Towards performance evaluation of energy efficient buildings

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SUMMARY

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ABSTRACT

En France, le secteur du bâtiment est le principal consommateur d'énergie. En outre, le secteur de la maison individuelle représente environ 60% des constructions annuelles de logements. La construction des bâtiments à haute efficacité énergétique représente un grand pas vers l'économie d'énergie. Cependant, même si divers efforts sont déployés dans ce domaine, des outils et des méthodes manquent pour évaluer la performance énergétique de ces bâtiments. Cette évaluation doit permettre non seulement de comprendre les facteurs qui contribuent à cette performance mais également d'identifier les causes de la surconsommation, d’inconfort pour les occupants.

Cette thèse vise à contribuer à cet objectif en proposant une approche d'évaluation de la performance énergétique d'un bâtiment. Pour cela on compare la performance réelle et la performance attendue en utilisant le monitoring et la simulation thermique dynamique. Cette approche s’appuie sur différents cas d’études dont principalement une maison individuelle, situé en un climat méditerranéen.

Dans un premier temps, en phase de conception, nous utilisons des simulations thermiques dynamiques pour étudier l’impact du comportement sur les besoins énergétiques. L'objectif est d'analyser l'influence du scénario d'occupation sur le comportement du bâtiment et d'établir une plage de valeurs pour les besoins en énergie, basée sur des statistiques nationales. Le comportement du bâtiment est étudié en fonction de différents types de scénarii d'occupation, de consignes de température, de l'utilisation d’appareils domestiques et d'éclairage.

Dans un second temps, l'accent est mis sur l'évaluation globale de la performance de l'enveloppe. Un test dynamique in situ innovant a été développé pour en évaluer la performance réelle. Ce test est applicable sur une période courte (de l’ordre de la journée) tout en maitrisant les débits d’infiltrations. La comparaison des résultats théoriques en régime stationnaire avec les résultats expérimentaux montre une bonne précision inférieure à 10%.

Enfin, le suivi énergétique en continu des maisons performantes est étudié. Tout d’abord, des travaux sont réalisés dans l’optique de réduire le nombre de capteurs nécessaires au suivi, tout en minimisant la perte d’informations. Ensuite, une méthodologie d’instrumentation est développée et appliquée à une maison individuelle. Le suivi de cette maison a pu être étudié sur les six premiers mois de monitoring et a permis d’expliquer le comportement du bâtiment et ses consommations au regard de son usage et de faire le lien avec les prévisions faites en phase de conception.

MOTS CLES
Evaluation de la performance énergétique, bâtiment à énergie positive, simulation thermique dynamique, test in-situ, monitoring, phase de conception, phase opérationnelle, conditions intérieures, efficacité énergétique.

In France, the building sector is the main energy consumer. Moreover single-family houses represent about 60% of annual dwelling construction. The construction of energy efficient buildings represents a big step into energy saving. However, even though various efforts are made within this field, there is still a lack of methodologies about how to evaluate the energy performance of these buildings. The performance evaluation of an energy efficient building should allow understanding factors that contribute to its energy performance and as well as identifying the causes of overconsumption, poor indoor conditions.

This thesis seeks to contribute to this field, by proposing an approach towards evaluating the energy performance of a house. This is done by comparing the real performance and the expected performance, using monitoring and building performance simulation, from design to operational phases. The energy performance evaluation approach is carried out on different cases of studies, mainly on a single-family house, situated in a Mediterranean climate.

First, in the design phase, we use building performance simulation models to study the dispersions in energy use related to occupant's behavior. The goal is to analyze the influence of the occupancy scenario on the behavior of the building and to establish a range of values for energy demand, based on national statistics. This step studies the building's behavior based on different types of occupancy scenarios, appliances and lighting use and temperature set point.

Then, the focus is on the global evaluation of the envelope's performance. Within the present thesis an innovative in-situ dynamic test is developed to assess the real envelope's performance. This test is adapted to occupied houses (as it only takes 2 days) while controlling the infiltration air flow. The comparison between theoretical results of steady state calculation and experimental results show a good precision of less than 10%.

Finally, continuous monitoring of energy efficient houses is studied. First, a work is done to reduce the number of sensors required for monitoring, while minimizing the loss of information. Then, an instrumentation methodology is developed and applied to a single-family house. The follow-up of this house could be studied during the first six months of monitoring and allowed to explain the behavior of the building and its consumption with regard to its use and to make the link with the previsions made during the design phase.

KEYWORDS

Energy performance evaluation, energy efficient building, building performance simulation, in-situ dynamic test, monitoring, design phase, operational phase, indoor conditions, energy use.

NOMENCLATURE

General notation

Notation	Significance
DHW	Domestic Hot Water
HVAC	Heating, Ventilation and Air-Conditioning
$I-BB$	Experimental house (INCAS-Beton Banché)
R0	Ground floor
R+1	First floor
RT2012	French thermal regulation
$PosA$	Single-family detached home: case study
VOC	Volatile Organic Compounds

Physical notation

Notation	Significance	Unit
c_p	Specific heat capacity at constant pressure	[kJ/(kgK)]
c_L	Air leakage coefficient	[$m^3/(hPa^n)$]
C	Global thermal capacitance	[J/K]
C_{wall}	Walls thermal capacity	[J/K]
HT	Transmission Heat Loss Coefficient	[W/K]
HLC	Heat Loss Coefficient	[W/K]
BLC	Building Loss Coefficient	[W/K]
$Q4_{Pa-Surf}$	Ratio between the leakage flow required to maintain a differential pressure of 4 Pa and the total envelope's heat loss area (except lower floor)	[$m^3/(hm^2)$]
q_L	Volumetric leakage air-flow rate	[m^3/h]
Q_h	Total measured power input from space heating	[W]
Q_{LP}	Internal load power	[W]
ρ	Density	[kg/m^3]
ΔP	Pressure difference between the inside and the outside of the room or building	[Pa]
n	Air-flow exponent	[-]
ΔT	Air temperature difference between indoor and outdoor	[°C]
R	Global thermal resistance	[K/W]
R_{ext}	External thermal resistance	[m^2K/W]
R_{int}	Internal thermal resistance	[m^2K/W]

Notation	Significance	Unit
Q_h	Total heat gains (heater power)	[W]
S	Total envelope's heat loss area	[m^2]
T_{int}	Indoor air temperature	[°C]
T_{ext}	Outdoor air temperature	[°C]
T_{wall}	Mean walls temperature	[°C]
U_{ext}	External heat transfer coefficient($1/R_{ext}$)	[W/(m^{2}K)]
U_{int}	Internal heat transfer coefficient ($1/R_{int}$)	[W/(m^{2}K)]
K_{inf}	Infiltration enthalpy losses	[W/K]

Modeling notation

Notation	Significance
$CVRMSE$	Coefficient of variation of the RMSE
MCMC	Markov Chain Monte Carlo
$RMSE$	Root-mean-square error
$p(\theta)$	Prior distribution
$p(y, \theta)$	Posterior distribution
$p(\theta, y)$	Likelihood function
$y(x)$	Observations
$\eta(x, \theta)$	Model outputs
$\delta(x)$	Model discrepancy
x	Inputs
θ	Identification parameters

INTRODUCTION

Today, the building sector is the largest emitter of CO_2 in the European Union (EU) and therefore most developed countries and many developing countries have already taken steps toward prioritizing the building sector in their national climate change strategies. In this context, one of the most important goals in many environmental programs worldwide is to increase the energy efficiency of new and existing buildings (AlAjmi et al., 2016). This can be done by lowering the energy demand, improving the energy efficiency of systems and appliances, and substituting fossil fuels with renewable energies (Day et al. 2009). In Europe, the Energy Performance of Buildings Directive (EPBD) requires that by the end of 2020 all new buildings have a very high performance, demanding only a low amount of energy supplied mostly from renewable sources (DIRECTIVE 2010/31/EU, 2010).

Energy-efficient building design is an important step because it is not simply the addition of technologies of passive envelope, energy-efficient systems, etc. Instead, it can be viewed as an entire process, where the goal is to reduce the heating, cooling and lighting loads by investing in the building's form and enclosure (e.g., windows, walls) (Rossow 2001). An understanding of building occupancy and activities can lead to building designs that not only save energy and reduce costs, but also improve occupant's comfort and workplace performance (Rossow 2001). The technique for an energy-efficient building consists of energy saving measures together with the use of renewable energy sources. Various current demonstration projects are focused on providing realistic experiences about the design, construction and operation of energy-efficient buildings (Parker, 2009) (Guerra-Santin et al., 2013a) (Spitz et al., 2012). There is also the concept of so-called "zero-energy building"(called also "positive-energy buildings") which can roughly be defined as a building that produces as much renewable energy (using wind or solar energy for example) as it uses, while having low or zero carbon emissions. Its definition and energy calculation methodology vary greatly depending on the metric and period used for the calculation of the energy balance (primary versus delivered energy, annual versus monthly), the type of energy considered for the balance, etc. (Marszal et al., 2011) (Sartori et al., 2012) (Berry et al., 2014) (Deng et al., 2014).

In the context of reducing energy consumption by constructing only positive-energy buildings, the research program "COMEPOS" was established in 2013 in France. This project aims at designing, constructing, evaluating and optimizing the energy performance of occupied positive-energy individual houses. COMEPOS (Optimized Design and Construction of Near-Zero-Energy Buildings) brings together 22 partners (research centers, developers, manufacturers) with the goal of developing and implementing in practice the concept of positive-energy houses. The main result of the project will be the validation in real conditions of the feasibility of this concept by the construction of 20 real houses, located throughout France. The project includes optimization of the design process, as well as monitoring and in situ validation of houses performance in different climate conditions.

While optimizing building's design is one of the important issues, evaluation of the performance of the occupied houses is another challenge for research. The latter is the main objective of the present thesis and an important aim of the COMEPOS project used as an experimental case study in this work.

"Building performance" represents a complex term and several definitions can be encountered. Often, to evaluate the building performance (Deng et al., 2014) is to quantify its impact on the energy consumption, using data from experiments and simulation as well as its impact on the environment using lifecycle assessment with a quantification of the materials used and their environmental impact (Thiers and Peuportier, 2012). But, it's also mandatory to monitor the satisfaction of the building occupants, in order to make sure that the house provides a comfortable indoor environment. The evaluation process also includes verifying whether the energy performance predicted during the design stage corresponds to the real energy performance of the building, by using measurement and a verification protocol like in IPMVP (International Performance Measurement and Verification Protocol) (Efficiency Valuation Organization, 2012). Different approaches ranging from simple to more complex can be used to evaluate the building performance.

The simplest and cheapest way is to evaluate the energy use over one year (annual energy performance). It can be done by examining the energy consumption retrospectively through energy bills. The goal is to establish the energy efficiency of the building by looking at the real energy balance between energy consumption and production. The evaluation time step in this case is usually 1 year.

However, in a global approach, evaluating the performance of a building should take into account not only the energy use, but also the occupant's feedback about the domestic conditions such as thermal comfort, indoor air quality, etc. It could be that a building achieves a positive annual energy balance but the occupants are not satisfied with their indoor conditions. Moreover, the time-scale of the evaluation is also important. A building can have satisfactory behavior on yearly average, while problems occur on monthly or daily basis. Therefore, a more complete and complex evaluation of the building's performance is needed to be able to understand at any moment the building's behavior, eventual causes of overconsumption, as well as indoor conditions. The time step can vary from seconds to hours, months, etc. The need to know more about the performance at each time step will require some performance data which can be acquired through continuous monitoring. First, for each case, performance indicators (for example energy use, thermal comfort, heat loss coefficient, COP, etc.) are defined. They are used to characterize the building's envelope, the system's performance, etc. The type, duration and frequency of the building monitoring depend on these performance indicators. For example, if the goal is to characterize the electric energy consumption, monthly electric bills will meet the requirements. But if the goal is to evaluate the indoor conditions, additional measurements are needed. This can include measurements of indoor temperature, relative humidity, etc. Measurements of the real heating set-point temperature can help explaining, for example, overconsumption on a large scale. It can be done by comparing the set-point temperature suggested by the regulation /design with the real (measured) one. If a large difference in the energy use is observed, it may be that the occupants prefer a higher (than legislated) set-point temperature and the regulation calculation represents an unrealistic estimation of the future energy consumption in this case. However, other factors are also involved. Overconsumption can derive from an inefficient envelope, system malfunctioning, or the impact of the weather.

Evaluating the building's performance involves therefore understanding the different **components** that drive it. In a collaborative project of International Energy Agency (IEA) in the Buildings and Communities Program (EBC), Annex 53: Total Energy Use in Buildings, experts identified that energy use in building is influenced by six factors. They are differentiated by being climate related, building related (building envelope, building equipment) and human behavior related (operation and maintenance, occupant behavior, indoor environmental conditions), as shown in Figure 0-1.

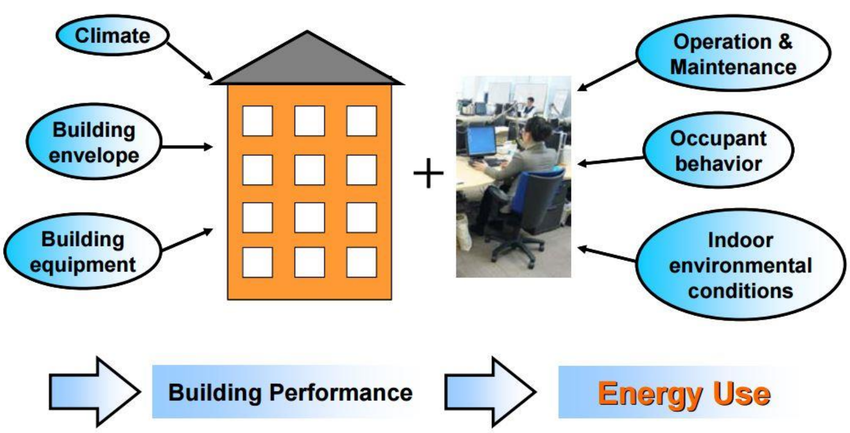


Figure 0-1: Six factors influencing total energy use in buildings, extract from Annex 53 Summary Report.

First, there are the components of the building that are optimized during the design process: the envelope and the equipment. The **envelope**, which is clearly an important part of the building, should be considered in the process of evaluating the building's performance. The envelope's components encompass various elements such as, among others: U value, building's orientation, interior/exterior wall structure, thermo-physical properties of the construction materials, the shape factor (ratio volume/surface) and thermal bridge effect. Efficient envelope attempts to reach an optimal combination of these components correctly implemented within the construction phase. Then, there is the performance of the building's **equipment**. Equipment are designed to ensure a good indoor air quality, to produce energy and to provide domestic hot water. Many innovative equipment and technologies are available for this purpose. However, in reality, the envelope and building's equipment may perform in an unexpected way (malfunctioning). Therefore, there is a need to evaluate their real performance.

Next, there are unpredictable loads that cannot be optimized during the design process. These dynamic loads refer to both outdoor conditions and the human factors. The **outdoor conditions** are the climate parameters (outdoor air temperature, wind, solar radiation etc.) and surrounding environment (nearby buildings, etc.). This impacts the building's performance in various ways. For example, weather conditions can lead to overconsumption or poor thermal comfort due to extreme temperatures in winter or summer. And last but not least, there is the **occupants' behavior,** which is a very important factor impacting the building's performance. Its dynamic aspect includes the opening and closing of windows, the occupants' presence and activity, thermostat settings etc.

Evaluating the contribution of each of these factors on the building's performance represents a major step toward improving the building's performance. Continuous monitoring (energy meters, etc.) or short tests and performance simulation are usually employed in this goal. For example, the contribution of outdoor conditions can be evaluated using a weather station. Short tests such as post-occupation survey, for instance, can also be used for a deeper understanding of the occupants' behavior. To complement monitoring, building performance simulation can be used to create various situations representing a year or an entire lifetime with different scenarios for occupancy, climate, etc. Simulation can be used before the building is constructed in the design phase to estimate the energy use, the temperature, etc., so as to optimize the design. It can also be used in the operational phase to evaluate and to better understand the building's behavior using different scenario.

This thesis will focus on two different types of evaluation. On one hand, the envelope's properties evaluation and on the other hand an evaluation approach of the whole building's performance. Within the present thesis the **"building performance"** refers to the following factors: first, a building is meant to be occupied, so it must provide a reasonable level of satisfaction for its occupants. But in order to do that, the house must be efficient regarding the energy use. Therefore, the term of "building performance" depends on one part on the envelope's properties (which exist as static attributes irrespective of how the building is used and are not affected by scenario such as exterior conditions, occupants etc.) and on the other part on the building's use (occupants, exterior conditions). Therefore, the building performance can only be measured in a given use scenario (such as energy use in a reference winter for a given occupation schedule).

The objective of the present thesis is to propose an evaluation approach to better understand the global performance of energy-efficient houses and contributing factors. Furthermore is to help to verify whether the performance predicted during the design stage corresponds to the real one. This will be done through monitoring and building performance simulation. Within the present thesis we will the focus on: energy use and indoor conditions, by looking at two aspects: building envelope and occupant's behavior.

The approach proposed here consist in:

- Firstly, we use building performance simulation to create different occupancy scenarios to better understand the factors related to occupancy that drive energy use and indoor conditions.
- Secondly, we will acquire performance data through continuous monitoring and in situ tests (to evaluate the envelope's properties for example). This will allow to get detailed information about the energy use, occupant's behavior etc.
- Finally, in order to better understand the real behavior of the building and of its occupants, the measurements will be compared with the results predicted in the design phase.

The thesis is organized in four chapters. Chapter 1 presents the state of the art of the methods used for the performance evaluation of an energy-efficient building: monitoring and simulation. Choosing the appropriate simulation tool or monitoring is a challenging task, considering the variety of available tools. This chapter gives an overview of both methods used worldwide. Once monitoring or simulation is chosen, the evaluation process provides information on the building's performance through data. The last part of this chapter presents some examples of this performance through several case studies.

Literature review confirms that in an occupied buildings an enormous impact on the building's performance comes from the stochastic nature of the occupants' behavior. In chapter 2, dispersions in energy use related to the occupants' behavior are identified by testing various scenarios of occupancy, appliances use and set-point temperature. The goal is to better understand the impact of occupants' behavior on energy use and to establish a range of values for energy demand, depending on the occupant.

However, when using simulation we assume that the building itself represented by the envelope is a perfect implementation of the "as designed" envelope's characteristics. In reality, differences can be encountered between the "as designed" and "as built" envelope. Therefore, in chapter 3 short-term tests are used to evaluate the constructed envelope. The test associate numerical simulation and experimental study. Some improvements of existing tests are proposed and tested on real houses.

Finally, chapter 4 presents the evaluation of the building's performance in the operational phase via continuous monitoring. First, the evaluation approach is described. Then a proposal of the monitoring methodology for a single family house is introduced. Furthermore, a practical application of the proposed evaluation approach on an occupied house is shown. For a better understanding of the building's performance, the performance data collected during the operational phase are compared with the performance estimated during the design phase. Energy efficiency and thermal comfort are analyzed through measurements and occupant surveys.

CHAPTER 1. A state of the art on methods used for the evaluation of the performance of an energy efficient building

1.1. Introduction

This chapter presents the state of the art in methods used for evaluating the performance of an energy-efficient building. As described earlier, these methods comprise monitoring and building performance simulation. Choosing the appropriate monitoring or simulation tool can be a challenging task, considering the wide variety available and the rapid developments in both fields. This chapter gives a background overview of the various monitoring and simulation methods used worldwide.

Before starting the monitoring, evaluation of the energy performance should start with a precise description of the physical parameters that need to be monitored, that is, energy use, thermal comfort, etc. Then, the monitoring activity can start. Differences in the type, the duration, the frequency as well as in sensor placement can be observed in monitoring. These differences are determined by the purpose of the study or the user’s experience. As with the simulations, various tools are increasingly used to estimate the energy use, indoor conditions, and system performance. Choosing the appropriate tool for each particular case depends on the purpose of the study, the user’s experience and the data available. As mentioned earlier, the present thesis uses both simulation and monitoring for a continuous evaluation of the global performance. Therefore, this chapter seeks to review the current background information on both methods.

After the monitoring or simulation methods are chosen, the evaluation process reveals the building’s performance through real performance data. Some examples have shown that buildings perform as expected. In some cases, however, the real energy performance does not match the one expected, a term so called ‘performance gap’. The last part of this chapter presents examples of the real performance for both cases.

1.2. Monitoring

Continuous global performance can be evaluated via monitoring. This section presents an analysis of the current background in the framework of monitoring and evaluation of the energy performance of efficient buildings. An attempt is made to identify typical in situ sensors or technical information deriving from the design data.

Certain differences in the monitoring of buildings have been identified. On one hand, there are measurements performed in the residential sector (Dall'O' et al., 2012) (Gans et al., 2013) or in the service or retail sectors (Agha-Hossein et al., 2013) (Li et al., 2016a). Another difference is whether the measurements are performed in a facility/research laboratory conditions (Saelens et al., 2004) (Loutzenhiser et al., 2009) (Mateus et al., 2014) or in real-life conditions (single house family, office buildings, for example) (Andersen et al., 2013a) (Rohdin et al., 2014). On the other hand, monitoring depends greatly on the purpose of the study and the performance indicators that are being assessed. These performance indicators are usually established before the monitoring process. There are quantitative performance indicators requiring objective data that can be measured: for example, energy use, indoor temperature, etc. There are also qualitative performance indicators requiring subjective data: for example, evaluating the thermal comfort (Guerra-Santin and Tweed, 2015) (Olivia and Christopher, 2015) or the environmental impact (Meggers et al., 2012). These performance indicators are defined by the purpose of the evaluation, whether is to understand and to improve the energy performance or to give feedback about the energy performance (checking whether the building complies with legislation requirements). Once the purpose is defined, these performance indicators are evaluated through measurements: whether it is the evaluation of energy consumption (Sree, Paul, and Aglan 2010), of the thermal comfort (Rohdin et al., 2014), of the indoor air quality (Wallace et al., 2002) (Gunschera et al., 2013), of the building's operation (Andersen et al., 2013b), or of the impact of the building on the occupants' health (Wolkoff 2013). Table 1-1 lists some examples of studies, describing the purpose of the study and the measurements that were performed. The table shows that, depending on the purpose of the study, some authors used short duration test (occupant survey, etc.), while others have used continuous monitoring over a period of months, years, etc. Short-term measurements are less expensive and allow for the rapid and more complex assessment of the performance indicators. Compared with short-term measurements, continuous measurements allow us to study the energy performance over a longer period, establishing patterns and providing a better understanding of the behavior of the occupants' and buildings alike. However, it is more expensive, complex, and it requires setting up sensors in the occupants' homes.

Another finding is that while some authors focused only on one building, others used measurements from dozens or even hundreds of buildings in their study. The goal when using several case studies is to benchmark the energy performance of several buildings, to make comparisons and to extract occupancy habits. When focusing on only one building, the goal is to extract detailed information on the energy performance of one specific case study. Therefore, with more complex monitoring, deeper analysis is possible.

Reference	Purpose of the study	Measurements
(Eskin and Türkmen, 2008)	The effect of climatic conditions and envelope on annual building energy requirements	Electric power; flow device; temperature; relative humidity; solar radiation
(Ke et al., 2013)	Analysis of the impact of energy consumption parameter changes on the overall energy consumption in a building	Electricity billing
(Katunsky et al., 2013)	A practical method for analysis and calculation of thermal energy consumptions and saving in buildings	Energy consumption for heating, heat flow, relative humidity, air and surfaces temperatures; infrared camera
(Jiménez and Madsen, 2008)	Overview of the models that can be applied for modelling the thermal characteristics of building components using data from outdoor testing	Global vertical solar radiation, heating and ventilation power, indoor and outdoor temperatures
(Mahdavi and Doppelbauer, 2010)	A performance comparison of passive and low-energy buildings	Indoor air temperature, relative humidity, and CO_2 concentration, metered energy use, construction costs, embodied energy assumptions, and CO_2 emission, occupant's survey
(Tronchin and Fabbri, 2008)	Energy performance building evaluation	Energy bills
(Hesaraki and Holmberg, 2013)	Energy performance of low-temperature heating systems	Heat pump electricity consumption
(Vadodaria et al., 2014)	Winter and spring-time indoor temperatures in UK homes over the period 1969–2010	Indoor and outdoor temperatures, occupant survey
(Johansson et al., 2011)	Occupancy levels in multi-family dwellings	CO_2 concentration

(Summerfield et al., 2007)	Changes in internal temperatures and energy usage for 15 "low-energy" dwellings	Gas and electricity meter, surveys, internal temperature and relative humidity, occupant survey
(Filippín and Beascochea, 2007)	Performance assessment of low-energy buildings	Energy consumption, occupant survey, solar irradiance on horizontal surface, outdoor temperature, wind velocity
(Persson and Westermark, 2012)	Evaluate the effect the phase change material night cool storage has on the climate in a passive house	Outdoor and exhaust air temperature
(Okuyama and Onishi, 2012)	Reconsideration of parameter estimation and reliability evaluation methods for building airtightness measurement using fan pressurization	Indoor and outdoor temperatures, wind velocity, airflow rate, pressure difference
(Ridley et al., 2013)	Monitored performance of the first new London dwelling certified to the passive house standard	Dry bulb temperature, relative humidity, wind speed and direction, global solar radiation, atmospheric pressure, precipitation, room temperature relative humidity, concentrations of CO_2, utilities metering, duct temperatures, heat meters
(Huebner et al., 2013a)	The reality of English living rooms – A comparison of internal temperatures against common model assumptions	Survey and internal temperature
(Karjalainen, 2009)	Thermal comfort and use of thermostats in Finnish homes and offices	Survey
(Newsham et al., 2013)	Reduce the peak electrical demand for houses	Individual appliance energy use, interior temperature and humidity, exterior climate
(Pfafferott et al., 2007)	Thermal comfort comparison	Weather at the building site, room temperatures

Table 1-1: Short background on monitoring

Another finding that can be observed in Table 1-1 is that in the context of evaluating the energy performance, the general focus of the monitoring is on energy consumption and indoor conditions. However, when dealing with occupied buildings, a trade-off between low energy consumption and thermal comfort is usually encountered. A global evaluation of these two parameter indicators should include the necessary monitoring.

When energy use is of interest, some studies focused only on total energy use (Hiller, 2012). Other authors have taken into account each end use item separately (heating, household electricity, etc.) (Lopes et al., 2005). Some authors used a simple measure for energy use, using only utility bills (Fumo et al., 2010). Other authors (Sree et al., 2010) however, also considered different factors that influence energy use, and therefore they used more complex monitoring such as: relative humidity and temperature inside, electric power consumption (kWh), outdoor temperature and relative humidity, air temperature and humidity, wind speed and direction, wind chill, solar radiation, barometric pressure, and rainfall data. Whereas only the delivered energy use is metered, evaluation of the primary energy use becomes necessary when the various technologies are compared (for example, electric heating or wood), etc.

Regarding indoor conditions, a wide variety of studies focused on the thermal comfort of occupants. Some authors analyze the thermal comfort based on Fanger's model (global PMV and PPD index), which is usually recommended for buildings equipped with air conditioning systems and various information is available. The thermal comfort is assigned using a complex measurement that depends on many aspects such as temperature, humidity, air velocity, occupants' clothing and activity (Pfafferott et al., 2007). More recently, other authors studied the adaptive comfort concept (Albatayneh et al., 2016) (Desogus et al., 2015) (Mahdavi and Doppelbauer 2010), which is recommended for buildings that use natural ventilation. This takes into account the fact that occupants have a natural tendency to adapt in their environment and once they are not satisfied with their thermal comfort they dynamically interact to restore it (Brager and de Dear, 2001) (RP, 1997). Thermal comfort is assessed as a function of indoor and outdoor temperature, and therefore associated measurements are performed. In (Dili, Naseer, and Zacharia Varghese 2011), the authors devised an instrument set-up with electronic sensors to record air temperature, mean radiant temperature, relative humidity, and air movement, with a data logger, memory module (to record data from all sensors), and a computer interface (to view and download data to the computer) to continuously record the comfort parameters over a period of time. Each of these two methods have their advantages and advantages. For example, the adaptive comfort method requires less information, but it cannot be used during winter because of the low temperatures. A combination of these two methods can also be used. There are also some short-term tests for indoor climate measurements using the thermal comfort data logger. Occupant surveys are also often used as a method for evaluating the occupants' perception of thermal comfort (Knight et al., 2007). Occupant surveys can be used separately or combined with one of the two methods to better understand the results, the occupants' perception of their thermal comfort, etc.

Occupants' health and indoor air quality are also a subject of great interest in the evaluation of indoor conditions (Wolkoff, 2013) (Krupińska et al., 2012). This is mainly because the wrong indoor temperature and humidity as well as poor indoor air quality can cause a number of health problems, affecting the skin, the respiratory system, and the immune system against various pathogens causing irritation of the eyes and having chronic and carcinogenic effects. It has been demonstrated in studies that there is a relationship between moisture problems, mold growth, and respiratory health effects (Hargreaves et al. 2003) (Liao et al. 2004). It is recommended that the internal temperature be kept between 20°C and 26°C and the indoor relative humidity between 30% and 60% (Nicol and Wilson 2010). The increase in temperature and humidity also affects the release of volatile organic compounds (VOCs) (Reijula 2004). The outdoor air that enters a building can be a source of indoor air pollution and there is also the problem of fungi that are able to grow on almost all natural and synthetic materials, especially if they are hygroscopic or wet (Haleem Khan and Mohan Karuppayil 2012). One of the most important and therefore frequently investigated substances that can influence indoor air quality is formaldehyde. In (Gunschera et al. 2013), the authors reported that the formaldehyde concentration in real indoor air is influenced by multiple parameters and does not simply result from additive emissions from the materials involved. Thus, monitoring usually includes measurements of CO_2 concentration levels, concentrations of VOCs, temperature, humidity, etc.

Other authors studied both energy consumption and indoor conditions (Mahdavi and Doppelbauer 2010). Monitoring included data on indoor environmental conditions (indoor air temperature, relative humidity, CO_2 concentration levels, indoor air relative humidity), user evaluation, metered energy use, calculated embodied energy and CO_2 emissions, as well as construction costs.

Weather conditions are also often monitored. In (Bhandari, Shrestha, and New 2012), the authors specify that the minimum weather data parameters necessary for accurate whole-building simulations are: dry bulb temperature; wet bulb temperature and/or relative humidity; global, direct normal, and diffuse solar radiation and wind speed and wind direction (for natural ventilation and infiltration); moreover, the authors also measured the barometric pressure and the liquid precipitation depth. When measurements of the outdoor conditions are not available, the nearest weather station is often used for the calculations.

Following these observations, it can be seen that the type, duration, and frequency of the monitoring depends significantly on the purpose of the study (energy consumption, thermal comfort, etc.), the building type (residential or tertiary, occupied or laboratory facility), the performance indicators and the users' experience. However, an overestimation/underestimation of the monitoring can be easily encountered. This is mainly because even if the purpose of the study is clearly defined in the design phase, it can be hard to predict which measurements are required for each case. Another problem is that in occupied buildings, the number of sensors must be limited, while maintaining sufficient robustness and precision of the data. Some studies have focused on this aspect. For example, in (Naveros, Jiménez, and Heras 2012) the focus was on determining the minimum integration period and the minimum set of variables necessary to carry out the analysis of full-size building components. The parameters that were measured comprised: air temperature; surface temperature; heat flux density; vertical global solar irradiance; vertical long-wave radiation on the surface of the test component; wind speed; and outdoor relative humidity.

To sum up, the building's metering can be classified into several categories, depending on the purpose of the monitoring. Within the present thesis, the monitoring is approached from two aspects: energy efficiency and indoor conditions. These aspects will be more detailed in chapter 4, where it's presented the practical application of monitoring implemented on a single-family detached home.

One more important aspect concerns the intrusive installation and duration of metering devices. Indeed, in real dwellings, the measuring system must be accepted by the occupants. It is therefore proposed that technical measures consist of two complementary sets:

- Continuous measurements (air temperature sensors, energy meters, etc.)
- Punctual measures (e.g. blower door test)

1.3. Building performance simulation

Using only measurements is not always enough when one wants to better understand overconsumption or to improve energy saving. Building performance simulation models can help overcome this limitation and are often used as a complement in the process of evaluating the energy performance of energy-efficient buildings. Models are assumed to be able to simulate the actual thermal behavior of the building and to predict its energy consumption. They are increasingly used in the design phase or for retrofit existing buildings, to verify the adequacy of the project regarding the energy performance standards. Building performance simulation can also be used to study and understand the modeled system use and properties and to predict its evolution. However, estimating a building's energy demand is a big challenge knowing that it is almost impossible to model a true level of occupancy, lighting, and systems heat gains or natural air flow.

The simulation process can be performed by examining three aspects: the building itself, with its actual geometry and envelope; the behavior of its occupants; and of course the systems used. Weather conditions are also taken into account in the simulation process. A wide variety of simulation models have been developed worldwide. The main distinction between them is that:

- Some are meant to represent and understand the entire physics process – the so-called white box model (TrnSys, EnergyPlus, Comfie+Pleiade, Fluent, Dymola, etc.).
- Others use statistical methods (linear or nonlinear mathematical function) and actual data to estimate the building's behavior – the so-called black box model
- Yet others use a combination of white and black box models – the gray box models.

The advantages and drawbacks of these models have already been discussed elsewhere (Foucquier et al., 2013). The choice of using each method depends on the user (modeler) preference, experience, and, of course, the purpose of the study. As explained, the aim of this thesis is to better comprehend the actual thermal behavior of the building, and therefore white and gray box models are chosen. Moreover, as we are interested in the global performance of a building, the nodal approach (which considers the building as a simple zone approximated to nodes) is used. Because of various reasons, which will be described here, the EnergyPlus software (Crawley et al., 2001) is chosen for this work. This is a verified whole-building energy simulation program widespread in the building simulation community around the world. It calculates the heating and cooling loads necessary to maintain optimal thermal conditions and the energy consumption for ventilation, lighting, water use, etc. Among its significant capabilities, the following list summarizes the reasons it is considered here:

- It has thermal zone modeling including air movement between zones
- It allows for system modeling: HVAC, photovoltaic, DHW, etc.
- The software is free and open source
- Use of this software is widespread in the community, allowing for stimulating exchanges
- Functional linking with other engines (e.g., Matlab).

Numerous studies have shown the widespread utility of this software (Zhang et al., 2013) (Mateus et al., 2014) (Anđelković et al., 2016) (Zhao et al., 2016) which are examples of the utility of this software in studying the energy performance of a building. Some authors used EnergyPlus Benchmark models to estimate the hourly and fuel energy consumption of a building (Fumo, Mago, and Luck 2010). Others used EnergyPlus to benchmark the energy performance of 400 residential buildings and to study future energy saving (Shabunko et al., 2016). In the present thesis, EnergyPlus is mainly used to study and understand the impact of occupants' behavior on energy use and thermal comfort.

In the process of estimating the energy performance of a building through energy models, three steps can be identified. The first is the modeling of a building's parameters (envelope, HVAC system, etc.). The next step is the search for the weather file corresponding to the closest location. The third step is to include the occupants' behavior into the modeling (occupancy schedule, thermostat settings, etc.). However, studies have revealed that occupants' behavior represents a major source of uncertainty in predicting the energy performance of a building (Yan et al., 2015). In current building energy modeling there are several examples of modelers that do not consider occupancy. The tendency here is to simplify and to focus on the first step by considering an idealized condition of the building's operation (Spitz et al., 2012) (Loutzenhiser et al., 2009) (Mateus et al., 2014). These models are useful when one wants to isolate and then observe only the building's envelope and systems. The drawback is that these models do not take into account real-life conditions and consequently it can lead to over- or underestimation of the building energy performance (Ryan and Sanquist, 2012).

Consideration of the building's occupants should reduce the gaps between the forecasts and the actual behavior, as the model gets more sophisticated, more complex, and more realistic. However, modeling occupant behavior is related to several uncertainties, ranging from the modeler's disregard of future occupancy in the design phase, the stochastic nature of user behavior, etc.

Most national regulations represent the user using a deterministic schedule, which is generalized and used for all buildings (Melo et al., 2014) (RT2012, 2010). To capture the occupants' influence on the building's performance in the design phase, modelers have to determine the "appropriate" schedule for occupancy and systems use (normative profile, estimated data from the future owner, etc.). Moreover, considering the diversity, complexity, and uncertainty associated with each occupant, this is not a straightforward task. To obtain realistic information on occupant behavior, observational data can be used. These are measurements performed on a real dwelling to detect adaptive behavior as well as survey or laboratory measurements (Yan et al., 2015). This can provide big data streams that can be used to test the robustness of the building design by using different schedules, creating some archetypal working profiles (D'Oca and Hong, 2015). The drawback is that implementing a schedule on the basis of data from national statistics can easily become a huge computational task in terms of time. Furthermore, the diversity in building design, climate, and culture prevent hinder a universal approach to modeling occupancy. Apart from modeling using standardized/normative profiles, there is a tendency in current modeling to take into account the stochastic nature of occupant behavior, as in (Vorger, 2014). This involves several approaches such as the Bernoulli process, Markov chains, or survival analysis. All these models use probability functions to predict an event. The differences are that Markov chains use a previous state to predict the probability of a future event, the Bernoulli process is memoryless, and the survival model determines the time until an event will happen (Yan et al., 2015).

There is also the calibration process which compares and tries to minimize the gap between actual data (e.g. utility bills) and design data estimated against an acceptance criterion (CVRMSE, etc.) (Raftery et al., 2011a). This can be done by an ad hoc estimation of the user or by using an optimization process mean to search within a widespread interval of solutions (Li et al., 2015; Raftery et al., 2011b). Using a calibrated model can help improve the design process by identifying which of the input parameters were over- or underestimated.

As mentioned, the white box models require the entry of data on hundreds of parameters of the building and its immediate environment such as the envelope, energy systems, internal loads, and the outdoor climate. However, these various parameters impact differently the energy performance of the building. It is therefore very important to identify parameters that have a strong influence so as to increase the reliability of the simulation. For example, using sensitivity analysis can help to identify which parameters will have a greater effect on the energy consumption of a building and if the model correctly represents the physical phenomena involved, and can give valuable indications for future monitoring. On the other hand, identifying the input parameters with less influence can help reduce the complexity of the model or even of the monitoring. A definition of sensitivity analysis, according to (2004), is: “the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input.” Various sensitivity analysis methods have been developed. These methods can be classified into: screening, local, and global sensitivity analysis.

The screening method is generally used as a qualitative analysis (impossible to rank) of the effect of a large number of input variables on the output (Heiselberg et al., 2009).

Local sensitivity analysis studies the effect on the output by the variation of one input parameter. This method is well adapted to energy models with many inputs. The drawback is that is does not take into account the interaction between parameters or the entire variation range of all the parameters (Ioannou and Itard, 2015).

Global sensitivity analysis can evaluate the interaction effect, but it is a time-consuming and expensive method. The most widely used methods are Sobol, FAST, Random Balance Design, and the Monte Carlo method (Spitz et al., 2012). (Sobol, 2001) (Sobol’ and Kucherenko, 2009) (Saltelli et al., 2007) (Xu and Gertner, 2011).

To use the sensitivity analysis it is possible to set the studied model in the following form:

$$y = f(x_1, x_2 \dots \dots \dots x_n) = f(x) \qquad (1\text{-}1)$$

y is the model output and $x = [x_1, x_2 \dots \dots \dots x_n]$ is the set of parameters of the model.

To investigate the contribution of the model input parameters to the variation of its outputs, this method determines the parameters that have a strong influence on the model output and/or have high variability. The results are given in the form of the sensitivity indices that quantify the impact of the parameter x_i on the output y. The greater the sensitivity index, the stronger the influence of parameter x_i on the output.

1.4. Real performance exemples

As previously mentioned, today there is true awareness of the need to move forward toward energy-efficient buildings. This can be observed in the increased construction of these buildings in various countries. Some experience feedback on the real performance in operational phase of this kind of building can be used to better understand and evaluate the building's performance.

Occasionally the performance predicted during the design stage is close to the real performance once a building is in use (Zhu et al., 2009) (Parker, 2009). For example, in (Gill et al., 2011) the authors studied the energy and water consumption for the annual energy and water performance of 25 houses and concluded that these individual dwellings performed efficiently in terms of electricity, heat, and water consumption. In (GSA Public Buildings Service, 2008), great potential results outperforming national averages for real energy performance were found for 14 buildings in terms of energy and water use, CO_2 emissions, and occupants' satisfaction. Other examples, as in (Guerra-Santin et al., 2013b), when monitoring the energy performance of two low-energy building have shown that the dwellings perform close to the design expectations.

In some cases, buildings don't perform as expected, facing a so-called "performance gap", leading to overconsumption, poor indoor conditions etc. The causes behind this performance gap vary from building to building (Menezes et al., 2012). The authors of (Branco et al., 2004) compared predicted versus real heat consumption and concluded that the main gaps are due to occupant behavior (room temperature higher than predicted 22,5° over 20°C, etc.), the real performance of systems, and the real meteorological conditions. For this case, the envelope's performance is close to the predicted value and represents, according to the authors, the basis of an energy-efficient building. The authors of (Thomsen et al., 2005) compared the target and the actual consumption of heating, electricity, and domestic hot water (DHW) consumption and indoor conditions for 12 advanced solar low-energy houses. The DHW consumption seemed to be well estimated. Regarding space heating and electricity consumption, the actual values were higher than expected. The authors concluded that the main causes are due to the building envelope's performance (airtightness) and the system efficiency that did not perform as expected. The other main reason is due to the occupant behavior, regarding their preference for higher indoor air temperature than assumed or higher household appliances energy consumption. Other examples have shown (Audenaert et al., 2011) that user influence can generate certain unforeseen factors that interfere in the energy efficiency balance, for instance, some areas of the house that are not heated, etc. In (Majcen et al., 2013) the authors used a large-scale study of Dutch housing to investigate their performance. The authors showed that for energy-efficient buildings the theoretical gas consumption is underestimated when compared with actual annual gas consumption. However, the real electricity consumption seems to be underestimated compared with the theoretical one. A well-designed and properly implemented envelope can support energy saving. Along with that, on-site production assured by well-sized photovoltaic and thermal systems can successfully achieved a net-zero-energy building as shown in (Fanney et al., 2015). The authors exposed some challenges regarding the building's systems: for example, the snow and/or ice covering the photovoltaic and thermal solar system. Also the actual performance of the heat pump was less that the rated one. However, the gaps stemming from the stochastic aspect of the occupants were ignored. A virtual family was used here to simulate the impact on the building's energy consumption of a typical family of four occupants. In some cases (Dall'O' et al., 2012), when considering similar flats, the energy consumption gaps are fully due to the occupants' behavior, regarding temperature settings, windows and shutters opening/closing, etc.

Summarizing all these points, several main causes of the performance gap can be identified, as explained in (de Wilde, 2014). These causes are encountered in the design phase, in the predicted performance, in the construction phase, and of course in the operational phase, within the building's actual performance.

In the design phase, there are many unknown (lack of building and system details) or uncertain input factors (future occupancy, weather) that are used to predict the future performance. Moreover, even with a well-experienced user/modeler, the models are based on assumptions and simplifications, and therefore they are not always able to capture the entire process. The performance gap causes can also be rooted in the construction phase. Problems when the construction itself does not meet the target can be due to insufficient attention to the insulation and airtightness process, miscommunication, etc. (de Wilde, 2014). Furthermore, once the building is constructed, verification of its envelope's performance is not always a straightforward and easy task. Many of the causes of the performance gap are often due to the occupants' behavior during the operational phase. Future occupants are not always known in the design phase, and often deterministic assumptions are used to estimate future occupancy. However, the future use of electric household appliances, thermostat settings, window behavior, etc. cannot be fully predicted because of the stochastic nature of human behavior. Another cause of the performance gap in the operational phase is related to the fact that systems do not always operate as expected. Also, an important decision factor in the energy use of a building is the unpredictable dynamic parameter represented by weather conditions. Numerous uncertainties are associated with the weather, and the robustness of the building's design is often tested under extreme meteorological conditions (for example, heat waves). In the operational phase, another cause of performance gap can be due to the measurements. Once the sensors are installed, malfunctioning may occur in the data (outliers), in the network between the sensors, and in the data transmission, etc.

To sum up, as shown in (Li et al., 2014) no single factor (climate, occupancy, and envelope) determines the real energy performance. A global integrated design that takes into account all these factors could help produce the highest energy savings for energy-efficient building. However, buildings should provide not only the highest energy saving, but also a healthy and comfortable environment for the occupants. Therefore, the real energy performance should also take into account this aspect. Feedback on the occupants' perception can help improve the design and refurbishment. For example, cases of cold floors were found in postoccupancy evaluations (Rohdin et al., 2014). The indoor thermal comfort and energy use, however, were found to be generally good and in line with predictions. Moreover, feedback on the real energy performance can help improve the occupants' perception of the building's energy management. For example, knowing that using the use of roller blinds for solar energy along with a lower set-point temperature during winter could help increase the energy savings. Also the use of roller blinds along with natural ventilation could provide better indoor conditions during summer. Understanding and evaluating the real energy performance should be able to identify if there is a performance gap and, if so, the factors contributing to it.

1.5. Findings

This chapter has presented the methods used to evaluate the energy performance of a building: monitoring and building performance simulation.

Monitoring depends on the purpose of the study and the performance indicators that are investigated in the study. For example, if the annual global performance is of interest, the monitoring is simple including only energy bills. However, when the focus is on a continuous global performance, the monitoring becomes more complex. It can involve monitoring of the total energy use or it can include monitoring of each end-use item (heating, appliances, etc.). The type of monitoring, its duration, and the size and placement of sensors also depend on the purpose of the study. In the context of evaluating the energy performance, the general focus of studies is on energy use and indoor conditions. The main conclusion here is that although there are a wide variety of studies in the literature, the monitoring can yield over-/underestimated values. To contribute on this fields, the present thesis proposes an effective application of monitoring used to evaluate the performance of a building.

Building performance simulation can be used as a complementary method to monitoring in the evaluation of the energy performance. Increased developments in simulation tools have been witnessed in the past few years. Simulations tools are successfully used to optimize the envelope's and system's characteristics during the design phase, to estimate their energy use, to test their performance using different climate files, to test different scenarios of occupation, etc. These physical components of the energy performance (envelope and systems) seemed to be more easily manageable in the simulation method and various examples exist on successful validation of the simulation models. However, studies have revealed that the occupants' behavior represents a major source of uncertainty in predicting the energy performance of a building. This is mainly due to its stochastic nature and the complexity of predicting occupant's behavior. Although various efforts are made regarding this aspect, there is still a lack of confidence when it comes down to including the occupants' behavior in the simulation process. Considering the diversity, complexity, and uncertainty associated with each occupant, this is not a straightforward task. Within the present thesis, we use simulation to study the occupants' behavior simulation by using a deterministic schedule and a statistical approach.

The present thesis seeks to enhance this field by presenting a single-family house case study in which both monitoring and building thermal simulation are used to for a continuous evaluation of the global performance of this house.

CHAPTER 2. Dispersions in energy use related to occupant's behavior: a numerical investigation in the design phase

2.1. Introduction

The literature shows (first chapter) that a serious impact on the energy performance of buildings stems from the stochastic and unpredictable nature of the occupants' behavior. Moreover, it also show that the uncertainties associated with the occupants' behavior are also elevated. To treat this aspect and to better understand the factors related to occupancy that drive the energy use and indoor conditions, in this chapter we use building performance simulation. Section 1.3 shows the main problems that can arise when simulating the dynamic aspect of occupants' behavior. This comes with the difficulty of considering unpredictable human behavior within the models. This chapter presents a study of the dispersions in energy use related to the occupants' behavior using an EnergyPlus model on a case study, described in the following. Various occupancy, appliances power and set-point temperature scenarios are used. We start by applying the deterministic schedule, suggested by the French thermal regulation RT2012. The goal is to assess and verify the future energy demand of this building according to legislative requirements. Then we use another deterministic schedule that has been called the owner's view. This schedule is constructed after questioning the occupants of the building about their future presence and equipment use. This allows the construction of a schedule, which tends to be more realistic than the RT2012 schedule. Moreover, it offers an inside view of how the future occupants predict their own energy use. Four different schedules, assuming different set-point temperatures and appliances energy uses, while maintaining the same occupancy, are tested here.

In the end, the robustness of this building's design is evaluated for varying occupant behaviors. The dynamic thermal simulation model is coupled to an integrated stochastic multi-agent behavioral model, which uses a French database to provide different family profiles. The occupants' presence, the use of household appliances, lighting and the set-point temperature schedules are varied for every hour of the entire year. As a result, energy demand is calculated for 1000 families.

2.2. The case study: single-family detached home (PosA)

The case study represents a single family detached home situated in the setting of a Mediterranean climate, in the south of France, called PosA. The geometry of this 229 m^2 living area is complex, constrained by the sloping land. This geometry gives a compactness coefficient – the ratio of the envelope's thermal losses surface and the living volume – of 2.58. The building plans can be found in ANNEX A and southern façade is showed in (see Figure 2-1).

Figure 2-1: PosA house: southern view

The house was designed in order to minimize the energy demands both during the heating and cooling season. With regard to the envelope, highly insulating materials were chosen, as shown in Table 2-1. More information about the walls composition can be found in the Annex A.2.

TYPE OF WALL	Thermal resistance [m^2K/W]
Exterior wall	6,25
Garage wall	0,21
Intermediate wall Garage / Housing	6,25
Terrace slab: bedroom 1	9,65
Roof	9,65
Roof terrace: Garage	0,24
Slab on crawl space	6,91
Intermediate floor	3,28
Slab: Garage	3,57

Table 2-1: Wall thermal properties for the PosA house

This house has substantial glazed surfaces for natural lighting and winter solar heat gains. All windows are double-glazed with an interspace of 15 mm filled with argon, with an Ug value of 1 (W/m^2.K), a light transmittance of 0.71 and a solar heat gain coefficient of 0.5. The building is also equipped with sunscreens, blinds, and automatic shutters that allow for the optimization of thermal comfort in summer. Potential overheating problems were indeed carefully analyzed, taking into consideration that the house is situated in a Mediterranean climate and solar gains will be very important.

On-site energy production is ensured by the integration of photovoltaic panels of 20 % efficiency that will cover a surface of 40 m^2. There is also a 12-m-high wind turbine. The systems were sized to cover the annual energy demand of the house, including: space heating, domestic hot water, ventilation, lighting, auxiliaries (pumps, fans, etc.), as well as appliances.

Energy storage is carried out through 24 electric batteries of 2 kWh.

For the domestic hot water, for four bathrooms and six sinks, an air–water heat pump with a 300-L tank capacity (type ODYSSÉE SPLIT) (Atlantic) is installed. There are three bathrooms on the ground floor and one on the first floor.

For ventilation, a mechanical outlet system “type hygro B” is installed. This system indirectly detects human presence through moisture due to occupant’s activity and adjusts air outflow to the level of indoor relative humidity. This has the advantage of limiting the heating by obtaining an optimal air exchange. The minimal system airflow rate is equal to the sum of the minimal outflows connected to the fan. The calculated value is about 133 m^3/h. The maximum target airflow rate is about 328 m^3/h. Both are calculated according to the Technical Notice: (CSTB :Avis Technique 14/13-1911, 2014).

Electric heaters (type ALIPSIS, Atlantic) of 8,000 W total nominal power meet the heating energy demand. On the ground floor zone, there are four electric heaters (4*1,000 W) ensuring the heating demand for the children rooms and one (1,000 W) in the office room. On the first floor zone, there is one electric heater (1,000 W) in the parent’s room and one in the living room area of 2,000-W. No cooling system is implemented and natural ventilation is used to provide adequate indoor conditions.

The building electric system connections are shown in Figure 2-2.More information can be found in ANNEX A.

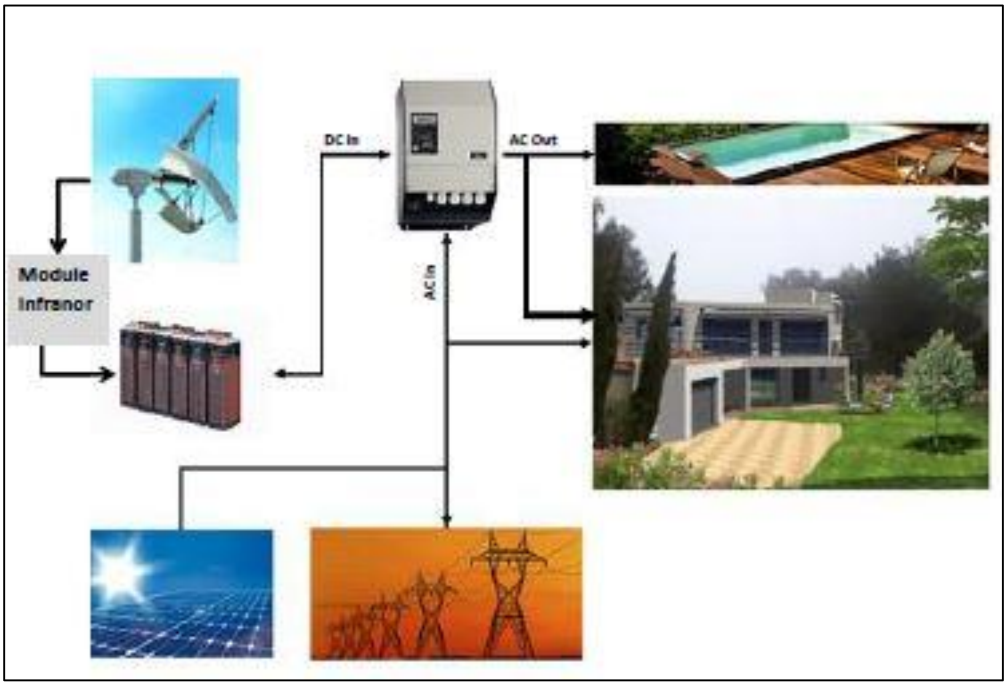


Figure 2-2: PosA electric systems connection chart

- **Modeling assumption**

The simulations are performed with EnergyPlus software. Building plans (see annex A.1) and information on future construction materials were available and provided in the design phase. As a modeling assumption, this building is divided into nine thermal zones, to coincide with the building's room distribution as shown in Figure 2-3. The red zone represents the children's bedrooms. The dark green zone is the living area, which includes the kitchen. The blue zone represents the parents' bedroom and light green the office and a storage room. Also included are the garage zone (grey) and the stairway zone (dark blue). The stairway zone is not heated. However, there is no door between the living area and the stairway and a passageway between the children's bedrooms and the stairway is made. Within the simulation, air transfer is modeled between these zones. The algorithm used here is the Conduction Transfer Functions (EnergyPlus). The TARP algorithm which was developed by Walton in 1983 was used for the indoor and outdoor surface heat transfer convection algorithm (EnergyPlus).

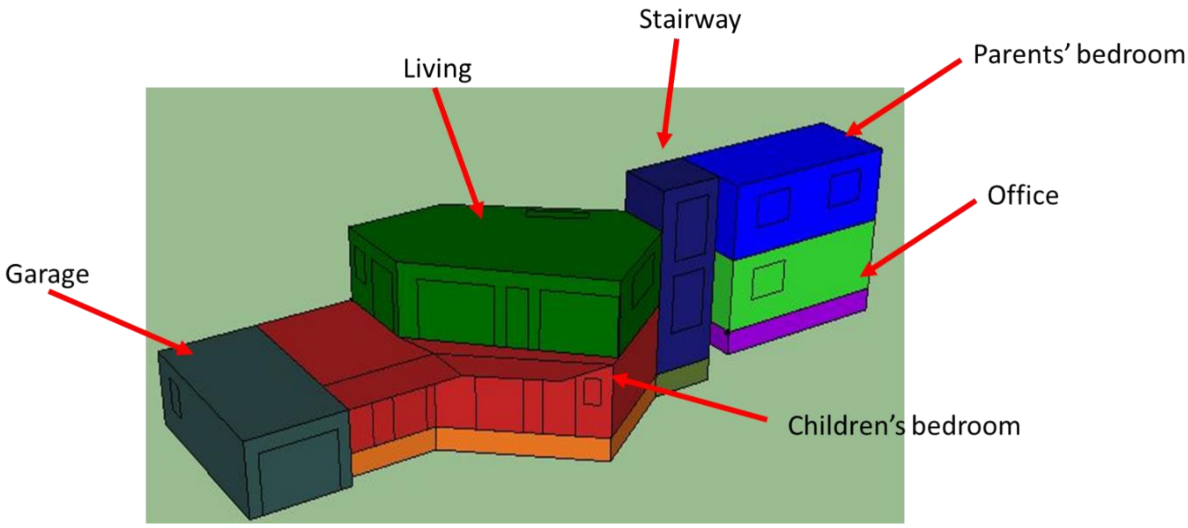


Figure 2-3: 3D representation of the building

A weather file for Carpentras, a small town, generated with the Meteonorm software, is used. This town is located approximately 38 km from the building location. The energy demand for DHW is not simulated but estimated by the manufacturer in the design phase according to RT2012. The same model of PosA house supported all the simulations presented in this chapter. Therefore all differences are due to exclusively to the differences in the tested occupancy schedules.

2.3. Deterministic schedule modeling

This section presents the simulation results from five different deterministic schedules. The objective here is to study the varied energy demand when using different schedules for occupant presence, set-point temperature, appliances and lighting use, while keeping the same number of occupants. The first, called "schedule 1," represents the schedule suggested by the French thermal regulation: RT2012, described in the next subsection 2.3.1. The other four deterministic schedules (schedule 2 to 5) represent the schedules created using information from the owner in the design phase. They are described in subsection 2.3.2.

2.3.1. Modeling using the French thermal regulation RT2012 schedule

In France, the building sector is the leading energy-consuming sector. Furthermore, approximately 60% of annual housing construction is single-family dwellings. The French thermal regulation: RT2012 therefore imposes high energy performance requirements on new buildings. The characteristics and requirements of RT2012 have gradually become stricter over the years and are as follows:

- Annual primary energy use: less than 50 kWh per square meter of floor area. This represents total energy consumption needed for heating, cooling, domestic hot water (DHW), auxiliary (usually ventilation fans) and lights. This value is adapted for different climatic zones and altitude;
- The building's envelope energy efficiency;
- A maximum indoor temperature in summer;
- Access to natural lighting;
- Mandatory treatment of thermal bridges and of air permeability.

In this context, the schedule suggested by the RT2012 is an energy-saving schedule, in agreement with the requirements.

Regarding the set-point temperature during heating period, the RT2012 schedule is based on two values: a reduced set-point temperature of 16°C during conventional working hours (10:00-18:00) and 19°C for the remaining time (see Figure 2-4). During the weekend, a set-point temperature of 19°C is maintained.

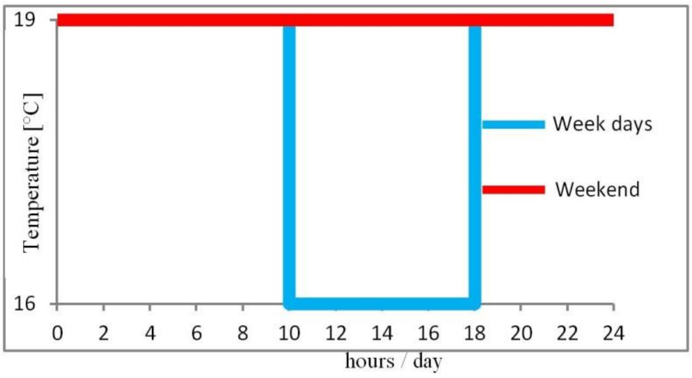


Figure 2-4: Heating set-point temperature from the RT2012 schedule

Internal sources are taken into account by the RT2012 schedule as follows: appliances with 5.7 W/m^2 and lighting with 1.4 W/m^2. More information on the equipment and lighting use scenario can be found in (RT2012, 2010). The constant ratio of 5.7 W/m^2 is used as the value of averaged energy delivered for domestic appliances in the present schedule.

Here, as specified, the goal is to study the energy demand of the PosA house, when applying the RT2012 schedule. This schedule will be referred to as 'schedule 1' in the rest of the manuscript.

2.3.2. Modeling using the owner's view schedules (schedule 2 to 5)

For this building, the future owners were already known in the early stages of the design phase, before the construction. This house was actually designed in collaboration with them, to provide an energy-efficient dwelling for their family, a couple with four children. Before the construction of the house, the future owner provided a detailed description of the expected presence of the occupants and use of electrical equipment. This information is used to create another deterministic schedule; a detailed scenario of building use. The owner provided hourly schedule of family presence in the house. The Monday presence chart used in this detailed deterministic scenario is exemplified in Figure 2-5. As can be seen here, four persons are present in the house 13 hours a day. During the lunch break (12:00–14:00) the occupants' presence is recorded, as the parents come home for lunch. Figure 2-6 illustrates the complete schedule for the entire week, starting on Monday. In fact, based on these information four different schedules are proposed (schedules 2 to 5) as will be detailed in the next paragraphs.

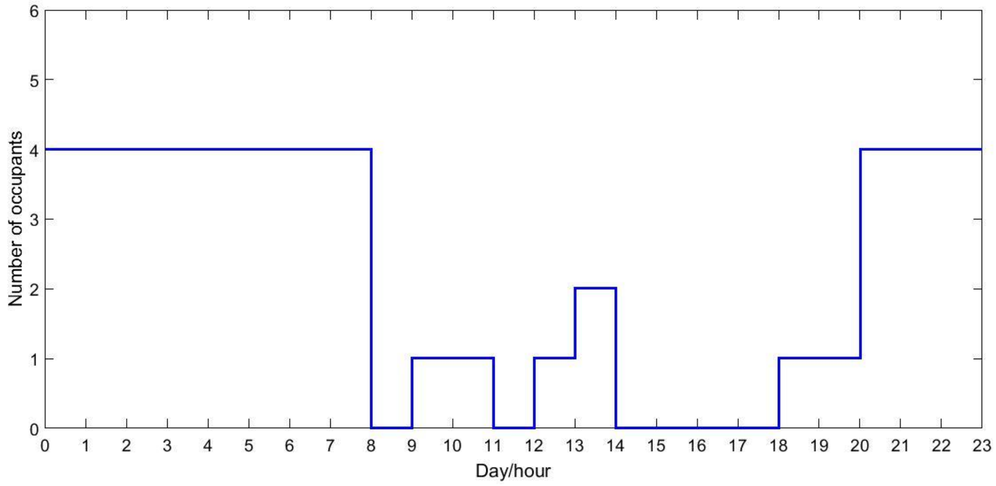


Figure 2-5 : Monday occupation chart

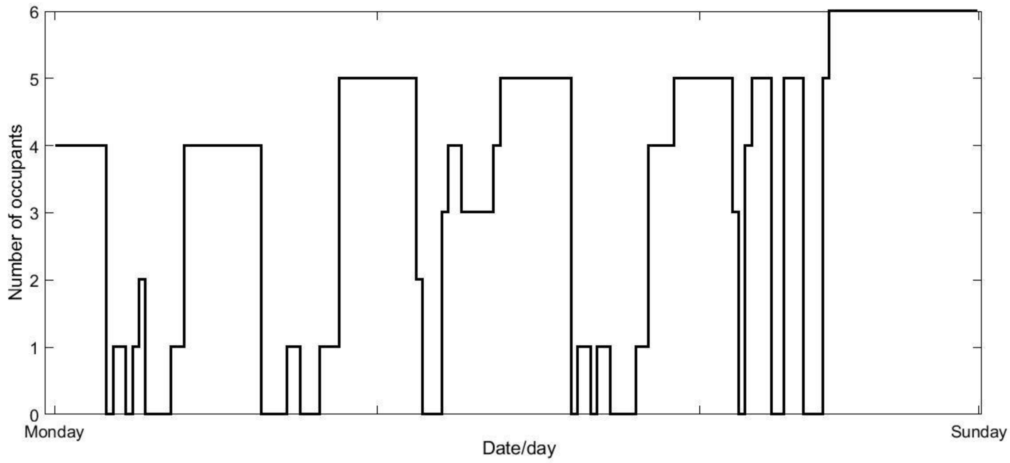


Figure 2-6: Week occupation charts, starting with Monday

Regarding the set-point temperature, some assumptions are made as the set-point temperature value was not provided by the owner in the design phase. Consequently, we chose to adopt two-value scenarios, as suggested by the RT2012 thermal regulation. Therefore, when occupants are present the set-point temperature is fixed at Tocc. During the night and when the house is unoccupied, the set-point temperature is at Tlow. In the first variant, schedule 2, Tocc = 19°C and Tlow = 16°C, strictly following RT2012 indications. The resulting schedule is showed in Table 2-2.

WEEK DAYS	T [°C]	WEEK DAYS	T [°C]
Monday–Friday		Weekend-Wednesday	
00:00–07:00	16	00:00–09:00	16
07:00–08:00	19	09:00–00:00	19
08:00–12:00	16		
12:00–14:00	19		
14:00–18:00	16		
18:00–00:00	19		

Table 2-2: Owner's view: set-point temperature schedule

The power used by the appliances is modeled according to owner's specifications. The homeowner provided the list of the appliances, the use and the nominal power of each device. The reason to use the nominal power is because it's available and simply to obtain, using only information from the owner's specification. However, large uncertainties are associated, considering the fact that the electric appliances (for example oven) do not always function at their full nominal power. The implemented schedule is shown in Table 2-3. This table contains the nominal power and the use of each item for each day, as provided by the owner. For example, the oven is used for 1 hour three times a week, which has been translated to 0.43 h/day. The stovetop is used for 1 hour every day, etc. The moment of the day which each item is used is also implemented according to owner's specifications.

ELECTRIC EQUIPMENT	NOMINAL POWER [W]	USE [h/day]
Oven	2850	0.43
Stovetop	3675	1
Microwave	1000	0.25
TV (children)	64	8.5
TV (living)	64	2
Laptop	90	2
Iron	2100	0.29
Fridge	80	24
Washing machine	2200	0.04
Dishwasher	2100	0.06
Tablet	50	0.09

Table 2-3: Power demand and use of appliances

As for lighting use, a scenario is implemented here based on occupation charts provided by the owner. The time of day (day/night) is also taken into account. As can be seen, the occupants arrive home at 18:00. Therefore, the lighting use schedule is constructed to simulate the lights on at this time (Table 2-4). Again, information on the power demand for lighting was not available in the design phase. An arbitrary scenario, following the RT2012, is implemented here, considering a mean value of 1.4 W/m^2 for lighting.

LIGHTS	MONDAY–FRIDAY	WEEKEND	SUMMER	WINTER
00:00–07:00	OFF	OFF	OFF	OFF
07:00–08:00	ON	OFF	OFF	ON
08:00–18:00	OFF	OFF	OFF	OFF
18:00–23:00	ON	ON	ON	ON
23:00–00:00	OFF	OFF	OFF	OFF

Table 2-4 : Lighting use

- **Schedule 3: alternative scenarios (Tint+2)**

However, as said before, in real-life conditions, the set-point temperature is often higher than the one suggested by legislation. To study this aspect, an alternative simulation is performed by increasing the value of Tocc and Tlow by 2°C. Therefore, using the same occupancy schedule as in Figure 2-9, a value of 21°C is used instead of 19°C and a value of 18°C instead of 16°C. This forms schedule 3. All the other data are identical to schedule 2.

- **Schedule 4 and 5: alternative scenarios (appliances power)**

Another assumption is that in an occupied building is that, in real-life conditions, the appliances do not work at their full nominal power most of the time, as used in previous simulations (schedules 2 and 3). Therefore, another possibility is to assume that each device (oven, fridge, etc.) operates at approximately average power. Therefore, in schedules 4 and 5 the power of the electric equipment is amended around an average value in order to take this aspect into account. Table 2-5 shows the adjusted power of each device that is considered, referred to as “average”. These values are selected after collecting data from the literature analysis.

ELECTRIC EQUIPMENT	NOMINAL POWER [W] (SCHEDULE 2 AND 3)	AVERAGED POWER [W] (SCHEDULE 4 AND 5)
Oven	2850	1040
Stovetop	3675	778
Microwave	1000	213
TV (children)	64	64
TV (living area)	64	64
Laptop	90	90
Iron	2100	625
Fridge	80	36
Washing machine	2200	520
Dishwasher	2100	1222
Tablet	50	50

Table 2-5: Nominal and average power for the appliances

2.3.3. Summary of five deterministic schedules

These schedules are differentiated as presented in Table 2-6. First, the schedule 1 is the RT2012 schedule, as presented previously. The next four schedules (schedules 2–5) are the schedules based on the owner's view. The difference between these four schedules is that schedules 2 and 4 use the set-point temperature 16–19°C presented in Table 2-2. Schedules 3 and 5 use the set-point temperature 18–21°C. In addition, schedules 2 and 3 use the appliances' nominal power presented in Table 2-3. For the other two scenarios (schedules 4 and 5), the same appliances use remains unchanged; however the averaged power of appliances given in Table 2-5 is used. For all schedules, only one scenario for DHW based on RT2012 is used.

NAME	SCHEDULE1 (RT2012)	SCHEDULE 2	SCHEDULE 3	SCHEDULE 4	SCHEDULE 5
Set-point temperature	16- 19°C	16- 19°C	18- 21°C	16- 19°C	18- 21°C
Appliances power	5,7 W/m^2	nominal	nominal	average	average
Occupancy	RT2012	Owner's view	Owner's view	Owner's view	Owner's view
Lighting	RT2012	RT2012+ occupancy	RT2012+ occupancy	RT2012+ occupancy	RT2012+ occupancy
DHW	RT2012	RT2012	RT2012	RT2012	RT2012

Table 2-6 : Main characteristics of schedules 1 to 5

2.4. *Results using deterministic scenarios*

- **Results for schedule 1: RT2012 schedule**

The results for the annual energy demand when using the RT2012 schedule (Figure 2-7) show that for this building more than 50% (25 kWh/m^2/year) of the energy is consumed by the household **appliances.** In the RT2012 schedule (schedule 1) the average power (5.7 W/m^2) is linked to the dwelling surface and not to the number of inhabitants. Here, the results are linked to the large area of the building (229 m^2). This is a distinctive case compared to more usual French housing covering about half this area. The second energy consumer (11 kWh/m^2/year) representing 24% is **heating**. This low estimated value for heating energy demand is based on a number of factors. These may be the use of the set-point temperature suggested by the economical feature of the RT2012 schedule, the design of the house (highly insulated walls etc.), the Mediterranean climate location (warm winters) etc. The RT2012 calculation for the **DHW** of the building gave an annual energy demand of 4,25 kWh/m^2/year and it represents 9% of the total energy demand. The energy demand for auxiliary ventilation systems rise to 600 kWh/year, or 2,6 kWh/m^2/year, representing 6%. The annual energy demand (3,1 kWh/m^2/year) of the **lighting** accounts for only 7% of the total energy demand.

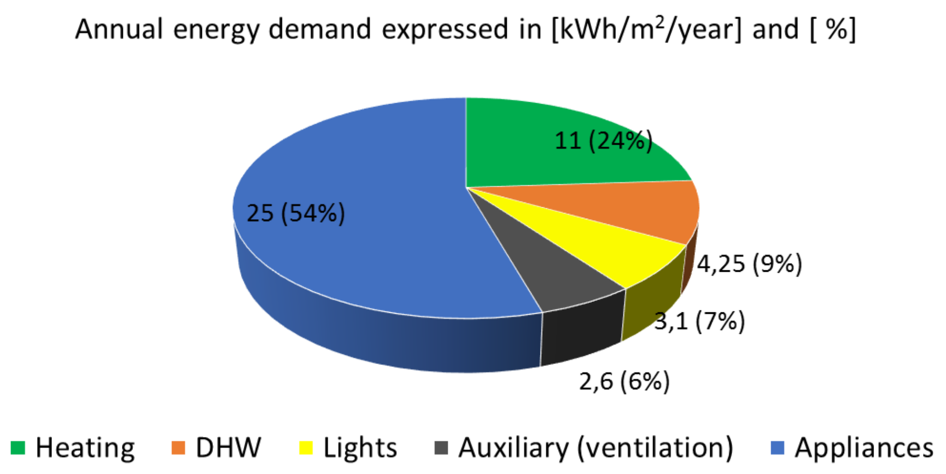


Figure 2-7: Annual energy demand, using the RT2012 schedule

The RT2012 schedule is a required building performance simulation calculation, which serve as reference and it's an available tool to test and compare different houses. However, the occupants' behavior can be hard to capture using a fixed schedule, which is generalized and used for all the buildings. Studies have shown that the tendency is to use a higher set-point temperature. Also, in real-life conditions, various and usually numerous appliances are used by the occupants. In the following lines, we present the results four different deterministic schedules of appliances use and temperature set point, based on owner's view forecast in order to quantify the impact of these two.

- **Results for schedule 2: owner's view, set point temperature 16-19°C, appliances' nominal power**

The results of the simulations using the occupancy schedule given by the owner show that half of the total annual energy demand comes from the appliances (Figure 2-8), totaling 19,3 kWh/m^2/year. This value is slightly lower than the one obtained from using RT2012 schedule (25 kWh/m^2/year). The estimation of the annual heating demand shows that it accounts for about 26% (10,5 kWh/m^2/year) of the total annual energy demand. Almost the same value as the first simulation is obtained here for heating. This is mainly because the same set-point temperature is used (16–19°C). The difference between the two simulations is in the occupation chart. The lighting energy demand represents 8% of the total annual energy demand. As for the DHW and ventilation, the same values that are considered for RT2012 schedule are used and presented here (identical scenario).

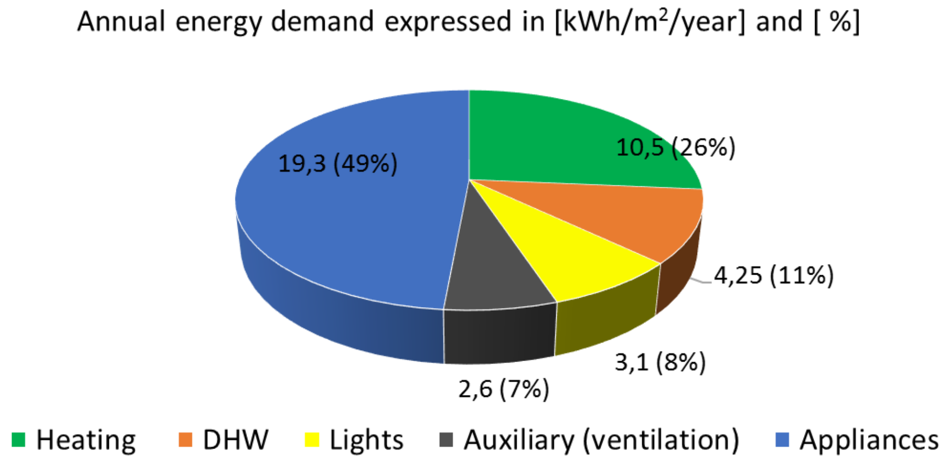


Figure 2-8: Total annual energy demand for schedule 2 (owner's view, using 16–19°C set-point temperature)

- **Results for schedule 3: alternative scenarios (Tocc+2) : owner's view, set point temperature 18-21°C, appliances' nominal power**

The results when using schedule 3 implies a significant change in the total annual energy demand. The majority of the total annual energy demand comes from heating and appliances. They have almost equal outcome on the total annual energy demand. By increasing the set-point temperature by 2°C, the heating demand increases by 7 kWh/m^2/year. This increase almost 15% of the total energy demand.

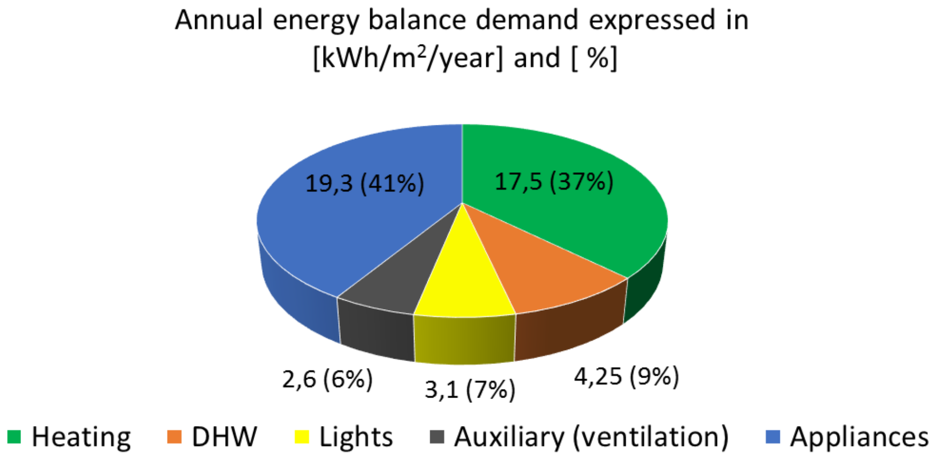


Figure 2-9: Total annual energy demand for schedule 3 (owner's view using 18–21°C set-point temperature)

- **Results for schedules 1 to 5**

Figure 2-10 summarizes the results for heating, appliances and lighting demand, for all five schedules tested. The results highlight that using a set-point temperature as suggested by the RT2012 (16–19°C) is the most economical scenario for energy savings. When using the 18–21°C set-point temperature instead, the annual heating energy demand rises by approximately 7 kWh/m^2/year. The other factor that changes the annual heating demand by approximately 2 kWh/m^2/year is the choice of appliances power (nominal vs. average power). The results show here that using a set-point temperature of 16–19°C and a nominal power for the appliances schedule are closer to the schedule used within the RT2012 for this house. Regarding the appliances energy demand, the difference between using a nominal or an average power schedule is more than double. This can represent a real problem when modeling occupied buildings, leading to uncertainties. The lighting is modeled using the RT2012 recommendations, and the results are very close.

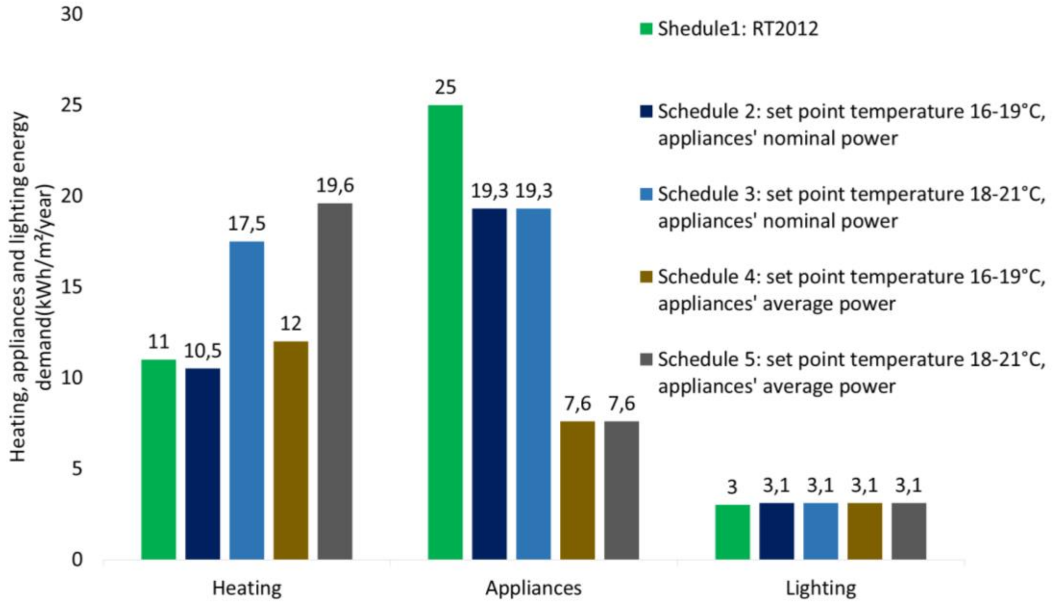


Figure 2-10: Heating, appliances and lighting energy demand for each type of schedule implemented

2.5. *Stochastic approach modeling*

2.5.1. Agent-based behavioral model description

In the previous section, the variations in energy demand when using deterministic schedules for different set-point temperature, appliances are shown. The presence and occupancy schedule were provided in the design phase by the owner of the building. In this section, the robustness of the energy design presented above is assessed using a stochastic approach of scenarios of occupancy and building use. In this aim, a comprehensive agent-based behavioral model for residential buildings described in (Parys et al., 2014) is coupled to the building simulation software. The model includes presence of occupants their activities and related appliances and lighting use as well as the heating set-point temperature. Its elements are described below.

Presence of occupants and activity models are based on a French TUS (time use survey), a survey that includes people's activities through a 24-h cycle, used by (Wilke, 2013). Here, the presence is modeled using a first-order Markov chain model. A Markov chain represents a stochastic process with discrete random time where predicting the future state depends only on the current state, and it is not dependent on the previous state. The results of the presence model are then used as an input to the activity model. The model contains 20 different activities and is a hybrid model. This means that it uses both the Markov chain for the choice of when a certain action occurs and a survival study for modeling the activity duration. These activities include paid work, sleep, housework etc., and are therefore differentiated with regard to the time and the day of the week and the sociodemographic aspects. More details can be found in (Parys et al. 2014). The main principle is to use starting probabilities to model the next activity. Furthermore, the correlated activities between members of the same house are not modeled specific. Children's activities and presence are not included due to lack of data in the database. Therefore, here the children activities and presence are modeled as adults.

As for the **appliances,** Wilke's model (Wilke, 2013) is selected for sampling the household appliances ownership, which is based on the type of building, the house location, etc. Also, a random probability is drawn to choose whether an appliance is used or not when an individual is performing an activity (Richardson et al., 2010). This is not the case, however, for the cold appliances such as the fridge, which is modeled with a constant value for electrical power.

Regarding **lighting** use, the approach proposed by (Richardson et al., 2010) is selected here. A hybrid model is used as well as the activity model to decide whether all the light bulbs are switched on and their duration based on external conditions and occupancy.

For the **heating set-point temperature**, the model samples a single heating set-point temperature from a Gaussian distribution at the start, with a mean of 20,6°C and a standard deviation of ±2,5°C using the data of (Huebner et al., 2013b). This model uses the activity model to decide whether or not an individual is present, and when there is no occupancy in the building, a reduced temperature of 16°C is considered.

2.5.2. Integration into building performance simulation

The robustness of the building's energy performance is assessed using a Monte Carlo type uncertainty analysis. The uncertain input parameters are linked to the sociodemographic parameters of the inhabitants and to individual variability. The integrated behavioral model produces input for the building performance simulation model. Figure 2-11 shows a schematic overview of the integrated behavioral model and its coupling to the building performance simulation model.

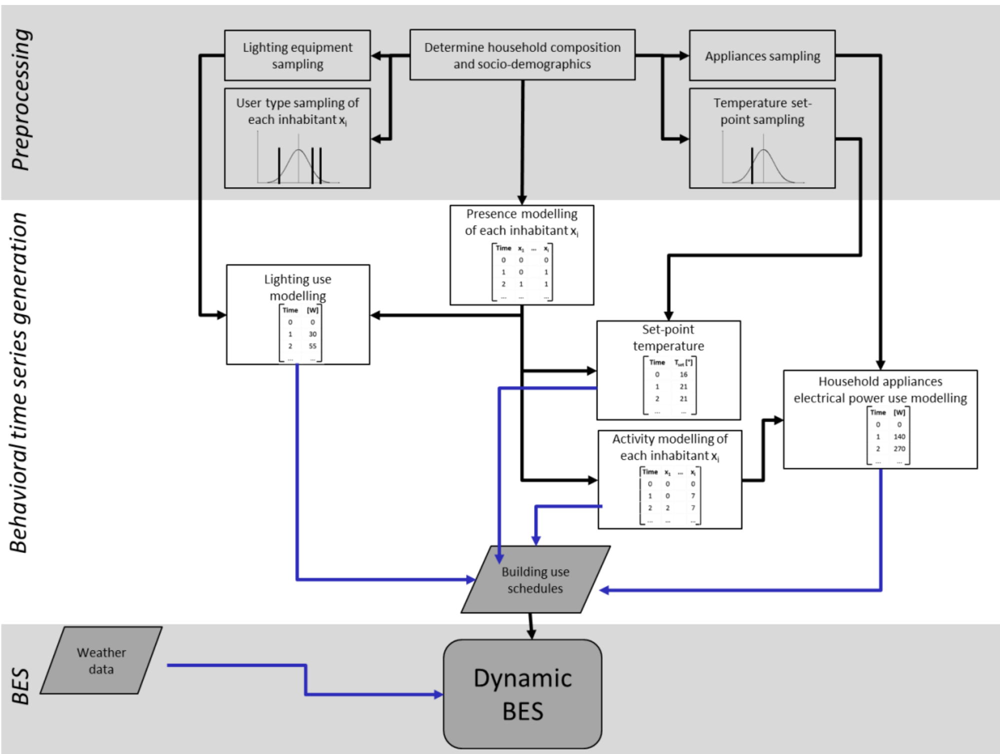


Figure 2-11: Schematic overview of the integrated behavioral model and its coupling to building performance simulation mode (adapted from (Parys et al., 2014))

One thousand families with different presence, activity, set-point temperature, appliances and lighting use are sampled and used as input schedules for building simulation. A database containing a variety of families is therefore created. First, the number of members of each family varies between one and seven people. Within these 1000 families, there are young active adults, returning home in the evening. There are also families component of one elderly retired person. The social aspect (paid work, sleep, housework) is also taken into account. For example, the energy savings for a family of young active adults can be significant, considering that they work during the day, for example in the set-point temperature. The families differs in these aspects as well is the use of the building they occupied.

These 1000 schedules corresponding to each family are simulated using the EnergyPlus Schedule file element. The goal is to estimate the energy demand. The simulation software and the agent-based behavioral model are coupled using a Matlab script. This script is also used to calculate the heating, appliances and lighting energy demand for each family.

2.6. *Results using probabilistic scenarios*

2.6.1. Heating demand

This section presents the main outputs from more than 1000 simulations and for various schedules (including the five discussed previously) implemented in EnergyPlus

- the RT2012 schedule (schedule 1);
- the owner's view schedule (for the set-point temperature 16–19°C and 18–21°C, average and nominal power for the appliances) (schedules 2 to 5);
- 1000 families' schedules from the agent-based model.

Figure 2-12 presents the histogram of heating energy demand for each family.

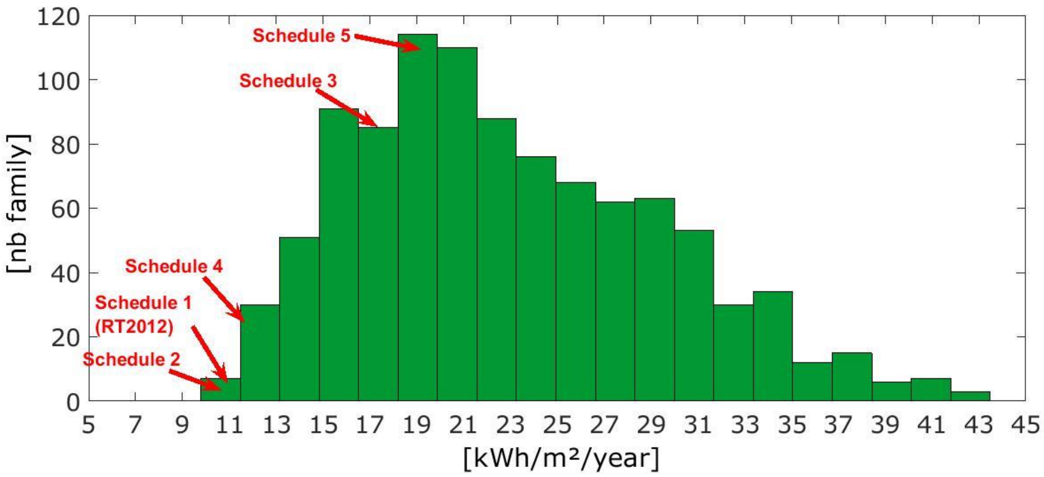


Figure 2-12: Histogram representing heating energy demand for different families

Regarding the heating energy demand (Figure 2-12), the majority of the families' heating energy demand is between 13 and 35 kWh/m^2/year, rising up to 43 kWh/m^2/year. This highest value is obtained when the indoor temperature is set at 25°C during occupation. This can be the case of a retired family spending most of the time inside the building, or it can be the case of a couple with a young baby.

Indeed, Figure 2-13 shows, as expected, an almost linear variation for the annual heating energy demand with the maximum set-point temperature. The maximum energy demand that rises to 43 kWh/m^2/year corresponds to the case of families preferring a set-point temperature of 25°C. However, the majority of families prefer a set-point temperature ranging from 18 to 23°C. An increase of 1°C on the set-point temperature increases the heating demand with approximately 3 to 4 kWh/m^2/year. The sampling of the set-point temperature in the agent based model is random and independent of the family composition as shown in the Figure 2-14.

Within 1000 families there are families with two people that prefer a set-point temperature of 16 or 25°C. Another observation here is that the majority of the results include families with 1, 2 and 3 members (Figure 2-14 and Figure 2-15).

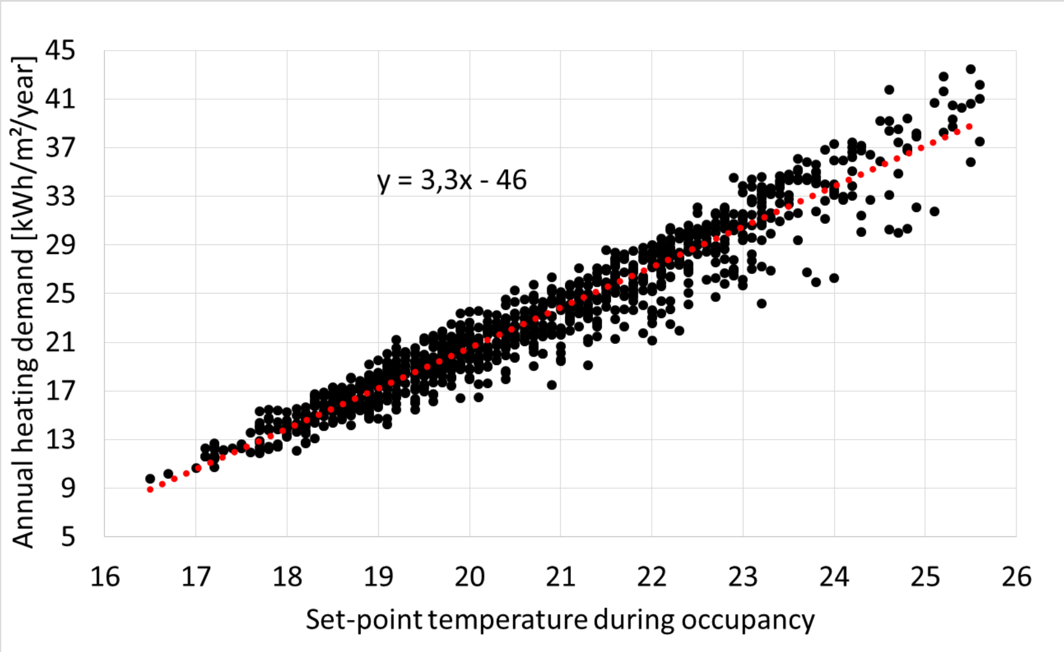


Figure 2-13: Annual heating demand as a function of set-point temperature during occupancy

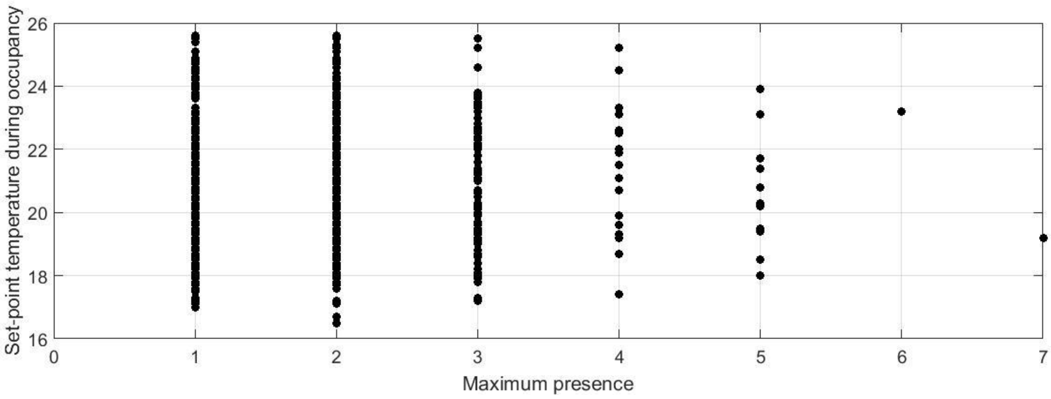


Figure 2-14: Set-point temperature as a function of maximum number of occupants

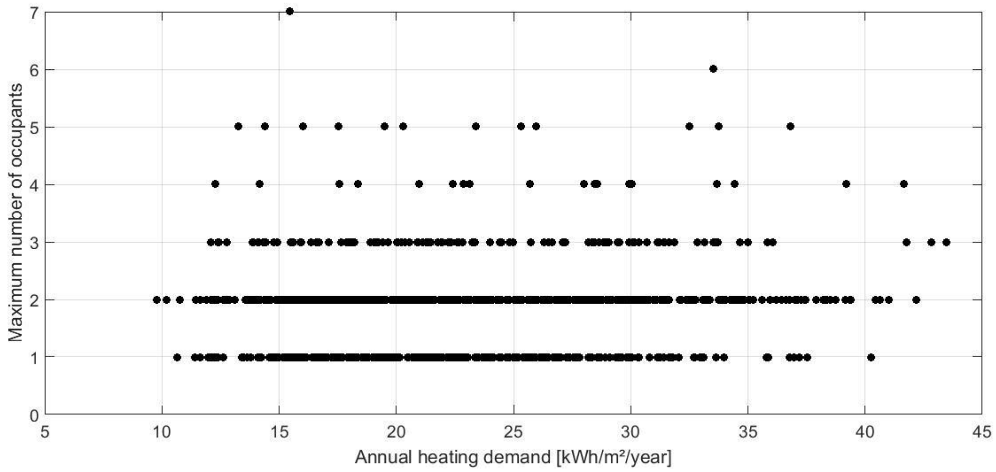


Figure 2-15: Annual heating demand as a function of number of occupants

As is shown here, schedules 1, 2 and 4 (set-point temperature 16-19°C) are in the lower bound of the heating energy demand, when compared with the national statistics. On the other hand, when considering a set-point temperature of 18°C and 21°C the heating energy demand results are close to the majority of the families extracted from the French national statistics results.

The only six-member family within the agent-based results preferred a maximum set-point temperature of 23,2 °C. To sum up these results, it can be observed that the majority of the families extracted from the French national statistics prefer a higher set-point temperature than the one suggested by the RT2012 which coincides with previous studies (Branco et al., 2004). The results have confirmed, once again, the obvious impact of the set-point temperature on the heating demand.

The maximum number of occupants from the entire range of 1000 families is seven people. Figure 2-16 presents such a family. The estimated heating energy demand for this specific family is 15,4 kWh/m^2/year. For this specific family, the value of the annual appliances energy demand is about 12,4 kWh/m^2/year. This value is calculated considering different activities and times of day and that the appliances' energy power ranged from 211 to 1395 W/h. As for lighting use, the model seems to follow an economic schedule (as can be seen in Figure 2-16). The maximum power for lighting considered for this family is 320 W, corresponding to the lighting power used between 23:00 and 00:00 on 21st of January.

Figure 2-16: Set-point temperature, occupancy, appliances and lighting use for 2 days, for a specific 7-members family

2.6.2. Electrical appliances demand

As shown in Figure 2-17, the majority of families represented by the agent-based behavioral model consume between 6 and 12 kWh/m^2/year for appliances. Compared to the RT2012 schedule (schedule 1), which estimates at 25 kWh/m^2/year, this represents a significant lower value. However, it should be noted that in the RT2012 schedule the average power (5.7 W/m^2) is connected to the dwelling's area (229 m^2) and not to the number of inhabitants or their activity, explaining this large difference due to a very specific house. The appliances energy demand using schedules 2 and 3 when using the nominal power of the electrical equipment is also in the higher band of the histogram. In this case the energy demand for appliances is over 19 kWh/m^2/year. Moreover, four of the occupants of this modern building are teenagers and each child's bedroom has a TV, a computer, etc. It is therefore expected that the multimedia and appliances will be a major factor in the total energy consumption, as foreseen by the owner.

The situation changed, however, in the second case, schedules 4 and 5, when using the averaged power for the appliances (given in Table 2-5).

In this case, the energy demand for appliances is slightly lower than 8 kWh/m^2/year and is close to the statistical behavior represented by the comprehensive agent-based behavioral model.

As shown here, the results vary between the agent-based model and the simulations using schedules 1–5. It seems, therefore, interesting to compare these results with the actual measurements of the appliances energy use, once monitoring begins. This aspect will be treated in chapter 4.

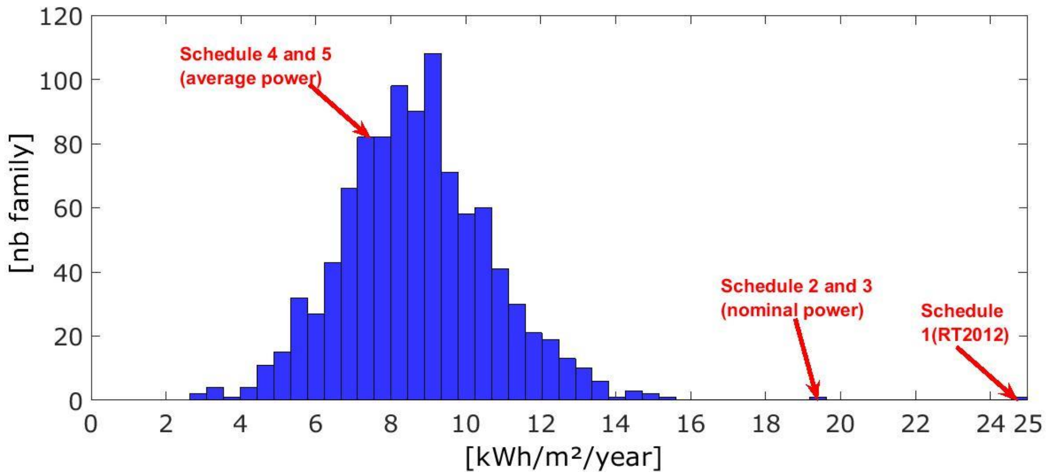


Figure 2-17: Histogram representing appliances energy demand for different families

2.6.3. Lighting demand

The results for lighting energy demand (Figure 2-18) show high discrepancies between the lighting demand estimated by the model and that estimated by the standard. The main cause may be because the RT2012 schedule considers a lighting power of 1.4 W/m^2. This building has a large living area so when one considers the power per square meter the tendency is to overestimate the energy demand for lighting. The agent-based behavioral model tends to give a low value for the lighting energy demand, based on national statistics. Here, the simulations for this house, due its distinctive features (large surface, occupied by six persons) appear to be very different from the national statistics.

However, the energy demand for lighting is only a small fraction of the total energy demand (less than 10% as shown Figure 2-8 and Figure 2-9).

Therefore this large difference in lighting energy demand has only a limited impact on the total energy demand of the present building.

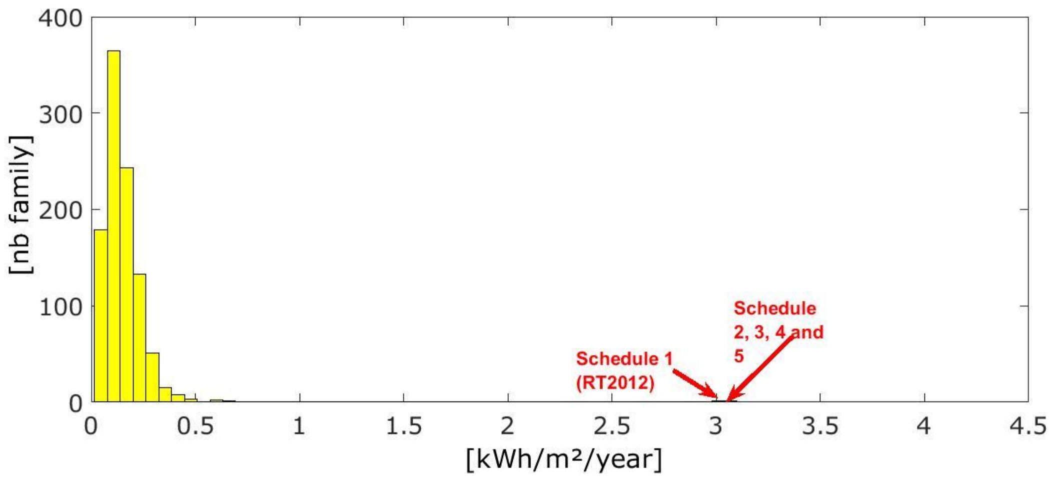


Figure 2-18: Histogram representing lighting energy demand for different families

2.6.4. Annual energy balance

Another goal of this section is to study the energy behavior of the building when looking at the annual energy balance. This mainly means answering the question "can this building be energy-positive when using different types of schedules, with different occupancy rates, different set-point temperatures and energy use?" We estimated that the on-site energy production would be up to 60 kWh/m^2/year. The estimated DHW energy demand is equal to 4,25 kWh/m^2/year and fans for the ventilation consume 2,6 kWh/m^2/year. This leads to the results presented in Figure 2-19. We calculated the annual energy balance as the difference between the total annual energy production and the annual total energy demand. Finally, except for a few families (representing only 2 %) the annual energy balance is positive. This is also the case when using schedules 1 to 5.

The building's design seems to be robust against various occupation scenarios. According to estimations (Figure 2-19), this well-insulated building achieves a positive annual energy balance. A large share in the annual energy balance stems from energy production. However, this is only an estimation. Within the evaluation of the energy performance of this building, it is therefore important to measure the building's real on-site energy production.

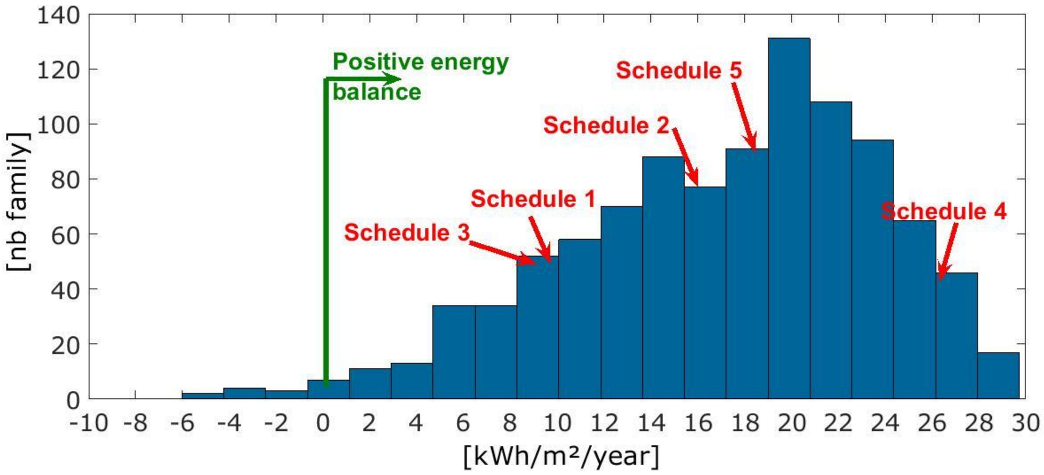


Figure 2-19: Histogram of annual total energy balance for different families

This study has only focused on the different energy demands for heating, appliances and lighting. However, for a more detailed understanding, the same methodology should be followed and repeated for the DHW and fan energy use as well as energy production. Even though here we showed that a positive energy balance is achieved for almost all families, during less sunny years or during a higher energy demand for DHW the situation may change. However, it is not investigated within this work.

2.7. Findings

The goal of this chapter is to study the impact of the occupant's behavior using building performance simulation. We show the discrepancy in thermal behavior of a low-energy building when comparing different schedules for occupancy, set-point temperature, appliances and lighting power. The different schedules were constructed using two approaches. First, we used deterministic schedules for presence of occupants, set-point temperature, appliances and lighting use maintaining the same number of occupants: the schedule related to the French thermal regulation RT2012 and four schedules based on the future owner's viewpoint. Secondly, one thousand schedules were generated using an agent-based model, based on national statistics.

When using the deterministic schedules, the results showed that the heating energy demand can vary from 10 to 19,6 kWh/m^2/year depending mainly on the set-point temperature. Moreover, modeling the appliances can change the energy demand outcome. Using the RT2012 schedule to model the appliances gives a high value for the energy demand. Differences in appliances energy demand also appeared when using nominal or average power. Compared to schedules 4 and 5 (average power for the appliances), schedules 2 and 3 (nominal power for the appliances), doubled the value for appliance energy demand. Consequently, this input (appliances power and use) creates uncertainty and differences in energy demand.

Then, using different occupant behavior schedules based on national statistics results in a wide range of values for heating, appliances and lighting energy demand. The results from simulations using deterministic scenarios (schedules 1–5) and statistical scenarios were also compared here, showing that the RT2012 schedule for the heating demand tends to consider a low value of the actual set-point temperature, and consequently of the heating energy demand, as compared to national statistics. However, the opposite is true for appliances energy demand, which tends to give a high value according to the standard. This can be explained by the fact that the RT2012 suggests a power of 5,7 W/m^2 and the present house has a large living area (229 m^2). Moreover, there is a discrepancy between the results obtained by the behavioral model and the deterministic results used here (the RT2012 schedule and the schedule provided by the owner). This may be due to the distinctive features of this house (large surface and six-member family), which distinguishes it from the national statistics. Indeed, within 1000 families there are only 12 families with five members, one family with six members and one family with seven members. Furthermore, for lighting demand, it was shown that the simulations for this house (due to its large surface) do not characterize the majority of the results of the agent-based behavioral model. Therefore, the actual heating, appliances and lighting use need to be monitored to provide a clearer idea of the actual energy consumption of these devices.

Furthermore, it is instructive to investigate whether or not the occupants' optimal set-point temperature is indeed close to the one suggested by the RT2012. By using a higher set-point temperature, overconsumption can occur, as shown in this chapter. Monitoring the actual set-point temperature is therefore suggested. This can more clearly indicate the future energy use and the occupants' behavior.

After testing different scenarios both deterministic and probabilistic we establish a range of values for the energy use, depending on occupant's behavior and based on national statistics. Now, we can use these scenarios in the design phase for future house which can give a more adequate image of the energy use compared to the national statistics, when evaluating the energy performance of the house.

Furthermore, it is important to repeat this statistical analysis also for the energy production for a complete assessment, taking into account the variability of weather conditions, but also the correlation between energy use and energy production.

In addition, this study only takes into account one indicator: energy use. An energy-efficient building must also provide thermal comfort and indoor quality for its occupants. Within the evaluation of the energy performance of this building, a tradeoff between energy consumption and thermal comfort should be considered. For this, future monitoring should include not only measurement of energy parameters, but also measurements of indoor temperature, some feedback concerning indoor comfort etc.

Given that this is a low-energy building, it should be noted that a positive annual energy balance is achieved for most families, showing the theoretical robustness of the design. Hence, a large proportion of this energy balance equation depends on the building's envelope. When performing the simulations, we assumed that the real envelope had been successfully implemented. However, as presented in section 1.4, the performance gap can also be caused by poor implementation of the envelope's components. Therefore, it is important to evaluate the envelope's real performance and to check if it meets the requirements.

Consequently, in the next chapters we will investigate the real behavior of this building. First, the envelope's performance will be evaluated in chapter 3 and the energy use will be monitored in chapter 4.

CHAPTER 3. Numerical and experimental study of the envelope's proprieties of a building

3.1. *Introduction: characterizing the envelope's proprieties*

As mentioned in previous chapters, the envelope is an important component of the global performance of a building. This is the "stationary" building's component that separates the outdoor environment from the indoor living conditions. Given its importance this building component has been widely studied (International Energy Agency, EBC Annex 58, 2016) (Hung et al., 2012), (Rode et al., 2010) (Jack, 2015), (De Meulenaer et al., 2005), (Oral and Yilmaz, 2002) . An energy-efficient envelope combined with a proper architectural design can contribute to lower requirements for heating, cooling and lighting, and increase thermal comfort. This can be done by selecting the optimal combination of design parameters such as the building's shape, orientation, window type, the materials' thermal properties, etc. Hence, predicting through design the optimal proprieties of a building's envelope is a complex process that includes a large series of inputs (outdoor conditions, surrounding environment, properties of the opaque and transparent components of the envelope etc.). This is meant to ensure outcomes such as maximum energy performance, as well as thermal, visual and acoustic comfort (Oral et al., 2004). For example among others works, in (Sozer, 2010) the authors showed that a precise design of the building envelope such as appropriate thermal insulation, glazing type and shading elements can significantly help to achieve the heating and cooling objectives and improve energy efficiency.

Once the design is optimized, the construction process is meant to successfully implement the optimal energy-efficient envelope as designed. In some cases, such as seven Passivhaus-certified dwellings presented in (Johnston and Siddall, 2016), the thermal performance of the building fabric has very closely met the predicted targets, also considering the various uncertainties associated with the in-situ test performed. However, different causes such as poor workmanship in the construction phase, uncertainties regarding the thermophysical properties of the materials used for construction etc., can lead to unexpected discrepancies between the predicted and the real thermal proprieties of the building's envelope (Rode et al., 2010). These performance gaps can reach up to 100% of the predicted values, as shown for 27 dwellings in the UK (Leeds Beckett Coheating Database (Johnston and Siddall, 2016)).

Evaluating the envelope's real proprieties is a challenging task. This is mainly because the envelope comprises many different elements (walls, windows, etc.). The envelope proprieties can be assessed using a global approach by looking at the whole building or a local approach by looking only at certain components separately. When considering the global approach, the whole building envelope's proprieties is examined. The heat loss coefficient (HLC) that will be more detailed in section 3.2.1, is the quantitative value used to evaluate the thermal envelope losses. The local approach comes as a complement and it includes checking for thermal bridges, workmanship defects or measuring the U-value of walls, for example.

In this chapter an approach is proposed for an overall evaluation of the envelope's proprieties. A theoretical value of the HLC is estimated in the design phase of a building through analytical calculation. Then an innovative in-situ dynamic test is developed. The real "as-built" thermal envelope's proprieties is calculated using measurements from the in-situ test. Finally, a comparison between the theoretical and the real value of the envelope's proprieties is presented.

In the preliminary step, the method is developed and validated on an experimental house described below. Then it is applied in order to assess the performance of the PosA building described in section 2.1.

3.2. Existing methods

In this section we present the existing methods for evaluating the global envelope's proprieties. There are two approaches. First, a steady state calculation is used to obtain a theoretical value of the overall envelope's proprieties, "as-designed". Second, in-situ tests, measurements and identification methods are used to obtain an "as-built" value. This section gives an overview of both approaches. Finally, local methods for complementary investigations are presented.

3.2.1. Global assessment

One way to express the overall thermal proprieties of the envelope is to study the energy transfer between the building and its exterior environment. It represents the transmission heat loss coefficient (**HT**) expressed in [W/K] which is the sum of transmission heat losses through the envelope (floor, walls, roof, windows, doors, thermal bridges etc.). This HT coefficient does not take into account infiltration losses.

There is also the heat loss coefficient (**HLC**) expressed in [W/K]. It represents the sum of transmission heat losses through the envelope (floor, walls, roof, windows, doors, thermal bridges etc.) and infiltration and/or uncontrolled ventilation (HT and infiltration losses). The HLC can be stated as the ratio between averages of the heating power Q_h [W] supplied to the building and averages of the air temperature difference ΔT [°C] between the building's indoor and outdoor environments.

$$Q_h = HLC \cdot \Delta T \qquad (3\text{-}1)$$

In an occupied building, there is also the concept of the building loss coefficient (**BLC**). It represents the addition of the thermal impact of air provided by ventilation systems to HLC. Table 3-1 presents a summary of all these coefficients used to characterize the global envelope proprieties.

NAME	NOTATION	SIGNIFICANCE	UNIT
Transmission heat loss coefficient	HT	The sum of transmission losses through the envelope (floor, walls, roof, windows, doors, thermal bridges etc.)	[W/K]
Heat Loss Coefficient	HLC	HT and infiltration losses	[W/K]
Building Loss coefficient	BLC	HLC and ventilation losses	[W/K]

Table 3-1: Summary of the main coefficients used to characterize overall envelope proprieties

3.2.1.1. Steady-state calculation

The European standard EN ISO 13790 and the French thermal regulation RT2012 specify a steady-state calculation of HT expressed in [W/K]. Moreover, the RT2012 thermal regulation gives tabular values for different elementary coefficients (for example, the linear thermal transmittance coefficient, etc.) to assist in the calculation of the HT. It is done in the design phase, to ensure that the building's energy performance complies with the RT2012 thermal regulation.

3.2.1.2. Calculations from in-situ tests using measurements

In-situ tests were developed to evaluate the overall envelope's real proprieties by identifying the heat loss coefficient (add papers Annex 58). These tests use the building's heating system and measurements (indoor and outdoor temperatures). Some noticeable differences were found depending on whether the test is performed with occupancy or within an empty building. Hence the duration and the uncertainty of such tests depend on this aspect.

First approach, when the test is performed under occupation, the thermal envelope's proprieties of a building can be characterized using the building's energy data along with information on the building's physical characteristics (area, windows, orientation etc.) (Erkoreka et al., 2016). For occupied buildings, the calculation needs to take into account the air flow used by the ventilation system. This methodology therefore involves the calculation of the BLC, instead of HLC, which is called the energy signature (Sjögren et al., 2007), (Vesterberg et al., 2016).

Regarding the other approach, when the building is not occupied, several short term in-situ dynamic tests are developed in literature to characterize the thermal proprieties of the envelope over a short period of time. For example, current short duration experiments are adopted in:

- Co-heating (Modera, and Sonderegger, 1979) (Bauwens and Roels, 2014), (Jack, 2015)
- PStar (Subbarao, 1988) (Judkoff et al., 2000)
- QUB (Mangematin et al., 2012) (Pandraud, 2014) (Alzetto et al., 2016)
- ISABELE (Bouchié, 2015)

These tests are done in an empty building (no occupants inside the building during the test). A complete description of these existing tests along with examples can be found in the report of European project PERFORMER (Bouchié, 2015), see (Table 3-2).

Among all these tests, the **co-heating test** is the most popular (Jack, 2015). It implies assessing the HLC by calculating, over a sufficient period of time (1–3 weeks), the ratio between the averaged heating power supplied to the building and the averaged air temperature difference between the indoor and outdoor environments of the building. The co-heating test is a sustainable and traditional method to test the as-built envelope of a building in real-life conditions. The test protocol includes the use of electric heaters to set a constant indoor temperature (usually 25°C) and several measurements (indoor and outdoor temperatures, supplied power etc.). While the test protocol is straightforward, practical implementation in a real occupied building can be difficult, intrusive and expensive given its duration and the limitation to only winter conditions. These limitations make this test quite unsuitable when measuring an actual occupied building. One option can be to perform a co-heating test during the holidays, when the building is not occupied. However, this option may not always be available.

Therefore, some additional short-term tests were developed. Some of these tests require maintaining a constant power during the experiment (ISABELE, QUB). For other methods such as already described co-heating and PStar, the test protocol involves maintaining a constant temperature (usually 25°C).

In all these short dynamic tests the heating power along with the indoor and outdoor temperatures should be measured. Some of these tests may need additional measurements such as horizontal radiation, wind conditions, or the infiltration air-flow rate. The test duration varies from: 1–2 days (QUB) or 2–3 days for Pstar, to 5–15 days for ISABELE. Yet, when the real performance of a newly built house is being tested, a short in-situ dynamic test seems to be a reasonable choice. This is mainly because data from several months or years are not available.

After performing these tests, the measured values (indoor air temperature, outdoor temperature etc.) are then used in order to identify envelope's global proprieties, as described in the Figure 3-1. Here a simplified model is used to simulate some measured values (for example indoor air temperature), given some deduction for model parameters. Identification methods are used along with the simplified model. Their goal is to identify the model's different parameters (building's thermal resistance etc.). An inverse approach is then used within the identification process to minimize the difference with the actual measured indoor temperature.

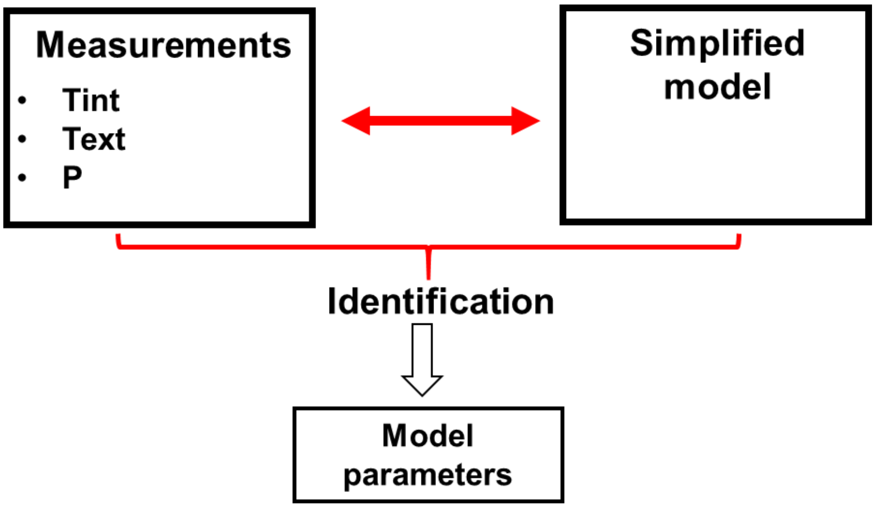


Figure 3-1: Systematic model identification procedure

In this purpose co-heating test users apply linear regression analysis or multiple regression (Bauwens and Roels, 2014). Furthermore, other test operators (QUB, ISABELE) use identification models as described in the next sub-section.

3.2.1.3. Simple models used to characterize the envelope's proprieties

This sub-section describes the calculation of the envelope's thermal performance using the measurements from the in-situ dynamic test. The main objective is to identify a thermal building model in order to simulate its behavior in any conditions and thus characterize its performance. In general, this is done through the identification of a lumped parameter circuit (short RC model).

The RC model proposes a simplified physical representation of a building. It uses the analogy between thermal balance and electrical current conservation equation. The analogy includes identifying the heat flux in the thermal model as the total electric current in the electric model. Internal thermal inertia, represented as the overall thermal capacitance of the building C, is the capacitor in the electric circuit. Finally, the overall thermal resistance of the building R is identified as the resistor in the electric circuit. Temperatures are expressed by the voltages of the electric circuit.

Essentially, the following equation gives the thermal characteristics of a building, using the simplest 1R1C (one resistor-one capacitance) model as shown in Figure 3-2.

$$C\frac{dT_{int}(t)}{dt} = Q_h(t) - \frac{1}{R}(T_{int}(t) - T_{ext}(t)) \qquad (3\text{-}2)$$

where:

C is the overall thermal capacitance in [J/K],

T_{int} is the indoor room air temperature [°C],

T_{ext} is the outdoor air temperature [°C],

Q_h is the supplied power [W]

R is the overall thermal resistance [(m²K)/W].

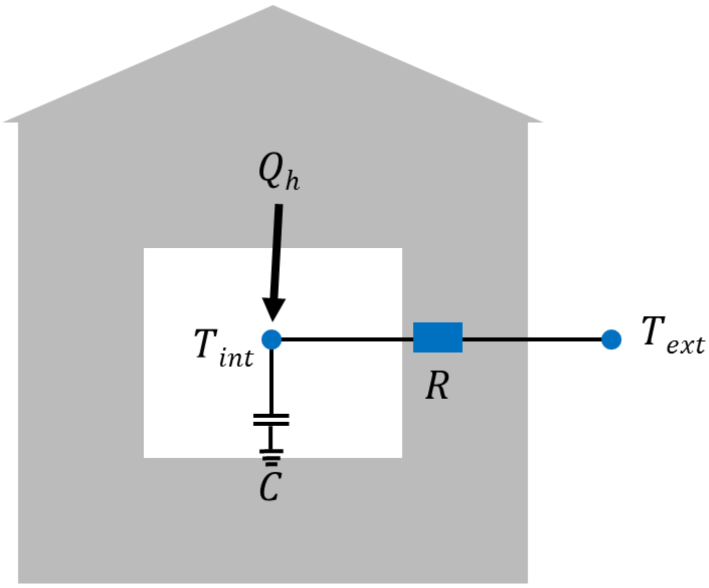


Figure 3-2: Simple model RC

This simplest RC model, as shown in Figure 3-2, a first-order RC lumped parameter circuit used in (Park et al., 2011) provided good results in estimating the internal temperature of a well-insulated room. The authors claimed to have good agreement between the measured and simulated results. Further good agreement between the RC model simulation (modeled in SIMSPARK) and measurements was shown in (Chahwane et al., 2009). First, the authors validated the accuracy of their model for the case of a high-weight concrete and then a phase-change material wall. The model showed good performance on building scale also in the case of ventilation for both summer and winter. Many other studies have shown good results when using a RC model. In (Jiménez et al., 2008) the flexibility of several models, with different inputs and outputs were validated using Matlab to estimate the thermal properties of a wall. However, in some cases 1R1C model is not precise enough. For example, in (Fraisse et al., 2002) more complex RC circuits were used for overall modeling of the building. The authors considered using an aggregation of several similar walls into a 3R4C model to reproduce the conductive transfers in the walls. They suggest that this is relevant if the temperature distribution within the wall is not of interest, and the period of internal inputs is longer than 3 hours. To model the heating floor, a water loop model (1R2C) was connected to a two-wall model (3R4C). The results showed only a small difference between experimental data and the simulation results for indoor temperature and heat flux.

In (Bacher and Madsen, 2011) the authors compared a hierarchy of models of increasing complexity to identify the heat dynamics of a single-story 120-m^2 building. Among other results, they found that the estimated total thermal resistance of the building envelope was quite similar for all models.

All these studies have shown a good potential to assess the thermal properties of a building using an electric analogical model.

Therefore, a RC model is often used to identify the thermal resistance and capacitance of a building, and therefore the HLC, which represents the inverse of thermal resistance. Measurements from the in-situ tests presented in the previous subsection are used as input data.

- **Accuracy**

As explained above, the envelope represents a complex component of the building. An overall evaluation includes all its constituents (walls, windows, etc.), possibly leading to uncertainties. For the calculation of the HLC (or HT) various uncertainty ranges are accepted. For example, in (Thomsen et al., 2005) the authors specified a 10% difference between the calculated and measured value of the HLC for a Finnish house, and 14% for an American house constructed as part of the IEA Task 13.

In (Bauwens, 2015) the author compared results between expected and assessed transmission HLC, after performing a co-heating test on different buildings. The difference was about 1.4% when using linear regression and 2.9% using ARX models, for a detached test house.

In (Jack, 2015) the author used co-heating method to determine the HLC, and the accuracy was ±15%.

In the European PERFORMER project, the accuracy for currently developed methods for measuring the envelope's proprieties (Bouchié et al., 2015) is specified. For example, for QUB the accuracy is specified to be up to 20% (open to debate) and 5% for Pstar/STEM for good repeatability. Also within this project, the authors proposed a summary of all these methods used to evaluate the envelope's proprieties (Table 3-2).

METHOD NAME	INDICATOR MEASURED	OCCUPANCY	HOW LONG?	STRONG LIMITATIONS(SCOPE)	COMPLEXITY	ACCURACY
Heat flow meters	U value of some envelope components	Yes	1-3 weeks	No solar radiation, "simple" wall (no thermal bridge, no air cavity, no window…)	May require a lot of sensors to be more accurate	15-30% if tested walls included in the scope
QUB	HLC	No	1-2 days	Shut down ventilation system	Measurement need: Text, Tint, heat power injected in the zone by a specific heater	20% (up to debate)
Pstar/STEM	HLC	No	2-3 days	Only in winter conditions under cold climate, shut down ventilation system	Measurement need: Text, Tint, heat power injected in the zone by a specific heater	Good repeatability (5%) but bad comparison with co-heating test (35%)
Co-heating	HLC	No	2-5 weeks	Only in winter conditions under cold climate (avoid overheating due to sun radiation), shut down ventilation system, avoid building with high thermal inertia	Measurement need: Text, Tint, heat power injected in the zone by a specific heater	5-20% up for debate: difference with theoretical value is improved if solar gain is modeled with more precision
ISABELE	HLC	No	5-15 days	Avoid (or shade) glazing surfaces, shut down ventilation system	Measurement need: Text, solar radiation, Tint, heat power injected in the zone by a specific heater	To be calculated
HYBRID	HLC	No	5 days	Shut down ventilation system, have adequate weather conditions	Measurement need: Text, solar horizontal radiation, Tint, power injected	Data dependent, usually lower than 15%
EBBE	Mean-U value of the building	Yes	3-4 months	Only in winter conditions under cold climate, occupancy scenarios are needed(by audit presence detection), avoid building with high thermal inertia	Measurement need: Text, solar horizontal radiation, wind,Tint, heat power, airtightness (n50 or eq), air flow by ventilation system	Not developed yet

Energy signature	BLC	Yes	1-3 years	Originally under cold climates, not too much glazing surfaces, “quasi-constant” occupancy for month to month, avoid building with high thermal inertia	Measurement need: monthly Heat Degree-Days (or Text), Tsetpoint (or Tint), heat power	Not developed yet
PRISM	NAC (Normalized Annual Consumption index)	Yes	several years	Only in winter conditions under cold climate, not too much glazing surfaces, “quasi-constant” occupancy for month to month,, avoid building with high thermal inertia, efficiency of the heating system must be constant	Measurement need: monthly Heat Degree-Days (or Text), Tsetpoint (or Tint), monthly global energy consumption (from billing data)	Good for the NAC index (5%) but can by greater if BLC is deduced
Blower door test	n50(or eq.)	No	1 day	Avoid extremely large buildings, specific climatic conditions (wind < 6 m/s…)	-	Given in the standard and national guides
Tracer gas decay	Air flow rate	Yes	1-5 days	Avoid extremely large buildings, practical aspect such as secure gas bottle storage must be considered, specific climatic conditions (wind…)	Measurement need: gas injection, gas analyzer (can be complex to use depending on tracer gas)	Given in the standard
Thermography analysis	Envelope insulation damages/defaults	Yes	1 day	Specific climatic conditions (wind, temperature difference, solar radiation…)	-	Not designed to provide quantitative information

Table 3-2: Summary of methods used to evaluate a building envelope’s proprieties (adapted from PERFORMER report (Bouchié et al., 2015)

As specified, the HLC takes into account infiltration losses, which may significantly impact the results. In the next subsection, we provide an overview on this aspect.

3.2.1.4. Infiltration air-flow rate

According to the ASHRAE Handbook, infiltration represents the unwanted introduction of outside air into a building through cracks in the building envelope and doors. The main causes can be the wind effect, a negative pressurization of the building, or a stack effect (air buoyancy forces). The infiltration rate represents the volumetric flow rate of infiltration, usually expressed in cubic meters per hour (m^3/h). It is very important to ascertain the infiltration air flow rate when assessing the thermal proprieties of a building’s envelope. The RT2012, BBC Effinergie and Effinergie+ labels use the $Q_{4Pa\text{-}Surf}$ value to estimate the infiltration air-flow rate. $Q_{4Pa\text{-}Surf}$ represents the ratio between the leakage flow required to maintain a differential pressure of 4 Pa and the total envelope’s heat loss area (except the lower floor) [$m^3/(hm^2)$]. In France, the $Q_{4Pa\text{-}Surf}$ target value imposed by the RT2012 thermal regulation for the residential sector is 0.6 [m^3/'(hm^2)] (Table 3-3).

TARGET VALUE	RT2012, EFFINERGIE, BBC	PASSIV'HAUS
Residential sector	0.6 [$m^3/(hm^2)$]	0.16 [$m^3/(hm^2)$]
Single-family house		

Table 3-3: Mandatory airtightness treatments for single-family homes: RT 2012 target value

Limiting the infiltration air-flow rate can help increase energy savings. In (Charrier and Jobert, 2011) the authors showed that infiltration air flow can increase energy consumption by about 5 and 10 kWh/m^2/year. In addition, a good estimation of the infiltration flow rate is very significant in the design of systems. This is because it can lead to lower requirements for heating and cooling system capacity and better performance of ventilation systems. As a result, good proprieties for envelope airtightness leads to good management of the ventilation air flow and consequently to optimal thermal comfort and air quality for the occupants. The European Standard EN 13829 gives more details about how to perform in-situ testing to establish the building envelope's air tightness level. The most popular methods for assessing the infiltration air flow rate are tracer gas (ASTM International Designation: E 741 – 00) (Laussmann and Helm, 2011) (Sherman, 2013) ((Labat et al., 2013) and blower-door test (European Standard EN 13829) .

- **Tracer gas (under real pressure conditions)**

The most popular tracer gas technique is the "decay" method. It implies injecting and mixing a gas into the air volume of a room (building) until a certain concentration is reached. Then the injection of the gas is turned off and the decrease of the gas concentration is recorded as a function of time. Often, the tracer gas is CO_2 (Muhič and Butala, 2006) measured through CO_2 transmitters, which are not very expensive and give good accuracy (Ghazi and Marshall, 2014).

- **Blower-door test (under imposed pressure difference)**

The goal of the blower-door test is to measure the air leakage of a room or building. The operational principle is to use a specially designed calibrated fan that is mounted in a doorway for a temporary period of time and used to blow air into or out of a room or building. The objective is to establish a pressure difference between the inside and the outside of the room or building that will force air to leak through all the envelope holes. Therefore, the air-flow value that is required to maintain a constant pressure difference is equal to the quantity of air that is leaking from the building (Blower Door Operation Manual for For Series 200, 300, 1000 and 3000 systems). More information about a blower door functioning can be found in Annex B.1.

The infiltration air-flow rate can be expressed by the relationship between the air-flow rate and the pressure difference across the building (equation 3-3).

$$q_L = C_L \Delta p^n \tag{3-3}$$

where:

q_L is the volumetric leakage air-flow rate [m^3/h]

$C_L$is the air leakage coefficient [m^3/(hPa^n)]

Δp^n is the pressure difference between inside and outside the room or building [Pa]

n is the airflow exponent ($0.5 \leq n \leq 1$)

Both methods are widely used to measure a building's infiltration air-flow rate. The advantage of using the tracer gas method is that it gives the real infiltration air flow, as it is performed under real pressure conditions. However, this method is very subjective to the tracer gas used, the accuracy of the instruments used and the weather conditions (Patel et al., 2011). The blower-door test seems a less complicated and realistic approach to measuring the infiltration air-flow rate of a building (Patel et al., 2011). However, low wind speed, the stack effect etc. must be taken into account. In addition, it imposes a pressure difference between the indoor and outdoor environments of the building. Therefore, the real infiltration air flow needs to be calculated posteriorly, but it requires a difficult calculation.

3.2.2. Complements: detection of local problems with the envelope

As a complement for characterizing the overall envelope's proprieties, several methods exist to detect local envelope problems. Most popular are thermography analysis and local measures of the U-value.

A qualitative assessment of local anomalies within the envelope can be made using **thermography analysis** (Taylor et al., 2014), (Balaras and Argiriou, 2002). This technique detects thermal bridges due to connections between different elements (walls, windows), poor workmanship etc. It implies using a thermographic camera while existing a temperature difference between the indoor and outdoor environments. Several considerations should be taken into account as shown in (Van De Vijver et al., 2014). The authors claimed that the indoor-outdoor temperature difference plays a significant role for the execution of a thermographic analysis. The optimal moment for performing the infrared thermography analysis can be defined by analyzing the direction of the heat flux, the defect type and the temperature gradient (Bauer et al., 2016). However, in general, it is recommended that the test to be performed early in the morning, before sunrise.

Another technique for evaluating the envelope's local proprieties consist in measuring the **U-value** of each component (walls, windows). This is done using heat-flow meters and temperature gradients (Asdrubali et al., 2014) (Ficco et al., 2015). However, the unpredictability of climatic conditions and thermal inertia of the component under study can lead to uncertainties (Ficco et al., 2015).

As presented above, the HLC takes into account transmission and infiltration heat losses. Essentially HLC can be split into two parts: transmission heat loss and infiltration heat loss. However, these tests do not measure precisely infiltration air flow. Usually the experiments presented here are conducted with a shutdown of the ventilation systems to reduce uncertainties. Nevertheless, the envelope's airtightness must not be neglected. Therefore, infiltration air flow is measured using a blower door (European Norm EN 13829) or tracer gas or both (Thébault and Bouchié, 2015) (Patel et al., 2011) before the test. However, uncertainties associated with the actual building air infiltration, during the test, are present. To exceed these limits, an experimental dynamic in-situ test measuring infiltration air-flow during the test is been developed within this thesis. Section 3.3 describes the protocol method and identification procedure used within the present thesis.

3.3. Proposed experimental protocol and identification procedure

The protocol for a specific experimental test is presented in this section. Then the numerical model used for the HT and HLC calculation using measurements is presented. Finally, the identification methods used within the proposed method are presented in subsections 3.3.3 and 3.3.4.

3.3.1. Proposed test protocol: including infiltration

The in-situ dynamic test used to characterize thermal envelope proprieties an energy efficient single-family house is described below.

In order to be suitable for this type of building this test has to be short, as this is an occupied house and the house is not always accessible. Also it has to be simple, in order to be easily replicate. In addition, it needs light monitoring, as it takes time to install. All this conditions means more uncertainties, therefore these uncertainties will need to be reduced.

Based on the existing methods presented previously, the contribution of the present thesis was to reduce uncertainties by focusing on two aspects:

- developing an experimental dynamic in-situ test separate evaluation of infiltration air-flow during the test and therefore calculation the HT
- using a Bayesian inference to reduce measurements and model uncertainties

The approach used here was to find a way to combine these two well-known tests: using electric heaters and a blower door.

The main idea is to use controlled electric heaters programed to function through an on/off cycle every 12 hours. This cycle represents a heating and a no-heating phase. This also capture the charging and discharging of the thermal inertia of the building. To avoid uncertainty due to internal and solar gains, the house must remain unoccupied and the blinds kept closed. Also, ventilation must be turned off during the test. Measurements of indoor and outdoor temperatures are requested along with the heating power needed to perform the test as shown in Figure 3-3. We only use the first complete cycle of 12 h heating and 12h no heating for the determination of the HLC and HT. Nevertheless, the duration of the test is approximately 48h, when including the test preparation (sensors implementation). More, the internal gains are also measured during the test.

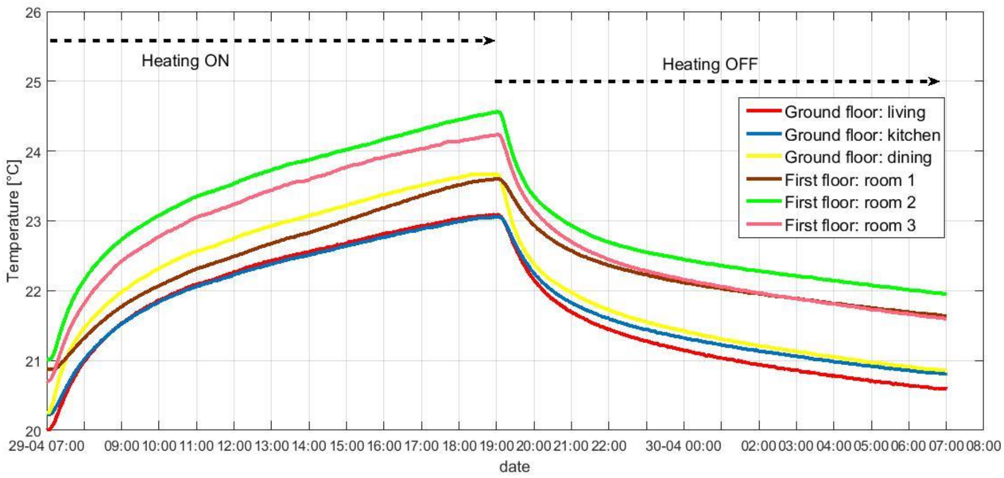


Figure 3-3: Temperature measurements

As it is explained in section 3.2.1, the expression of the HLC takes into account the infiltration air-flow. Usually, a blower test performed before or after the test can give a reference value for the infiltration air-flow, but this can lead to uncertainty, mainly because this value is influenced by the wind pressure on the exterior surfaces of the building and the stack effect. Therefore, the goal here is to characterize the thermal envelope's proprieties of the building by assessing actual infiltration air flow at each time step. A blower-door test at a low air flow value is performed during the test to measure infiltration air-flow. The protocol is very straightforward and simple. Practical application will be reported in the following sections.

3.3.2. Description of the 3R2C model

The goal here is to identify, using measurements, the total thermal resistance of the building envelope. Following literature, the three resistances and two capacities (3R2C) model is implemented and is shown in Figure 3-4.

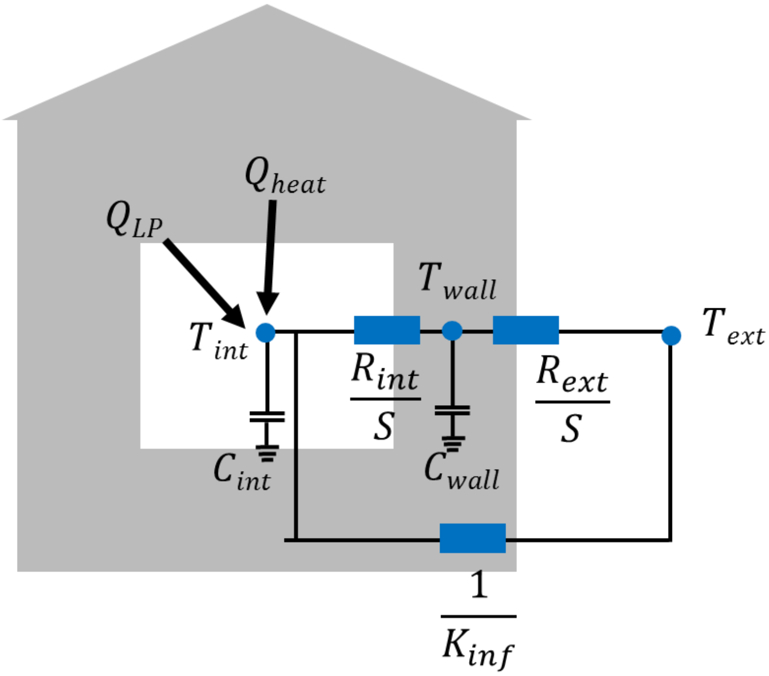


Figure 3-4: 3R2C model representing an electrical analogy of the house

For this model, there are two direct output T_{int} and T_{wall}. They represent, respectively, the mean indoor air temperature and the mean wall temperature of the building. The simplicity of this hypothesis appears to be valid since the model seeks to estimate the overall heat loss coefficient of the entire building. The interior thermal capacity C_{int} [J/K] takes into account the capacity of the interior walls, air and the furniture of the house. An additional capacity is added to the model C_{wall}, representing the building envelope capacity, or as called here the walls' thermal capacity [J/K]. The second capacity appears to be a plausible choice, since this model aims to represent the process of the charge and discharge of a building. Therefore, thermal inertia plays an important role.

The thermal resistance of the building is modeled as the sum of two resistances R_{int} and R_{ext}, following the conclusions of (Bacher and Madsen, 2011).

The main hypothesis here is that internal thermal resistance R_{int} combines the convective and conductive components in a single variable and a part of the wall resistance. The other part of the wall resistance is considered in the external thermal resistance R_{ext} , which also combines the external convective and conductive component.

An additional thermal resistance representing the infiltration losses is also included.

Here, Q_{heat} represents the heaters' electric power [W] and Q_{LP} the internal load electric power (computer, data loggers etc.) [W].

The dynamic state-space model for this system can be written as:

$$C_{int}\frac{dT_{int}}{dt} = Q_{heat}+Q_{LP} - S/R_{int}(T_{int} - T_{wall}) - K_{inf}(T_{int} - T_{ext}) \quad (3\text{-}4)$$

$$C_{wall}\frac{dT_{wall}}{dt} = S/R_{int}(T_{int}-T_{wall}) - S/R_{ext}(T_{wall} - T_{ext}) \quad (3\text{-}5)$$

We note U_{int}=1/R_{int} and U_{ext}=1/R_{ext}. Finally we obtain the output, which in this case represents the indoor air and wall temperature as:

$$\dot{T} = A_p T(t) + B_p \mu(t) \quad (3\text{-}6)$$

$$T(t_0) = T_0,$$

where $T^{\dot{}} = \begin{bmatrix} \dot{T_{int}} \\ \dot{T_{wall}} \end{bmatrix}$, $A_p = \begin{bmatrix} \frac{S*(-U_{int})-K_{inf}}{C_{int}} & \frac{S*U_{int}}{C_{int}} \\ \frac{S*U_{int}}{C_{wall}} & \frac{S*(-U_{int}-U_{ext})}{C_{wall}} \end{bmatrix}$

$$B_p = \begin{bmatrix} \frac{1}{C_{int}} & \frac{1}{C_{int}} & \frac{K_{inf}}{C_{int}} \\ 0 & 0 & \frac{S*U_{ext}}{C_{wall}} \end{bmatrix}, \mu(t) = \begin{bmatrix} Q_{heat} \\ Q_{LP} \\ T_{ext} \end{bmatrix}$$

A Matlab code is implemented to reproduce this system of equations, where:

C_{wall} is the walls' thermal capacity [J/K]

T_{wall} is the wall temperature [°C]

S is the heat loss surface [m^2]

K_{inf} is the infiltration enthalpy losses [W/K]

Once the model was created, an inverse approach must be used to search for the best fit and to identify the input parameters. This can be done using either deterministic or probabilistic approach.

3.3.3. Deterministic identification

A deterministic identification searches for the best fit between the model outputs time-dependent, indoor air temperature in this case, and the actual observed values (measurements). For this case the coefficient of the variation of the root mean square error ($CVRMSE$) is chosen as the accuracy indicator. If S_i represents a simulated temperature during the time i and M_i represents a measured temperature during the same time i, and $\overline{M_i}$ represents the mean of all the measured values, then the $CVRMSE$ can be expressed as:

$$CVRMSE = \frac{\sqrt{\sum_i^n (S_i - M_i)^2/n}}{\overline{M_i}} \quad (3\text{-}7)$$

A Matlab program using the *fmincon* function is implemented to optimize the search for the minimum $CVRMSE$ between the model's indoor simulated temperature T_{int} and the actual measured air temperature. *Fmincon* finds a constrained minimum of a function of several variables.

3.3.4. Bayesian inference as probabilistic identification

As we said, we first used the deterministic identification to identify thermal resistances and capacitances. However, these deterministic values obtained for the model's parameters of the RC model represent only a single value. Un-quantified existing uncertainties such as model form uncertainty (model assumptions, simplifications etc.) and measurement uncertainties can lead to computing a cumulative effect on model outputs (such as temperature in this case). To improve the estimation of parameters by quantifying their associated uncertainties, a Bayesian formulation as proposed by Kennedy and O'Hagan (Kennedy and O'Hagan, 2001) can be used.

The Bayesian framework is currently used worldwide for different kinds of applications: parameter estimations, predictions etc. (Ling et al., 2014) (Sankararaman and Mahadevan, 2015), (Vernay et al., 2015), (Li and Mahadevan, 2016). For example, in (Tagade et al., 2016) the results showed that the calibrated P2D-ECT (pseudo-two-dimensional electrochemical thermal) model predictions using a Bayesian framework match the experimental data. The framework also assesses the credibility of the model through posterior variance of the model's uncertainty while simultaneously estimating the parameters. A successful parameter estimation and performance prediction while using a Bayesian inference of a gas turbine and a steam cycle is also reported in (Boksteen et al., 2014). The authors highlight the advantage of accurate information on the plant performance, while accounting for the uncertainties.

In the building field, several studies have been conducted, (Heo and Zavala, 2012) (Manfren et al., 2013) (Rouchier et al., 2015). In the framework proposed by (Tian et al., 2016) Bayesian inference could be used, in case of missing data, to search for the informative data used to accurately infer unknown input parameters of building energy models. A solution showing considerable alignment between building energy model prediction, monthly consumption and demand data using lightweight Bayesian inference is presented in (Li et al., 2015). To help decision-makers better assess performance risk when retrofitting existing buildings, the authors of (Heo et al., 2015) used a methodology that demonstrates that calibration reduces the uncertainty of model predictions.

All the above reasons lead to choosing the Bayesian inference to improve accuracy and to quantify the uncertainty for the proposed 3R2C model. The program developed by (Li et al.,

2015) (Heo, 2011) is used for the calibration process. Bayesian inference starts with a prior belief $\mathrm{p}(\theta)$, which represents the modeler's knowledge and experience quantified as probability distributions. This prior distribution is updated through Bayes theorem (3-8) by assimilating observations or measurements through the likelihood function $p(\theta, y)$, which will determine how closely the model outputs match the measurement data, and so it acquires parameter probability distribution called posterior distribution $p(y, \theta)$ (Heo et al., 2015). The likelihood function as formulated by (Kennedy and O'Hagan, 2001) is expressed as in (3-8):

$$p(\theta, y) \propto p(y, \theta) \times \mathrm{p}(\theta) \tag{3-9}$$

$$y(x) = \eta(x, \theta) + \delta(x) + \varepsilon(x) \tag{3-10}$$

where,

$y(x)$ stands for observations;

$\eta(x, \theta)$ represents model outputs at given input settings (conditions) x and calibration parameters θ;

$\delta(x)$ describes where the model falls short, as in the quantification of the discrepancy of the model regarding reality (the actual behavior of the building);

$\varepsilon(x)$ represents the measurement errors, assumed to follow a Gaussian distribution.

Here, both the discrepancy term $\delta(x)$ and the model outputs $\eta(x, \theta)$ are modeled as a Gaussian process. The uncertainties associated with the measurements are assumed to be normal with zero mean and an unknown variance. A detailed description of the inference process and the mathematical formula used can be found in (Heo, 2011). The posterior distribution is obtained using a Markov chain Monte Carlo (MCMC) method, as explained in and (Heo, 2011) (Li et al., 2015).

3.4. Application to I-BB experimental house

In this section we present the results after applying the methodology to evaluate the envelope's proprieties on the I-BB house, described in the following lines. The methodology is first tested and validated on this precisely controlled experimental house. There are no occupants inside the building and therefore no additional uncertainties regarding this aspect. Moreover, building performance was already assessed in previous studies, enabling validation.

3.4.1. Experimental building (I-BB)

The experimental building (Figure 3-5) used in this chapter is located on the INCAS experimental platform, situated on the Technolac site in Bourget du Lac, France, at the National Institute of Solar Energy (INES).

Figure 3-5: I-BB house

This house, called I-BB, has external insulation. The vertical and horizontal wall assembly was selected to optimize the future energy performance (Stefanoiu et al., 2014) (Spitz et al., 2012) and is presented in Table 3-4 and Table 3-5.

EXTERIOR WALL	THICKNESS [cm]	THERMAL CONDUCTIVITY [W/(mK)]	THERMAL RESISTANCE [m^2K/W]
Exterior rendering	1.5	1	0.015
Extruded polystyrene	20	0.03	6.667
Shuttered concrete	15	1.75	0.086
Interior rendering	1.5	0.43	0.035

Table 3-4: Exterior vertical wall composition for the I-BB building

HORIZONTAL WALL		THICKNESS [cm]	THERMAL CONDUCTIVITY [W/(mK)]	THERMAL RESISTANCE [m^2K/W]
Low-floor	Concrete screed	8	1.75	0,05
	Concrete slab	16	2.5	0,06
	Extruded polystyrene	20	0.03	6,67
	Rendering	1	0.41	0.02
Intermediary floor	Concrete screed	8	1,75	0,05
	Slab	4	1,75	0,02
	Block floor unit	16	1,23	0,13
	Interior plaster	1	0.4	0,035
High-floor	Glass wool	40	0.035	11.4

Table 3-5: Horizontal wall composition for the I-BB building

Solar blinds and windows were chosen to obtain maximum energy efficiency in winter and thermal comfort in summer. On the south, west and east sides there are double-glazed windows with a Ug-value of 1.1 [W/(m^2K)]. On the north side, triple-glazed windows with an Ug-value of 0.7 [W/(m^2K)] were selected. This is an airtight building with energy-efficient mechanical ventilation intended to reduce heating loss, through heat recovery unit.

The house is not occupied. Internal gains stem from electrical equipment and data loggers. On the ground floor there is an inverter, a computer, three transformers and two data loggers. Upstairs, there are two data loggers and two transformers. We considered that the energy consumed equals the energy dissipation loads corresponding to a value of 160 W on the ground floor and 40 W, on the first floor.

Heating demand is provided by electric heaters.

This experimental house is part of a four houses platform. It was built for research purposes: to test different systems; to validate models, etc. Therefore, the monitoring of this house includes approximately 100 sensors. Indoor conditions are measured using air temperature sensors (air, surface, operative) and relative humidity sensors. Outdoor conditions are measured using a weather station on the INES site, including measures of temperature, humidity, pressure, wind (speed and direction), rainfall as well as the different radiation measurements (global, infrared, diffuse and direct). A detailed description can be found in (Spitz, 2012).

3.4.2. Preliminary study: theoretical HT

3.4.2.1. Steady-state calculation

The HT is calculated for the I-BB building using RT2012 standard procedure, giving a value of 73 W/K, as shown in Figure 3-6. The majority of transmission losses (31 W/K representing 42%) are represented by opaque walls (vertical and horizontal), followed by window thermal losses (29 W/K representing 40%) and thermal bridges (13 W/K representing 18%).

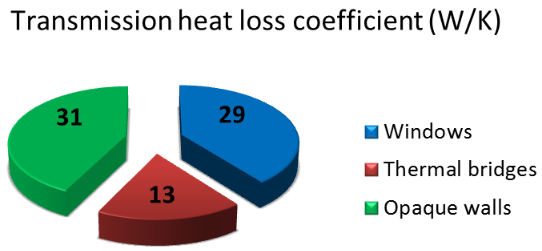


Figure 3-6: Theoretical calculation according to RT2012

3.4.2.2. Using a dynamic building performance simulation

Here, a steady-state simulation is performed for the I-BB building. A validated EnergyPlus model (Stefanoiu et al., 2014) is used to recreate an ideal experiment where outdoor environments (temperature, solar gains) are set constant throughout the year.

To represent an ideal situation without uncertainties, the internal gains are set to zero. Also, ventilation and infiltration flow rate are considered null. A situation with closed blinds is simulated, to reduce solar gain uncertainty. The internal temperature is set to 25°C.

The simulated situation represents a day where the outdoor temperature T_{ext} is almost 10°C as first performed for co-heating in (Modera, and Sonderegger, 1979). Then the HT is simply calculated by dividing the heating load supplied to the building Q_h by the temperature difference between inside and outside ΔT.

A weather files has been generated through the Weather Statistics and Conversions software, using the values presented in Table 3-6 for different fields.

WEATHER PARAMETERS	VALUE
Outdoor temperature [°C]	10,5
Atmospheric pressure [hPa]	975
Wind direction []	103
Wind speed [m/s]	2,07
Global radiation [W/m^2]	807

Table 3-6: Values chosen for the EnergyPlus constant weather file

The results have shown that the simulated heating power Q_h is 1030 W and ΔT is 14,5°C. The HT value is about 71 W/K.

Nevertheless, the sensitivity of the HT associated with the outdoor conditions is not studied here. However, in (Jack, 2015) the author studied the sensitivity of the HLC to a change in ΔT. The author showed that the sensitivity of the HLC to a variation of ±1°C in the ΔT measurement is approximately 5% on average.

In (Mejiri, Peuportier, Guiavarch, 2013) the HLC was calculated for the same building. The value obtained from the steady-state theoretical calculation for the HLC was 76 W/K. Another calculation was done in (Mejiri, Peuportier, Guiavarch, 2013) using the energy signature method, based on long-term measurements, provided a value of 82 W/K for the HLC. The authors considered the steady-state value as a reference value because this is a new experimental energy-efficient building, and therefore the data available (geometry, construction materials' thermo-properties etc.) are considered accurate. Therefore, here only the calculated steady-state value (76 W/K) of the HLC in (Mejiri, Peuportier, Guiavarch, 2013) is considered for the comparison. However, as described above the HLC takes into account the infiltration air flow; therefore this phenomena must be included before comparison between HT and HLC.

For a better assessment of infiltration air flow, a blower-door test was performed on 14 March 2016. As can be seen in Table 3-7 for the experimental house, a value of 0.12 m³/h/m² for the $Q_{4Pa\text{-}Surf}$ was found. The blower-door test results show a good level of air tightness that meets the RT2012 and Passiv'Haus targets (see also Table 3-3) and section 3.2.1.4.

RESULTS	
Air leakage rate at 4 Pa, Q_4 [m³/h]	23.7
Air permeability at 4 Pa, $Q_{4Pa\text{-}Surf}$ [m³/(hm²)]	0.12

Table 3-7: Blower-door test results for I-BB building

The heat loss due to infiltration air flow is then calculated using the EN 12831 resulting in the value of 2.5 W/K. By adding this infiltration value to the HT, the HLC can be then calculated. The results presented in Table 3-8 show good agreement when comparing the steady-state value calculated in section 3.4.2.1 and the value obtained in (Mejiri, Peuportier, Guiavarch, 2013). Compared to the value using the EnergyPlus model, the results showed a 6% difference (Table 3-8).

HLC [W/K] calculated previously in (Mejiri, Peuportier, Guiavarch, 2013)	HLC [W/K] calculated steady state (section 3.4.2.1)	HLC [W/K] calculated using EnergyPlus (section 3.4.2.2)
76	75.5	71

Table 3-8: Comparison of HLC results

3.4.3. Testing and experimental results

The I-BB house is equipped with a large number of sensors. Here, only the air temperature (indoor and outdoor) and energy meters were used for this test. The air temperature sensors are located in the middle of each room at 1.1 m height. These sensors were PT100, Class A: ± 0.35°C from −100 to 100°C. The weather station described in section 3.4 is used to measure the outdoor air temperature. The test was performed in April 2016.

Four simple electric heaters (Applimo) were used for this test. A total average heating output of 2500 W was used during the test, distributed as follows:

- two on the ground floor (nominal power 1000 W and 500 W)
- two on the first floor, (nominal power 500 W)

To record energy consumption, a 4000 Logger Wemeter was used. The data can be recorded on the device’s internal memory or transmitted using a SDHC card. A digital weekly programmer (Blyss) was used to program the 12-hour on/off cycle for the electric heaters. For this case, the heater-ON phase began at 07:00 and ended at 19:00, when the heaters were OFF during the night. However, it should be noted that this test only uses nighttime for the HLC and HT calculation, when the heaters were OFF.

Indoor and outdoor air temperature and electrical heater power were measured with a 1-minute time step. Also, the internal load, due to the other equipment in the house (QLP) was measured before the test and estimated at a constant value of 230 W. This includes the energy consumption of the data loggers, computer etc. Overall solar irradiance is disregarded in this case. The blinds were closed for the test period, and only the night time is used for the calculation.

Figure 3-7 represents the evolution of indoor air temperature measured at different points during the night from 29 to 30 April 2016. For this case, the selected air temperature sensors located at 1.1 m high in the middle of the each room were chosen to be the most representative of a global mean air temperature. Figure 3-7 shows that temperatures recorded on the first floor are higher, by about 1,5 °C, than those recorded on the ground floor, due to thermal stack. On the other hand, the temperature on the ground floor present a difference lower than 0,4°C for the three sensors. Moreover, the general shape of all curves decreases very similar. We calculated the mean indoor air temperature as the average between all the indoor temperature measurements located at 1.1 m high in the middle of the each room. In Figure 3-7 this mean indoor air temperature is represented as the dotted line.

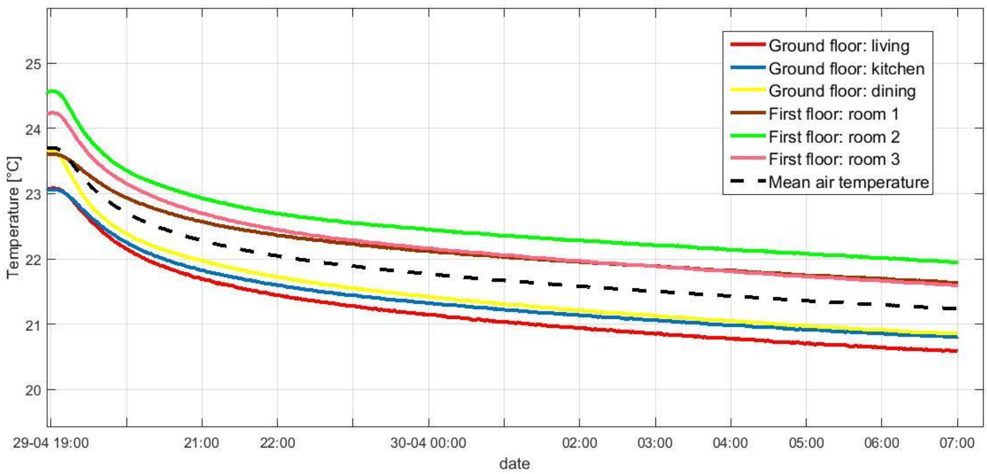


Figure 3-7: Temperature measurements

In Figure 3-8 is presented this mean indoor air temperature and the outdoor temperature, during the night. The mean difference between these two temperatures is approximately 16°C.

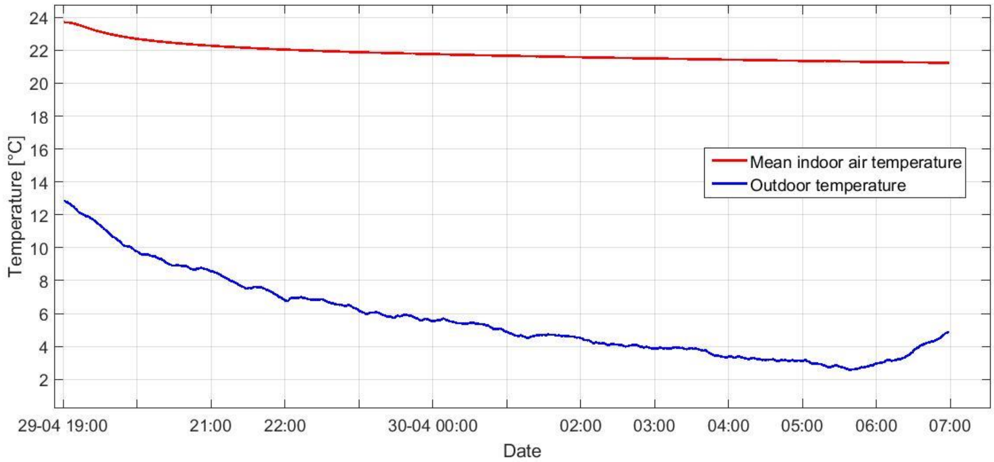


Figure 3-8: Indoor and outdoor air temperatures during the night

A typical blower-door test, as described in section 3.2.1.4, assumes using a door panel to temporarily seal a building's doorway. Installing a door panel to seal a window, in this case (see Figure 3-9), creates an additional thermal loss in the envelope. It basically creates a low-insulated surface (0.8 m² surface) within the envelope.

Figure 3-9: Blower-door test, for the I-BB house

For a high- proprieties envelope, as it is the case here, the additional losses, due to the low-insulated surface added, can rise to 9 W/K (see ANNEX B Figure B- for further detail). The first attempt is to perform the in-situ test following the protocol described in section 3.3.1 using a blower door for the duration of the test. As it was expected, the uncertainties associated with these additional losses had a significant influence on the results. Infiltration losses were measured. Therefore, the uncertainties associated with the building infiltration are reduced. However, the additional uncertainties created by the replacing the window can lead to inaccurate and unreliable results. (See ANNEX B for further detail on the calculation).

The solution retained here is to use a smaller model fan series (Retrotec Model 300), a duct tester. This fan is connected to an existing ventilation opening (Figure 3-10). Therefore, no replacement of door nor window is needed.

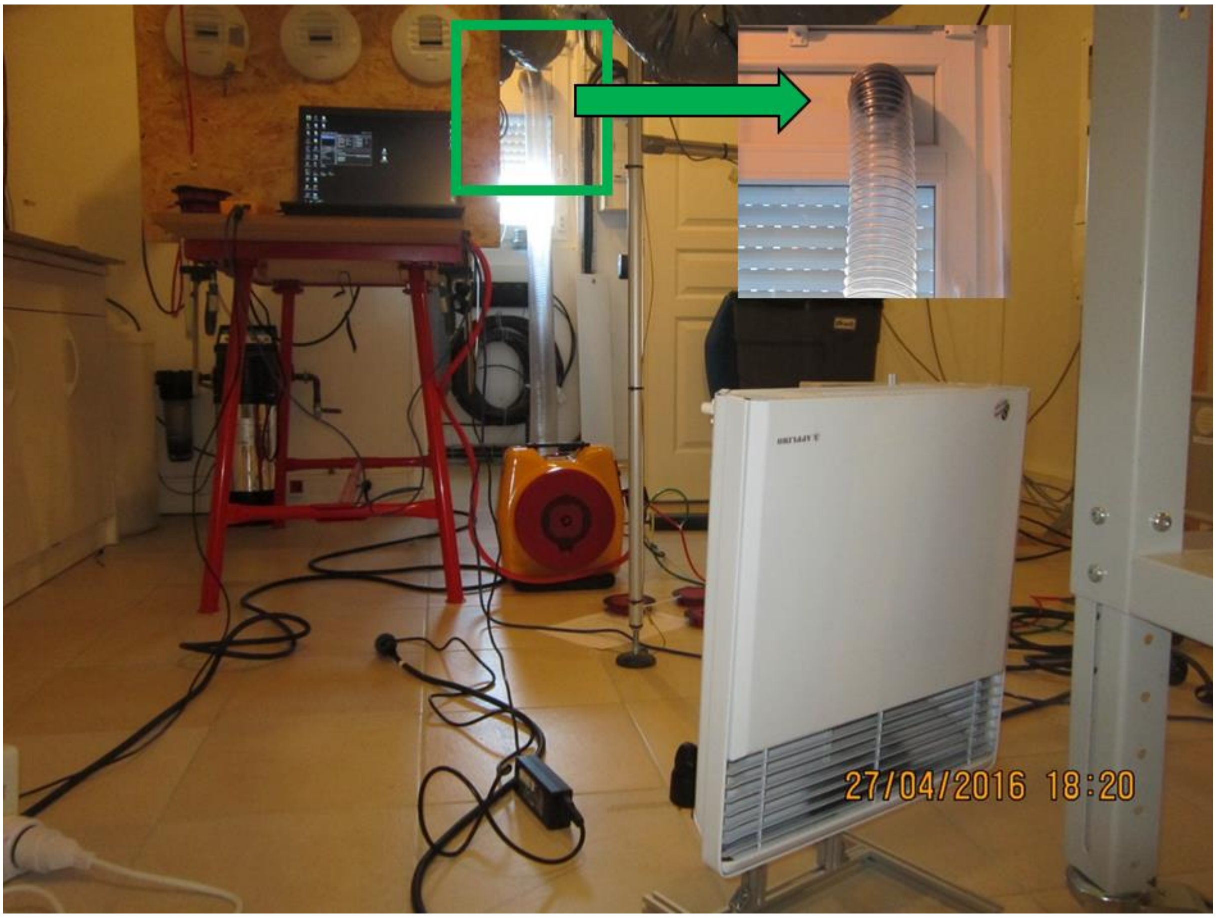


Figure 3-10: Thermal envelope proprieties test: experimental set-up

The Retrotec Model 300 is a duct tester, adapted for low but stable flow measurement (Model-301-Specifications-Retrotec Inc.) The minimum air flow for this fan model series can drop to 0.61 m^3/h with a measurement accuracy of ±3%. It is therefore well adapted to our case.

The room pressure is kept constant at a value of 4 Pa the entire time, using the gauge "*set pressure*" function. In addition to the gauge differential pressure sensor, two other differential pressure sensors were used to reduce measurement uncertainty. First, they were verified and calibrated. Then these different differential pressure sensors were tested by submerging the sensor's tube in a container filled with water at different heights. The measurements (Annex B.4) showed good agreement between these three pressure sensors.

The infiltration air flow is calculated at each time step (every minute) using measurements of the fan pressure and room pressure along with coefficients characterizing this fan model (Annex B.1). Infiltration losses are obtained by multiplying the air flow rate by the air heat capacity (considered at 1004 kJ/ (kg K)) and air density of 1.2 kg/m^3. The infiltration losses were calculated for each time step, as shown in Figure 3-11. The infiltration losses can vary from 5.2 to 8.2 W/K in this test, and a standard deviation of $\pm$ 0.6 W/K. Moreover, the mean value of 7.2 W/K is close to the results obtained from the blower door test (7.9 W/K), as presented in Table 3-7 (Q_4=0.007 m^3/s). The difference between the maximum and the minimum value represents up to 4% of the total HT value.

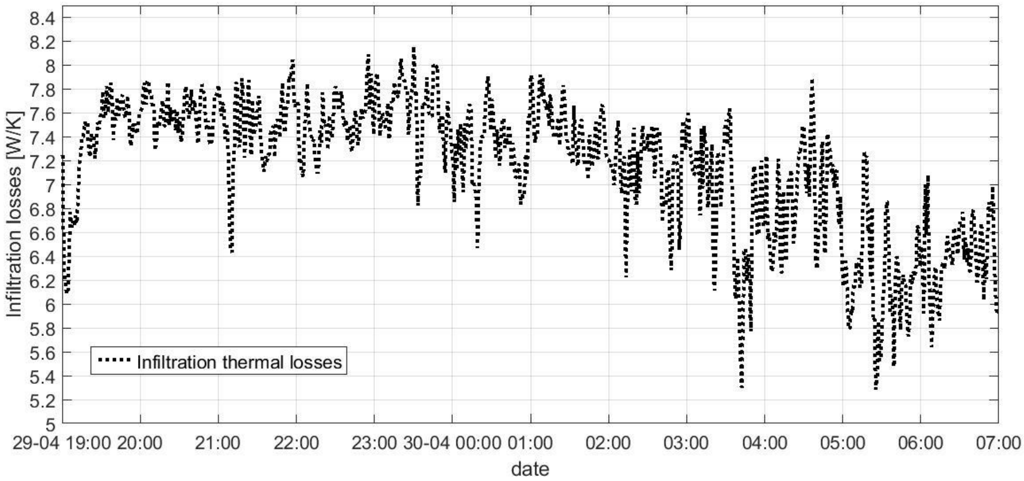


Figure 3-11: Infiltration losses [W/K]

The model parameters are first identified using a deterministic approach, as presented in the next section.

3.4.3.1. Deterministic identification

Here, the goal is to identify the thermal resistances and capacities, used within the 3R2C model. The primary model parameters that are identified here are U_{int} and U_{ext}. They will be used posteriorly to calculate the HT coefficient. Two other secondary model parameters are also identified: C_{wall} and T_{wall}. Here, T_{wall} represents the initial wall temperature at 19:00. The model does not represent the reality so that the initial wall temperature can be measured, and this is a fictive temperature. Therefore it becomes an unknown of the problem of identification. To realize the identification we defined intervals in which the parameters can take a value, which are ±2°C of theT_{int}. C_{int} is set as the air volume of the building multiplied by 4.

The results obtained after 68 seconds and 54 iterations are presented in Table 3-9. A good fit between the simulated temperature and the measured temperature is obtained here (CVRMSE of $9e^{-4}$) (see Figure 3-12). With the values of the two resistances, the HT coefficient is calculated at the value of 76.6 W/K. The HT represents the inverse of the sum of two resistances multiplied by the surface. Compared with the steady-state calculation 73 W/K (section 3.4.2.1), there is a 5% difference.

IDENTIFIED PARAMETERS	DETERMINISTIC VALUE
U_{int}	1.13
U_{ext}	0.46
C_{wall}	9.34E+07
T_{wall}	21.43

Table 3-9: Results of the deterministic identification for input values

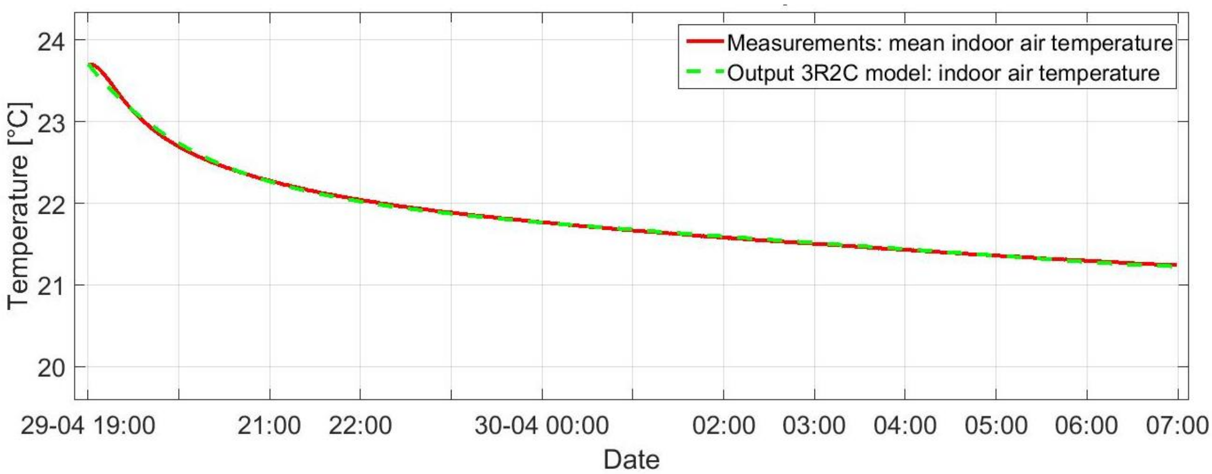


Figure 3-12: Simulated vs. measured indoor air temperature

3.4.3.2. *Bayesian inference*

In order to include uncertainties in the results a Bayesian inference method on the 3R2C is used. As presented above, Bayesian inference needs a prior distribution of probabilities of all the unknowns. This choice may significantly impact the results. Moreover, in order to ensure correct quality of numerical results, we need to ensure correct convergence. In practice, several steps are needed before achieving the goal.

Here, three main steps are reported. In our case the most impacting elements occurred to be the prior distribution and the number of parameters to be identified. Concerning prior distribution, a distribution around deterministic value occurred as a reasonable choice. It is used as explained in the following example.

Concerning the number of parameters to be identified, an investigation is performed. It is summarized in the following sections, where:

- first, all parameters are supposed as unknowns
- second, a sensitivity analysis is performed
- third, the less influential parameters are fixed, and Bayesian inference is performed on the most significant variables.

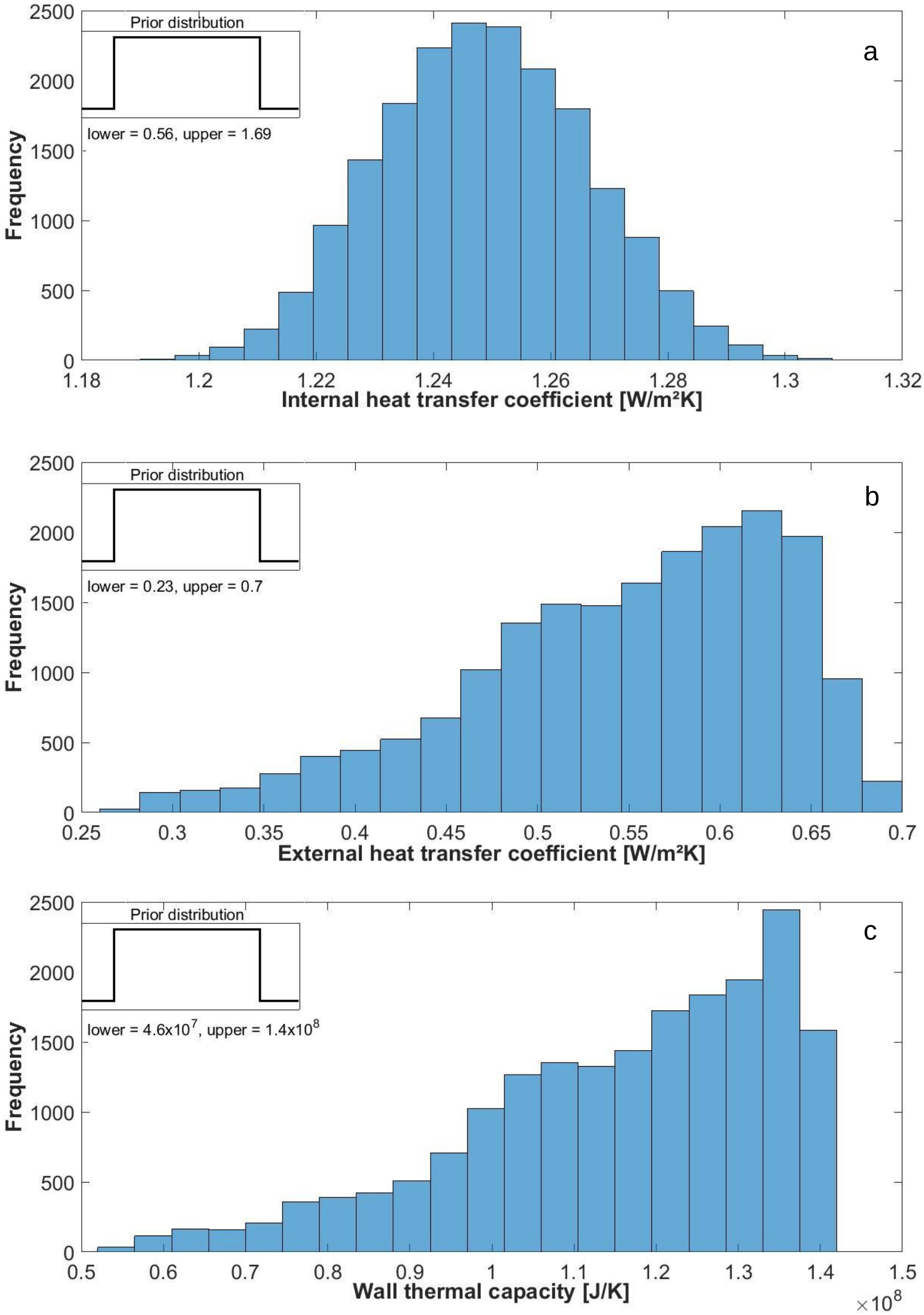
- **Bayesian inference on all the variables**

Here the prior distribution is assumed to follow a uniform distribution. All parameters (U_{int},U_{ext},C_{wall}, T_{wall}) are assumed unknowns. The upper bound increases the deterministic value by 50%, as showed in Table 3-10. The lower bound decreases the deterministic value by 50%. Thus, a wide range of values are possible for all parameters (U_{int},U_{ext},C_{wall}, T_{wall}). This should allow the model to search within a wide variety of solutions. Therefore, a more reliable estimation of the envelope properties is expected.

IDENTIFICATION PARAMETERS	LOWER BOUND	UPPER BOUND
U_{int}	0.56	1.69
U_{ext}	0.23	0.70
C_{wall}	4.67E+07	1.40E+08
T_{wall}	10.72	32.15

Table 3-10: Prior distributions for the Bayesian inference

Prior distributions for the discrepancy between the model and the actual behavior of the building $\delta(x)$ are assumed to be at 20% with a 5% value for the measurement errors $\varepsilon(x)$. (Li et al., 2016). Results obtained after 20000 steps are presented in Figure 3-13. Figure 3-13.a shows a narrow posterior distribution for the internal heat transfer coefficient U_{int}, compared to the prior. This indicates the increased confidence on the estimated parameter. Here, the range of reasonable values has been clearly reduced from [0.56, 1.69] to [1.2, 1.3] W/m^{2}K. As the distribution shows, for this model the most plausible value for the internal heat transfer coefficient is 1.25 W/m^{2}K. This value is slightly higher than the deterministic value of 1.13 W/m^{2}K.



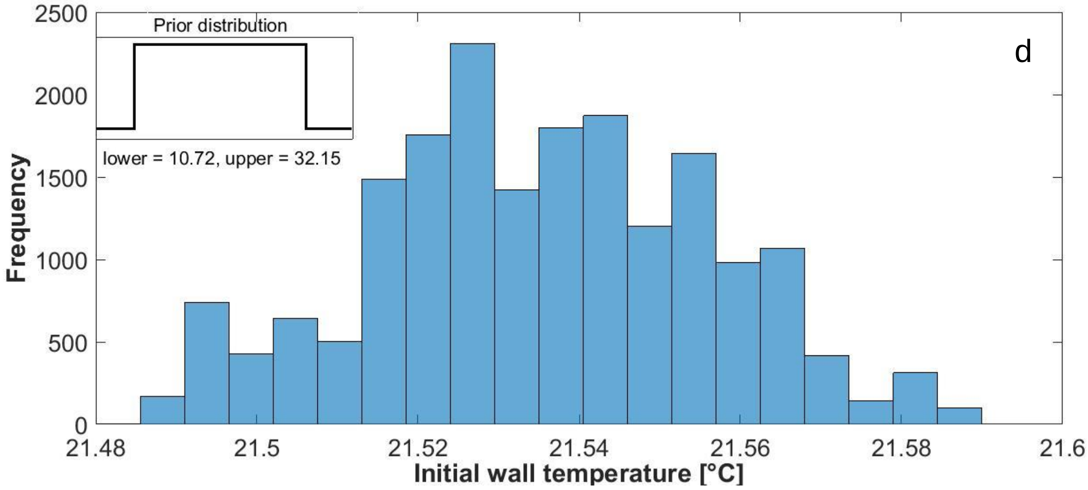


Figure 3-13: Posterior distribution for: a) the internal heat transfer coefficient U_{int} [W/(m^{2}K)], b) the external heat transfer coefficient U_{ext} [W(/m^{2}K)], c) the wall thermal capacity C_{wall} [J/K] and d) the initial wall temperature T_{wall} [°C]

The posterior distribution for the external heat transfer coefficient U_{ext} (Figure 3-13, b) remains as wide as the prior distribution. Moreover, this wide posterior distribution slides toward the upper bound, indicating that here this specific parameter cannot be identified using the available observation data. Since a similar behavior is observed for the wall thermal capacity (Figure 3-13 c), both input parameters are expected to be correlated. Indeed, the results showed a clear indication of their correlation when plotting C_{wall}, as a function of U_{ext}, (Figure 3-14). The thermal mass of the building represented by the wall capacity is strongly related to the thermal resistance of the wall. This can be somehow related to the thermal diffusivity of a material ($a = \frac{\lambda}{\rho c}$) in heat transfer equation. Such correlation requires indeed some modifications in our methodology that will be discussed in the following paragraphs.

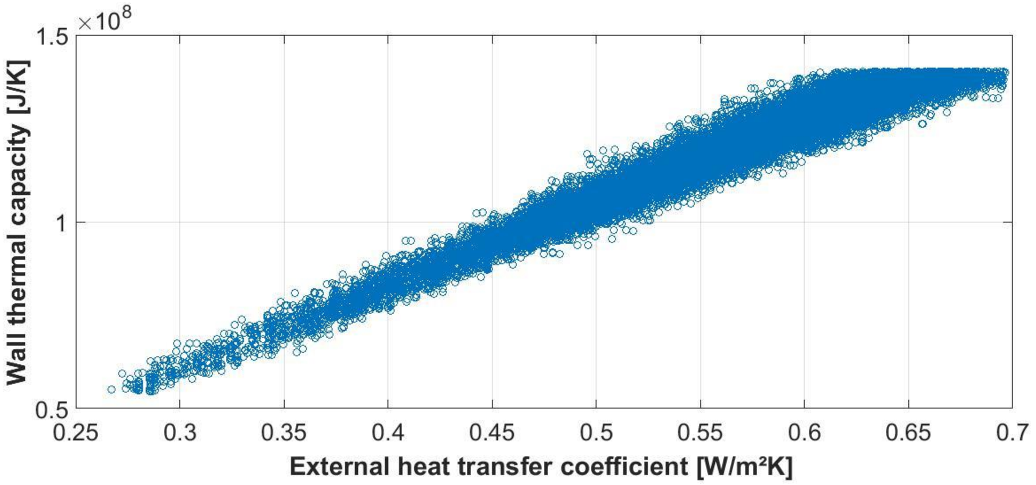


Figure 3-14: Scatter plot for U_{ext} and C_{wall}

As for the initial wall temperature (corresponding to the wall temperature at 19:00), the posterior distribution showed good reduction of the range. Even though the initial range of values for the initial wall temperature is very wide, posterior distribution reduced it to a mean value of 21,5°C +/-0,1°C.

- **Sensitivity analysis on the 3R2C model**

As shown in Figure 3-14, a correlation between C_{wall} and U_{ext} is observed, or identification methods require independent variables. One possibility consists in fixing one of the dependent variables to an 'a priori' value. However, it should be done with a minimal loss of information.

To get a better understanding of the situations and to rank each input parameter, the standardized regression coefficient (SRC) sensitivity analysis method (Tian, 2013) is used here. Parameters are ranked in order of importance. A negative SRC indicates that the input and output tends to move in opposite directions.

The output for the sensitivity analysis represents the $CVRMSE$ between the model's indoor simulated temperature T_{int} and the actual air temperature measured.

The selected input parameters are the internal capacity and wall thermal capacity (C_{int} and C_{wall}), the internal and external heat transfer coefficient (U_{int} and U_{ext}), the initial wall temperature T_{wall} and the infiltration losses measured during the test. A uniform distribution using as interval the deterministic value $\pm$ 50% is assumed. The input parameters are first sampled using a Latin hypercube sampling, using 300 samples.

The results are presented in Figure 3-15. The most important input variable influencing the model fit is the initial value for the wall temperature (SRC= 0.97). Not surprisingly, the indoor temperature evolution depends strongly on its initial value. Another interesting finding here is that, as expected, the internal wall capacity had the least influence on the output, due to its smaller value compared to the wall thermal capacity. It should be noted that C_{int} was considered fixed in all Bayesian identifications in the present work.

Furthermore, this analysis showed that the absolute value of SRC (-0.08) corresponding to U_{ext} is slightly higher than the SRC (0.06) for C_{wall}. Therefore, U_{ext} has a greater influence on the outcome than C_{wall}. More, we should remember that the goal of this identification method is to determine the two thermal resistances (U_{int} and U_{ext}) that are used in the 3R2C model. Fixing U_{ext} can lead to a loss of information; fixing the C_{wall}, U_{int} and U_{ext} can be identified. As a consequence, the C_{wall} is fixed at the value obtained from the deterministic identification.

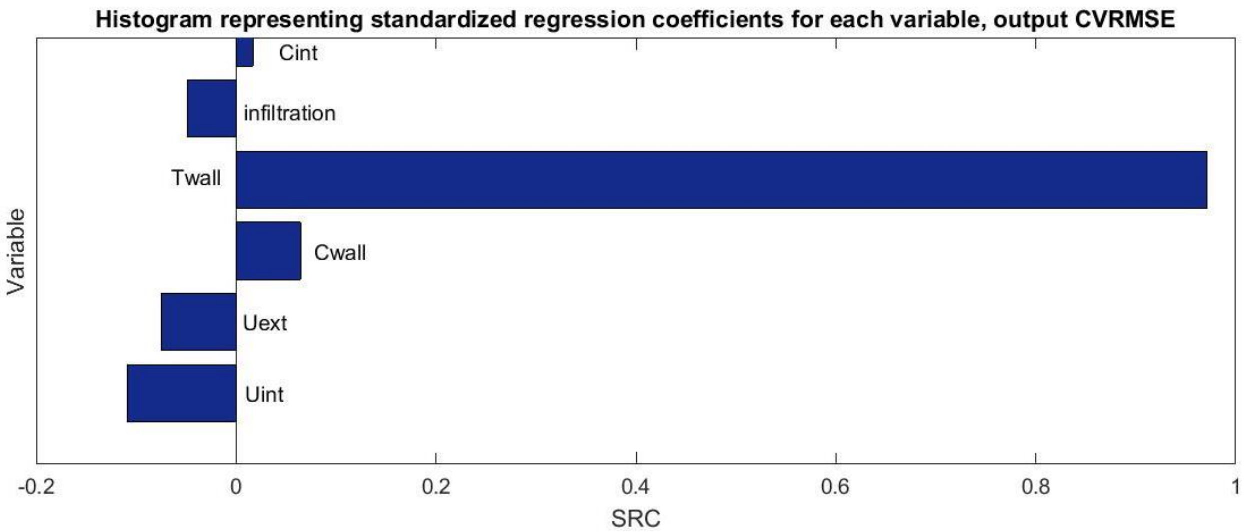


Figure 3-15: Sensitivity analysis on the 3R2C model

- **Bayesian inference, C_{wall} fixed**

A new set of simulations is performed with C_{wall} fixed at the value obtained from the deterministic identification. The prior distribution chosen for the other values is the same as in section 3.4.3.2 (see Table 3-11).

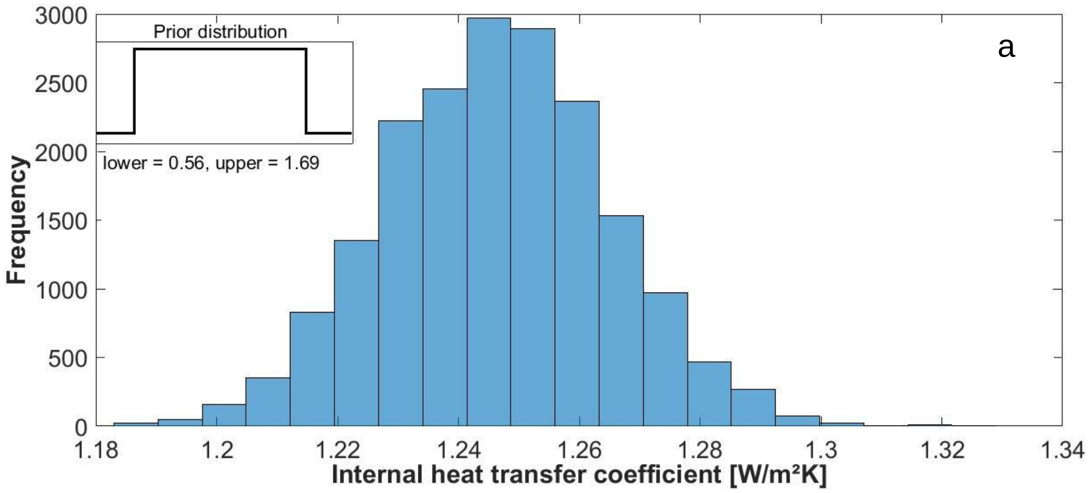
IDENTIFICATION PARAMETERS	LOWER BOUND	UPPER BOUND
U_{int}	0.56	1.69
U_{ext}	0.23	0.70
C_{wall}	Fixed at 9.34E+07	
T_{wall}	10.72	32.15

Table 3-11: Prior distributions for the Bayesian inference

The results after fixing the thermal wall capacity C_{wall} are showed in Figure 3-16. The same posterior distribution for the internal heat transfer coefficient U_{int} is found; the mean value stays at 1.25 W/m^{2}K and the range of values is still included in the interval [1.2, 1.3] W/m^{2}K. This input parameter is independent and can be easily identified.

The posterior distribution for the external heat transfer coefficient U_{ext} is different from the previous output; now it is narrow, as shown in Figure 3-16b. The new calibration process has pinpointed this parameter. Moreover, the mean value obtained (0.45 W/m^{2}K) is close to the deterministic value (0.46 W/m^{2}K).

The posterior distribution for the initial wall temperature is very similar to the one obtained from previous simulation and the same mean value of 21,5°C is obtained here.



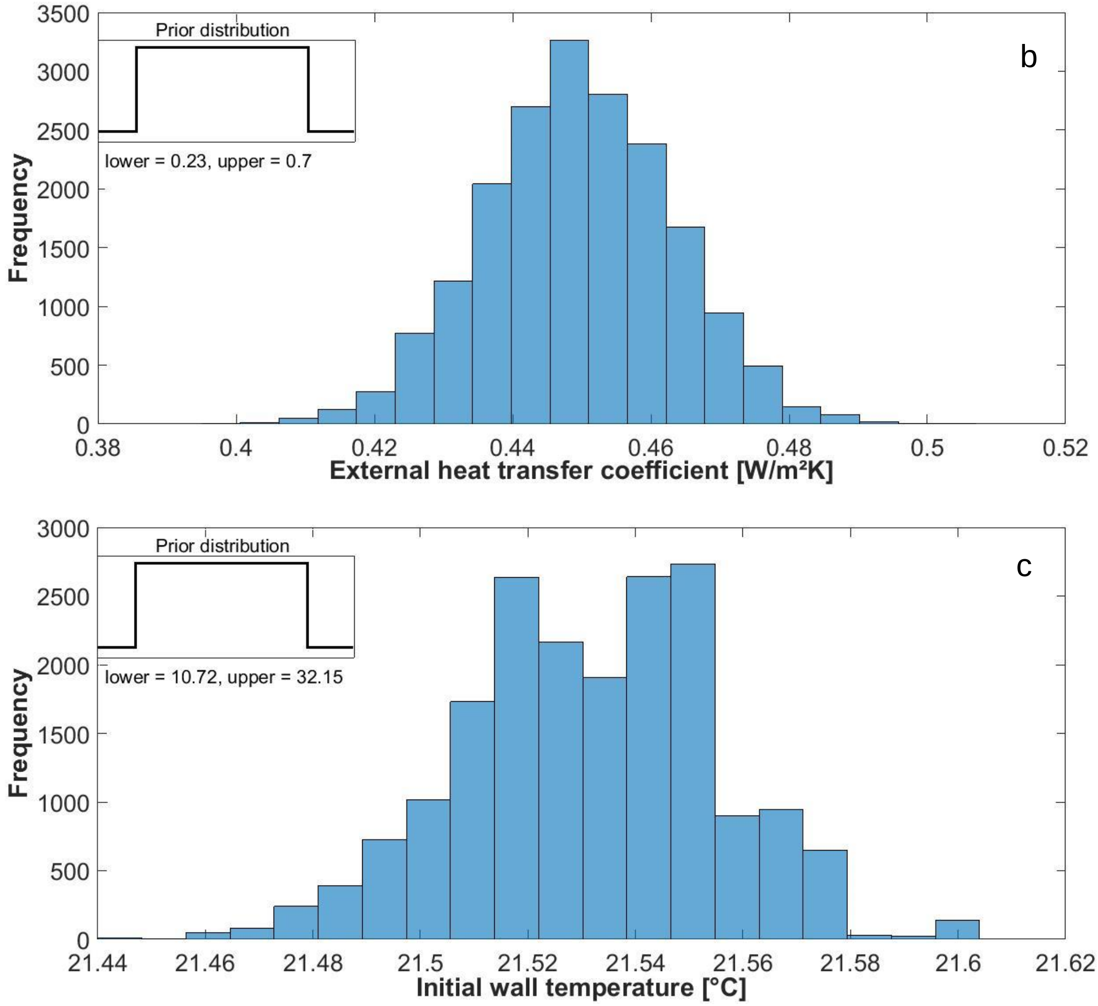


Figure 3-16: Posterior distributions for: a) the internal heat transfer coefficientU_{int} [W/(m^{2}K)], b) the external heat transfer coefficient U_{ext} [W/(m^{2}K)], c) the initial wall temperature T_{wall} [°C]

Finally, the HT is then calculated using the values obtained for the two heat transfer coefficients U_{int} and U_{ext} (where $HT = S * \left(\frac{1}{U_{int}} + \frac{1}{U_{ext}}\right)^{-1}$). Here, the results presented in Figure 3-17 show that the range of values for the HT is narrowed down to the interval of [72, 81] W/K with a mean value of 77 W/K. These values quantify the model discrepancy and the measurement uncertainties.

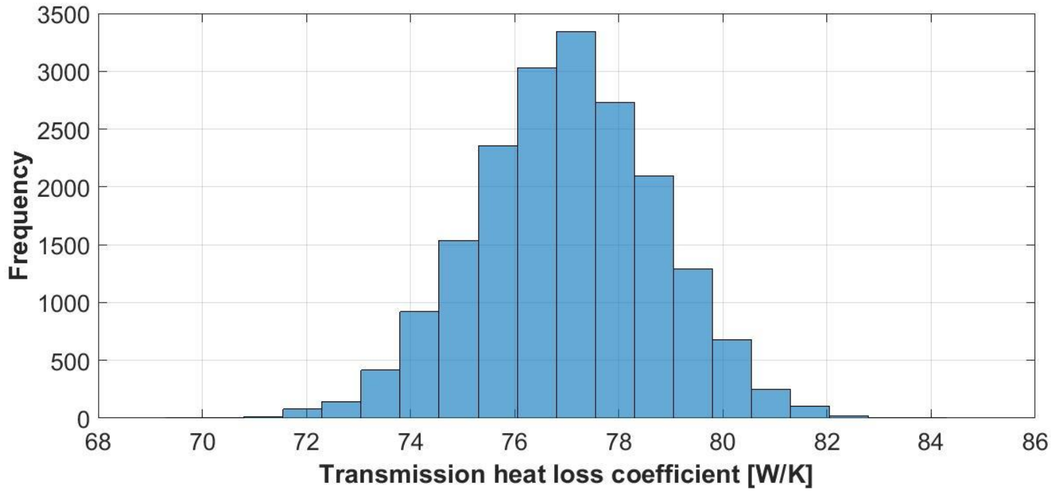


Figure 3-17: Posterior distribution for transmission heat loss coefficient HT [W/K]

It can also be noticed that the shape of the curve is close to Gaussian, indicating correct convergence of the calibration method.

3.4.3.3. Comparison between numerical and experimental studies

The main goal of the new test proposed here is to assess the HT coefficient: i.e. transmission heat losses corresponding to opaque and transparent walls (including thermal bridges) but excluding infiltration losses. Indeed, the originality of the method lies in the simultaneous measurements of temperature decrease in the tested house, while a simultaneous blower-door type procedure enables controlling the infiltration air flow.

The HT coefficient representing building envelope's proprieties is identified using a 3R2C model and two identification procedures: a deterministic one using a minimization function and a probabilistic one using a Bayesian inference. These new values are compared with previously computed theoretical values in Table 3-12.

HT steady state (RT2012 procedure)	HT using building simulation (validated E+ model)	HT experimental deterministic identification	HT experimental Bayesian inference identification
73	71	76.6	77 ± 1.8

Table 3-12: Comparison of theoretical and experimental HT values [W/K]

Indeed, a low 5% difference is observed when comparing the theoretical HT (using the steady-state calculation; section 3.4.2.1) and the experimental HT (using Bayesian inference; section 3.4.3.2).

Here, this analysis showed good agreement between the theoretical and measured HT values. The precision is similar to the precision provided by the existing method (Bouchié, 2015). This is particularly interesting taking into account the short time needed to perform the test (about 24h against 10 days for co-heating). Nevertheless, further tests will need to be conducted to assess the precision of this method on different buildings.

3.5. Application to PosA occupied house

This methodology to evaluate the building envelope's proprieties is now applied to the PosA house. Indeed, determining whether the envelope's proprieties falls within the standards and achieves the estimated values announced in the design phase is the first step of evaluating the energy performance of a building. As presented in section 3.1, a substantial proportion of energy savings can be made through an efficient envelope. Here, we attempted to determine whether the "as-designed" envelope came close to reality, using the proposed method described in section 3.3.

3.5.1. Preliminary study

- **Steady-state calculation: theoretical HT**

The theoretical method based on RT2012 thermal regulation and presented in 3.4.2.1, is used to calculate the HT for this single-family dwelling. A HT value of 159 W/K is obtained and its main elements are presented in Figure 3-18. The majority of transmission losses (60 W/K representing 38%) came from the opaque wall (vertical and horizontal). This house has a large window area, so the window thermal losses are close to 57 W/K signifying 36%. Thermal bridges account for 41 W/K representing 26% of the building losses due to the complex geometry of this house.

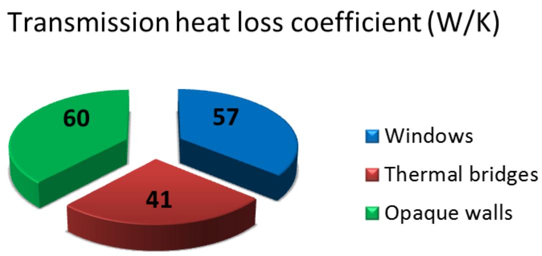


Figure 3-18: Theoretical calculation of the transmission heat loss coefficient [W/K] for the PosA house

- **Infiltration air flow**

For this house, two blower-door tests were performed 1 year apart. The results for both tests can be found in Table 3-13. As shown here, the air permeability of the house falls within the standard, requiring 0.6 m3/h/m² at 4 Pa. When comparing the second test performed after the construction in 2016 with the test carried out 1 year before by the manufacturer during the construction process, 20% difference can be noted. This may be due to new “vent” within the envelope over a year, measurement uncertainties etc. Nevertheless, the $Q_{4Pa-Surf}$ value is still low and admissible.

RESULTS	05.06.2015 (during construction)	17.06.2016 (after construction)
Air leakage rate at 4 Pa, Q_4 [m³/h]	134.8	167.1
Air permeability at 4 Pa, $Q_{4Pa-Surf}$ [m³/(hm²)]	0.34	0.42

Table 3-13: Blower-door test results

3.5.2. Experimental HT: measurements and identification

3.5.2.1. Measurements

To test the real overall envelope proprieties of the PosA building the dynamic in-situ test presented in 3.3.1 was performed during the Christmas holidays when the house was unoccupied.

- **Air infiltration**

Considering that this is an occupied building, the blower door could not be used throughout the test. Indeed, replacing an actual door or window with a cloth panel for 2 days is impossible for safety reasons. Unfortunately, the solution using only a smaller fan was not available at the time of the test. Consequently, the infiltration air flow rate was not measured during the test.

- **Measurements and results**

The measurements (indoor and outdoor air temperature, heaters power) proposed for the protocol described in section 3.3.1 are used here. Indoor air temperature sensors already installed in the house are used. Furthermore, an additional outdoor temperature sensor (type PT100) was installed during the test period, due to a malfunction of the house weather station. The electric heaters already presented in section 3.3.1 were used during the test.

- three electric heaters (nominal power 500 W) on the ground floor area;

- one electric heater (nominal power 500 W) in the office;
- one electric heater (nominal power 500 W) in the living and kitchen area, and one electric heater (power 750 W) beside the staircase.

The devices presented in section 3.4.3 were used for programing a 12-hour cycle (heating on at 7:00 am and off at 19:00). To measure the power generated by the electric heater, we used the energy meters already implemented in the house.

During the test, the ventilation system was cut off, the interior doors were opened and the roller blinds were closed. The test was carried out between 22th and 25th of December 2015. A mean indoor air temperature between two floors is also taken here. Figure 3-19 presents the distribution of this indoor air temperature and outdoor temperature for 24 December. A difference of approximately 10°C can be observed between the indoor and outdoor temperatures. Both temperatures along with measurements of the heaters and loads power are used within the RC model presented in the next section.

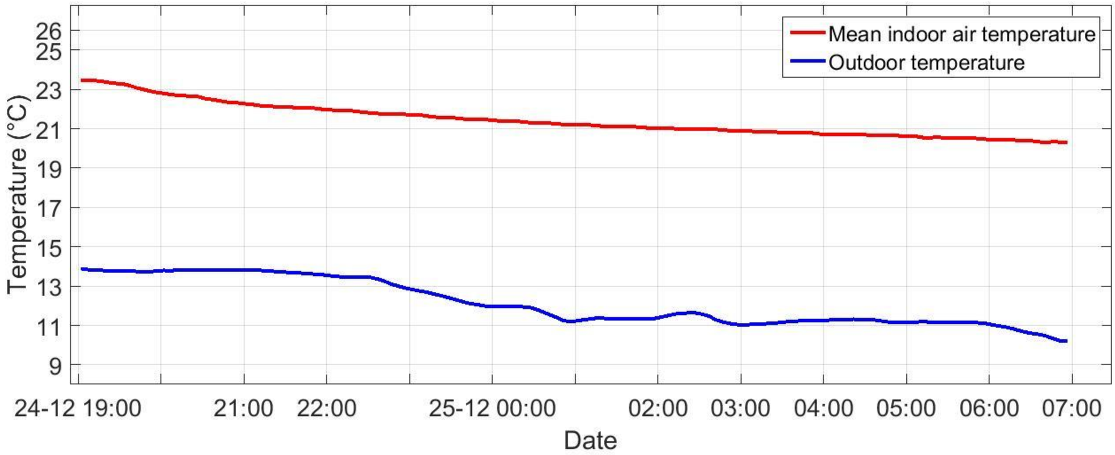


Figure 3-19: Indoor and outdoor air temperature distribution

3.5.2.2. 2R2C model

The model used here represents a simplification of the 3R2C model presented in section 3.3.2. It is a two-resistance and two-capacity (2R2C) model. The third resistance from the 3R2C model was not considered here, as infiltration was not measured separately during the test. Consequently, the two resistances also take into account the infiltration losses.

3.5.2.3. Results and findings

- **Deterministic identification**

First, deterministic identification is used to optimize the search for the minimum $CVRMSE$ between the simulated indoor temperature T_{int} and the actual mean indoor air temperature. All four parameters(U_{int},U_{ext},C_{wall}, T_{wall}) are identified here.

The results presented in Table 3-14 are obtained after 23 seconds and 103 iterations. The final value CVRMSE is 0.003. This suggests a slightly lower agreement between the simulated and measured temperatures, as can be seen in Figure 3-20. Using the identified values of the two U_{int} and U_{ext} the HLC is calculated equal to 179 W/K. Even though the house was empty, there were some appliances functioning: two fridges, the DHW tank etc. Measuring these internal gains caused considerable uncertainties, which can explain the inability of the model to represent the precise thermal conditions during the test. According to the measurements, at 5:00 in the morning there were electric appliances that triggered substantial electric consumption, as shown in Figure 3-21. However, at that time, the measured mean indoor air temperature was not affected by this injected power. Therefore, only the first 10 hours of measurements are considered here, instead of 12 hours.

IDENTIFICATION PARAMETERS	DETERMINISTIC VALUE
U_{int}	1.23
U_{ext}	0.52
C_{wall}	3.49E+07
T_{wall}	21.40

Table 3-14: Results of the deterministic identification for input values

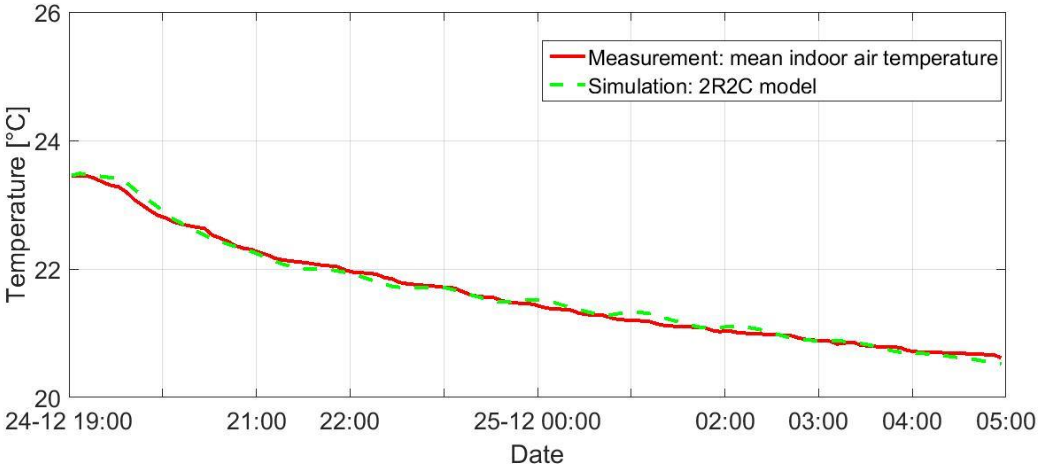


Figure 3-20: Measured vs. simulated air temperature during the night of the test

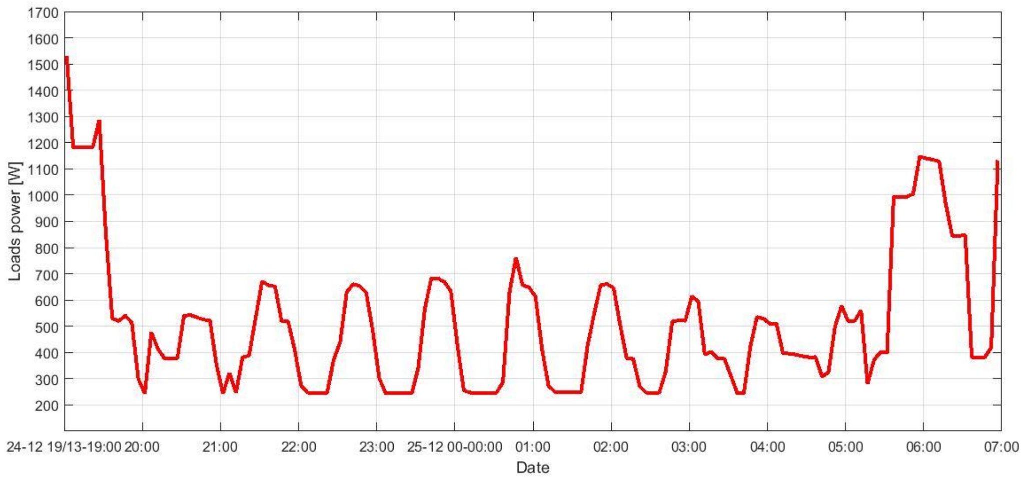


Figure 3-21: Measured load power during the night of the test

This HLC value cannot be directly compared to the theoretical value presented in section 3.5.1, because the infiltration air flow rate was not measured during the test. The real infiltration losses were calculated using the EN 12831. A value of 6 W/K is obtained for the PosA house. Subtracting this value from the HLC, the HT is estimated at a value of 173 W/K.

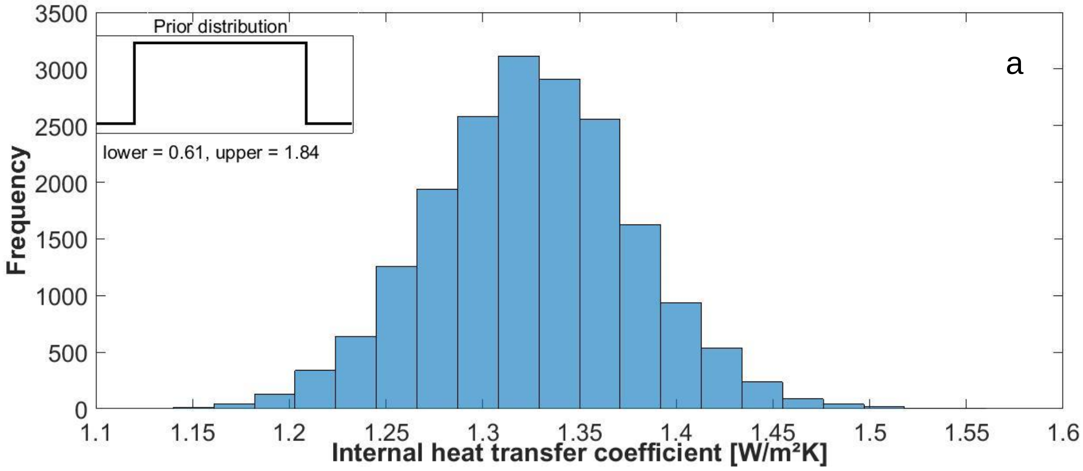
- **Bayesian inference for the proposed model**

A Bayesian inference is also performed here. Following the proposed method, these simulations are performed while fixing C_{wall} at the value obtained from the deterministic identification. The prior distributions can be found in Table 3-15.

IDENTIFICATION PARAMETERS	LOWER BOUND	UPPER BOUND
U_{int}	0.61	1.84
U_{ext}	0.26	0.78
C_{wall}	Fixed at 3.49E+07	
T_{wall}	10.7	32.1

Table 3-15: Prior distributions for Bayesian inference

The results can be found in Figure 3-22. A narrow posterior distribution is observed for the internal heat transfer coefficient U_{int}. The mean value obtained here (1.3 W/m^{2}K) is slightly higher than the one obtained when using the deterministic identification (1.2 W/m^{2}K). As for the external heat transfer coefficient U_{ext}, a mean value of 0.47 W/m^{2}K is obtained, after the identification process. It is slightly lower than the deterministic value (0.52 W/m^{2}K). When using the deterministic identification, the value obtained for the initial wall temperature is 21,4°C. The posterior distribution from the Bayesian inference, however, showed that this parameter can be slightly higher; situated within the interval [21,5; 21,7] °C.



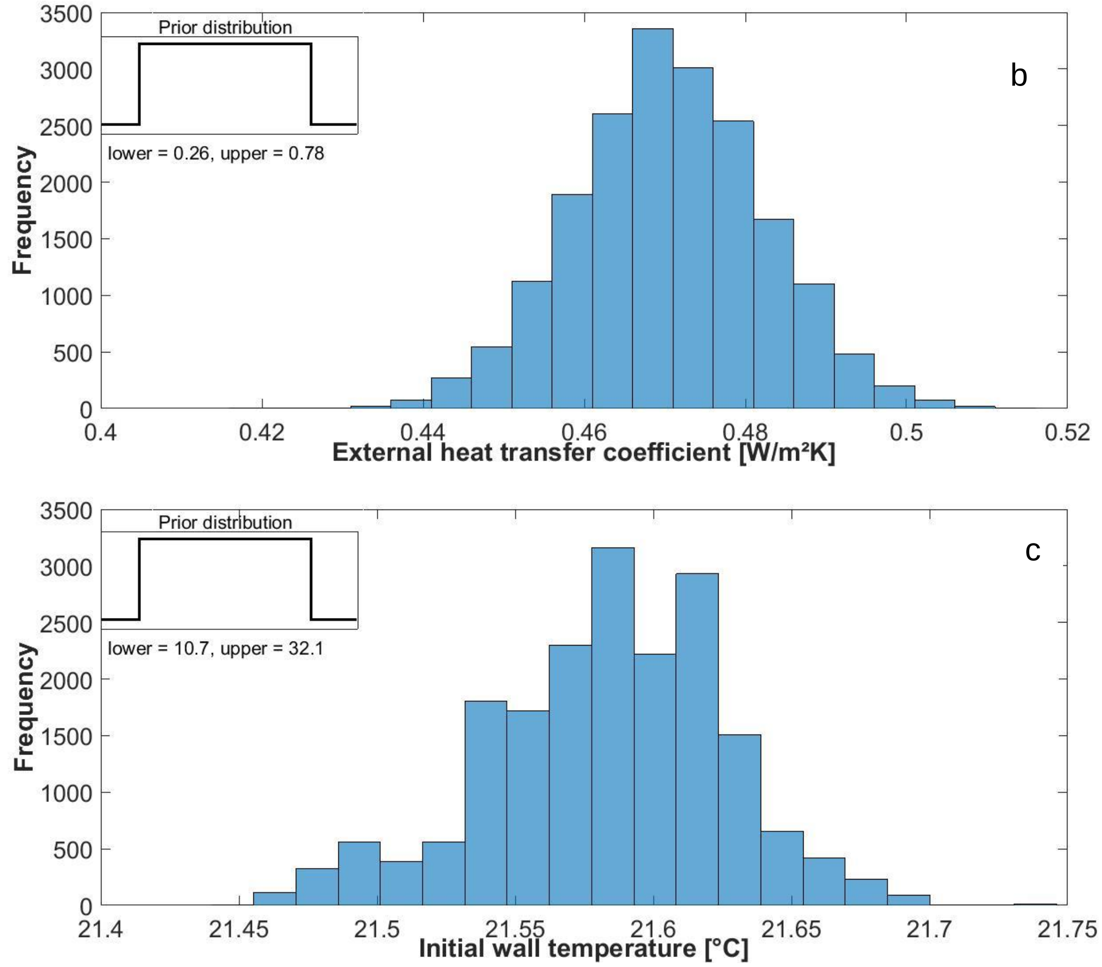


Figure 3-22: Posterior distributions for: a) the internal heat transfer coefficient U_{int} [W/(m^{2}K)], b) the external heat transfer coefficient U_{ext}[W/(m^{2}K)], c) the initial wall temperature T_{wall} [°C]

A HLC distribution is also calculated using the results obtained from Bayesian inference. Here, the results show (Figure 3-23) that the range of values for the HLC is between [160, 180] W/K with a mean value of 170 W/K $\pm$ 3, 7 W/K.

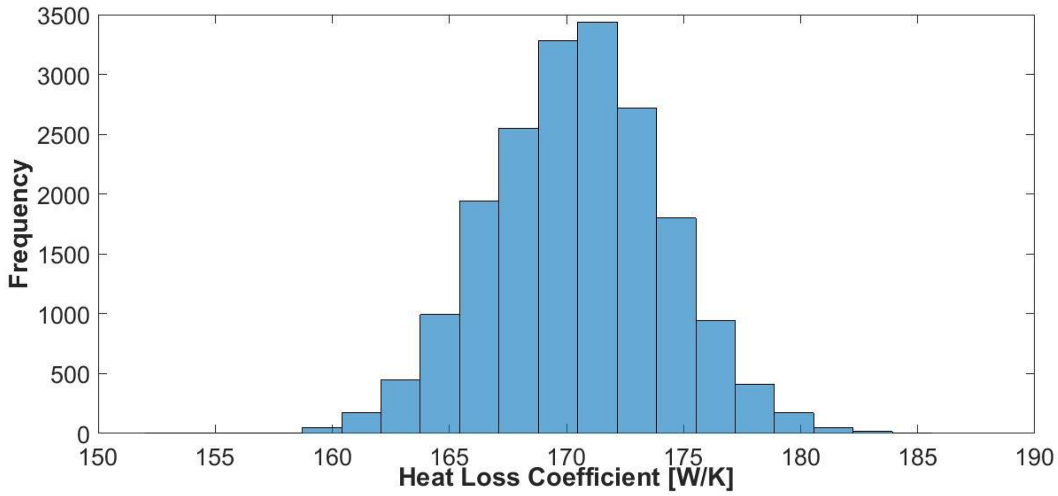


Figure 3-23: Heat loss coefficient [W/K]

By subtracting the value of 6 W/K calculated for infiltration losses, one obtains a value of 164 W/K for the HT. A rough comparison between the theoretical value and the mean value can be obtained here. A 9% difference is found here (Table 3-16), which is still consistent with the accuracy obtained within other methods as presented in section 3.2.1.2. However, uncertainties should be considered and additional tests performed on other buildings can increase the accuracy of the results.

HT steady state (RT2012 procedure)	HTexperimental deterministic identification	HTexperimental Bayesian inference identification
159	173	164 ± 3.7

Table 3-16: Comparison of theoretical and experimental HT values [W/K]

3.5.3. Complementary local measurements

The results from calculating the theoretical HT using the RT2012 standard procedure (section 3.4.2) showed that thermal bridges can have a great impact on the energy performance of this building, considering its surface and its complex geometry. For a better understanding of these singular points within the envelope's proprieties, we also performed, as a complement, a thermography analysis, presented in ANNEX B.

As a general conclusion, as expected most of the thermal losses occur at the inter-floor level (exterior wall/floors), which is consistent with the design phase calculation. However, no particular anomalies are detected.

3.6. Findings

The objective of the work presented in this chapter was to develop and test a new methodology to characterize the envelope's proprieties. Therefore, after reporting main existing tests from the literature, here we describe an alternative methodology that includes comparing the "as-designed" envelope's proprieties with the "as-built" envelope's actual behavior. This is done by assessing an experimental and a theoretical value for the HT coefficient.

First the theoretical value of the HT coefficient is calculated using a steady-state calculation. Then an innovative in-situ dynamic test is developed to evaluate the envelope's overall real proprieties. Indoor and outdoor temperatures along with energy use data monitoring is required during the test. This experimental data is used for the calculation of the HT using identification models. The proposed model is a grey box RC model that is designed by combining physical knowledge and measured data.

Based on the exiting methodologies such as co-heating, QUB, the objective of this work is to improve them in two ways: first we couple the envelope's proprieties characterization to a blower door in order to reduce uncertainties linked to infiltrations by imposing and measuring infiltration air flow during the test, Therefore, with the methodology developed in this chapter, it is possible to evaluate the envelope's real proprieties, which not only compares the theoretical value with the real value of the HT, but also reduce the uncertainties associated with the infiltration losses. Secondly, we use a Bayesian inference that improves the estimation of parameters by quantifying their associated uncertainties (e.g., model form and measurement uncertainties) and by using a probabilistic approach to take into account the range of possible values. Furthermore, this model only uses nighttime calculations so the impact of solar gains is not taken into account. This hypothesis is chosen to reduce uncertainty associated with solar gain in an attempt to simplify the identification process. Ultimately it requires less expensive metering.

The methodology is applied to two case studies: an experimental house I-BB and the PosA house.

First, for the experimental house, applying the methodology revealed that the model estimation matched the "as assumed" theoretical calculations of the envelope proprieties with a difference of 4%. This was expected given that a lot of attention was given to the construction process of this experimental unoccupied building. More, the internal gains only stem from data loggers and computers. Compared to a real occupied building, where everything evolves dynamically, the uncertainties associated to internal gains are lower.

Regarding the second case study, the design of this 229-m^2 living area is a challenging task when considering its complex geometry, constrained by the sloping land. Here efforts are made to evaluate the role played by the envelope's proprieties. First, both blower-door tests performed 1 year apart provided the same outcome: this building's envelope has good air permeability, which fits within the national standards. Therefore, infiltration thermal losses are low. During the thermography analysis, thermal bridges and small insulation connection defects were identified. This was expected, considering the surface and the complex geometry of this house. In a global approach, a 9% difference was observed between the theoretical and experimental HT. As a sum up, regarding this house, the case study of this present thesis, it can be stated that the envelope's real thermal proprieties is relatively close to that estimated in the design phase, considering uncertainties. This reinforces the robustness of the building's design. Nevertheless, there are a number of uncertainties associated with the measurements. Most particularly, measurements of internal gains taken on occupied buildings can be hard to assess. In addition, the theoretical HT does not take into account the infiltration air flow. Future tests using the protocol presented in section 3.3.1 measuring the infiltration losses with the smaller blower door are recommended. This can help reduce uncertainties.

Furthermore, determining that the envelope's real proprieties of this building comes close to the predicted proprieties is a first step in evaluating the energy performance of a building. This is mainly because once it is known that the envelope's real proprieties matches the predicted proprieties, the uncertainties regarding the cause of the performance gap are reduced.

Here, we showed that this approach by calculating the HT is of interest when one wants to compare the "as designed" with the real envelopes proprieties. However, this technique was only performed on new buildings in which infiltration are low compared to the global envelope losses. However, for existing buildings the infiltration may represent a larger part of the envelope's losses. It will thus be interesting to apply this technique which coupled infiltration measurement in parallel with an in situ test to existing buildings.

Once the envelope's proprieties had been studied, the next step is to evaluate the building's performance through monitoring, considering its occupants, systems and their efficient or inefficient building management. The next chapter presents an evaluation of the continuous global performance of the PosA building. The main focus is on energy use and indoor conditions.

CHAPTER 4. Continuous evaluation of the global energy performance: a practical application

4.1. Introduction

As shown in section 1.3, the real performance of a construction depends to a large extent on the efficiency of the design process. But the energy efficiency of the building is also determined by its use, and continuous evaluation of its performance remains a major challenge.

This chapter focuses on the evaluation of the building's **performance** via continuous monitoring (temperature sensors, energy meters etc.). The main goal here is to evaluate the **performance** in the operational phase and to achieve a more detailed understanding of the energy use and indoor conditions.

The performance evaluation through monitoring is a part of the **overall methodology**. Therefore, the overall methodology is first described. Then, a proposal of global monitoring for an individual house is introduced intending a comprehensive monitoring list, based on literature review. Here, in occupied buildings, the number of sensors must be limited for reasons of cost and acceptability. Therefore, a preliminary study on **ambient temperature measurements** is presented. The global monitoring is then applied to PosA house as a case study. We present the monitoring of this house, 'as defined' in the design phase and the monitoring 'as-operating' in the house. Finally, this analysis examines the results of the monitoring over a 6-month period. It starts with an analysis of the real **energy use**, for each item (heating, DHW etc.). The **indoor conditions**, especially thermal comfort, are studied in section 4.5.5. Thermal comfort is evaluated through measurements and a post-occupancy survey. Finally, the findings regarding the global performance of this house are discussed.

4.2. Performance evaluation approach

The ambition of the present thesis is to contribute to the performance evaluation of occupied individual houses. This is done by combining building performance simulation in the design phase with in situ tests as schematically represented in Figure 4-1.

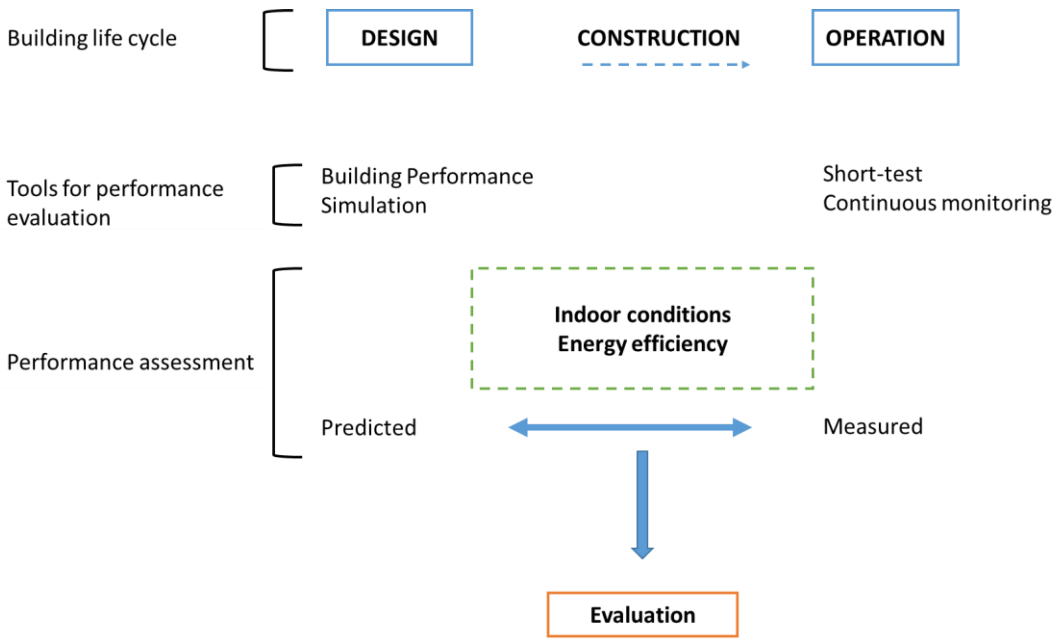


Figure 4-1: Outline of proposed performance evaluation approach

In the design phase, we use **building performance simulation**, to look at the performance based on certain assumptions of use. Specifically a standard weather file is used to represent outdoor conditions and occupant's behavior is represented by assumed 'a priori' scenarios. In the present thesis, we study the impact of occupants' behavior on energy use and more specifically we establish a range of values for energy use, depending on occupant is discussed.

Then, once the house is constructed, we perform an in situ dynamic test to check if the real implemented envelope complies with the design assumptions. Furthermore, in the operation phase we acquire detailed performance data through continuous monitoring. This detailed **monitoring** is approached from two aspects: energy efficiency and indoor conditions. Evidently the measurements represent the building's behavior under real weather loads and actual users' behavior, which differs from the assumptions used in the design phase. Finally, the results are used to evaluate the building's performance by comparing the measurements with the design predictions.

First aim of this evaluation approach is to gain more discernment about the building's performance and its occupant's behavior. It is therefore important to evaluate the building's performance in comparison with the design phase, against some reference energy performance, such as legislation for example. However, it should be noted that this comparison is only informative, on a scale size only, due to different interior and exterior conditions between the real life and the simulation assumptions. Ideally, simulations from the design phase could be re-run using measured weather and occupancy data. Such process would enable building performance model validation and would deepen performance analysis. Certainly, exterior conditions can be measured using a weather station, and therefore can be used within the simulations. This is not however the case of interior loads, such as the air flow due to windows' opening, metabolic heat gains etc. very difficult to measure. This last point makes nearly impossible precise validation of the simulation model in case of occupied buildings. Such approach was the considered out of scope of the present thesis.

The second aim of the evaluation approach is to give feedback about the design assumptions, for example concerning occupant's behavior whenever the used scenarios (deterministic and stochastic) are realistic or not. It can be done by comparing monitoring results with the predictions and assumptions made in the design phase.

4.3. Continuous monitoring specifications

The objective of the proposed monitoring system is to assess and analyze building's performance, in terms of:

- Energy efficiency: use and production;
- Indoor conditions: thermal comfort and indoor air quality;

Indeed, the **energy efficiency** of the building is a very important component of building performance. Consequently, the monitoring should include energy meters for both energy use and production. First, concerning the energy use, there is the monitoring of RT2012 items, which is imposed by the French standard on new buildings, on annual scale. Energy meters recording the heating, auxiliary equipment (ventilation), lighting and DHW energy use are therefore mandatory. This can be straightforward for some systems, such as electric appliances. If however, the wood energy is used for heating for example, a lot of attention should be attached to measurements uncertainties, which can rise up from the estimation of wood volume and weight, the nature of wood, as well as its moisture content (ADEME).. Second, energy meters measuring the energy production are also mandatory. Nevertheless, the remaining element of energy consumption that has not been yet regulated is the energy consumption of domestic appliances. To determine it, energy meters for other energy uses such as cooking, dishwasher, electronic devices etc. are proposed to be installed. In order to analyze the results, the measurements should be recorded with an infra-hour timestep. Additional information about the building's systems like the temperature of the DHW tank, or the ventilation air flow is also needed for a clearer image.

Monitoring system should also take into account the occupant of the house and the **indoor conditions**. Here, we propose measurements of indoor air temperature. More, measurements of relative indoor humidity, CO_2 levels, VOC (Volatile Organic Compounds) and natural lighting are proposed for a better assessment of the indoor environments. Short tests and /or occupant survey for evaluating the perception of visual, thermal and acoustic comfort and are also proposed.

Complementary measurements of boundary conditions like the occupant's presence, opening / closing windows and blinds, ground temperature and weather conditions (external temperature, solar radiation, wind direction etc.) are recommended to gain more information. The envelope's durability can be evaluated as well, using measurements of temperature and humidity within the wall structure.

The generic list of proposed sensors is summarized in Table 4-1. Note that this monitoring list will need to be adapted for each house, due to specifically installed equipment, particular user demand and other specific data.

ITEM TO CHARACTERIZE	MEASURED DATA	TIME STEP
Energy efficiency: RT2012 items energy consumption	Heating	1 h
	DHW	1 h
	Lighting	1 h
	Auxiliary (Ventilation fan consumption)	1 h
	Cooling	1 h
Energy efficiency: Systems (To be narrowed depending on the systems installed and measurements already available)	Efficiency of the ventilation system (air flow)	10 min to 1 h
	Efficiency of the ventilation system (temperature)	10 min to 1 h
	Domestic hot water	10 min
Energy efficiency: Other uses energy consumption	Cooking	1h
	Appliances	1h
Energy production	Wind turbine production	1 h
	Solar domestic hot water	10 min
	Electrical power supplied by the photovoltaic field	1 h
Indoor conditions	Indoor air temperature	10 min
	Relative humidity of indoor air	10 min
	CO_2 and VOC levels	10 min
	Natural lighting	10 min
Complementary measurements	Opening / closing windows sensors	10 min
	Blinds positions	10 min
	Presence of occupants	10 min
	Ground temperature	
	Weather station: horizontal global radiation, outdoor temperature, wind speed, relative humidity	10 min
Envelope's durability	Temperature and relative humidity in the wall	1 h

Table 4-1: Monitoring for performance assessment of individual houses

Furthermore, in real houses, the occupants will not accept a too intrusive metrology. Therefore the problem is that in occupied buildings, the number of sensors must be reduced, while maintaining sufficient robustness and precision of information. Information on the real operating conditions of a building is essential to improve the evaluation of energy performance. Therefore, there is a trade-off between trying to obtain as much as information as possible, with the lowest number of sensors. The practical solution is to use existing industrial sensors and to limit their number with a minimal loss of information on the indoor environment. We will illustrate this question with the assessment of the indoor temperature. In theory the best location of air temperature sensor is in the middle of the room (as we can see in the left part of Figure 4-2). This can be easily done in experimental houses, but is unrealistic in occupied dwellings. In real life conditions we can imagine a situation similar to the illustration in the right part of Figure 4-2, where the temperature sensor is placed on a furniture, close to a wall. In order to verify the representativity of such measurements some additional investigations were conducted and are presented in the next section.

Experimental house *Single family house*

Figure 4-2: Ambient temperature sensors placement

4.4. Preliminary study: Monitoring ambient temperature in occupied houses

To provide a clear and complete view of the energy performance of a building, a large number of sensors should be implemented. As just mentioned, in occupied buildings, the number of sensors must be reduced, while maintaining sufficient robustness and precision of the information. One reason is that in real homes, the occupants will not accept a too intrusive metrology. Consequently, there is a strong practical need to limit the number and intrusiveness of indoor temperature sensors. Therefore, the results presented here focus on this component of the indoor conditions, estimated by measurements of air, or operative, temperature. We will focus on two aspects: the difference between air and wall temperatures within one room and the difference between air temperatures in different rooms.

A highly instrumented experimental house is used for this study. Available experimental data are analyzed in order to quantify possible correlations between them. Then, complementary analyses are conducted on an occupied house.

4.4.1. Experimental data

The data were measured in an unoccupied experimental house called I-DM, located on the INCAS experimental platform, at the National Institute of Solar Energy (INES). This low-energy detached house has almost the same geometry as the house presented in section 3.1; however, construction approach differs. This building has also a good level of insulation (20 cm for walls and 40 cm for roof), active and passive solar shadings and efficient energy recovery ventilation. A 1200-W electric resistance is sufficient to heat the house and to provide an optimal thermal comfort. More information on this building can be found in (Spitz, 2012) and (Stefanoiu et al., 2014).

On the ground floor there is a large living area, including kitchen, living and dining rooms, with windows oriented to the south. On the first floor, there are three bedrooms with a different orientation as follows: room 1 is oriented to the northwest, room 2 to the southwest and room 3 is oriented to the southeast. The windows in rooms 2 and 3 are oriented to the south, and the one in room 1 to the west (see Figure 4-3).

Figure 4-3: IDM house: general view and room orientation

The metering is similar to the I-BB house described in section 3.1.The house is equipped with a large number of sensors for air and wall temperature, humidity, flow meters, energy meters, a full weather station etc., with a continuous acquisition system (every minute). Temperature, the focus of this study, is measured at different locations: ambient air, external and internal surface, and also inside the wall structure. In each room there are several sensors implemented to measure room temperature which are located in the middle of each volume and on one exterior wall of each volume, at standard comfort heights: 0.1 m, 1.1 m, and 1.7 m (Figure 4-4). The following list summarizes the sensors used to measure the ambient temperature:

- air temperature: platinum thermoresistance, PT100, Class A: ± 0.35°C from −100 to 100°C;
- surface temperature: T-type thermocouple, Class 1: ± 0.5°C from −40 to 125°C;
- black globe, only on the ground floor zone, PT100 1/2 DIN Class A ± 0.1°C from -40 to 80°C.

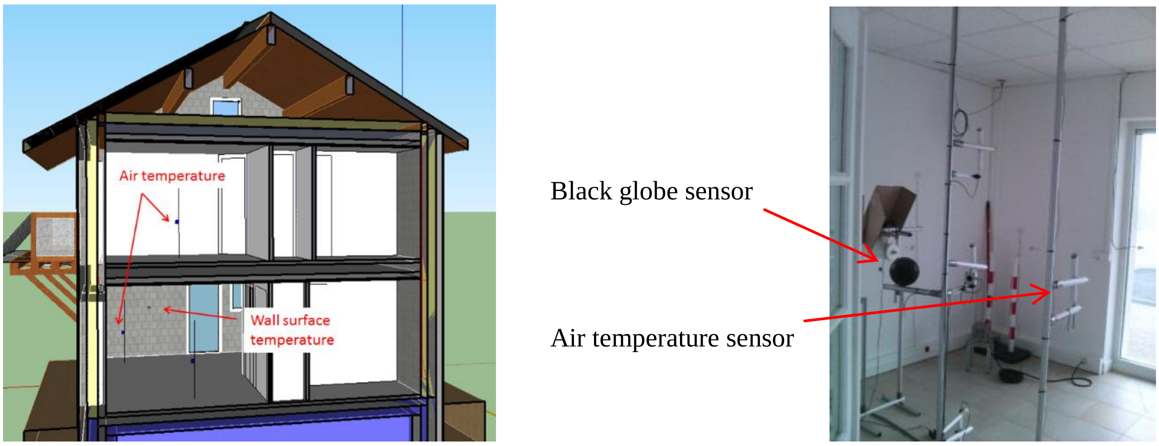


Figure 4-4: IDM house: sensor placement

In this study we only used air and interior surface of the exterior wall temperature sensors situated at 1.1 m, assumed to be the most representative of temperatures perceived by the human body. The list of sensors used here is presented in Table 4-2.

TEMPERATURE SENSOR	GROUND FLOOR			FIRST FLOOR		
	LIVING	DINING	KITCHEN	ROOM 1	ROOM 2	ROOM 3
Air (at 1.1 m)	1	1	1	1	1	1
Wall (at 1.1 m)	1	1	1	1	1	1
Black globe	0	1	0	0	0	0
Total	2	3	2	2	2	2

Table 4-2: Number of temperature sensors used

We started by analyzing the temperature differences between the values measured by these sensors. In the following, air1 represents the measurements for the air temperature in room 1. Correspondingly, air2 and air3 represent the measurements for the air temperature in room 2 and 3. Wall1, wall2, wall3 represent the measurements for wall temperature in room 1, 2 and 3, respectively. The absolute difference is calculated for each minute of each month for all the "wall to air" and "air to air" temperature measurements. Then the mean value is calculated for each month. Table 4-3 shows the results for the three bedrooms. The mean differences between all the temperatures for each month are always less than 1°C. It indicates strong correlations between these temperature measurements. Also, as can be seen here, the difference between the wall temperature and air temperature sensors is slightly higher than the difference between the air temperature sensors. The air temperature sensors situated in different rooms seem to be even more correlated than air and wall temperature sensors situated in the same room. This is explained by the fact that the air temperature measurements are more influenced by solar gains.

Following these observations, it seems useful to investigate more deeply the measurements using a statistical approach, as presented in the next section.

MONTH/ SENSORS	air1/wall1 [°C]	air2/wall2 [°C]	air3/wall3 [°C]	air1/air2 [°C]	air1/air3 [°C]	air2/air3 [°C]
January	0.66	0.62	0.73	0.36	0.45	0.23
February	0.71	0.50	0.62	0.22	0.36	0.47
March	0.67	0.62	0.80	0.21	0.41	0.56
April	0.63	0.50	0.52	0.20	0.25	0.24
May	0.65	0.50	0.53	0.21	0.32	0.14
June	0.60	0.50	0.61	0.21	0.22	0.07
July	0.57	0.36	0.44	0.06	0.07	0.06
August	0.62	0.40	0.48	0.22	0.20	0.17
September	0.63	0.56	0.65	0.34	0.40	0.12
October	0.75	0.67	0.68	0.55	0.82	0.34
November	0.71	0.46	0.58	0.21	0.32	0.16
December	0.69	0.51	0.62	0.20	0.39	0.31
Mean	0.66	0.52	0.61	0.25	0.35	0.24
Maximum	0.75	0.67	0.80	0.55	0.82	0.56
Minimum	0.57	0.36	0.44	0.06	0.07	0.06

Table 4-3: Mean absolute value of differences between temperatures measurements situated on the first floor for the entire year 2014

4.4.2. Selected approach

A step-by-step methodology is used to quantify the correlations between different indoor temperature measurements. First, the temperatures measured within one room are analyzed. Then temperatures measured within one floor are analyzed, and finally the correlations between temperatures measured on the two floors are investigated. One year of measurements (all of 2014) is included in the analysis. In total, over 5 million of data are used here. This data set is divided into 12 sets representing 1 month of records each and used as the basis of the analysis. This division is necessary because of the large data set, with temperatures recorded every minute. An example of temperature measurement during March is shown in Figure 4-5. It can be seen from this figure that the data covers various thermal conditions, with different daily and monthly temperature amplitudes.

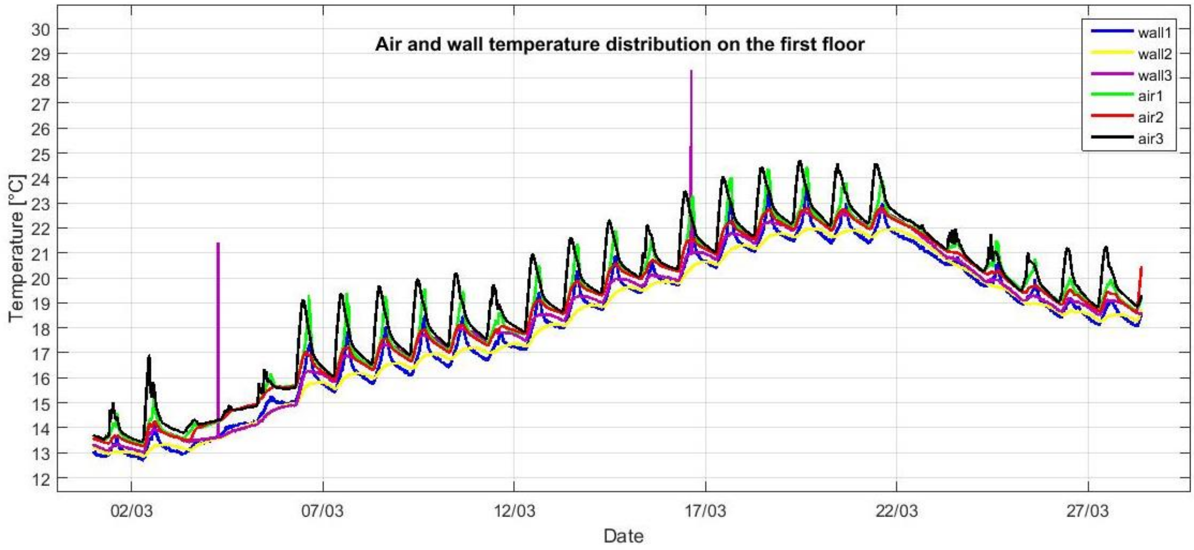


Figure 4-5: First floor temperature measurements for March

The measurement of the degree of linear dependence between two variables X and Y, the Pearson product-moment correlation coefficient r is used here to search for correlations between indoor temperatures (see Annex D.1). This r coefficient can take values between −1 and +1 and can be interpreted as follows: if r is close to zero, there is no linear correlation between the two samples, if r is close to +1 there is a positive correlation and if r is close to −1 there is a negative linear correlation between the samples.

The statistical tool, presented in (Najemeddine et al., 2012), applied to these measurements gives the correlation results, with a typical sample presented in Figure 4-6. The correlation coefficient for each pair of measurements is computed. The graphical representation of the correlation illustrates the discrepancy between values. Indeed, correlation coefficients higher than 0.99 correspond to an almost perfect line, while the plot for $r = 0.96$ shows greater dispersion. As correctly represented by the mean value, in the following sections mainly the mean monthly values of the correlation coefficients are presented.

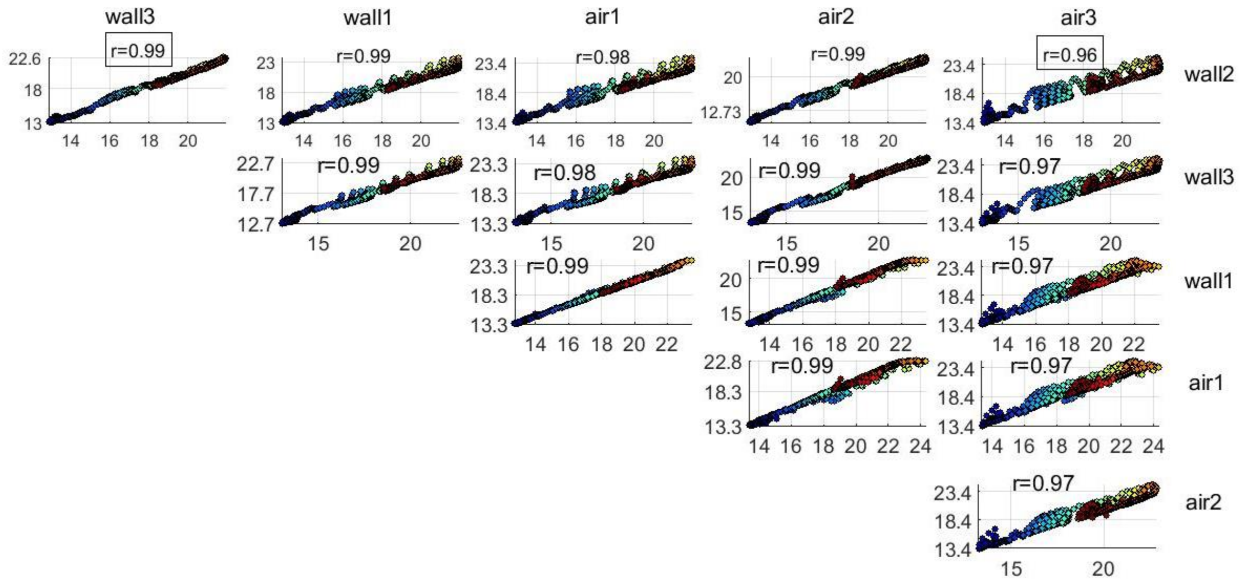


Figure 4-6: Correlation between air and wall temperatures for March

4.4.3. Results and discussions

4.4.3.1. Correlations between sensors located in one room

Here, correlations between wall surface and air temperatures in one room are of interest. The Figure 4-7 (left and right) shows monthly averaged values of the correlation coefficients. Again, “air” represents here the air temperature sensor and “wall” the wall temperature sensor for: room 1, room2 and room3, kitchen, living and dining areas. On both, ground and first floors, a strong correlation between air and wall surface temperature is shown. In all cases the correlation coefficients are higher than 0.85 for the first floor and higher than 0.7 for the ground floor. In all the rooms, the correlation coefficient is higher than 0.9 over 9 months. The months with the lowest correlation coefficients are February, August and October. No heating was used in February, which can explain more complex behavior of the free-floating temperature, which is only locally affected by solar radiation.

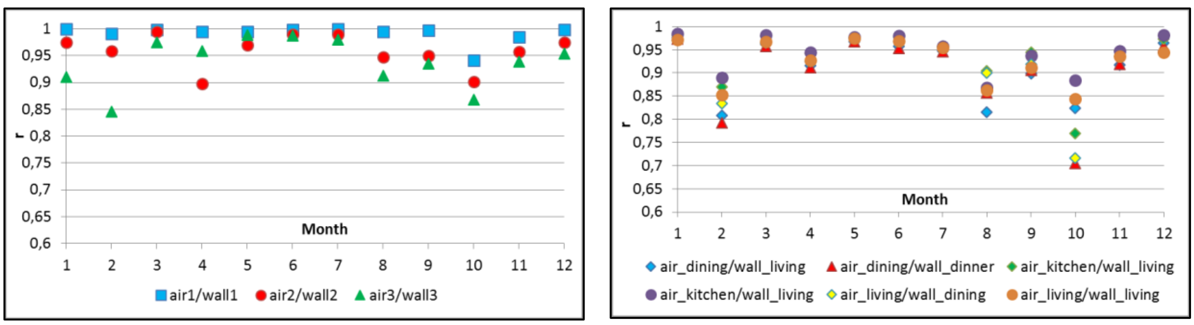


Figure 4-7: Correlation coefficient between air and wall temperature sensors for the entire year 2014: (left) ground floor; (right) first floor.

Indeed, Figure 4-8 left, presents the temperatures recorded in room 3 in February and illustrates the effect of the solar radiation, which causes a strong and quick variation of the air temperature. Wall temperature is not directly affected and shows smaller variations for this month (see Figure 4-8, left). However, in July (see Figure 4-8, right) both temperatures are strongly correlated and the differences do not exceed 1°C. This may be due to closing the blinds, or to higher position of the sun in the sky, limiting direct solar radiation in the rooms.

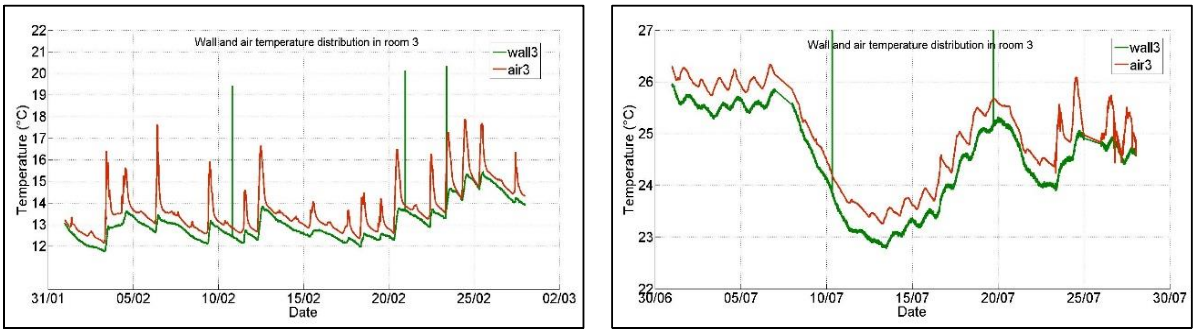


Figure 4-8: Air and wall temperature in room 3: (left) February (right) July

4.4.3.2. Correlations between sensors situated on the same floor

The second part of this analysis looked for correlations between the air and operative (black globe) temperature measurements in different rooms on the same floor. The air temperature measurements located in the bedrooms on the first floor (shown in Figure 4-9, left) are strongly correlated (r > 0.9). The only exception is in February and in October. Also, it can be seen that the correlation coefficients between the air temperature measurements in room 2 and room 3 are close to 1. This can be explained by the fact that the windows in both rooms have the same orientation.

Figure 4-9 also shows that all sensors located within the large dining and living space are strongly correlated (r > 0.9). Indeed, all are located within the same large room with well-mixed air. Also, the windows are evenly distributed in the living room so the effect of direct sunlight is spread evenly.

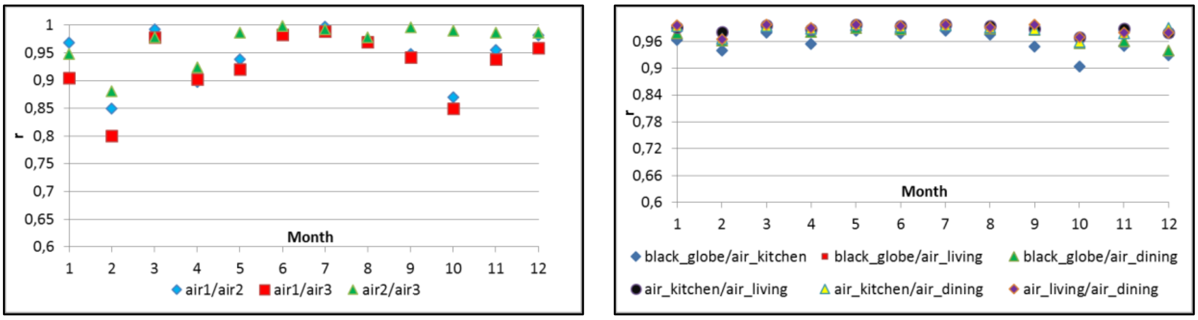


Figure 4-9: Correlation coefficient between air temperature measurements, first floor (left), ground floor (right)

4.4.3.3. Correlations between inter-floor measurements

The final step is to study correlations between all the air temperature measurements placed on both floors. The results for room 1 vs. the living space are presented in Figure 4-10, left, and for room 3 vs. the living space in Figure 4-10, right. Air temperature measurements situated in room 1 are not so well correlated with those situated on the ground floor. This is mainly due to different solar gains (different orientation as specified before, living space is oriented to the south and room 1 to the west). In contrast, the air temperature measurements in room 3 (southern orientation) are strongly correlated to those on the ground floor, with correlation coefficients higher than 0.85 (see Figure 4-10, right).

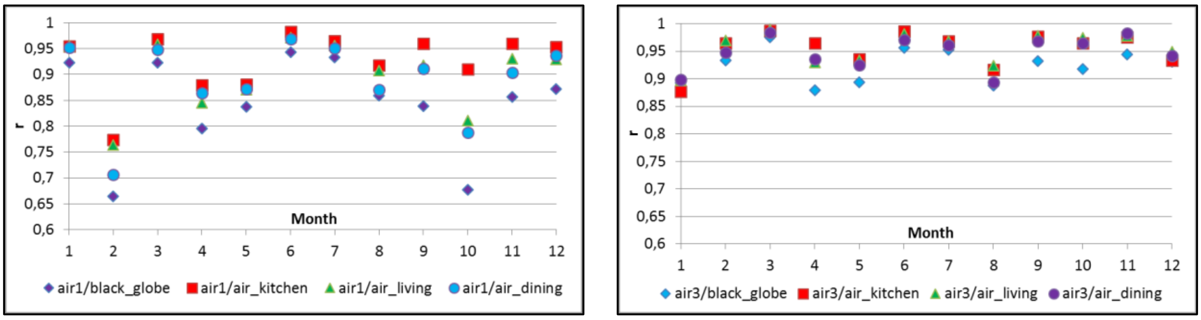


Figure 4-10: Correlations between air temperature sensors, IDM house, (left) room 1 and ground floor; (right) room3 and ground floor

4.4.3.4. Findings

A first conclusion here is that within one room the surface temperature is correlated with the air temperature. Consequently, we conclude from this first analysis that measurements close to room walls can be considered representative of room air temperatures. Secondly, here it was showed that air temperature sensors situated within rooms having the same orientation are strongly correlated. This assumption will be further tested on an occupied house, as presented in the following subsection.

4.4.4. Additional test on an occupied house

4.4.4.1. Brief description of the house

Complementary analyses are conducted on an occupied building. This house surface is about 168 m^2 and it is occupied by a family of five, including two children and a baby. Walls are timber-framed with cellulose filling and highly insulated windows. A granulated wood stove located on the ground floor can heat the entire house, but there is also a small heater in the upstairs bathroom. The main focus here is the ambient temperature in the first-floor bedrooms. Here there are two children's bedrooms, which have the same orientation and the same surface, and the parents' bedroom, which is oriented differently, facing east (see Figure 4-11).

Figure 4-11: 3D representation of the occupied real house

Given that this is a dwelling, commercial sensors are used. The ambient temperature sensors location is not in the middle of the room (as for the experimental building, section 4.4.1) but at 1 m high along the wall. These sensors are placed by the occupants to avoid sunspots and reflect their everyday life.

4.4.4.2. Results

The same method of calculating correlation coefficients is used here, except that for this house the focus is only on air temperature measurements. Figure 4-12 shows monthly averaged correlation coefficients. Temperature measurements in the children's bedrooms are strongly correlated ($r > 0.9$ for 10 months), but not with the parents' bedroom. This illustrates the effect of internal gains, which are different (two adults versus one child), and of the working program of each occupant (parents versus children), as well as the different orientations of the three rooms.

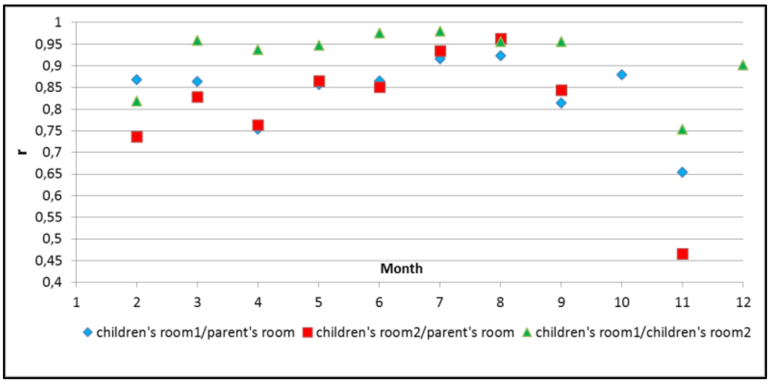


Figure 4-12: Correlation coefficients between air temperature measurements in an occupied real house

4.4.5. Findings

This correlation study showed how the number of ambient temperature sensors can be limited. We validated that the thermal behavior of similar rooms in terms of use and orientation, is correlated. It was also verified here that in an unoccupied house strong linear correlations are found between the temperature measurements of rooms located on different levels but with the same orientation. Regarding the real single-family house, the internal gains and the working program of each occupant lowered the correlation coefficients. However, the thermal behavior of similar rooms in terms of use – children's bedrooms in this case, with similar orientation – is also correlated. Therefore, for this type of similar rooms (regarding orientation and use) the choice of reducing the number of sensors seems valid.

Moreover, the measurements close to the wall surface are strongly correlated to air temperature measurements. As already mentioned, this has a practical application: in occupied houses it is almost impossible to place the sensors in the middle of the room, whereas locations close to the wall are possible.

However, it should be noted that this study has some limitations: it represents only two specific case studies of very well insulated houses and further tests on different buildings need to be performed in order to generalize the sensors limitation procedure. Furthermore, using Computational Fluid Dynamics simulation in future investigation could help a deeper understanding of the difference between the air temperature sensors.

4.5. Global monitoring of the PosA house: practical implementation and first results

This section presents a practical approach for evaluating the building's performance through monitoring of the PosA house. First, the case study is presented. Then, the monitoring system is described. Finally, the measurement results for energy consumption and thermal comfort are presented and are contrasted with the performance predicted in the design phase.

4.5.1. Case study and its "special features"

The PosA house was used as a case study within the present thesis due to two main reasons: this is the first house built within the COMEPOS project and therefore providing the only data available at the time of the present study. Furthermore, the family living in this house is involved in the COMEPOS project which enables an easier collaboration.

However, using PosA house as case study introduces some limitations, mainly due to specific features of this particular house rather different from typical French dwellings. As presented in section 2.2 this house has a large living area of 229 m^2 with a complex geometry, rather different from French average housing with a surface of approximately 100 m^2. This particular house is occupied by a family of 6, which again is not very representative of the French average housing. Furthermore, this specific house is situated in the south of France, in a Mediterranean climate, with warm winters. Another "special feature" concerns the heating energy. In the design phase, electric heaters were supposed to be used. However, in the real life the occupants of the house used wood energy for the first floor, which generated additional measurement uncertainties. It should also be specified that this is a modern house with 4 teenagers so multimedia and appliances are abundant.

Nevertheless, the approach of performance evaluation was tested on this house, against all these limitations.

4.5.2. Proposed monitoring system

The monitoring system was implemented following the guidelines presented in 4.3, focused on both energy use and indoor conditions.

Regarding the **energy use**, for electric part, energy meters are implemented to measure the energy consumption for: heating, lighting, ventilation (fan consumption), DHW, but also the other household appliances as well as the energy production (solar panels and wind turbine).

Monitoring wood energy consumed for space heating is more difficult. Wood use is assessed via occupant's survey only, introducing large uncertainties. An air temperature sensor located above the wood stove is added enabling monitoring of stove operation periods.

Following the results of section 4.4, the indoor conditions were monitored only in a few rooms. As it can be seen in building's plan (Annex A.1), this house contains three floors (the parent's bedroom is situated slightly higher than the living room). Therefore, the sensors are to be placed: in the living room, in the parents' bedroom and in one of the children' bedroom. Indeed, the three children's bedrooms are similar in terms of surface, orientation and use. Therefore, we propose a limitation to one indoor air temperature, instead of three. Furthermore, as this is an occupied building these sensors cannot be placed in the middle of the room. Location in the volume of the air (on a furniture, close to the wall etc.) not exposed directly to sunlight is proposed. In addition, measurements of relative indoor humidity, CO2 and VOC (Volatile Organic Compounds levels), natural lighting are proposed for a better assessment of the indoor environments. Short tests and /or occupant survey for evaluating the perception of visual, thermal and acoustic comfort and are also proposed.

Furthermore, the envelope's insulation and durability properties are approached as following. For evaluating the envelope's insulation property we use short tests as described in chapter 3. The envelope's durability is evaluated as well, using measurements of the temperature and humidity in the wall (2 sensors situated in the northern wall in the ground floor bathroom, at the interface between materials (concrete/ insulation and in the middle of insulation layer)).

As mentioned, complementary measurements of **boundary conditions**: occupant presence in different rooms, opening / closing windows and blinds, ground temperature and weather conditions (external temperature, solar radiation, wind direction etc.) are implemented to gain more information.

Figure 4-13 shows a theoretical representative sensor distribution for a ground-floor bedroom. More information on all the sets of sensors installed in this house can be found in annex D.3.

It should be noted that the metering list is quite exhaustive. Indeed, the family living in this particular building is strongly involved in the COMEPOS project and therefore approved the installation of different sensors.

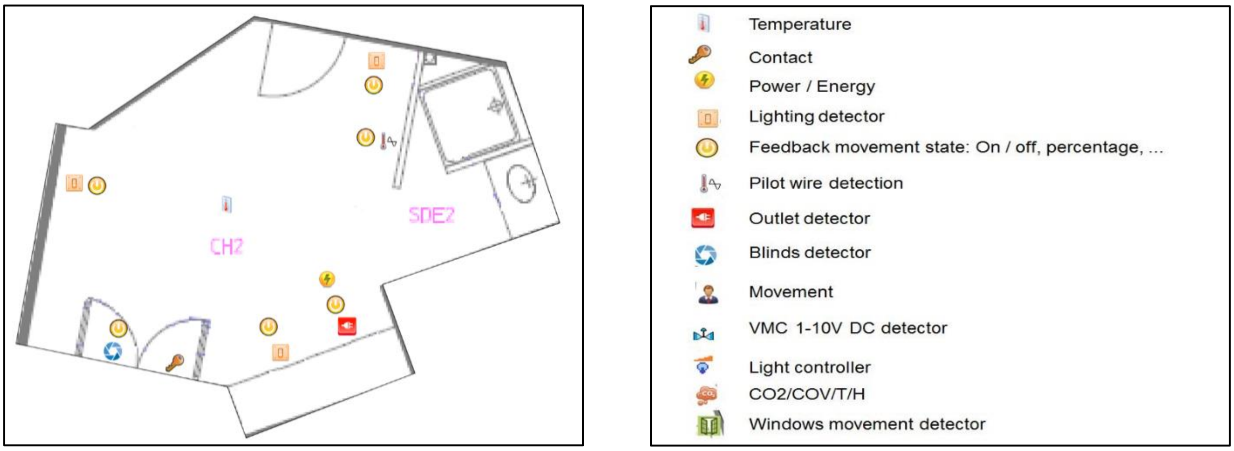


Figure 4-13: Example of sensors distribution for a ground floor bedroom

4.5.3. 'Operational' monitoring

In reality, the monitoring list presented in the previous paragraphs was reduced, mainly for the reasons of cost. For example, the sensors for moisture and temperature within the wall, as well as ground temperature sensor were not installed. Regarding the quantity, only two instead of three sensors measuring the level of CO_2 and VOC were installed (in the living room and in the parents' bedroom). However, two additional indoor air temperature and relative humidity sensors were installed on the ground floor bedrooms.

The construction of this house has been finished in spring 2015 and the monitoring started in October 2015, 24/7. A private web service allows acquiring the data. Measurements such as temperature and energy use are continuously monitored. For temperature, every variation (higher than 0.5°C) is recorded as new data with its time of appearance.

However, due to malfunctioning or installation problems, of the 121 sensors (including 97 actuators) tested in May 2016, only 79 sensors were fully operational. At the time of this study (November 2015- April 2016), the following sensors were operational:

- 22 energy meters (Eltako brand, type FWZ12) (Eltako), installed at the electrical panel of the home. Energy meter data is sent every 10 min.
- 3 air temperature sensors (type TYBOX 127) (DeltaDore) in the ground floor children's bedrooms, located on a shelf or furniture, as shown in Figure 4-14.
- 2 ambient condition sensors (type E4000, Nano-Sense) measuring air temperature, relative humidity, CO_2 and VOC concentrations in the living room and the parents' bedroom. Both are located away from doors, windows and electric heaters, at 1.60 m high.

- 26 light state controller (type TYXIA 4610) (DeltaDore).
- 6 electric heater state feedback (ON/OFF) (Eltako brand, FWZ12) (Eltako).
- 3 movement detectors (type IRSX, detecting infrared motion presence or absence in the room. However, the number of people remains unknown) (DeltaDore).
- 12 window movement detectors (mini COX) (DeltaDore).

Figure 4-14: Indoor temperature sensors

Unfortunately, at the time of the study, the weather station and the energy production measurements were nonoperational. Outdoor temperature data from a weather station located approximately 5 km from the house (Eyragues) was available and used within the present thesis.

Moreover, short additional tests using for example classic thermal comfort device could not be performed at the time of the study.

Furthermore, a survey was sent to the owner of the house in August 2016. This survey included questions regarding thermal, visual and acoustic comfort, systems performance and indoor conditions, which will be more detailed in the following sections. A list with all the survey questions can be found in Annex (D.4).

Measurements of energy use and indoor temperature allowed us a first approach in evaluating the energy performance of this house, which will be presented in the following sections.

4.5.4. Energy use

We are interested here in the energy use, as the first indicator of building's performance. In the beginning, measurements are presented. As discussed before, even when considering a similar building, energy consumption gaps occur due to the occupants' behavior (Dall'O' et al. 2012). Therefore secondly, an attempt to identify the contribution of occupants' behavior on the energy use is made by comparing simulations from the design phase with the actual measurements.

4.5.4.1. Measurements

This subsection presents the measured values of the energy use over a 6-month period (November 2015 to April 2016). Here, only the delivered energy is used. It starts with presenting the so called "RT2012 items" included in the French thermal regulation (ventilation, lighting, DHW and heating) and related energy use. Then section (b) focuses on the appliances energy use. Finally, measurements of total energy use are presented in section (c).

(a) RT2012 items energy use

Here four out of five RT2012 items' real energy use are presented. As mentioned earlier, no cooling system is installed. The metering of heating, ventilation, domestic hot water and lighting is available in Table 4-4. For this house, the heating supply comprises two systems: electricity and wood. The electric heating system was used for the ground-floor children's bedrooms. The wood was used for the first floor: the parents' bedroom, the living room and the stairway zone.

The wood consumption for heating was determined using information given by the owner about the amount of wood used during this period. This was approximately 2 m^3 wood corresponding to approximately 2850 kWh, over the heating system. More details can be found in (Gondian, 2016).

The results show that, for this period, as excepted, the most significant energy consumer is the heating system. More, as can be seen here, except for November and March, the major heating energy consumer was the first-floor heating, which is in fact the wood energy use. The second energy consumer, among the RT2012 items, is the DHW, which covers the hot water demand for six persons. Furthermore, ventilation, DHW and lighting energy consumption values are low compared to heating energy use.

When considering the variability over time, it can be observed that the heating energy consumption was the highest in December, January and February, whereas the other items (DHW, lighting) have a tendency to maintain a relatively constant level.

ENERGY USE [kWh/month]	VENTILATION	LIGHTING	DHW	HEATING		
				TOTAL	ELECTRIC	WOOD
November	78	85	115	269	147	121
December	79	82	131	846	87	759
January	14	78	142	1136	226	911
February	65	64	140	778	201	577
March	73	67	140	403	221	182
April	65	49	117	84	54	30

Table 4-4: Measurements of 6 winter months for energy use of RT2012 items

(b) Appliances energy use

Here we present the measurements of domestic appliances. Table 4-5 shows all the available energy consumption measurements for certain home appliances over a 6-month period (November to April). Unfortunately, only the oven, fridge, dishwasher and stovetop measurements were available as separate values. The total other appliances energy use was calculated by deducting the energy use of the above-mentioned known appliances from the overall energy use measurements. These other appliances (column 6, Table 4-5) accounted for the highest value of appliances energy use compared to fridge energy use for example. It may be explained by the fact that this last column of the Table 4-5 includes all the other items present in the house: an additional refrigerator, TV, internet box, etc. that are connected to these indoor electric outlets.

The appliances energy use values are between 178 kWh recorded in March and 333 kWh in December. The mean value is approximately 217 kWh, which is almost double comparing to the mean value of the DHW energy use.

ENERGY USE [kWh/month]	OVEN	FRIDGE	DISHWASHER	STOVETOP	OTHER APPLIANCES: TV, washing machine, microwave, iron, tablet, laptop etc.
November	17	28	7	4.6	208
December	17	30	9	0	333
January	10	34	8	0	203
February	14	31	11	0.1	182
March	16	31	8	0.8	178

April	23	39	8	0	196
Minimum	10	28	7	0	178
Maximum	23	39	11	4,6	333
Average	16,2	32,2	8,5	0,92	216,7

Table 4-5: Appliances energy use

(c) Total energy use

In Figure 4-15 is presented the total energy use for each month during the winter period, separating the four RT2012 items and the appliances. We observe that the heating represents the highest energy consumer for only 4 months of the year. Its highest value is in January - the coldest month during this period. Another reason may be that this period coincides with the winter holidays, when the occupants spend more time indoors. As expected, in April, very low heating energy was needed for this house, situated in a Mediterranean climate. In April, the principal energy consumer was the appliances. This was anticipated considering this modern well insulated house and the increased number of the household appliances nowadays.

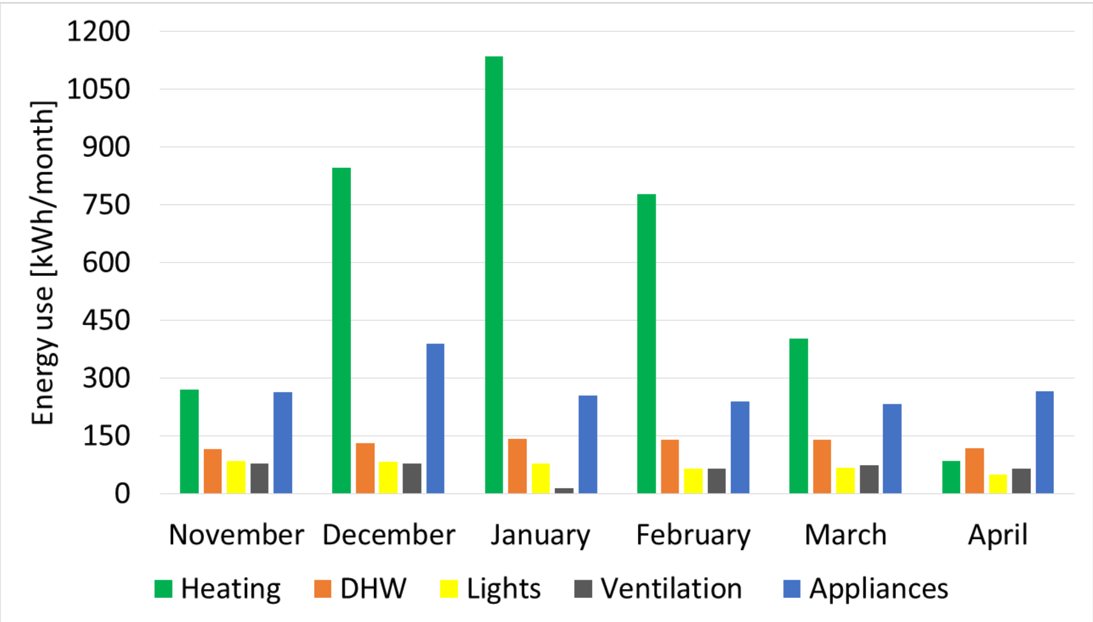


Figure 4-15: Total energy use for 6-month period

(d) Annual projection

Using 6 month measurements we calculated an annual projection for each item, divided by the area of the house. For heating, the value presented here is the sum of the heating energy use (electricity and wood) for the period November-April, divided by the house's surface (229 m²). Indeed, no heating need was assumed from May to October.

We considered that ventilation, lighting, DHW and appliances energy use have a constant trend over the year: the annual value corresponds to the average value over the 6-month period for each item multiplied by 12 (the number of months) divided by the house's surface. The results are presented in Figure 4-16. Here it can be seen that heating and the appliances energy use are the principal energy consumers, representing about one third of energy use each. This is consistent with the study of (Elsland et al., 2014) which stated that increased ownership of appliances has led to rising electricity demand.

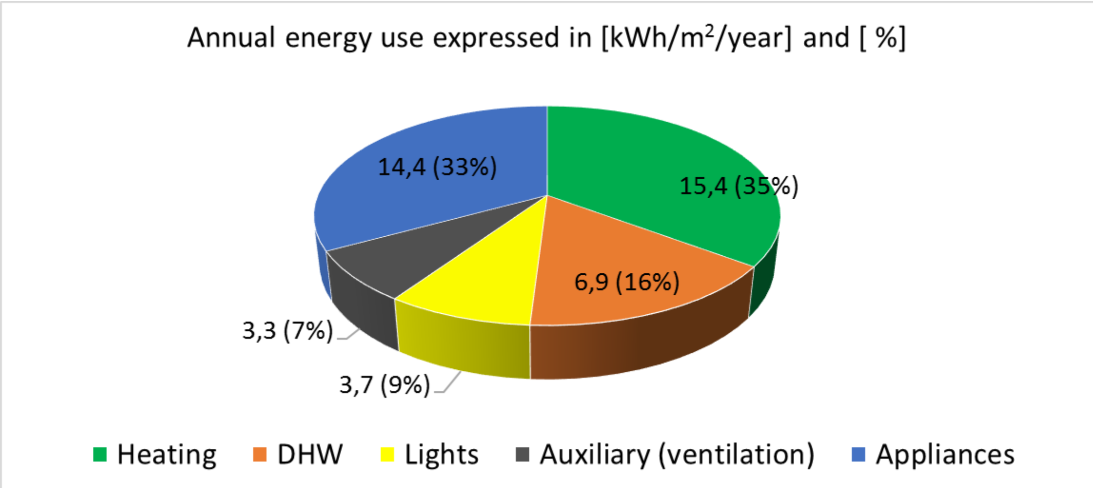


Figure 4-16: Annual projection of the total energy use

4.5.4.2. Real versus predicted

In assessing the energy performance of a building it is important to compare the actual measurements with the estimation made within the design phase. This is mainly because feedback on the real-life conditions is necessary to verify the actual performance and to better understand the real behavior. Another reason is the validation and further improvements of the design process. Therefore, in this subsection, we compare the measurements with the results from the design phase using the deterministic and probabilistic schedules discussed in section 2.3. It should be noted that the simulations were performed using the design weather file presented in chapter 2.

(a) Energy use of RT2012 items

The next objective is to compare the real energy use with the national statistics when using the probabilistic occupancy scenarios presented in section 2.5. As mentioned previously, only the delivered energy is used.

In the simulation, the annualized heating energy demand represents the annual heating energy demand, divided by the house surface. Here, within the simulations scenarios, we assume that no heating is used from May to October. Furthermore here we present the results using the standard schedule (schedule 1) and a schedule so called "owner's view", which represent schedule 5 from Table 2-6.

Figure 4-17 presents the annualized heating energy use/ demand. Here it's showed that the real energy consumption for heating is situated within the results based on statistics, provided by the agent-based model and correspond to one of the efficient scenarios. In this case, the robustness of the design is verified, as the real heating energy use stays between the ranges established in the design phase. Furthermore, according to the survey (see Annex D.4), the owner stated that he was satisfied with the heating system and that he did not feel cold during winter days. However, it should be noted that almost 70% (11 kWh/m²/year) of heating correspond to wood energy.

Additional elements on indoor temperatures will be discussed in section 4.5.5.

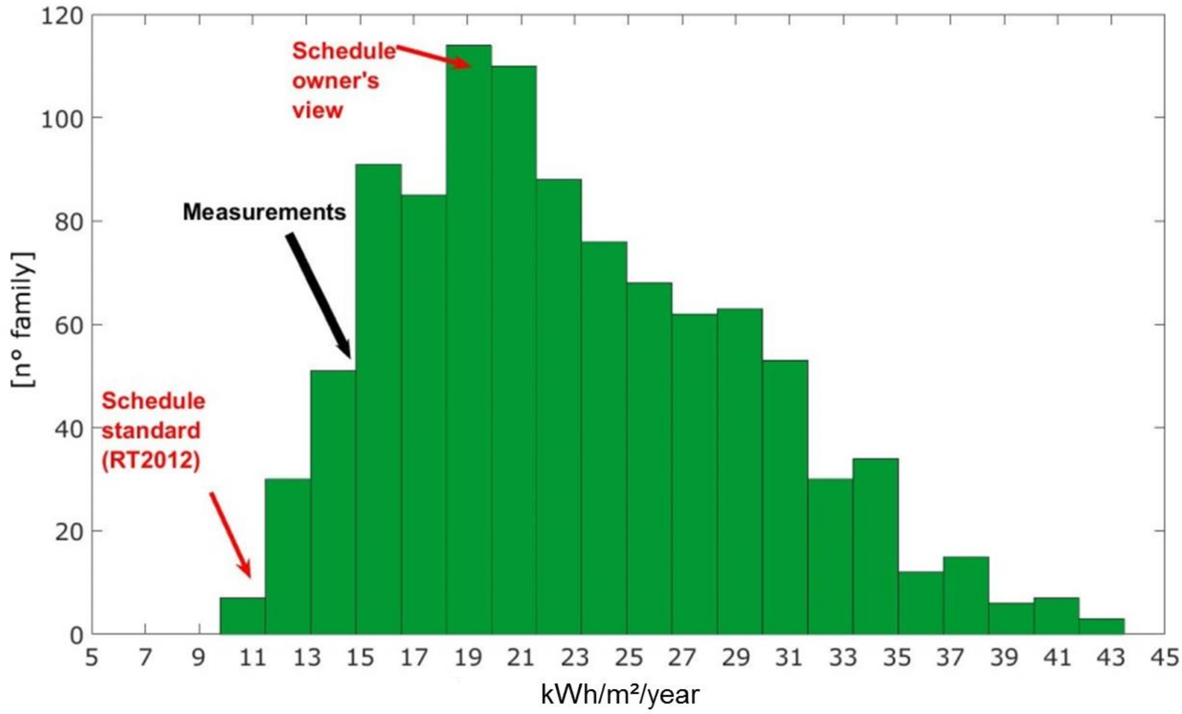


Figure 4-17: Heating: measured vs. predicted

The results for the other RT2012 items are now presented. The values estimated in the design phase (chapter 2) are reported: the DHW energy demand estimated by the manufacturer using the RT2012, the ventilation and lighting energy demand estimated using the EnergyPlus model. For the lighting we present the results when using schedules 2 to 5 (which are identical for lighting use) where we used a schedule based on occupancy charts (see Table 2-4). For the ventilation, the air flow specific for each zone was estimated based on the technical manual provided by the manufacturer, then the EnergyPlus model was used to estimate the ventilation energy demand.

As for the measured value for each item (ventilation, lighting and DHW), the annual average value was calculated for the sake of comparison. As mentioned, we considered that these items have a constant trend over the year: the annual average corresponds to the average value over the 6-month period for each item. These results are compared to the estimated values from the design phase (Table 4-6). The numbers show an underestimation in the design phase calculation. The largest discrepancy between the design calculation and measurements is for DHW, which is probably due to unpredictable human behavior and measuring uncertainties.

ENERGY USE [kWh/month]	REAL	PREDICTED
Ventilation	62	49
Lighting	71	59
DHW	131	81

Table 4-6: Real versus predicted mean energy use/ demand value for ventilation, lights and DHW

(b) Appliances energy consumption

As explained above, two types of schedule are used for deterministic simulation of appliances energy consumption. First, (schedules 2 and 3) the simulations are performed using the nominal power of each device provided by the owner of the house. Second, (schedules 4 and 5), the power of the electric equipment was amended around an average value.

For measurements, the annual average value correspond to the average calculated over the 6-moths period (as explained in section (a)).

The comparison presented in Table 4-7 shows that, all simulation results overestimate the energy use of the dishwasher and stovetop (Table 4-7). However, it should be mentioned that gas was also used for cooking. This was estimated at about 61.5 kWh/month, using information from the owner. As for the fridge and oven energy use, not surprisingly, the simulation using an average electric power seems to better reflect the actual energy use.

ENERGY USE/ DEMAND [kWh/month]	OVEN	FRIDGE	DISHWASHER	STOVETOP
Measurements	16	32	8	1
Simulations using nominal power (schedules 2 and 3)	37	58	41	112
Simulations using mean power (schedules 4 and 5)	14	26	24	24

Table 4-7: Comparison of the predicted and the actual uses of four appliances

The total energy use for all electrical appliances (oven, fridge, dishwasher, stovetop, TV, washing machine, microwave, iron, tablet, laptop etc.) is compared to the energy demand estimated in the design phase in Table 4-8. As the schedules are deterministic and fixed, the simulation results remained constant over the 6-month study. Again, the same overestimation of energy use by the simulations when using schedules 2 and 3 (nominal power) is observed here, except for December. As for results regarding simulations using schedules 4 and 5, the average power of the electric equipment underestimated the actual consumption.

ENERGY USE/DEMAND [kWh/month]	MEASUREMENTS	SIMULATIONS results using nominal power (schedules 2 and 3)	SIMULATIONS results using average power (schedules 4 and 5)
November	264	369	146
December	389	369	146
January	255	369	146
February	238	369	146
March	234	369	146
April	265	369	146
Average	274	369	146

Table 4-8: Actual vs. estimated energy consumption for all the appliances

The comparison of all these results shows differences in the simulations using deterministic scenarios and the simulations using the agent-based behavioral model and measurements. Figure 4-18 shows that the simulated data are highly scattered. It can be seen that the real energy consumption for appliances corresponds to the right bound of the range, i.e., the higher values. When comparing the results from simulations using the RT2012 schedule and the actual measurements, the results show the appliances energy demand using the RT2012 tends to be overestimated by the standard, as confirmed here. On the other hand, appliances energy use tends to be underestimated by the agent-based model and by schedules 4 and 5, using the average power for the appliances. Again, this may be due to the fact that this modern house, occupied by six persons, is not representative of the national French housing data. Moreover, the agent-based behavioral model is based on statistics from 1998. Today, families tend to have a larger number of appliances and electronic devices compared to previous years.

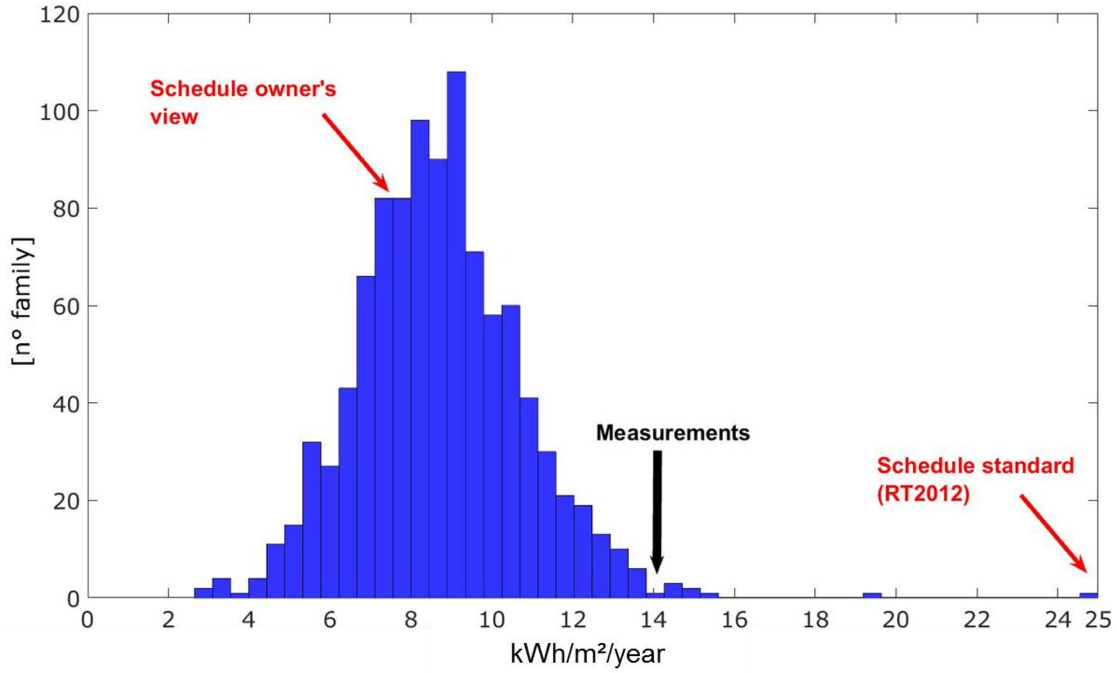


Figure 4-18: Predicted vs. real energy use for appliances

4.5.5. Indoor conditions

In this section we present the indoor conditions and discuss the occupants' impact on them. It starts with the presentation of the real temperature measurements. Then, following the same pattern as in section 4.5.4, we present an attempt to come within a range of values, using simulations. The occupants' feeling of thermal comfort is assessed through surveys. This can also clarify certain aspects regarding the measurements taken.

4.5.5.1. Indoor and outdoor temperatures

(a) Measurements

This part focuses on thermal comfort estimated by measurements of air temperature in the rooms. Usually, as presented in chapter 1, the measurements of thermal comfort is given by the operative temperature, in combination with other factors (humidity, metabolism etc.) However, an indoor operative temperature sensor can be very intrusive (black globe temperature sensor) and therefore not very convenient for occupied buildings. For this reason, here we used only the air temperature sensors situated in each room, as presented in section 4.4. For this type of efficient buildings in Mediterranean climate, this hypothesis seems reasonable since surface temperature is close to air temperature in a "comfort zone". For the outdoor temperature we used measurements from a local weather station situated near-by (5 km), as specified in subsection 4.5.3.

In (Figure 4-19) experimental data for indoor and outdoor temperatures for a representative room on each floor are presented. A period of 5 consecutive days in December 2015 is selected to represent the thermal comfort in the house during the heating season. As shown here, the ground-floor air temperature is almost constant at 19°C, contrary to the first-floor air where the temperature varies between 19 and 25°C. The temperature of the first floor is represented by the temperature in the living room. The rapid increase in temperature in the living room at the end of a day is due to the use of a wood-burning stove manually filled by the owner.

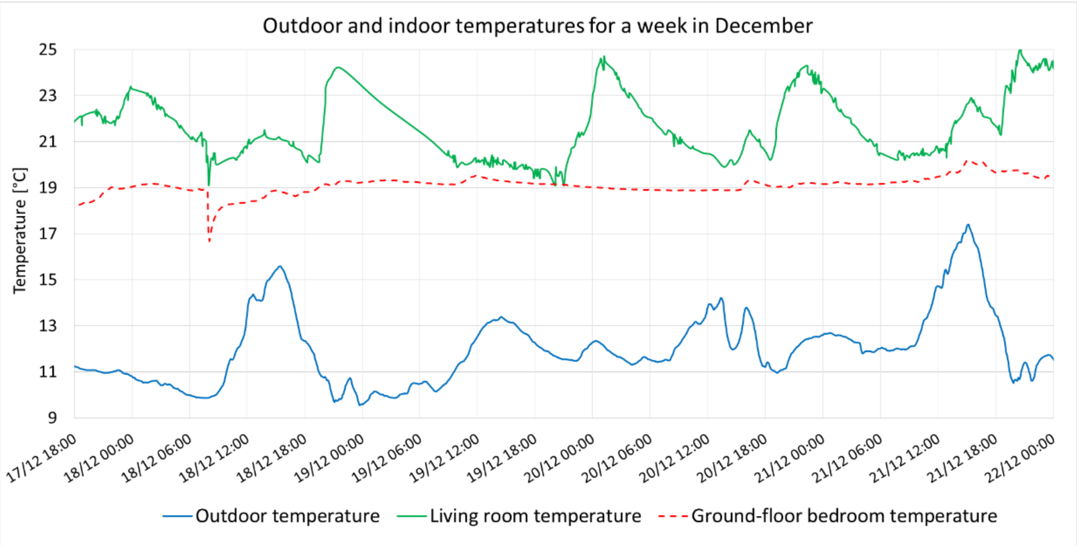


Figure 4-19: Outdoor and indoor temperatures for the living room and the ground-floor bedroom

After investigations over a week in December, the next step is to analyze the behavior of these measurements for a longer period. The hours when the occupants were absent are disregarded, given that thermal comfort refers to occupants. Measurements of indoor and outdoor temperatures can help determine the occupants' comfort range. This analysis can help better understanding of occupants' perception of their building's performance behavior. Moreover, it gives an inside view of the contribution of the occupants' behavior to energy use.

In (Gondian, 2016) the author, in her master's project, observed that the inhabitants of this house had a comfort temperature range of [20°C; 25°C] (Figure 4-20, when looking just at the measurements results. Another conclusion of her study was that the highest temperature observed here (above 25°C) was frequently due to the use of the wood-burning stove combined with high solar gains common in this Mediterranean region. The lowest indoor temperature (below 20°C) observed here is recorded mainly in the morning.

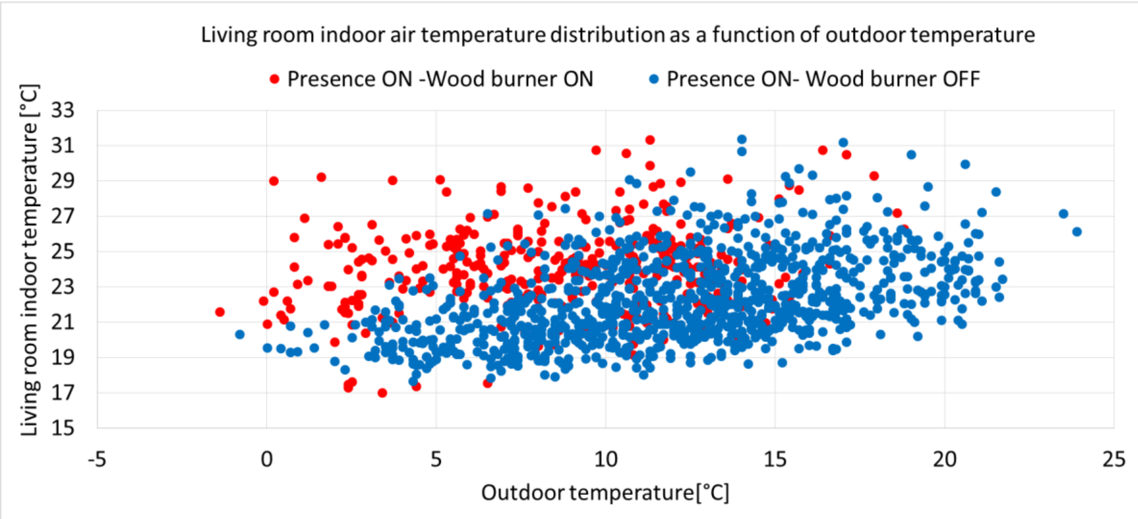


Figure 4-20: Living room indoor temperature as a function of outdoor temperature distribution (from (Gondian, 2016)

(b) Measured vs. simulated temperatures

Here, real indoor temperatures are compared with temperatures assumed in the design phase. This analysis is not straightforward, as many different variants can be used for comparison.

First, the data following the French standard RT2012 are used. Outdoor temperatures are given by the weather file used in section 2.3. It is of course different from the actual weather conditions influencing the building between November 2015 and April 2016. The indoor conditions correspond to the standard schedule with set-point temperature between 16-19°C

First, the period from November the 2nd to December the 20th is studied (7 weeks during the heating period). The mean, minimum and maximum values for the temperature as well as the standard deviation are given in Figure 4-21. It should be noted that rooms 1 to 3 are located on the ground floor. Here we observed that there is a 2°C difference between the mean air temperatures obtained by the simulation and those measured. Within the simulations in the RT2012 schedule, set-point temperatures are set at 19°C during occupancy and 16°C the rest of the time, which explains lower temperatures in this case.

The maximum air temperatures in the house were reached for an afternoon when the external conditions were favorable, around 20°C for the outside air temperature. The substantial increase in the internal temperatures can be explained by the presence of large southwest-facing windows in all rooms. The standard deviations show that the mean temperatures were constant (20°C) in the ground floor rooms (children's bedrooms), where electric heaters were used for heating.

On the first floor, in the living area and in the parents' bedroom, the values were higher (21°C) and variable. We observed that the mean temperature is higher in the living room compared to the parents' bedroom. This is mainly due to the use of the wood-burning stove, located in the living room. An important finding here is that when using a wood-burning stove the set-point temperature is not adjustable, which ultimately leads to higher energy use for heating. This is fact is often mentioned by different manufacturers.

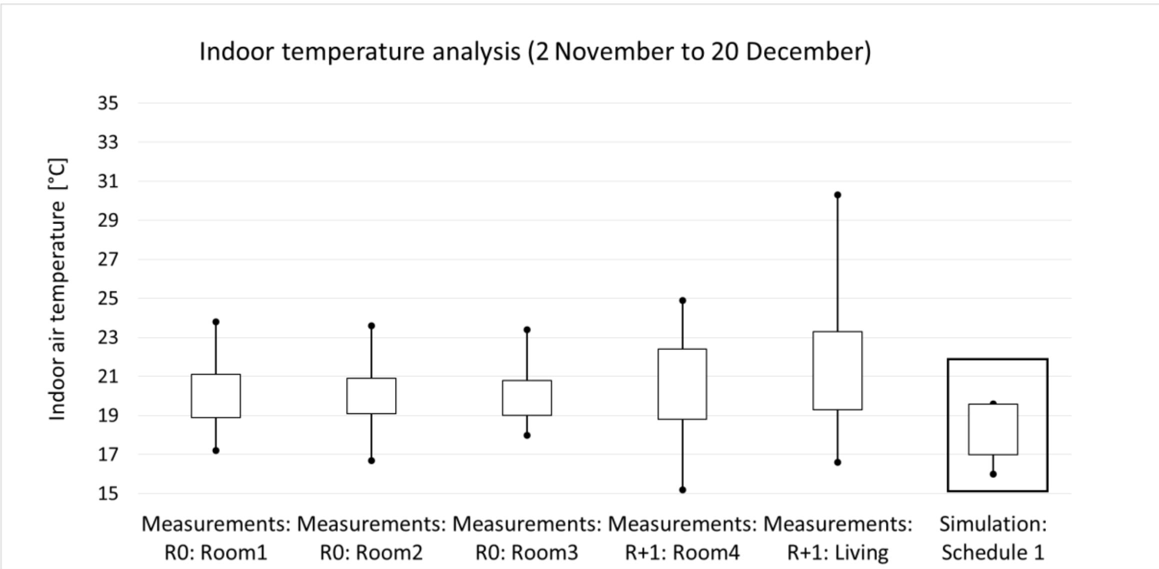


Figure 4-21: Minimum and maximum values for the predicted and real temperatures and standard deviation

As a next step some additional analyses were conducted on measured and simulated temperatures for the month of December, as an example of a winter month. Figure 4-22 gives the mean, minimum, maximum values as well as the standard deviations for the measured indoor temperature, the design set-point temperature and the outdoor temperatures. Low discrepancy shows that the ground floor temperatures (children's bedrooms) were stable (19°C). It can be partly explained by controlled electric heaters used for heating. However, on the first floor, in the living area and in the parents' bedroom, the values were higher (average value of 21°C) and more variable. As mentioned earlier, this is mainly due to the use of the wood-burning stove, located in the living room and not anticipated in the design.

Here we can observe that there is a 2-3°C difference between the mean air temperatures obtained by the simulation and those measured. As discussed above, the simulations of the RT2012 schedule use the set-point temperatures set at 19°C during occupancy and at 16°C the rest of the time, which explains lower temperatures in this case.

There is also a difference between the actual outdoor temperature and the one from the standard weather file. As mentioned above, the weather station was not operational at the time of the study and we used outdoor temperature data from a weather station located close to the house. As illustrated in Figure 4-22, in December, the mean real outdoor temperature was 4°C higher than the temperature used in the simulations. Similar trend was observed for the whole winter period. Consequently, we identify that the following factors compensate: warmer exterior conditions versus higher indoor conditions. This shift in both temperatures enables keeping the energy used for heating at a very similar level between the design and the actual situation.

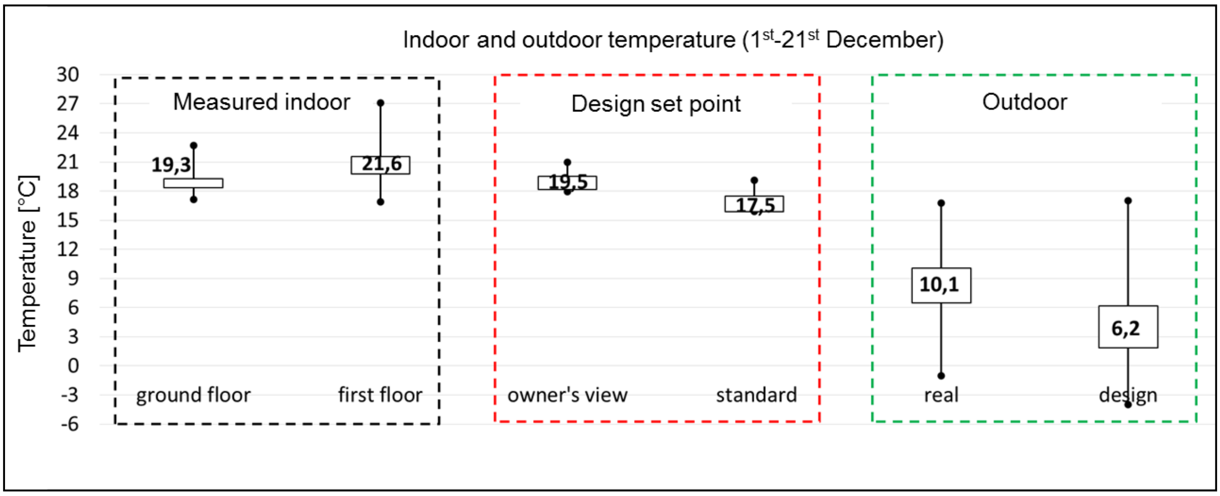


Figure 4-22: Minimum, maximum and standard deviation values for the predicted and real temperatures

In summary, two important findings can be observed here. First, the real outdoor temperature was higher than the weather file temperature used for the simulations. Second, the temperature preferred by the occupants was almost always higher than the temperature suggested by the RT2012. It is therefore important to identify the real set-point temperature, as preferred by the occupants. Some additional information was provided by the occupant and is discussed in the next subsection.

4.5.5.2. Occupant survey on indoor conditions

(a) Thermal comfort

As previously mentioned, the owner of the house was also questioned using a survey. The questionnaire was designed to help understanding situations observed in the data analysis: for example low and high values of indoor air temperatures.

The occupants were questioned on the temperature range they wished to achieve for optimal comfort. The answer varied slightly for the two adults [22–24°C] for the husband and [21–22°C] for the wife. This means a 3 or even 5°C gap between the temperature considered in the design process or in the thermal regulations and the owner’s ideal set-point temperature.

When the air temperature in the living room was below 19°C, the occupants reacted and lit the wood-burning stove, as was done every evening as part of their daily routine. This led to air temperature values about 27°C or even higher (31°C). When the temperature was above 25°C the occupants opened the window to reduce the temperature.

Furthermore, the concept of thermal comfort in summer was not treated in the present thesis due to lack of measurement. Nevertheless, the occupant survey included also a question about the overall level of satisfaction in terms of thermal comfort in summer. The level of satisfaction is 6 of 10 (not very high). This is mainly due to unfinished home automation and facades shading. Another interesting finding is that this family possesses an energy-saving awareness during summer time, as they closed the blinds during heat waves, opened the window at night for natural ventilation, and avoided using the household appliances that produce heat. However, additional studies are needed to evaluate the thermal comfort.

(b) Acoustic comfort and indoor air quality

As we presented in the beginning, a global evaluation of the energy performance should not only focus on the energy use, but also on the indoor conditions and the occupants’ wellbeing within their own home. Therefore, the occupant survey included also additional questions focusing on acoustic comfort, as well as on perceived indoor air quality. The general feeling of the occupant of the house is about 8 of 10, which is rather a good evaluation.

Regarding the acoustic comfort, the occupants declared that they don't perceive external noise.

Furthermore, the owner declared to be satisfied with the air quality and the humidity levels in the house (9 of 10). In general, the house performance regarding the general indoor conditions seems to fulfill design objectives, a according to the owner (8 of 10). However, there are still some systems adjustments that are needed. Future survey (1 year after the overall completion of the house installation and its settings) is highly recommended.

4.5.6. Preliminary conclusions from the performance evaluation of the PosA house

Continuous monitoring system was installed in our case study – the PosA house. The data recorded over 6 moths enabled first assessment of building's performance. Measured data were compared with the building performance simulation results from the design phase.

Within this comparison, several findings can be observed. In our case, using French thermal regulation scenario is relevant to estimate the ventilation (fans) and lighting energy use. Indeed, the energy consumption for **ventilation** is well estimated (approximately 0.6 kWh/ m^2/year difference, or 2%). As for the real **lighting** energy use, it is also well estimated (approximately 0.7 kWh/ m^2/year difference less than 2%). Here, for the **DHW** item, the family consume more (approximately 2.6 kWh/ m^2/year difference, or 17%) than estimated by the manufacturer in the design phase. However, this remains still in the admissible range of predictions. As for the **appliances** it is found that for this large surface house (229 m^2) the appliances energy use is in the upper bond of the national statistical results, i.e., corresponding to the higher values.

When looking at the **heating** results, the evaluation approach allows us to observe a **compensation** of various aspects that are involved. First, compared to the simulations when only electric heaters were used, the family turned to a more pleasant option: a wood-burning stove. Therefore, the wood energy became the only energy provider for the first floor zone. Moreover, when using a wood-burning stove there is tendency to overconsume, because resulting temperature cannot be controlled precisely, as in the case of electric heaters, a fact often mentioned by the manufacturers. Indeed, here the measurements show that at ground-floor, where electric heaters are used, the air temperature is almost constant at approximately 20°C. However, for the other half of the house (first-floor) the air temperature reaches 31°C, mainly due to the daily use of the stove manually filled by the owner. Therefore, we observed, that as anticipated, in real life the occupants prefer a higher (than given by the thermal regulation) **set-point temperature**, which is the case here especially for the living room. After discussions with the owner and measurements analysis, we observe that in reality, in the living room, the mean values of the occupants' desired set-point temperature are between 21 and 24°C. Measured amplitude is very high with a minimum of 17°C and a maximum of 31°C. Another factor is that the actual **outdoor temperature** is in fact higher than the temperature from the weather file used for the simulations. This fact impacts the heating energy use as well. Nevertheless, the real heating energy use is within the national statistics range and close to the design estimation. We identify that this is due to the compensation of the following factors: warmer exterior conditions versus higher indoor conditions.

As an outlook, it seems important to study the performance of this house during the summer period, especially regarding the thermal comfort. Furthermore, due to some monitoring malfunctioning, several sensors are not used within the analysis. For example the CO_2 levels and VOC measurements can give a better image about the indoor conditions.

4.6. Findings

In this chapter we study a practical application of the performance evaluation using continuous monitoring on the PosA house.

First, we present the general approach and the monitoring system specifications. One focus here is to provide guidance on a practical application of the monitoring for evaluating the building's performance. We define a monitoring approach that includes measurements of different components of energy consumption and production and of indoor conditions.

Some results on how to limit **the number of indoor temperature sensors** in occupied houses, with a minimal loss of information, is presented. It is shown that in rooms similar in terms of occupancy and orientation, indoor temperatures are strongly correlated and therefore the number of sensors can be reduced. In addition the wall surface and air temperature measurements are also strongly correlated. Main conclusion is that one temperature sensor over one floor, situated at mid-height, will provide enough data, when a global approach is of interest. We apply these results to PosA house.

Once the monitoring operational, we test the **feasibility of the evaluation approach** of the energy performance through monitoring. The goal here is to establish if the energy performance of this house is as planned and to better understand the building's real behavior. Therefore, to get more information about the real behavior of the house, we compare internal temperature and the energy demand ranges established in the design phase using national statistics with data collected during the operational phase, over 6 months of winter. This helps us to identify and analyze the discrepancies between the energy demand estimated in the design phase and the real energy use.

In this case study, using French thermal regulation scenario is relevant to estimate the ventilation (fans) and lighting energy use. However, the real DHW use is higher than anticipated. In this particular case the energy really used for **space heating** is similar to the values from the design phase. Detailed analysis of temperatures shows that this fact is mainly due to the compensation between contradictory elements. We observed, that as anticipated, in real life the occupants prefer a higher (than given by the thermal regulation) **set-point temperature**, which is the case here especially for the living room. It is compensated by the fact that the actual **outdoor temperature** is higher than the temperature from the weather file used for the simulations. We identify that this is due to the compensation of the following factors: warmer exterior conditions versus higher indoor conditions.

As for the **appliances** it is found that for this large surface house (229 m²) the appliances energy use is in the upper bond of the national statistical results, i.e., corresponding to the higher values.

As an outlook, it seems important to study the performance of this house during the summer period, especially regarding the thermal comfort. Furthermore, due to some monitoring malfunctioning, several sensors could not be used within the analysis. For example the CO_2 levels and VOC measurements can give a better image about the indoor conditions.

This first application shows the feasibility of the proposed approach of assessing the energy performance of a single family house. For the PosA house (located in Mediterranean climate), the energy performance complies with the design project: the real energy use is within the national statistics and the occupants are satisfied with the indoor conditions.

However, performance evaluation is a complex task. This approach needs to be tested on different types of houses, situated in different climates. This is in fact the goal of the COMEPOS project, as presented in Introduction.

CONCLUSION

In the present thesis, the **objective** was to contribute to the development of a performance evaluation approach of energy-efficient houses. This was done using building performance simulation, continuous monitoring as well as in-situ test for evaluating the energy use, but also of the occupant's feedback about the domestic conditions. Also, on a more detailed scale, we proposed an approach to evaluate the building's performance by understanding its different **components**. Our work focused on envelope's properties and occupant's behavior.

In this context, our evaluation approach consisted in the following steps.

First, in the design phase we generated **scenarios**, depending on occupant's behavior, based on national statistics and on future owner predictions. This allowed us to establish a range of values for energy demand which can be used as reference for the real energy use. Dispersions in energy demand related to the occupants' behavior were identified by testing various scenarios of occupancy, appliances power, and set-point temperature. We used both **deterministic and statistical approaches** to study the occupant's behavior impact on energy demand.

Then, once the house constructed, we investigated improvement to existing methodologies such as QUB and co-heating. The objective here was to evaluate the envelope's properties, by comparing the theoretical value with the real value of the **Transmission Heat Loss Coefficient (HT)**. More, we also reduced the uncertainties associated with the infiltration losses, by imposing and measuring infiltration air flow during the test. This was done by coupling the envelope's proprieties characterization to blower door test. Furthermore, for the identification process we used Bayesian inference method that improves the estimation of parameters by quantifying associated uncertainties (e.g. model form and measurement uncertainties) and by taking into account the range of possible values. This new test to assess the real envelope's proprieties of the future houses is adapted to occupied houses, as it only takes 2 days. To reduce occupant' behavior uncertainties the test must be performed within an empty house. It can be performed before the actual occupation of a house or during holidays.

Last but not least, the evaluation approach proposed within the present thesis included practical application of continuous monitoring. First, we presented a detailed guidance on the effective application of monitoring when a house is in use. We defined a monitoring approach focusing on two aspects: energy efficiency and indoor conditions. Then, we identified and proposed an approach to **limit the number of temperature sensors** for occupied houses.

We tested this performance evaluation approach on an occupied house situated in a Mediterranean climate, called PosA. To better understand the building's performance and the real behavior we compared measurements with the results from the design phase.

As explained, we used **building performance simulation** in the design phase. This study allowed us to observe, that for the PosA house, the heating energy demand varied between 13 and 35 kWh/m^2/year, depending on the used schedule. A 1°C increase in set-point temperature increases the energy demand by approximately 3 to 4 kWh/m^2/year. Regarding the majority of appliances energy demand can vary between 6 and 12 kWh/m^2/year, depending also on the used schedule, whether it is a deterministic schedule (using nominal and average power of the appliances) or a schedule based on national statistics. These results are mainly related to the set-point temperature variation; even if there is also a variation related to the other uses of electricity. Secondly, we focused on the real **envelope's proprieties** evaluation for this case study, to evaluate if the envelope is as efficient as designed. Here, for the PosA house, we concluded that the envelope's proprieties concur with the design project plans (less than 9% difference between the theoretical and experimental HT), and therefore the envelope plays its role in the energy saving. We carried on with the evaluation approach by using **continuous monitoring** of the building's performance, when in use. Therefore, we tested the feasibility of the approach by analyzing the results of monitoring and simulations. The approach allowed us to conclude that for this case study concerning the **Domestic Hot Water** item, this family consumed approximately 17% more than estimated by the manufacturer in the design phase (2,6 kWh/m^2/year difference), which remains still in the admissible ranges of predictions. Regarding the **appliances** energy use we observed that for this house the energy use was in the upper part of the statistical results, the higher values. As for **heating** energy use, on a deeper approach, we showed that, this family prefer a higher set-point temperature than the one used within the simulations (the mean measured values are between 21-24°C, with limits between 17°C and 31°C) for half of the house surface (first floor). More, when using wood burner there is a tendency to over consume. Furthermore, **outdoor temperature** was in fact higher than the temperature from the weather file used for the simulations. In total, the compensation between warmer weather conditions versus higher indoor temperatures made that the energy efficiency of this house complies with the design plans. Nevertheless, as we presented in the beginning, a **performance evaluation** should not only focus on the energy use, but also on the indoor conditions and the occupants' wellbeing within their own home. The evaluation approach also allowed us to identify that the owner is satisfied with the indoor conditions.

To sum up, within the present thesis the **evaluation** allowed us to better understand which part is using the most energy (appliances and heating) and which improvements would have the biggest impact on the house's performance (using electric heaters instead of wood) and the factors that impact it (indoor and outdoor temperatures).

Last but not least, within this present work, efforts were made towards evaluating the performance of energy efficient houses. However, this represents a challenging task, due to its complexity, and there is still a lot of work to be done.

- **Outlooks**

The evaluation approach proposed within the present thesis is just a first step. In the design phase, we propose to replicate the statistical predictions also for the **energy production** and for the **weather conditions**. This will allow a complete assessment, taking into account the variability of weather conditions, but also the correlation between energy use and energy production. Also it will give a more comprehensive representation of the building's performance and will allow studying the zero energy balance ranges.

Also, to complete the evaluation process, the contribution of the other performance components: equipment and exterior conditions should be investigated. Methodologies to test the actual equipment performance and different weather conditions will need to be accomplished. Systems commissioning is also recommended, as systems play an important part in the energy balance. Furthermore, in order to generalize the monitoring approach at large scale on occupied buildings, there is still a need to create an evaluation tool which will be reliable, cheap and easy to implement.

On the other hand, this methodology was only applied on a single case study. More, it represents a particular case, occupied by six persons and with a complex geometry. As an outlook it is recommended to test this methodology on different case studies, more representatives of the French national statistics. In particular, the short in-situ test coupling infiltration measurements with heat transmission measurements needs to be further tested, also for existing houses. Indeed, additional investigations are needed in order to quantify its real interest to reduce the uncertainty associated with the infiltration losses.

Also, it's interesting to observe the **house follow-up**, using performance data from several years. Our analysis represents only the first 6 months of occupation, but it's important to study the building's performance over several years. Such long-term approach will allow observing the house performance stability or deterioration over a long period of time.

Furthermore, **an energy performance optimization** during operational phase can be proposed to the owner, for example opening solar blinds during the day, or using electric heaters where the set-point temperature is adjustable, etc. This could allow obtaining **a positive energy balance**.

Getting performance evaluation aims at controlling the energy savings and ultimately the energy costs. This is an important contribution to the actual discussions about the **energy performance guarantee**. Answering questions such as “what can be guarantee?”, “who can guarantee what?” is the follow-on objective. For example once the energy demand range is available in the design phase, are the manufacturers able to certify that the future energy use stays within this range of values? under which conditions?

In the present thesis we showed that the real performance of this new house comes close to the design. However, the houses refurbishment represents another big challenge. Proposed evaluation approach could help getting a deeper understanding of the real performance after refurbishment. We propose to test first the envelope’s properties to establish the current state before the refurbishment. For existing houses however, this methodology can be used to better quantify and separate the envelope’s losses (infiltration vs. transmission). Then, we propose to test different occupation scenarios in order to establish a range of energy demand values, depending on occupation and based on national statistics. Furthermore, we propose the monitoring of the actual performance after refurbishment to determine the building’s performance. This will allow better understanding of the building’s performance.

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RESUME EN FRANCAIS

Vers l'évaluation de la performance des bâtiments à haute efficacité énergétique

Introduction

Aujourd'hui, le secteur de la construction est le premier émetteur de CO2 au niveau de l'Union européenne. Il est responsable de 40 à 45% de la consommation totale d'énergie en Europe et de 30 à 40% dans le monde (Day et al., 2009). La plupart des pays développés et de nombreux pays en développement ont déjà pris des mesures prioritaires concernant le secteur du bâtiment et la lutte contre le changement climatique. Ainsi, l'un des principaux objectifs présents dans de nombreux programmes environnementaux est d'augmenter l'efficacité énergétique des bâtiments neufs et existants or la conception de bâtiments à haute efficacité énergétique est une étape importante qui dépasse le simple fait d'ajout de composants d'enveloppe ou de systèmes efficaces, etc.

Dans ce contexte, le programme de recherche "COMEPOS" a été créé en 2013. Ce projet se concentre sur les maisons individuelles neuves à énergie positive et vise à évaluer et optimiser leur performance énergétique en optimisant le processus de conception, le suivi et la validation in situ de systèmes technologiques innovants dans différentes conditions climatiques. La présente thèse s'intègre dans le projet COMEPOS et s'appuie notamment sur un cas d'étude expérimentale. Sa finalité est de contribuer au développement d'une méthodologie d'évaluation de la performance énergétique réelle d'un bâtiment à haute efficacité énergétique. Une telle méthodologie d'évaluation doit permettre de quantifier l' impact sur la consommation d'énergie, sur le confort de l'occupant et sur l'environnement (Deng et al., 2014). L'impact sur l'environnement est généralement évalué à travers l'analyse du cycle de vie avec une quantification des matériaux utilisés et de leur impact environnemental (Thiers et Peuportier, 2012). En ce qui concerne l'impact sur la consommation d'énergie, le processus d'évaluation peut être réalisé à partir de données issues d'expériences et de la simulation. Le processus comprend la confrontation entre la performance énergétique prévue en phase de conception et celle mesurée en phase d'habitation. Différentes approches allant du plus simple au plus complexe peuvent être utilisées pour évaluer la performance énergétique réelle.

Par ailleurs, dans une approche globale, l'évaluation de la performance énergétique réelle d'un bâtiment doit tenir compte non seulement de la consommation d'énergie, mais aussi du ressenti des occupants sur les conditions intérieures telles que le confort thermique, la qualité de l'air intérieur, etc. Par conséquence, une évaluation plus complète et plus complexe de la seule performance énergétique en continue est nécessaire pour pouvoir comprendre le comportement du bâtiment, les causes éventuelles de surconsommation et le service rendu (conditions intérieures). Le pas de temps des analyses peut alors varier de quelques secondes à des heures, des mois, etc.

A la suite d'une étude bibliographique, nous avons identifié les quatre principaux facteurs qui influent sur la performance énergétique d'un bâtiment: la performance de l'enveloppe, la performance des systèmes techniques, les conditions extérieures et le comportement des occupants..

Dans la présente thèse, la « performance du bâtiment » est envisagée de manière indissociable de son occupation ainsi le bâtiment doit fournir un niveau de satisfaction raisonnable pour ses occupants et être efficace en ce qui concerne la consommation d'énergie. Dans ce contexte,, le terme "performance du bâtiment" dépend d'une partie de propriétés de l'enveloppe (qui existent comme attributs statiques indépendamment de la façon dont le bâtiment est utilisé et ne sont pas affectés par un scénario tel que les conditions extérieures, les occupants, etc.) et d'autre part de l'utilisation du bâtiment (occupants, conditions extérieures

Comme nous l'avons déjà mentionné, l'objectif de la présente thèse est de contribuer au développement d'une méthodologie d'évaluation de la performance énergétique réelle des maisons à haute efficacité énergétique et des facteurs contributifs. En outre, il est nécessaire d'aider à vérifier que la performance prévue en conception se retrouve en phase d'occupation. Nous envisageons de faire cela par monitoring et par simulation thermique dynamique en se concentrant sur la consommation de l'énergie et les conditions intérieures en examinant deux aspects: l'enveloppe du bâtiment et le comportement des occupants.

Notre démarche sera la suivante :

• Tout d'abord, nous utilisons la simulation thermique dynamique pour créer différents scénarios d'occupation afin de mieux comprendre les facteurs liés à l'occupation qui alimentent la consommation d'énergie et les conditions intérieures.

• Deuxièmement, nous allons acquérir des données de performance grâce à un monitoring continue et à des tests in situ (pour évaluer les propriétés de l'enveloppe par exemple). Cela permettra d'obtenir des informations détaillées sur la consommation d'énergie, le comportement des occupants, etc.

• Enfin, afin de mieux comprendre le comportement réel du bâtiment et de ses occupants, les mesures seront comparées aux résultats prévus dans la phase de conception.

Ce mémoire de thèse est composé de quatre chapitres. Le chapitre 1 présente l'état de l'art des méthodes utilisées pour l'évaluation de la performance énergétique d'un bâtiment à haute efficacité énergétique: aperçu international des méthodes utilisées pour la STD et pour le monitoring. Le choix de l'outil de simulation ou du monitoring adapté constitue une tâche difficile compte tenu de la variété des outils disponibles et des développements accrus dans ce domaine. Ce chapitre montre également que dans les bâtiments occupés, un impact énorme sur la performance énergétique vient de la nature stochastique du comportement des occupants.

Dans le chapitre 2, l’objectif est double, il vise dans un premier temps a mieux comprendre l’impact de l’occupant et de son comportement sur les consommations et dans un second temps de passer d’une prévision de consommation en phase de conception unique et déterministe à une plage de valeurs réaliste. Pour cela, un focus a été fait sur l’intégration de la variabilité du comportement de l’occupant. Ainsi, nous avons utilisé la simulation thermique dynamique pour mieux comprendre les facteurs liés à l'occupation influençant la consommation d'énergie et les conditions intérieures. Les dispersions dans la consommation d'énergie liées au comportement des occupants sont identifiées en testant différents scénarios d'occupation, d’utilisation des appareils électrodomestiques et de la température de consigne. L'objectif est de mieux comprendre l'impact du comportement des occupants sur la consommation d'énergie et d'établir une plage des valeurs pour les besoins d'énergie, en fonction du comportement des occupants, sur la base des statistiques nationales.

Après s’être intéressé à la phase de conception, le chapitre 3 se concentre sur la phase de réception et l’enveloppe du bâtiment. Des tests de courte durée sont utilisés pour évaluer la performance de l'enveloppe réelle. Cela se fait par une comparaison entre une étude numérique et une étude expérimentale, appliquée pour deux cas d’études.

Dans le chapitre 4 est présentée l'évaluation de la performance énergétique réelle en phase opérationnelle via un monitoring continu (capteurs de température, compteurs d'énergie, etc.). Premièrement, une étude préliminaire est présentée pour la réduction du nombre de capteurs pour des raisons de coût et d'acceptabilité. Ensuite, une application pratique de l'approche d'évaluation proposée sur une maison individuelle est illustrée. Pour une meilleure compréhension de la performance énergétique, les données de performance recueillies pendant la phase opérationnelle sont comparées avec les performances estimées au cours de la phase de conception. L'efficacité énergétique et le confort thermique sont analysés à l'aide de mesures et d'enquêtes auprès des occupants.

Plusieurs maisons sont utilisées pour développer et valider les travaux réalisés, en particulier la première maison du projet COMEPOS qui servira de fil rouge à cette étude.

Chapitre 1 : Etat de l'art sur les méthodes utilisées pour l'évaluation de la performance énergétique d'un bâtiment à haute efficacité énergétique

Introduction :

Ce chapitre présente un état de l’art sur les méthodes utilisées pour évaluer la performance énergétique d'un bâtiment. On y retrouve le monitoring, les test courts et les simulation thermiques dynamiques.

Développements :

Les principales raisons amenant une différence notable dans le monitoring de bâtiment proviennent :

- de la destination de l’objet de l’étude (par exemple secteur résidentiel (Dall'O et al., 2012) (Gans et al., 2013) ou dans le secteur des services ou du commerce (Agha-Hossein et al., 2013) (Li Et al., 2016a)),
- de son occupation réelle (maison individuelle, bureaux, par exemple) (Andersen et al., 2013a) (Rohdin et al., 2014) ou reproduit et contrôlée : maison « laboratoire » (Saelens et al., 2004) (Loutzenhiser et al., 2009) (Mateus et al., 2014. Une difficulté supplémentaire apparait pour les bâtiments occupés : celle de limiter le nombre de capteurs, tout en maintenant une robustesse et une précision suffisantes des données.
- de l’échelle d’analyse qui varie selon l’étude allant d’un unique bâtiment à un ensemble de bâtiments. Selon l’échelle les objectifs du monitoring varient d’une compréhension détaillée à une comparaison microscopique entre bâtiments à une meilleure appréhension des différents usages de scenarii.
- et des indicateurs de performances que l’on cherche à évaluer. Ces indicateurs de performance sont définis dans le but de l'évaluation, qu'il s'agisse de comprendre et d'améliorer la performance énergétique ou de donner des informations sur la performance énergétique (vérifier si le bâtiment est conforme aux exigences règlementaires).

On peut trouver des indicateurs de performance quantitatifs qui exigent des données objectives qui peuvent être mesurées: par exemple, consommation d'énergie, température intérieure, etc. mais également des indicateurs qualitatifs de performance nécessitant des données subjectives: par exemple, évaluer le confort thermique (Guerra-Santin et Tweed, 2015) (Olivia et Christopher, 2015) ou l'impact environnemental (Meggers et al., 2012). Néanmoins, la plus part de ces indicateurs sont évalués par des mesures: que ce soit l'évaluation de la consommation d'énergie (Sree, Paul et Aglan 2010), du confort thermique (Rohdin et al., 2014) de la qualité de l'air intérieur (Wallons et al., 2002) (Gunschera et al., 2013), du fonctionnement du bâtiment (Andersen et al., 2013b) ou de l'impact du bâtiment sur la santé des occupants (Wolkoff, 2013).

Par ailleurs, nous avons identifié deux approches pour l'évaluation des performances par la mesure. L'une repose sur la mise en place de tests de courte durée (enquête auprès des occupants, one-shoot, etc.), tandis que l'autre s'appuie sur un monitoring continu sur une période longue allant du mois à plusieurs années.. Comparées aux mesures à courte durée, les mesures en continu permettent d'étudier la performance énergétique sur une plus longue période, d'établir des modèles et de mieux comprendre le comportement des occupants et des bâtiments. Toutefois, cela est plus coûteux et complexe, et il nécessite la mise en place de capteurs dans les bâtiments occupés.

Résultats et Conclusions :

A la suite de ces observations, on constate que le type, la durée et la fréquence du monitoring dépendent de manière significative de l'objectif de l'étude (consommation d'énergie, confort thermique, etc.), du type de bâtiment (résidentiel ou tertiaire), et des indicateurs de performance retenus. Par ailleurs, les bâtiments devraient fournir non seulement la plus grande économie d'énergie, mais aussi un environnement sain et confortable pour les occupants. Par conséquence, la performance énergétique réelle devrait également tenir compte de cet aspect. Le retour sur le ressenti des occupants peut aider à améliorer la conception et la rénovation. La compréhension et l'évaluation de la performance énergétique réelle devraient permettre de déterminer lorsqu'il ya un écart de performance, les facteurs qui y contribuent.

Dans ce contexte et pour la présente thèse, nous utilisons la simulation pour étudier l'impact du comportement des occupants à l'aide des scénarios déterministes et d'une approche statistique. Cette approche par simulation est complétée par un monitoring abordé à partir de deux aspects: l'efficacité énergétique et les conditions intérieures. Ces aspects seront plus détaillés au chapitre 4, où il est présenté l'application pratique du monitoring mise en œuvre sur une maison individuelle.

Pour limiter le caractère intrusive, la méthodologie d'évaluation proposée s'appuie sur des mesures techniques complémentaires: d'une part des mesures en continu (capteurs de température de l'air, compteurs d'énergie, etc.), d'autre part des mesures ponctuelles (par exemple le test de la porte soufflante).

Chapitre 2 : Approche numérique de la variabilité de la performance en phase de conception liée au comportement de l'occupant

Introduction

Nous avons relevé dans le chapitre précédent que la performance énergétique des bâtiments pouvait être fortement influencée par la nature stochastique et imprévisible du comportement de l'occupant. Nous allons tenter ici de mieux comprendre les facteurs dépendant de l'occupation et influençant cette performance énergétique. Pour ce faire nous avons eu recours à la simulation numérique telle qu'elle pourrait être faite en phase de conception.

Développements :

Nous avons retenu une maison individuelle (2 adultes et 4 enfants) conforme à la RT2012, située dans le sud de la France et soumis à un climat méditerranéen. Cette habitation fait partie du programme de recherche COMEPOS. Nous dispositions de toutes les informations relatives à cette maison correspondant à la phase de conception. Cette maison de 229 m^2, dénommée maison PosA, est de forme complexe (compacité de 2.58) sur un terrain en pente. La production d'énergie sur place est assurée par 40 m2 de panneaux photovoltaïques et une éolienne de 12 m. L'énergie peut être stockée dans 24 batteries de 2 kWh. L'ECS est assurée par une pompe à chaleur air-eau, la ventilation est de type « hygroB ». Le chauffage est électrique d'une puissance de 8 000 W et il n'y a pas de climatisation.

Pour toutes nos simulations, nous avons utilisé le logiciel EnergyPlus. Le bâtiment a été modélisé avec neuf zones thermiques ce qui permet de faire varier de nombreux scénarios. Par ailleurs, les transferts d'air ont été modélisés dans chaque zone et entre les zones.

Un fichier météo correspondant à la ville de Carpentras a été généré avec le logiciel Météonorm. Cette ville est située à 38 km de l'implantation réelle de la maison.

Nous avions identifié que les horaires de présence de l'occupant, les températures de consigne, l'éclairage et les appareils spécifiques branchés par l'occupant avaient comme caractéristique une grande incertitude et pouvaient influencer la performance globale du bâtiment. Afin de tester les répercussions de cette variabilité nous avons construit plusieurs scénarios d'occupation avec une approche déterministe. Le premier s'appuie sur les exigences imposées par la RT2012. Les quatre suivants correspondent à des usages déterministes du bâtiment. Les derniers sont basés sur une approche probabiliste.

Scénario 1 : à partir des exigences de la RT2012, nous avons extrait un scénario d'usage. Celui-ci se traduit par deux températures de consigne en période de chauffage. La première de 16°C la nuit et en cas d'absence et de 19°C le reste du temps, dont les week-ends. Les charges internes provenant des équipements sont estimées à 5.7 W/m^2 et ceux de l'éclairage à 1.4 W/m^2. Les horaires de présences sont fixes.

Scénario 2 : ce scénario a été construit suite aux discussions avec le futur propriétaire. Il a dans ce contexte fourni le scénario de présence prévisionnelle de l'ensemble des membres de la famille, la liste et les temps d'utilisation des équipements électrique ainsi que leur puissance nominale. Le scénario pour l'éclairage découle des présences données. Les températures de consignes n'ont pas été fournies par le propriétaire mais ont été fixées arbitrairement aux valeurs imposées par la RT soit 19°C et 16°C.

Scénario 3 : alternative du scénario 2 sur les consignes de chauffage avec les informations de présence du propriétaire. Nous retenons une température de 21°C en cas de présence et de 18°C la nuit.

Scénario 4 : alternative toujours du scénario 2 sur la puissance nominale des équipements. Partant du constat que chaque équipement ne fonctionne pas à sa puissance nominale à chaque utilisation mais autour d'une puissance moyenne, nous avons construit un nouveau scénario. Une analyse bibliographique nous a permis d'évaluer cette puissance moyenne pour chaque type d'appareil. Les consignes de températures sont celles de la RT2012 et l'occupation correspond aux informations fournies par le propriétaire

Scénario 5 : cette fois ci, nous conservons les hypothèses de puissance moyenne des équipements, l'occupation du propriétaire mais les températures de consignent passent à 21°C et 18°C suivant les moments de la journée

Pour ces cinq scénarii, l'ECS et l'éclairage ont été défini en suivant les exigences de la RT (1.4 W/m2 pour l'éclairage). Il ne s'agit pas ici de regarder la variation puisque nous avons pris les mêmes hypothèses mais de pouvoir estimer les besoins globaux d'énergie puis la part relative des différents postes.

Par simulation, appliquée à la maison PosA et avec le logiciel EnergiePlus, nous cherchons à déterminer les besoins :

- électriques pour l'énergie spécifique,
- de chauffage,
- de l'ECS
- de l'éclairage
- l'énergie totale consommée

Le tableau 2.6 donne une synthèse des scénarios utilisés.

Scénario déterministe	1 - RT	2	3	4	5
T° consigne	16-19°C	16-19°C	18-21°C	16-19°C	18-21°C
Energie spécifique	5.7 W/ m2	nominal	nominal	moyenne	moyenne
Présence	RT	propriétaire	propriétaire	propriétaire	propriétaire
Eclairage	RT	RT+ présence	RT+ présence	RT+ présence	RT+ présence
ECS	RT	RT	RT	RT	RT

Table 2.6 : Principales caractéristiques des scénarios de 1 à 5

Une autre approche, cette fois-ci probabiliste (Parys et al., 2014) a été utilisée pour construire non pas un sixième scénario mais mille nouveaux scénarios et pour évaluer leurs besoins énergétiques.

Mille types de familles ayant une présence, une activité, une température de consigne, des appareils et une utilisation de l'éclairage différents ont été échantillonnés et utilisés pour la détermination du scénario. Le tri pour l'état du scénario à chaque pas de temps (horaire) est construit à partir des 1000 familles par tirage au sort avec un modèle de chaine de Markov. Le principe est d'utiliser les probabilités de départ pour modéliser l'activité suivante de l'habitant. Le premier tire fixe la typologie de famille (retraité, salarié, nb de membres…). De la typologie nous déduisons les charges internes liées aux équipements (Wilke, 2013) et les températures de consignes (Huebnet et al., 2013b). Un second tir défini la présence ou l'absence des membres de la famille à chaque pas de temps. Des deux tirs précédents découlent le nombre et la nature des équipements ménagers qui seront pris en compte pour l'estimation de l'énergie spécifique ainsi que l'éclairage (Richardson et al., 2010) .

Chaque scénario avec un pas de temps horaire est couplé au logiciel EnergiePlus afin de déterminer les besoins énergétiques globale et par postes.

Résultats et Conclusions :

Les résultats des simulations sur scénarios déterministes mettent en évidence l'impact de la variation des consignes de chauffage sur les besoins de chauffage et sur le besoin global. Deux degrés d'élévation des consignes représentent une augmentation d'environ 7kWh/m^2/an.

L'approche probabiliste montre qu'une consigne de 18°C-21°C comme dans nos scénarios déterministes 3 et 5, est proche de la majorité des ménages obtenus par tirage. Le tirage fait également apparaitre 1 famille sur mille avec une température de plus de 24°C. Les références RT peuvent être considérées comme des références d'économies d'énergie.

Pour ce qui est de l'énergie spécifique c'est-à-dire pour l'énergie consommée par les appareils électrodomestiques branchés par l'occupant, on constate avec l'approche déterministe que celle-ci représente une part très importante (de 40% à 55%) du besoin total. La simulation de ce besoin pose la question de la traduction de la puissance des équipements.

L'approche probabiliste a tendance à minorer cette consommation spécifique par rapport aux résultats obtenus avec les hypothèses de la RT.

Pour l'éclairage, on relève une disparité entre les besoins basés sur le scénario RT (que la présence soit RT ou propriétaire) et les scénarios probabilistes. Ces derniers ont tendance à minorer les besoins en éclairage par rapport à la RT.

Afin d'évaluer le comportement énergétique du bâtiment et de pouvoir statuer sur sa capacité à avoir un bilan énergétique annuel positif, une première piste a été suivie. Nous avons fixé de manière déterministe la production énergétique à 60 kWh/m^2/an compte tenu des équipements installés et nous avons étudié le bilan entre cette production déterministe et les besoins globaux obtenus précédemment de manière probabiliste. A l'exception de quelques familles (2% sur les 1000), ce bilan énergétique est positif. Ces réflexions menées à la fois de manière déterministe et probabiliste sur la disparité des besoins en lien avec le comportement de l'usager doivent également être poursuivies pour la partie production d'énergie. Tout comme le comportement de l'usager, les conditions météorologiques sont sujettes à une grande incertitude et il est nécessaire de bien appréhender les répercussions de ces variations (sur les besoins et sur la production).

Chapitre 3 : Etudes numérique et expérimentale de la performance de l'enveloppe d'un bâtiment

Introduction :

Dans le chapitre 1, nous avions identifié 4 facteurs principaux influant la performance énergétique d'un bâtiment. L'enveloppe d'un bâtiment est l'un de ces facteurs. Elle constitue la frontière entre l'extérieur de ce bâtiment et l'intérieur. Elle comprend donc la toiture, les murs extérieurs avec tous ses composants (comme les volets, fenêtres, bouches de ventilation, ect.) ainsi que le plancher le plus bas. L'enveloppe a beaucoup été étudiée compte tenu de son rôle important tant en thermique, en acoustique, qu'en confort visuel (Hung et al., 2012),(Rode et al., 2010) (Jack, 2015),(De Meulenaer et al., 2005) (Oral and Yilmaz, 2002). En effet, une enveloppe bien conçue peut contribuer à la performance énergétique du bâtiment par la réduction des besoins de chauffage, de refroidissement et d'éclairage et améliorer le confort thermique comme le souligne (Sozer, 2010).

La conception d'une telle enveloppe est un processus complexe qui tient compte d'un grand nombre de paramètres propres au bâtiment (forme, orientation, propriétés thermiques des matériaux, …) mais également spécifique au site d'implantation (conditions climatiques, environnement,…). Par ailleurs, une enveloppe bien conçue doit également être bien réalisée afin d'obtenir la performance attendue. Si (Johnston and Siddall, 2016) ont pu monter sur sept maisons certifiées Passivhauss un très faible écart entre la performance de l'enveloppe attendue et la performance mesurée une fois réalisée, d'autres comme (Rode et al., 2010) font état d'écart pouvant aller jusqu'à 100% des valeurs prédites (Johnston and Siddall, 2016). Une mauvaise exécution, des incertitudes sur les propriétés thermiques des matériaux mis en œuvre, … peuvent expliquer ce constat.

Nous prenons ici le parti d'appréhender la performance « livrée » d'une enveloppe par une approche globale de l'ensemble de l'enveloppe pouvant se compléter par une approche locale en ne s'intéressant qu'à certains composants pris séparément.

Développements :

Le taux d'infiltration qui représente le débit d'air extérieur s'introduisant par les fissures de l'enveloppe peut influencer considérablement la consommation énergétique (Charrier, and Jobert, 2011). Dans ce sens, la RT 2012 entre autre, impose pour le secteur résidentiel, une valeur maximale de 0.6 $m^3/h/m^2$ pour la valeur $Q_{4Pa\text{-}Surf}$. Ce dernier correspond au débit de fuite sous une pression imposée de 4 Pa divisé par la surface déperditive de l'enveloppe (hors plancher bas). La norme européenne EN 13829 donne les détails sur les protocoles des tests in-situ (comme les méthodes à gaz traceurs, ou les portes soufflantes) visant à établir le niveau étanchéité à l'air.

Par ailleurs, on retrouve dans la littérature trois coefficients pouvant traduire la performance d'une enveloppe (Table 3.1). Tous les trois s'exprime en W/K. Le premier représente le coefficient de déperdition surfacique et linéique de l'enveloppe, il est appelé « transmission heat loss coefficient » noté

HT. La détermination du HT théorique, en phase de conception, est encadrée par la norme européenne EN ISO 13790 et la réglementation RT2012. Le second intègre en plus les pertes d'infiltration. Il est appelé « heat loss coefficient (HLC) ». Le dernier correspond au HLC auquel on ajoute les pertes liées à la ventilation mécanique. Il est appelé « building loss coefficient (BLC)".

Nom	Notation	Signification	Unité
Transmission heat loss coefficient	HT	Somme des déperditions surfaciques et linéiques	W/K
Heat loss coefficient	HLC	HT + les déperditions d'infiltrations	W/K
Building loss coefficient	BLC	HLC + les déperditions de la ventilation	W/K

Table 3.1 : récapitulatif des différents coefficients caractérisant les performances d'une enveloppe

Des tests dynamiques ont été développés pour évaluer in-situ la performance réelle d'une enveloppe. Ces tests peuvent se différencier de par leur durée (de 1à 2 jours jusqu'à 3 semaines) ou de par leur domaine d'application (bâtiment occupé ou non occupé). (Bouchie, 2015) dans le rapport du projet Européen PERFORMER en dresse une description complète. Les écarts entre les HLC ou HT déterminés par ces méthodes avec les valeurs théoriques peuvent variés de 10 % pour (Thomsen et al., 2005), de 15 % pour (Jack, 2015) ou 1 à 3 % suivants les traitements effectués pour (Bauwens, 2015). Néanmoins, l'analyse de ces différentes méthodes montre qu'elles ne mesurent pas les infiltrations au cours de l'essai, tout au mieux la quantification des infiltrations est estimée avant le test or celles-ci varient en fonction des conditions climatiques. Partant de ce constat, un test innovant a été mis au point.

L'idée principale de ce test est de coupler une porte soufflante et des radiateurs électriques contrôlés et programmés pour fonctionner avec des cycles « marche/arrêt » de 12 heures ce qui représente un cycle de chauffage et un cycle de décharge. Ces cycles permettent d'identifier l'inertie du bâtiment. Pour éviter les incertitudes dues à des gains internes et solaires, les stores sont maintenus fermés et la maison n'est plus accessible pendant la durée du test. La ventilation mécanique est désactivée. Le test enregistre les températures intérieures, la température extérieure, la puissance de chauffage ainsi que le débit d'air pour maintenir une pression à 4 Pa, le tout avec un pas de temps d'une minute. Ce test a pour objectif après traitement des données de déterminer la valeur de HLC. Ceci nécessite comme pour les autres tests une démarche inverse, c'est-à-dire, en connaissant les conditions intérieures et extérieures (les entrées et les sorties), de rechercher la valeur HLC qui correspond le mieux à l'ensemble des mesures.

Les modèles RC proposent une représentation physique simplifiée d'un bâtiment en utilisant l'analogie entre l'équilibre thermique et l'équation de conservation du courant électrique. Le flux de chaleur dans le modèle thermique est apparenté au courant électrique total du modèle électrique. L'inertie thermique devient une capacité du circuit électrique et la résistance thermique devient une résistance électrique. Les températures sont introduites comme les tensions du circuit électrique. Un modèle RC donne déjà de bons résultats comme l'ont montré (Park et al., 2011) ou (Chahwane et al., 2009). Suivant la précision que l'on souhaite, on peut faire évoluer le modèle RC en 3R4C – 3 résistances et 4 capacités - par exemple comme l'ont fait (Fraisse et al., 2002).

Afin d'exploiter le test pour l'identification de la valeur HLC, un modèle 3R2C a été construit et un code matlab développé pour résoudre le système d'équation. Les 3 résistances et les 2 capacités représentent respectivement la résistance extérieure Rext (rayonnement, convection et une partie de la résistance du mur), la résistance intérieure Rint (rayonnement, convection et une partie de la résistance du mur) , la résistance Rinf (déperdition par infiltration) la capacité Cint (mur intérieur, air et le mobilier), Cwall (inertie du bâtiment).

Pour ajuster au mieux les sorties du modèles (résistances et capacités), les températures et puissances issues des relevés, des traitements sont nécessaires. Deux approches ont été utilisées. La première est une recherche d'identification déterministe afin d'identifier les valeurs des R et des C, complétée par une identification probabiliste bayésienne pour quantifier l'incertitude du modèle. De nombreux auteurs ont utilisés l'inférence bayésienne pour la calibration pour des prédictions comme (Sankararaman and Mahadevan, 2015), (Vernay et al., 2015),(Ling et al., 2014) (Li and Mahadevan, 2016)., ((Heo and Zavala, 2012) (Rouchier et al., 2015) (Manfren et al., 2013) ou (Tian et al., 2016) (Tagade et al., 2016).

Résultats et Conclusions :

Deux applications réelles d'évaluation de la performance thermique de deux enveloppes sont présentées. Ils utilisent tous les deux le test in-situ, un modèle RC et l'identification déterministe complétée par l'inférence bayésienne.

La première application est effectuée sur un bâtiment non habité. Il s'agit du bâtiment expérimental, nommé I-BB, situé sur la plate-forme expérimentale énergétique bâtiment, située sur le site d'INES Le Bourget du Lac, France. Ce bâtiment avait déjà fait l'objet d'une identification du HLC (Mejiri, Peuportier, Guiavarch, 2013) en utilisant la signature énergétique et le calcul théorique. Les résultats par le calcul théorique RT2012, par la signature énergétique et par notre proposition (test + modèle 3R2C) sont comparés (Table 3.12).

Détermination théorique			Détermination expérimentale avec le test in situ	
HT steady state (RT2012 procedure)	HT [W/K] calculated previously in (Mejiri, Peuportier, Guiavarch, 2013)	HT using building simulation (validated E+ model)	HTexperimental deterministic identification	HTexperimental Bayesian inference identification
73	73.5	69.5	76.6	77 ± 1.8

Table 3-12: Comparison of theoretical and experimental **HT** values [W/K]

La seconde application a été réalisée dans une maison habitée, la maison POSA (décrite dans le chapitre 2). Les résultats de notre évaluation par le test in-situ sont comparés avec la valeur théorique suivant le calcul RT2012. Nous nous sommes heurtés à la difficulté de laisser cette maison habitée avec une porte soufflante en « tissus » pendant 2 jours lors du test. Dans ce contexte, le test in-situ a été réalisé sans utiliser la porte soufflante donc juste avec un cycle chauffage/arrêt et nous avons pris la valeur des infiltrations obtenus lors d'autres campagnes de mesures. Nous n'avons donc pas pu considérer l'effet dynamique des infiltrations. Ceci nous a également contraints à utiliser un modèle 2R2C et non 3R2C n'ayant pas d'information sur les infiltrations dynamique. Par contre, nous avons développé depuis une mini-porte soufflante pouvant s'adapter à une bouche de ventilation et donc nous sommes à présent en mesure de réaliser le test dans une maison occupée comme initialement prévu.

Les résultats obtenus sont les suivants :

Détermination théorique	Détermination expérimentale avec le test in-situ 2R2C	
HLC steady state (RT2012 procedure)	HLC experimental deterministic identification	HLC experimental Bayesian inference identification
159	173	164 ± 3.7

Table 3-16: Comparison of theoretical and experimental **HT** values [W/K]

Nous avons montré dans ce chapitre que la valeur du HLC pouvait être un indicateur pertinent de la performance réelle d'une enveloppe de bâtiments car il fait intervenir non seulement les choix de conception comme les matériaux, les dispositions contre les ponts thermiques mais il prend également en considération la qualité de réalisation par l'intégration entre autre des infiltrations. L'objectif de pouvoir comparer la valeur théorique estimée en conception à la valeur mesurée une fois le bâtiment construit est également atteint. En effet dans les 2 cas, nous avons été en mesure d'évaluer la performance thermique des enveloppes des bâtiments telle que livrées. Dans nos deux applications nous constatons que les différences entre ces deux valeurs sont relativement faibles : 4% pour la maison I-BB et 9 % pour la maison Posa.

Pour ce faire nous avons mis au point un test compatible avec une maison occupée, qui prend en compte l'influence dynamique de l'infiltration et qui ne nécessite que 24h de mesures. Par ailleurs l'instrumentation pour mettre en œuvre le test est relativement simple.

Chapitre 4 : Evaluation en continu de la performance énergétique globale: cas d'application

Introduction :

Notre objectif est ici, d'évaluer la performance énergétique réelle d'une maison en phase d'exploitation et d'obtenir entre autre une compréhension détaillée de la consommation d'énergie et des conditions intérieures. Le suivi mis en place se concentre sur deux aspects : l'efficacité énergétique et les conditions intérieures.

L'approche d'évaluation de la performance proposée dans le présent travail pour les maisons unifamiliales consiste en phase de conception, d'utiliser la simulation thermique dynamique, pour « prédire » la performance en fonction de certaines hypothèses d'utilisation puis d'effectuons un test in situ concernant l'enveloppe et de mettre en place un monitoring continu intégrant l'usage et le confort. La finalité est de confronter la performance du bâtiment mesurée avec les résultats du projet de conception. Cette approche d'évaluation offre l'avantage d'acquérir plus d'informations sur la performance du bâtiment et sur le comportement de ses occupants. En cas d'écart constaté entre la mesure et le prédictif, le deuxième objectif de l'approche d'évaluation est de donner un retour sur les hypothèses de conception, par exemple en ce qui concerne le comportement des occupants et les scénarios utilisés (déterministes et stochastiques).

Dans la section 1.2, nous avons montré que la performance énergétique d'un bâtiment occupé nécessitait la surveillance de nombreux paramètres (efficacité énergétique, conditions intérieures, performance et durabilité de l'enveloppe). Ces grandeurs physiques correspondent à différents indicateurs de performance qui peuvent caractériser le bâtiment, le comportement des occupants et le comportement des systèmes dans diverses situations et saisons.

Ainsi, pour fournir une vision claire et complète de la performance énergétique d'un bâtiment, un grand nombre de capteurs devraient être mis en œuvre. Le positionnement de ceux-ci n'est pas toujours sans contraintes techniques (globe noir obligatoirement au centre d'une pièce par exemple). On se heurte là à une première difficulté « d'intrusivité » pour un site occupé. Cette difficulté s'accompagne d'une seconde qui est la réduction du nombre. En effet, dans les bâtiments occupés, le nombre de capteurs et la gêne occasionnée par cette instrumentation doivent être réduits, tout en conservant une robustesse et une précision d'information suffisantes. Cette contrainte est due au fait que dans une habitation « occupées », les occupants n'accepteront pas une métrologie trop intrusive. Néanmoins, l'information sur les conditions réelles d'exploitation d'un bâtiment est essentielle pour améliorer l'évaluation de la performance énergétique. Nous avons dans ce contexte travaillé dans un premier temps sur les corrélations possibles entre les paramètres et dans un second temps sur la réduction des informations à collecter pour un suivi de performance.

Développements :

Notre démarche pour identifier les corrélations entre les différents paramètres a été d'utiliser dans un premier temps, les résultats d'une maison très fortement instrumentée mais non occupée. Il s'agit de la maison INCAS nommée I-DM. Cette maison est implantée sur la même plateforme que la maison INCAS I-BB présentée dans la section 3.1. Elle présente la même géométrie (salon cuisine et salle à manger au RDC et 3 chambre à l'étage) que la précédente mais dispose d'une enveloppe en double mur (Spitz, 2012) et (Stefanoiu et al., 2014). Notre objectif est d'étudier – pour la thématique « température » dans un premier temps - la possibilité de réduire le nombre de capteur, de restreindre leur encombrement (nuisance générer par leur présence) tout en maintenant une précision satisfaisante avec notre objectif d'évaluer le niveau de confort dans le bâtiment.

Dans ce bâtiment, la température est mesurée à différents endroits, au milieu de chaque volume et sur les murs extérieurs, le tout à des hauteurs de 0.1 m, 1.1 m et 1.7 m :

- température d'air ambiant par thermorésistante au platine, PT100, classe A: ± 0,35 ° C de -100 à 100 ° C;
- température de surface externe et interne, par thermocouple de type T, classe 1: ± 0,5 ° C de -40 à 125 ° C;
- température à l'intérieur de la structure de la paroi, par thermocouple de type T, classe 1: ± 0,5 ° C de -40 à 125 ° C;
- température de rayonnement par globe noir, uniquement sur la zone du rez-de-chaussée, PT100 1/2 DIN Classe A ± 0,1 ° C de -40 à 80 ° C.

Nous avons analysé les différences de température entre les valeurs pour chaque capteur, pour chaque minute pour une hauteur donnée. Les valeurs moyennes mensuelles ont été calculées et comparées deux à deux (air pièce x/air pièce y et air/mur dans une même pièce). Par la suite et pour étudier les corrélations entre les différentes mesures de température intérieure, nous avons raisonné au niveau de chaque pièce puis au niveau d'un étage et pour finir entre les deux étages. Ce travail a été effectué sur une année complète de mesures soit plus de 5 millions de données. Ces données ont été classées par mois (12 ensembles) avec un pas de temps de la minute. Toujours 2 par 2 nous avons mesuré le degré de dépendance linéaire entre les 2 variables avec le coefficient de Pearson « r ».

Dans un second temps, nous avons testé, sur un bâtiment occupé, la réduction de capteurs proposées. La maison retenue pour ce faire est la maison de 168 m^2 occupée par cinq personnes. Toutes les pièces du logement sont équipées de capteur de température d'air du commerce placés « au mieux » par l'occupant.. Aucun capteur n'est situé dans une zone de tache solaire. La même démarche avec le calcul des coefficients de corrélation moyens mensuels a été mise en place. Nous cherchons là encore à réduire le nombre de capteur pour la thématique « température » tout en étant en mesure d'évaluer le confort intérieur de l'ensemble de la maison.

Par ailleurs, nous nous sommes concentrés sur le monitoring d'une maison « habitée ». Nous avions lors du ce chapitre mis en évidence que ce monitoring devait couvrir trois aspects : l'efficacité énergétique ; les conditions intérieures et la performance et durabilité de l'enveloppe. Nous avons travaillé ici sur l'identification des paramètres à suivre, sur la nature du suivi (continu ou ponctuel), sur la localisation et le pas temps de temps de chaque paramètre. Ces réflexions, initiées par l'analyse bibliographique, étaient contraintes par un objectif de réduction du nombre et limitation de l'intrusivité. La partie instrumentation fixe ne permettant pas de couvrir l'ensemble des informations nécessaires, nous avons travaillé sur l'éventualité de mesures ponctuelles ou d'enquêtes auprès de l'occupant.

La mise en œuvre de notre travail d'identification et de réduction de capteurs pour permettre le suivi de performance a été testée dans la maison PosA du programme COMEPOS. – (présentée dans le chapitre 2). Cette maison instrumentée a été livrée au printemps 2015 et elle fait l'objet d'un suivi depuis octobre 2015. Compte tenu des informations recueillies nous avons tenté d'évaluer la performance énergétique de la maison. Nous nous sommes intéressés à la consommation d'énergie. Notre démarche était de d'apprécier l'évolution des consommations au court du temps puis de comparer les simulations de la phase de conception avec les mesures réelles et d'essayer d'en comprendre les écarts. Dans ce contexte nous avons repris les différents scénarios construits dans le chapitre 2 (5 scénarios déterministes et 1 probabiliste). Nous nous sommes intéressés à une période de six mois (novembre 2015 à avril 2016).

Dans un premier temps, nous avons analysé le chauffage (électrique et bois pour cette maison), la ventilation, l'eau chaude sanitaire et l'éclairage. Les informations sur les consommations du bois sont obtenues par l'enquête auprès du propriétaire, les autres informations par les capteurs. Par la suite nous avons étudié les mesures liées aux appareils électroménagers (cuisson, lavage, loisirs,…). Certaines consommations d'appareils ont pu être différenciées (four, réfrigérateur, cuisinière et lave-vaisselle.

Les comparaisons entre les estimations en phase de conception et les valeurs mesurées en phase d'exploitations ou par relevés d'enquêtes se sont poursuivies par l'étude des conditions intérieures. Nous avons pris le parti d'ignorer les valeurs enregistrées des mesures de confort dès lors que les occupants étaient absents. La période d'analyse du confort est donc limitée aux périodes de réelle occupation. Afin de mieux comprendre les attentes de confort thermique des occupants et leur participation à celui-ci nous nous sommes dans un premier temps concentrés sur une période de 5 jours consécutifs en décembre 2015. Nous avons analysé l'évolution des températures au court du temps et leur variation dans l'espace. L'étude c'est ensuite poursuivie sur une période complète de chauffage.

Résultats et Conclusions :

L'analyse des écarts de température des différents capteurs de la maison INCA-DM (fortement instrumentée mais non occupée) a montré que ceux-ci sont toujours inférieurs à 1°C. Les capteurs de température d'air entre les différentes pièces semblent être plus corrélés que les capteurs murs et air d'une même pièce. Ceci s'explique par le fait que la température de l'air est davantage influencée par les gains solaires que par les déperditions surfaciques.

Lorsque l'on s'intéresse aux résultats pour une même pièce, on retrouve des corrélations élevée (0.85) entre les différents capteurs Ces corrélations sont très bonnes 9 mois sur 12. Les mois de février, aout et octobre présentent les plus faibles coefficients de corrélation sans pour autant perdre cette corrélation (r>0.7). Pour comprendre le pourquoi de cette variation, nous nous sommes intéressés au mois de Février qui présente la corrélation la plus faible. Cette situation peut s'expliquer par l'absence de consigne de chauffage (pas d'apport régulé mais uniquement du rayonnement solaire qui provoque une variation forte et rapide de la température de l'air et non des parois) durant cette période. Si l'on compare les mesures de température d'air et les mesures par globe noir sur un même étage, on constate un fort lien entre les pièces soumises à la même orientation. L'importance de l'orientation est également soulignée (r>0.85) entre les pièces ayant la même exposition.

Par conséquence, nous concluons de cette première analyse que l'on peut se contenter de ne mesurer que les températures d'air dans les pièces ou proche des parois. Ceci nous permet de réduire le nombre de capteurs.

Pour la seconde maison (maison occupée où les températures d'air sont mesurées, dans toutes les pièces) on constate que les gains internes (occupation des locaux) et les gains solaires (orientation des pièces) influent sur le taux de corrélation. Dans ce contexte nous proposons de ne mesurer qu'une seule température à une hauteur d'environ 1m par typologie d'occupation des pièces et par orientation.

Pour la partie monitoring, une liste de grandeurs à instrumenter a été définie. Cette liste couvre les aspects de production et de consommation énergétique, les aspects de confort intérieur et de performance et durabilité de l'enveloppe. Cette liste de 121 capteurs a été mise en œuvre dans la maison PosA déjà présentée dans le chapitre 2. La famille vivant dans ce bâtiment «test» est impliquée dans le projet COMEPOS et a par conséquence accepté l'installation de tous ces capteurs. Certains sont vraiment spécifiques aux équipements innovants installés et ne seront pas reconduits lors de suivis « standards ». Dans ce sens, cette liste de surveillance est adaptable pour chaque maison et certains capteurs peuvent devenir facultatifs, selon le type d'enveloppe, les systèmes techniques et autres spécificités. Précisons en plus que certains de ces compteurs sont obligatoires par la RT2012 comme les compteurs de consommations d'énergie pour le chauffage, la ventilation, l'éclairage ou l'ECS. Les compteurs de productions d'énergie sont également obligatoires. Par contre, nous préconisons un pas de temps pour les mesures d'une heure alors que la RT exige un cumul annuel.

Pour évaluer le confort thermique adaptatif, nous mesurons les températures d'air intérieur et le nombre de point de mesure a été réduit grâce à l'étude précédente des corrélations. Les mesures d'humidité intérieure relative, les niveaux de CO_2, de COV et d'éclairage naturel sont proposés pour une meilleure évaluation de l'environnement intérieur.

Des tests courts (mesure ou enquêtes) viennent compléter l'instrumentation fixe afin d'évaluer ou compléter le confort visuel, thermique et acoustique.

Suite à des problèmes techniques qui ne remettent pas en cause la méthodologie du suivi, nous ne disposions sur la période de novembre 2015 à avril 2016 que de 79 capteurs. Nous nous sommes ainsi rabattus sur des données météorologiques disponibles à 5 km de notre implantation. Notons que le climat subit durant la période d'analyse se trouve être supérieure (2 à 5 °C d'écart) aux données utilisées en phase de conception.

La confrontation des différents scénarios élaborés au chapitre 2 (5 déterministes, 1 probabiliste) avec les consommations mesurées montrent que globalement les écarts sont assez faibles. Pour les puissances des équipements on constate que la consommation réelle se situe dans la partie haute de résultats de l'approche statistique.

L'approche probabiliste présentait déjà en simulation une forte différence (à la baisse) avec les scénarios déterministes, or on constate que ceux-ci sous-estime également la consommation réelle. Cet écart est cependant à relativiser compte tenu de la géométrie et de la surface totale de la maison posA qui n'est pas représentative des maisons courantes.

D'un point de vue de la répartition dans le temps des consommations, les mesures confirment que sur la période d'hiver, le chauffage a la part la plus importante des consommations, suivi par la consommation des appareils. L'eau chaude sanitaire, l'éclairage et la ventilation restent avec des consommations relativement faibles par rapport au chauffage et aux équipements domestiques sur la période hivernale. Sur une année, on peut affirmer que le consommateur principal d'énergie sont ces équipements or ce poste reste pourvu de beaucoup d'incertitudes.

Il est intéressant de souligner que sur le bilan global avec les scénarios RT, les écarts constatés individuellement pour chaque poste, se compensent et que l'écart final est réduit (compensation chauffage avec équipements).

Sur les aspects de confort intérieur, les mesures analysées sur une période de 5 jours mettent en évidence la constance de la température du rez-de-chaussée (20°C – il s'agit d'une partie des chambres) - alors que la température à l'étage (salon) varie entre 17 et 31°C. Une augmentation rapide de cette température du salon en fin de journée traduit l'utilisation (manuelle) du poêle à bois et parfois même la difficulté à réguler cette température lors d'apport solaire complémentaire. Dans ce sens, l'instrumentation proposée fournit bien l'aide nécessaire à la compréhension des conditions de confort de l'occupant.

Sur une période plus longue, nous pouvons évaluer à [20°C ; 25°C] la plage de confort de cette famille. L'enquête précise que la température souhaitée était de 24°C. Ceci confirme bien que les scénarios basés sur des consignes de 16°C-19°C sous-estimeront les consommations à venir et qu'il est préférable de considérer des températures de consignes plus élevées. Par ailleurs, l'enquête a également mis en évidence que l'utilisation du poêle à bois amenait parfois à réguler la température intérieure par l'ouverture d'une fenêtre. Aux incertitudes liées à cette température de confort souhaitée par l'occupant, vient s'ajouter les incertitudes liées aux gains internes, les conditions extérieures comme les apports solaires et les dysfonctionnements des systèmes (la difficulté de la régulation d'un poêle à buche et son inertie – par exemple).

Toujours pour le confort intérieur mais cette fois ci concernant le confort acoustique, visuel et la qualité de l'air, les disposions du monitoring mis en place (instrumentation ponctuelle et enquête) ont permis d'évaluer la performance.

Par ailleurs, précisons que l'instrumentation proposée a permis de confirmer la compréhension de la famille des gestes efficaces en terme de confort comme la gestion de stores et l'ouverture/fermeture des fenêtres en été ou la diminution de l'emploi des équipements en période de forte chaleur.

Conclusions et Perspectives de la thèse

L'objectif de la thèse était de contribuer à l'évaluation de la performance énergétique d'une maison individuelle à énergie positive.

Les travaux de recherche présentés en chapitre 1 et introduction nous a permis d'identifier les quatre facteurs déterminants pour l'évaluation de cette performance qui sont le comportement des occupants, la performance de l'enveloppe et la performance des systèmes ainsi que les conditions extérieures. Nous nous sommes par conséquence concentrés dans les chapitres suivants à apporter des réponses sur deux de ces points et à la métrologie à mettre en place.

Le chapitre 2 s'est concentré sur l'estimation par simulation de l'impact de différents scénarios d'occupations pour les postes les plus importants que sont l'énergie spécifique due aux équipements, le chauffage, la ventilation, l'ECS et l'éclairage. Notre approche s'est appuyée sur la construction de scénarios déterministes et sur le tirage de scénarios probabilistes. Ce travail a abouti à la construction de scénarios plus plausibles que le scénario réglementaire. Ces scénarios sont à utiliser en phase de conception afin de quantifier les besoins énergétiques. Les besoins ainsi déterminés servent de référence à la performance attendue.

Le chapitre 3 se focalise sur l'enveloppe. Nous avons développé une nouvelle méthode d'évaluation de la performance d'une enveloppe de bâtiment. Cette méthode est basée sur la détermination du coefficient HT. La méthode permet de vérifier si la performance de l'enveloppe correspond aux objectifs fixés par la conception et de quantifier les pertes dues aux infiltrations ou les défauts de mise en œuvre. Les incertitudes de mesures sont prises en compte par inférence bayésienne dans l'évaluation de la performance et le résultat est présenté par une fourchette de variation. La méthode a été mise en œuvre sur deux bâtiments. Par ailleurs elle présente l'avantage d'être réalisée sous forme de test court (2 jours) dans un bâtiment occupé.

Le chapitre 4 précise la métrologie à mettre en place pour un suivi et une évaluation de la performance énergétique d'une maison occupée à énergie positive. Cette instrumentation s'intéresse aux consommations d'énergie, à sa production et au confort intérieur. Grace à l'étude des corrélations, nous avons pu justifier la réduction du nombre de capteur et nous avons également défini leur positionnement et le pas de temps de mesure à utiliser. Cette instrumentation fixe est compléter par des tests ponctuels et par un questionnaire à l'attention de l'occupant. L'ensemble de ces dispositions ont été mis en œuvre sur un bâtiment occupé. L'analyse des résultats obtenus a mis en évidence que le chauffage et les équipements électrodomestiques étaient les deux principaux consommateurs d'énergie. Nous avons également montré la pertinence et l'apport des scénarios que nous avons construits et proposés au chapitre 2 pour estimer la performance attendue. Globalement, la performance énergétique de cette maison est conforme aux prédictions et les occupants sont satisfaits de cette performance. Cependant, bien que l'estimation du chauffage correspondent aux consommations mesurées, nous pouvons montrer que de nombreux facteurs sont impliqués dans cette consommation comme la température de consigne (ici plus élevée que l'estimation), les conditions météorologiques (plus clémentes que celles considérées) l'attractivité et la difficulté de régulation de certains équipements comme le poêle à bois (allumage manuel quasi-systématique, ouverture des fenêtres pour réguler la montée rapide de température).

Perspectives :

Plusieurs perspectives d'amélioration et de détournement d'usage peuvent être identifiées.

Au niveau de la méthode développée et notamment sur la partie scénario. Nous avions identifié au chapitre 1 et introduction le rôle important de 4 facteurs. Nous avons traité dans cette thèse les deux premiers qui sont le comportement des usagers et l'enveloppe du bâtiment. Il reste donc à traiter les deux derniers que sont les conditions extérieures et les équipements techniques. A partir de la même démarche de construction présentée au chapitre 2, il serait intéressant d'approfondir dans un premier temps les impacts associés aux données météorologiques. En effet celles-ci se caractérisent par une forte incertitude et interviennent aussi bien dans les consommations d'énergie (chauffage, éclairage) que dans la production d'énergie pour ces bâtiments à énergie positives. Ce travail pourrait également être réalisé sur le dernier facteur important affectant la performance énergétique qui est l'efficacité énergétique des équipements. Nous pensons qu'une approche probabiliste des rendements de équipements pourrait être envisagée et utiliser en phase de conception pour estimer la performance attendue.

Nous avons identifié une difficulté qui est apparue lors de la mise en œuvre de l'instrumentation fixe. Il s'agit d'un problème de commissionnement de cette instrumentation. Une étude sur ce sujet est indispensable afin de créer un outil qui permettra de tester la fiabilité de mesures, afin de pouvoir généraliser la métrologie sur d'autres maisons.

Au niveau des études de cas : Nous avons notamment appliqué nos propositions sur la maison PosA du projet COMEPOS. Il serait pertinent de multiplier l'analyse des données issues des autres maisons de ce programme et sur une période plus longue afin lisser les incertitudes liées aux conditions extérieures. La multiplication des études de cas permettrait également de généraliser les résultats obtenus actuellement sur une maison à géométrie complexe accueillant six personnes.

Le but de la démarche développée était d'évaluer la performance énergétique. On constate qu'elle nous permet aussi de mieux comprendre la performance du bâtiment et les actions des occupants. Dans ce sens, elle peut devenir un outil pédagogique auprès des occupants (lien entre gestes / confort / consommation) et un outil d'aide à la mise en route et à la détection des disfonctionnements technique.

Il est également intéressant d'observer le suivi de la maison, en utilisant les données de performance de plusieurs années. Comme notre analyse ne représente que les six premier mois d’occupation, il est important d'étudier la performance énergétique sur plusieurs années. Cela permettrait d'observer la dégradation de la maison sur une courte et une longue période en ce qui concerne le suivi de la performance de l'enveloppe et des systèmes. Pour pouvoir généraliser cette démarche à grande échelle sur les bâtiments occupés, il est encore nécessaire de créer un outil d'évaluation qui sera fiable, pas cher et facile à mettre en œuvre.

Une autre valorisation que nous imaginons concerne le transfert à la réhabilitation. L’enjeu de la réduction des consommations énergétiques dans le secteur du bâtiment est bien au niveau de la réhabilitation. Les outils (scénarios, test enveloppe et métrologie) avaient pour vocation la vérification de la performance obtenue par comparaison avec la performance attendue en phase de conception. Nous imaginons pouvoir utiliser nos outils (test enveloppe et métrologie) pour avoir une image à t0 de la performance actuelle. Nous avons vu par ailleurs que notre instrumentation nous permettait également d’appréhender le comportement des utilisateurs (T° de confort, niveau d’éclairage, ECS, gestion des occultations…) dans ce contexte nous pouvons à partir de ces informations reconstruire des scénarios spécifiques à ce bâtiment. La conception de la réhabilitation peut alors lieu avec une bonne connaissance de la performance avant travaux et des scénarios d’usage spécifique. En phase de réception, nos outils retrouvent une utilisation « normale ».Cela permettra de mieux comprendre la performance énergétique future.

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ANNEXES

ANNEX A. PosA house: construction information

A.1. Building's plans

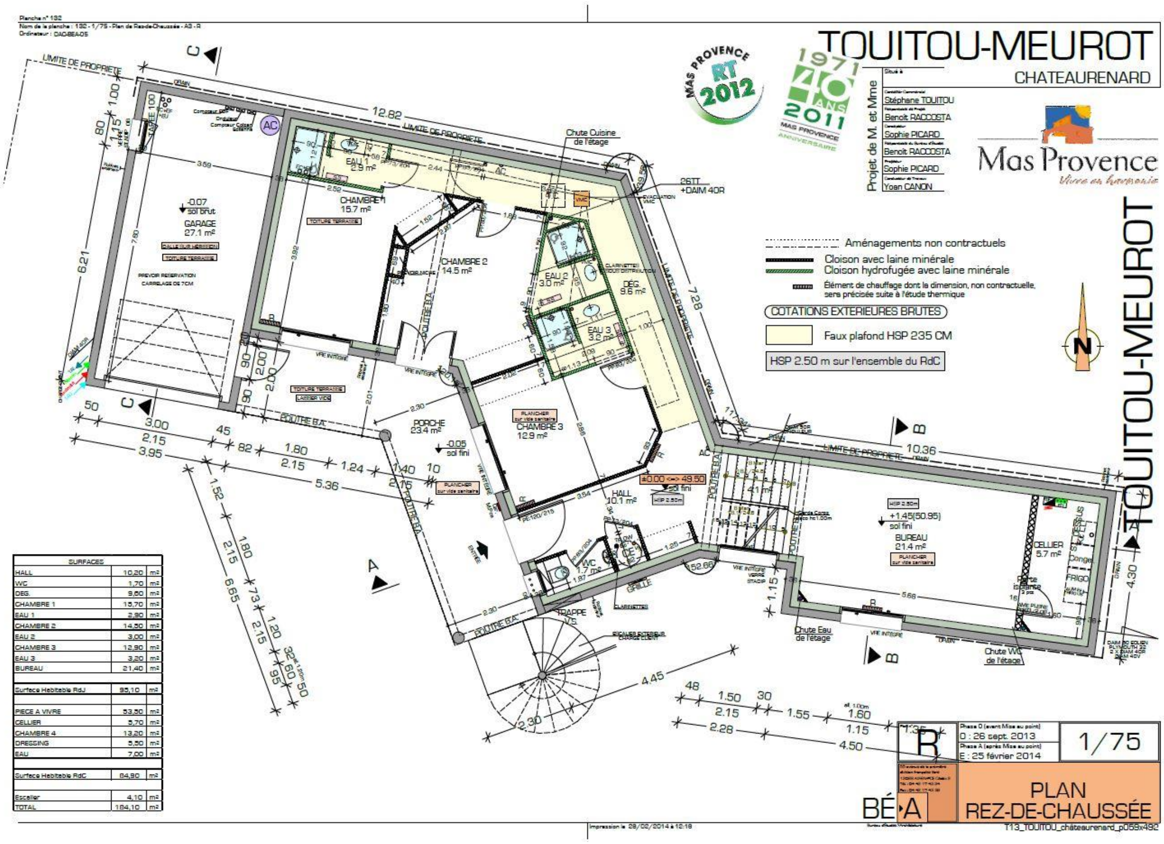


Figure A-1: Ground floor building's plan

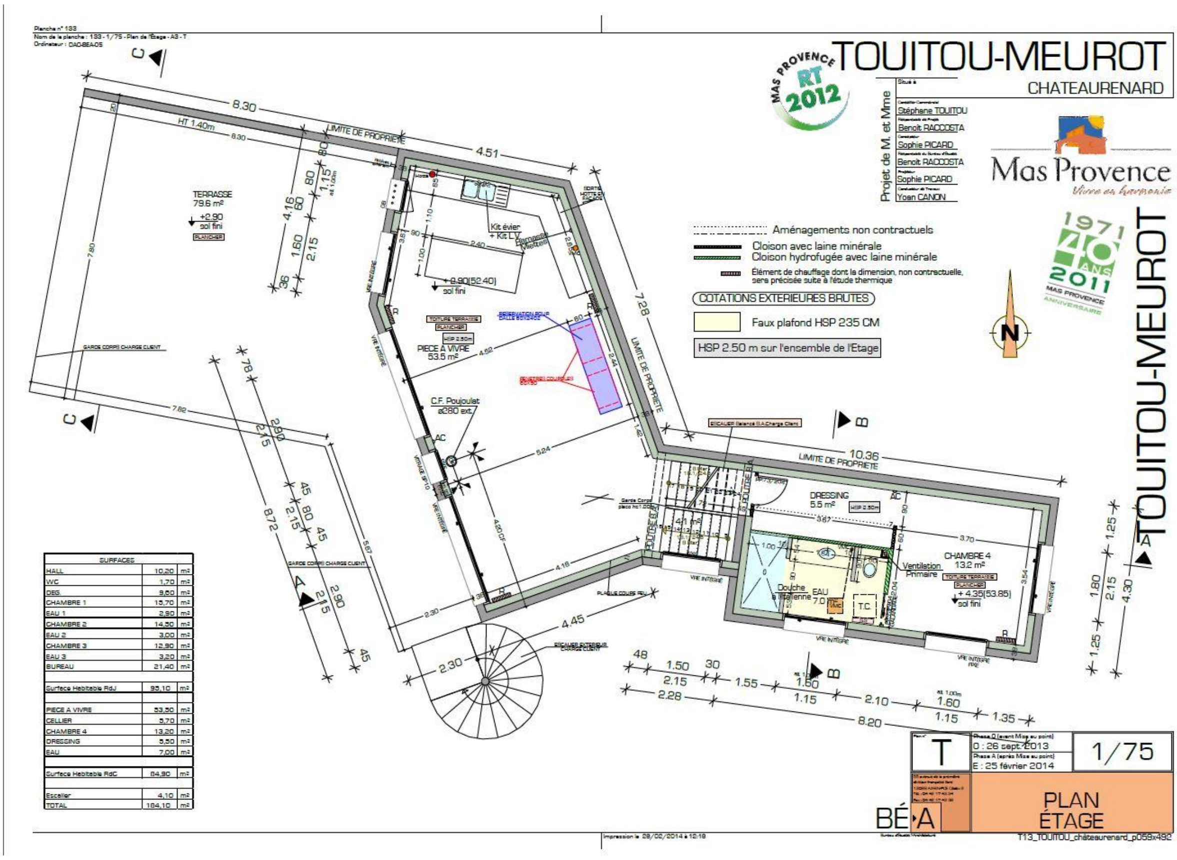


Figure A-2: First floor building's plan

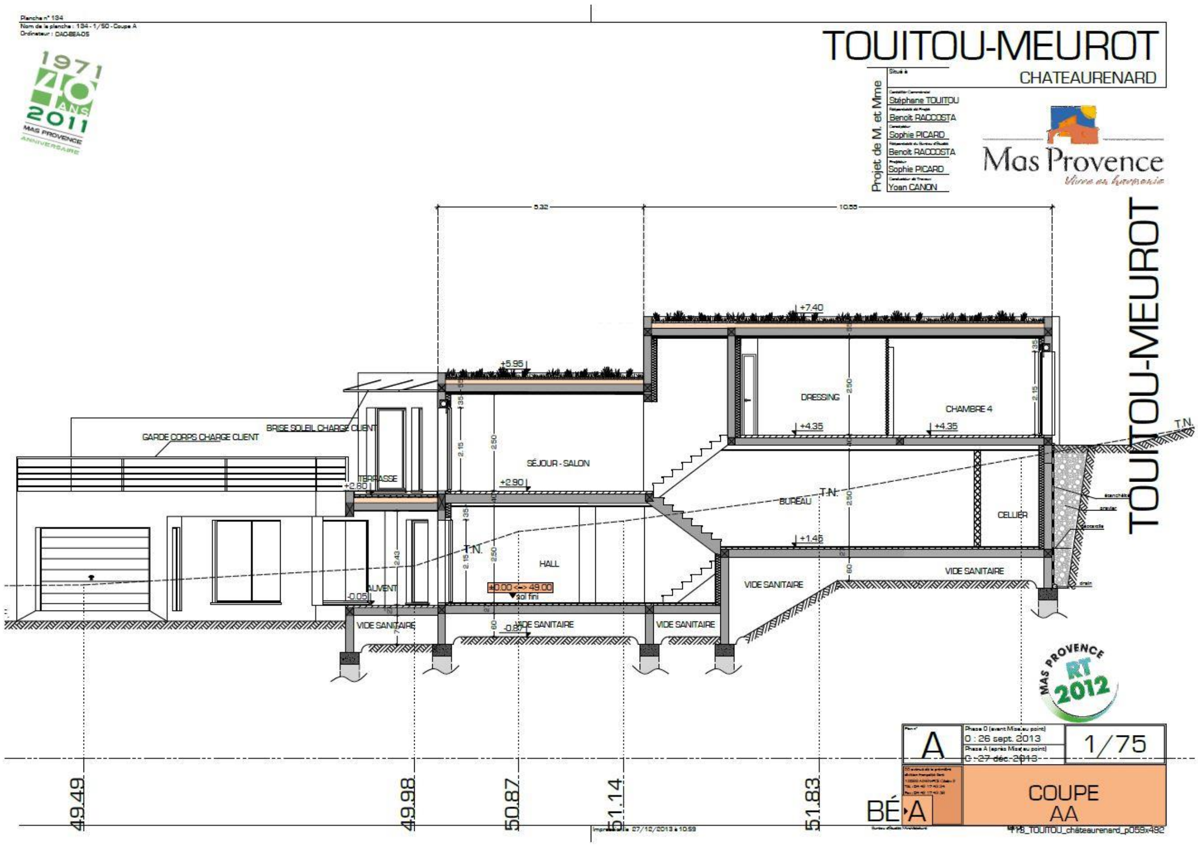


Figure A-3: Lateral view building's plan

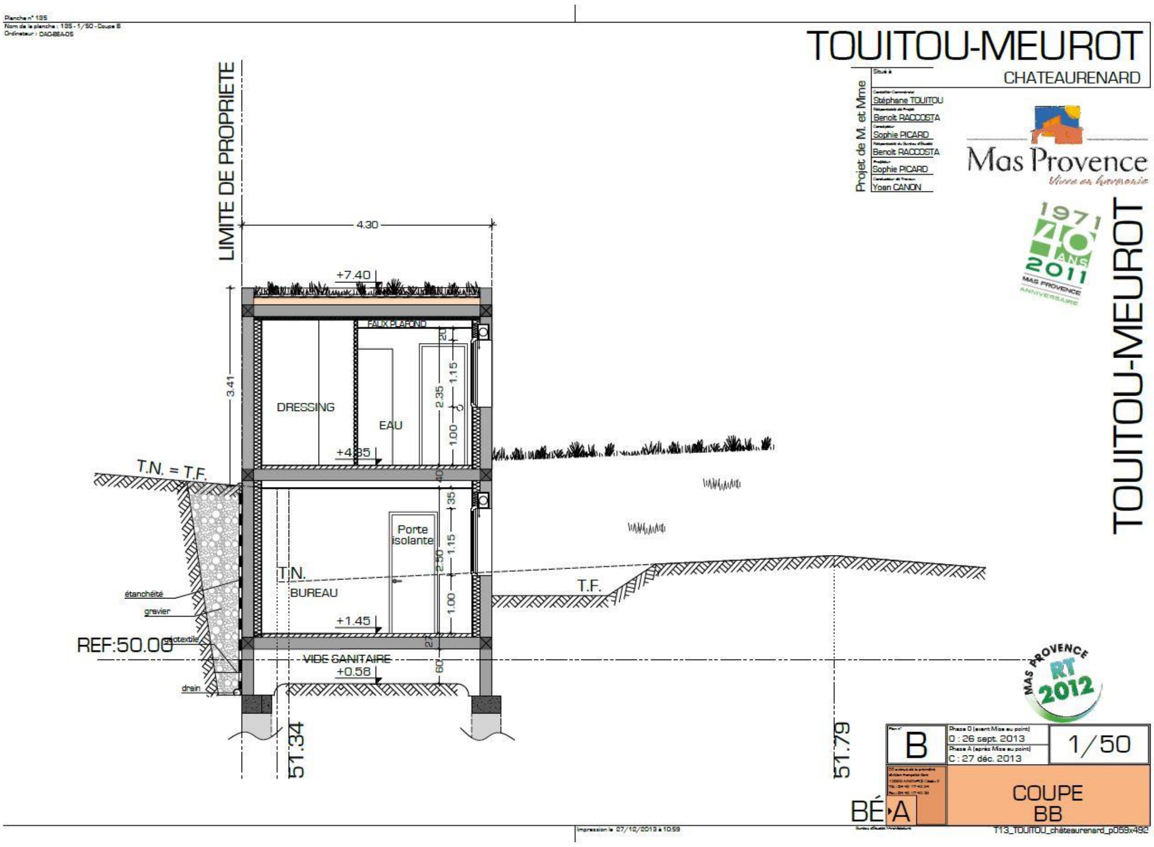
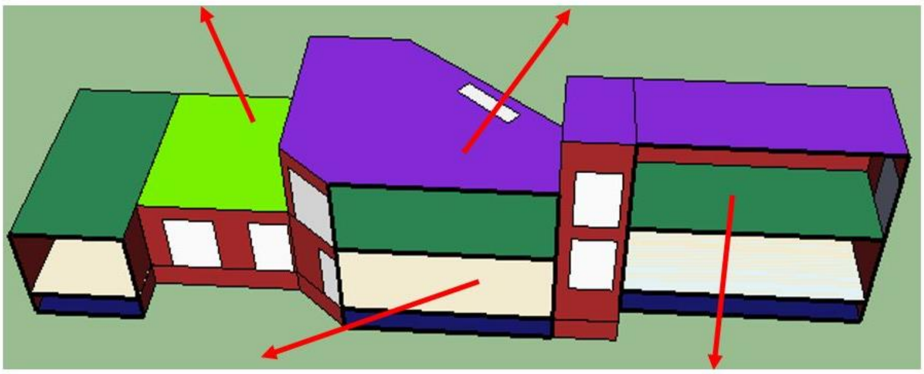


Figure A-4: Backside view building's plan

A.2. Envelope's composition

Terrace slab on the ground floor façade wall (20+5 little beam+ floor unit)
Composition (from outside - inwards):
- Multilayer sealing λ=1 (W/ mK) , thickness= 1 cm
- Extruded polystyrene insulation λ=0,034 (W/ mK) , thickness = 12 cm
- Concrete slab λ= 2,5 (W/ mK) , thickness = 5 cm
- Interjoists polystyrene + concrete beam λ= 0,036 (W/ mK) , thickness = 9 cm
- Glass wool λ=0,032 (W/ mK), thickness = 7,5 cm
- Plasterboard λ=0,41 (W/ mK) , thickness = 1 cm

Terrace slab on the first floor façade wall (20+5 little beam + floor unit)
Composition (from outside - inwards):
- Multilayer sealing λ=1 (W/ mK) , thickness = 1 cm
- Extruded polystyrene insulation λ=0,034 (W/ mK) , thickness = 12 cm
- Concrete slab λ= 2,5 (W/ mK) , thickness = 5 cm
- Interjoists polystyrene + concrete beam λ= 0,036(W/ mK), thickness = 9 cm
- Glass wool λ=0,040 (W/ mK), thickness = 16 cm
- Plasterboard λ=0,41 (W/ mK) , thickness = 1 cm



Slab on crawl space (16+4 little beam + floor unit)
Composition (from outside - inwards):
- Polystyrene + Concrete small beam λ=0,036(W/ mK), thickness =24cm
- Concrete λ= 2,5 (W/ mK) , thickness = 4 cm
- Concrete screed λ= 2,75 (W/ mK) , thickness = 5 cm
- Tile or laminate flooring λ= 0,41 (W/ mK), thickness = 1 cm

Intermediate slab (20+5 little beam + floor unit)
Composition (bottom - up):
- Plasterboard λ=1 (W/ mK) , thickness = 1 cm
- Air plenum λ= , thickness = 7 cm
- Concrete floor unit λ= 1,23 (W/ mK) , thickness = 20 cm
- Concrete slab λ= 2,5 (W/ mK) , thickness = 5 cm
- Concrete screed λ= 2,75 (W/ mK) , thickness = 6 cm
- Tile or laminate flooring λ=0,41 (W/ mK) , thickness = 1 cm

Figure A-5: Horizontal wall composition

Type of exterior wall	Thickness [cm]	Thermal conductivity [W/mK]	Thermal resistance [m^2.K/W]
Exterior monolayer rendering	1	1	0.01
Concrete	20	0.182	1.1
Mineral wool	18	0.032	5.62
Interior rendering	1	0.43	0.02

Table A-1: Vertical wall composition

Terrace slab on the first floor façade wall (20+5 little beam + floor unit)
• Thermal bridges transversely to little beams: 0,20 (W/ m.K)
• Thermal bridges horizontally to little beams: 0,13 (W/ m.K)
Slab on crawl space (16+4 little beam + floor unit)
• Thermal bridges transversely to little beams: 0,24 (W/ m.K)
• Thermal bridges horizontally to little beams: 0,13 (W/ m.K)
Intermediate slab (20+5 little beam + floor unit)
• Thermal bridges transversely to little beams: 0,31 (W/ m.K)
• Thermal bridges horizontally to little beams: 0,18 (W/ m.K)

Table A-2: Thermal bridges calculation, complements of MasPorovence

Within the simulation, the consideration of thermal bridges was made by increasing infiltration flow rates according to the following equation::

$$Flow_{infiltration} = \frac{1}{1{,}2 * 1000} \sum \Psi_i * L_i$$

Additional equivalent flow corresponding to the heated area: 0.01 m^3/s

Additional equivalent flow corresponding to the garage area: 0.002 m^3/s

A.3. Electric system connections

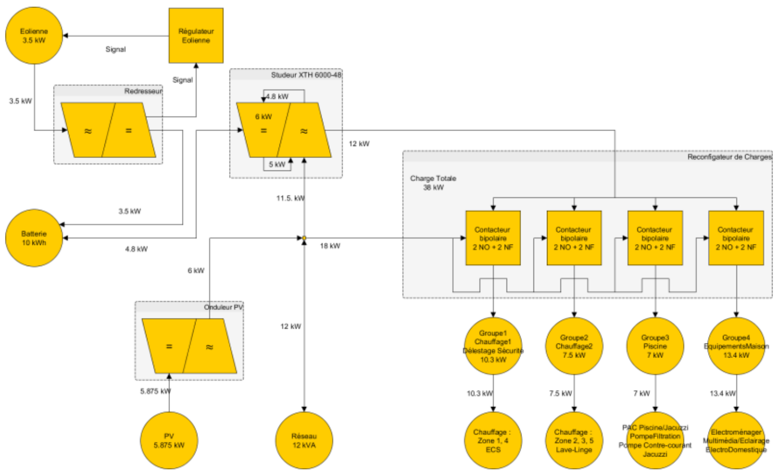


Figure A-6: Systems (wind turbine, electrical batteries, heating, appliances etc.) connections

ANNEX B. Envelope's performance complements

B.1. Blower door principle

The essential equipment for a typical blower door is the following

- A Door Panel, that is used to temporary seal a building's doorway
- The calibrated fan used to blow air into or out of the building
- A specially designed two-channel differential pressure gauge used to measure: differential pressure between the area in which the gauge is located, and the other side of the Door Panel (called Room Pressure)
- Fan Pressure which is the pressure inside the fan that is developed while the fan brings the room to the desired Room Pressure.

Therefore the gauge is used to calculate the air flowing through the fan which can then be used to determine the total size of all those leaks. This gauge can also provide a fan controller to change the air flow through the fan.

Once the rotating fan blade is turned on, a suction pressure (Fan Pressure) is created and the air is pulled through the holes on the inlet side. In order to control and adjust the Fan Pressure, special Range Ring and Plates are typically installed on the inlet side of the fan. All this will allow calculating the air flow moving through the calibrated fan. The flow equation is different for each fan and each range combination. Tables B-1 and Table B-2 summarizes the coefficients characteristic for two fans (Retrotec 3000 and 300 Fan), which were used later for calculating the infiltration air-flow.

There are two possibilities for performing a bower door test

- flow away from the operator,
- flow towards the operator.

Equation B-1 bellow describes the system flow equation, if the flow is away from the operator holding the gauge, which means that the gauge and the operator are on the inlet side of the fan.

$$Flow(CFM) = (FP - |RP| \times K1)^N \times (K + FP \times K3) \times K4 \qquad \text{(B-1)}$$

Where,

FP is the fan pressure

RP is the room pressure.

Kx are the coefficients given by the manufacturer.

For the case where the flow is towards the operator holding the gauge and the gauge is on the exhaust side of the fan, the following system flow equation is used:

$$Flow(CFM) = ((FP - RP) - RP \times K1))^N \times (K + (FP - RP) \times K3) \times K4 \quad \text{(B-2)}$$

B.2. N and K coefficients for the Retrotec 3000 and 300 Fans used

Retrotec3000 Fan last calibrated: (Flow Equation Parameters).						
Range	**n**	**K**	**K1**	**K2**	**K3**	**K4**
Open(22)	0,5214	519,6183	-0,07	0,8	-0,115	1
A	0,503	264,9959	-0,075	1	0	1
B	0,5	174,8824	0	0,3	0	1
C8	0,5	78,5	-0,02	0,5	0,016	1
C6	0,505	61,3	0,054	0,5	0,004	1
C4	0,5077	42	0,009	0,5	0,0009	1
C2	0,52	22	0,11	0,5	-0,001	1
C1	0,541	11,9239	0,13	0,4	-0,0014	1
L4	0,48	4,0995	0,003	1	0,0004	1
L2	0,502	2,0678	0	0,5	0,0001	1
L1	0,4925	1,1614	0,1	0,5	0,0001	1

Table B-1: N and K coefficients for the Retrotec 3000 Fan

Retrotec300 Fan last calibrated: (Flow Equation Parameters- B1). Published Flow Equation Parameters, Round B1 CFM							
Range	**n**	**K**	**K1**	**K2**	**K3**	**K4**	**MF**
Open	0.501	28.91	0	0.4	0	1	20
102	0.59	10.7	0	0.4	0	1	100
74	0.5045	7.077	0	0.25	0	1	15
47	0.5	3.241	0	0.1	0	1	10
29	0.502	1.19	0	0.2	0	1	20
18	0.499	0.457	0	0.25	0	1	25
11	0.48	0.28	0	0.25	0	1	25
7	0.5	0.0718	0	0.11	0	1	25

Table B-2: N and K coefficients for the Retrotec 300 Fan

B.3. Additional low insulated surface calculation

To integrate a blower door on a building brings some difference in the envelop thermal loss to the change of a door or window with the blower door which is not at all insulated. The annex aims to quantify the additional loss generated due to the blower door integration.

Surface [m²]	1,6
Internal thermal resistance [m²K/W](source RT2012)	0,13
External thermal resistance [m²K/W] (source RT2012)	0,04
Additional low insulate surface thermal resistance	0
Thermal losses [W/K]	9,4

Figure B-1: Thermal losses calculation for the additional low insulated surface created by the blower door panel

B.4. Differential pressure sensors validation table

To reduce pressure measurements uncertainties, three different differential pressure sensors were tested by submerging at different height the sensor’s tube in a container filled with water.

The accuracy of each sensor, as specified by the manufacturer can be found bellow:

- Pressure sensor (Type Swema): range from -100...1500Pa, ±0,3%, min ± 0,3 Pa
- Model DM32 Gauge pressure sensor: range from 0 Pa to ±1000 Pa: (0.1 + 0.05 % rdg) Pa
- Pressure transmitter: accuracy <0.5% of reading

Water column height (mm)	Gauge pressure [Pa]	Pressure sensor (Type Swema) [Pa]	Pressure transmitter (used for the test) [Pa]
5	30,4	31,4	31,7
	28,7	29,4	28,7
	26,7	27,7	26,6
10	38,7	38,7	38,8
	38,2	38,7	38,2
	38	38,8	37,6
15	63	63	63
	62,7	64,7	63,5
	62,5	63	62,9
20	110,5	112,5	110,7
	110,5	111,4	109
	107	109	106,4
30	134	136	133
	133	135,2	133
	128,7	130	129
40	171	174	170,7
	167	169	167,4
	166	167	166
50	194	193,6	194,6
	196,5	197,9	196,1
	199,5	200	198,9

Table B-3: Fan Pressure sensors validation table

In Figure A-12 it's presented the room pressure difference recorded during the night of the test on I-BB house. As it can be seen here, there is a good agreement between both sensors.

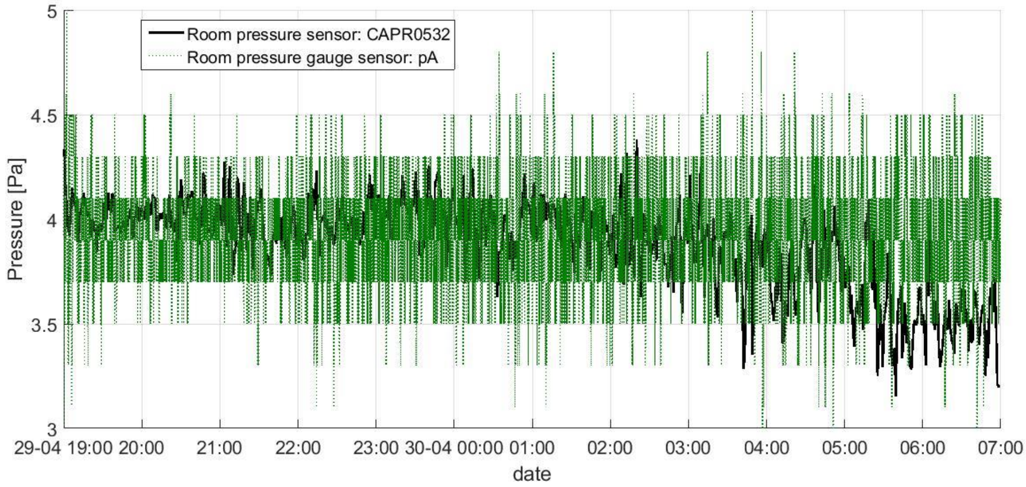


Figure B-2: Pressure measurements: room pressure [Pa]

B.1. Blower door results on the I-BB house

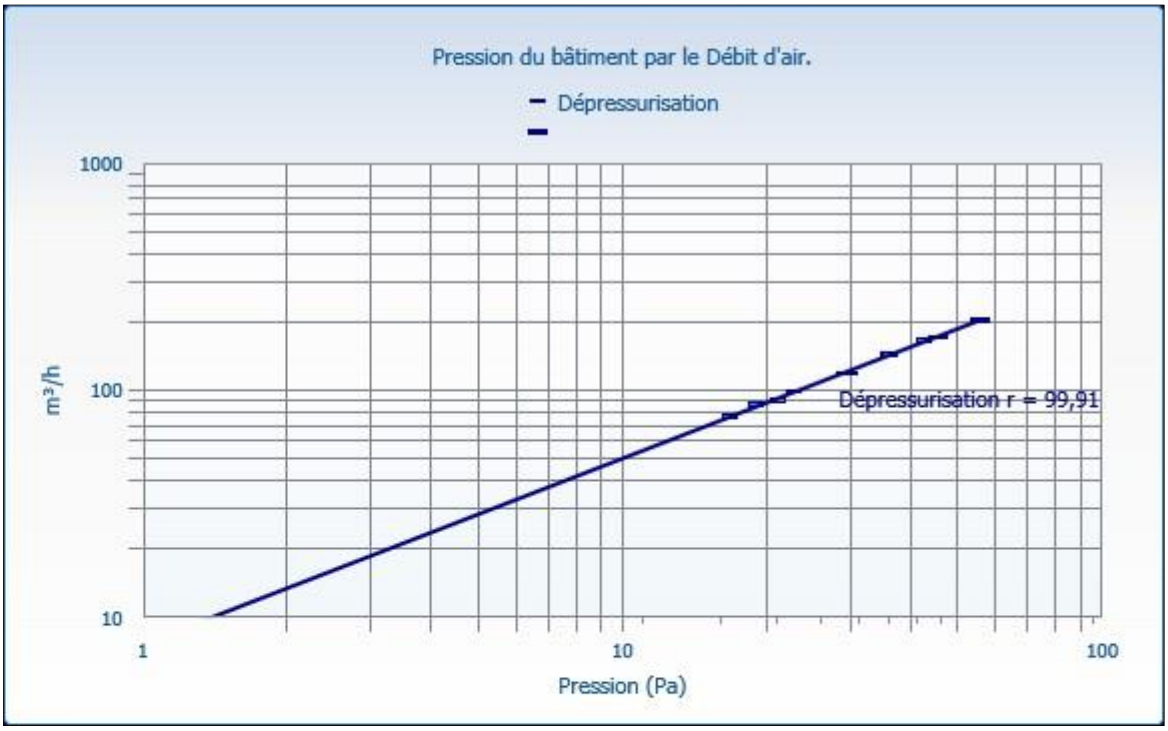
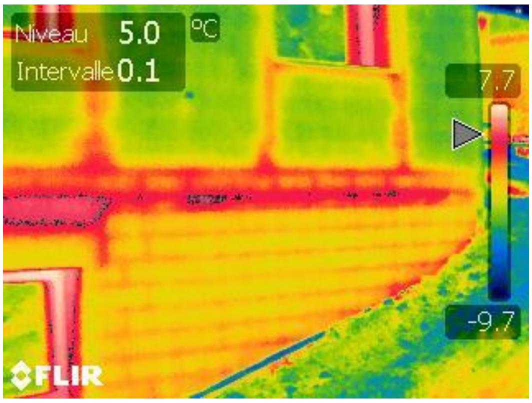
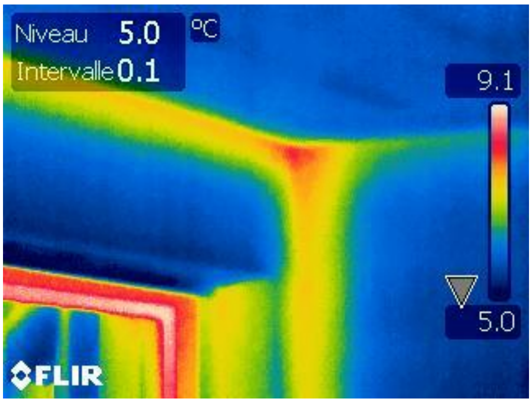


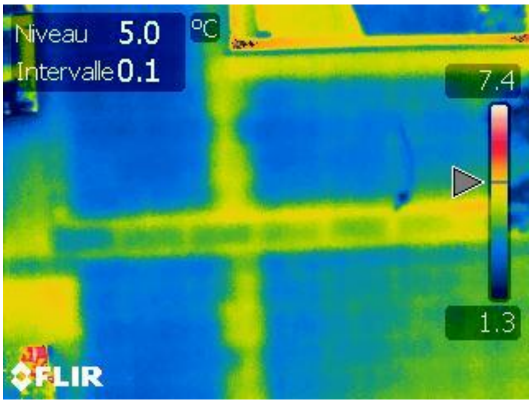
Figure B-3: Blower door test performed on results 14.03.5016 for the experimental building: air pressure against air flow

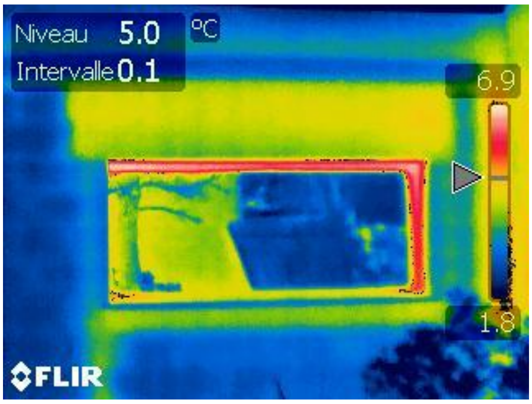
ANNEX C. Thermography analysis on PosA house

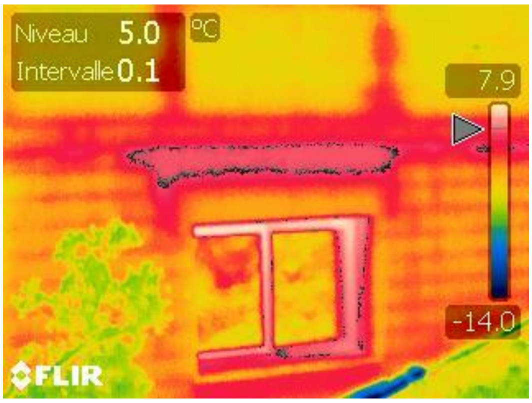
A thermography analysis was performed on 17 December 2015. The envelope's interior insulation facilitates this analysis, offering a clear view of the wall structure. In the first set of pictures, the difference between the ground floor and the first floor's vertical wall structure can be explained by the fact that there are different construction materials and therefore different thermal resistance values. In this set of pictures, the horizontal bonds within the intermediate floor wall structure can also be identified. They are meant to support and prevent the separation of these two side walls. Similarly, the vertical bonds are shown in the first and second set of pictures. In these set of pictures, thermal bridges created by the roller blind box are visible, as are those created by the exterior wall and the intermediate floor. This could have been reduced by the use of external insulation as an alternative.
However, no particular anomalies are detected.

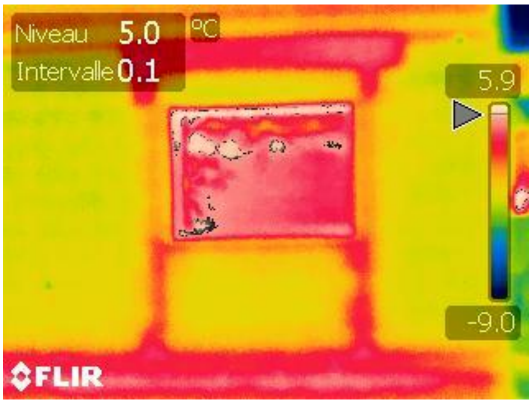





Niveau 5.0
Intervalle 0.1
°C
7.4
1.3
FLIR


Niveau 5.0
Intervalle 0.1
°C
6.9
1.8
FLIR


Niveau 5.0
Intervalle 0.1
°C
7.9
-14.0
FLIR


Niveau 5.0
Intervalle 0.1
°C
5.9
-9.0
FLIR

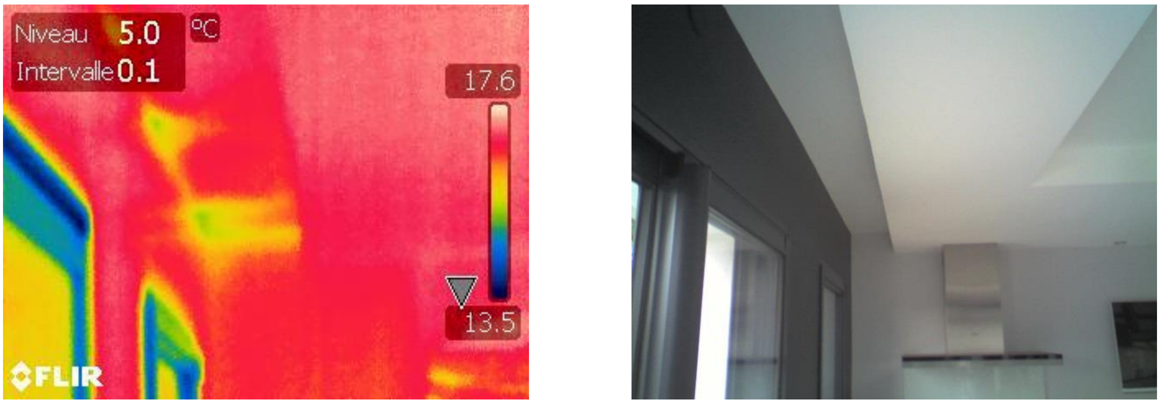


Figure C-1: Thermography analysis on PosA house

ANNEX D. Monitoring complements

D.1. Limiting the number of sensors : selected approach description

The Pearson product-moment correlation coefficient is a measure of the degree of linear dependence between two variables X and Y. This coefficient represents the covariance of the two variables divided by their standard deviations. When applied to a sample, the Pearson's correlation coefficient is commonly referred to as 'correlation coefficient' and it is represented by the letter r. The formula for r is:

$$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}} \quad \text{(D.1)}$$

Where $\overline{X}$, represents the mean of the X sample .

This r coefficient can take values between -1 and 1 and can be interpreted as follows: if r is close to zero, there is no linear correlation between the two samples, if r is close to 1 there is a positive correlation and if r is close to -1 there is a negative linear correlation between the samples. Following figures show correlation coefficients between ground and floors of the I-DM house.

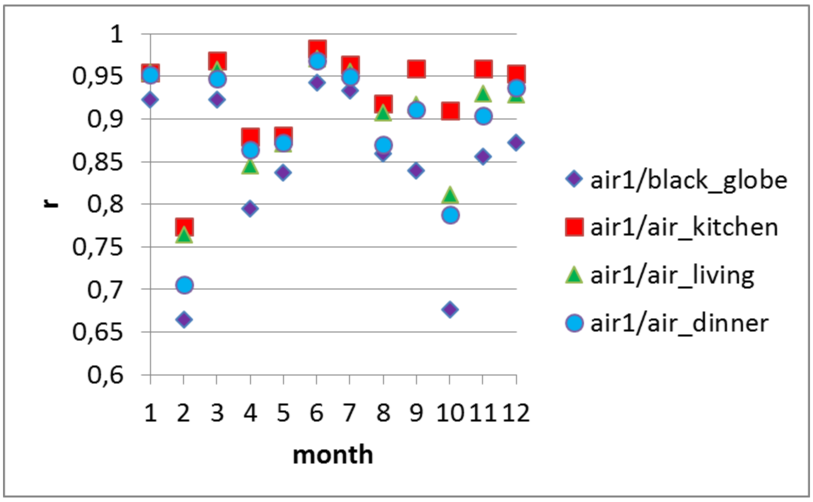


Figure D-1: Correlation coefficient between air temperature measurements, first floor room1 and ground floor room

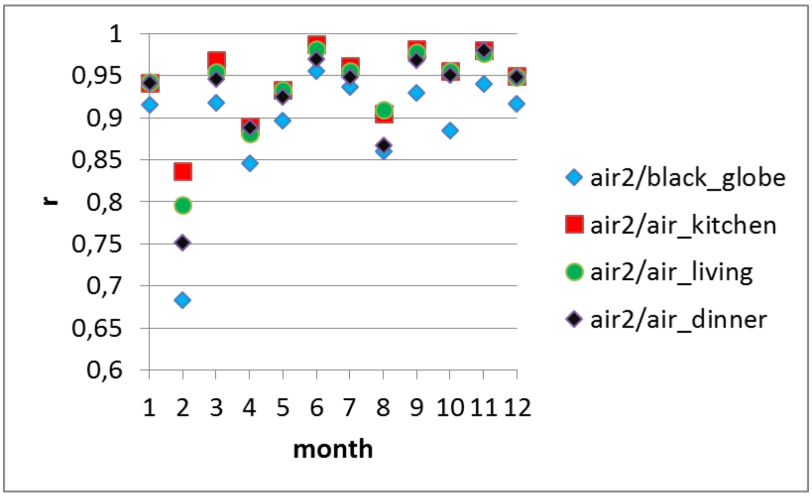


Figure D-2: Correlation coefficient between air temperature measurements, first floor room2 and ground floor room

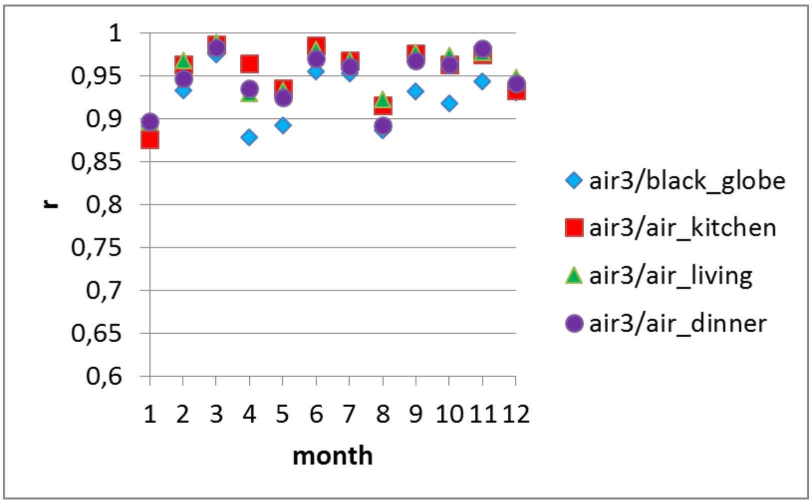


Figure D-3: Correlation coefficient between air temperature measurements, first floor room3 and (ground floor room

D.2. *'As defined' sensors distribution for the PosA house*

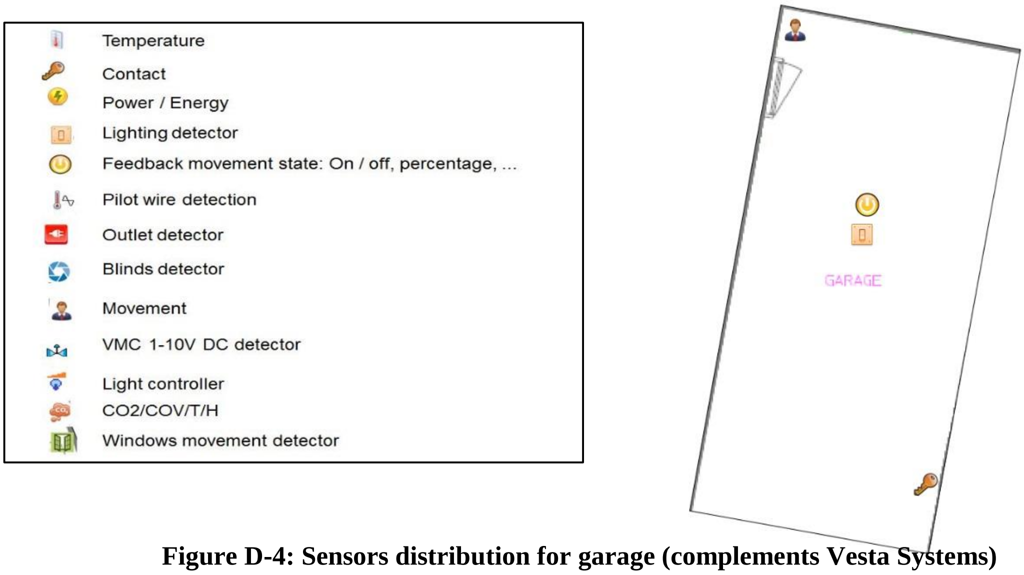


Figure D-4: Sensors distribution for garage (complements Vesta Systems)

Figure D-5: Sensors distribution for ground floor bedrooms and garage

Figure D-6: Sensors distribution for a ground floor bedroom: room2 (CH2) and room 1 (CH1)

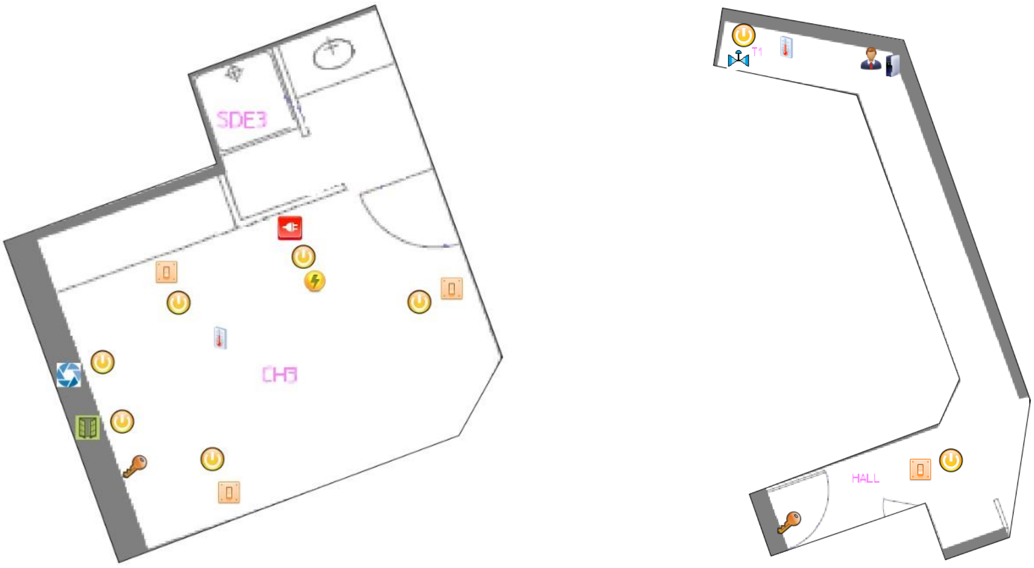


Figure D-7: Sensors distribution for a ground floor bedroom (room 3 (CH3)) and hall

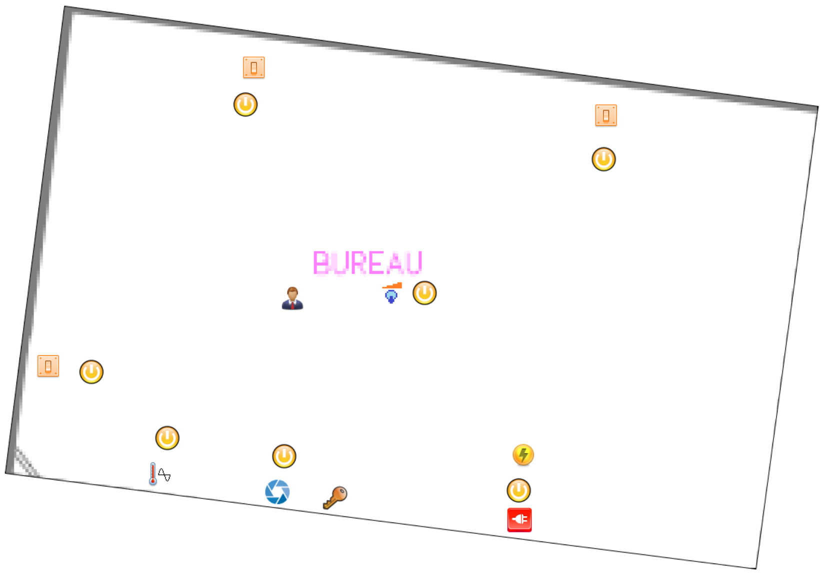


Figure D-8: Sensors distribution for the office room

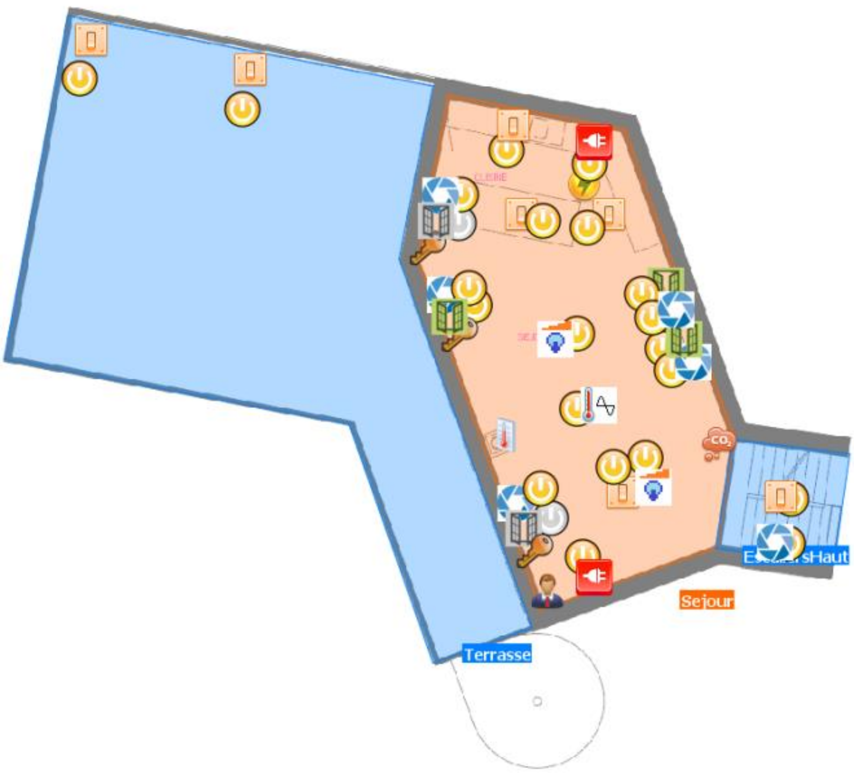


Figure D-9: Sensors distribution for the living room

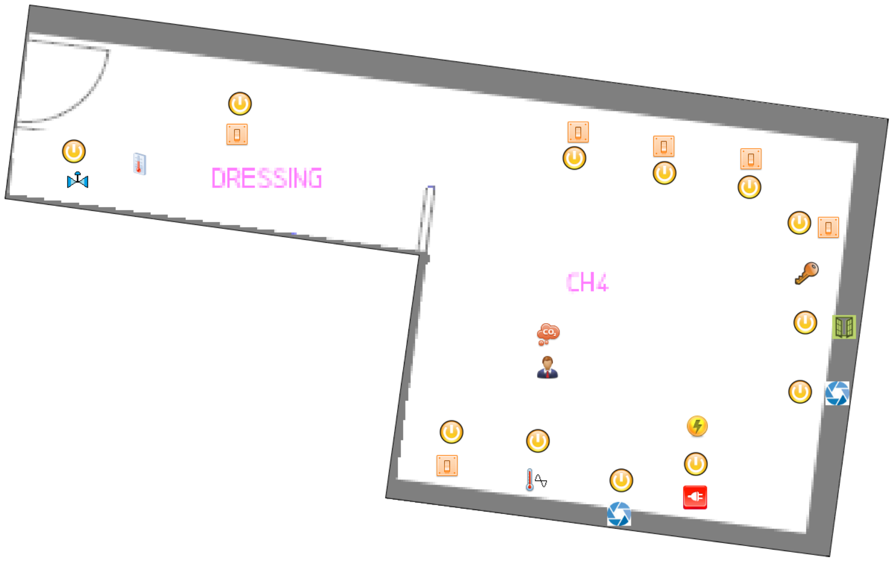


Figure D-10: Sensors distribution for parents' bedroom

D.3. Implemented sesnsors for the PosA building

Zone	Type	Name	Reference	Localization	Installation	Comment
Chambre2	Actuator	ActionneurLampe14	TYXIA 4610	Derrière interrupteur I14	Alimentation : en série sur 230 V	Domotique
Chambre2	Actuator	ActionneurLampe15	TYXIA 4610	Derrière interrupteur V15A	Alimentation : en série sur 230 V	Domotique
Chambre2	Actuator	ActionneurLampe33	TYXIA 4610	Derrière interrupteur V33A	Alimentation : en série sur 230 V	Domotique
Chambre2	Actuator	ActionneurVoletChambre2	TYXIA 4730		Alimentation : 230V	RT2012
Chambre2	Sensor	CompteurTV	SERFSR61VA-10A	Encastré derrière la télé P11	Alimentation : en série sur 230V	Domotique
Chambre2	Sensor	ContactFenetre	MINI COX Brun	Fenêtre Chambre	Alimentation : piles	Métrologie
Chambre2	Sensor	EtatTV		Encastré derrière la télé P11	Alimentation : en série sur 230V	Domotique Retour d'état du compteur TV
Chambre2	Actuator	EtatVoletChambre2				Retour d'état Volet Chambre 2
Chambre2	Sensor	TemperatureHumidite	TYBOX 5102	1m60 du sol Eloigné du portes, fenêtres et radiateurs	Alimentation : piles	Métrologie
Chambre3	Actuator	ActionneurFenetreChambre3	TYXIA 4730 modifié		Alimentation : 230V	Domotique NOVAL
Chambre3	Actuator	ActionneurLampe16	TYXIA 4610	Derrière interrupteur I16	Alimentation : en série sur 230 V	Domotique
Chambre3	Actuator	ActionneurLampe17	TYXIA 4610	Derrière interrupteur V17A	Alimentation : en série sur 230 V	Domotique
Chambre3	Actuator	ActionneurLampe38	TYXIA 4610	Derrière interrupteur V38A	Alimentation : en série sur 230 V	Domotique
Chambre3	Actuator	ActionneurVoletChambre3	TYXIA 4730		Alimentation : 230V	RT2012
Chambre3	Sensor	CompteurTV	SERFSR61VA-10A	Encastré derrière la télé P15	Alimentation : en série sur 230V	Domotique
Chambre3	Sensor	ContactFenetre	MINI COX Brun		Alimentation : piles	Métrologie
Chambre3	Actuator	EtatFenetreChambre3				Retour d'état Fenêtre Chambre 3
Chambre3	Sensor	EtatTV		Encastré derrière la télé P15	Alimentation : en série sur 230V	Domotique Retour d'état du compteur TV
Chambre3	Actuator	EtatVoletChambre3				Retour d'état Volet Chambre 3
Chambre3	Sensor	TemperatureHumidite	TYBOX 5102	1m60 du sol Eloigné des portes, fenêtres et radiateurs	Alimentation : piles	Métrologie
Hall	Actuator	ActionneurLampe18	TYXIA 4610	Derrière interrupteur V18A	Alimentation : en série sur 230 V	Domotique
Hall	Actuator	ActionneurVMC2	SERFSG71	A côté de la VMC	Alimentation : Repiquage sur alim VMC 230V	Métrologie Dimmer 1-10V DC
Hall	Sensor	ContactPorteEntree	MINI COX Brun		Alimentation : piles	Métrologie
Hall	Sensor	Presence1	IRSX	Dans un angle au plafond	Alimentation : piles	Domotique
Hall	Sensor	TemperatureAirVMC2	Sonde Universelle	Placé par M. TOUITOU proche du sol	Alimentation : piles	Métrologie
Bureau	Actuator	ActionneurPc1	TYXIA 4610	Derrière interrupteur I1_3	Alimentation : en série sur 230 V	Domotique
Bureau	Actuator	ActionneurPc2	TYXIA 4610	Derrière interrupteur I1_3	Alimentation : en série sur 230 V	Domotique
Bureau	Actuator	ActionneurPc3	TYXIA 4610	Derrière interrupteur I1_3	Alimentation : en série sur 230 V	Domotique
Bureau	Actuator	ActionneurVoletBureau	TYXIA 4730		Alimentation : 230V	RT2012
Bureau	Sensor	CompteurPrise21	SERFSR61VA-10A	Encastré derrière la prise P21	Alimentation : en série sur 230V	Domotique
Bureau	Sensor	ContactFenetre	MINI COX Brun		Alimentation : piles	Métrologie
Bureau	Sensor	EtatPrise21		Encastré derrière la prise P21	Alimentation : en série sur 230V	Domotique Retour d'état du compteur TV
Bureau	Actuator	EtatVoletBureau				Retour d'état Volet Bureau

Bureau	Actuator	VariateurLampe19	TYXIA 4850	Derrière interrupteur I19_2	Alimentation : en série sur 230 V	Domotique
WC	Sensor	ContactFenetre	MINI COX Brun		Alimentation : piles	Métrologie
Chambre1	Actuator	ActionneurFenetreChambre1	TYXIA 4730 modifié		Alimentation : 230V	Métrologie NOVAL
Chambre1	Actuator	ActionneurLampe32	TYXIA 4610	Derrière interrupteur V32A	Alimentation : en série sur 230 V	Domotique
Chambre1	Actuator	ActionneurLampe4	TYXIA 4610	Derrière interrupteur I4	Alimentation : en série sur 230 V	Domotique
Chambre1	Actuator	ActionneurLampe5	TYXIA 4610	Derrière interrupteur V5A	Alimentation : en série sur 230 V	Domotique
Chambre1	Actuator	ActionneurVoletChambre1	TYXIA 4730		Alimentation : 230V	RT2012
Chambre1	Sensor	CompteurTV	SERFSR61VA-10A	Encastré derrière la télé P30	Alimentation : en série sur 230V	Domotique
Chambre1	Sensor	ContactFenetre	MINI COX Brun		Alimentation : piles	Métrologie
Chambre1	Actuator	EtatFenetreChambre1				Retour d'état Fenêtre Chambre 3
Chambre1	Sensor	EtatTV		Encastré derrière la télé P30	Alimentation : en série sur 230V	Domotique Retour d'état du compteur TV
Chambre1	Actuator	EtatVoletChambre1				Retour d'état Volet Chambre 3
Chambre1	Sensor	TemperatureHumidite	TYBOX 5102	1m60 du sol Eloigné des portes, fenêtres et radiateurs	Alimentation : piles	Métrologie
Escaliers	Actuator	ActionneurVoletEscalierBas	TYXIA 4730		Alimentation : 230V	RT2012
Escaliers	Actuator	EtatVoletEscalierBas				Retour d'état Volet Escalier
ECS	Sensor	AffichageDebitTemperature	TYWATT 5200		Alimentation : 230V Repiquage sur alimentation ECS	Métrologie
ECS	Sensor	DebitTemperatureChaud	DN 15	Sortie Eau Chaude Ballon	Alimenté par TYWATT 5200	Métrologie
ECS	Sensor	DebitTemperatureFroid	DN 15	Entrée Eau Froide Ballon	Alimenté par TYWATT 5200	Métrologie
Garage	Actuator	ActionneurLampe1	TYXIA 4610	Derrière interrupteur V1A	Alimentation : en série sur 230 V	Domotique
Garage	Sensor	CompteurEauFroide	TYWATT 5100	Sortie pulse compteur	Alimentation : piles	Métrologie
Garage	Sensor	CompteurGaz	TYWATT 5100	Sortie pulse compteur	Sur le ITRON GALLUS	Métrologie
Cellier	Actuator	ActionneurLampe20	TYXIA 4610	Derrière interrupteur I20	Alimentation : en série sur 230 V	Domotique
Cellier	Actuator	ActionneurLaveLinge	VITA1001SP	A définir	Pas de câblage	Métrologie
PoolHouse	Actuator	ActionneurLampe	SERFSR61-230V	Derrière interrupteur	Alimentation : en série sur 230 V	Domotique
PoolHouse	Actuator	ActionneurPAC	SERFSR61-230V	Derrière la PAC	Alimentation : 230V	Métrologie Contact sec
PoolHouse	Actuator	ActionneurPompeFiltration		Tableau électrique	Alimentation : en série sur 230V	Métrologie
PoolHouse	Sensor	CompteurChauffage5	SERFWZ12-16A	Tableau électrique	Alimentation : DIN	Métrologie
PoolHouse	Sensor	CompteurECS	SERFWZ12-16A	Tableau électrique	Alimentation : DIN	Métrologie
PoolHouse	Sensor	CompteurPAC	SERFWZ12-16A	Tableau électrique	Alimentation : DIN	Métrologie PAC Piscine et Jacuzzi
PoolHouse	Sensor	CompteurPlaque	SERFWZ12-65A	Tableau électrique	Alimentation : DIN	Métrologie
PoolHouse	Sensor	CompteurPompeContreCourant	SERFWZ12-16A	Tableau électrique	Alimentation : DIN	Métrologie
PoolHouse	Sensor	CompteurPompeFiltration	SERFSR70W-16A	Tableau électrique	Alimentation : en série sur 230V	Métrologie
PoolHouse	Sensor	TemperatureHumidite	UBID1005	1m60 du sol Eloigné des portes, fenêtres et radiateurs	Alimentation : Autonome	Métrologie
PoolHouse	Micro PC	VestaBox3	VestaBox	Tableau électrique	Alimentation : 230V Câblage sur prise ethernet	Métrologie Dongle USB EnOcean
Toiture	Sensor	FluxSolaire	Sonde SE 2100	Mur sud	Alimentation : piles Proposition : plutôt au milieu pour	RT2012
Toiture	Sensor	Meteo	WSC11	Toit	Alimentation : 24V DC Communication : RS 485 vers tableau	Métrologie
Toiture	Sensor	TemperatureExterieure	Sonde STE 2000	Mur nord	Alimentation : piles	RT2012
Porche	Actuator	ActionneurLampe3	TYXIA 4610	Derrière interrupteur BP3C	Alimentation : en série sur 230 V	Domotique
Terrasse	Actuator	ActionneurLampe21	TYXIA 4610	Derrière interrupteur I21	Alimentation : en série sur 230 V	Domotique
Terrasse	Actuator	ActionneurLampe23	TYXIA 4610	Derrière interrupteur I23	Alimentation : en série sur 230 V	Domotique
Sejour	Actuator	ActionneurDomeVelux1	Dome		Alimentation : 230V	Domotique
Sejour	Actuator	ActionneurDomeVelux2	Dome		Alimentation : 230V	Domotique
Sejour	Actuator	ActionneurFenetre1	TYXIA 4730 modifié		Alimentation : 230V	Domotique NOVAL
Sejour	Actuator	ActionneurFenetre2	TYXIA 4730 modifié		Alimentation : 230V	Domotique NOVAL
Sejour	Actuator	ActionneurFenetre3	TYXIA 4730 modifié		Alimentation : 230V	Domotique NOVAL
Sejour	Actuator	ActionneurLampe10	TYXIA 4610	Derrière interrupteur I10_30	Alimentation : en série sur 230 V	Domotique
Sejour	Actuator	ActionneurLampe26	TYXIA 4610	Derrière interrupteur V26	Alimentation : en série sur 230 V	Domotique
Sejour	Actuator	ActionneurLampe27	TYXIA 4610	Derrière interrupteur I29_27	Alimentation : en série sur 230 V	Domotique
Sejour	Actuator	ActionneurLampe29	TYXIA 4610	Derrière interrupteur I29_27	Alimentation : en série sur 230 V	Domotique
Sejour	Actuator	ActionneurPc4	TYXIA 4610	Derrière interrupteur V4	Alimentation : en série sur 230 V	Domotique
Sejour	Actuator	ActionneurStoreVelux1	Store		Alimentation : 230V	Domotique
Sejour	Actuator	ActionneurStoreVelux2	Store		Alimentation : 230V	Domotique
Sejour	Actuator	ActionneurVolet1Sejour	TYXIA 4730		Alimentation : 230V	RT2012
Sejour	Actuator	ActionneurVolet2Sejour	TYXIA 4730		Alimentation : 230V	RT2012
Sejour	Actuator	ActionneurVolet3Sejour	TYXIA 4730		Alimentation : 230V	RT2012
Sejour	Actuator	ActionneurVoletVelux1	Volet		Alimentation : 230V	Domotique
Sejour	Actuator	ActionneurVoletVelux2	Volet		Alimentation : 230V	Domotique
Sejour	Sensor	CO2HumiditeTemperature	E4000	1m60 du sol Eloigné des portes, fenêtres et radiateurs	Alimentation : 24V DC	Métrologie EnOcean ou X3D ?
Sejour	Sensor	COV		1m60 du sol Eloigné des portes, fenêtres et radiateurs	Alimentation : 24V DC	Métrologie EnOcean ou X3D ?
Sejour	Sensor	ContactFenetre1	MINI COX Brun		Alimentation : piles	Métrologie
Sejour	Sensor	ContactFenetre2	MINI COX Brun		Alimentation : piles	Métrologie
Sejour	Sensor	ContactFenetre3	MINI COX Brun		Alimentation : piles	Métrologie
Sejour	Sensor	ContactFenetre4	MINI COX Brun		Alimentation : piles	Métrologie
Sejour	Actuator	EtatDomeVelux1				Retour d'état Dome 1
Sejour	Actuator	EtatDomeVelux2				Retour d'état Dome 2

Sejour	Actuator	EtatFenetre1				Retour d'état Fenêtre 1
Sejour	Actuator	EtatFenetre2				Retour d'état Fenêtre 2
Sejour	Actuator	EtatFenetre3				Retour d'état Fenêtre 3
Sejour	Actuator	EtatStoreVelux1				Retour d'état Store 1
Sejour	Actuator	EtatStoreVelux2				Retour d'état Store 2
Sejour	Actuator	EtatVolet1Sejour				Retour d'état Volet 1
Sejour	Actuator	EtatVolet2Sejour				Retour d'état Volet 2
Sejour	Actuator	EtatVolet3Sejour				Retour d'état Volet 3
Sejour	Actuator	EtatVoletVelux1				Retour d'état Volet 1
Sejour	Actuator	EtatVoletVelux2				Retour d'état Volet 2
Sejour	Sensor	Presence3	IRSX	Dans un angle au plafond	Alimentation : piles	Domotique
Sejour	Sensor	TemperaturePoele	Sonde Universelle	Proche du conduit en partie basse	Alimentation : piles	Métrologie
Sejour	Actuator	VariateurLampe25	TYXIA 4850	Derrière interrupteur I25	Alimentation : en série sur 230 V	Domotique
Sejour	Actuator	VariateurLampe30	TYXIA 4850	Derrière interrupteur I10_30	Alimentation : en série sur 230 V	Domotique
Sejour	Micro PC	VestaBox2	VestaBox	Sous l'évier	Alimentation : Repiquage sur P47 Câblage sur prise ethernet RJ19	Métrologie Dongle USB EnOcean Dongle USB X3D
Chambre4	Actuator	ActionneurFenetre	TYXIA 4730 modifié		Alimentation : 230V	Métrologie NOVAL
Chambre4	Actuator	ActionneurLampe24	TYXIA 4610	Derrière interrupteur V24	Alimentation : en série sur 230 V	Domotique
Chambre4	Actuator	ActionneurLampe28	TYXIA 4610	Derrière interrupteur I28	Alimentation : en série sur 230 V	Domotique
Chambre4	Actuator	ActionneurLampe31	TYXIA 4610	Derrière interrupteur I31_34	Alimentation : en série sur 230 V	Domotique
Chambre4	Actuator	ActionneurLampe34	TYXIA 4610	Derrière interrupteur I31_34	Alimentation : en série sur 230 V	Domotique
Chambre4	Actuator	ActionneurLampe35	TYXIA 4610	Derrière interrupteur I35	Alimentation : en série sur 230 V	Domotique
Chambre4	Actuator	ActionneurLampe36	TYXIA 4610	Derrière intterupteur I36	Alimentation : en série sur 230 V	Domotique
Chambre4	Actuator	ActionneurLampe37	TYXIA 4610	Derrière interrupteur V37A	Alimentation : en série sur 230 V	Domotique
Chambre4	Actuator	ActionneurPrise5	TYXIA 4610	Derrière interrupteur I5	Alimentation : en série sur 230 V	Domotique
Chambre4	Actuator	ActionneurVMC1	SERFSG71	A côté de la VMC	Alimentation : Repiquage sur alim VMC 230V	Métrologie Dimmer 1-10V DC
Chambre4	Actuator	ActionneurVolet1	TYXIA 4730		Alimentation : 230V	RT2012
Chambre4	Actuator	ActionneurVolet2	TYXIA 4730		Alimentation : 230V	RT2012
Chambre4	Actuator	ActionneurVolet3	TYXIA 4730		Alimentation : 230V	RT2012
Chambre4	Sensor	CO2HumiditeTemperature	E4000	1m60 du sol Eloigné des portes, fenêtres et radiateurs Mur nord (?)	Alimentation : 24V DC + RS485 2 fils vers tableau élec	Métrologie EnOcean ou X3D ?
Chambre4	Sensor	COV		1m60 du sol Eloigné des portes, fenêtres et radiateurs Mur nord (?)	Alimentation : 24V DC + RS485 2 fils vers tableau élec	Métrologie EnOcean ou X3D ?
Chambre4	Sensor	CompteurTV	SERFSR61VA-10A	Encastré derrière la télé P36	Alimentation : en série sur 230V	Métrologie
Chambre4	Sensor	ContactFenetre1	MINI COX Brun	Fenêtre Chambre	Alimentation : piles	Métrologie
Chambre4	Sensor	ContactFenetre2	MINI COX Brun	Fenêtre Chambre	Alimentation : piles	Métrologie

Chambre4	Actuator	EtatFenetre				Retour d'état Fenêtre
Chambre4	Sensor	EtatTV		Encastré derrière la télé P36	Alimentation : en série sur 230V	Métrologie Retour d'état du compteur TV
Chambre4	Actuator	EtatVolet1Chambre4				Retour d'état Volet 1
Chambre4	Actuator	EtatVolet2Chambre4				Retour d'état Volet 2
Chambre4	Actuator	EtatVolet3Chambre4				Retour d'état Volet 3
Chambre4	Sensor	TemperatureAirVMC1	Sonde Universelle	Dans conduit soit proche VMC soit proche	Alimentation : piles	Métrologie
Chambre4	Sensor	TemperatureHumidite	TYBOX 5102	1m60 du sol Eloigné des portes, fenêtres et radiateurs SdB	Alimentation : Piles	Métrologie
Escaliers	Actuator	ActionneurLampe22	TYXIA 4610	Derrière interrupteur BP22B	Alimentation : en série sur 230 V	Domotique
Escaliers	Actuator	ActionneurVoletEscalierHaut	TYXIA 4730		Alimentation : 230V	RT2012
Escaliers	Actuator	EtatVoletEscalierHaut				Retour d'état Volet Escalier
Escaliers	Sensor	Presence2	IRSX	Dans un angle au plafond	Alimentation : piles	Domotique Orienté vers la chambre parents
Compteurs	Actuator	ActionneurECS	UBID2009	Armoire électrique	Alimentation : en série sur fil commande	Métrologie Contact sec
Compteurs	Sensor	Alimentation24V	SERSNT12-24VDC	Armoire électrique	Alimentation : DIN	Métrologie Transfo pour Sonde météo et 2
Compteurs	Sensor	CompteurChauffageBureau	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurChauffageChambre1	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie Radiateur + prise pour futur
Compteurs	Sensor	CompteurChauffageChambre2	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie Radiateur + prise pour futur
Compteurs	Sensor	CompteurChauffageChambre3	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie Radiateur + prise pour futur
Compteurs	Sensor	CompteurChauffageChambre4	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie Radiateur + Sèche-serviette
Compteurs	Sensor	CompteurChauffageCouloir	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurChauffageSejour	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie 2 Radiateurs
Compteurs	Sensor	CompteurECS	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurEclairage	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurFour	SERFWZ12-65A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurFrigo	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurLaveLinge	SERFSR70W-16A	Armoire électrique	Alimentation : en série sur 230V	Métrologie

Compteurs	Sensor	CompteurLaveVaisselle	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurPV	SERFWZ12-65A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurPlaques	SERFWZ12-65A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurPoolHouse	SERFWZ12-65A	Armoire électrique	Alimentation : DIN	Métrologie Dépend de du schéma du tableau
Compteurs	Sensor	CompteurPrises	SERFWZ12-65A	Armoire électrique	Alimentation : DIN	Métrologie
Compteurs	Sensor	CompteurTIC	USBTIC	Armoire électrique	Alimentation : DIN	Métrologie Abonnement HP/HC ou Base ?
Compteurs	Sensor	CompteurVMC	SERFWZ12-16A	Armoire électrique	Alimentation : DIN	Métrologie Comptage des 2 VMC
ActionneursFilPilote	Actuator	ActionneurRadiateurZone1	RF 6600 FP	Armoire électrique	Alimentation : 230V par Protection Fil Pilote 2A	RT2012 Zone Jour 1 : - Cuisine - Séjour
ActionneursFilPilote	Actuator	ActionneurRadiateurZone2	RF 6600 FP	Armoire électrique	Alimentation : 230V par Protection Fil Pilote 2A	RT2012 Zone Jour 2 : - Bureau - Couloir
ActionneursFilPilote	Actuator	ActionneurRadiateurZone3	RF 6600 FP	Armoire électrique	Alimentation : 230V par Protection Fil Pilote 2A	RT2012 Zone Nuit 1 : - Chambre1 - Chambre2 - Chambre3
ActionneursFilPilote	Actuator	ActionneurRadiateurZone4	RF 6600 FP	Armoire électrique	Alimentation : 230V par Protection Fil Pilote 2A	RT2012 Zone Nuit 2 : - Chambre 4
ActionneursFilPilote	Actuator	ActionneurRadiateurZone5	RF 6600 FP	Armoire électrique	Alimentation : 230V par Protection Fil Pilote 2A	RT2012 SdB Vérifier si le fil pilote du sèche
ActionneursFilPilote	Actuator	ActionneurRadiateurZone6	RF 6600 FP	Armoire électrique	Alimentation : 230V par Protection Fil Pilote 2A	RT2012 PoolHouse
SelecteurDeCharge	Actuator	ActionneurContacteurs12	UBID2006	Armoire électrique	Alimentation : DIN	Métrologie Récepteur modulaire bidirectionnel 2 canaux 5A Position 1 sur charge 1
SelecteurDeCharge	Actuator	ActionneurContacteurs34	UBID2006	Armoire électrique	Alimentation : DIN	Métrologie Récepteur modulaire bidirectionnel 2 canaux 5A Position 1 sur charge 3
SelecteurDeCharge	Sensor	CompteurGroupe1	SERFWZ12-65A	Armoire électrique	Alimentation : DIN	Métrologie
SelecteurDeCharge	Sensor	CompteurGroupe2	SERFWZ12-65A	Armoire électrique	Alimentation : DIN	Métrologie
SelecteurDeCharge	Sensor	CompteurGroupe3	SERFWZ12-65A	Armoire électrique	Alimentation : DIN	Métrologie
SelecteurDeCharge	Sensor	CompteurGroupe4	SERFWZ12-65A	Armoire électrique	Alimentation : DIN	Métrologie
SelecteurDeCharge	Sensor	ContacteurGroupe1	A9C20868	Armoire électrique	Alimentation : DIN	Métrologie
SelecteurDeCharge	Sensor	ContacteurGroupe2	A9C20868	Armoire électrique	Alimentation : DIN	Métrologie
SelecteurDeCharge	Sensor	ContacteurGroupe3	A9C20868	Armoire électrique	Alimentation : DIN	Métrologie
SelecteurDeCharge	Sensor	ContacteurGroupe4	A9C20868	Armoire électrique	Alimentation : DIN	Métrologie
Box	Sensor	CALYBOX	CALYBOX 2020 WT	Armoire électrique		RT2012
Box	Sensor	PasserelleVelux	PasserelleIP			Métrologie
Box	Sensor	TYDOM20002	TYDOM 2000	Armoire électrique		Domotique
Box	Micro PC	VestaBox	VestaBox	Armoire électrique	Alimentation : 230V Câblage sur prise ethernet	Métrologie Dongle USB EnOcean Dongle USB X3D USB TIC RS 232 ou XComLan (Studer) Velux
Box	Sensor	XCOMLANStuder	Xcom-LAN			Métrologie

Table D-1: Sensors distribution, type and location (complements Vesta Systems)

D.4. Occupant survey

Date 17/10/2016, Q: Question, A: Answer.

Systems:

Q: Are you satisfied with your heating system? If not, why not?/ *A: yes*

Q: Are you satisfied with your ventilation system? If not, why not?/ *A: Yes, but home automation could be improved rate: 7/10*

Acoustic comfort

Q: External noises: Do you perceive them? If so, is it uncomfortable? */ A: No*

Q: Noise of individual equipment (ventilation, sink, individual boilers, etc ...): Do you perceive them? If so, is it uncomfortable?/*A: Yes, uncomfortable a few times (Photovoltaic inverter)*

Winter thermal comfort

Q: During winter, did you feel cold in your home? */A: No*

Q: How do you act to reduce this discomfort? */A: I cut the ventilation when we are absent during the day/ A: I dress more warmly*

Thermal comfort in summer

Q: In your opinion, what is the maximum allowable summer temperature in a room? (In ° C) */A: 28 °C during day and 24 ° C at night*

Q: On a scale of 1 to 10 (1 = very dissatisfied, 10 = very satisfied), how satisfied are you with overall comfort in summer?/ *A: 6 today, as it remains to finalize some domotic management and sun shadows on the facades as originally planned.*

Q: During the summer, do you feel that it is too hot in your home? */A: Yes*

Q: How do you act to reduce this discomfort?*/A: I close the shutters; I open some windows at night and I close them the day; I ventilate stronger at night and less at day; I cut the ventilation system during day time; I avoid the use of household appliances releasing internal gains; I use light clothing; I take a shower to refresh*

Indoor air quality

Q: On a scale of 1 to 10 (1 = very dissatisfied, 10 = very satisfied), are you generally satisfied with the quality of the air inside your dwelling? */ A: 9*

Q: During heating, do you ventilate your house every day? (By opening the windows) */ A: Yes, some parts; Yes, almost all the pieces*

Q: Have you found excessive or persistent moisture in some rooms? Which ones? */A: No*

Q: In general, what are your reasons for dissatisfaction with the air in your dwelling? (Several possible answers) */A: None*

Q: In summer or outside the heating period) */A : None*

Q: On a scale of 1 to 10 (1 = very dissatisfied, 10 = very satisfied), are you satisfied overall with your house? */A: 8/10 as there are still a few adjustments to be made. It will be necessary to reply to this questionnaire again within 1 years after the overall finalization of the installation and all its adjustments.*

D.5. Additional results on desing versus real for energy use and indoor conditions

Figure D-11 illustrates the measured and simulated energy use for space heating over the 6-month period (November to April). In overall, when comparing the measured and simulated energy use, the results are quite close. The closest simulation results (1.5 kWh/m²/year difference) seem to be when using schedule 4, which uses a set-point temperature of 16–19°C and the average power for the appliances. It should be noted that the electric energy for heating here represents only 4 kWh/m²/year. The rest of the 11 kWh/m²/year is wood energy.

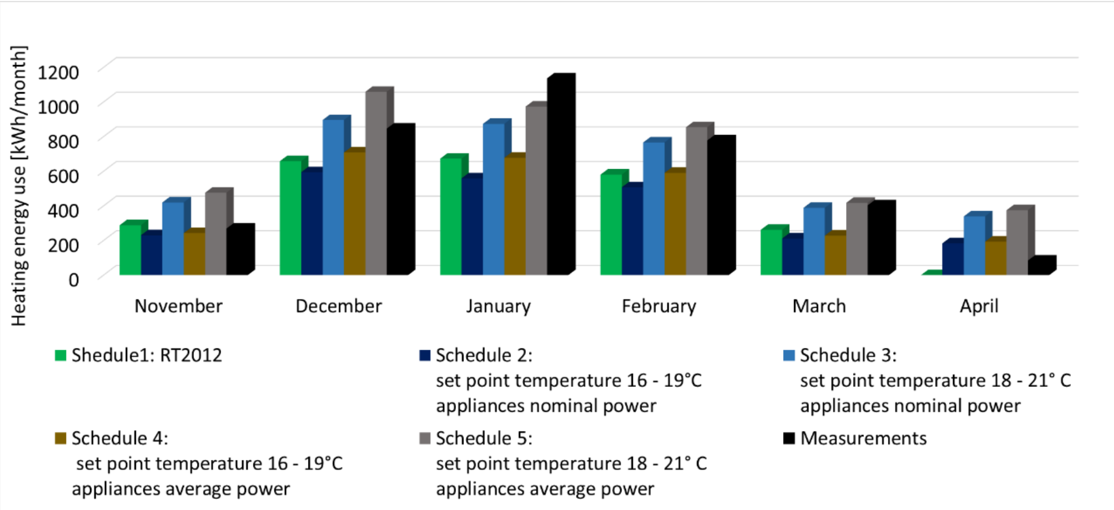


Figure D-11: Measured and simulated heating energy use/ demand for each month

The actual outdoor temperature should also be studied given that heating energy use is also influenced by outdoor conditions. As mentioned above, the weather station was not operational at the time of the study and we used outdoor temperature data from a weather station located close to the house. As illustrated in Figure D-12 the mean real outdoor temperature was higher than the temperature used in the simulations. Moreover, in winter months (December, January and February) when the highest heating energy use was recorded, the real mean outdoor temperature was about 2–5°C higher than the temperature used for the simulations. Consequently, these warmer weather conditions lead to less heating energy use. However, it was not confirmed by the data. The differences between predicted and measured values can be due to various factors.

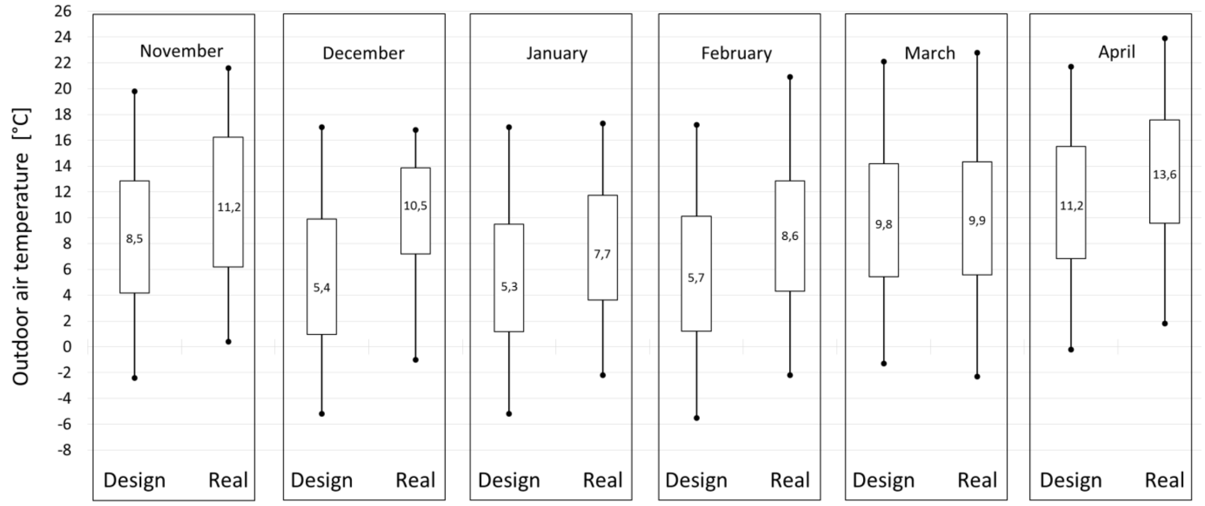


Figure D-12: Outdoor temperature: design vs. real

A comparison with the design phase estimation presented in section 2.5 and the measurements for lighting energy use/ demand is presented in Figure D-13. It can be seen that the agent-based model highly underestimates lighting energy use when compared with the measurements. We acknowledge that the agent behavioral model uses a more economical scenario. This may be due to the large surface area of the house (229 m^2). This specific case study differs from the average home in France, which has only half this surface area.

In addition, when comparing real lighting energy use with the simulation using schedules 1–5, the values are close. The real lighting energy use is, however, slightly higher (0.6 kWh/m^2/year difference) than predicted.

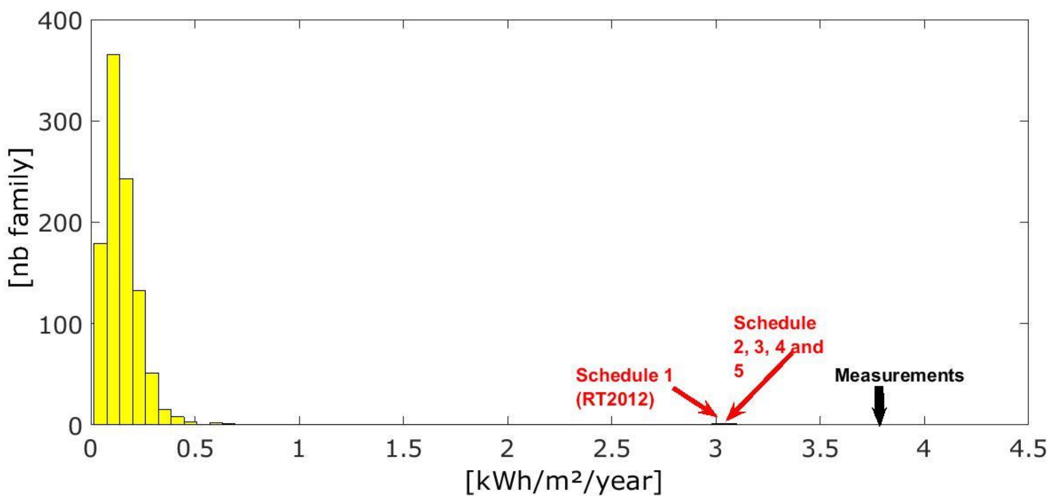


Figure D-13: Lighting energy consumption: measured vs. predicted

Total energy consumption

Here we present the comparison between the total energy demand results from the design phase when using the RT2012 schedule and the measurements for total energy use. First, we estimated the energy demand using the RT2012 schedule over the net floor area for the 6-month period. Then we compared it with the total real energy use.

The results (Figure D-14) show that for the winter months, as expected, heating is the main energy consumer. Appliances were the second energy consumer. Whereas lighting consumption was well estimated, the results of the simulations for heating seem underestimated. In the design phase, it was assumed that only electric heaters would be used for heating. Actually, on the first-floor area, electric heaters were not used at all. Here, the heating was provided by a wood-burning stove. In addition, when using a standard weather file combined with the RT2012 scenario, very similar heating energy demand for November and March as for December and January was obtained. However, it can be seen that there is a tendency for higher energy use in December and January. This is due to the weather conditions (lower temperature during January compared to other months) and human behavior (higher set-point temperature, higher occupancy etc.).

Some RT2012 items are easier to predict and some remained quite constant over the year: lighting energy use. Here, the actual DHW consumption covering four bathrooms and six sinks is underestimated. The expected DHW use and power was not provided by the owner in the design phase. A typical estimation for six people based on the expected presence was made here. We also observe an overestimation of the ventilation only in January. This is explained by the fact that the owner of the house managed the ventilation air flow himself, by reducing or even cutting off the fan at certain times, or measurement uncertainty.

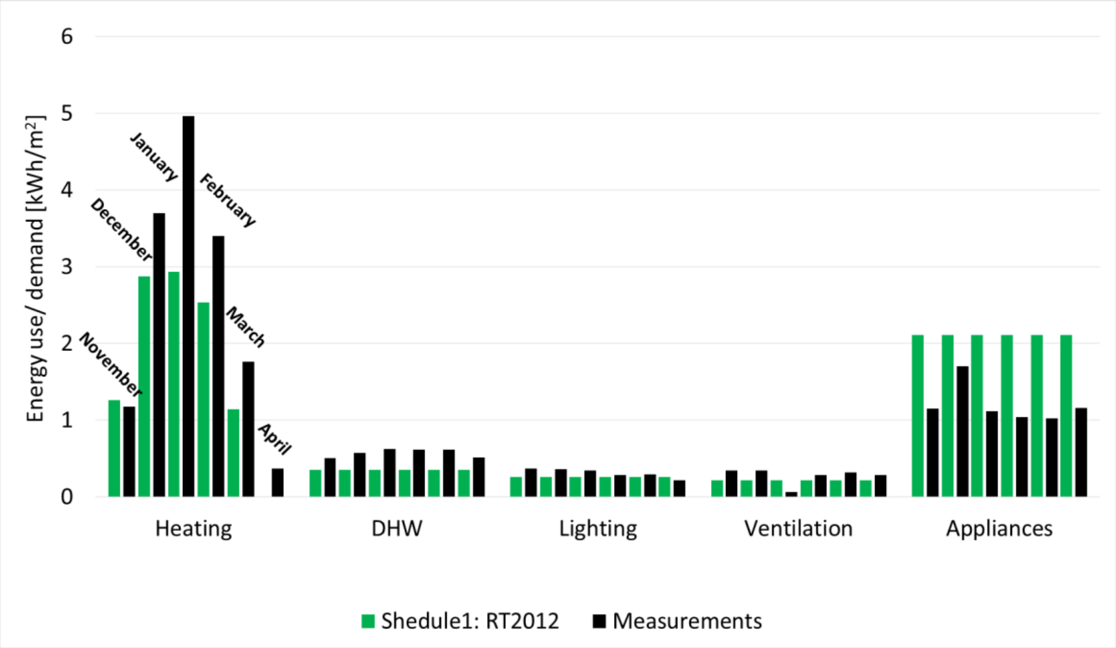


Figure D-14: Predicted vs. real total energy consumption for 6 winter months

The same annual average over the net floor area was also estimated for DHW, lighting, ventilation and appliances. As for heating, the value presented here is the sum of the heating value (estimated in the design phase and measured) for each month. The results presented in Figure D-15 show that when considering an annual projection, the appliances and heating energy use are the main energy consumer for this building. Considering that electric consumption represents only 4 kWh/m^2/year, it can be stated that the main electric energy consumer for this building is the appliances. The DHW energy consumption is the third energy consumer for this building. As expected, for this energy-efficient building, ventilation and lighting energy consumption is low, compared to other items.

However, modeling the occupants' behavior is indeed a challenge. Here, it was shown that even when information on the appliances' power is available in the design phase, their energy use can be difficult to predict. Choosing the nominal power provided by the owner seems to overestimate energy use (schedules 2 and 3). On the other hand, choosing an average power for appliances seems to underestimate the results for appliances energy use (schedules 4 and 5). Also, in the design phase, there is usually a large uncertainty regarding the use of the appliances. Moreover, in occupied buildings there are always household appliances that were not considered in the design phase: a new TV, an additional fridge etc.

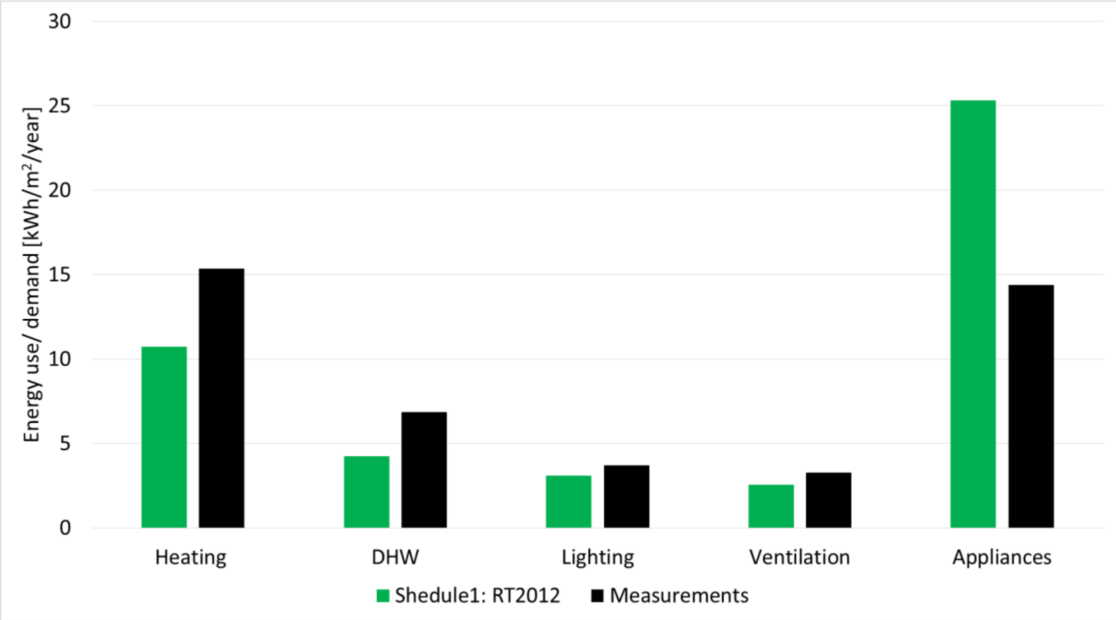


Figure D-15: Predicted vs. real total annual energy use/ demand

When considering an overall approach (RT2012 items and other uses such as appliances) (Figure D-16) a number of differences can be observed. The measurements for the energy use of the RT2012 items are higher than the simulations. For this house, it seems that the RT2012 schedule tends to underestimate the energy consumption of the RT2012 items with about 9 kWh/m^2/year, but, when comparing the real appliances energy use with the simulations, the RT2012 schedule overestimates their energy consumption with about 11 kWh/m^2/year.

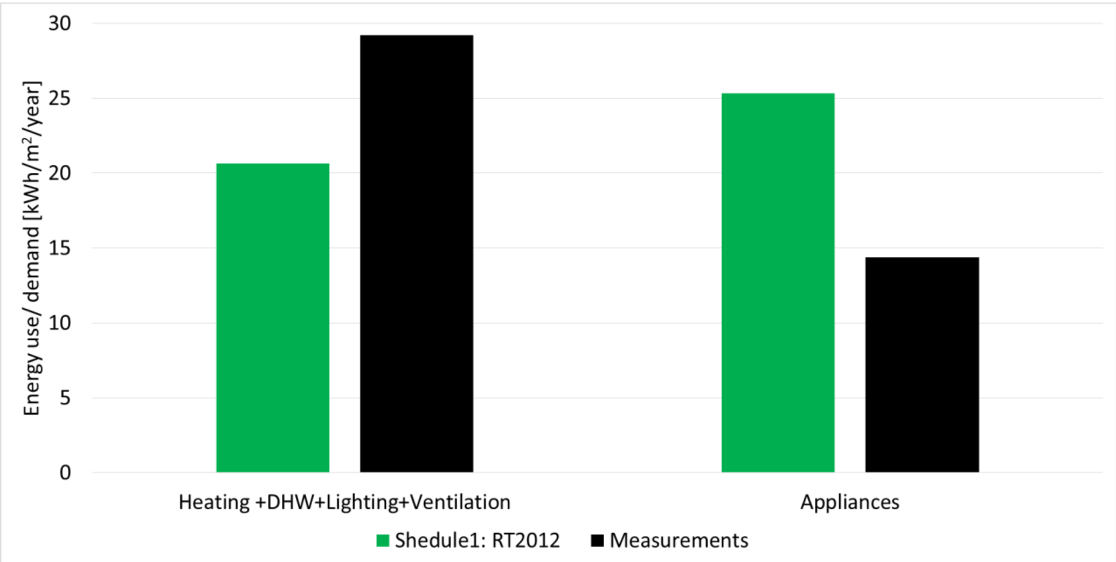


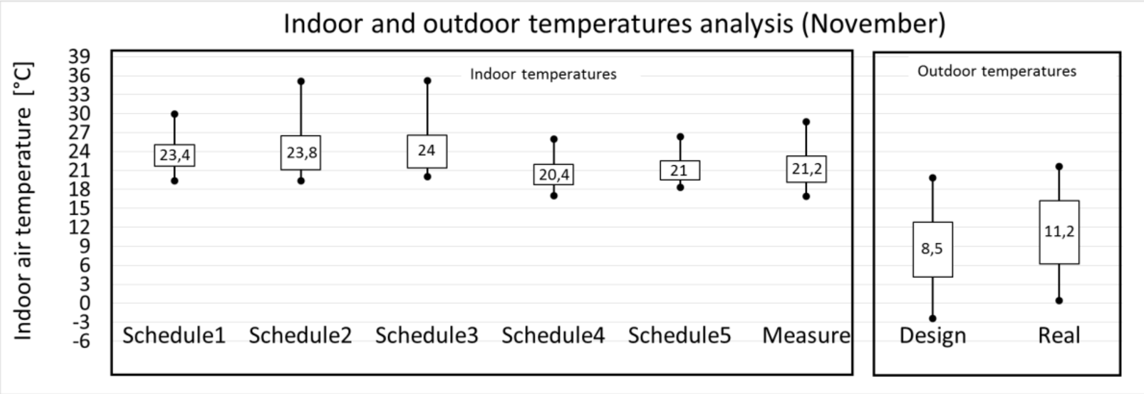
Figure D-16: Predicted vs. real total annual energy consumption (RT2012 items+ appliances)

However, even if the appliances use is a large part of the total energy use, we show that another big part represents the set-point temperature used for optimal thermal comfort. These two performance indicators (energy use and indoor conditions) are highly interdependent. For example, during the winter period, the energy use is highly influenced by the occupants' set-point temperature preference. As shown in chapter 1, usually this is the case of a higher than standard RT2012 set-point temperature. Therefore, for the evaluation of the real energy performance, these two performance indicators should be analyzed together. Consequently, in the following section, various aspects of the indoor conditions will be discussed.

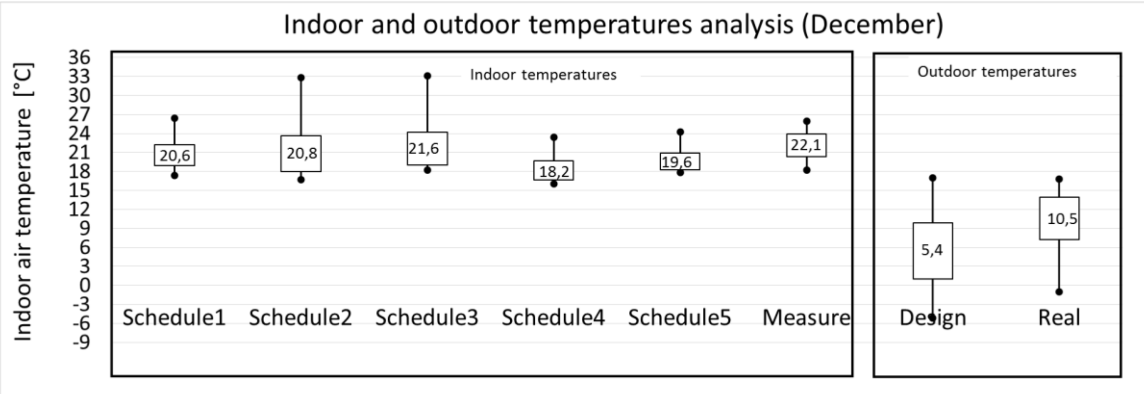
The next step is to compare the simulations and measurements in greater detail. Here, only the living room temperatures are presented. The same mean, minimum and maximum values for the temperature as well as the standard deviation were calculated for each month. The results (Figure D-17) show that simulations using all the schedules cannot emulate the real temperature, as expected. The first problem is predicting the occupant's preferred temperature. Moreover, regardless the occupants' behavior, the indoor temperature is also influenced by other factors: internal gains, external conditions and system use (i.e., the use of wood-burning stove instead of electric heaters).

Here we can see that using nominal power for the appliances (schedules 2 and 3) generated a maximum indoor temperature of 35°C in the living room, mostly because almost all the devices (oven, stovetop etc.) are situated in the living area, making for significant internal gains here. However, the real indoor temperature in the living room was also high (31°C) during some periods but for completely different reasons, mainly because of the use of wood-burning stove and the warm Mediterranean climate. When considering the real mean indoor temperatures, we can observe that they varied between 21°C (November) and 24°C (April).

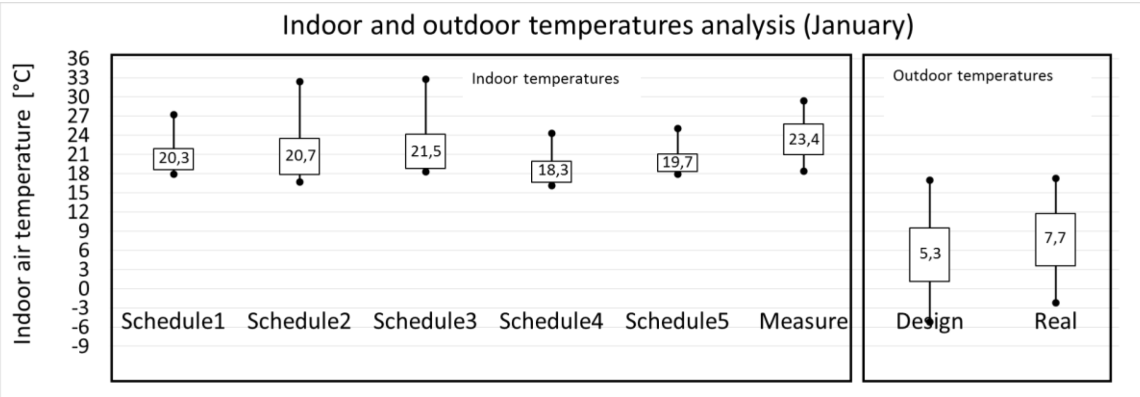
Another interesting observation here is that during January, when the highest heating energy use was observed, the real outdoor temperature was higher with 2,7°C than the temperature used in the simulation (design weather file).



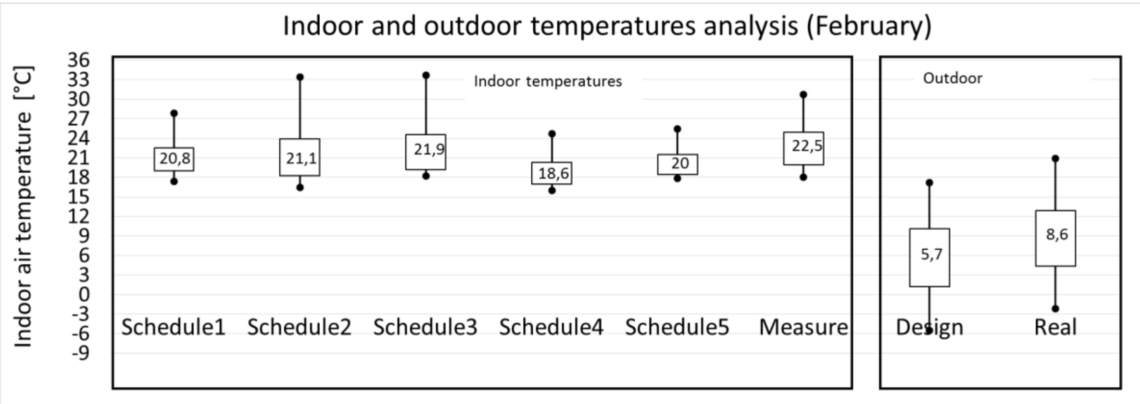
Indoor and outdoor temperatures analysis (November)
Indoor air temperature [°C]
Indoor temperatures
Outdoor temperatures
Schedule1 23,4
Schedule2 23,8
Schedule3 24
Schedule4 20,4
Schedule5 21
Measure 21,2
Design 8,5
Real 11,2



Indoor and outdoor temperatures analysis (December)
Indoor air temperature [°C]
Indoor temperatures
Outdoor temperatures
Schedule1 20,6
Schedule2 20,8
Schedule3 21,6
Schedule4 18,2
Schedule5 19,6
Measure 22,1
Design 5,4
Real 10,5



Indoor and outdoor temperatures analysis (January)
Indoor air temperature [°C]
Indoor temperatures
Outdoor temperatures
Schedule1 20,3
Schedule2 20,7
Schedule3 21,5
Schedule4 18,3
Schedule5 19,7
Measure 23,4
Design 5,3
Real 7,7



Indoor and outdoor temperatures analysis (February)
Indoor air temperature [°C]
Indoor temperatures
Outdoor
Schedule1 20,8
Schedule2 21,1
Schedule3 21,9
Schedule4 18,6
Schedule5 20
Measure 22,5
Design 5,7
Real 8,6

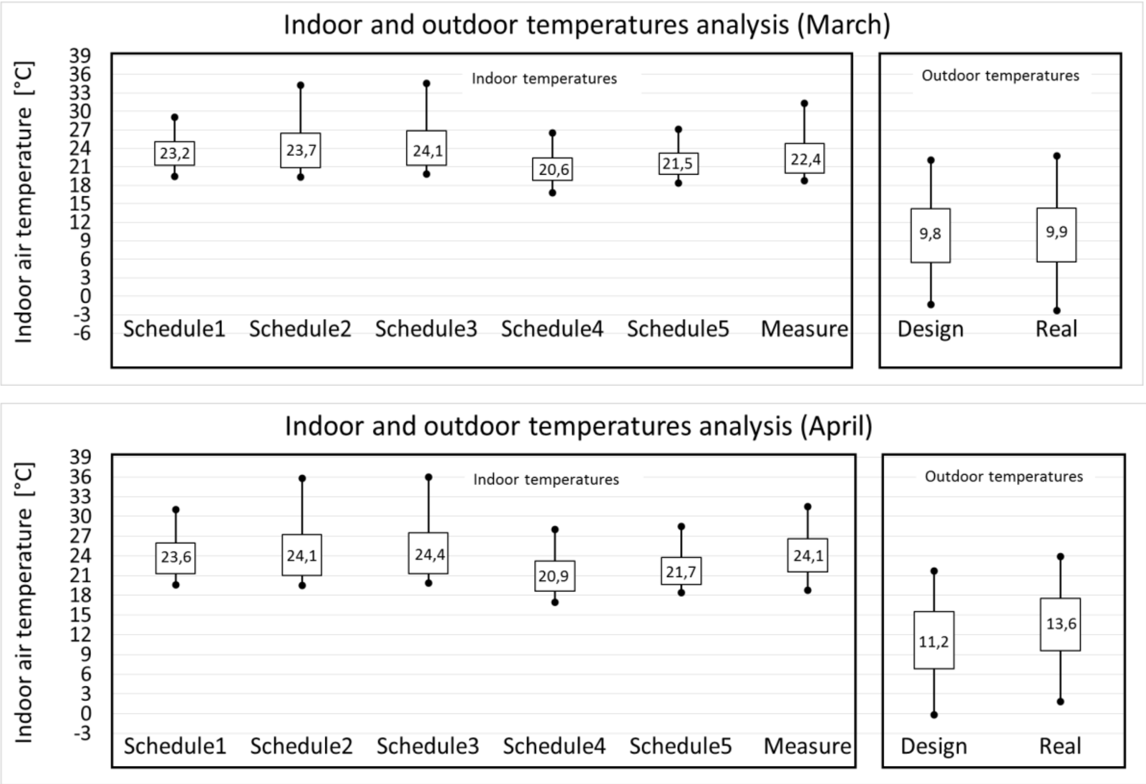


Figure D-17: Minimum and maximum values for the predicted and real temperature and standard deviation