the model that is also compulsory for this research.

The final fit of the model it is reached with one last adjustment, which required to investigate the boundary conditions applied to the walls which divide the different dwellings that compose the whole building block. Being the houses sharing the same plant concept, they are likely to have the same zone disposition, though assuming initially those partitions adiabatic can be hardly a good choice. For example, if we consider the North Wall of the living room, the east side will be opposite to the entrance of the next house, and so it is likely that in that area we can find the same conditions simulated in our model: that is way there are reason to believe that in that area the temperature won't be 20°C ore close, so the partition can be considered not adiabatic. Also, the composition of this partition it is assumed equal to the internal partition of the house, but there is no certainty about it. To adjust the model to these new considerations, will be investigate the boundary conditions for each required construction element on EnergyPlus. The modification applied, is a new setting for the wall, which involve the *"Other Side Coefficient"* (OSC) object. By referring to this, it can be affected the outer plane of a surface or directly the temperature of a "virtual zone", opposite to the construction element in consideration. Also, the partition's heat transfer properties can be modified, adjusting the *"Combined Convective/Radiative Film Coefficient"* (CCR) [24]. To fit the model, after several simulations and comparisons of data, it is decided to apply an average constant temperature of 18°C to the "adjacent virtual zone" and setting the partition's CCR to a value of 2,5 W/m^{2}K (see fig 22). The result of this final modification will give the calibrated model, which output, and characteristics are described in the next chapter.

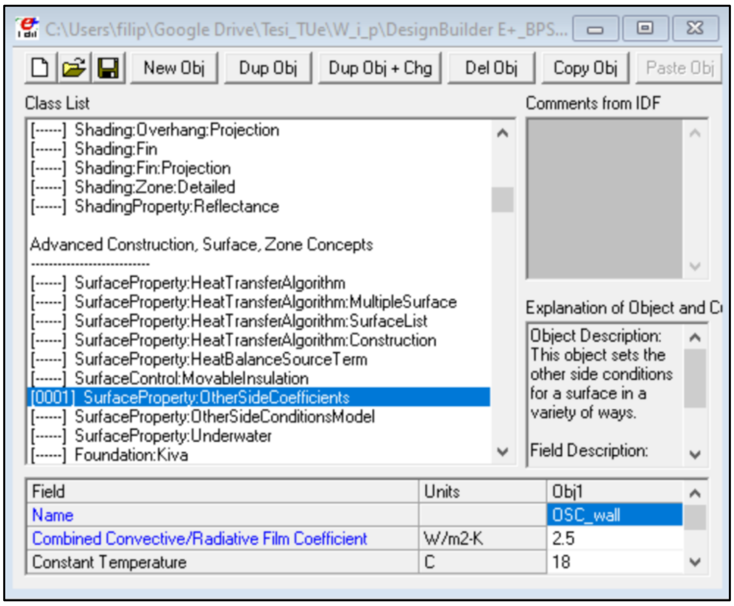

Fig. 23: EnergyPlus screen-shoot: Other Side Coefficient input

5.6. Calibrated Model

In table 11 reported below, are showed the accuracy level indicators for the different parameters selected for the calibration of the model. The coefficient's levels are in accordance with what said at § 6.3.1 and so the model can be considered fitted. Though it needs to be paid attention to the parameters describing to the two window's temperature. Those two indicators are showing strange values if compared with the others, indeed the front window's Cv(RMSE) is 11% and the back's once is 20%, while all the others are 6% and 3%. The explanation lays in the fact that the solar radiation used in the simulation has not been registered on the site, but at the TU/e's Vertigo Station, thus it is likely to have completely different values from the once that affected the real building, and so the data registered. Considering also that the two windows are exposed to East and West, is assumed that the solar radiation plays an important role in affecting the surface's temperature.

Model Accuracy Level: Calibrated Model

Run Period 7-28 March / Time step 10 min						
LIVING ROOM:	**T Air**	**T Wall**	**T B. Win**	**T F. Win**	**T Ceiling**	**T Ground**
NMBE(T)	-4%	-5%	-9%	3%	1%	-6%
RSME(T)	1.22	1.23	3.98	2.45	0.74	1.23
Cv(RMSE)	**6%**	**6%**	**20%**	**11%**	**3%**	**6%**

Tab. 11: Accuracy level of the model based on the living room's indicator parameters

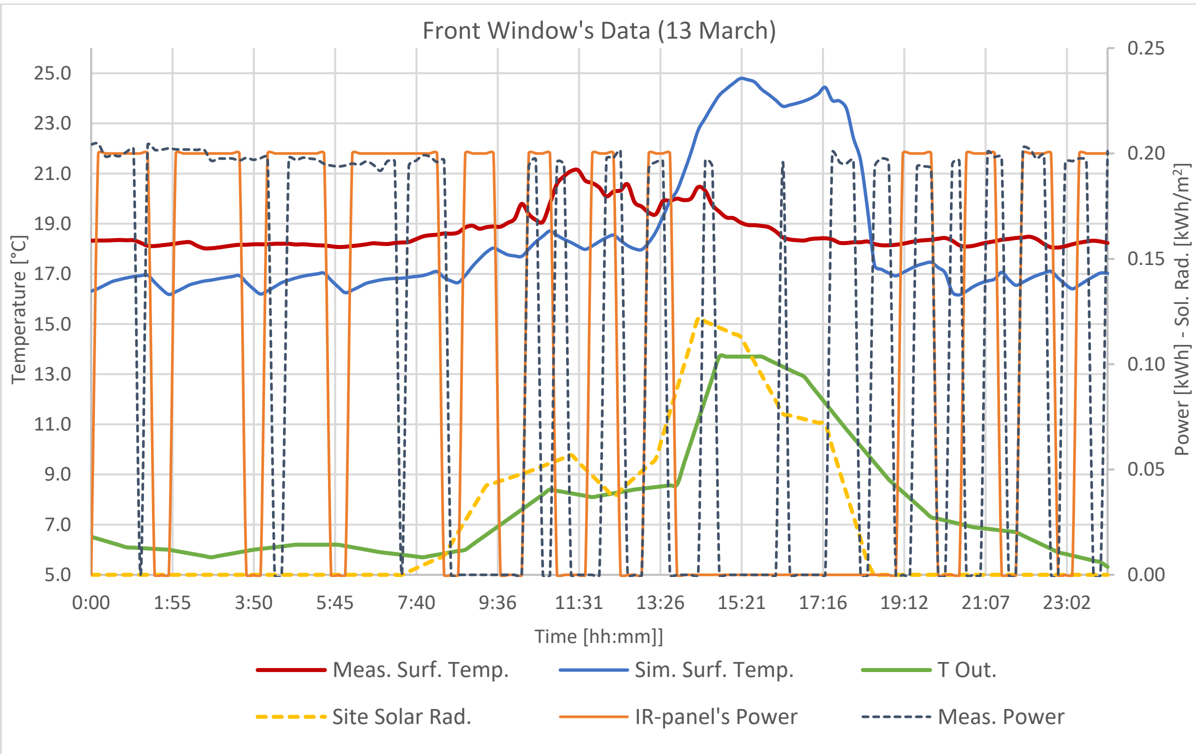

Fig. 24: Analysis of the front window's surface temperature

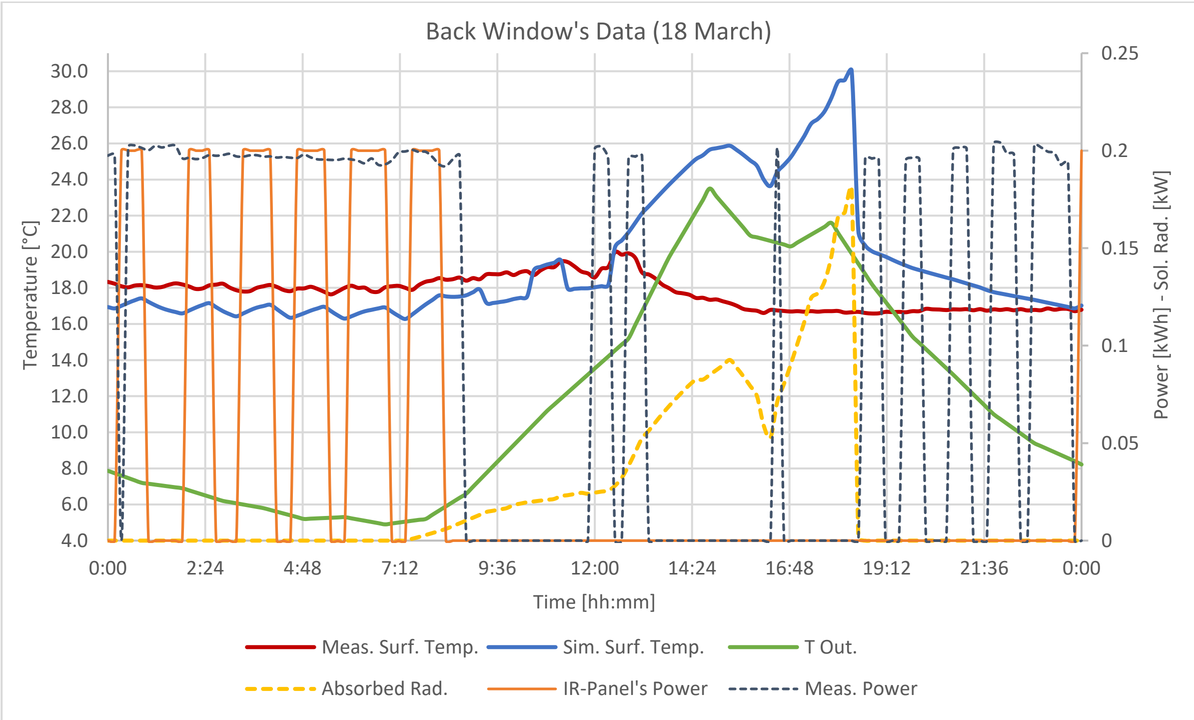

Fig. 25: Analysis of the back-window's surface temperature

Analysing the window's surface temperature, and comparing the simulation's output with measured data, it emerged that the divergence of the two is connected to the solar radiation as expected. That is clear from figure 25, where the model's front window is hit, around 15:00, by a considerable amount of radiation, indeed for an outdoor temperature of 14°C, the simulation's output for the window's surface temperature is 25°C, while the IR-panels are switched off. That temperature is never reached by the measured data, and the window's temperature measured is almost constant around 19°C, which is also in line with the outdoor temperature. Note that, on the contrary of what done for the back-window, in this analysis it was considered the total radiation of the site, not the direct-absorbed once from the glazing like done for the back-window. That is because the moment when the high temperature is reached is during the afternoon, when this window, facing East, is not hit directly from the solar beam. From figure 26, and so from the analysis of the back window, is even more clear what said previously: the peak of the window's surface temperature is reached coincidently with the absorbed radiation peak, which happens when the panels are not working, the increasing of the surface's temperature is so due mainly to the solar radiation. For these considerations there are reason to believe that the accuracy level of the model is even better than what emerged from the indicator coefficients. That is due to uncertainties around the measured data, acquired with not a considerable number of sensors, and mainly for the construction of the weather data which is missing the solar radiation on the site. Despite these implications, the accuracy level reached from the model is found reliable and solid for the research purposes.

To give a complete overview of the general accuracy of the model, table 10 reported below is showing the indicator coefficients regarding the mean air temperature calculated for the other zones where the panels were active.

Model Accuracy Level: Calibrated Model			
Run Period 7-28 March / Time step 10 min			
T Air	**Kitchen**	**Bed. Front**	**Bed. Back**
NMBE(T)	-2%	8%	1%
RSME(T)	1.92	2.09	0.38
Cv(RMSE)	**10%**	**10%**	**2%**

Tab. 12: Model accuracy indicator for different zone's air temperature

Assessed the confidence degree of the model, there are still some things that need to be defined before moving on with the next steps. An element that can considerably affect simulations is the choice of the time step. For this research, the temperature data acquired in the house have been registered with a time step of 10 minutes, and so the same time step it has used for the simulations. It is important to notice though that when it comes to analyse the energy consumption, the choice of the time step becomes crucial, since even a 10 minutes once could miss some moments when the system switch on and off, affecting the simulation with possible errors, things that can't be accepted since the aim of these research is to evaluate the heating systems in their efficiency and affordability. Also, since the IR-panels are reaching really high temperatures (around 80 – 90 °C) when operating, it is important to investigate how fast they do it, so to understand if that is happening in a range of time that is missed from the time step choose for the simulations. To acknowledge that, the panels have been tested in the TU/e labs, recording surface's temperature data, with thermal sensors and infrared camera. The data are showing differences in the distribution of the heat over the panels surfaces, indicating that the panels temperature is not uniform, but lower on the edge and higher in the core. These aspects have been found important to acknowledge, and research is still going on within the HERSCHEL Project, from which are provided these data, though, for this research purposes, considering an area averaged temperature for the panels is found a reliable approach.

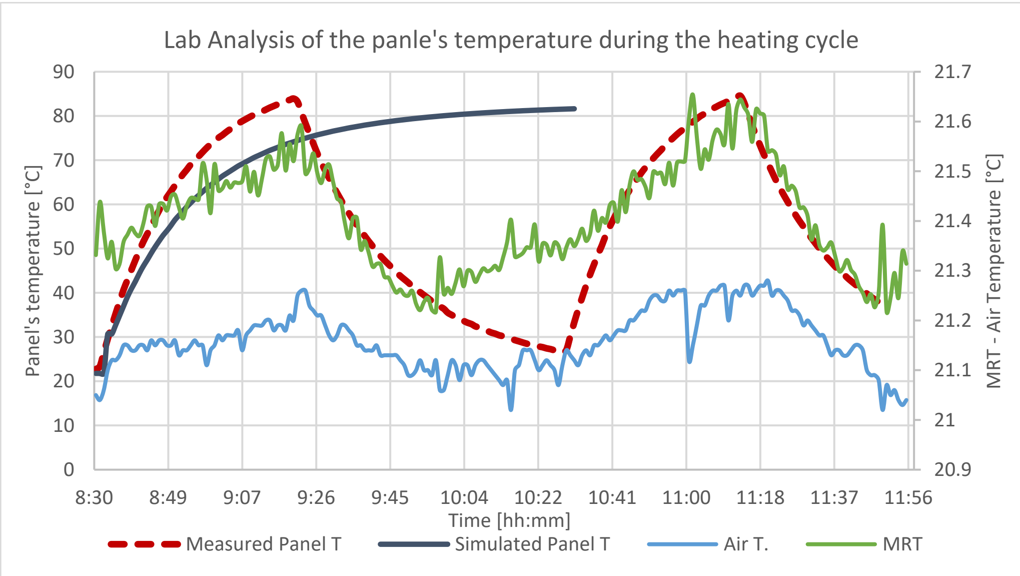

Fig. 26: Analysis of the Panel's surface temperature - Lab test

Figure 26 is showing the comparison of simulation with the data registered in the lab during a heating cycle, where the panels are reaching the full capacity and then switched off. The time step for the measures it has been 1 minute, and the surface temperature is calculated with an average based on the area's surface. That data is compared with the simulation's output of the calibrated model, and it is found a good match. The real panels need almost one hour to reach the maximum operating temperature, almost 85 °C, which is line with the simulation, both considering the maximum temperature reached and time needed. Also, since the increasing of the surface's temperature is happening in 1 hour, having a simulation time step of 10 minutes can be considered a good approach for the calibration, but it needs to be investigated more deeply as comes the time for consideration around the energy consumption. Note that the lab results are influenced by the absence of a relevant thermal mass of the element, being the panel not attached to a ceiling slab. That is affecting the results, causing a faster variation of the temperature. This is assumed as the main reason for the gap verified between simulated and measured surface's temperature.

As mentioned, with a 10-minute time step, it is possible to miss instants where the heating system switch on and off, producing errors in estimating the energy consumption. To investigate that, the calibrated model will be used to run simulation with different time steps as reported below, note that also 1 hour will be tested to evaluate the differences within a bigger variation.

A. 1 hour
B. 10 minutes
C. 5 minutes
D. 1 minute

Then, the total energy consumptions for a simulation made during the months from October to April are compared to understand which differences will emerge.

Calibrated Model: Comparison of Heating Energy Used- Electricity

Run period: 1 October - 1 April

Simulation	Time Step	Tot. Energy Used [kWh]	Energy Per Tot. Build. Area [kWh/m2]	Energy Per Heated Area [kWh/m2]	Variation
A	1 h	7311.89	55.29	86.13	-
B	10 min	7266.44	54.95	85.59	-1%
C	5 min	7281.82	55.06	85.77	0%
D	1 min	7262.66	54.92	85.55	0%

Tab. 13: Comparison of energy consumption for different time step simulations

Table 13 shows the influence of the time step over the simulations results. It needs to be said though that the variation between the simulations is revealed less important than what could have been expected. It is indeed only with the reduction of the time step from 1 hour to 10 minutes that it can be appreciated a significant variation, while changing from that to 5 or 1 minute, is not affecting in a considerable way the results. Nevertheless, the little variation from 10 minutes to 5 is positive, while instead the energy demand decrease again (as expected) changing the time step from 5 to 1 minute, but though the values for the energy usage are almost the same for the simulations B, C and D.

Another aspect that can be evaluated during the choice of the simulation's time step, is if changing it causes differences in the comfort levels obtained. To assess that, the ASHREA 55 adaptive approach is applied, and is assessed that these variations are not affecting in a considerable way the results (see figures 27-28-29-30 below). For these reasons, the time step that it is decided to use within this research's simulations is 10 minutes, which also will require to handle a not too big amount of data.

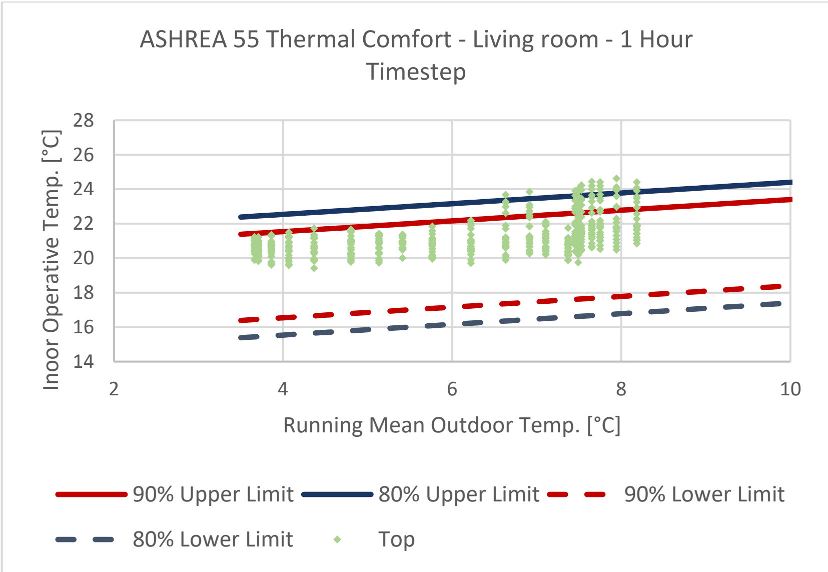

Fig. 27

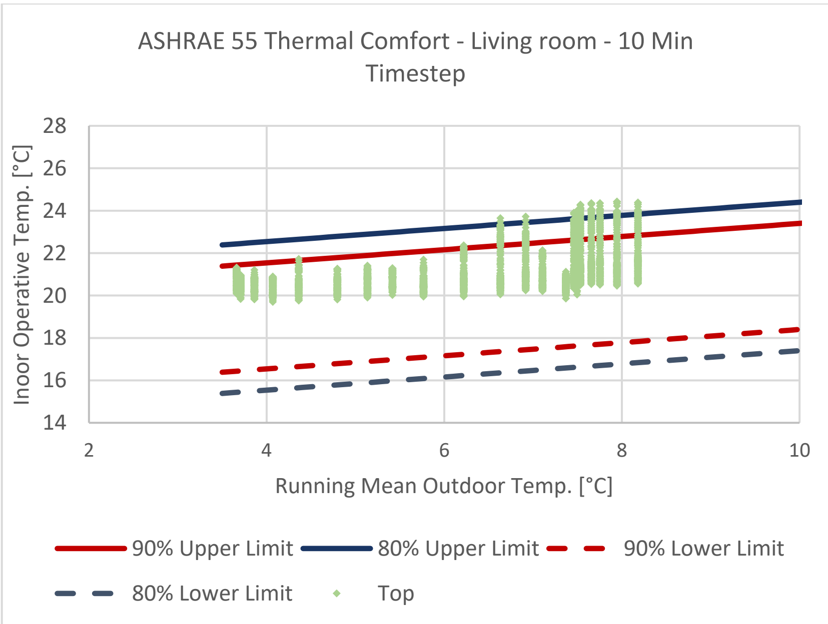

Fig. 28

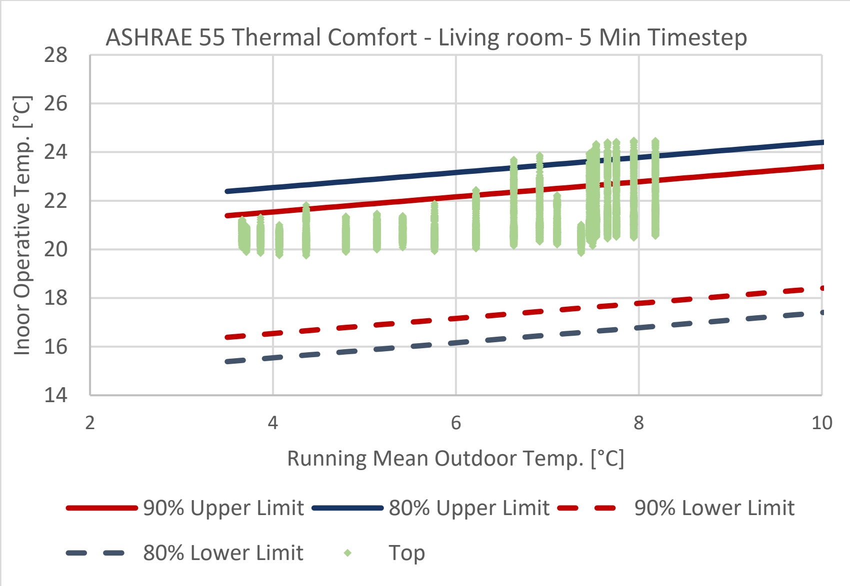

Fig. 29

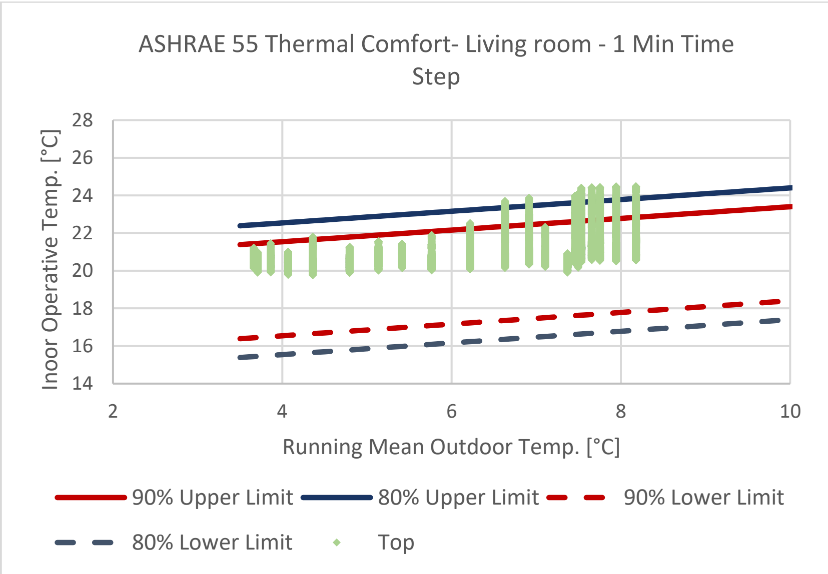

Fig. 30

6. Developing the Heat Pump BPS Model

As comparison with the infrared panel's model, is used the same BPS model but with implemented a different heating system: an electric air to water heat pump with radiant floors. Air to water heat pump take the heat from the outside air and transfer it to a fluid, usually water, that then is directed to the terminal in the house, usually radiant floors (like in this research case) or baseboard water heaters. These systems can also be used in cooling mode but, within this research, it is only considered the heating season. The source of these systems can be electric or gas, though to compare it with the IR-panels is only evaluated the first option, since electricity is the same source. The benefits claimed by heat pumps are several, within them, the most relevant are high efficiency even in cold climate, rather than low energy consumption.

The BPS model is straightforward defined with DesignBuilder, where, between several available pre-defined templates, is available an air to water heat pump once, to which are added as terminal radiant floors. Then, like what has been done for the IR-panels model, on EnergyPlus are defined the heating control settings (defined in Tab. 5 at § 3.2.4), so to perform energy simulation and collect data for the performance comparison between the two systems in their multiple configuration.

In the Annex E is provided a more detailed overview about the scheme of the system, and the characterization of the radiant floor.

7. Results – Performance Comparison

The model performances are compared in terms of thermal comfort and energy consumption, estimated on a run period that goes from October the 1st to April the 1st, with a ten-minute time step. The full detail of the results is showed in the "Annex F" while here, in this chapter, are enlightened the most relevant outcomes, from which is develop the discussion and the final considerations. It is reminded that at § 3.3 are defined in detail the criteria for the performance comparison.

Note that, in the next figures, with Trmo (see definition at Eq. 2) is defined the running (prevailing) mean outdoor temperature used to implement the setpoint temperature with the adaptive approach proposed by the ASHRAE 55 method. While, with Tref, is defined the reference temperature (see Eq. 13) proposed by Van Der Linden et al. [20] and used to define the specific setpoint temperature for the different rooms of the building (as required for the temperature characterization proposed by Peeters et al. [19].

7.1. Comfort Level

From fig.31 below, is appreciable that the actual configuration of the panel, so the one obtained from the calibrated model (IR_C1), in the living room has met with good result the comfort level assessed with the ASHRAE 55 adaptive approach. Though it is important to investigate why for some low values of the running mean outdoor temperature, between 6,5°C and 8,5°C, it is verified overheating. That is assessed with fig. 32 and 33, where is understood that that happens when the system is turned off, and the reason of overcoming the comfort limits it is due to the impact of solar radiation.

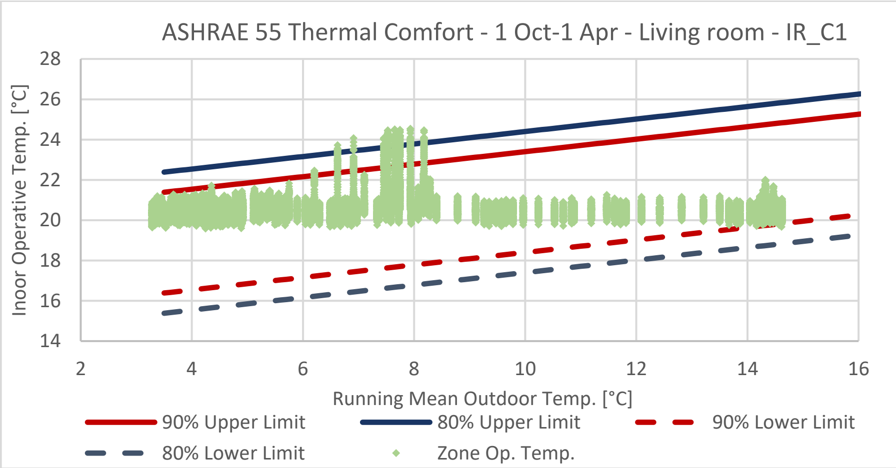

Fig. 31: Living room comfort assessment - IR_C1 (Calibrated IR configuration)

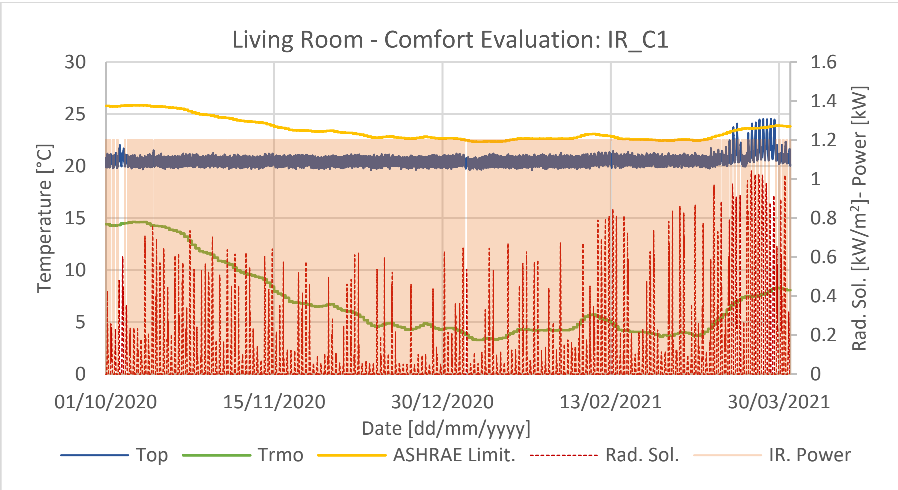

Fig. 32: Overheating analysis - Living room

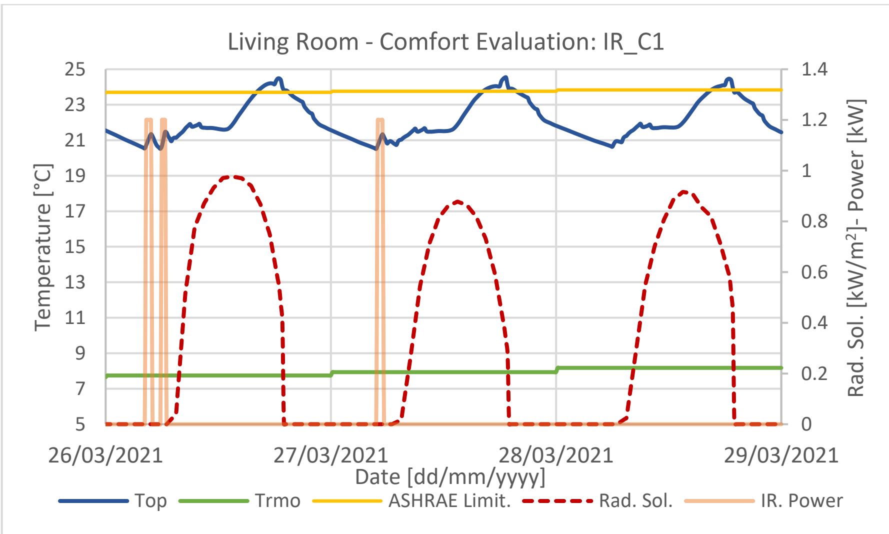

Fig. 33: Overheating analysis - Living room

IR_C1: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	2%	0%	0.11%	1%	0.31%	0%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	0%	100%	100%	100%	0%
9 <= Trmo < 16	0%	0%	0%	0%	0%	0%

Tab. 14

Living room - IR_C1: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1%	32%	1%	1%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%
9 <= Trmo < 16	0%	0%	0%	0%

Tab. 15

Vertical Radiant Asymmetry - Warm Ceiling: IR_C1 - (1 Oct. - 1 Apr.)				
Limit PPD 10% = 7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	23.92	28.59	18.00	14.38
Tot Unplesant time [%]	58%	64%	54%	51%
PPD Max [%]	73%	84%	52%	36%
PPD Average [%]	31%	40%	21%	16%
ΔT_{pr} > 10 °C	52%	59%	46%	7%
ΔT_{pr} > 15 °C	42%	49%	30%	0%
ΔT_{pr} > 20 °C	30%	39%	0%	0%
Horizontal Radiant Asymmetry - ΔTpr Max: IR_C1 - (1 Oct. - 1 Apr.)				
Horizontal N-S [°C]	0.31	0.28	0.27	0.27
Horizontal S-N [°C]	1.05	1.00	1.47	1.47
Horizontal E-W [°C]	1.91	1.28	7.98	8.58
Horizontal W-E [°C]	2.80	2.26	19.61	16.63

Tab. 16

Table 14 confirms that the percentage of unmet time for the comfort levels are considerably low, indeed the zone with the highest one is the kitchen which has a value of 2%. Then, from tab. 15, investigating the comfort in specific positions of the living room, it is verified that the values obtained in the position 1 (person seated in centre of the room) is close to the average living room's once. Within the different positions, the number 2 (person standing in the centre of the room – below the central panel) is the one that shows worse result for the comfort level (unmet time 32%). That is verified from tab. 15 and enlightened from fig. 34 below.

Tab 16 instead shows the results for the assessing of the radiant asymmetry. The one due to warm ceiling (which is the relevant one considering the heating system installed to the ceiling) has an average total unmet time of almost 50% in all the positions evaluated in the living room, with a PPD peak of 84% verified for the position 2. To give a complete evaluation is analysed also the horizontal radiant asymmetry, which is showing high values that could bring to local discomfort in the position 3 and 4, especially if the condition occurred is of cool walls. It is important to acknowledge that what verified in these two positions regarding the horizontal asymmetry, for the geometry of the room, windows' position, and exposure, are in line with what expected to encounter in such critical condition. For these reasons, this data is considered not relevant for the research purposes.

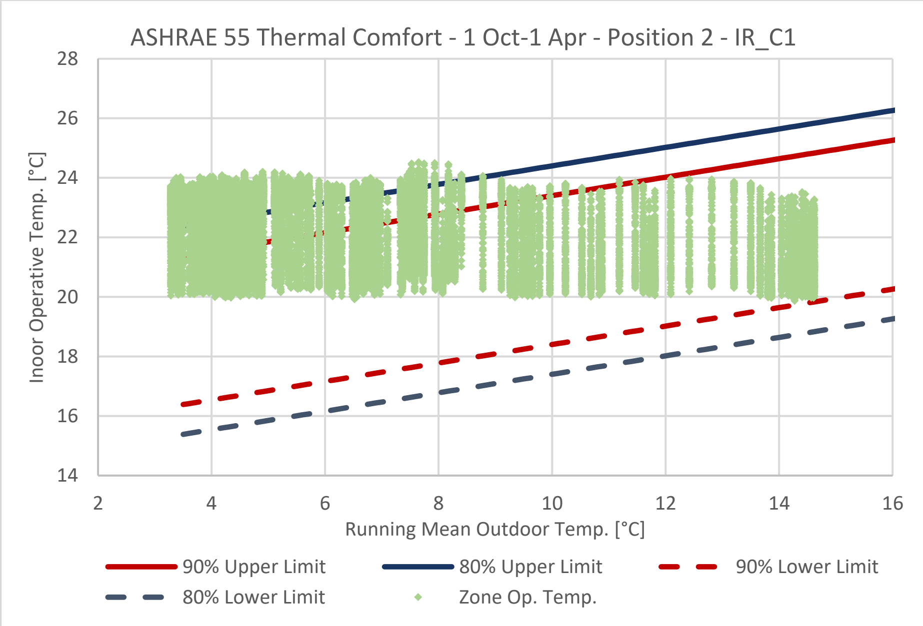

Fig. 34

Mostly the same comfort results are obtained from the model IR_C2_1, so these are just reported in the Annex F.

Switching from an On/Off control to an ideal once instead, done in the IR_C2_2 model, brings to a little improvement in how is perceived the thermal environment, reflected also in less fluctuations in the operative temperature registered in the zones (the results are showing that the operative temperature registered are better following the central line of the ASHRAE comfort model). This upgrade perceived in the overall comfort sensation is followed by a more visible improvement, appreciable from tab 17 below, where the value for the unmet time obtained in the position 2 is reduce of the half to the 17% if compared with the other model seen this far. Same thing cannot be said for the radiant asymmetry (see tab. 18), which, for all the position, still shows the same critic values for the discomfort due to warm ceiling seen in the model IR_C1.

Living room - IR_C2_2: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1%	17%	1%	1%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%
9 <= Trmo < 16	0%	0%	0%	0%

Tab. 17

Vertical Radiant Asymmetry - Warm Ceiling: IR_C2_2 - (1 Oct. - 1 Apr.)				
Limit PPD 10% =7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	23.94	28.61	18.01	14.39
Tot Unplesant time [%]	66%	75%	57%	50%
PPD Max [%]	74%	84%	52%	36%
PPD Average [%]	27%	38%	17%	13%
ΔT_{pr} > 10 °C	55%	66%	40%	7%
ΔT_{pr} > 15 °C	33%	49%	11%	0%
ΔT_{pr} > 20 °C	12%	28%	0%	0%
Horizontal Radiant Asymmetry - ΔTpr Max: IR_C2_2 - (1 Oct. - 1 Apr.)				
Horizontal N-S [°C]	0.36	0.32	0.32	0.32
Horizontal S-N [°C]	1.07	1.02	1.49	1.49
Horizontal E-W [°C]	1.92	1.28	7.89	8.55
Horizontal W-E [°C]	2.81	2.27	19.57	16.59

Tab. 18

What is interesting to observed is that generally, the IR_C2_2 (Ideal control type) model, shows higher percentage of total unpleasant time due to radiant asymmetry for all the position if compared with IR_C2_1 with an On/Off control type. Despite this general greater unmet percentage of time, an ideal control brings to a reduction of the time when the radiant asymmetry falls into the higher ranges (e.g. in the position 2 the model IR_C2_1 registered ΔT_{pr} > 20 °C for the 39% of time, while in the IR_C2_2 the 28%).

The model IR_C3_1 shows, excellent results for the comfort levels assessed with the ASHRAE adaptive approach, indeed from tab. 19 we can see that the percentage of unmet time are almost 0% for all the zones of the building.

IR_C3_1: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	1.28%	0%	0%	0.22%	0.18%	0%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo< 9	100%	0%	0%	100%	100%	0%
9 <= Trmo < 16	0%	0%	0%	0%	0%	0%

Tab. 19

This improvement achieved for the overall comfort sensation, is verified also with the values obtained from the evaluation of the comfort level in the specific positions of the living room, see fig 35 with position 2, the most critic once, and tab. 20 below, where the percentage of unmet verified are below the 1% in all the positions. Also, tab. 21 shows that the radiant asymmetry due to warm ceiling is reduce to a maximum value of the 54% of time verified always in the position 2.

Living room - IR_C3_1: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	0.24%	0.33%	0.63%	0.43%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	99%	100%	100%
9 <= Trmo < 16	0%	1%	0%	0%
16 <= Trmo	0%	0%	0%	0%

Tab. 20

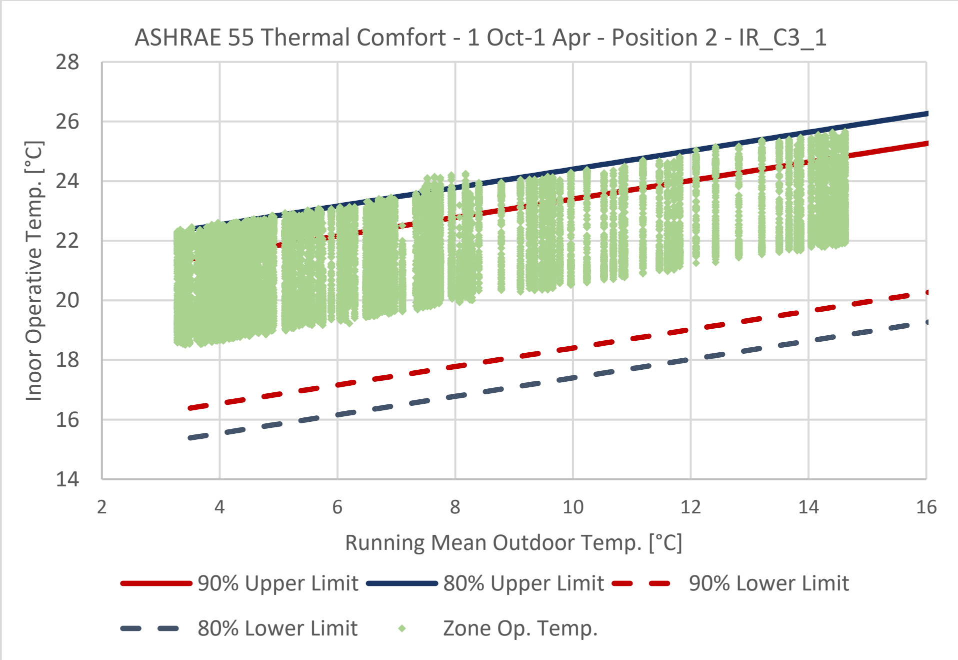

Fig. 35

Vertical Radiant Asymmetry - Warm Ceiling: IR_C3_1 - (1 Oct. - 1 Apr.)				
Limit PPD 10% =7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	24.39	28.98	18.40	14.70
Tot Unplesant time [%]	48%	54%	45%	41%
PPD Max [%]	75%	85%	53%	38%
PPD Average [%]	26%	33%	17%	14%
ΔT_{pr} > 10 °C	43%	48%	38%	7%
ΔT_{pr} > 15 °C	34%	41%	24%	0%
ΔT_{pr} > 20 °C	24%	32%	0%	0%
Horizontal Radiant Asymmetry - ΔTpr Max: IR_C3_1 - (1 Oct. - 1 Apr.)				
Horizontal N-S [°C]	0.18	0.16	0.16	0.16
Horizontal S-N [°C]	0.96	0.91	1.26	1.26
Horizontal E-W [°C]	1.90	1.28	7.29	7.98
Horizontal W-E [°C]	2.84	2.30	19.48	16.50

Tab. 21

The model IR_C3_2 shows the same variation in terms of comfort appreciated in switching from an On/Off control to an ideal once seen for the models IR_C_2_1 and IR_C2_2 (slightly better overall comfort levels – higher percentage of total unmet time for radiant asymmetry, but verified with lower values of ΔT_{pr}), full detail in Annex F.

From fig 36 to 38, are shown the different results obtained from the model IR_C4_1, with a specific characterization of the setpoint temperatures for the zones of the building, defined as described at § 3.2.4. Those are all showing good comfort levels but, at a first glance, slightly worse than the other model seen previously. Is noted indeed that these setpoint temperatures are bringing to generally low operative temperature in the bedroom, while instead is verified over-heating in the bathroom.

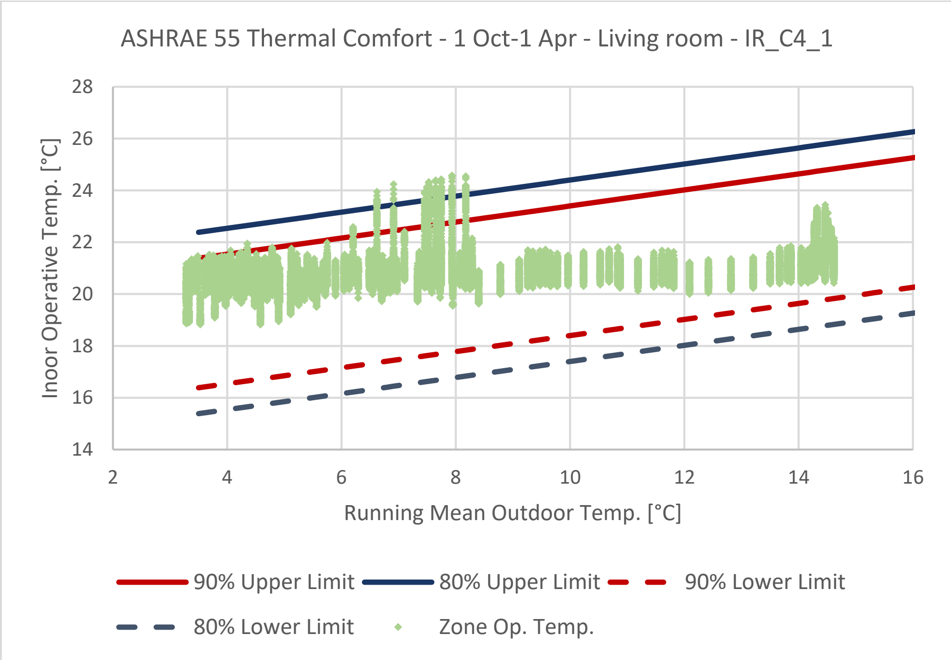
ASHRAE 55 Thermal Comfort - 1 Oct-1 Apr - Living room - IR_C4_1
Inoor Operative Temp. [°C]
28
26
24
22
20
18
16
14
2
4
6
8
10
12
14
16
Running Mean Outdoor Temp. [°C]
90% Upper Limit
80% Upper Limit
90% Lower Limit
80% Lower Limit
Zone Op. Temp.

Fig. 36

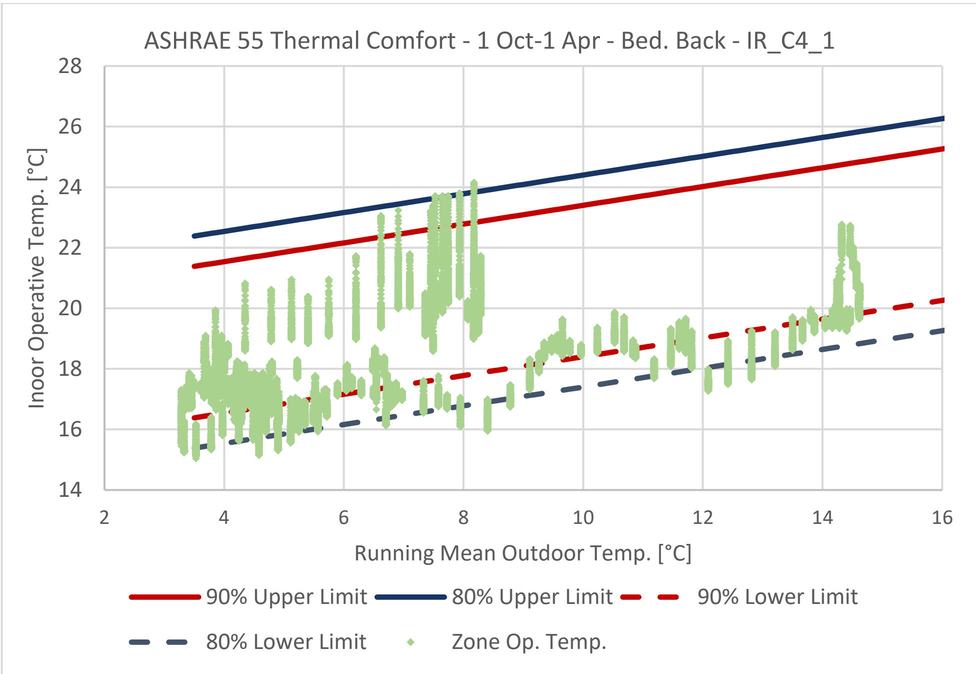
ASHRAE 55 Thermal Comfort - 1 Oct-1 Apr - Bed. Back - IR_C4_1
Inoor Operative Temp. [°C]
28
26
24
22
20
18
16
14
2
4
6
8
10
12
14
16
Running Mean Outdoor Temp. [°C]
90% Upper Limit
80% Upper Limit
90% Lower Limit
80% Lower Limit
Zone Op. Temp.

Fig. 37

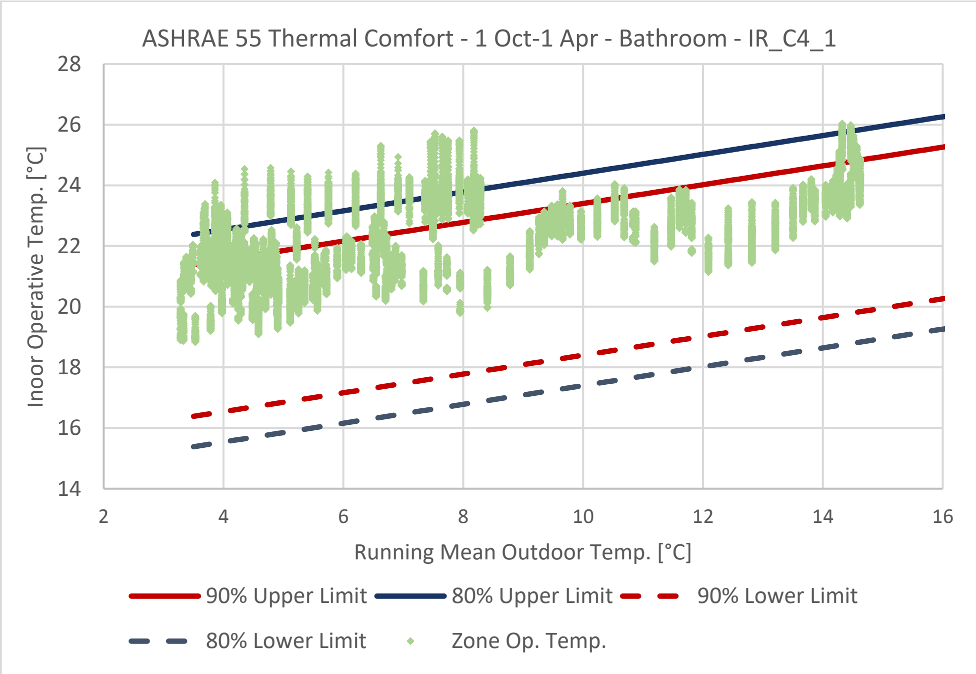

Fig. 38

IR_C4_1: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	2.7%	2.9%	5.4%	0.5%	9.3%	6.1%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	0%	68%	100%	97%	52%
9 <= Trmo < 16	0%	46%	32%	0%	3%	48%
16 <= Trmo	0%	54%	0%	0%	0%	0%

Tab. 22

Living room - IR_C4_1: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1%	46%	1%	1%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%
9 <= Trmo< 16	0%	0%	0%	0%
16 <= Trmo	0%	0%	0%	0%

Tab. 23

The percentage of unmet time for the overall comfort level of the IR_C4_1 model indeed, are higher than the once verified for the IR_C3_1, see tab. 22 and 23, with considerable high percentage of unmet time verified in the bathrooms. As verified for the other control strategies, switching to an ideal control type with the model IR_C4_2 brings little improvement for the overall comfort level, mostly appreciable for a reduction of the unmet time registered in the position 2 (the results for these model are showed just in Annex F).

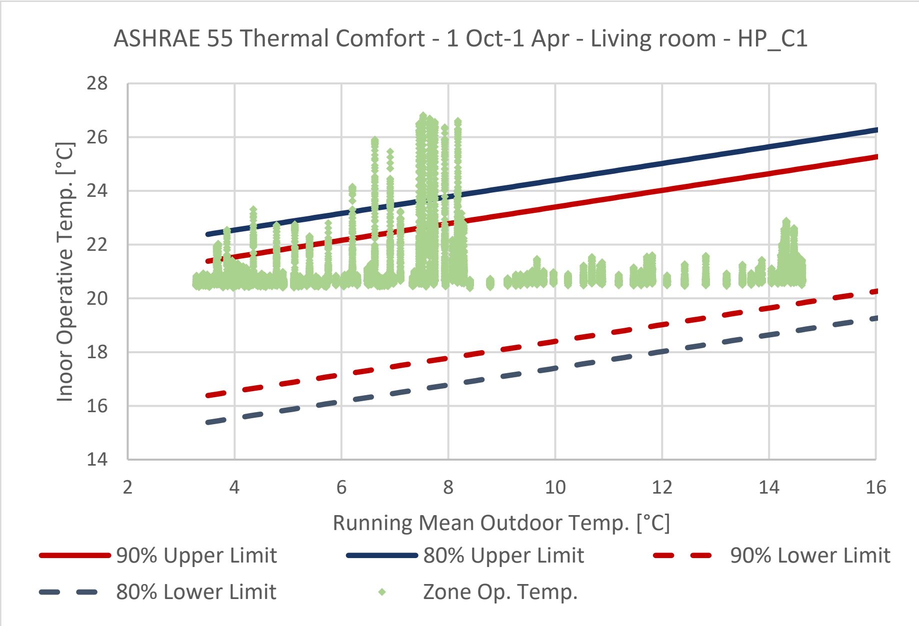

Fig. 39

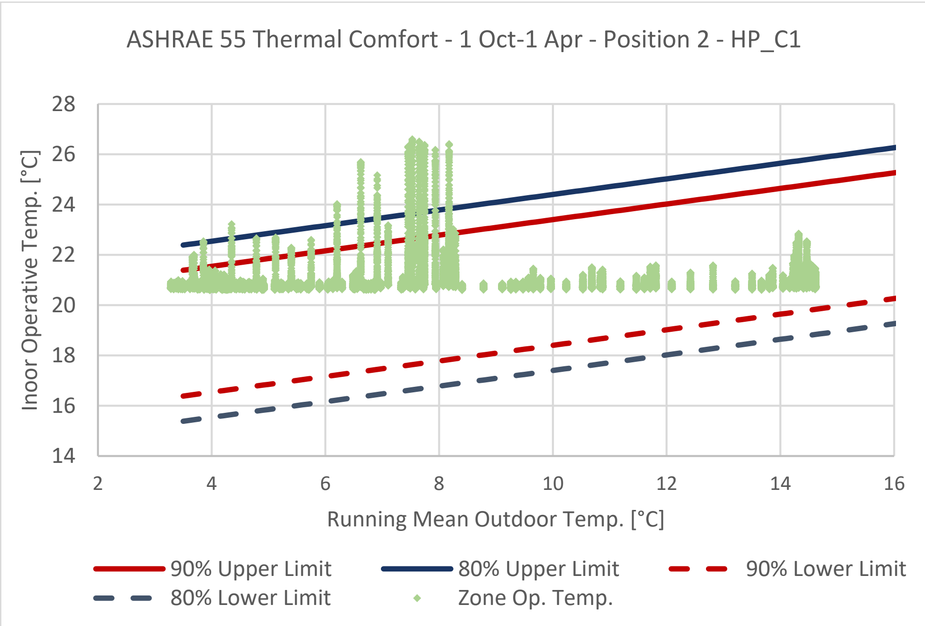

Fig. 40

HP_C1: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	3.26%	0.08%	0.83%	1.41%	0.72%	0.00%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo< 9	100%	100%	100%	100%	100%	0%

Tab. 24

Living room - HP_C1: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1.46%	1.36%	1.44%	1.32%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

Tab. 25

Evaluation of Vertical Radiant Asymmetry (Cool Ceiling): HP_C1 - (1 Oct. - 1 Apr.)

Limit C = PPD 10% = 18°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	7.81	5.26	5.07	4.01
ΔT_{pr} Av.[°C]	3.21	0.95	1.24	2.12
Tot Unplesant time [%]	0%	0%	0%	0%
Limit A = PPD 5% = 14°C				
Tot Unplesant time [%]	0%	0%	0%	0%
Horizontal Radiant Asymmetry - ΔTpr Max: HP_C1 - (1 Oct. - 1 Apr.)				
Horizontal N-S [°C]	0.40	0.37	/	/
Horizontal S-N [°C]	1.18	0.37	1.63	1.63
Horizontal E-W [°C]	1.92	1.29	/	/
Horizontal W-E [°C]	2.81	2.27	20.66	17.53

Tab. 26

The comfort level assess in the living room with the heat pump model HP_C1, so with a constant operative temperature of 20,5°C as setpoint, shows good results for the ASHRAE adaptive comfort method (see fig. 39). Indeed, the percentage of unmet time in tab. 24 and 25 are showing good values for all the other zones too (highest percentage registered in the kitchen 3,26%). Also, all the different position evaluated in the living room are showing results in line with the average once. For all those positions, the analysis of the radiant asymmetry in tab. 26 shows that the PPD is always 0% (Limit class A = 5%). Differently from the IR models, this time is considered the radiant asymmetry due to cool ceiling. The horizontal once shows, for the W-E direction, the same high values registered also for the IR-panels models. That occur for the position 3 and 4, which, considered the geometry of the room, windows' positions, and exposures, is considered normal to be verified and so not relevant for the research purposes. The same results, regarding the radiant asymmetry, are also obtained in all the heat pump models evaluated (full detail in Annex F).

Almost the same outcomes, in terms of overall comfort sensation and unmet time, are verified with the HC_C2 model, the once with the implementation of the ASHRAE adaptive setpoint temperature. These results are just reported in the Annex F, though it is important to acknowledge that the implementation of this adaptive setpoint temperature, is bringing the operative temperatures to better follow the central line of the ASHRAE graph and so to better meet the comfort levels, which results also in lower overall percentage of unmet time.

From fig. 41 to 43 are showed the results obtained for the comfort level assessed in the living room, bedroom back, and bathroom, for the heat pump model HP_C3, where different setpoint temperature are defined regarding each zone's specific requirement. The results, supported from the percentage of unmet time verified with tab. 27, are showing that these setpoint temperature are bringing to slightly worse result of overall comfort level, averagely assessed for all the rooms around 4%, except for the bathroom where instead is registered a percentage of unmet time of 79%. Also, it needs to be considered that that happens almost the 90% of the time when the outdoor temperatures are considerably low, which corresponds to a running mean average temperature between 3°C and 5°C (see fig. 43).

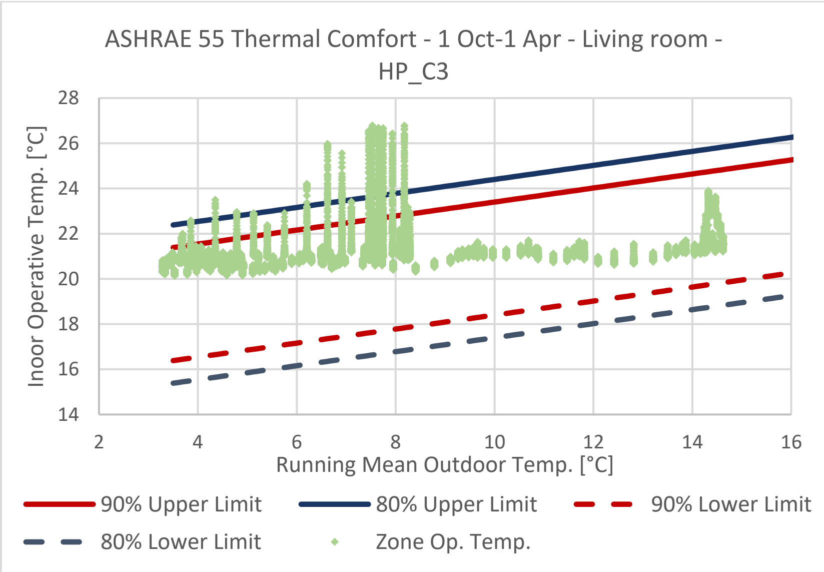

Fig. 41

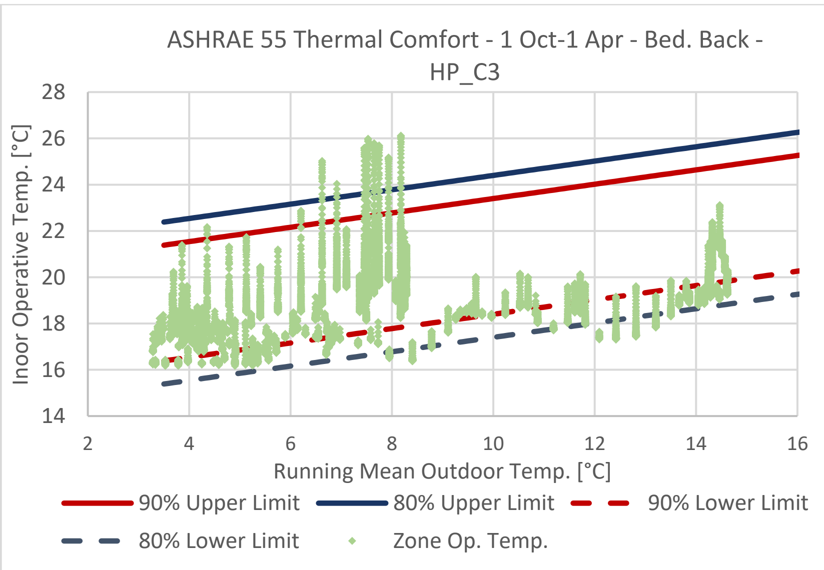

Fig. 42

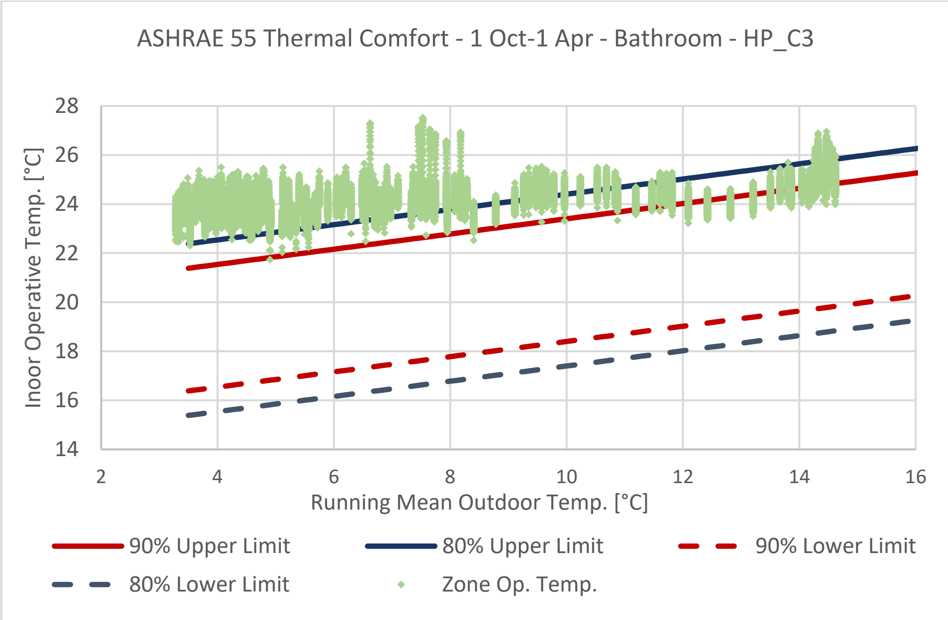

Fig. 43

HP_C3: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	5.9%	4.4%	4.6%	1.5%	78.9%	4.4%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	36%	41%	100%	93%	31%
9 <= Trmo < 16	0%	64%	59%	0%	7%	69%
16 <= Trmo	0%	0%	0%	0%	0%	0%

Tab. 27

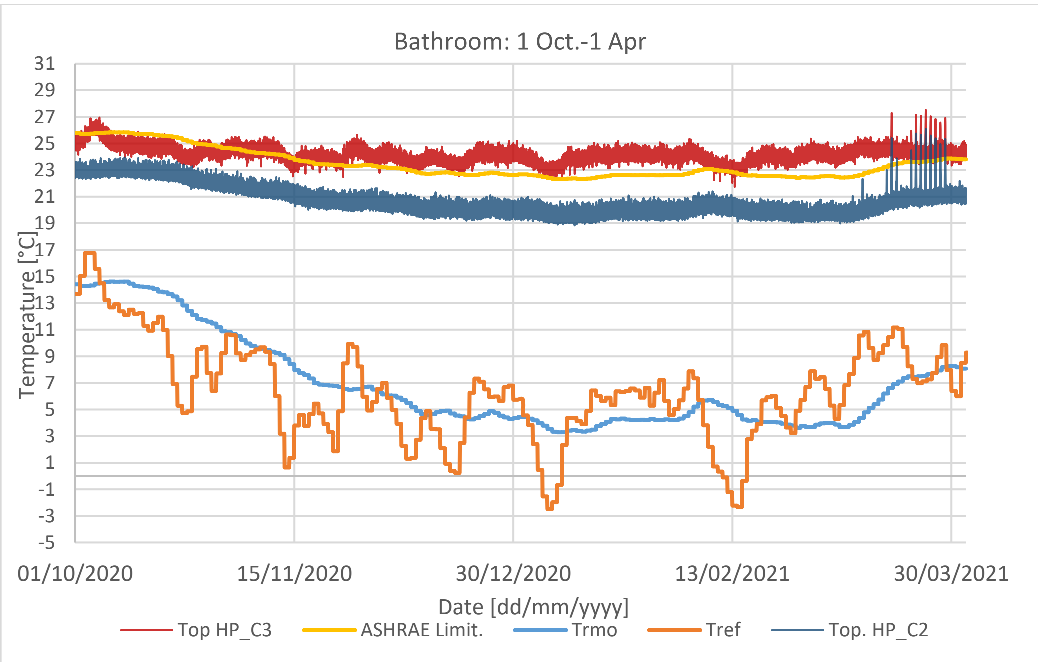

Fig. 44

Fig. 44 is showing the operative temperature obtained in the bathroom for two different heat pump model. The HP_C2, with the ASHRAE adaptive setpoint temperature derived from Eq. 1 and function of Trmo (defined at Eq.3) , and the HP_C3, with the adaptive temperature characterization proposed by Peeters et al. [19] defined at Eq. 13 and function of Tref (defined with Eq. 12). The HP_C3 model for most of the time brings the operative temperature over the limit proposed by the ASHRAE method. It is relevant to notice that, when e.g. there is one of the lowest av. running mean outdoor temperature (Trmo = 3,69 °C), the upper limit for an 80% acceptability is 22,44 °C. This situation is stable from December until February, where the limit is averagely constant around 22,5°C. During that time, Tref fluctuate its value between 8°C and -3°C, but is only for Tref lower than zero that the setpoint temperature, for the bathroom, becomes lower than the ASHRAE limit of 22,5°C, and even with Tref of 0°C the setpoint temperature is 22,65°C.

Note from fig. 45 and 46 below, that the same conditions of discomfort for the bathroom, are not verified in the IR_C4_2 model (with the same temperature characterization of HP_C3), where the panel is almost always ON, but the operative temperature doesn't overcome the limit. That is due to a lack of power of the panel implemented in that area. Indeed, the only times that the operative temperature verified in the zone is over the limit, happens in March during warmer outdoor temperature, and is coincident with the peak of the solar radiation, which helps considerably to increase the temperature that otherwise would probably remain within the limitations.

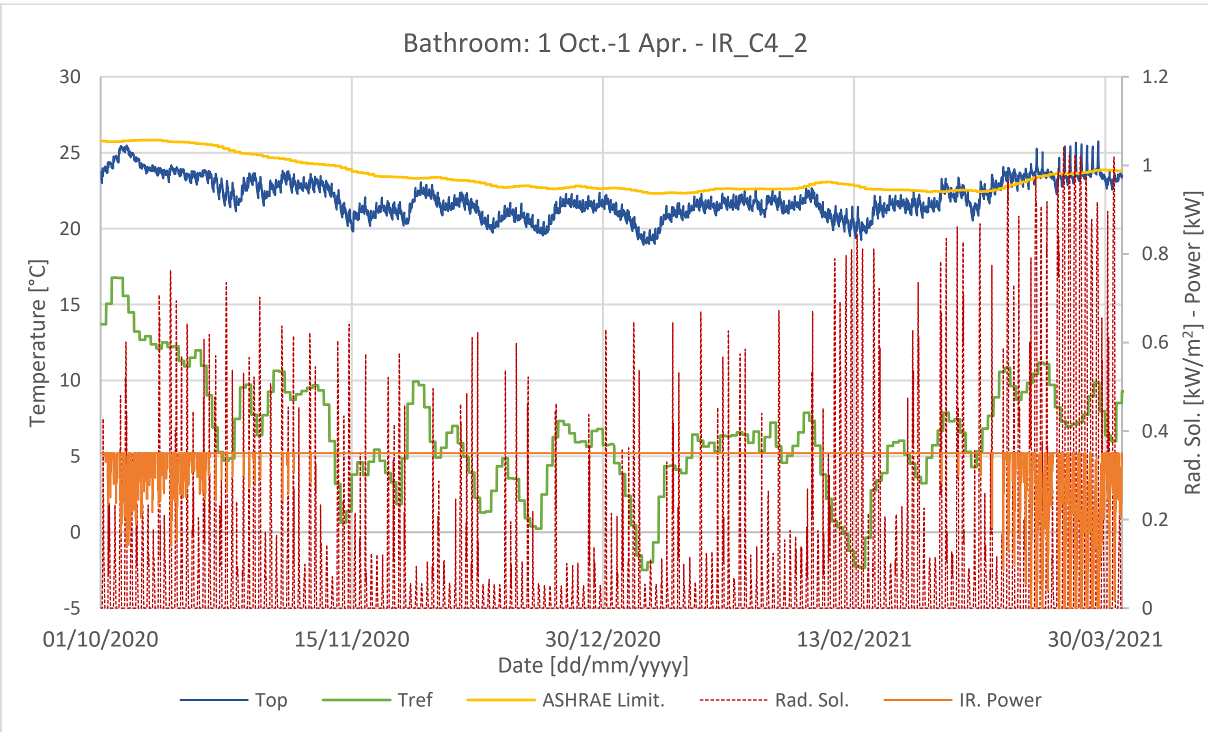

Fig. 45

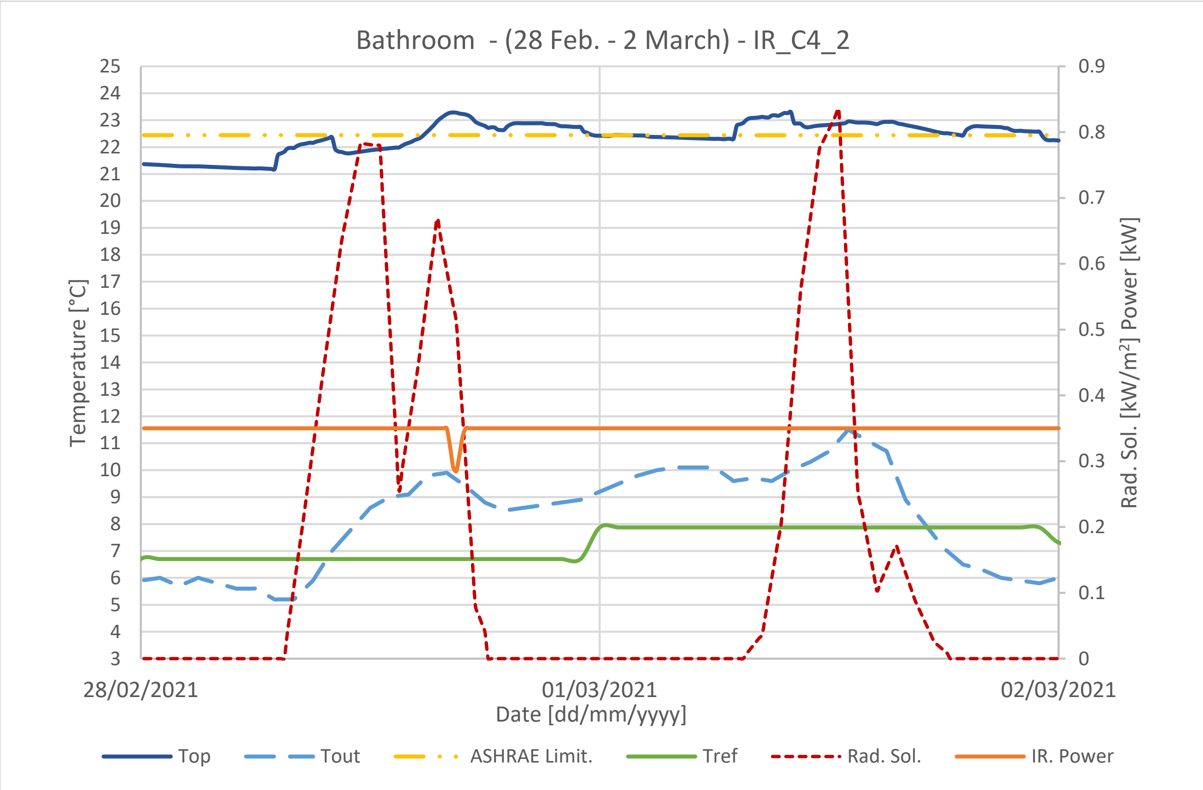

Fig. 46

7.2. Energy Consumption

SITE SECONDARY ENERGY - ELECTRICITY - Run Period: 1 Oct. - 1 Apr.

Model	*Total Energy [kWh]*	*Energy Per Tot. Build. Area [kWh/m2]*	*Energy Per Cond. Build. Area [kWh/m2]*	*Heating Energy [kWh]*	*Lights Energy [kWh]*	*Equip. Energy [kWh]*
IR_C1	9428.54	71.49	111.36	8143.95	756.23	528.36
				86%	8%	6%
IR_C2_1	9752.82	73.75	114.88	8468.23	756.23	528.36
				87%	8%	5%
IR_C2_2	9647.33	72.95	113.64	8362.75	756.23	528.36
				87%	8%	5%
IR_C3_1	8961.74	67.76	105.56	7677.15	756.23	528.36
				86%	8%	6%
IR_C3_2	8964.78	67.79	105.60	7680.19	756.23	528.36
				86%	8%	6%
IR_C4_1	8899.8	67.3	104.83	7498.96	756.23	528.36
				84%	8%	6%
IR_C4_2	8851.43	66.93	104.26	7566.85	756.23	528.36
				85%	9%	6%
HP_C1	4220.44	31.68	49.71	2935.85	756.23	528.36
				70%	18%	13%
HP_C2	3912.13	29.58	46.08	2627.54	756.23	528.36
				67%	19%	14%
HP_C3	4448.39	33.39	52.40	3163.80	756.23	528.36
				71%	17%	12%

Tab. 28

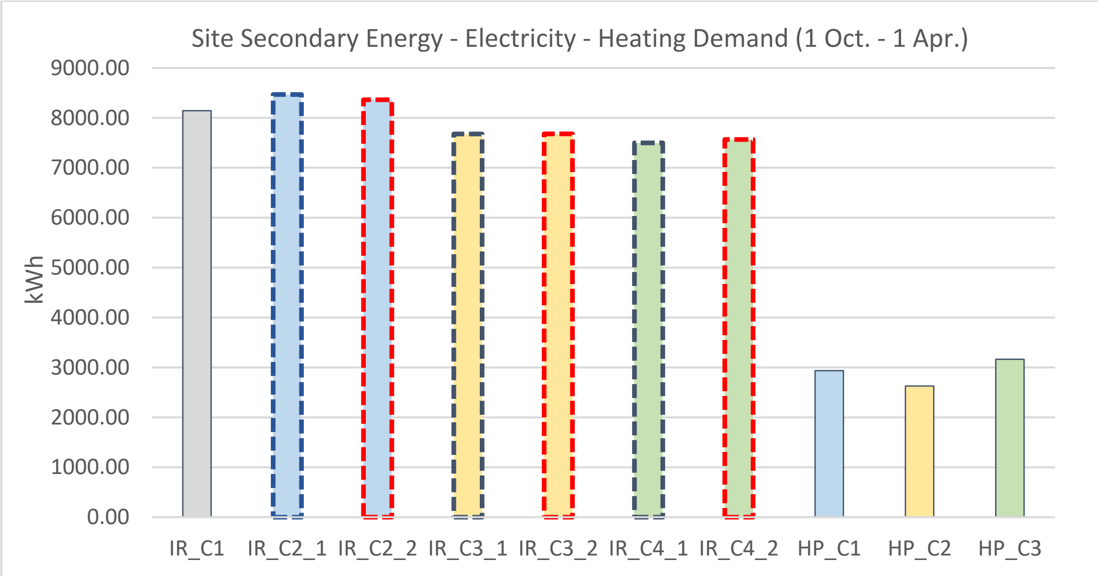

Fig. 47

Actual IR configuration — Setpoint = Constant Op. Temperature — On/Off control type

Setpoint = ASHRAE 55 — Setpoint = Peeters et al. Temp. — Ideal control type

Tab. 28 shows the results obtained for the evaluation of the total site energy consumption (site secondary energy – electricity) for a run period from October the 1st to April the 1st. The energy demand is determined in its total amount, and in detail for the heating system, lights, and the all the other equipment. It is then appreciable how the implementation of the adaptive theories brought the IR-models to a reduction of the heating energy used, though this system's demand is more than twice the energy required from the heat pump models, thing that it's true if considered the total energy amount, or the power demand in the "Peak Day", which for the IR models occurs on the 6th of January, while for the heat pump on the 5th (see tab. 29 below). Always from the evaluation of the peak day, it is noted that the same reduction obtained with the implementation of the adaptive theories for the total end uses, is appreciable also in the peak of the power demand, which on the IR models decreases of almost 10 kWh. The load duration curves are also showing how the model with implemented the adaptive setpoint temperatures have lower values of energy demand. That is appreciable from fig. 48 (below), with the daily values, and is confirmed in fig. 49 with the hourly once. Always from fig. 49 is better appreciable that the implementation of the setpoint temperatures proposed by Peeters et al. [19] brings the model IR_C4_1 to reduce considerably faster the peak of energy demand.

Building Power Demand - Electricity

Model	Peak Day	kWh
IR_C1	Jan-06	90.00
IR_C2_1	Jan-06	91.86
IR_C2_2	Jan-06	90.04
IR_C3_1	Jan-06	82.44
IR_C3_2	Jan-06	80.84
IR_C4_1	Jan-06	78.03
IR_C4_2	Jan-06	79.15
HP_C1	Jan-05	45.28
HP_C2	Jan-05	40.16
HP_C3	Jan-05	44.13

Tab. 29

Building Power Demand - Electricity

Average day: 7 March	
Model	kWh
IR_C2_1	43.08
IR_C2_2	44.25
IR_C3_1	30.73
IR_C3_2	33.25
IR_C4_1	42.00
IR_C4_2	42.97
HP_C1	18.58
HP_C2	14.49
HP_C3	20.45

Tab. 30

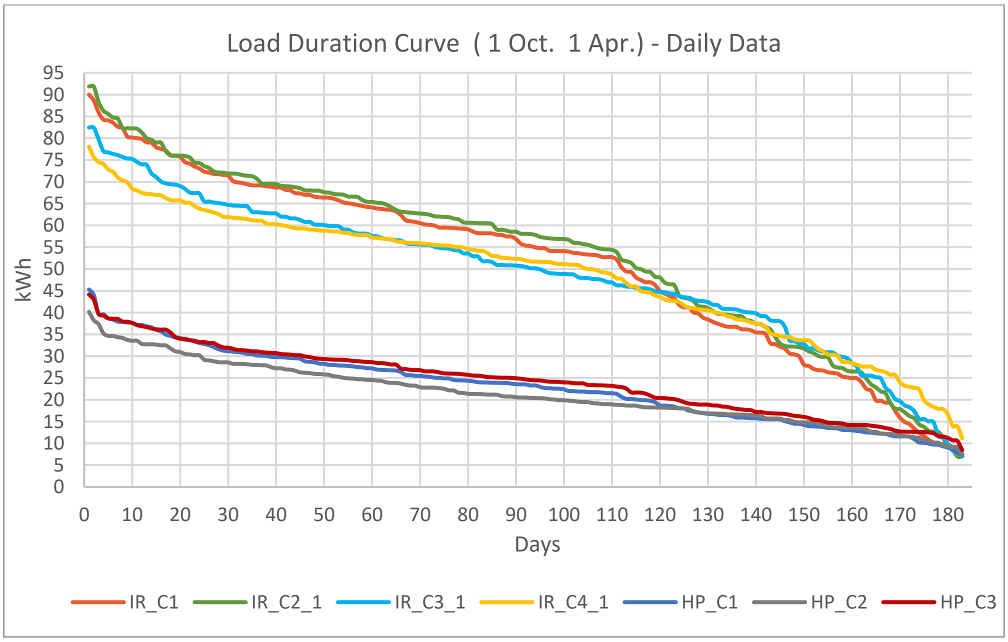

Fig. 48

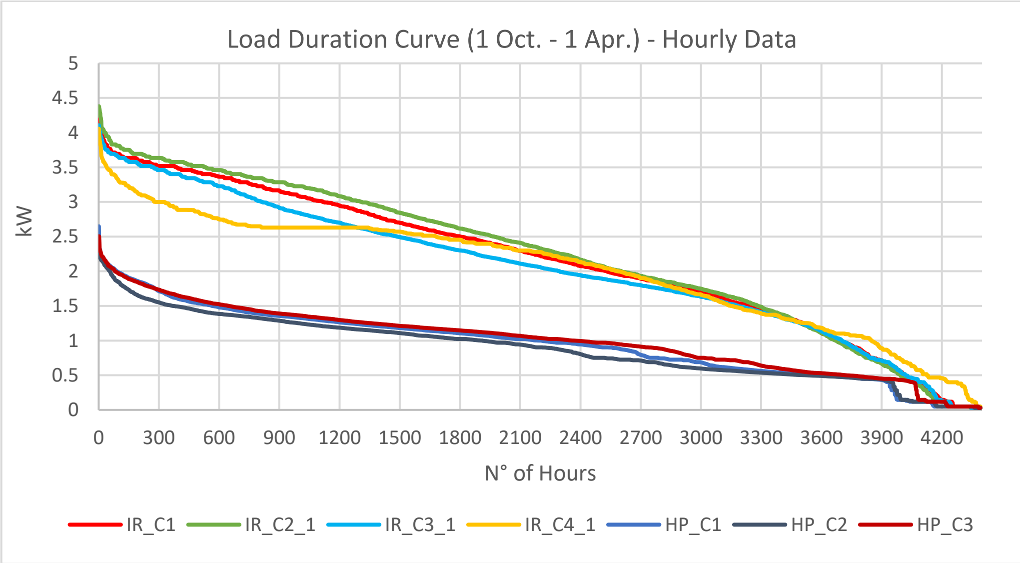

Fig. 49

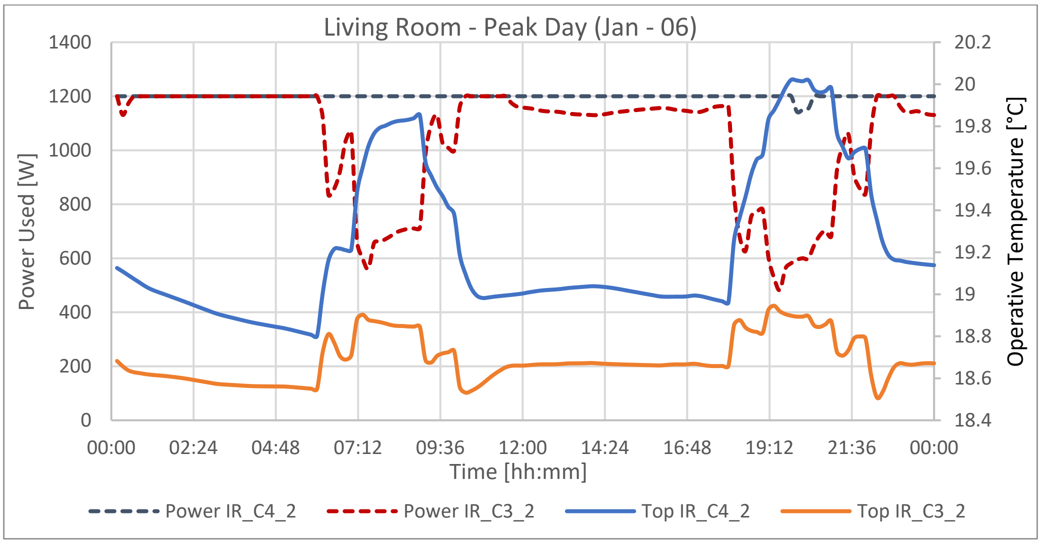

Fig. 50

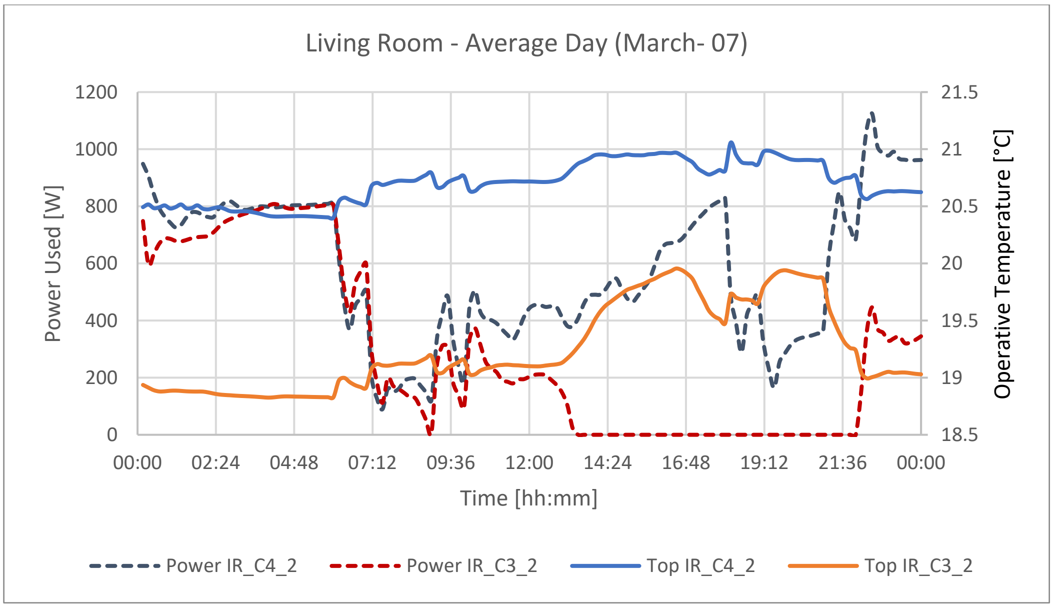

Fig. 51

Fig. 50 and 51 analyse respectively what happen in the living room on January the 6th (Peak Day), and on March the 7th, comparing the results verified for the power used and operative temperature obtained from the model IR_C3_2 and IR_C4_2. It is notable that the higher setpoint temperature proposed by Peeters et al. is bringing the IR-panels to be always active on the 6th of January, while with the ASHRAE setpoint temperature the system switch Off. Same thing happens for the 7th of March, where, even in the warmer hours, and despite operative temperature averagely above 20,5°C, the IR_C4_2 model does not reduce the power usage. Indeed Tab. 30, which shows the total energy demand for an "average" day (when the energy consumption is almost half of what verified on the peak day), the 7th of March, proves the difference in the energy consumption of two models. In these conditions, the implementation of the ASHRAE setpoint temperature, brings to a significant reduction of the energy consumption.

An Ideal control type does not bring any big difference in terms of total energy consumption if compared with an On/Off control. That is confirmed comparing the results obtained from the models IR_C2_1 and IR_C2_2 in fig. 52 and 53, respectively for the peak and average day, investigating the site energy demand. It is true though, that the ideal control type brings to a significant lower peak of power demand (fig. 52).

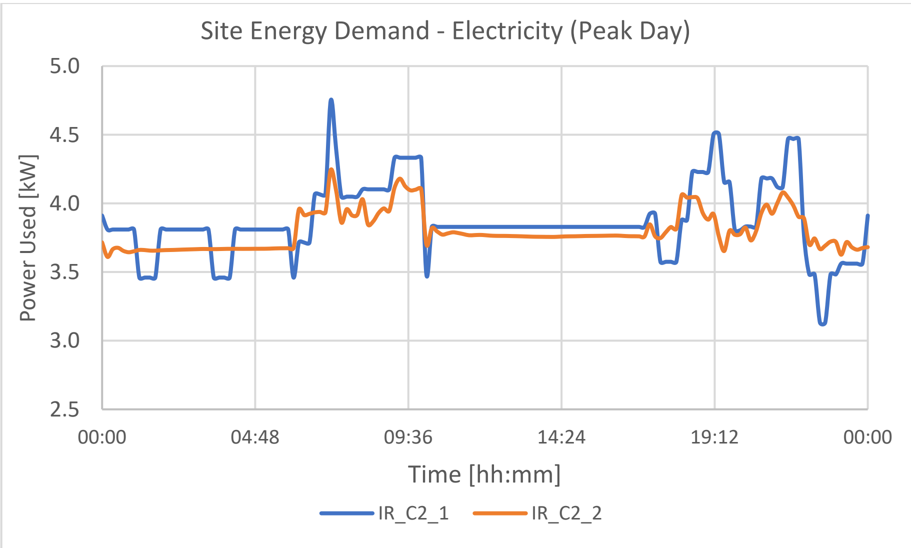

Fig. 52

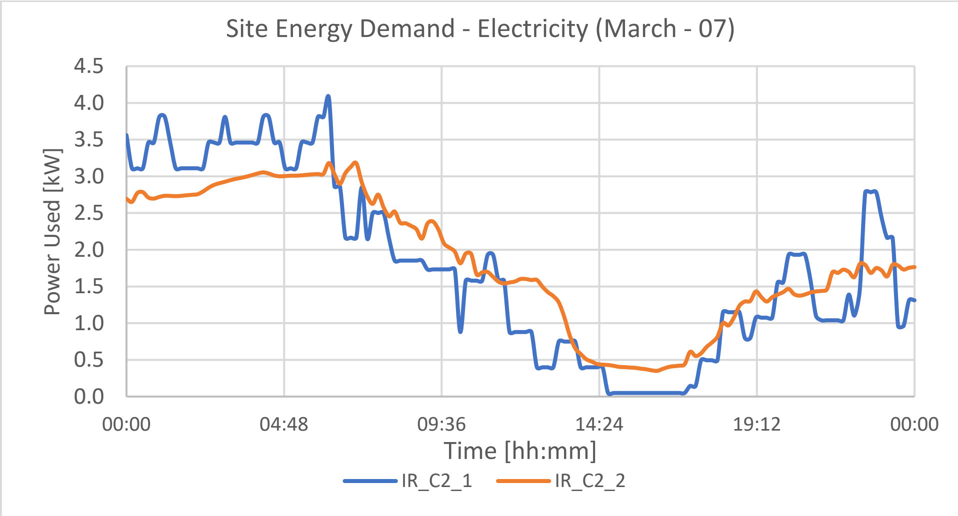

Fig. 53

8. Discussion

Research over assessing thermal comfort in residential environments is nowadays clearly pointing towards adaptive theories, indeed many studies and surveys are enhancing circumstances where the PMV firmly diverges from the actual thermal sensation. That is true for specific conditions, e.g. with elevated air velocity even warm conditions can be assessed as comfortable, and applies also to residential houses, where the environment is characterized by occupant's personal adaptation. It is on that belief that adaptive theories are founded, being people an integral part of the thermal environment, free to adapt clothing, opening windows or changing activity. The principal aspect added to the thermal comfort knowledge, is the acceptance as input parameter of a running mean outdoor temperature, based on the previous days outdoor temperature, so to defined an optimal setpoint temperature for the ambient, that accounts for occupants' personal adaptation to the outdoor climate within the passing of time. This becomes crucial for the application of the ASHRAE 55 standard adaptive approach used within this research, which also is the only one, within the evaluated method, that officially applies to residential environments. Debate is still going on around the various comfort models' conditions of applicability, tough ASHRAE 55 method it is found a reliable and solid approach, but with some limitations. Indeed, the analysis of the thermal comfort obtained for the case study building with the IR-panels operating, enhanced some of its weaknesses, like not having specific prescription for local discomfort included in the adaptive approach. It is reminded that the adaptive method already accounts for local discomforts, and that the procedure of assessing the comfort level is simplified with a graphical check of the operative temperature. With that method, the overall comfort levels defined from the standard are met with an average good results by all the IR-panel's models, indeed even the one which replicate the actual system, the model IR_C1, that corresponds to the calibrated status of the model, shows excellent results. That is true if accounting the overall-average comfort, so considering the average mean radiant temperature, but its evaluation, in the specific positions defined in the living room, shows that being close to the panel sometimes can bring to overcame the comfort limit proposed. Indeed, within all the position evaluated, the number 2 (person standing in the centre of the living room – under the central panel) is the one which is more affected by the panels temperature, and is the one showing worse value of comfort achieved (the implementation of the ASHRAE adaptive setpoint temperature in the IR_C3_1 heal this problem). The conditions of discomfort are enhanced with the analysis of the radiant asymmetry due to warm ceiling in the same positions, which shows that the limits given are not respected from all the models, nevertheless, with an accepted limit of 10% PPD, the results are showing peak even of 84%. It is true that the ASHRAE 55 adaptive approach already accounts for local discomfort, but the panels are reaching almost 90°C (data acquired from lab tests), which is a really high temperature concentrated in specific positions of the ambient. Being exposed to such a temperature is reasonable to assume it could bring to perceive discomfort to occupants. Still, reminding that the distance from the ceiling is significant, the general state of comfort may be also affected in positive way by other parameters, like air velocity. That one, in the simulations, is set to 0,13 m/s, following the guidelines and in accordance with the limitation on the applicability of the method.

Within this research are implemented 3 different configuration of control strategies for the IR-panels, attempting to define the optimum configuration for residential environments in the Netherlands. For all the 3 type (constant, adaptive ASHRAE, and residential characterization), changing the control from On/Off to Ideal, doesn't bring any relevant achievement in the overall comfort level assessed. Indeed, the average comfort level verified in the zones remain the almost same in both configurations but, modulating linearly the power, limits considerably the fluctuation of the operative temperature, bringing the IR-panels to spend more time operating, but at lower power, and so at lower surface temperatures. For these reasons, despite a greater time when the PPD due to warm ceiling overcome the limitation of 10%, the results for the Ideal control are showing lower values of the radiant asymmetry, which brings to lower PPD itself. Also, an important difference is noted in the peak of power demand, which is reduced with the Ideal control type, both if considered a cold day (like January the 6th) or an average once (March the 7th). Not finding benefits in the site end-uses can be so overlooked, since it is assessed that modulating the power released while heating brings to lower panel's surface temperatures (see fig. 56 below), so that it's reduce not only the value of the radiant asymmetry but, in general, the possibility that that discomfort may occur. Also, being the panels operating more time, they are working not always at the maximum power, resulting in a lower peak of power demand, required to reduce the stress on the net-grid which otherwise would probably suffer. This aspect is enhanced by the load duration curves in fig. 54 and 55 below, where are compared the heating power demands of the models IR_C3_1 (On/Off control), and IR_C3_2 (Ideal control) during an average day and the peak once. The Ideal control shows considerably lower values of power demand, especially during the high demand hours, which confirms the possibility of a reduction of stress on the grid.

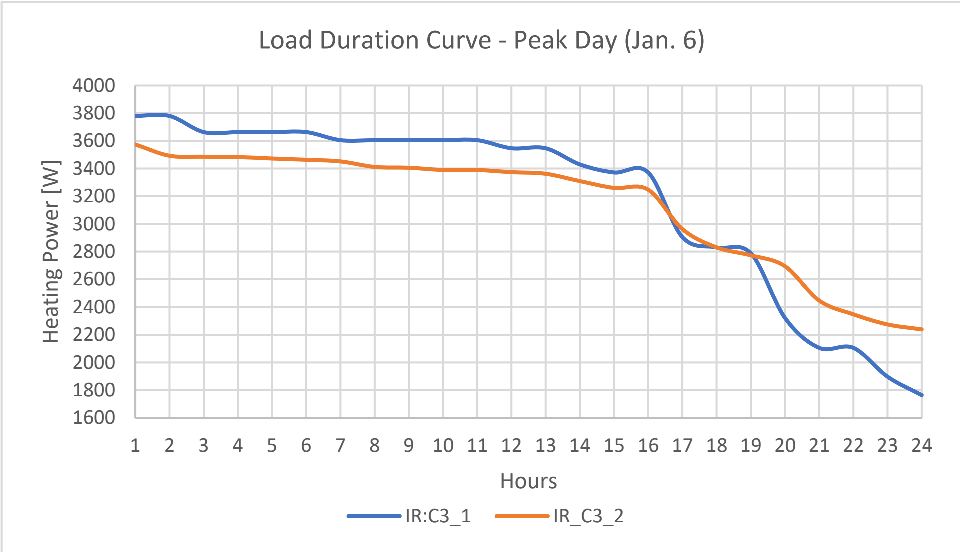
Load Duration Curve - Peak Day (Jan. 6)
Heating Power [W]
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hours
IR:C3_1
IR_C3_2

Fig. 54

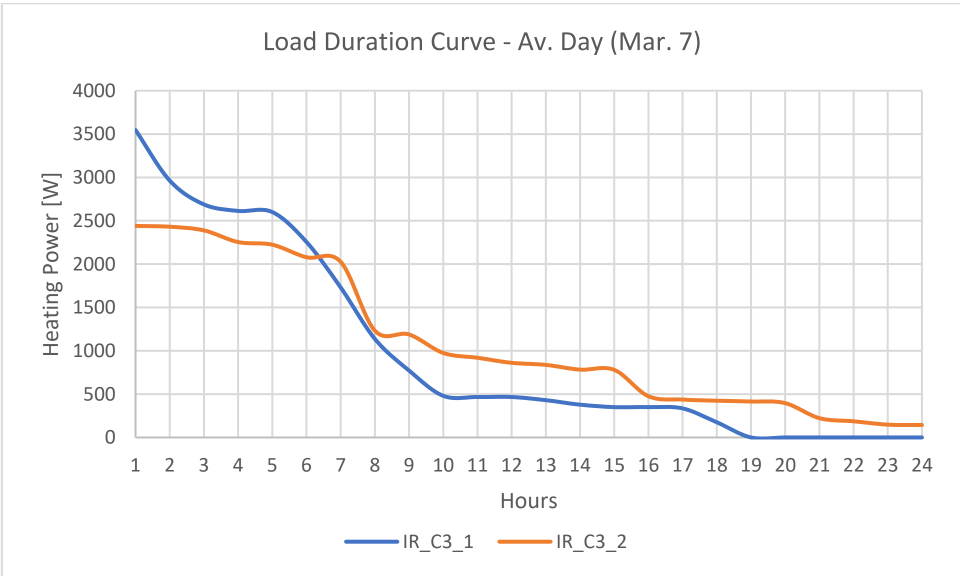
Load Duration Curve - Av. Day (Mar. 7)
Heating Power [W]
4000
3500
3000
2500
2000
1500
1000
500
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hours
IR_C3_1
IR_C3_2

Fig. 55

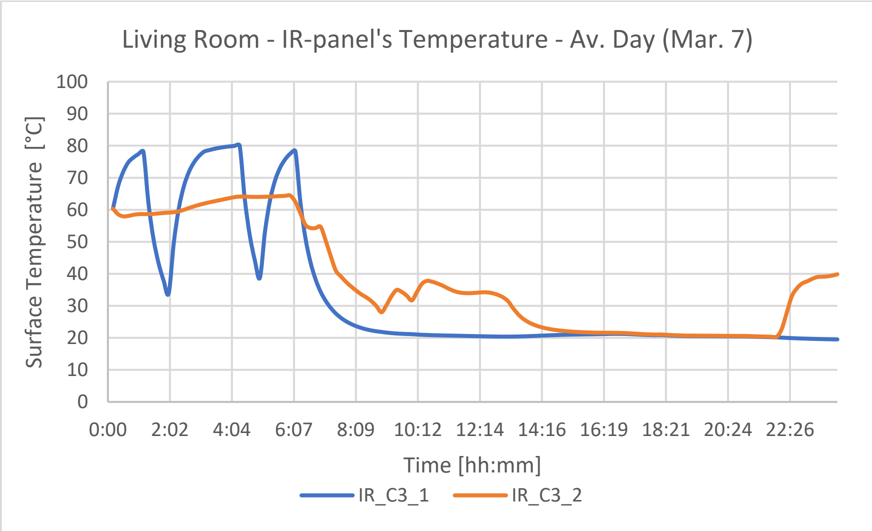

Fig. 56

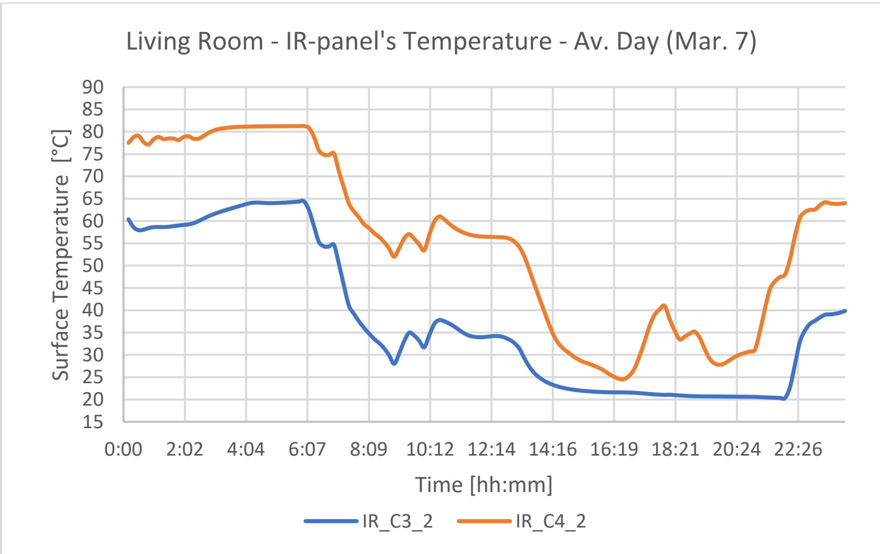

Fig. 57

The results are showing that the implementation of adaptive setpoint temperatures, accordingly with the ASHRAE 55 standard, is bringing to better comfort levels than the once obtained with what proposed by Peeters et al. That is true for the IR-panel models, and the heat pump as well, where with the Peeters' setpoint temperatures, in both it is verified condition of over-heating in the bathroom, while are registered temperature colder than the limit in the bedrooms. It needs to be said though that temperature characterization proposed by Peeters et al. [19] is meant to be verified with the limitations proposed by Van Der Linden et al. in the New Adaptive Guideline for the Netherlands [20]. That would have result in assessing a better level of comfort in the bathroom, but not in the bedrooms, where still some temperatures verified remain too cold. The benefit of the ASHRAE setpoint temperature are more evident if analysed the outcomes of the comfort level assessed for the IR-panel models in the specific position of the living room. Indeed, the results are showing that the ASHRAE approach brings to good level of overall comfort, while with what proposed by Peeters et al. are obtained worse values even than what verified with the IR_C1 model, which is the actual state of the panel. This time the result is not a matter of limitations, the reason lays in the higher setpoint temperature defined, which brings the panel to release more power and reach higher surface temperature for a longer time (see fig. 57 above). This is enhanced also from the investigation of the radiant asymmetry in the same positions, done in tab. 31 and 32 below. Indeed, in the model IR_C3_2 are registered radiant asymmetry considerably lower than in the IR_C4_2, with consequently lower values of PPD (e.g. tab. 31 for the model IR_C3_2 shows that the radiant asymmetry in the position 2 is higher than 20°C the 18% of time, while in the model IR_C4_2, tab. 32, it happens the 51% of time). It is straightforward then that the energy consumption that result from the implementation of Peeters et al. setpoint temperatures gives higher values than with what proposed by the ASHRAE standard, which is verified for the heat pump model, but not for the IR once, where the energy demand of the models is almost the same. It is reminded though, as verified for the bathroom in fig. 45, that some zones of the building model the IR-panels implemented have been under-sized, so no capable of release enough power to reach the setpoint temperature proposed by Peeters et al., which limits the model's energy consumption (note that the size and capacity of the panels implemented, it has been defined accordingly with what done in the HERSCHEL project).

Vertical Radiant Asymmetry - Warm Ceiling: IR_C3_2 - (1 Oct. - 1 Apr.)

Limit PPD 10% = 7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	24.36	29.04	18.37	14.71
Tot Unplesant time [%]	63%	74%	52%	45%
PPD Max [%]	75%	85%	53%	38%
PPD Average [%]	23%	34%	15%	12%
ΔT_{pr} > 10 °C	50%	63%	32%	7%
ΔT_{pr} > 15 °C	23%	43%	7%	0%
ΔT_{pr} > 20 °C	7%	18%	0%	0%

Tab. 31

Vertical Radiant Asymmetry - Warm Ceiling: IR_C4_2 - (1 Oct. - 1 Apr.)

Limit PPD 10% = 7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	24.18	28.79	18.21	14.49
Tot Unplesant time [%]	80%	86%	73%	67%
PPD Max [%]	74%	84%	53%	37%
PPD Average [%]	40%	52%	26%	18%
ΔT_{pr} > 10 °C	72%	80%	60%	7%
ΔT_{pr} > 15 °C	55%	67%	31%	0%
ΔT_{pr} > 20 °C	31%	51%	0%	0%

Tab. 32

It is important to acknowledge that, rather than directly to the setpoint temperature, to understand the difference in the results obtained between the models with the ASHRAE adaptive characterization and the one by Peeters et al., it needs to focus on how those setpoint temperature are defined within their respective running mean outdoor temperature. Indeed, the characterization of it, done accordingly with the ASHRAE method, brings to the acceptance of a prevailing mean outdoor temperature (Trmo, see Eq. 2) based on the previous 30 days' temperatures. Peeters et al. instead, propose a reference temperature (Tref, see Eq. 12) which is based on a total of 4 days' temperatures. The differences that results are evident in fig. 44, where, during the winter season, Trmo remains stable around 4°C, while Tref fluctuate between -3°C and 10°C. This is proof that Tref responds in a more effective way to the outdoor temperature's variations occurred in the most recent previous days.

The comfort assessed with the IR-panel and heat pump models is in both the situation showing good results if analysed from an overall point of view but, what verified with a direct comparison of the models with same setpoint temperatures (as defined at § 3.3), shows that the IR-panels models are reaching in all cases better values than the heat pump once. It needs to be considered though that the percentage of unmet time are always averagely in the range of 0-5%, which brings the evaluation to overlook this data. To assess which system provides a better level of comfort, it needs then to be investigated the possibility to encounter local discomforts and, analysing the one due to radiant asymmetry, is clear that the heat pump models are drastically reducing the chance that that condition may occur. It is then in lack of an accepted methodology to assess thermal comfort, capable of clear the uncertainties derived from the presence of such high surfaces temperature, that is reasonable to prefer heat pumps heating system rather than IR-panels, if the aim is reach a sure comfortable environment. Though there are reason to believe that the results obtained for the IR-panels model, are showing good possibilities to enhance its comfort performances with an optimization of the controller. Indeed, modulating the power released, brings to reduce considerably the radiant asymmetry perceived. Also, when it comes to choose the most suitable heating system from a comfort point of view, it needs to be considered that personal preferences are crucial. Regarding this, heat pumps may also be used in cooling mode, while the infrared solution not, so once more, to understand which solution fits better it needs to be considered the specific requirements of the application.

Finding an optimal fit for the IR-panels' control configuration, is believe would bring benefits also to their energy consumption, which, as assessed within the same run period, with this system properties is the double of what required from the heat pump models. Another reason to prefer the heat pumps rather than IR-panels, is the peak of power demand reached, which, as well for the site end-uses, is the double for the infrared solution. Other than be higher than the heat pump once, the peak of demand of the IR-panels model is also reaching critic values regarding a possible stress on the electricity grid, which, in these conditions, is most likely to occur if the same heating system is adopted in multiple dwellings of the same net. It is true though, that the discussion about which of the two system is more affordable cannot just focus on the energy consumption, also because in this comparison are involved two systems with different coefficient of performance (COP). It is acknowledged that a heat pump achieve efficiency over the 100%, since with one unit of electrical energy can produce over four units of heat [2], while IR-panels with the electricity can achieve no more than 100% of efficiency. For these reasons, as proposed in the TKI Urban Energy study "Infraroodverwarming versus de warmtepomp" [2], a smarter index to consider could be the Total Cost of Ownership (TCO), which include all the investment's cost, with energy consumption, installation, and maintenance all combined, but, unfortunately, the data available are not enough to produce a proper evaluation.

9. Conclusions

Within this research, for assessing thermal comfort it is applied the ASHRAE 55 adaptive approach, which already accounts for local discomfort, and with which it is verified a good overall comfort level for the IR-panels models. A deeper analysis of the exposure to radiant asymmetry showed though that, despite its strengths like accounting for personal adaptation, the adaptive approach, in conditions of exposure to high surface's temperature, may overlook situations of discomfort. These conditions, which occur with IR-panels heating systems, should be supported by deeper analysis, like chamber and lab experiments, both with manikins and persons. That would guarantee a solid approach for a more accurate evaluation of the discomfort, which remains something likely to occur.

From the study of new comfort theories, the implementation of adaptive setpoint temperatures accordingly with the ASHRAE 55 approach brings to reach better comfort levels than what verified with the temperature characterization proposed by Peeters et al. [19]. Indeed, the higher values of the setpoint temperatures defined by Peeters et al., brings the IR-panels to reach higher surfaces temperatures, increasing the chance to find conditions of discomfort. Also, the peak of power demand is higher for these models, enhancing the possibility of dangerous stress on the electricity net-grid. The same conclusion is derived also from the comparison of an Ideal and On/Off control type for the IR-panels, where the first is showing that modulating the power provides better comfort levels, and an important reduction of the stress on the electricity grid. For these reasons it should be considered to develop this system's configuration rather than the On/Off once.

In terms of cost, IR-panels are cheap and easy to maintain, other than of straightforward installation without any pipework required. These are all important advantages to the infrared solution on the heat pump once but, if analysed over the same average lifespan of 15-20 years [2], the final evaluation of which system is more affordable may not indicate the IR-panels. Indeed, the results are showing that the IR-panels energy consumption is the double of the heat pump's once, so the initial saving for the heating system's cost and its maintenance, could be tied within years. Also, to produce domestic hot water the IR-panels need to be supported at least by an electric boiler, while heat pumps provide that, and even the possibility of cooling. These considerations though do not exclude that an IR-panels heating system could be a good solution for small apartments, or dwellings not much occupied during the day, or by not many persons. Their fast effectiveness, if combined with an optimal control configuration, could be a smart application for these situations, rather than family houses like the case study building. Also, it needs to be considered that the heat pumps require important storage space for their installation, which not always is available.

There is not a straightforward method to understand which heating system, between IR-panels and heat pumps, is better suitable-affordable and in which conditions. Instead, it is needed a peculiar investigation of the specific requirements of the single application, its environmental properties, performance expected, occupancy profile, and their preferences.

The performances of infrared heating systems can increase, both in terms of comfort and energy consumption, by developing a modulated control, also oriented to meet the occupancy needs. Combining that with an optimal configuration of the system itself, in its capacity-design and positions, is then the right direction to chase, aiming at developing this heating system.

Acknowledgments

This research is related to the HERSCHEL Project, sharing information and data. Within the companies involved, Beligreen is into developing and supplying sustainable heating systems, and it is the one who also supplies the heating panels that are installed in the case study building analysed for the research. The activity of collecting data, all the work done into the case study building and in the lab test, has been carried on from the people involved in the HERSCEHL Project, and it is thanks to them that data acquired during the measurements have been provided and used to produce the research.

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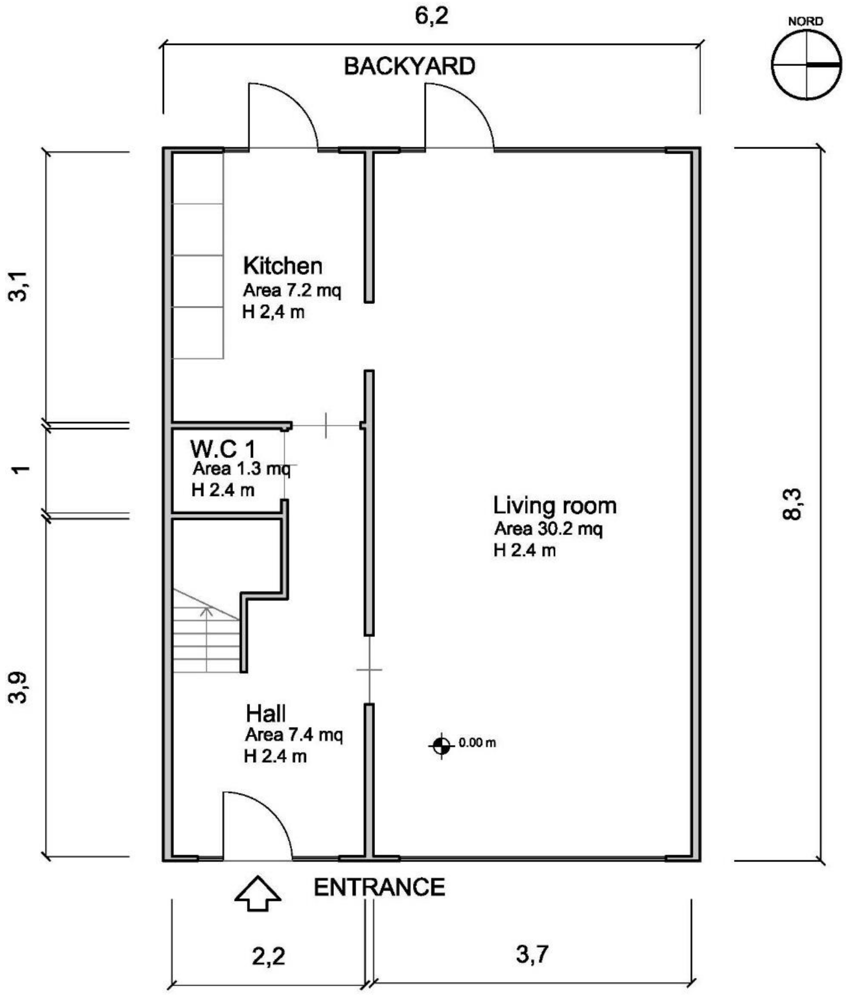
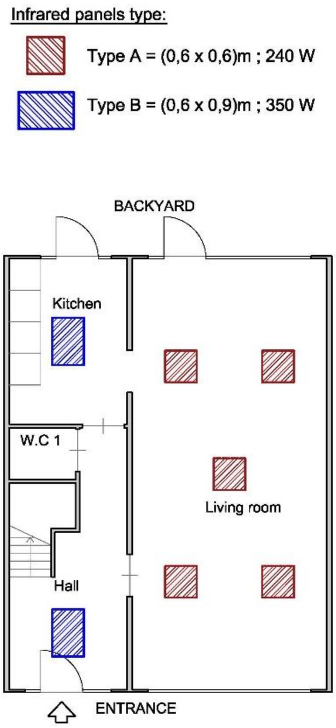
Annex A: Building’s plans and IR-panels position

Drawings not in scale, unit in meter.

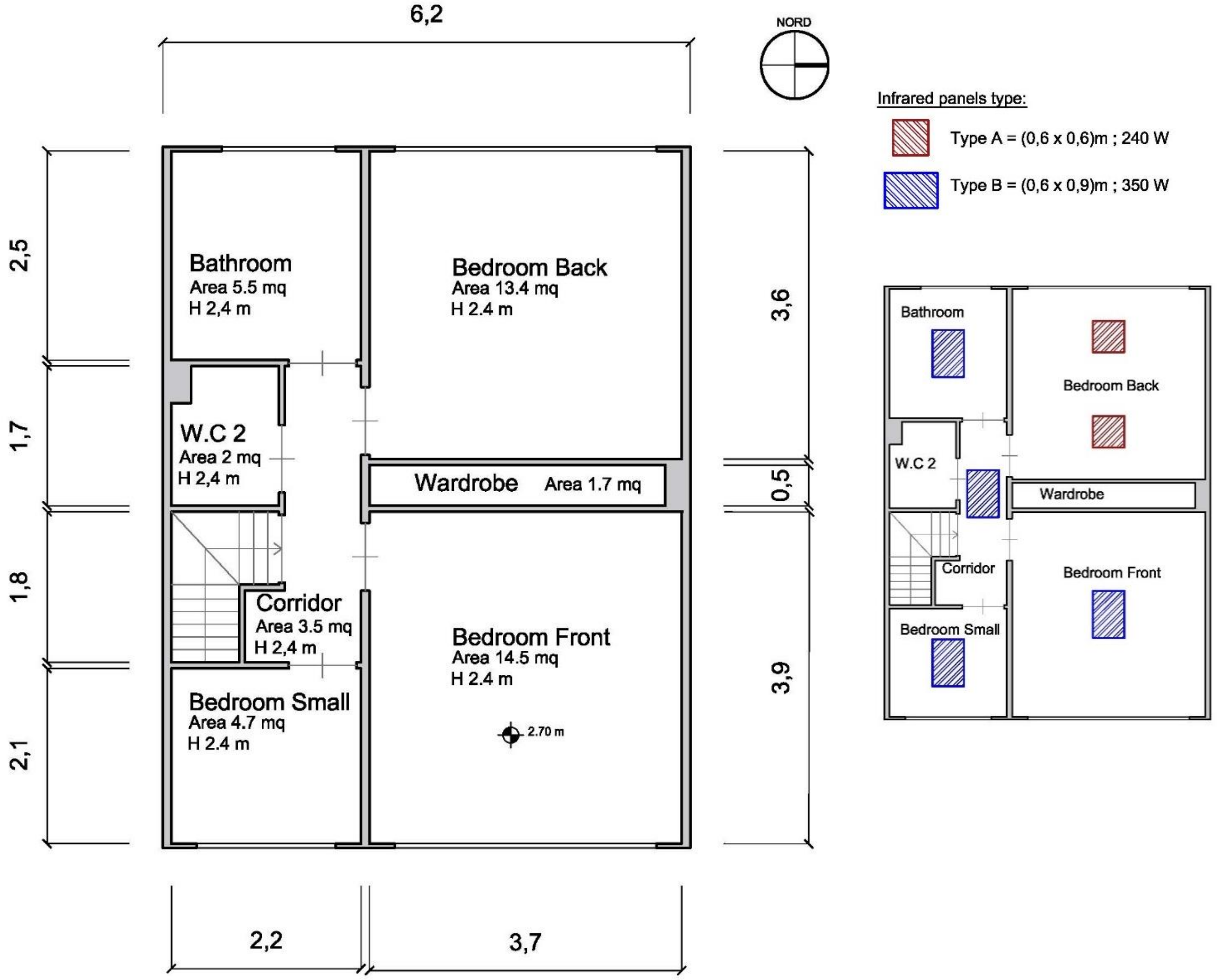
Note that in the house, during the measurement, the only panel installed were the once in the living room, kitchen, bedrooms back and front. All the others have been added due to simulation porpuses.

- **Ground floor**





- **First Floor**



The construction elements defined are described below, for each of them will be reported:

- U = thermal transmission coefficient
- Composition of the layers (thickness; material thermal conductivity)
- Cross section (drawings out of scale)

- External Wall:

  U = 0,58 W/m^{2}K

  Composition from the outermost layer:

  - Outer Bricks: (10 cm; λ = 0,84 W/mK)
  - EPS: (5 cm; λ = 0,04 W/mK)
  - Inner bricks: (10 cm; λ = 0,62 W/mK)
  - Plaster: (1 cm; λ = 0,42 W/mK)

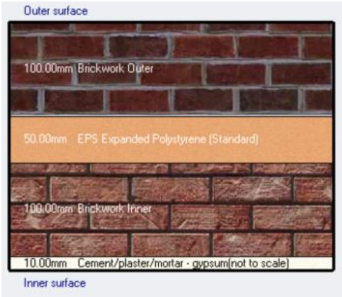


Fig. 58: Cross-section of the external wall (note: construction not horizontal)

- Ground floor slab:

  U = 0,295 W/m^{2}K

  Composition from the outermost layer:

  - EPS: (12 cm; λ = 0,04 W/mK)
  - Cast concrete: (20 cm; λ = 1,13 W/mK)

Fig. 59: Cross-section: ground floor slab

- Internal floor slab:

  U = 2,29 W/m^{2}K

  Composition from the outermost layer:

  - Cast concrete: (20 cm; λ = 1,13 W/mK)
  - Plaster: (1cm; λ = 0,42 W/mK)

Fig. 60: Cross-section: internal floor slab

- Pitched roof:

  U = 0,298 W/m^{2}K

  Composition from the outermost layer:

  - Tiles block: (1,5 cm; λ = 0,48 W/mK)
  - Air Gap: (0,5 cm; -)

- Wood roofing slab: (1,5 cm; λ = 0,1 W/mK)
- EPS: (11 cm; λ = 0,04 W/mK)
- Wood roofing slab: (1,5 cm; λ = 0,1 W/mK)
- Plaster: (1 cm; λ = 0,42 W/mK)

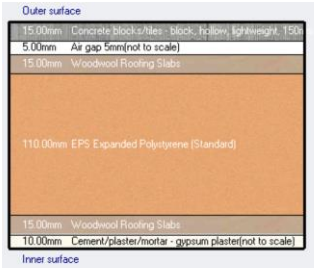


Fig. 61: Cross-section: Pitched Roof

- <u>Internal Partition:</u>
  U = 2,17 W/m^{2}K
  Composition from the outermost layer:
  - Plaster: (1 cm; λ = 0,42 W/mK)
  - Inner bricks: (10 cm; λ = 0,62W/mK)
  - Plaster: (1 cm; λ = 0,42 W/mK)

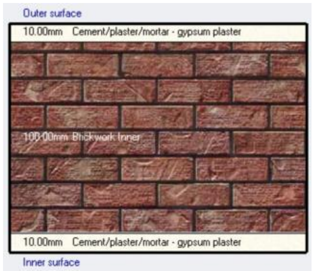


Fig. 62: Cross-section: Internal partition wall

- <u>Glazing:</u>
  U = 1,97 W/m^{2}K
  Composition from the outermost layer:
  - Plan Glass: (3 mm; λ = 0,9 W/mK)
  - Air gap: (13 mm; -)
  - Plan Glass: (3 mm; λ = 0,9 W/mK)
- <u>Window's wooden frame:</u>
  Thickness = 20 mm; λ = 0,19 W/m^{2}K

Note that it has not been possible to acknowledge the window's dimension, so it has been chosen an opening area of 30% of the total surface of the walls with a fixed window's height of 1,5 m and no shading applied.

Annex B: Photos of the Building

Fig. 63: Photo of the entrance of the house

Fig. 64: Photo of the living room

Fig. 65: Photo of the kitchen

Fig. 66: Photo of the bedroom back

Fig. 67: Photo of the window of beedroom front

Fig. 68: Photo of the attic

Annex C: Internal Heat Gains Schedule

Occupancy Schedule Values							
Building			**People**				
Floor	*Zone*	*Sq. m*	*People*	*Activity Level [W]*	*Rad Fract*	*Occupancy Schedule*	*Clothing Ins*
Ground	Hall	9.26	1	136	0.3	Common Areas	Dynamic ASHRAE-55
	Livingroom	28.87	3	99	0.3	Living-Dining Room	Dynamic ASHRAE-55
	Kitchen	6.59	1	136	0.3	Kitchen	Dynamic ASHRAE-55
1st	Corridor	3.88	1	136	0.3	Common Areas	Dynamic ASHRAE-55
	Bed Back	12.66	1	81	0.3	Bedrooms	Dynamic ASHRAE-55
	Bed Front	13.71	2	81	0.3	Bedrooms	Dynamic ASHRAE-55
	Bed Small	4.16	1	81	0.3	Bedrooms	Dynamic ASHRAE-55
	Bathroom	5.08	1	108	0.3	Bathroom	Dynamic ASHRAE-55
	Toilet 2	2.05	1	126	0.3	Toilet	Dynamic ASHRAE-55
	Toilet 1	1.23	1	126	0.3	Toilet	Dynamic ASHRAE-55

Legenda	**People Occupancy Schedule**					
Schedule	*Common Areas*	*Living-Dining Room*	*Kitchen*	*Bedrooms*	*Bathroom*	*Toilet*
Type	*Fraction*	*Fraction*	*Fraction*	*Fraction*	*Fraction*	*Fraction*
Program Lines	*Through 12/31*	*Through 12/31*	*Through 12/31*	*Through 12/31*	*Through 12/31*	*Through 12/31*
	For: Weekdays	*For: All Days*	*For: All Days*	*For: All Days*	*For: All Days*	*For: All Days*
	Until: 07:00	*Until: 06:00*	*Until: 07:00*	*Until 7:00*	*Until 7:00*	*Until: 06:00*
	0	*0*	*0*	*1*	*0*	*0*
	Until: 08:00	*Until: 07:00*	*Until: 10:00*	*Until 8:00*	*Until 10:00*	*Until: 07:00*
	0.5	*0.25*	*1*	*0.5*	*1*	*0.25*
	Until: 09:00	*Until: 09:00*	*Until: 19:00*	*Until 9:00*	*Until 19:00*	*Until: 09:00*
	1	*1*	*0*	*0.25*	*0*	*1*
	Until: 10:00	*Until: 10:00*	*Until 22:00*	*Until 22:00*	*Until 23:00*	*Until: 10:00*
	0.5	*0.25*	*0.2*	*0*	*0.2*	*0.25*
	Until 17:00	*Until 18:00*	*Until: 24:00*	*Until 23:00*	*Until 24:00*	*Until 18:00*
	0	*0*	*0*	*0.25*	*0*	*0*
	Until 18:00	*Until: 19:00*		*Until 24 :00*		*Until: 19:00*
	0.25	*0.5*		*0.75*		*0.5*
	Until: 19:00	*Until 21:00*				*Until: 22:00*
	0.5	*1*				*0.2*
	Until: 20:00	*Until 22:00*				*Until : 24:00*
	0.75	*0.3*				*0*
	Until 22:00	*Until 24:00*				
	1	*0*				
	Until 23:00					
	0.75					
	Until 24:00					
	0.25					
	For: Weekends					
	Until: 09:00					
	0					
	Until: 21:00					
	1					
	Until 24:00					
	0					

Lights Schedule						
Building			**Lights**			
Floor	*Zone*	*Sq. m*	*Schedule*	*Capacity Design [W/m ^{2}]*	*Capacity [W]*	*Rad Fract*
	Hall	9.26	Common Areas	5	46	0.42
Ground	Livingroom	28.87	Living-Dining Room	7.5	217	0.42
	Kitchen	6.59	Kitchen	15	99	0.42
	Corridor	3.88	Common Areas	5	19	0.42
	Bed Back	12.66	Bedrooms	5	63	0.42
	Bed Front	13.71	Bedrooms	5	69	0.42
1st	Bed Small	4.16	Bedrooms	5	21	0.42
	Bathroom	5.08	Bathroom	7.5	38	0.42
	Toilet 2	2.05	Toilet	5	10	0.42
	Toilet 1	1.23	Toilet	5	6	0.42

Legenda	**Lights Schedule**					
Schedule	*Common Areas*	*Living-Dining Room*	*Kitchen*	*Bedrooms*	*Bathroom*	*Toilet*
Type	*Fraction*	*Fraction*	*Fraction*	*Fraction*	*Fraction*	*Fraction*
Program Lines	*Through 12/31*	*Through 12/31*	*Through 12/31*	*Through 12/31*	*Through 12/31*	*Through 12/31*
	For: Weekdays	*For: All Days*	*Until: 07:00*	*For: All Days*	*For: All Days*	*For: All Days*
	Until: 07:00	*Until: 06:00*	*0*	*Until 7:00*	*Until 7:00*	*Until: 06:00*
	0	*0*	*Until: 10:00*	*1*	*0*	*0*
	Until: 08:00	*Until: 07:00*	*1*	*Until 8:00*	*Until 10:00*	*Until: 10:00*
	0.5	*0.25*	*Until: 19:00*	*0.5*	*1*	*1*
	Until: 10:00	*Until: 09:00*	*0*	*Until 9:00*	*Until 19:00*	*Until 18:00*
	1	*1*	*Until 23:00*	*0.25*	*0*	*0*
	Until 17:00	*Until 18:00*	*1*	*Until 22:00*	*Until 23:00*	*Until: 22:00*
	0	*0*	*Until: 24:00*	*0*	*1*	*1*
	Until 24:00	*Until 22:00*	*0*	*Until 23:00*	*Until 24:00*	*Until : 24:00*
	1	*1*		*0.25*	*0*	*0*
	For: Weekends	*Until 24:00*		*Until 24 :00*		
	Until: 09:00	*0*		*0.75*		
	0					
	Until: 21:00					
	1					
	Until 24:00					
	0					

Equipment Schedule							
Building			**Other Equipments**				
Floor	*Zone*	*Sq. m*	*Schedule*	*Capacity Design [W/m ^{2}]*	*Capacity [W]*	*Rad Fract*	*End/Use SubCat*
Ground	Hall	9.26	Common Areas	2.16	20.00	0.2	Electric
	Livingroom	28.87	Living-Dining Room	3.06	88.34	0.2	Electric
	Kitchen	6.59	Kitchen	30.28	199.55	0.2	Electric
1st	Corridor	3.88	Common Areas	2.16	8.38	0.2	Electric
	Bed Back	12.66	Bedrooms	3.58	45.32	0.2	Electric
	Bed Front	13.71	Bedrooms	3.58	49.08	0.2	Electric
	Bed Small	4.16	Bedrooms	3.58	14.89	0.2	Electric
	Bathroom	5.08	Bathroom	1.67	8.48	0.2	Electric
	Toilet 2	2.05	Toilet	1.61	3.30	0.2	Electric
	Toilet 1	1.23	Toilet	1.61	1.98	0.2	Electric

Legenda	**Equipment Schedule**					
Schedule	*Common Areas*	*Living-Dining Room*	*Kitchen*	*Bedrooms*	*Bathroom*	*Toilet*
Type	*Fraction*	*Fraction*	*Fraction*	*Fraction*	*Fraction*	*Fraction*
Program Lines	*Through 12/31*	*Through 12/31*	*Through 12/31*	*Through 12/31*	*Through 12/31*	*Through 12/31*
	For: All Days	*For: All Days*	*0.06*	*For: All Days*	*For: All Days*	*For: All Days*
	Until: 07:00	*Until: 06:00*	*Until: 10:00*	*Until 7:00*	*Until: 07:00*	*Until: 07:00*
	0.046	*0.08*	*1*	*1*	*0.06*	*0.06*
	Until: 23:00	*Until: 07:00*	*Until: 19:00*	*Until 8:00*	*Until: 08:00*	*Until: 08:00*
	1	*0.31*	*0.06*	*0.5*	*0.53*	*0.53*
	Until 24:00	*Until: 09:00*	*Until 23:00*	*Until 9:00*	*Until: 09:00*	*Until: 09:00*
	0.33	*1*	*0.25*	*0.25*	*1*	*1*
		Until: 10:00	*Until: 24:00*	*Until 22:00*	*Until: 10:00*	*Until: 10:00*
		0.31	*0.06*	*0*	*0.25*	*0.25*
		Until 18:00		*Until 23:00*	*Until 18:00*	*Until 18:00*
		0.08		*0.25*	*0*	*0*
		Until: 19:00		*Until 24 :00*	*Until: 19:00*	*Until: 19:00*
		0.54		*0.75*	*0.5*	*0.5*
		Until 21:00			*Until: 22:00*	*Until: 22:00*
		1			*0.3*	*0.3*
		Until 22:00			*Until : 24:00*	*Until : 24:00*
		0.36			*0*	*0*
		Until 24:00				
		0.08				

Annex D: Evaluation of The Mean Radiant Temperature and Radiant Asymmetry

The accounting of the mean radiant temperature and local discomfort due to radiant asymmetry is done accordingly with ASHRAE Handbook of fundamental. That is done in different position of the living room, so to investigate properly the chance to encounter local discomfort due to radiant asymmetry, but also to assess comfort in specific position like close to an IR-panel or a windows: places where is likely perceived a considerable difference in the around surface's temperature.

Below, are reported the equation and the criteria applied to determine the angle factor for the different position evaluated, while the radiant asymmetry is determined accordingly with what said at § 7.2. for Eq. 21 and 22.

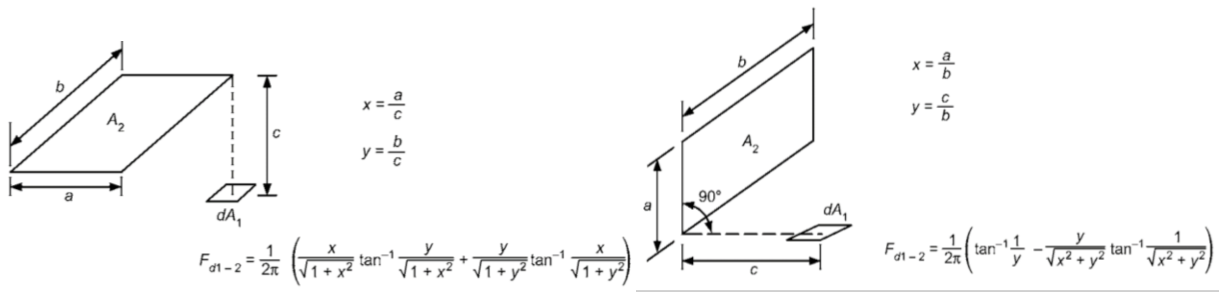


Fig. 69: ASHREA Handbook of Fundamental -: analytical equation to determine the angle factor of small plane element

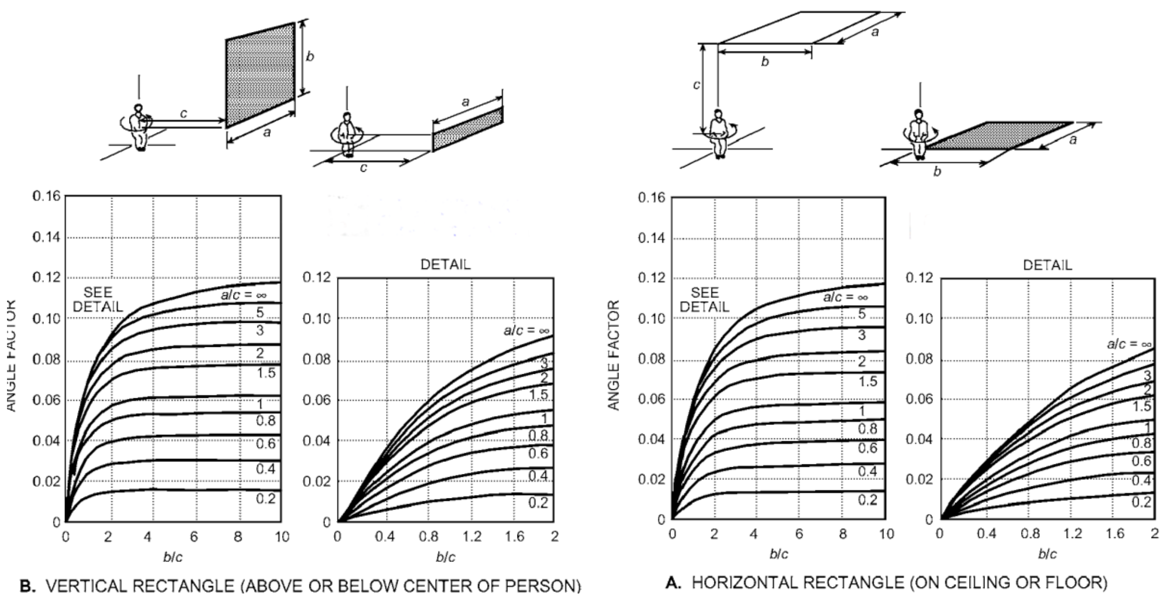
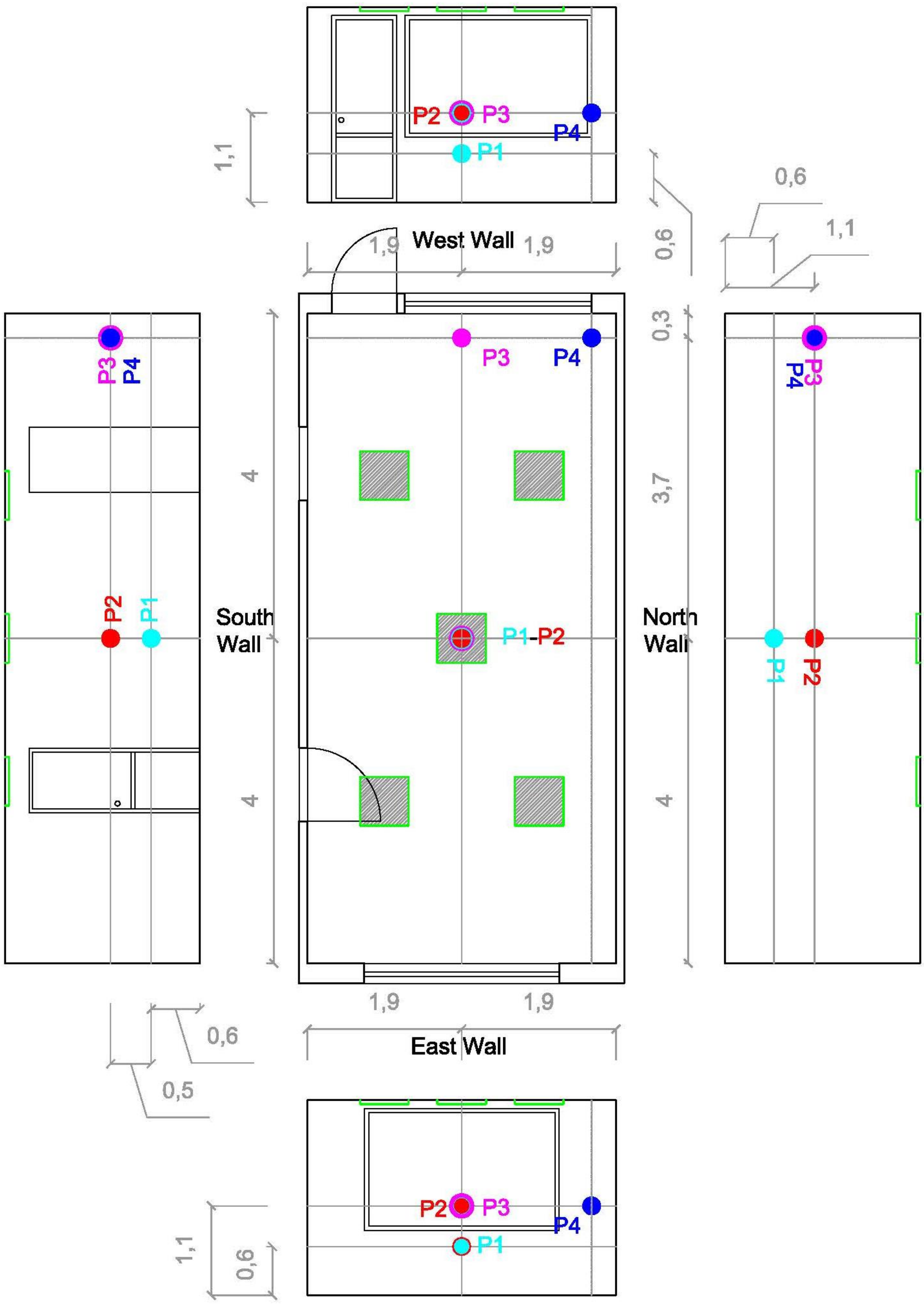


Fig. 70:ASHRAE Handbook of Fundamental - Mean values of angle factors for a seated person

- Living room plan – Comfort Position Evaluated:

Drwing out of scale, units in meters.



Position 1: Person seated in the centre of the room - Angle Factors

North Wall

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Wall	1	1	+	4	1.8	1.9	0.45	0.48	0.0649111
	2	2	+	4	0.6	1.9	0.15	0.48	0.0111713
	3	3	+	4	0.6	1.9	0.15	0.48	0.0111713
	4	4	+	4	1.8	1.9	0.45	0.48	0.0649111
								TOT	0.1521649

South Wall

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Wall	1	1	+	4	1.8	1.9	0.45	0.48	0.0649111
		2	-	2.6	1.5	1.9	0.58	0.73	0.047016
		3	+	1.8	1.5	1.9	0.83	1.06	0.0408508
	2	1	+	4	0.6	1.9	0.15	0.48	0.0111713
		2	-	2.6	0.6	1.9	0.23	0.73	0.0104075
		3	+	1.8	0.6	1.9	0.33	1.06	0.0092027
	3	1	+	4	0.6	1.9	0.15	0.48	0.0111713
		2	-	2.15	0.6	1.9	0.28	0.88	0.0098511
		3	+	1.35	0.6	1.9	0.44	1.41	0.007946
	4	1	+	4	1.8	1.9	0.45	0.48	0.0649111
		2	-	2.15	1.5	1.9	0.70	0.88	0.0441147
		3	+	1.35	1.5	1.9	1.11	1.41	0.0347882
								TOT	0.1335633

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Hole	1	1	+	2.6	1.5	1.9	0.58	0.73	0.047016
		2	-	1.8	1.5	1.9	0.83	1.06	0.0408508
	2	1	+	2.6	0.6	1.9	0.23	0.73	0.0104075
		2	-	1.8	0.6	1.9	0.33	1.06	0.0092027
								TOT	0.00737

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Door	3	1	+	2.6	0.6	1.9	0.23	0.73	0.0104075
		2	-	1.8	0.6	1.9	0.33	1.06	0.0092027
	4	1	+	2.15	1.5	1.9	0.70	0.88	0.0441147
		2	-	1.35	1.5	1.9	1.11	1.41	0.0347882
								TOT	0.0105313

West Wall

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Wall	1	1	+	1.9	1.8	4	0.95	2.11	0.011256
		2	-	1.6	1.7	4	1.06	2.50	0.0088969
		3	+	1.6	0.2	4	0.13	2.50	0.000144
	2	1	+	1.9	0.6	4	0.32	2.11	0.0014578
	3	1	+	1.9	0.6	4	0.32	2.11	0.0014578
		2	-	1.6	0.6	4	0.38	2.50	0.001272
		3	+	0.8	0.6	4	0.75	5.00	0.0006829
	4	1	+	1.9	1.8	4	0.95	2.11	0.011256
		2	-	1.6	1.7	4	1.06	2.50	0.0088969
		3	+	0.8	1.7	4	2.13	5.00	0.0047562
		4	-	0.7	1.7	4	2.43	5.71	0.0041849
		5	+	0.7	0.2	4	0.29	5.71	6.811E-05
								TOT	0.0078282

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Window	1	1	+	1.6	1.7	4	1.06	2.50	0.0088969
		2	-	1.6	0.2	4	0.13	2.50	0.000144
	4	1	+	0.7	1.7	4	2.43	5.71	0.0041849
		2	-	0.7	0.2	4	0.29	5.71	6.811E-05
								TOT	0.0128696

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Door	3	1	+	1.6	0.6	4	0.38	2.50	0.001272
		2	-	0.8	0.6	4	0.75	5.00	0.0006829
	4	1	+	1.6	1.7	4	1.06	2.50	0.0088969
		2	-	0.8	1.7	4	2.13	5.00	0.0047562
								TOT	0.0047298

East Wall

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Wall	1	1	+	1.9	1.8	4	0.95	2.11	0.011256
		2	-	1.2	1.7	4	1.42	3.33	0.0069317
		3	+	1.2	0.2	4	0.17	3.33	0.0001125
	2	1	+	1.9	0.6	4	0.32	2.11	0.0014578
	3	1	+	1.9	0.6	4	0.32	2.11	0.0014578
	4	1	+	1.9	1.8	4	0.95	2.11	0.011256
		2	-	1.2	1.7	4	1.42	3.33	0.0069317
		3	+	1.2	0.2	4	0.17	3.33	0.0001125
								TOT	0.0117893

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Window	1	1	+	1.2	1.7	4	1.42	3.33	0.0069317
		2	-	1.2	0.2	4	0.17	3.33	0.0001125
	4	1	+	1.2	1.7	4	1.42	3.33	0.0069317
		2	-	1.2	0.2	4	0.17	3.33	0.0001125
								TOT	0.0136383

IR Panels

Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F
				Analytical convention			X	Y	
IR Angle 1	1	1	+	1.25	2.3	1.8	0.69	1.28	0.1242417
		2	-	1.25	1.7	1.8	0.69	0.94	0.1110433
		2	-	0.65	2.3	1.8	0.36	1.28	0.0748813
		4	+	0.65	1.7	1.8	0.36	0.94	0.0673521
								TOT	0.0056692

Element	Quadrant	F
IR Angle 2	2	0.0057
IR Angle 3	3	0.0057
IR Angle 4	4	0.0057

Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F tab
IR Central	1	1	+	0.3	0.3	1.8	0.17	0.17	0.008531
	2	2	+	0.3	0.3	1.8	0.17	0.17	0.008531
	3	2	+	0.3	0.3	1.8	0.17	0.17	0.008531
	4	4	+	0.3	0.3	1.8	0.17	0.17	0.008531
								TOT	0.0341241

Ceiling

Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F tab
Ceiling	1	1	+	1.9	4	1.8	1.06	2.22	0.05
		2	-	1.25	2.3	1.8	0.69	1.28	0.035
		3	+	1.25	1.7	1.8	0.69	0.94	0.03
		4	+	0.65	2.3	1.8	0.36	1.28	0.015
		5	-	0.65	1.7	1.8	0.36	0.94	0.011
		6	-	0.3	0.3	1.8	0.17	0.17	0.003
								Subtot 1	0.046
	2		+					Subtot 2	0.046
	3		+					Subtot 3	0.046
	4		+					Subtot 4	0.046
								TOT	0.184

Floor	Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F tab
	Floor	1	1	+	1.9	4	0.6	3.17	6.67	0.1011786
		2	2	+	1.9	4	0.6	3.17	6.67	0.1011786
		3	2	+	1.9	4	0.6	3.17	6.67	0.1011786
		4	4	+	1.9	4	0.6	3.17	6.67	0.1011786
									TOT	0.4047143

Position 2: Person standing in the centre of the room – Angle Factors

North Wall	Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
					Analytical convention			X	Y	
	Wall	1	1	+	4	1.3	1.9	0.33	0.48	0.041714784
		2	2	+	4	1.1	1.9	0.28	0.48	0.032222469
		3	3	+	4	1.3	1.9	0.33	0.48	0.041714784
		4	4	+	4	1.1	1.9	0.28	0.48	0.032222469
									TOT	0.147874507

South Wall	Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
					Analytical convention			X	Y	
	Wall	1	1	+	4	1.3	1.9	0.33	0.48	0.041714784
			2	-	2.6	1	1.9	0.38	0.73	0.025562194
			3	+	1.8	1	1.9	0.56	1.06	0.022449205
		2	1	+	4	1.1	1.9	0.28	0.48	0.032222469
			2	-	2.6	1.1	1.9	0.42	0.73	0.029805213
			3	+	1.8	1.1	1.9	0.61	1.06	0.026122778
		3	1	+	4	1.1	1.9	0.28	0.48	0.032222469
			2	-	2.15	1.1	1.9	0.51	0.88	0.028088445
			3	+	1.35	1.1	1.9	0.81	1.41	0.02239461
		4	1	+	4	1.3	1.9	0.33	0.48	0.041714784
			2	-	2.15	1	1.9	0.47	0.88	0.024114034
			3	+	1.35	1	1.9	0.74	1.41	0.019276093
									TOT	0.130547306

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Hole	1	1	+	2.6	1	1.9	0.38	0.73	0.025562194
		2	-	1.8	1	1.9	0.56	1.06	0.022449205
	2	1	+	2.6	1.1	1.9	0.42	0.73	0.029805213
		2	-	1.8	1.1	1.9	0.61	1.06	0.026122778
								TOT	0.006795425

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Door	3	1	+	2.6	1.1	1.9	0.42	0.73	0.029805213
		2	-	1.8	1.1	1.9	0.61	1.06	0.026122778
	4	1	+	2.15	1	1.9	0.47	0.88	0.024114034
		2	-	1.35	1	1.9	0.74	1.41	0.019276093
								TOT	0.008520377

West Wall

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Wall	1	1	+	1.9	1.3	4	0.68	2.11	0.006357273
		2	-	1.6	1.2	4	0.75	2.50	0.00478618
	2	1	+	1.9	1.1	4	0.58	2.11	0.004671467
		2	-	1.6	0.3	4	0.19	2.50	0.000323106
	3	1	+	1.9	1.1	4	0.58	2.11	0.004671467
		2	-	1.6	1.1	4	0.69	2.50	0.004073196
		3	+	0.8	1.1	4	1.38	5.00	0.002183428
		4	-	0.7	0.3	4	0.43	5.71	0.000152782
	4	1	+	1.9	1.3	4	0.68	2.11	0.006357273
		2	-	1.6	1.2	4	0.75	2.50	0.00478618
		3	+	0.8	1.2	4	1.50	5.00	0.002564593
		4	-	0.7	1.2	4	1.71	5.71	0.002257004
								TOT	0.010427053

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Window	1	1	+	1.6	1.2	4	0.75	2.50	0.00478618
	2	2	+	1.6	0.3	4	0.19	2.50	0.000323106
	3	1	+	0.7	0.3	4	0.43	5.71	0.000152782
	4	2	+	0.7	1.2	4	1.71	5.71	0.002257004
								TOT	0.007519072

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
				Analytical convention			X	Y	
Door	3	1	+	1.6	1.1	4	0.69	2.50	0.004073196
		2	-	0.8	1.1	4	1.38	5.00	0.002183428
	4	1	+	1.6	1.3	4	0.81	2.50	0.005541004
		2	-	0.8	1.3	4	1.63	5.00	0.002967791
								TOT	0.004462982

East Wall

				Analytical convention			X	Y	
Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
Wall	1	1	+	1.9	1.3	4	0.68	2.11	0.006357273
		2	-	1.2	1.2	4	1.00	3.33	0.00373377
	2	1	+	1.9	1.1	4	0.58	2.11	0.004671467
		2	-	1.2	0.3	4	0.25	3.33	0.000252409
	3	1	+	1.9	1.1	4	0.58	2.11	0.004671467
		2	-	1.2	0.3	4	0.25	3.33	0.000252409
	4	1	+	1.9	1.3	4	0.68	2.11	0.006357273
		2	-	1.2	1.2	4	1.00	3.33	0.00373377
								TOT	0.014085121

				Analytical convention			X	Y	
Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
Window	1	1	+	1.2	1.2	4	1.00	3.33	0.00373377
	2	1	+	1.2	0.3	4	0.25	3.33	0.000252409
	3	1	+	1.2	0.3	4	0.25	3.33	0.000252409
	4	1	+	1.2	1.2	4	1.00	3.33	0.00373377
								TOT	0.007972359

IR Panels

				Analytical convention			X	Y	
Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F
IR _1	1	1	+	1.25	2.3	1.3	0.96	1.77	0.161234148
		2	-	1.25	1.7	1.3	0.96	1.31	0.150291226
		2	-	0.65	2.3	1.3	0.50	1.77	0.105168501
		4	+	0.65	1.7	1.3	0.50	1.31	0.098784805
								TOT	0.004559227

Element	Quadrant	F
IR_2	2	0.0046
IR_3	3	0.0046
IR_4	4	0.0046

Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F tab
IR Central	1	1	+	0.3	0.3	1.3	0.23	0.23	0.01583904
	2	2	+	0.3	0.3	1.3	0.23	0.23	0.01583904
	3	2	+	0.3	0.3	1.3	0.23	0.23	0.01583904
	4	4	+	0.3	0.3	1.3	0.23	0.23	0.01583904
								TOT	0.063356161

Ceiling

Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F tab
Ceiling	1	1	+	1.9	4	1.3	1.46	3.08	0.068
		2	-	1.25	2.3	1.3	0.96	1.77	0.048
		3	+	1.25	1.7	1.3	0.96	1.31	0.042
		4	+	0.65	2.3	1.3	0.50	1.77	0.028
		5	-	0.65	1.7	1.3	0.50	1.31	0.023
		6	-	0.3	0.3	1.3	0.23	0.23	0.004
								Subtot 1	0.063
	2		+					Subtot 2	0.063
	3		+					Subtot 3	0.063
	4		+					Subtot 4	0.063
								TOT	0.252

Floor

Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F tab
Floor	1	1	+	1.9	4	1.1	1.73	3.64	0.093889723
	2	2	+	1.9	4	1.1	1.73	3.64	0.093889723
	3	2	+	1.9	4	1.1	1.73	3.64	0.093889723
	4	4	+	1.9	4	1.1	1.73	3.64	0.093889723
								TOT	0.375558892

Position 3: Person standing in front of the back window (west wall) – Angle Factors

North Wall

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**b**	**a**	**c**	**a/b**	**c/b**	**F**
Wall	1	1	+	7.7	1.3	1.9	0.17	0.25	0.04335313
	2	2	+	7.7	1.1	1.9	0.14	0.25	0.03341438
	3	3	+	0.3	1.3	1.9	4.33	6.33	0.00790722
	4	4	+	0.3	1.1	1.9	3.67	6.33	0.00622174
								TOT	0.09089647

South Wall

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**b**	**a**	**c**	**a/b**	**c/b**	**F**
Wall	1	1	+	0.3	1.3	1.9	4.33	6.33	0.00790722
	2	1	+	0.3	1.1	1.9	3.67	6.33	0.00622174
	3	1	+	7.7	1.1	1.9	0.14	0.25	0.03341438
		2	-	5.85	1.1	1.9	0.19	0.32	0.03313046
		3	+	5.05	1.1	1.9	0.22	0.38	0.03287236
		4	-	1.9	1.1	1.9	0.58	1.00	0.02675457
		5	+	1.1	1.1	1.9	1.00	1.73	0.01955825
	4	1	+	7.7	1.3	1.9	0.17	0.25	0.04335313
		2	-	5.85	1	1.9	0.17	0.32	0.02834556
		3	+	5.05	1	1.9	0.20	0.38	0.02813093
		4	-	1.9	1	1.9	0.53	1.00	0.022985
		5	+	1.1	1	1.9	0.91	1.73	0.01685129
								TOT	0.07709371

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**b**	**a**	**c**	**a/b**	**c/b**	**F**
Hole	3	1	+	1.9	1.1	1.9	0.58	1.00	0.02675457
		2	-	1.1	1.1	1.9	1.00	1.73	0.01955825
	4	1	+	1.9	1	1.9	0.53	1.00	0.022985
		2	-	1.1	1	1.9	0.91	1.73	0.01685129
								TOT	0.01333004

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**b**	**a**	**c**	**a/b**	**c/b**	**F**
Door	3	1	+	5.85	1.1	1.9	0.19	0.32	0.03313046
		2	-	5.05	1.1	1.9	0.22	0.38	0.03287236
	4	1	+	5.85	1	1.9	0.17	0.32	0.02834556
		2	-	5.05	1	1.9	0.20	0.38	0.02813093
								TOT	0.00047272

West Wall

Element	Quadrant	Portion	Contribute	a	b	c	b/c	a/c	F tab
Wall	1	1	+	1.9	1.3	0.3	4.33	6.33	0.105
		2	-	1.6	1.2	0.3	4.00	5.33	0.096
	2	1	+	1.9	1.1	0.3	3.67	6.33	0.091
		2	-	1.6	0.3	0.3	1.00	5.33	0.06
	3	1	+	1.9	1.1	0.3	3.67	6.33	0.091
		2	-	1.6	1.1	0.3	3.67	5.33	0.089
		3	+	0.8	1.1	0.3	3.67	2.67	0.082
		4	-	0.7	0.3	0.3	1.00	2.33	0.057
	4	1	+	1.9	1.3	0.3	4.33	6.33	0.105
		2	-	1.6	1.2	0.3	4.00	5.33	0.096
		3	+	0.8	1.2	0.3	4.00	2.67	0.085
		4	-	0.7	1.2	0.3	4.00	2.33	0.0835
								TOT	0.0775

Element	Quadrant	Portion	Contribute	a	b	c	b/c	a/c	F tab
Window	1	1	+	1.6	1.2	0.3	4.00	5.33	0.095
	2	2	+	1.6	0.3	0.3	1.00	5.33	0.071
	3	1	+	0.7	0.3	0.3	1.00	2.33	0.071
	4	2	+	0.7	1.2	0.3	4.00	2.33	0.09
								TOT	0.327

				Analytical convention			**X**	**Y**	
Element	**Quadrant**	**Portion**	**Contribute**	**b**	**a**	**c**	**a/b**	**c/b**	**F**
Door	3	1	+	1.6	1.1	0.3	0.69	0.19	0.18074056
		2	-	0.8	1.1	0.3	1.38	0.38	0.16736346
	4	1	+	1.6	1.3	0.3	0.81	0.19	0.18925597
		2	-	0.8	1.3	0.3	1.63	0.38	0.17365751
								TOT	0.02897556

					Analytical convention		X	Y	
East Wall	**Element**	**Quadrant**	**Portion**	**Contribute**	**b**	**a**	**c**	**a/b**	**c/b**	**F**

Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
Wall	1	1	+	1.9	1.3	7.7	0.68	4.05	0.00104758
		2	-	1.2	1.2	7.7	1.00	6.42	0.00057921
	2	1	+	1.9	1.1	7.7	0.58	4.05	0.00075588
		2	-	1.2	0.3	7.7	0.25	6.42	3.7017E-05
	3	1	+	1.9	1.1	7.7	0.58	4.05	0.00075588
		2	-	1.2	0.3	7.7	0.25	6.42	3.7017E-05
	4	1	+	1.9	1.3	7.7	0.68	4.05	0.00104758
		2	-	1.2	1.2	7.7	1.00	6.42	0.00057921
								TOT	0.00237446

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**b**	**a**	**c**	**a/b**	**c/b**	**F**
Window	1	1	+	1.2	1.2	7.7	1.00	6.42	0.00057921
	2	1	+	1.2	0.3	7.7	0.25	6.42	3.7017E-05
	3	1	+	1.2	0.3	7.7	0.25	6.42	3.7017E-05
	4	1	+	1.2	1.2	7.7	1.00	6.42	0.00057921
								TOT	0.00123245

					Analytical convention			X	Y	
IR Panles	**Element**	**Quadrant**	**Portion**	**Contribute**	**a**	**b**	**c**	**a/c**	**b/c**	**F**

Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F
IR_1	2	1	+	1.25	2	1.3	0.96	1.54	0.15682355
		2	-	1.25	1.4	1.3	0.96	1.08	0.14046062
		3	-	0.65	2	1.3	0.50	1.54	0.10262607
		4	+	0.65	1.4	1.3	0.50	1.08	0.09286279
								TOT	0.00659965

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**a**	**b**	**c**	**a/c**	**b/c**	**F**
IR_3	2	1	+	1.25	6	1.3	0.96	4.62	0.17239844
		2	-	1.25	5.4	1.3	0.96	4.15	0.17206034
		3	-	0.65	6	1.3	0.50	4.62	0.11135146
		4	+	0.65	5.4	1.3	0.50	4.15	0.11117179
								TOT	0.00015843

Element	Quadrant	F
IR_2	2	0.0066
IR_3	3	0.0002

Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F tab
IR Central	2	1	+	0.3	4	1.3	0.23	3.08	0.015
		2	-	0.3	3.4	1.3	0.23	2.62	0.011
	3	2	+	0.3	4	1.3	0.23	3.08	0.015
		4	-	0.3	0.3	1.3	0.23	0.23	0.011
								TOT	0.008

Floor

Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F tab
Floor	1	1	+	1.9	0.3	1.1	1.73	0.27	0.02
	2	2	+	1.9	7.7	1.1	1.73	7.00	0.08
	3	2	+	1.9	7.7	1.1	1.73	7.00	0.08
	4	4	+	1.9	0.3	1.1	1.73	0.27	0.02
								TOT	0.2

Ceiling

F ceiling = 1 - Fi

	F tab
Ceiling	0.22148402

Position 4: Person in the corner (north-west) of the living room – Angle Factors

North Wall

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**b**	**a**	**c**	**a/b**	**c/b**	**F**
Wall	1	1	+	7.7	1.3	1.9	0.17	0.25	0.04335313
	2	2	+	7.7	1.1	1.9	0.14	0.25	0.03341438
	3	3	+	0.3	1.3	1.9	4.33	6.33	0.00790722
	4	4	+	0.3	1.1	1.9	3.67	6.33	0.00622174
								TOT	0.09089647

South Wall										
				Analytical convention			X	Y		
Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F	
Wall	1	1	+	0.3	1.3	1.9	4.33	6.33	0.00790722	
	2	1	+	0.3	1.1	1.9	3.67	6.33	0.00622174	
	3	1	+	7.7	1.1	1.9	0.14	0.25	0.03341438	
		2	-	5.85	1.1	1.9	0.19	0.32	0.03313046	
		3	+	5.05	1.1	1.9	0.22	0.38	0.03287236	
		4	-	1.9	1.1	1.9	0.58	1.00	0.02675457	
		5	+	1.1	1.1	1.9	1.00	1.73	0.01955825	
	4	1	+	7.7	1.3	1.9	0.17	0.25	0.04335313	
		2	-	5.85	1	1.9	0.17	0.32	0.02834556	
		3	+	5.05	1	1.9	0.20	0.38	0.02813093	
		4	-	1.9	1	1.9	0.53	1.00	0.022985	
		5	+	1.1	1	1.9	0.91	1.73	0.01685129	
								TOT	0.07709371	

				Analytical convention			X	Y	
Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
Hole	3	1	+	1.9	1.1	1.9	0.58	1.00	0.02675457
		2	-	1.1	1.1	1.9	1.00	1.73	0.01955825
	4	1	+	1.9	1	1.9	0.53	1.00	0.022985
		2	-	1.1	1	1.9	0.91	1.73	0.01685129
								TOT	0.01333004

				Analytical convention			X	Y	
Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
Door	3	1	+	5.85	1.1	1.9	0.19	0.32	0.03313046
		2	-	5.05	1.1	1.9	0.22	0.38	0.03287236
	4	1	+	5.85	1	1.9	0.17	0.32	0.02834556
		2	-	5.05	1	1.9	0.20	0.38	0.02813093
								TOT	0.00047272

West Wall										
	Element	Quadrant	Portion	Contribute	a	b	c	b/c	a/c	F tab
	Wall	1	1	+	0.3	1.3	0.3	4.33	1.00	0.06
		2	2	+	0.3	1.1	0.3	3.67	1.00	0.054
		3	1	+	3.5	1.1	0.3	3.67	11.67	0.095
			2	-	3.2	1.1	0.3	3.67	10.67	0.095
			3	+	2.4	1.1	0.3	3.67	8.00	0.095
			4	-	2.3	0.3	0.3	1.00	7.67	0.052
		4	1	+	3.5	1.3	0.3	4.33	11.67	0.12
			2	-	3.2	1.2	0.3	4.00	10.67	0.12
			3	+	2.4	1.2	0.3	4.00	8.00	0.12
			4	-	2.3	1.2	0.3	4.00	7.67	0.12
									TOT	0.157

Element	Quadrant	Portion	Contribute	a	b	c	b/c	a/c	F tab
Window	3	1	+	2.3	0.3	0.3	1.00	7.67	0.062
	4	1	+	2.3	1.2	0.3	4.00	7.67	0.12
								TOT	0.182

				Analytical convention			X	Y	
Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
Door	3	1	+	3.2	1.1	0.3	0.34	0.09	0.18377001
		2	-	2.4	1.1	0.3	0.46	0.13	0.18309429
	4	1	+	3.2	1.2	0.3	0.38	0.09	0.18882242
		2	-	2.4	1.2	0.3	0.50	0.13	0.18803912
								TOT	0.00145902

East Wall

				Analytical convention			X	Y	
Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
Wall	1	1	+	0.3	1.3	7.7	4.33	25.67	0.00017177
	2	1	+	0.3	1.1	7.7	3.67	25.67	0.00012396
	3	1	+	3.5	1.1	7.7	0.31	2.20	0.00128063
		2	-	2.8	0.3	7.7	0.11	2.75	8.0849E-05
		3	+	0.4	0.3	7.7	0.75	19.25	1.2515E-05
	4	1	+	3.5	1.3	7.7	0.37	2.20	0.00177534
		2	-	2.8	1.2	7.7	0.43	2.75	0.0012659
		3	+	0.4	1.2	7.7	3.00	19.25	0.00019579
								TOT	0.00221325

				Analytical convention			X	Y	
Element	Quadrant	Portion	Contribute	b	a	c	a/b	c/b	F
Window	3	1	+	2.8	0.3	7.7	0.11	2.75	8.0849E-05
		2	-	0.4	0.3	7.7	0.75	19.25	1.2515E-05
	4	1	+	2.8	1.2	7.7	0.43	2.75	0.0012659
		2	-	0.4	1.2	7.7	3.00	19.25	0.00019579
								TOT	0.00113844

IR Panels

				Analytical convention			X	Y	
Element	Quadrant	Portion	Contribute	a	b	c	a/c	b/c	F
IR_1	3	1	+	0.95	2	1.3	0.73	1.54	0.13449779
		2	-	0.95	1.4	1.3	0.73	1.08	0.12108657
		3	-	0.35	2	1.3	0.27	1.54	0.05995046
		4	+	0.35	1.4	1.3	0.27	1.08	0.05446506
								TOT	0.00792581

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**a**	**b**	**c**	**a/c**	**b/c**	**F**
IR_3	3	1	+	0.95	6	1.3	0.73	4.62	0.14683929
		2	-	0.95	5.4	1.3	0.73	4.15	0.14657911
		3	-	0.35	6	1.3	0.27	4.62	0.06475158
		4	+	0.35	5.4	1.3	0.27	4.15	0.06465427
								TOT	0.00016287

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**a**	**b**	**c**	**a/c**	**b/c**	**F**
IR_2	3	1	+	2.85	2	1.3	2.19	1.54	0.19899859
		2	-	2.85	1.4	1.3	2.19	1.08	0.17527285
		3	-	2.25	2	1.3	1.73	1.54	0.19140274
		4	+	2.25	1.4	1.3	1.73	1.08	0.16928132
								TOT	0.00160432

				Analytical convention			X	Y	
Element	**Quadrant**	**Portion**	**Contribute**	**a**	**b**	**c**	**a/c**	**b/c**	**F**
IR_4	3	1	+	2.85	6	1.3	2.19	4.62	0.22550035
		2	-	2.85	5.4	1.3	2.19	4.15	0.22481064
		3	-	2.25	6	1.3	1.73	4.62	0.21489526
		4	+	2.25	5.4	1.3	1.73	4.15	0.21432327
								TOT	0.00011772

Element	**Quadrant**	**Portion**	**Contribute**	**a**	**b**	**c**	**a/c**	**b/c**	**F tab**
IR Central	3	1	+	1.9	4	1.3	1.46	3.08	0.07
		2	-	1.3	4	1.3	1.00	3.08	0.057
		3	-	1.9	3.4	1.3	1.46	2.62	0.065
		4	+	1.3	3.4	1.3	1.00	2.62	0.053
								TOT	0.001

Floor

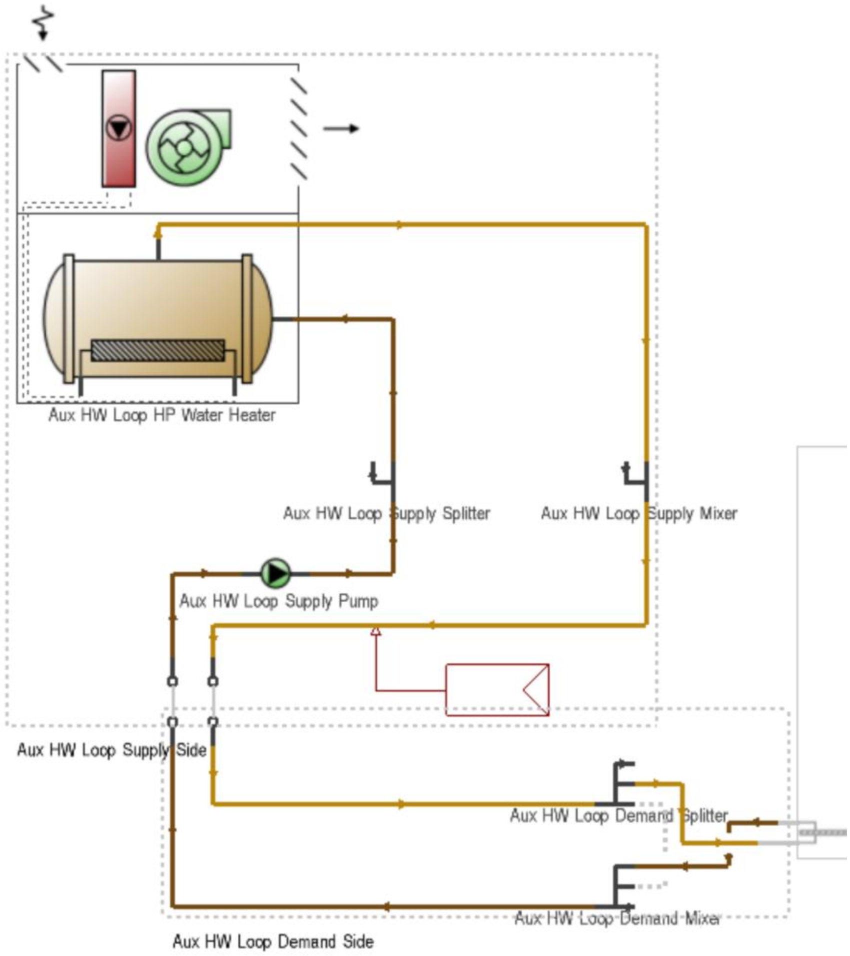
Element	**Quadrant**	**Portion**	**Contribute**	**a**	**b**	**c**	**a/c**	**b/c**	**F tab**
Floor	1	1	+	0.3	0.3	1.1	0.27	0.27	0.012
	2	2	+	0.3	7.7	1.1	0.27	7.00	0.018
	3	2	+	3.5	7.7	1.1	3.18	7.00	0.1
	4	4	+	3.5	0.3	1.1	3.18	0.27	0.02
								TOT	0.15

Ceiling

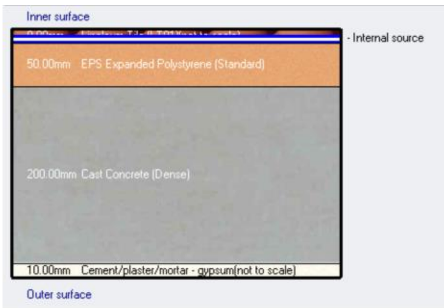
F ceiling = 1 - Fi

	F tab
Ceiling	0.31358564

Annex E: Heat Pump Model – Heating System Scheme



- Heat Pump COP = 3,2
- Radiant floor cross section:



U = 0,584 W/m^{2}K

Composition from the innermost layer:

- Linoleum: (0,8 cm; λ = 0,3 W/mK)
- Internal source = radiant coil
- EPS: (5 cm; λ = 0,04 W/mK)
- Case concrete: (20 cm; λ = 1,13 W/mK)
- Plaster: (1 cm; λ = 0,42 W/mK)

Annex F: Detailed Comfort Results – Tables

IR_C1: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	1.57%	0.00%	0.11%	0.53%	0.31%	0.00%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	0%	100%	100%	100%	0%

Living room - IR_C1: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1%	32%	1%	1%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

Vertical Radiant Asymmetry ΔTpr - Warm Ceiling: IR_C1 - (1 Oct. - 1 Apr.)

Limit PPD 10% = 7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	23.92	28.59	18.00	14.38
Tot Unplesant time [%]	58%	64%	54%	51%
PPD Max [%]	73%	84%	52%	36%
PPD Average [%]	31%	40%	21%	16%
ΔT_{pr} > 10 °C	52%	59%	46%	7%
ΔT_{pr} > 15 °C	42%	49%	30%	0%
ΔT_{pr} > 20 °C	30%	39%	0%	0%
Horizontal Radiant Asymmetry - ΔTpr Max: IR_C1 - (1 Oct. - 1 Apr.)				
Horizontal N-S [°C]	0.31	0.28	0.27	0.27
Horizontal S-N [°C]	1.05	1.00	1.47	1.47
Horizontal E-W [°C]	1.91	1.28	7.98	8.58
Horizontal W-E [°C]	2.80	2.26	19.61	16.63

IR_C2_1: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	1.56%	0.00%	0.08%	0.41%	0.30%	0.00%
Trmot < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	0%	100%	100%	100%	0%

Living room - IR_C2_1: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1%	33%	1%	1%
Trmot < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

Vertical Radiant Asymmetry ΔTpr - Warm Ceiling: IR_C2_1 - (1 Oct. - 1 Apr.)

Limit PPD 10% = 7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	23.85	28.53	17.94	14.33
Tot Unplesant time [%]	54%	58%	50%	47%
PPD Max [%]	73%	84%	51%	36%
PPD Average [%]	30%	38%	20%	16%
ΔT_{pr} > 10 °C	49%	54%	44%	7%
ΔT_{pr} > 15 °C	41%	47%	31%	0%
ΔT_{pr} > 20 °C	31%	39%	0%	0%

Horizontal Radiant Asymmetry - ΔTpr Max: IR_C2_1 - (1 Oct. - 1 Apr.)

Horizontal N-S [°C]	0.35	0.32	0.31	0.31
Horizontal S-N [°C]	1.07	1.01	1.49	1.49
Horizontal E-W [°C]	1.92	1.28	7.89	8.62
Horizontal W-E [°C]	2.82	2.27	19.54	16.56

IR_C2_2: Comfort Evaluation

UNMET TIME [%]	**Kitchen**	**Bed Small**	**Bed Back**	**Living**	**Bath**	**Bed Front**
TOTAL	1.64%	0.00%	0.17%	0.51%	0.36%	0.00%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	0%	100%	100%	100%	0%

Living room - IR_C2_2: Comfort evaluation for different position

UNMET TIME [%]	**Position 1**	**Position 2**	**Position 3**	**Position 4**
TOTAL	1%	17%	1%	1%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

Vertical Radiant Asymmetry ΔTpr - Warm Ceiling: IR_C2_2 - (1 Oct. - 1 Apr.)

Limit PPD 10% =7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	23.94	28.61	18.01	14.39
Tot Unplesant time [%]	66%	75%	57%	50%
PPD Max [%]	74%	84%	52%	36%
PPD Average [%]	27%	38%	17%	13%
ΔT_{pr} > 10 °C	55%	66%	40%	7%
ΔT_{pr} > 15 °C	33%	49%	11%	0%
ΔT_{pr} > 20 °C	12%	28%	0%	0%

Horizontal Radiant Asymmetry - ΔTpr Max: IR_C2_2 - (1 Oct. - 1 Apr.)

Horizontal N-S [°C]	0.36	0.32	0.32	0.32
Horizontal S-N [°C]	1.07	1.02	1.49	1.49
Horizontal E-W [°C]	1.92	1.28	7.89	8.55
Horizontal W-E [°C]	2.81	2.27	19.57	16.59

IR_C3_1: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	1.28%	0.00%	0.00%	0.22%	0.18%	0.00%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	0%	0%	100%	100%	0%

Living room - IR_C3_1: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	0.24%	0.33%	0.63%	0.43%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	99%	100%	100%
9 <= Trmo < 16	0%	1%	0%	0%

Vertical Radiant Asymmetry ΔTpr - Warm Ceiling: IR_C3_1 - (1 Oct. - 1 Apr.)

Limit PPD 10% =7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	24.39	28.98	18.40	14.70
Tot Unplesant time [%]	48%	54%	45%	41%
PPD Max [%]	75%	85%	53%	38%
PPD Average [%]	26%	33%	17%	14%
ΔT_{pr} > 10 °C	43%	48%	38%	7%
ΔT_{pr} > 15 °C	34%	41%	24%	0%
ΔT_{pr} > 20 °C	24%	32%	0%	0%

Horizontal Radiant Asymmetry - ΔTpr Max: IR_C3_1 - (1 Oct. - 1 Apr.)

Horizontal N-S [°C]	0.18	0.16	0.16	0.16
Horizontal S-N [°C]	0.96	0.91	1.26	1.26
Horizontal E-W [°C]	1.90	1.28	7.29	7.98
Horizontal W-E [°C]	2.84	2.30	19.48	16.50

IR_C3_2: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	1.35%	0%	0.02%	0%	0.25%	0%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	0%	100%	100%	100%	0%

Living room - IR_C3_2: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	0.32%	0.31%	0.65%	0.46%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

IR_C3_2: Vertical Rad. Asymmetry ΔTpr (Warm Ceiling)

Limit PPD 10% = 7°C	**Position 1**	**Position 2**	**Position 3**	**Position 4**
ΔT_{pr} Max [°C]	24.36	29.04	18.37	14.71
Tot Unplesant time [%]	63%	74%	52%	45%
PPD Max [%]	75%	85%	53%	38%
PPD Average [%]	23%	34%	15%	12%
ΔT_{pr} > 10 °C	50%	63%	32%	7%
ΔT_{pr} > 15 °C	23%	43%	7%	0%
ΔT_{pr} > 20 °C	7%	18%	0%	0%

Horizontal Radiant Asymmetry - ΔTpr Max: IR_C3_2 - (1 Oct. - 1 Apr.)

Horizontal N-S [°C]	0.22	0.19	0.20	0.20
Horizontal S-N [°C]	1.04	0.98	1.47	1.47
Horizontal E-W [°C]	1.92	1.29	7.45	8.05
Horizontal W-E [°C]	2.83	2.29	19.48	16.50

IR_C4_1: Overall Comfort Evaluation

UNMET TIME [%]	**Kitchen**	**Bed Small**	**Bed Back**	**Living**	**Bath**	**Bed Front**
TOTAL	2.7%	2.9%	5.4%	0.5%	9.3%	6.1%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	0%	68%	100%	97%	52%
9 <= Trmo < 16	0%	46%	32%	0%	3%	48%

Living room - IR_C4_1: Comfort evaluation for different position

UNMET TIME [%]	**Position 1**	**Position 2**	**Position 3**	**Position 4**
TOTAL	1%	46%	1%	1%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

Vertical Radiant Asymmetry ΔTpr - Warm Ceiling: IR_C4_1 - (1 Oct. - 1 Apr.)

Limit PPD 10% =7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	24.32	28.90	18.32	14.54
Tot Unplesant time [%]	71%	74%	68%	66%
PPD Max [%]	75%	84%	53%	37%
PPD Average [%]	44%	54%	30%	21%
ΔT_{pr} > 10 °C	67%	71%	64%	7%
ΔT_{pr} > 15 °C	61%	66%	53%	0%
ΔT_{pr} > 20 °C	53%	60%	0%	0%

Horizontal Radiant Asymmetry - ΔTpr Max: IR_C4_1 - (1 Oct. - 1 Apr.)

Horizontal N-S [°C]	0.34	0.31	0.30	0.30
Horizontal S-N [°C]	1.14	1.08	1.55	1.55
Horizontal E-W [°C]	1.91	1.28	7.55	8.15
Horizontal W-E [°C]	2.81	2.26	19.55	16.57

Living room - IR_C4_2: Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	2.70%	2.50%	3.06%	0.56%	7.71%	4.18%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	0%	45%	100%	100%	0%
9 <= Trmo < 16	0%	1%	55%	0%	0%	1%

Living room - IR_C4_2: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1%	36%	1%	1%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

Vertical Radiant Asymmetry ΔTpr- Warm Ceiling: IR_C4_2 - (1 Oct. - 1 Apr.)

Limit PPD 10% = 7°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	24.18	28.79	18.21	14.49
Tot Unplesant time [%]	80%	86%	73%	67%
PPD Max [%]	74%	84%	53%	37%
PPD Average [%]	40%	52%	26%	18%
ΔT_{pr} > 10 °C	72%	80%	60%	7%
ΔT_{pr} > 15 °C	55%	67%	31%	0%
ΔT_{pr} > 20 °C	31%	51%	0%	0%

Horizontal Radiant Asymmetry - ΔTpr Max: IR_C4_2 - (1 Oct. - 1 Apr.)

Horizontal N-S [°C]	0.33	0.30	0.30	0.30
Horizontal S-N [°C]	1.13	1.07	1.55	1.55
Horizontal E-W [°C]	1.91	1.28	7.56	8.23
Horizontal W-E [°C]	2.80	2.25	19.58	16.60

HP_C1: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	3.26%	0.08%	0.83%	1.41%	0.72%	0.00%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%	100%	0%

Living room - HP_C1: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1.46%	1.36%	1.44%	1.32%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

HP_C1: Vertical Rad Asymmetry ΔTpr (Cool Ceiling)

Limit C = PPD 10% = 18°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	7.81	5.26	5.07	4.01
ΔT_{pr} Av.[°C]	3.21	0.95	1.24	2.12
Tot Unplesant time [%]	0%	0%	0%	0%
Limit A = PPD 5% = 14°C				
Tot Unplesant time [%]	0%	0%	0%	0%

HP_C1: Horizontal Radiant Asymmetry - ΔTpr Max

Horizontal N-S [°C]	0.40	0.37	/	/
Horizontal S-N [°C]	1.18	0.37	1.63	1.63
Horizontal E-W [°C]	1.92	1.29	/	/
Horizontal W-E [°C]	2.81	2.27	20.66	17.53

HP_C2: Overall Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	2.34%	0.01%	0.66%	1.16%	0.62%	0.00%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%	100%	0%

HP_C2: Comfort in Living Room's Position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1.20%	1.12%	1.21%	1.13%
Trmo< 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

HP_C2: Vertical Rad Asymmetry ΔTpr (Cool Ceiling)

Limit C = PPD 10% = 18°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	13.25	10.64	9.82	3.95
ΔT_{pr} Av.[°C]	3.07	0.88	1.17	2.10
Tot Unplesant time [%]	0%	0%	0%	0%
Limit A = PPD 5% = 14°C				
Tot Unplesant time [%]	0%	0%	0%	0%

HP_C2: Horizontal Radiant Asymmetry - ΔTpr Max

Horizontal N-S [°C]	0.23	0.20	/	/
Horizontal S-N [°C]	1.15	0.20	1.59	1.59
Horizontal E-W [°C]	1.93	1.29	/	/
Horizontal W-E [°C]	2.82	2.29	20.56	17.44

Living room - HP_C3: Comfort Evaluation

UNMET TIME [%]	Kitchen	Bed Small	Bed Back	Living	Bath	Bed Front
TOTAL	5.9%	4.4%	4.6%	1.5%	78.9%	4.4%
Trmo < 3	0%	0%	0%	0%	0%	0%
3 <= Trmo < 9	100%	36%	41%	100%	93%	31%
9 <= Trmo < 16	0%	64%	59%	0%	7%	69%

Living room - HP_C3: Comfort evaluation for different position

UNMET TIME [%]	Position 1	Position 2	Position 3	Position 4
TOTAL	1.55%	1.43%	1.52%	1.39%
Trmo < 3	0%	0%	0%	0%
3 <= Trmo < 9	100%	100%	100%	100%

HP_C2: Vertical Rad Asymmetry ΔTpr (Cool Ceiling)

Limit C = PPD 10% = 18°C	Position 1	Position 2	Position 3	Position 4
ΔT_{pr} Max [°C]	9.84	7.15	6.79	3.91
ΔT_{pr} Av.[°C]	3.81	1.52	1.75	1.63
Tot Unplesant time [%]	0%	0%	0%	0%
Limit A = PPD 5% = 14°C				
Tot Unplesant time [%]	0%	0%	0%	0%

HP_C2: Horizontal Rad Asymmetry - ΔTpr Max

Horizontal N-S [°C]	0.39	0.36	/	/
Horizontal S-N [°C]	1.22	0.36	1.64	1.64
Horizontal E-W [°C]	1.91	1.28	/	/
Horizontal W-E [°C]	2.80	2.26	20.65	17.54