Master thesis : Evaluation of the overheating risk and the potential of ventilative cooling : A case study in Belgium

Auteur : Fani, Abdul Rahman
Promoteur(s) : Attia, Shady
Faculté : Faculté des Sciences appliquées
Diplôme : Master en ingénieur civil architecte, à finalité spécialisée en ingénierie architecturale et urbaine
Année académique : 2019-2020
URI/URL : http://hdl.handle.net/2268.2/9090

Evaluation of the overheating risk and the potential of ventilative cooling: A case study in Belgium

Master Dissertation submitted to obtain the academic degree of

Master of Science in Architectural Engineering

Academic Year 2019 – 2020

Author: Abdulrahman **FANI**

Supervisor: Prof. Shady **ATTIA**

Jury Members: Prof. Sigrid **REITER**

Prof. Jean-Marie **HAUGLUSTAINE**

Ir. Ramin **RAHIF**

Department of Architectural Engineering

Faculty of Applied Sciences

Acknowledgments:

First, I would like to thank my thesis advisor, Prof. Shady Attia, from the Department of Architectural Engineering, in the faculty of Applied Sciences at the University of Liege. The door to Prof. Attia was always open whenever guidance was required within the development of the thesis. He consistently assured that the direction of the thesis was always steered towards the correct path.

I would also like to thank the experts who are involved in the validation of this research project, including Prof. Sigrid Reiter, Prof. Jean-Marie Hauglustaine, and Ir. Ramin Rahif. Without their passionate participation and input, the validation of the thesis could not have been successfully conducted.

I would also like to thank my predecessors at the university. Their work was the basis of my master thesis and triggered my enthusiasm and motivation toward achieving and answering this master thesis topic.

I would like to thank Camille Gobin, for her impeccable work on her master thesis that had a significant influence and is the starting point for my topic.

I would also like to thank Tatiana de Meester for providing the necessary information and data for the selected case study.

Last but not least, I would also like to thank the combined work of Mohamed Hamdy (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017), that provided the new performance metrics that enabled me to achieve my research.

Finally, I must express my very profound gratitude to my parents and my spouse for providing me with unfailing support and continuous encouragement throughout my years of study and the process of researching and writing this thesis. This accomplishment would not have been possible without them.

Abstract:

Since buildings are responsible for approximately 40% of the EU energy consumption, the building sector is considered as the key element of European energy policies. From these policies comes the European Energy Performance of Building Directive (EPBD) that sets a clear direction for the full decarbonization of the European building stock by 2050. Within the Belgian context, the application of the EPBD is translated into Energy Performance Certificates (EPC) that are based on energy simulation softwares.

However, with the current direction of the European building sector that sets goals for achieving high-efficiency buildings, and with the constant climate change, an overheating risk is in question. This overheating risk has never been assessed in the EPC certification tool; therefore, this study aims to evaluate this overheating risk within the EPC tool of the Walloon Region, by using a verified dynamic simulation software “DesignBuilder.”

The objective of the study consists of establishing an energy simulation model of a verified case study within the Walloon Region and assessing its overheating risk compared to the DesignBuilder software, where the obtained results confirm a 216% difference in the overheated hours. As an additional contribution of the study, long-term discomfort indicators are applied to the simulation results to quantify the sensitivity of this overheating risk regarding climate change, where the obtained results confirm a minimum of 44% chance to resist climate change. Finally, the contribution of ventilative cooling is assessed within the simulation model, proving an 82% potential as a mitigation strategy.

The results of the proposed study emphasize the need to improve the current legislative framework of the Walloon Region by adopting the set of long-term thermal discomfort indicators that allow the classification of the building regarding future projections, and the necessity of adapting dynamic calculations instead of static based estimation.

Keywords:

- Thermal comfort
- Residential buildings
- Energy efficiency
- Performance indicators
- Dynamic simulations
- Passive cooling
- EPBD implementation

Titre alternatif:

Évaluation du risque de surchauffe et du potentiel de refroidissement ventilatoire: Une cas d’étude en Belgique

Abstrait:

Étant donné que les bâtiments représentent environ 40 % de la consommation d’énergie de l’UE, le secteur du bâtiment est considéré comme l’élément clé des politiques énergétiques européennes. De ces politiques vient la directive européenne sur la performance énergétique du bâtiment (EPBD) qui fixe une orientation claire pour la décarbonisation complète du parc immobilier européen d’ici 2050. Dans le contexte belge, l’application de l’EPBD est traduite en certificats de performance énergétique (EPC) basés sur des logiciels de simulation d’énergie.

Cependant, avec l’orientation actuelle du secteur européen du bâtiment qui fixe des objectifs pour la réalisation de bâtiments à haut rendement, et avec le changement climatique constant, un risque de surchauffe est en question. Ce risque de surchauffe n’a jamais été évalué dans l’outil de certification EPC; Cette étude vise donc à évaluer ce risque de surchauffe au sein de l’outil EPC de la Région wallonne, en utilisant un logiciel de simulation dynamique vérifié « DesignBuilder ».

L’objectif de l’étude est d’établir un modèle de simulation énergétique d’une étude de cas vérifiée au sein de la Région wallonne et d’évaluer son risque de surchauffe par rapport au logiciel DesignBuilder, où les résultats obtenus confirment une différence de 216% dans les heures surchauffées. En tant que contribution supplémentaire de l’étude, des indicateurs d’inconfort à long terme sont appliqués aux résultats de la simulation afin de quantifier la sensibilité de ce risque de surchauffe en ce qui concerne le changement climatique, où les résultats obtenus confirment un

minimum de 44 % de chances de résister au changement climatique. Enfin, la contribution du refroidissement ventilatif est évaluée dans le modèle de simulation, ce qui prouve un potentiel de 82 % en tant que stratégie d' atténuation.

Les résultats de l' étude proposée soulignent la nécessité d' améliorer le cadre législatif actuel de la Région wallonne en adoptant l' ensemble d' indicateurs d' inconfort thermique à long terme qui permettent la classification du bâtiment en ce qui concerne les projections futures, et la nécessité d' adapter les calculs dynamiques au lieu d' une estimation statique.

Mots clés:

- Confort thermique
- Bâtiments résidentiels
- Efficacité énergétique
- Des indicateurs de performance
- Simulations dynamiques
- Refroidissement passif
- Implémentation EPBD

Table of Contents

Acknowledgments: 2

Abstract: 3

Table of Contents 7

List of Figures 9

List of Tables 11

List of Equations 13

List of Acronyms 14

Chapter 1: Introduction 16

Chapter 2:The literature review 21

Chapter 3: Methodology 38

3.1. Data, tools & long-term discomfort indicators 40

3.2. Simulation process 51

3.3. Validation of the models 61

3.4. Assessment of the indicators 68

3.5. Boundaries of the adopted methodology 70

Chapter 4: Results 71

4.1. Overheating Assessment 71

4.2. Potential of free cooling 83

Chapter 5: Discussion 88

5.1 Key findings and recommendations 88

5.2 Strengths and limitations 92

5.3 Implication on practice and future research 94

Chapter 6: Conclusion 97

Bibliography 100

Annex: 106

4.1. Annex-1: The detailed geometry, envelope compositions, and systems 106

4.2. Annex-2: The activity schedule and minor details required for DesignBuilder 114

4.3. Annex-3: The report exported from the PEB software 127

4.4. Annex-4: Details of both simulation models in different software. 128

4.5. Annex-5: PEB regulations. 135

List of Figures

Figure 1.1-Observed global temperature change and modeled responses. Source: IPCC, 2018 18
Figure 1.2-The organization of the research. 20
Figure 2.1-The timeline of the nZEB implementation. Source: (JRC - European Commission, 2016). 23
Figure 2.2-The priorities taken into account in the EPC software. Source: SPW, 2018. 24
Figure 2.3-The set points of the overheating indicator. Source: SPW,2018. 25
Figure 2.4-The principles of the passive house standard. Source: Passive House Institute, 2016. 28
Figure 2.5-The principle of thermal mass cooling. Source: Holt, 2020. 32
Figure 2.6-Examples of Shading systems. Source: (Kamal, 2012) 33
Figure 2.7-The principle of wind-capturing towers. Source: (Sofia Energy Centre, 2009) 33
Figure 2.8-The principle of the earth air tunnel. Source: (Kamal, 2012) 34
Figure 2.9-The principle of earth berming. Source: (Kamal, 2012) 35
Figure 3.1-The conceptual study framework 39
Figure 3.2-Required criteria representation. Source: Le Guide PEB, 2018 40
Figure 3.3-DesignBuilder Interface. 41
Figure 3.4-Location of the Kettenis House. Source: Wikipedia 42
Figure 3.5-The Kettenis House. Source: De Meester,2008. 43
Figure 3.6-The plans of the Kettenis House. Source: De Meester,2008. 43
Figure 3.7-The typology of the building and its characteristics 51
Figure 3.8-The main compositions of the envelope. 53
Figure 3.9-The zones defined in DesignBuilder 58
Figure 3.10-The boiler. Source: De Meester,2008. 60
Figure 3.11-The ventilation system. Source: De Meester, 2008 61
Figure 3.12-The ASHRAE indicators before calibration 65
Figure 3.13-The The ASHRAE indicators after calibration. 67

Figure 4.1-The obtained EPC1 indicators compared with the nZEB standard. 73
Figure 4.2-The overheating indicator in EPC1. 75
Figure 4.3-The obtained EPC2 indicators compared with EPC1 and the nZEB standard.. 77
Figure 4.4-The overheating indicator in the adapted PEB simulation model. .79
Figure 4.5-The overheating hours in Case B1. 80
Figure 4.6-Comparison between the obtained overheated hours in both models and the nZEB. 80
Figure 4.7-The Ambient warmness degree obtained in DesignBuilder. 81
Figure 4.8-The indoor overheating Degree obtained in DB1. 82
Figure 4.9-Comparison between the overheated hours in DB1 and DB2 83
Figure 4.10-Comparison between the IOD obtained in DB1 and DB2. 84
Figure 4.11-The Overheating escalation factor of Case B2. 85
Figure 4.12-Comparison of the overheating hours between the different models. 85
Figure 4.13-Comparison of the obtained overheating indicators in EPC1 and EPC2. 87

List of Tables

Table 2.1-Characteristic days used in the EPC software. Source: Walloon Government, 2018....27
Table 2.2-Passive house criteria. Source: (Service public fédéral Chancellerie du Premier Ministre, 2009)....29
Table 2.3-The nZEB indicators defined by the Walloon Region. Source: SPW, 2020. 31
Table 2.4-Relevant literature review matrix....37
Table 3.1-Categories of buildings based on NBN EN 15251:2007. Source: Energie Plus, 2014....45
Table 3.2-Recommended long-term indoor overheating temperature. Source: Energie Plus, 2014....46
Table 3.3-Mechanical ventilation norms. Source: Energie Plus, 2014....47
Table 3.4-Summary of the envelope compositions modeled in both software 54
Table 3.5-The composition of the exterior wall....55
Table 3.6-The composition of the interior wall....55
Table 3.7-The composition of the ground floor....56
Table 3.8-The composition of the first floor....56
Table 3.9-The composition of the roof....57
Table 3.10-The ventilation rate of the zones in EPC....59
Table 3.11-The The verification concerning the EPC model....63
Table 3.12-The measured data used for calibrating the DesignBuilder model. Source: Attia and Gobin, 2020. 64
Table 3.13- The ASHRAE indicators before calibration....66
Table 3.14-The indicators after calibration....67
Table 4.1-The ventilation rate of the zones in EPC1....72
Table 4.2-Detailed monthly distribution of the characteristic primary energy consumption in EPC1....74
Table 4.3-The ventilation rate of the zones in EPC2....76
Table 4.4-The improvement in the ventilation within the EPC software....76

Table 4.5-Detailed monthly distribution of the primary energy consumption in EPC2. 78

List of Equations

Equation 2.1-The main equation to calculate the overheating indicator. Source: Walloon Government, 2018. 26
Equation 3.1-The operative temperature defined by EnergiePlus 45
Equation 3.2-The set of indicators used to evaluate the overheating sensitivity. Source: (Hamdy et al., 2017). 48
Equation 3.3-The set of indicators used to evaluate the potential of ventilation. Source: Hamdy&al, 2017. 50
Equation 3.4-The indices used for the calibration. Source: ASHRAE, 2014…62

List of Acronyms

ASHRAE	: American Society of Heating, Refrigerating, and Air-Conditioning Engineers
AWD	: Ambient Warmness Degree
CFD	: Computational Fluid Dynamics
CIBSE	: Chartered Institution of Building Services Engineers
DHW	: Domestic Hot Water
DOE	: Department of Energy
EED	: Energy Efficiency Directive
EPBD	: Energy Performance of Buildings Directive
EPC	: Energy Performance Certificate
EU	: European Union
GDP	: Gross Domestic Product
IEQ	: Indoor Environmental Quality
IOD	: Indoor Overheating Degree
IPCC	: Intergovernmental Panel on Climate Change
ISO	: International Standard Organization
nZEB	: Nearly Zero Energy Building
OEF	: Overheating Escalation factor
PE	: Primary Energy
PEB	: Performance Énergétique du Bâtiment
PER	: Performance Energétique des bâtiments Résidentiels.
PMV	: Predicted Mean Vote

POE : Post Occupancy Evaluation

PPD : Predicted Percentage of Dissatisfied

SPW : Service Public de Wallonie

EPB : Energy Performance of Buildings

Chapter 1: Introduction

The facts and statistics provided by the European Commission illustrate that buildings are responsible for approximately 40% of the EU energy consumption and 36% of its CO2 emissions, making the building sector one of the largest energy consumers in Europe as defined by (European Commission, 2019).

As a consequence, the building sector is considered to be crucial in achieving the EU's energy and environmental goals. Therefore, the EU has established a legislative framework (Energy Performance of Buildings Directive) that includes the EPBD 2010/31/EU and the EED 2012/27/EU.

These two directives promote specific policies that will allow the EU to modernize its building sector and achieve energy-efficient and decarbonized building stock by 2050 that will have a direct positive impact on Europe's GDP.

Within the context of the EPBD, specific instruments play a central role that will allow the implementation of the directive, from these instruments we can distinguish the EPCs that contribute to the enhancement of the energy performance of buildings (European Commission, 2014).

Each Member State is responsible for defining its set of reference values, and calculation methods regarding the EPCs and is also accountable for setting clearly defined milestones illustrating the implementation and transposition rates of each Member State towards the 2050 European goal.

However, for the Belgian context, the implementation of the EPBD is the responsibility of the regional governments (The Walloon, Flemish, and the Brussels-Capital regions), and it is their responsibility to ensure that EPCs are carried out independently by qualified and accredited experts (European Commission, 2014).

Regarding the Walloon region, the adopted EPCs are called *"Certificat PEB,"* these certificates evaluate the envelope performance of the building (thermal insulation) and the associated systems (heating, hot domestic water, ventilation, etc), translating this evaluation into a systematic classification system for the buildings based on different indicators.

These indicators include the energy class, the total and specific primary energy consumption ventilation rate, and indoor overheating (SPW Energie, 2015).

However, with the increase of the insulation level and airtightness in the buildings, followed by the application of EPCs, other problems start to arise.

From these problems, we can distinguish the overheating risk, which will become significant soon, especially with the current rate of climate change and the different climate projections concerning the global average surface temperature in general and the Belgian average surface temperature in particular.

Different studies highlight the rise of the yearly average temperature and its differences in the last two centuries. From these studies, we can cite (Hecq, Kris, Pirotton, Meire, & De Sutter, 2006), that illustrate a rise in the average surface temperature in Belgium, from 8,8 °C in 1909 to 10,4 °C in 1984.

In addition to the numerous studies demonstrating the rise in the average surface temperature, the IPCC projects climate scenarios based on the degree and speed of the human intervention (IPCC, 2018), these scenarios are illustrated in Figure-1.1, showing the different rise in global temperature depending on the situation.

According to these projections, it is inevitable to witness a rise in climate temperature. However, the severity of the outdoor temperature will be a direct consequence of human behavior and intervention.

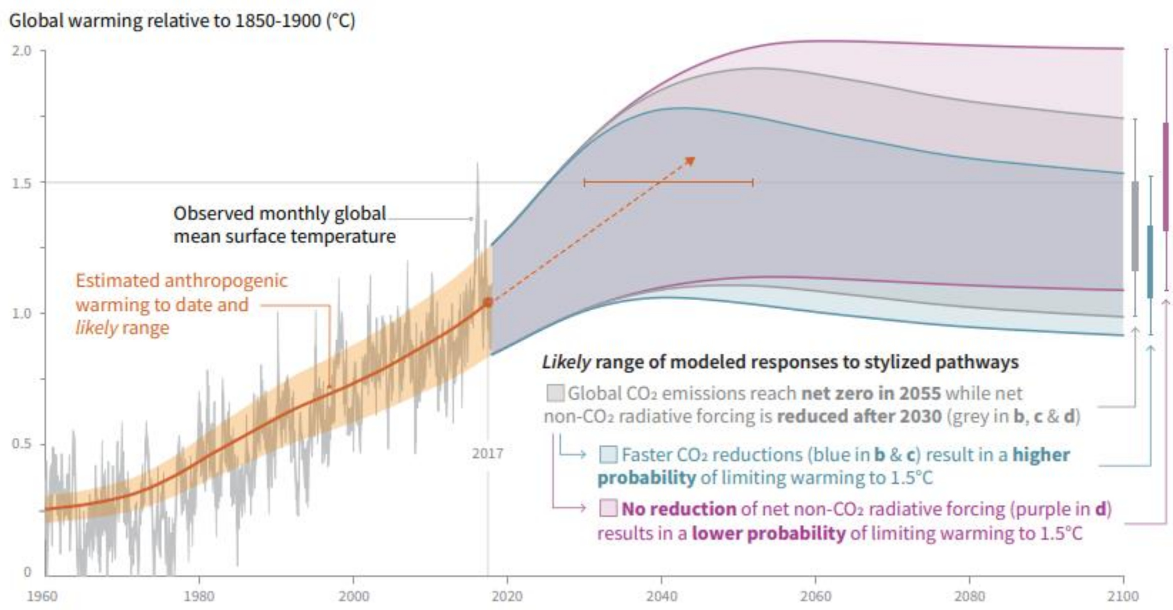


Figure 1.1-Observed global temperature change and modeled responses. Source: IPCC, 2018

Therefore, based on these facts, numerous studies were conducted on these high-efficiency buildings to verify their integrity against climate change.

From these studies, we can cite the work of (De Meester, 2008), where a verified case study of a high-efficiency building is modeled as an energy simulation model to overview the global performance of this building and the effect of the occupants on this performance.

Another study conducted is the work of (Gobin, 2016), where the previous high-efficiency case study is modeled as an energy simulation to overview the impact of climate change on overheating risk.

Finally, the study of (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017) proposes some long-term thermal discomfort indicators to evaluate the sensitivity of Dutch dwellings regarding climate change.

However, the assessment of the EPC tool adopted by the Walloon Region, which contributes to the classification of buildings, is never conducted, and the sensitivity of these high-efficiency buildings to climate change isn't represented in a quantitative value.

Another missing aspect within the Belgian context is the quantification of the contribution of passive solutions on these high energy efficiency buildings.

The proposed research is conducted to answer these questions by taking the same case study of the previous research and modeling it using both EPC DesignBuilder tools. These simulation models allow the comparison of the degree of accuracy of the EPC tool regarding overheating evaluation.

Also, the long-term indicators proposed by (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017) are applied to represent the sensitivity of the case study to climate change in a quantitative manner.

As a final contribution of the research, the impact of the chosen passive solution (ventilative cooling) is quantified.

Therefore, the research outcome is to establish guidelines and strategies that can be adopted by the policymakers that answer these two main questions:

- What is the degree of accuracy of the EPC regarding the overheating risk evaluation?
- How sensitive are current high energy efficiency buildings to climate change?
- How much is the potential of passive solutions to mitigate the overheating risk?

The research is organized into six chapters illustrated in Figure-1.2. To begin with, the introduction chapter that states the context of the problem and the motivation behind the study.

The following chapter is the literature review, where the different standards and overheating calculation methods will be defined (such as the passive house standard, the nZEB, and the calculation method of the EPC), in addition to the related studies conducted around the topic.

The third chapter consists of the applied methodology to achieve the research proposal, with the different simulation processes, the assessment methodology, and the equations used.

The obtained results from the applied methodology are present in chapter four.

The obtained results are discussed in chapter five, providing insight on the importance of the research and its impact on existing studies and theories.

Finally, within chapter six, a general conclusion is presented summarizing the research objectives and findings, and different recommendations are stated.

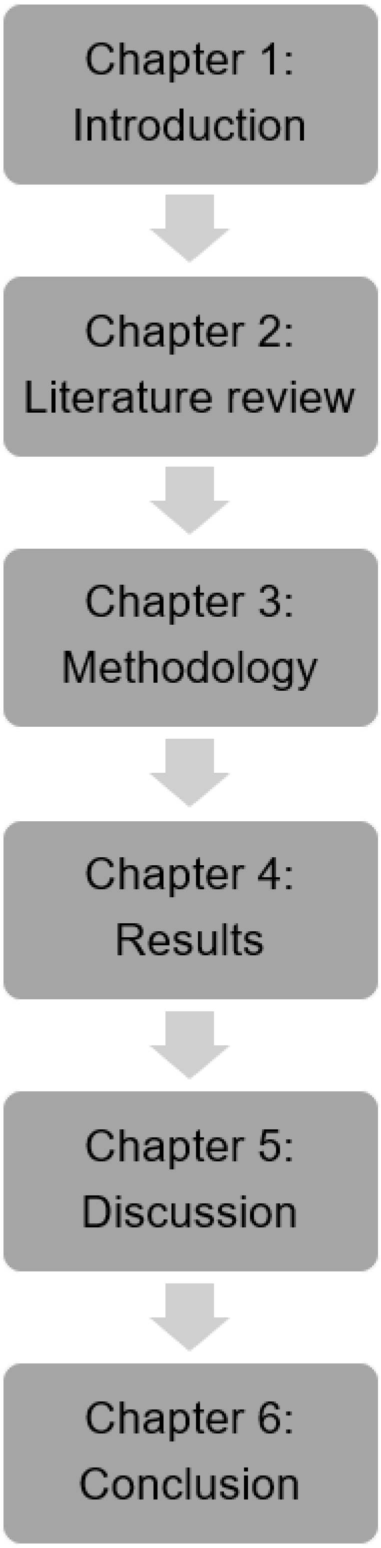


Figure 1.2-The organization of the research.

Chapter 2:The literature review

Within this chapter, an overview of the current knowledge and scholarly sources is defined and analyzed. This overview enables the identification of relevant theories, methods, and gaps in the existing knowledge that articulate around the desired topic concerning the overheating sensitivity within the Belgian context and the efficiency of passive solutions.

- **The EPBD Directive**

As mentioned in the introduction chapter, the Energy Performance of Building Directive (EPBD) came as a consequence of the EU's energy and environmental goals.

This EPBD aims to promote the improvement of the energy performance of buildings within the European Union, taking into account outdoor climate and local conditions as well as indoor climate requirements and cost-effectiveness (EPB Center, 2020).

The first version of the EPBD was published in 2002 (Directive 2002/91/EC), and the following four key points can summarize it (EUR-Lex, 2018):

- The definition of a standard methodology to calculate the integrated energy performance of buildings.
- The definition of the minimum standards on the energy performance of new buildings and existing buildings that are subject to a significant renovation.
- The definition of the systems used for the energy certification of new and existing buildings. And the prominent display of this certification.
- The regular inspection of boilers and central air-conditioning systems in buildings.

A recast of the EPBD was made in 2010 (Directive 2010/31/EU) with an interest of clarification, it is summarized by the following five key points (EUR-Lex, 2018):

- The EU countries must set optimal minimum energy performance requirements, that is revised every five years.
- A comparative methodology framework was established by the European Commission to calculate the cost levels for energy performance requirements.
- New buildings and existing buildings undergoing a significant renovation, must meet minimum standards, and public buildings should achieve the nZEB standard by December 31, 2018. Other new buildings must meet the nZEB standard by December 31, 2020.
- **EU countries must operate an energy performance certification system**.
- EU countries' national authorities must ensure schemes to inspect heating and air-conditioning systems.

A recently revised version of the EPBD was published in 2018 (Directive 2018/844/EU), requiring the EU countries to set long-term renovation strategies of both residential and non-residential buildings.

These strategies set roadmaps with measurable progress indicators, which include indicative milestones set at 2030, 2040, and 2050 (EUR-Lex, 2018).

Therefore, based on these regulations and as illustrated in Figure 2.1, the direction of the construction section is headed towards more and more high energy-efficient buildings, with the nZEB standard as the end goal. Making these buildings more and more susceptible to the overheating risk.

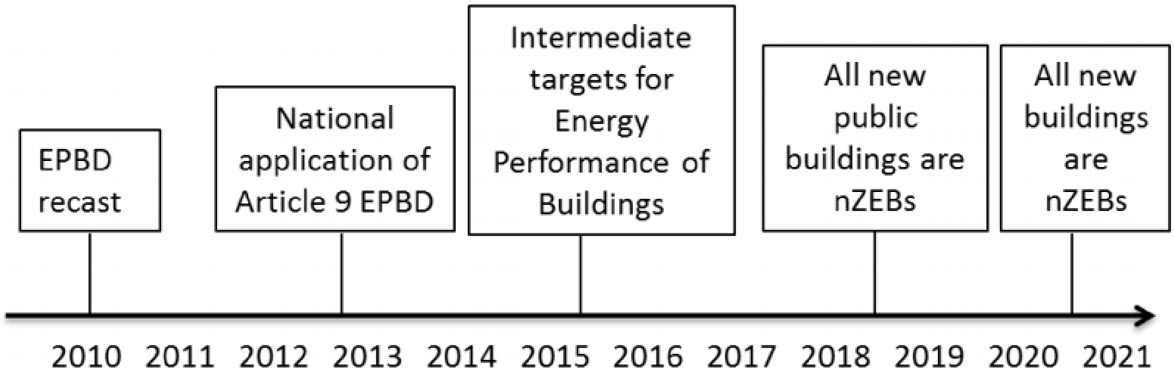


Figure 2.1-The timeline of the nZEB implementation. Source: (JRC - European Commission, 2016).

- **The EPC**

According to the EPBD Directive (Directive 2010/31/EU), Member states of the European Union must implement mandatory certification, Energy Performance Certification (EPC), of the new and existing building, along with periodic certification of the public buildings.

However, within the member state of Belgium, the implementation of the EPBD is the responsibility of the regional government. And within the Walloon Region of Belgium, these EPCs are defined as "*Certificat PEB."*

The EPCs' administrative procedure is divided into three stages, defined as (SPW - Wallonie Energie, 2017):

- The initial Energy Performance of the building (EPB) statement, which is submitted with the permit application.
- The Final EPB statement that is applied after the completion of the construction and demonstrating compliance with the energy performance requirements.
- Based on the information provided by the final EPB, an EPC is by an expert.

The EPB statement is calculated using a regional software called *"Le logiciel PEB"*.

The calculation used within this EPC software is based on three priorities as illustrated in Figure2.2, that define the energetic performance of the building (SPW - Wallonie énergie, 2018), which are:

- The quality of the envelope, which is represented by low thermal transmittance values (U-Values), the continuity of the tightness.
- The systems' quality that consists of (heating, DHW and lightning, ventilation, and air conditioning).
- The quality of the used renewable energy sources.

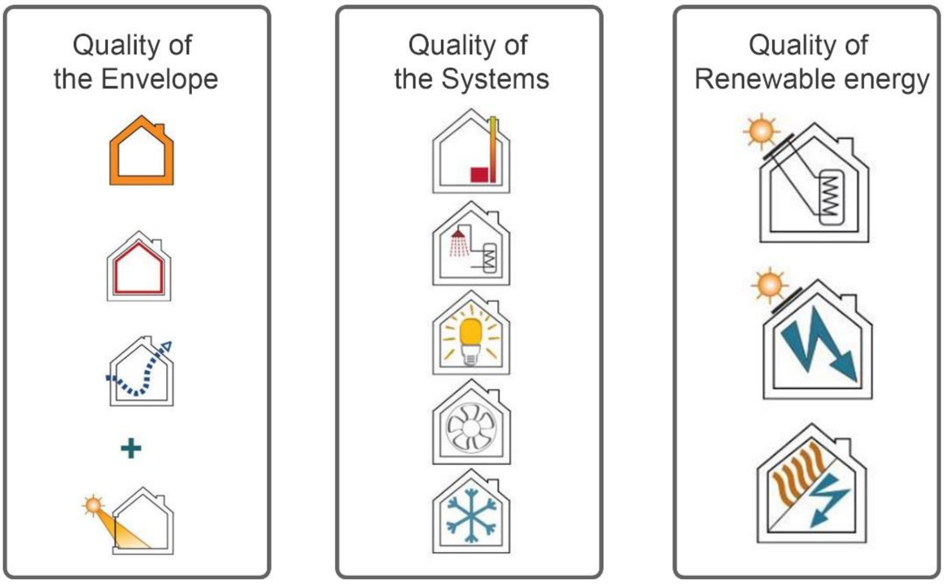


Figure 2.2-The priorities taken into account in the EPC software. Source: SPW, 2018.

These priorities are translated in the EPC software as six indicators, each having specific values that need to be respected and complied, these values are available in Annex-5. The six indicators defined by (SPW - Wallonie énergie, 2018) are:

- The thermal transmittance values of the envelope (U-values), which must conform with current regulations; these values are available in Annex-5.
- The isolation level (K), determined by the coefficient of thermal transmission of the envelope, the surface of the different elements and the compacity of the building.

- The primary energy consumption level (E_W), is calculated based on the ratio of the annual primary energy consumption of a unit, and a reference value. The details of its calculation are available in Annex-5.
- The specific primary energy consumption (E_{spec}), calculated based on the ratio between the annual primary energy consumption and the heated/cooled floor area.
- The ventilation regulations (V), based on the Annex C2 – VHR that refer to the norm NBN D 50-001.
- The overheating indicator (S).

The overheating indicator (S), is a function of the following parameters (SPW - Wallonie énergie, 2018):

- The thermal inertia of the construction
- The ratio between the heat gains (solar, intern), and the heat loss (transmission and ventilation).

The overheating indicator is expressed in [K.h] and has two set points as illustrated in Figure-2.3. The two set points are set at 6 500 K.h representing the upper limit value of the overheating indicator and at 1 000 K.h expressing the lower limit of the overheating indicator.

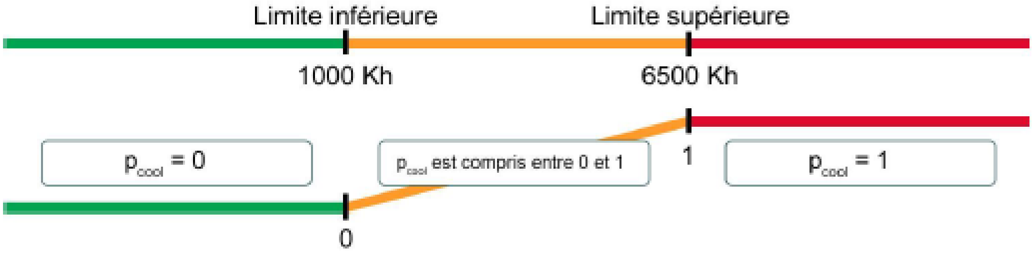


Figure 2.3-The set points of the overheating indicator. Source: SPW,2018.

Whenever the value of the overheating indicator surpasses 6 500 K.h in the simulation model, an evident risk of overheating is present, and a revision of the conception must take place.

However, when the overheating indicator is below 1 000 K.h, no risk of overheating is present.

If the value of the overheating indicator is higher than 1 000 K.h, a fictive active cooling system is introduced in the total energy consumption and reduces the classification of the simulation model.

Overheating is defined within the EPC software when the indoor operative temperature surpasses 23°C. The calculation of the overheating indicator is summarized by the following equation (Walloon Government, 2018):

$$I_{overh,sec\,i} = Q_{excess\,norm,\sec i,a} = \sum_{m=1}^{12} Q_{excess\,norm,\sec i,m} \qquad [K.h] \qquad (1)$$

Where;

$I_{overh,seci}$: is the overheating indicator for the energetic sector i.

$Q_{excess\ norm,\ sec\ I}$: is the excess heat gain compared to setpoint temperature of 23°C.

This general equation is mainly defined as the monthly sum of the excess heat gain regarding the setpoint temperature of 23°C. The detailed equations used to calculate this overheating indicator are available in Annex-5.

From these equations, and more specifically Eq.69 & 70, the variable ($\theta_{e,m}$) represents the average monthly exterior temperature, which is based on characteristic days of the year in Belgium and is described in Table 2.1 (Walloon Government, 2018).

The EPC software relies on these values to calculate its overheating indicator making it a static-based simulation tool, and therefore motivating the proposed research that aims to evaluate its degree of accuracy regarding indoor overheating.

Table 2.1-Characteristic days used in the EPC software. Source: Walloon Government, 2018.

Month	Characteristic Day	Length of the month t_m (Ms)	**Average exterior temperature $\theta_{e,m}$ (°C)**
January	15	2,6784	**3,2**
February	46	2,4192	**3,9**
March	74	2,6784	**5,9**
April	105	2,5920	**9,2**
May	135	2,6784	**13,3**
June	166	2,5920	**16,2**
Jully	196	2,6784	**17,6**
August	227	2,6784	**17,6**
September	258	2,5920	**15,2**
October	288	2,6784	**11,2**
November	319	2,5920	**6,3**
December	349	2,6784	**3,5**

- **Passive house & nZEB standard**

The passive house standard is a construction concept, aiming to improve the efficiency of a building and reduce its ecological imprint on the environment while providing a high level of comfort (Passive House Institute, 2016).

This concept is achieved by applying the following principles, which are illustrated in Figure 2.3:

- Having heating and cooling consumption that don't exceed 1.5 liters of fuel per m² of living space.
- The internal energy sources of the building, such as the body heat from residents and solar radiation, are used as energy sources.
- Containing appropriate windows and having well-insulated envelope compositions.
- A consistent ventilation system that supplies fresh air, and coupled with a heat recovery unit.

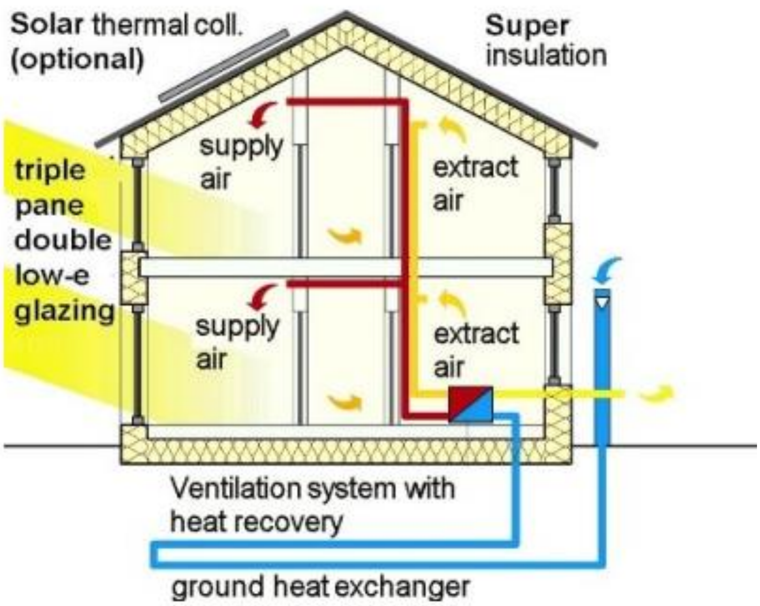


Figure 2.4-The principles of the passive house standard. Source: Passive House Institute, 2016.

This passive house standard is translated within the Belgian context by the implication of the values indicated in Table 2.2. These values are defined by Article 121 of the Royal Decree of 30 December 2009.

Table 2.2-Passive house criteria. Source: *(Service public fédéral Chancellerie du Premier Ministre, 2009)*

	Passive House Standard
Heating demand	< 15 [kWh/(m²y)]
Pressurization test results n_{50}	0,6 [vol/h]
Total Primary Energy consumption	< 45 [kWh/(m²y)]
Hours surpassing 25°C	≤ 5% of the year
U_{max} values	Corresponding to the current norms (Annex-5)

Another standard present in the research is the Nearly Zero Energy Building (nZEB) standard. This standard is the end-goal for the EPBD Implementation in the Member States of the European Union.

Each Member State sets precise definitions and implementations, and within the Belgian State, the definitions are set on a regional level (European Union, 2012). Therefore, introducing three sets of definitions in the three regions (Wallon Region, Brussels-Capital Region, and the Flemish Region).

In the Brussels-Capital Region, Individual housing units are considered as nZEBs if they meet the following requirements (European Union, 2012):

- Primary energy consumption for heating, domestic hot water, and electrical appliances must be below 45 kWh per m² per year.
- Net heating needs below 15 kWh/m² per year.
- An overheating temperature can exceed 25°C for only 5% of the year.
- An airtightness, at 50 Pa, below 0,6 volume per hour.

The calculation method of the primary energy includes the input of renewable energy sources like solar energy (thermal and photovoltaic), biomass heating, geothermal heating, heat pump systems as well as passive cooling techniques.

In the Flemish Region, the nZEB definition was established in 2013 and consists of the following measures (Biebaut & De Saedeleer, 2107):

- An energy performance level E-level ≤ 30 (for residential buildings)
- An insulation level K-level ≤ 40, and the U-values in Annex-5.
- Identical ventilation and overheating requirements, as the Brussels-Capital Region.
- A minimum level of renewable energy by:
    - The use of a solar boiler, with a minimum collector surface area of 0,02 m² per usable floor area.
    - A photovoltaic installation, that produces ≥ 10 kWh per m² of usable floor area.
    - The use of a heat pump as the primary heating system with a seasonal performance factor ≥ 4.
    - A biomass installation with an efficiency ≥ 85%.
    - A city grid connection for city heating and cooling, that is 40% from renewable energy sources.

Finally, for the Walloon Region, the nZEB standard is translated as specific indicator values in the EPC software. These values are defined in Table-2.3 and are extracted from (SPW, 2020).

Table 2.3-The nZEB indicators defined by the Walloon Region. Source: SPW, 2020.

Indicators	nZEB Standard
U-values	Conform with the regulations in Annex-5
K	≤ 35
E_w	≤ 45
E_{Spec}	≤ 85 kWh/m².year
Ventilation	Conform with the norm NBN D 50-001
Overheating	< 6500 Kh

- **Passive cooling**

Passive cooling is adopted as a means to achieve acceptable summer conditions sustainably by using no or limited use of conventional energy and through the use of environmentally non-harmful materials.

The passive cooling uses techniques that reflect and minimize solar radiation penetration in dwellings, or facilitate heat transfer from the interior to the exterior with minimum mechanical energy (Sofia Energy Centre, 2009).

Passive cooling covers a large variety of methods and strategies in which the following methods are mentioned (Sofia Energy Centre, 2009):

- Form and orientation
- The building envelope, glazing
- Shading
- Wind capture
- Ventilation
- Natural techniques

The form and orientation of the building can protect the building from excessive heating, wherein Belgium, the living areas are usually oriented towards the south to maximize winter heat gains and the auxiliary rooms within the north. And as illustrated by (Sofia Energy Centre, 2009), at a constant volume, a form with the maximum surrounding surface has maximum cooling.

The cooling process increases with the application of architectural and construction solutions, which is manifested by the building envelope, where (Sofia Energy Centre, 2009) describes it as the barrier that controls the level of heat transfer. From these construction solutions, thermal mass is considered, which is illustrated in Figure2.5.

The denser the material, the more it's capacity to store heat, which is signified by (Holt, 2020), where the use of dense concrete leads to up to 25% of reduction to the heating and cooling load.

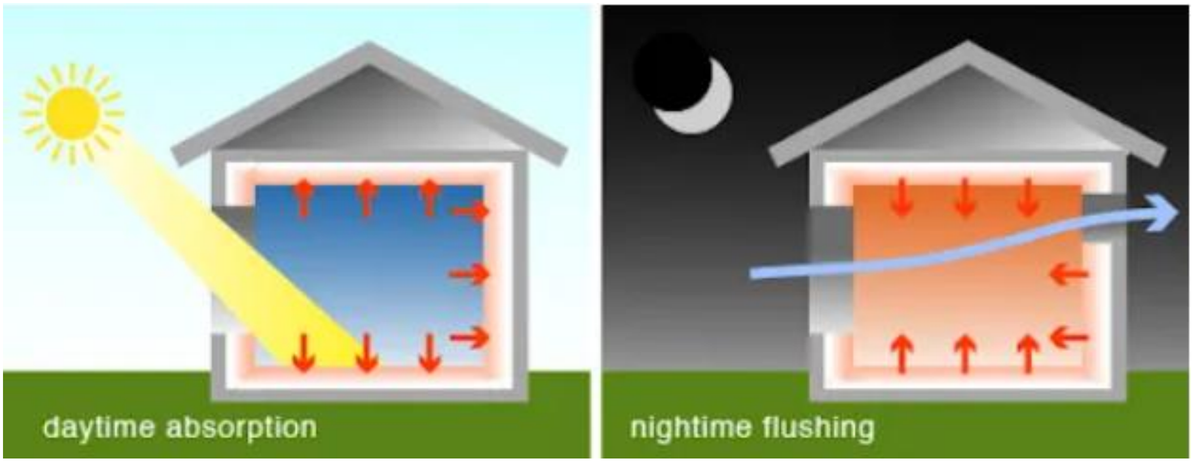


Figure 2.5-The principle of thermal mass cooling. Source: Holt, 2020.

Another traditional passive cooling measure is the use of shading systems, as illustrated in Figure-2.6. These shading systems reflect solar radiation and are divided into internal and external shading devices. The study conducted by (Kamal, 2012), illustrate that the use of solar shading has a decrease of 4.4°C to 6.8°C on the indoor temperature

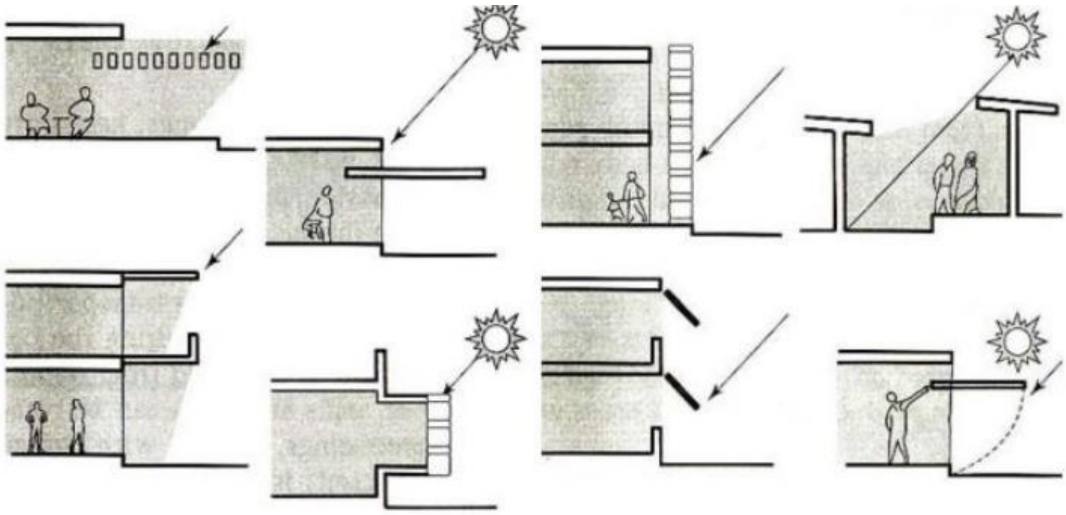


Figure 2.6-Examples of Shading systems. Source: (Kamal, 2012)

Another passive solution defined by (Sofia Energy Centre, 2009), is the use of wind capturing, as illustrated in Figure-2.7. The principle is to capture the wind from multiple directions with cool air entering the building and warmer air exiting either by the effect of the air density difference or by air movement.

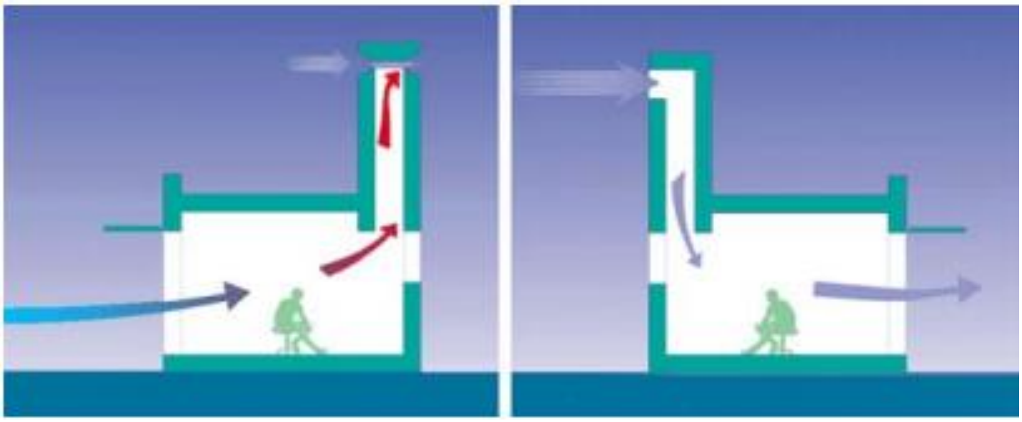


Figure 2.7-The principle of wind-capturing towers. Source: (Sofia Energy Centre, 2009)

Induced ventilation is another passive solution to reduce the cooling load; this ventilation has two main goals, that first to control the air quality and the second to keep thermal comfort during different seasons.

Two types of passive ventilation are defined by (Sofia Energy Centre, 2009). The first being the natural ventilation that functions based on three natural phenomena (wind pressure, chimney effect, and thermo-siphon effect).

The second type of ventilation is the “hybrid-ventilation”; this system is based on a two-component system controlling minimum energy consumption at maintaining acceptable air quality and thermal conform. These are two autonomous systems that function independently to solve specific problems, where natural ventilation covers the need for intermediate seasons (spring and autumn), forced ventilation systems to include mid-summer and mid-winter. Or mechanical ventilation systems are used during the day working hours, and natural ventilation provides cooling in the night.

Finally, a set of natural techniques is used as passive cooling, and these techniques are based on the basic physic laws leading to depriving the heat of bodies. The study conducted by (Kamal, 2012), group these natural techniques as earth coupling (earth air tunnel, earth berming).

In Figure-2.8, earth air tunnel is illustrated, where the use of earth as a heat sink or a source for cooling/ heating air in buried pipes or underground tunnels causes the exchange of heat between air and the surrounding soil.

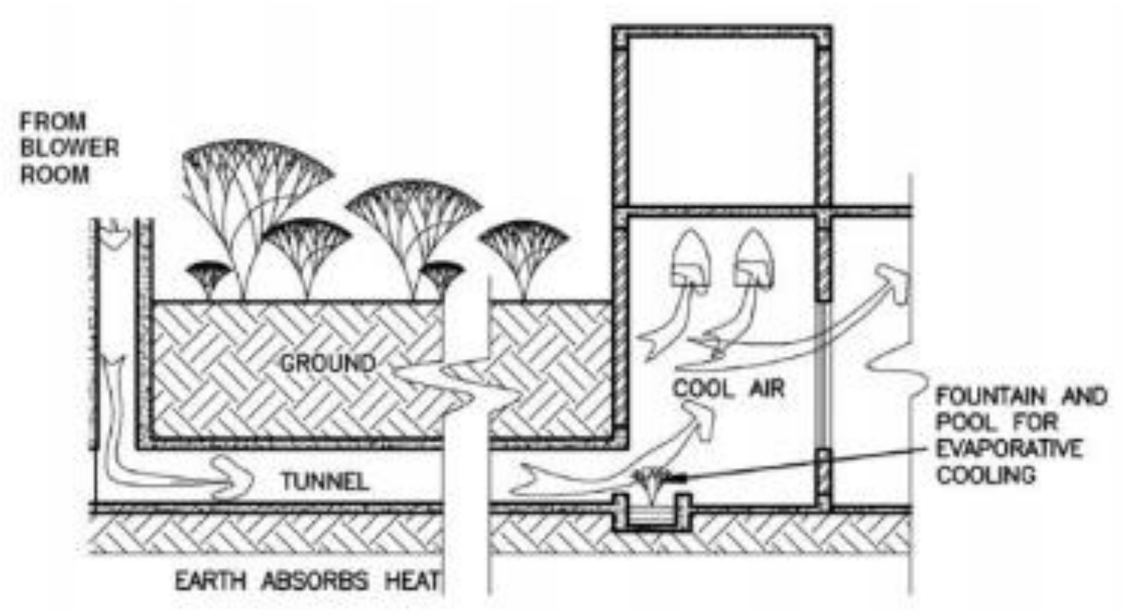


Figure 2.8-The principle of the earth air tunnel. Source: (Kamal, 2012)

In Figure-2.9, the concept of earth berming is illustrated, where the reduction of infiltration of the outside air and the additional thermal resistance of the surrounding soil considerably reduces the average thermal load.

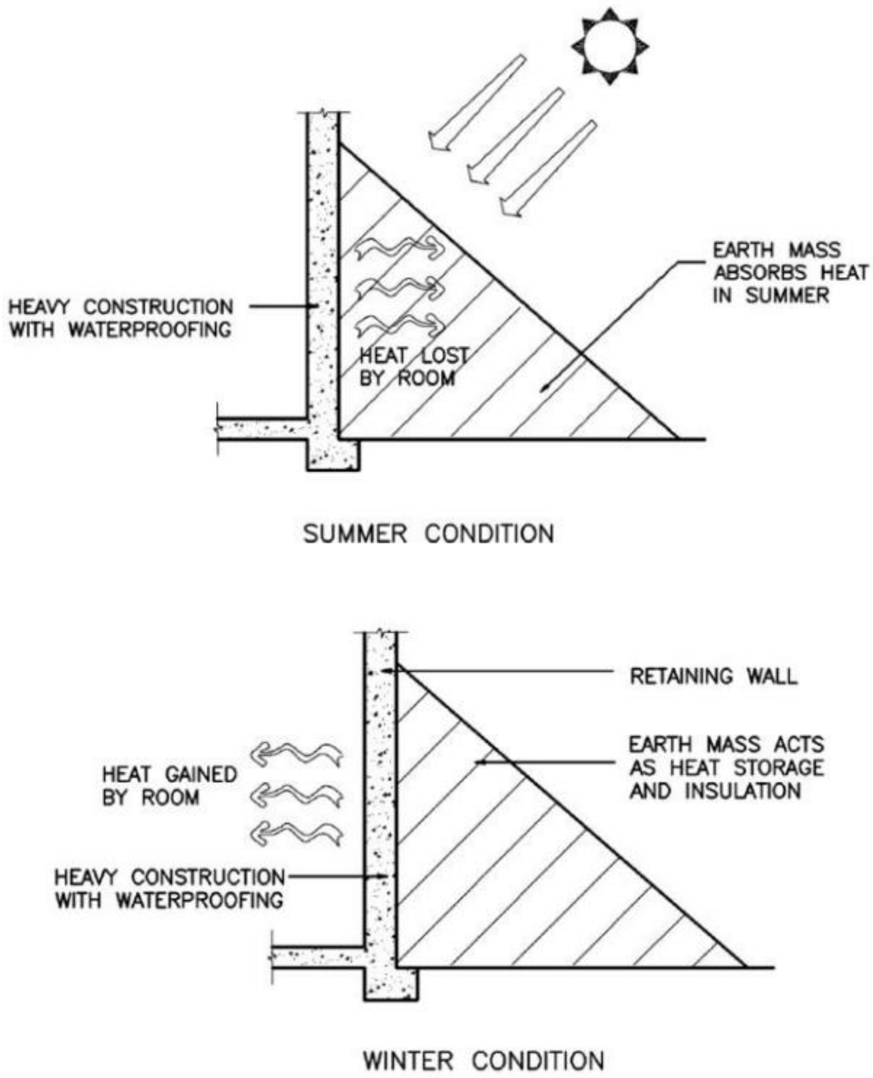


Figure 2.9-The principle of earth berming. Source: (Kamal, 2012)

Many other passive cooling methods exist; however, these methods are explained due to their widespread use within the construction sector and that they offer a decrease in the cooling load that can lead up to 50-70%, as described by (Kamal, 2012).

- **Review of related research**

Many studies circulate the topic of the relationship between the overheating risk caused by climate change and its effect on indoor environmental quality. From these numerous studies, the most recent are cited. These studies are related to the proposed research and consist the base-point in which the study is built upon.

Starting with the study conducted by (De Meester, 2008), were a simulation of the same verified case study of a high-efficiency house is undertaken. This simulation is used to confirm whether the same comfort level is attained in both summer and winter periods, and to develop a reflection on the different factors influencing this comfort level (such as the occupant behavior, and the various systems).

Following is the research conducted by (Haak, 2012), which aims to investigate the potential of different passive climate adaptation measures by simulating chosen dwellings in the Netherlands in a future climate, and applying these measures on them.

In 2016, A study conducted by Camille Gobin aimed to evaluate the impact of climate change on the indoor thermal condition, by using the same chosen study case of De Meester (2008). The objective of the study was to evaluate the indoor thermal conditions using four different climate scenarios applied to a DesignBuilder simulation model.

New metrics arre introduced in the work of (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017). These metrics are long-thermal discomfort indicators that allow the quantification of the overheating risk and ranking the various building types in terms of their overheating risk and sensitivity to climate change.

Finally, the most recent study was conducted by (Vanderavero, 2019). Within his research, a comparison of the results between the EPC tool and the thermodynamic simulation model TRNSYS is made using a theoretical building.

These researches are summarized within the review matrix in Table-2.4, illustrating their strength and limitations.

Table 2.4-Relevant literature review matrix.

Study	Country	Strong points	limitations
« Etude du comoprtement thermique et énergetique d'une maison passive par modelisation dynamique » (De Meester, 2008)	Belgium	Thermodynamic simulation model. A verified case study.	A global approach, no specifications concerning overheating.
« Climate change and heat stress in residential buildings: evaluation of adaptation measures. » (Haak, 2012)	Netherlands	Passive solutions evaluation.	Focuses on Netherlands climate. No specification concerning the BEP tool.
« Batiment d'aujourd'hui,, Climat de demain : Evaluation de l'impact du réchauffement climatique sur le confort thermique et l'efficacité énergétique d'un bâtiment passif existant en Belgique » (Gobin, 2016)	Belgium	Impact of climate change on a Belgium case study. Using dynamic simulation DesignBuilder.	Focuses on Belgium weather. No quantification of the risk. No passive solution evaluated.
« The impact of climate change on the overheating risk in dwellings – A Dutch case study » (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017)	Netherlands	New long-term discomfort indicators. Large sample size.	Focuses on Netherlands climate. No EPBD evaluation.
« Comparaison des résultats du logiciel PEB avec une simulation thermodunamique pour un bâtiment résidentiel » (Vanderavero, 2019)	Belgium	Comparing the EPC tool with a thermodynamic simulation tool.	Global approach with no specifications. No passive solutions evaluation.

Based on this existing theory, future research is still needed to evaluate the degree of accuracy of the overheating risk of the EPC tool and to quantify the sensitivity of this overheating, and taking into account the potential of passive cooling. Hence, the proposed research answers these uncertainties.

Chapter 3: Methodology

This study bases on a quantitative research methodology that evaluates the overheating risk and its sensitivity within a chosen case study in Belgium.

This evaluation takes place by establishing a simulation model of a verified case study in the legislative software of the Walloon Region "EPC" and a state-of-the-art energy performance software "DesignBuilder".

The results obtained from the DesignBuilder simulation model, coupled with long-term indicators, enables the evaluation of the overheating sensitivity. As an additional contribution of the research, the potential of free cooling is evaluated as a mitigation strategy to the overheating risk.

Within this chapter, the entire process and framework of the research are discussed for it to be reproduced in similar contexts, and the adopted methodology within this research is represented in the following study conceptual framework, Figure-3.1.

The results of both simulation models are compared to assess the overheating differences between them and the overheating sensitivity within the simulation results.

This overheating sensitivity is evaluated by applying the long-term indicators on the DesignBuilder simulation results.

As a final contribution proposed in this research, the potential of ventilative cooling as a mitigation strategy is assessed.

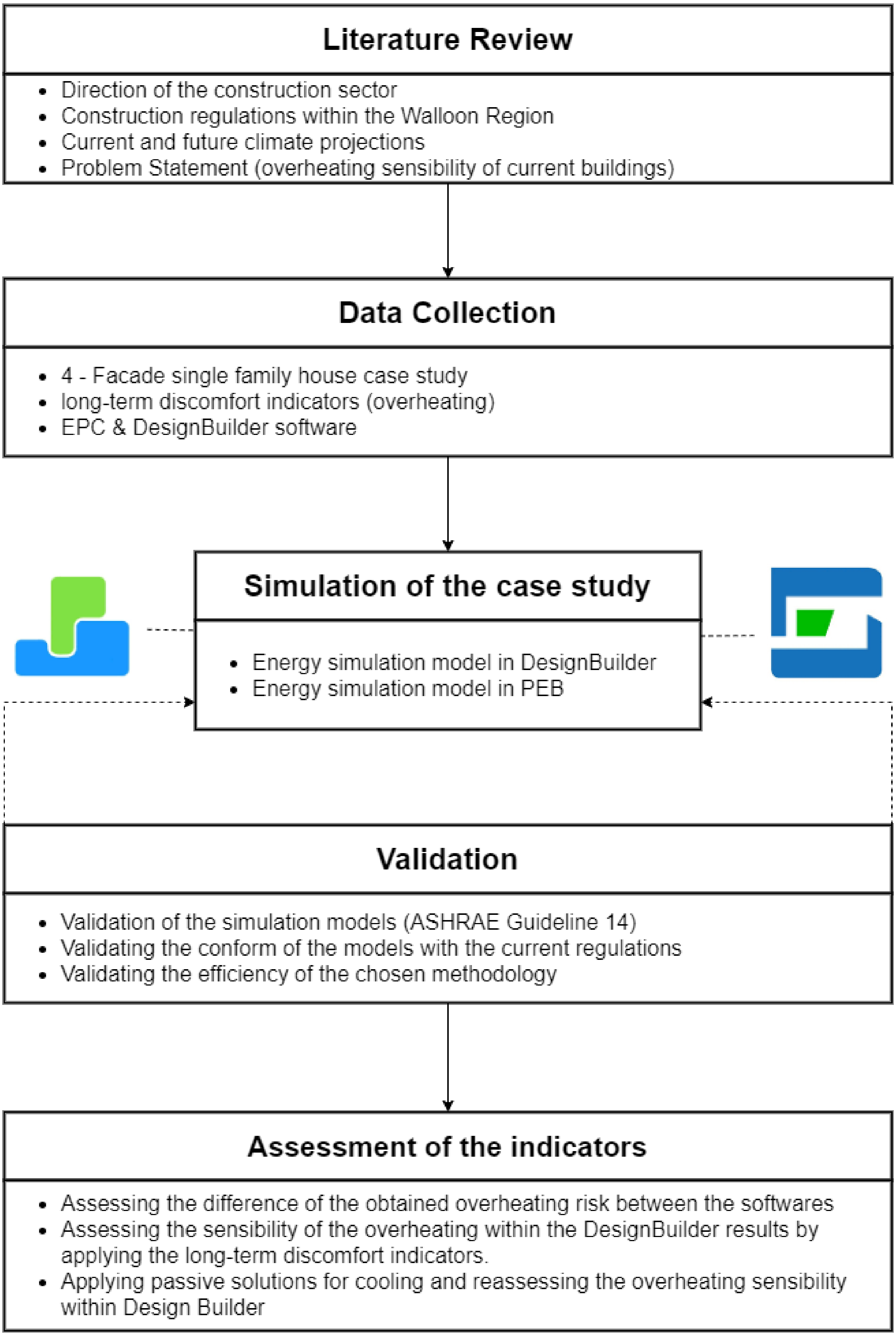


Figure 3.1-The conceptual study framework

3.1. Data, tools & long-term discomfort indicators

- **EPC tool**

As mentioned previously, the research focuses on two leading software, the first being the EPC that was developed by the Walloon region and is applied within its legislative framework.

The software is equipped with an easy-to-use interface divided into subdivisions based on the energetic category, this interface undergoes continuous evolution during the years and takes into account new modifications within the legislative context and the development of the construction market.

The energetic division and subdivisions, which is available in Annex-4, subdivide the building into its single units (in the case of multiple units in one building) obtaining the following divisions:

- The protected volume
- The isolation level K
- The ventilation zones
- The energetic sectors (heating, cooling, domestic hot water)
- The non-protected volume

Where each unit is programmed based on corresponding energetic systems.

The required criteria show during the data input and update each time data is added to the software. The final result is represented as values that meet the requirements, as shown in Figure 3.2.

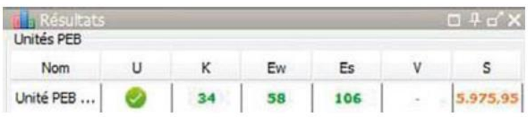
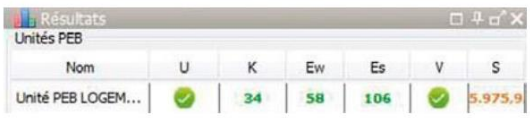
<table>
<tr><th>Stade déclaration initiale</th><th>Stade déclaration finale</th></tr>
<tr><td>Un tiret est présent au niveau du résultat lié à l'exigence de ventilation hygiénique:

</td><td>Le tiret est remplacé par un indicateur au niveau du résultat lié à l'exigence de ventilation:

</td></tr>
</table>

Figure 3.2-Required criteria representation. Source: Le Guide PEB, 2018

The representation can be more elaborate and contain a summary of specific data that is exported as a report that is submitted with the construction permit in the case of new construction. This summarized report is shown in Annex-3.

- **DesignBuilder**

As for the other software used, it is DesignBuilder v6.1.5.004. This software is an EnergyPlus based software tool used for energy, carbon, lighting, and comfort measurements and control. It combines fast three-dimensional building modeling with **dynamic energy** simulations based on hourly weather data (Alensis, 2015).

The EnergyPlus engine used in the current version of DesignBuilder is v8.9, and it is the most comprehensive building energy simulation program developed by the US Department of Energy (Alensis, 2015). In addition, it was validated using the normalized BESTEST procedure.

The interface of DesignBuilder differs from the EPC software, wherein this software, a more 3-dimensional approach is adopted, as shown in Figure-3.3, followed by associating the created geometry with the specific data and the different systems present within the model.

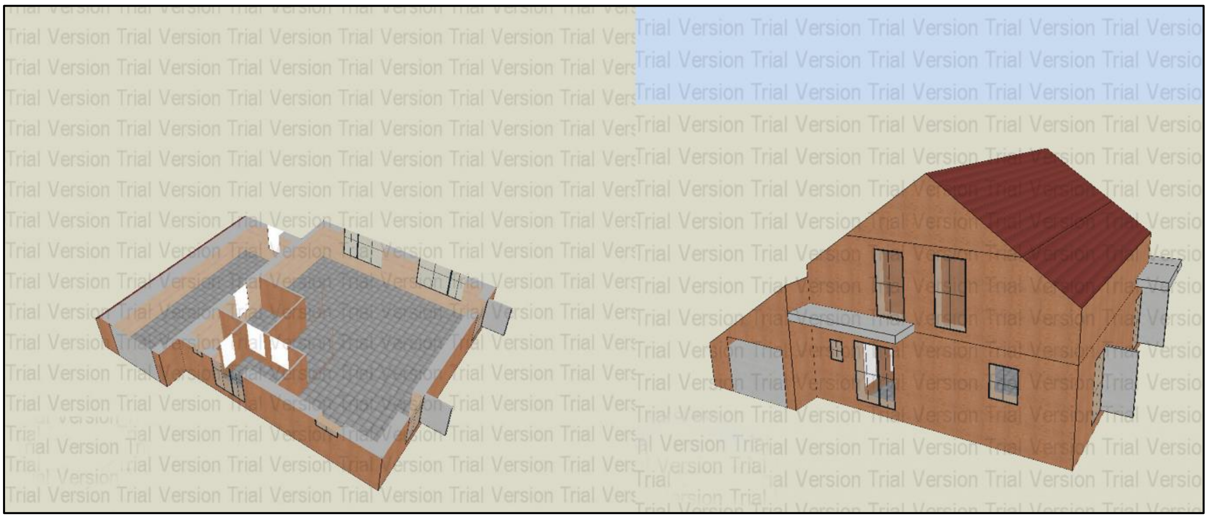


Figure 3.3-DesignBuilder Interface.

The results of the simulation can be exported either as detailed hourly measurements or in a simplified representing manner (such as graphs, average values) that represents the annual state of the simulation model.

- **Case study, "The Kettenis House."**

The chosen case study is the Kettenis House, located in the municipality of Eupen within the provenance of Liege, as shown in Figure-3.4.

Figure 3.4-Location of the Kettenis House. Source: Wikipedia

This case study (Figure-3.5) is a single-family passive house constructed for the Johanns family by the architect Léo Michaelis. It is a 4 – façade lightweight construction (the structural elements consists mainly of wood framing) with a surface of 174 m² and a protected volume of 536 m³ covered by a double sloped roof at an angle of 35°.

Figure 3.5-The Kettenis House. Source: De Meester,2008.

The plans (Figure3.6) are oriented towards the North-South axis, with the living areas occupying the ground floor and the bedrooms on the First Floor.

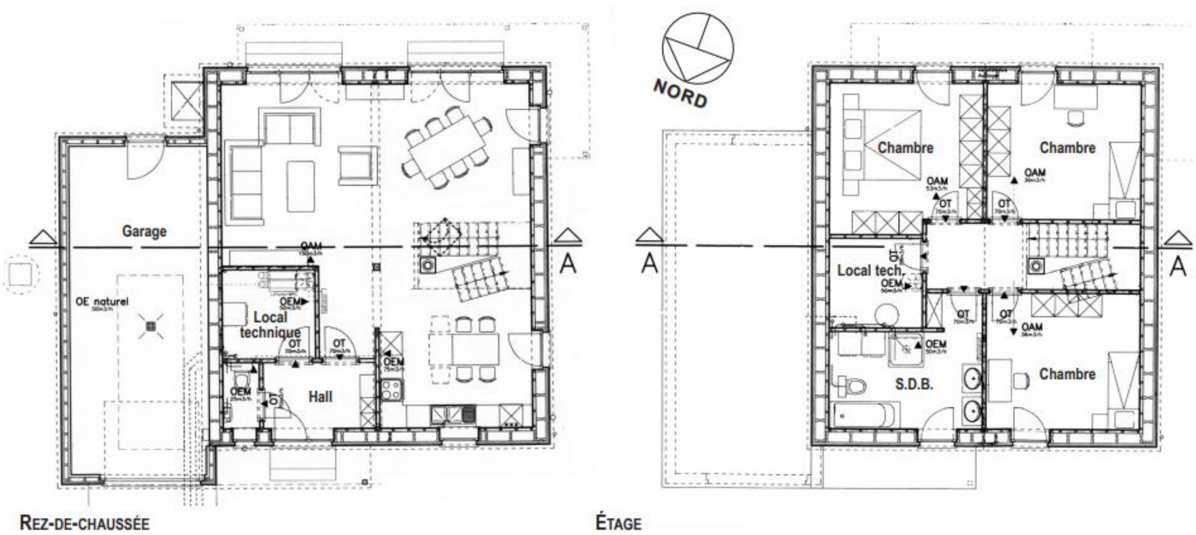


Figure 3.6-The plans of the Kettenis House. Source: De Meester,2008.

This case study is selected since it was constructed based on the Walloon initiative of 2004 *"Construire avec l'énergie"*, Making it rich with the necessary documentation.

The fact that this case study was the focus of previous studies, such as the Master thesis of both Tatiana De Meester in 2008 and Camille Gobin in 2016, making it ideal for the current research.

Since the required data is documented and verified, it leads to a more accurate and precise simulation model that results in a more reliable analysis.

- **Data collection**

The required data to establish the modeling in both software are quite similar, but each software has specific requirements that differ from the other. The related data needed for both software are summarized as:

- The details of the Geometry of the building and its orientation.
- The details of each element of the building envelope.
- The details of the different systems such as heating, ventilation, boilers, renewable energy sources.

However, as mentioned, each software has its individual specifications:

- For DesignBuilder, the activity and different schedules must be programmed in detail, while in the EPC, they are default values depending on the typology of the building.
- The hourly weather data required to run the simulation must either be chosen from the built-in library in DesignBuilder or can be downloaded from individual databases. At the same time, as discussed in Chapter 2, the EPC relies on characteristic days for the outdoor environment.

These data were made available due to the combined work of both Tatiana De Meester (2008) and Camille Gobin (2016). For example, all the details required for the plans, geometry, dimensions, and the different systems were provided in particular by Tatiana De Meester, which are available in Annex-1.

As for the different schedules and minor details required for DesignBuilder, they are complemented by the work of Camille Gobin. The various activity schedules and fine details related to DesignBuilder is found in Annex-2.

- **Standards and thermal comfort models**

The adopted thermal comfort models used to define overheating are based on the European Norm NBN EN 15251:2007 (Energie Plus, 2014).

This norm takes into account the indoor operative temperature, which is defined as the "felt" temperature in the thermal comfort conditions. It is the division of the room ambient temperature and the average room surface temperature (Energie Plus, 2007).

$$T_{Operative} = \frac{T_{air}}{T_{surfaces}} \quad [°C] \qquad (1)$$

Where; T_{air}: is the ambient room temperature, and $T_{surfaces}$: the average room surface temperature.

However, to identify the required indoor operative temperature used to classify the indoor thermal conditions as overheated, it was necessary to determine the classification of the building.

The norm NBN EN 15251:2007 classifies buildings into four categories that are illustrated in Table 3.1, wherein our case, the building is classified as a category II (newly constructed or renovated buildings) that has typical requirements.

Table 3.1-Categories of buildings based on NBN EN 15251:2007. Source: Energie Plus, 2014

Category	Explanation
I	The criteria of the interior ambiance are high (for spaces occupied by susceptible and fragile people with specific requirements).
II	**The criteria of the interior ambiance are standard (new buildings and significant renovations).**
III	The criteria of the interior ambiance are moderate (existing buildings).
IV	Values outside the criteria of the above categories. This category is accepted only for a limited part of the year

Based on this category, the "long-term" overheating state is defined when the maximum indoor operative temperature reaches a value higher than the recommended amount during the summer with relative humidity comprised between 25% – 60%, this value is defined from Table-3.2, which is an extract from the NBN EN 15251:2007 norm.

Table 3.2-Recommended long-term indoor overheating temperature. Source: Energie Plus, 2014.

Type of building or space	Category	Operative temperature °C	
		Minimum for heating (winter, 1 clo)	Maximum for cooling (summer, 0,5 clo)
Residential buildings: living rooms (bedrooms, living room, kitchen, etc.) Sedentary ~ 1.2 met	I	21	25.5
	II	**20**	**26**
	III	18	27
Residential buildings: other spaces (storage, circulation, etc.) Standing - walking ~ 1.6 met	I	18	
	II	**16**	
	III	14	

As illustrated in Table-3.2, the maximum indoor operative temperature differs depending on the utilization of the room, and the degree of clothing insulation factor (clo).

Therefore, according to the table, the maximum indoor operative temperature allowed is 26 °C with 0,5 clo in living areas (which is considered for the other spaces).

Regarding the hygienic mechanical ventilation flow rate, it was based on the European norms and, more particularly, the Annex 4 of the NBN D50-001, which is illustrated in Table-3.3.

Table 3.3-Mechanical ventilation norms. Source: Energie Plus, 2014.

	Fresh air supply [m³/h]	Extraction used air [m³/h]
General rule	**3,6 m³/h per m² of the surface of the floor**	
Living	75 [m³/h] min. 150 [m³/h] max	_ _
Bedrooms, playrooms	25 [m³/h] min 36 [m³/h] max p/p	_
Kitchen (closed), bathroom	_	50 [m³/h] min. 75 [m³/h] max.
Kitchen (open)	_	75 [m³/h] min.
WC	_	25[m³/h]

This table defines the general rule for the ventilation rate, which depends on the surface area, in addition to precise specifications, and it is based on these values, that the ventilation rates are changed in the EPC software.

As for the passive solutions defined in chapter-2, they will mainly consist of free cooling as a proposition. Free cooling is divided into two categories, which are either nocturnal natural-free cooling or intensive mechanical ventilation based on standard practices (EnergiePlus, 2014).

These two types of free cooling are defined as specific air change rates per hour (ac/h), as mentioned by Energie Plus in 2014.

"The natural cooling of a room (or free cooling) implies a significant rate of renewal of the air in the room. In natural systems (window opening), we speak of 4 / hour as the basis for sizing, ***8 renewals/hour are commonly encountered. In a mechanical system, on the other hand, we will limit ourselves to approximately 2 hourly renewals*** *to avoid excessive oversizing of the air distribution networks." Translated fom* (EnergiePlus, 2014).

By applying the suggested ventilation rates, we obtain specific air change rates, characterized by a nocturnal ventilation rate operating at 8 ac/h and intensive mechanical ventilation running at 2 ac/h.

These air change rates will uniquely operate in DesignBuilder during the summer period on the scheduled activity defined previously, illustrated in Annex-2.

Regarding the chosen long-term thermal discomfort indices introduced by (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017), they are divided into two categories.

The first category of indicators consists of defining the overheating sensitivity of the dwelling regarding climate change (cf.chapter 2). This category includes the Overheating Escalation Factor (OEF) and its associated indicators, the Indoor overheating degree(IOD), and the Ambient Warmness Degree (AWB). These associated indicators are taken into account in the calculation of the OEF, as illustrated in the following equations.

$$\alpha_{IOD} = \frac{IOD}{AWD_{18°C}} \qquad [-] \qquad (2)$$

$$IOD = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{ooc}(Z)}[(T_{fr,i,z} - TL_{comf,i,z})^{+}.t_{i,z}]}{\sum_{z=1}^{Z}\sum_{z=1}^{N_{occ}(z)} t_{i,z}} \qquad [°C] \qquad (3)$$

$$AWD_{18°C} = \frac{[(T_{a,i} - T_b)^{+}.\ t_i]}{\sum_{I=1}^{N} t_i} \qquad [°C] \qquad (4)$$

Where;

In Equation (2), α_{IOD} (OEF) : is the ratio between the Indoor overheating degree and the Ambient Warmness degree. This indicator has a value comprised between [0,1] representing the variation of the indoor temperature as a consequence of the severity of the outdoor temperature.

In Equation (3), (IOD): The indoor overheating degree quantifies the intensity of the overheating risk. This intensity is calculated based on the difference of the free-running indoor operative temperature $T_{fr,i,z}$ (obtained from the DesignBuilder simulation), and the chosen thermal comfort temperature $T_{comf,i,z}$.

$T_{comf,i,z}$: is defined by the EN ISO 7730 norm, which sets this thermal comfort temperature at 26°C. This value is based on obtaining acceptable indices called, the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) (Oleson & Parsons, 2002), that represent:

- Optimum operative temperature
- The vertical air temperature gradient
- Mean air velocity
- Floor temperature
- Relative humidity

In Equation (4), ($AWD_{18°C}$): the ambient warmness degree evaluates the severity of the outdoor warmness (T_a, the outdoor temperature from the DesignBuilder simulation) calculated according to a base temperature (T_b = 18°C, based on the CIBSE Guide A-2015 and representing the minimum summer comfort temperature limit).

Within all equations, (i) is defined as the time step, which is a 1-hour interval in the current research, (z) is defined as the zones, and (N_{occ}) is the total number of occupied hours in the given calculation, which is defined by the activity schedules provided in Annex-2.

These equations are only taken into account when there is a positive (ΔT) between the indicated temperatures (when the temperature exceeds a specific base value).

The second category of indicators consist of the $P_{ventilation}$ (cf.chapter 2) and its associated indicators ($C_{ventilation}$, $IOD_{min\ vent}$, $IOD_{max\ vent}$). These indicators are taken into account in the calculation method of P_{vent}, using this category of indicators, the potential of ventilation as a mitigation solution is evaluated (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017).

$$C_{ventilation} = IOD_{\min vent} - IOD_{\max vent} \qquad [°C] \qquad (5)$$

$$P_{ventilation} = \frac{C_{ventilation}}{IOD_{\min vent}} \qquad [\%] \qquad (6)$$

Where;

In Equation (5), $C_{ventilation}$: is defined as the contribution of ventilation after applying max ventilation (passive cooling solution) on the DesignBuilder simulation model. It is calculated based on the differences in the obtained indoor overheating degree.

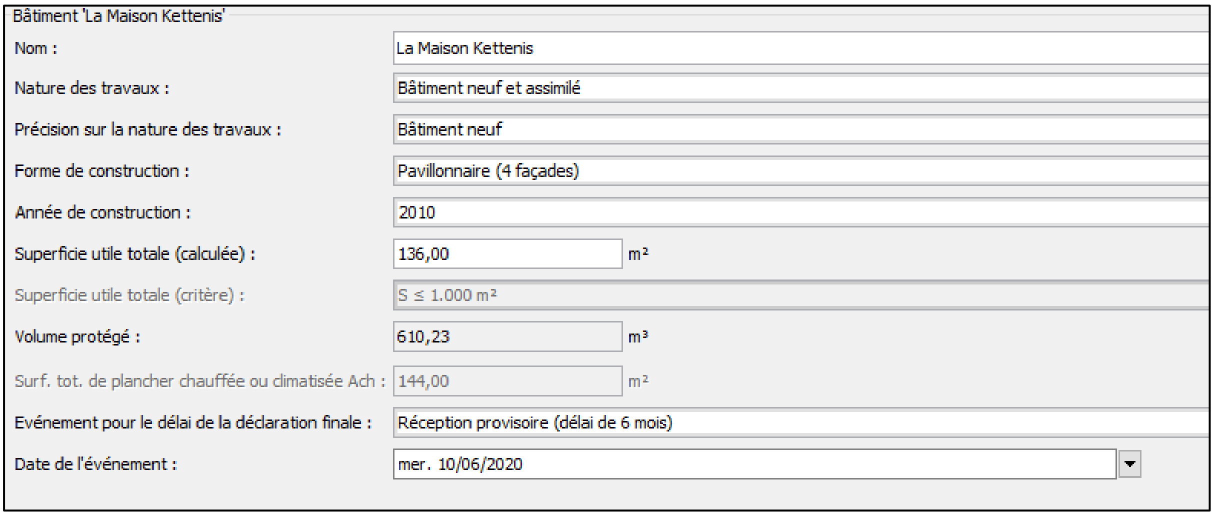
In Equation (6), $P_{ventilation}$: is defined as the potential of adaptation measure based on the applied passive solution (free-cooling within the case of the research).

3.2. Simulation process

The creation process of the simulation model in both software will be illustrated in this section, highlighting the main critical elements necessary to obtain the most reliable simulation model. Making this section the required blueprint to follow for future reproduction of the research.

The first step differs from one software to another, in the EPC software the first couple of actions consists of providing some administrative information required for the permit. For the sake of this research, these steps aren't that relevant and won't be illustrated given the fact that they don't affect the calculation methods (Figure-3.7).

However, the typology of the building needs to be defined, in addition to its state and construction date. These parameters affect the calculation methods and some default values that the software takes into consideration, such as the activity and density values.


Bâtiment 'La Maison Kettenis'

Nom :	La Maison Kettenis	
Nature des travaux :	Bâtiment neuf et assimilé	
Précision sur la nature des travaux :	Bâtiment neuf	
Forme de construction :	Pavillonnaire (4 façades)	
Année de construction :	2010	
Superficie utile totale (calculée) :	136,00	m²
Superficie utile totale (critère) :	S ≤ 1.000 m²	
Volume protégé :	610,23	m³
Surf. tot. de plancher chauffée ou climatisée Ach :	144,00	m²
Evénement pour le délai de la déclaration finale :	Réception provisoire (délai de 6 mois)	
Date de l'événement :	mer. 10/06/2020	

Figure 3.7-The typology of the building and its characteristics

As illustrated in Figure-3.7, the building typology was defined as a newly constructed 4-facades single-family house, therefore applying the criteria applicable to "residential destination" single-family houses (PER for the French abbreviation) (SPW - Wallonie énergie, 2018).

This typology of the building will introduce more specific and energy-restricted values (U, K, E_w, E_{spec}, V, S) to be respected within the EPC software (cf.chapter 2).

The construction date was set in 2010 since it is the earliest date that can be chosen in the software and the fact that this particular case study was constructed way beyond that date (2004). Choosing this date will have as a consequence of lowering the value of required criterias; however, within the analysis followed in the research, the current requirements are taken into account.

In addition to the lower value of the required criteria, the implementation of the fictive cooling (cf. chapter 5) isn't taken into account within the EPC software. However, its effect is mentioned in the research and is cited as a boundary condition of the study.

In DesignBuilder, the first step consists of defining the location and the desired weather file for the simulation. The hypothesis was made of choosing Liege airport as the location coordinates and the hourly weather data file used for running the simulation.

This hourly weather data file is built-in in the DesignBuilder software and is supplied by the Department of Energy (DOE) of the United States. It is composed of multiple years, where each month is selected to represent records that go back to the 1990s (DesingBuilder, 2019).

The chosen liege airport weather file is characterized as a maritime climate with specific annual representation concerning the outdoor dry-bulb temperature, humidity, wind, and solar radiation properties, which are available in Annex-2.

Following these steps was the creation of different envelope materials and compositions. Within this step, a particular focus was on obtaining the same composition values that will enable us to compare and assess the difference in overheating within these two softwares.

The different type of envelope compositions is illustrated in the following figure(Figure-3.8) and is based on the data of the previous research (Annex-1).

The glassed doors are modeled as windows with specific openings in both softwares, as for the other elements such as the exterior or interior doors, they are programmed according to the specifications provided by the thesis of Tatiana De Meester, to obtain the corresponding thermal transmittance value (U-value).

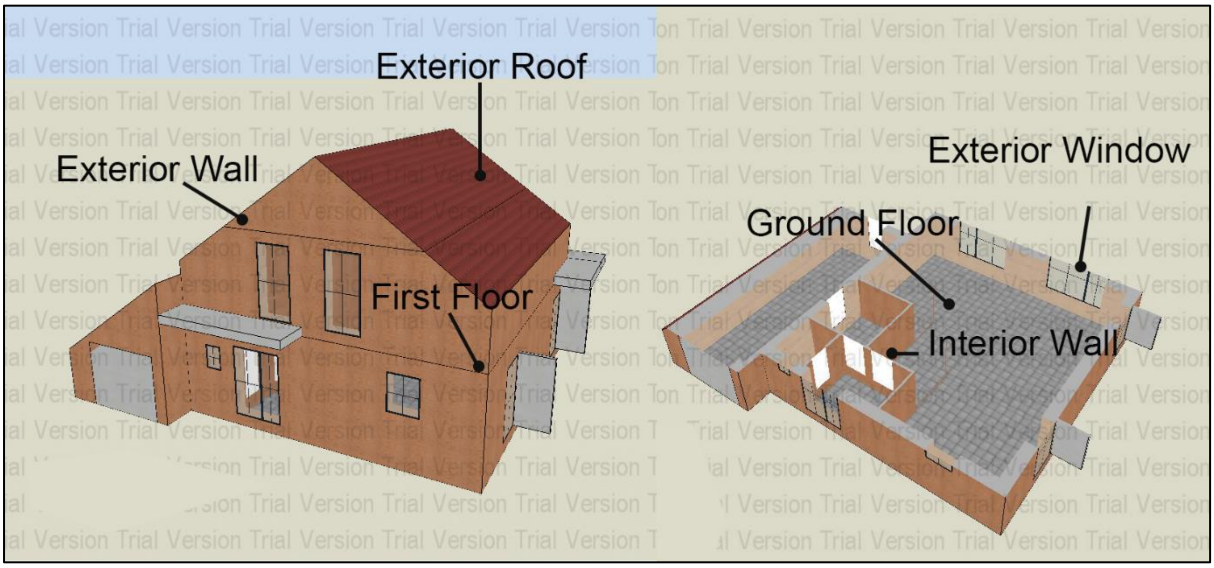


Figure 3.8-The main compositions of the envelope.

- **Envelope composition**

The envelope compositions modeled in both software are summarized in the following table (Table-3.4), Their thermal transmittance value (U-Value) is illustrated side by side for each software to assure that they don't differ from each other by more than 5%.

Table 3.4-Summary of the envelope compositions modeled in both software

Element	DesignBuilder U-VALUE (W/m²-K)	EPC U-VALUE (W/m²-K)
Exterior Wall	0,148	0,15
Interior Wall	0,611	0,61
Ground Floor Slab	0,177	0,18
First Floor Slab	0,328	0,32
Roof	0,128	0,13
Windows/glazed doors	0,500	0,50
Exterior doors (no glazing)	3,200	3,00

The composition of these elements is illustrated individually in the following tables (Table 3.5 to 3.9). The details and properties of these layers ensure the reliability of the modeling processes.

The visual representation of these elements is provided in Annex-4. Keeping in mind that it is inevitable to obtain certain deviations in each software, but the final U-Value and physical properties of each component are relatively similar.

- Exterior Wall

Table 3.5-The composition of the exterior wall

Layer	Thickness [mm]	Thermal Conductivity [W/mK]	Thermal Resistance [m²K/W]
Wood siding	30	0,163	0,184
Battening–counter battening	30	0,13	0,231
Wood fiber panel	20	0,045	0,154
Cellulose / Framing	250	0,04 / 0,13	4,673
OSB Panel	15	0,13	0,115
Mineral wool / Framing	60	0,04 / 0,13	1,121
Wood siding	18	0,13	0,138

- Interior Wall

Table 3.6-The composition of the interior wall

Layer	Thickness [mm]	Thermal Conductivity [W/mK]	Thermal Resistance [m²K/W]
Wood siding	20	0,163	0,184
Mineral wool / Framing	60	0,04 / 0,13	1,121
Framing	18	0,13	0,138

- Ground Floor Slab

Table 3.7-The composition of the ground floor

Layer	Thickness [mm]	Thermal Conductivity [W/mK]	Thermal Resistance [m²K/W]
Floor tile	30	1,2	0,025
Cement Screed	60	1,44	0,214
OSB Panel	22	0,13	0,169
Cellulose / Framing	250	0,04 / 0,13	5,01
Fiber Cement panel	10	1,25	0,02

- First Floor Slab

Table 3.8-The composition of the first floor

Layer	Thickness [mm]	Thermal Conductivity [W/mK]	Thermal Resistance [m²K/W]
Floor tile (wood)	15	0,13	0,115
Acoustic insulation	30	0,04	0,789
Wood Panel	24	0,13	0,185
Wood framing	2	0,13	0,154
Wood structure	200	0,13	1,538

- Roof

Table 3.9-The composition of the roof

Layer	Thickness [mm]	Thermal Conductivity [W/mK]	Thermal Resistance m²K/W]
Wood siding	18	0,13	0,138
Mineral wool / Framing	60	0,04 / 0,13	1,034
Cellulose / Framing	300	0,04 / 0,13	6,012
Wood Panel	22	0,13	0,169
Battening-counter battening	50	0,13	0,389
Roof tiles	20	1,4	0,012

- Windows / glazed doors

Concerning the windows / glazed doors, they are composed of 4mm triple glazing panels filled with a 12mm mix of Krypton – Argon (rare gases) to obtain a high-performance glazing system.

A low thermal transmittance value characterizes these windows in both of the glazed panels (U-Value: 0,5 W/m²K) and the frame (U-Value~0,7 W/m²K) (De Meester, 2008).

- Exterior doors

As for the exterior doors, which is mainly the garage door, and the interior doors, they were modeled by their default values that range from 3 to 2,5 (W/m²-K) for metal and wooden doors, respectively.

- **Definition of the zones**

Following the envelope's composition is defining the different zones. However, the application of the zoning system is different in each software.

As mentioned previously, the zoning system in DesignBuilder is used to specify the activity rate in addition to subtle details such as ventilation rate, lighting fixtures, etc.

The specifications of each zone are provided in detail by the work of (Gobin, 2016), which is available in Annex-2. Figure 3.9 illustrates these different zones defined in DesignBuilder.

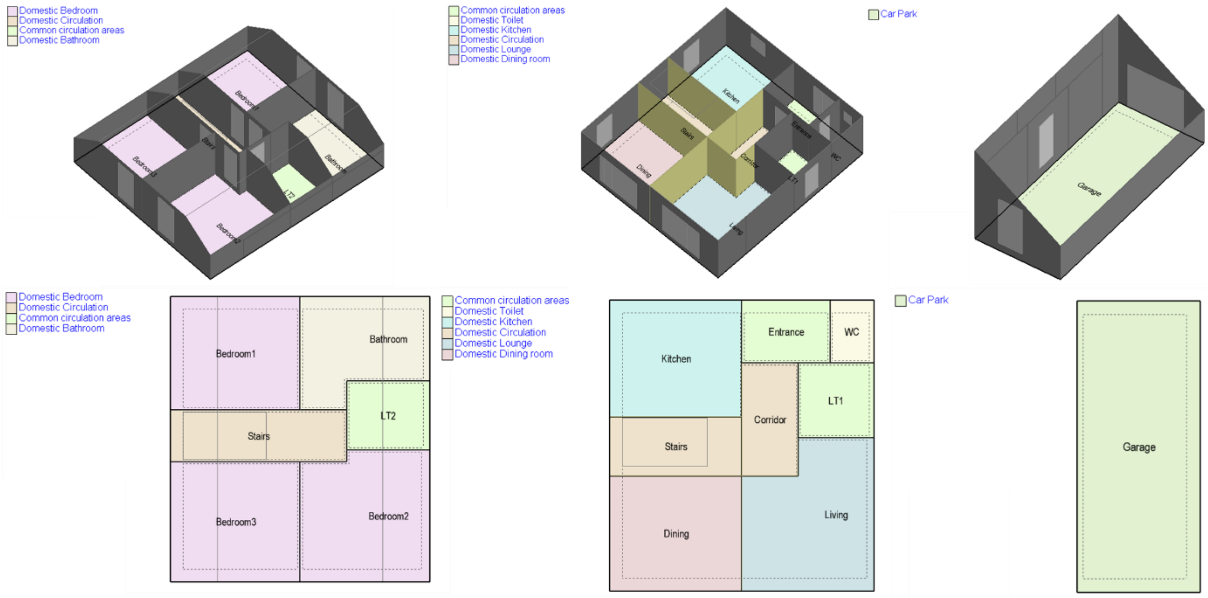


Figure 3.9-The zones defined in DesignBuilder

The zoning system in DesignBuilder is similar to the EPC software, where the zones are divided into three categories :

- Dry zones: which consist of the living areas (living, dining), bedroom, playrooms, etc.
- Humid zones: which consist of the kitchen, bathroom, toilet, etc.
- Circulation zones: which consist of the corridors and stairs.

However, in the EPC, the zones are defined to program the different ventilation rates and flow direction, which in the case study is set in Table 3.10.

Table 3.10-The ventilation rate of the zones in EPC

Zones	Fresh air supply [m³/h]	Transfer [m³/h]	Extraction [m³/h]	Fine [€]
Living	150	144	75	0
BR-PARENTS	**53**	28,8	0	**0,98**
BR-1	**36**	28,8	0	**55,15**
BR-2	**36**	28,8	0	**55,15**
HALL DOWN	0	115,2	0	0
VESTIAIRE - ENTREE	0	57,6	0	0
HALL UP	0	201,6	0	0
LT	0	86,4	50	0
SDB	0	28,8	75	0
LT-2	0	28,8	50	0
WC	0	28,8	75	0

- **Energetic systems**

As for the different energetic systems present in the case study, they were modeled with the specifications provided by the master thesis of (De Meester, 2008) which are available in Annex-1 and can be summarized by :

- The Heating system and boiler
- The ventilation system and airtightness

- The Heating system

The heating system consists of a single boiler situated beneath the stairs; this boiler operates on biomass and permits the heat to transfer from the ground floor to the bedrooms on the first floor (Figure-3.10).

It works automatically based on a thermostat or manually if desired and has a 94% yield efficiency and power varying from 2,5 to 10 kW.

Figure 3.10-The boiler. Source: De Meester,2008.

As for the production of domestic hot water, it is done by a combination of a natural gas boiler combined with 6 m² of solar panels situated on the rooftop and oriented with a 35° angle towards the south.

- Ventilation and airtightness

The hygienic ventilation is provided by mechanical system ventilation (System D); this type of system is centralized ventilation, where the supply and extraction rates are automated using a pipe network integrated with the building (Energuide.be, 2020).

This ventilation system is coupled with a 90% heat recovery by-pass. The airtightness of this case study was measured using the blower-door test, giving a value of 0,6 ac/h.

Figure 3.11-The ventilation system. Source: De Meester, 2008

This mechanical ventilation system (Figure-3.11), works in combination with an earth tube to preheat or precool the exterior air before entering the ventilation system, therefore reducing the necessary energy needed to regulate the air temperature.

3.3. Validation of the models

Before proceeding with the research proposal, a precise verification of both models are conducted, which is called the calibration process of the model.

The calibration process is an iterative process that consists of verifying the accuracy and reliability of the created simulation models by comparing the simulation results with real-life measured data until obtaining a validated model.

However, calibration isn't applied to the EPC software model, since it is used within the legislative context of Wallonia as a pre-construction tool and requirement. Therefore, the hypothesis was made to only verify the model in terms of administrative requirements and the current norms.

As for the calibration of the DesignBuilder model, it is conducted according to the ASHRAE Guideline 14 (ASHRAE, 2014). This guideline introduces three different engineering approaches to measure and validate that the uncertainty between the simulation and real-life measurement is below a certain threshold (enregywatch, 2020).

The three approaches are:

- Retrofit Isolation Approach.
- Whole Facility Approach.
- Whole Building Calibrated Simulation approach.

The adopted approach for this calibration process will be the Whole Building Calibrated Simulation approach, which uses two indices to evaluate the validity of the building energy model.

These two indices are the Mean Bias Error (MBE), and the Coefficient of Variation of the root mean square error (CV), which are defined according to ASHRAE Guideline 14 (ASHRAE, 2014) by the following equations.

$$MBE = \frac{\sum_{i=1}^{N_p}(m_i - S_i)}{\sum_{i=1}^{N_p} m_i} \quad [\%] \quad (7)$$

$$CV\ (RMSE) = \frac{1}{m}\sqrt{\frac{\sum_{i=1}^{N_p}(m_i - S_i)^2}{N_p}} \quad [\%] \quad (8)$$

Where;

m_i: are the real-life measured data.

Si: are the simulated data from DesignBuilder.

i: is the time interval (which is a monthly interval) due to the data availability in Table-3.12.

N_p: is the total number of data values (which is the 12 months).

These indicators are applied between the simulated and measured data and must be lower than a specific value, less than 5% for the MBE and no larger than 15% for the CV.

Now for the verification regarding the EPC simulation model, at first glance, we can notice that the hygienic ventilation rate doesn't meet with the current standards, wherein some zones (mainly the bedrooms) the ventilation rate was too low concerning the available surface. In addition to that, the overheating indicator was above the allowed value (with a value of 6788 K.h).

Therefore, the ventilation rate was adopted to meet the current requirements defined in (Table-3.3), in addition to some minor parameters such as the different systems equipment efficiency yield. The goal of this verification is to obtain the same values of the indicators of a residential nZEB defined by the Wallonia region (Table-3.11), which are discussed more deeply in chapter 2.

Table 3.11-The The verification concerning the EPC model.

Indicators	Before Verification	After Verification	Target Values
U-values	Conform	Conform	Reference values
K	16	16	≤ 35
E_w	**51**	49	≤ 45
E_{Spec}	**87**	83	≤ 85 (kWh/m²)
Ventilation	**Not Conform**	Conform	NBN D50-001
Overheating	**6788**	5111	< 6500 Kh

The difference obtained in the E_w value after verification is considered acceptable (<10% difference), because the building was constructed before the EPC legislative framework and is not an nZEB perse.

In addition to that, the defined requirements of a passive house are met within the model.

As for the calibration of the DesignBuilder model, the MBE and CV indicators are applied to the real-life measurement taken within three consecutive years (2004-2005,2005-2006,2006-2007), these measurements contain the monthly electricity consumption and monthly biomass consumption expressed in kWh (Table-3.12).

Table 3.12-The measured data used for calibrating the DesignBuilder model. Source: Attia and Gobin, 2020.

	REFERENCE YEAR-1 (2004-2005)		REFERENCE YEAR-2 (2005-2006)		REFERENCE YEAR-3 (2006-2007)	
	kWh	kWh	kWh	kWh	kWh	kWh
Date	ELECTRICITY	HEATING	ELECTRICITY	HEATING	ELECTRICITY	HEATING
January	285	425	290	365	265	325
February	275	395	280	325	305	300
March	285	365	295	295	300	265
April	255	285	260	185	275	175
May	255	135	250	95	240	50
June	245	0	260	0	270	0
July	210	0	250	0	205	0
August	245	150	265	105	270	35
September	255	280	295	205	275	190
October	280	345	305	295	290	225
November	290	390	310	325	300	295
December	300	415	330	340	300	310
	18,93 kWh/m²	**18,96 kWh/m²**	20,18 kWh/m²	**15,09 kWh/m²**	19,61 kWh/m²	**12,92 kWh/m²**

These real-life measurements were taken within another academic context and are provided by (Attia & Gobin, Predicting the impact of climate change on thermal comfort in a naturally-ventilated nearly zero energy building, 2020).

By comparing the consumption results (electricity & biomass) obtained from the initial DesignBuilder simulation model with the measured data, we get the following graphs (Figure-3.12) illustrating the deviations from these measurements.

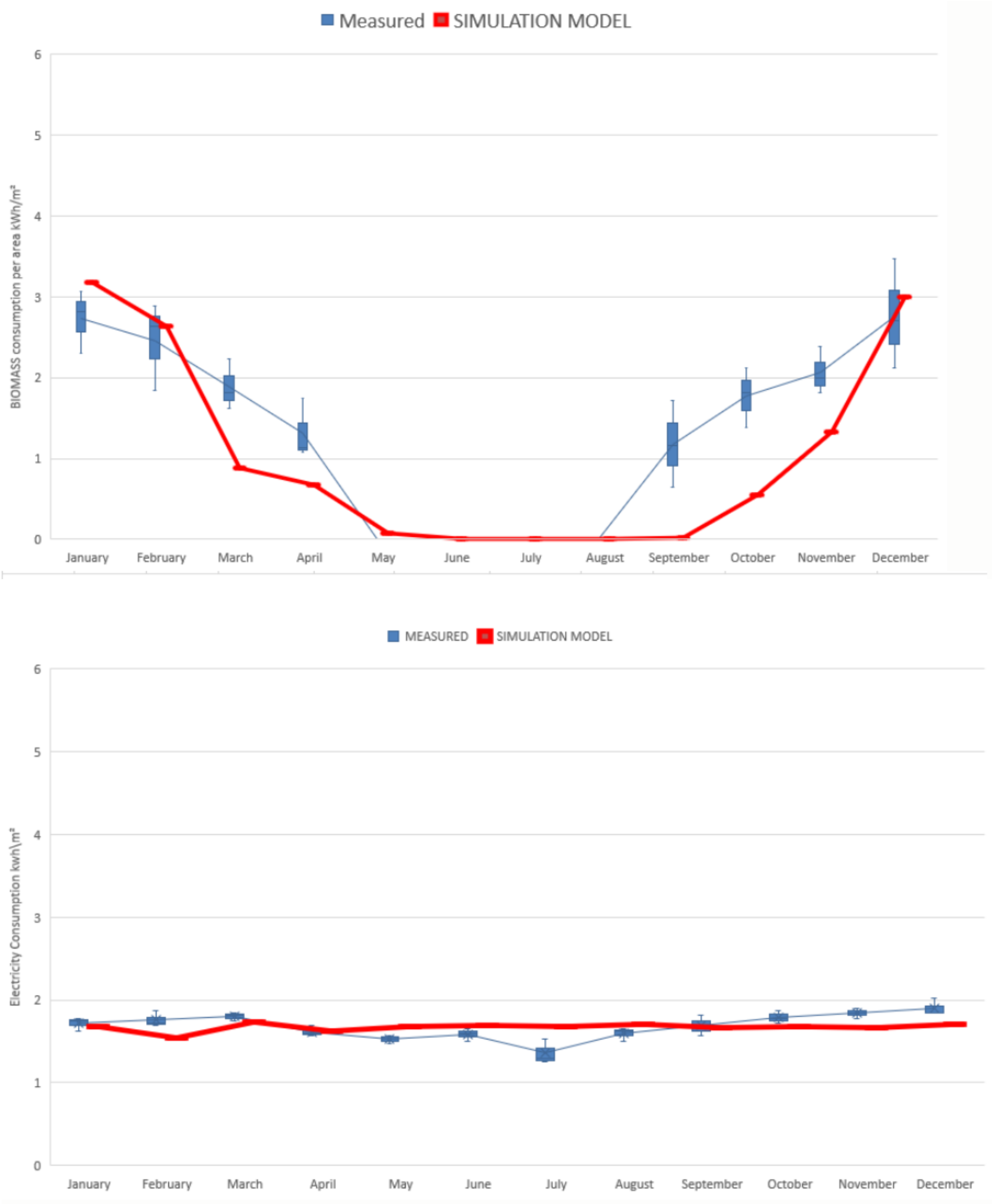


Figure 3.12-The ASHRAE indicators before calibration

These measurements illustrate a difference between the simulation results and the measured data concerning biomass consumption, therefore by applying the equations of the MBE and CV indices, we obtain the following values (Table-3.13), expressed per year.

Table 3.13- The ASHRAE indicators before calibration.

	YEAR	BIOMASS	ELECTRICITY
MBE	2004-2005	**27%**	-3%
	2005-2006	**8%**	4%
	2006-2007	**-7%**	1%
CV	2004-2005	3%	1%
	2005-2006	2%	1%
	2006-2007	2%	1%

The indices before calibrating the model exceeded 5% for the MBE concerning biomass consumption. Therefore the efficiency of the heating system was improved (including the yield coefficient and heat loss) to obtain results within the range of the real-life measurements.

The applied modifications provided another representation of biomass consumptions, which is illustrated in Figure-3.13.

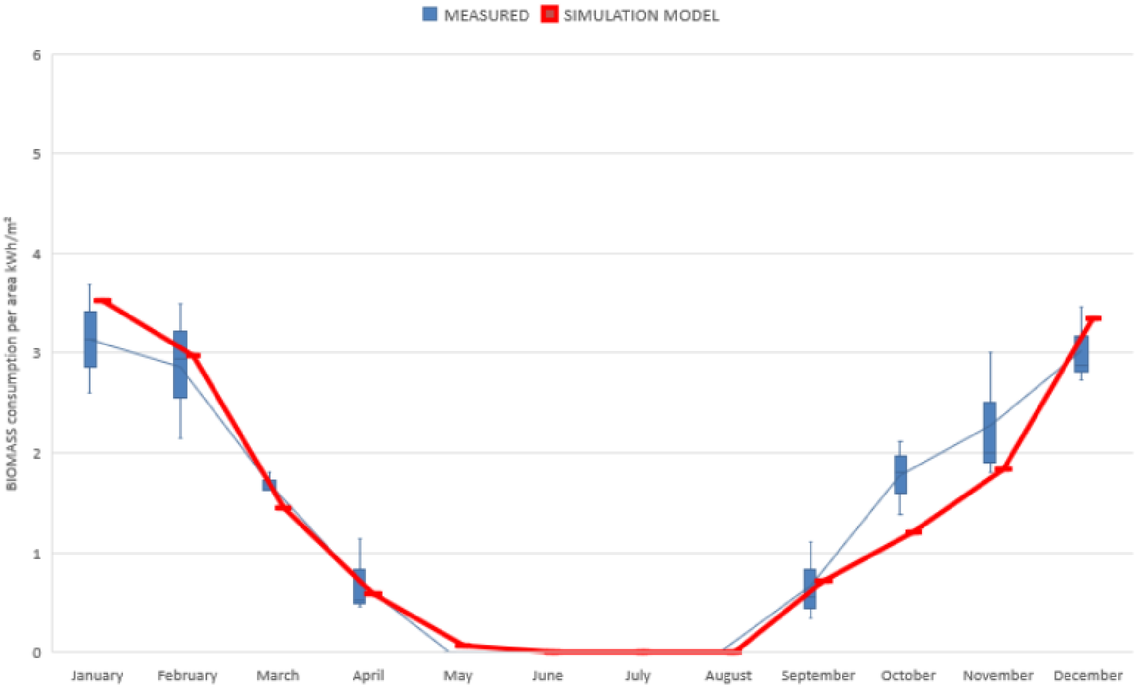


Figure 3.13-The The ASHRAE indicators after calibration.

As for the electricity consumption resulting from the DesignBuilder software, it is calibrated given the value of the indices obtained in Table-3.14. Applying the biomass modifications provides the following indices values, hence considering the model calibrated and verified.

Table 3.14-The indicators after calibration

	YEAR	BIOMASS	ELECTRICITY
MBE	2004-2005	**6%**	-3%
	2005-2006	5%	4%
	2006-2007	-5%	1%
CV	2004-2005	3%	1%
	2005-2006	2%	1%
	2006-2007	2%	1%

The 6% value of the MBE concerning the biomass consumption of the year 2004-2005 is considered acceptable given the fact that the total annual consumption regarding that year is abnormal compared to the following next two years.

3.4. Assessment of the indicators

Because the indicators of each software are different, the assessment methodology is adapted to create a link between them, enabling us to compare them regarding their degree of accuracy in general and the difference of the overheating risk in particular.

Regarding the EPC simulation model, the results use the definition of an nZEB residential building (cf. Chapter 2) as the link that enables the overheating risk assessment. The Walloon Region defines this nZEB standard as specific indicators that are discussed in chapter 2.

The nZEB standard corresponds to a specific limit of overheated hours, and based on this limit; the overheating is compared between the EPC and the DesignBuilder software.

The ventilation flow rate is adapted in the initial EPC model (EPC1) to obtain the nZEB standard in the EPC software.

This ventilation rate doesn't correspond to the NBN D50-001 norm even though the EPC1 satisfies the specific requirements regarding the ventilation of the bedroom; however, it doesn't meet the general rule (cf. Tale-3.3).

By applying the mentioned modifications on EPC1, another EPC simulation model results (EPC2) that is conforms with the nZEB standard, and based on this simulation model (EPC2), the overheating risk will be evaluated by comparing it with the DesignBuilder simulation model.

As for the DesignBuilder simulation model, a more thorough analysis is applied; this analysis consists of multiple stages.

The first stage consists of comparing the results of the initial simulation model of DesignBuilder (DB1) with the passive house standards (in terms of overheating hours), assessing the conformity of DB1 with these requirements.

The fact that the passive house standard has the same requirements (in terms of overheating hours) with the nZEB standard (cf. chapter 2) enables the creation of a link between DB1 and EPC2.

Hence, enabling the comparison of the obtained overheated hours in both simulation models, that leads to the evaluation of their degree of accuracy.

The second stage within the DesignBuilder simulation is to understand the magnitude of this overheating risk, and this will be done by applying the adopted long-term indicators (cf. 3.1.) on the DesignBuilder simulation results.

The long-term indicators are applied in multiple steps based on the type of assessment. The first step concerns assessing the overheating sensitivity and will be carried out by using the overheating sensitivity indicators (OEF, IOD, AWD) on the initial DesignBuilder simulation model (DB1), and more specifically on the indoor operative temperatures obtained from the simulation.

The second step concerns assessing the potential of free cooling as a mitigation strategy, this assessment will be carried out by introducing these passive solutions (cf.3.1.) in DesignBuilder and obtaining a modified simulation model (DB1). This simulation model will result in different indoor operative temperatures that are applied to the previous long-term indicators (OEF, IOD, AWD).

The difference in these indicators between DB1 and DB2 is applied within a new set of long-term indicators ($P_{ventilation}$, $C_{ventilation}$) that will assess the potential of free cooling as a mitigation strategy to suppress the effects of climate change.

Finally, as a final stage of the analysis, the three cases (EPC2, DB1, DB2) are compared to assess the overall differences regarding the overheating requirements and the base point principles.

3.5. Boundaries of the adopted methodology

It is inevitable to state the limitations of this research, which is mainly because this process is applied to a single case study. Still, due to the rarity of the complete availability of data, this single case study was chosen as sufficient.

This limited sample size can introduce some variations in the comparison of the chosen softwares if other cases are applied. However, due to the adopted methodology, which is extremely precise and takes into account all possible aspects, this process can be reproduced within similar contexts.

Therefore, making the process of the research itself valid and creating a precise blueprint to follow for further studies.

Another primary limitation of the adopted methodology was choosing the construction date of the model as 2010, therefore introducing specific criteria that were relevant to that date, such as the overheating indicator's upper limit set at 17 500 k.h. However, this aspect is taken into consideration within the analysis and is made accountable.

Besides these limitations, the fact that the level of accuracy between these two softwares broadly varies makes it sure to obtain deviations within the end product of these two simulations. In addition to that, the adopted long-term adaptive indicators are innovative and groundbreaking when it comes to the Belgian legislative framework.

Hence, making this research proposal a critical aspect when it comes to building energy simulation, shedding light on, and criticizing the weakness of specific methodologies adopted by the legislative framework. That may be the beginning of the path to select more long-term indicators In Belgium and, more particularly, within the Walloon region legislation.

Chapter 4: Results

The results of the simulations are stated in this chapter, highlighting the key findings that resulted from the applied methodology. The chapter is divided into different stages depending on the type of assessment, as mentioned in the methodology chapter.

The first stage consists of assessing the degree of accuracy of the EPC simulation model (EPC1) compared to the initial DesignBuilder simulation model (DB1) with a special focus on the overheating hours required by the chosen basepoint (the nZEB standard).

The second stage consists of assessing the overheating sensitivity using the DesignBuilder simulation model (DB1) and the long-term indicators (OEF, IOD, AWD).

Following the previous two stages, is assessing the potential of free cooling using a modified DesignBuilder simulation model (DB2) and another set of long-term indicators ($P_{ventilation}$, $C_{ventilation}$).

Finally, a general comparison between the three models (EPC1, DB1, DB2) will is established to overview the differences between the degree of accuracy of both softwares and to highlight the importance of the adopted long-term indicators and passive solutions.

4.1. Overheating Assessment

Starting with the EPC software, the initial state of the simulation model (EPC1) is based on the specifications and data from the previous studies, which is characterized by the following ventilation rates shown in Table-4.1.

Table 4.1-The ventilation rate of the zones in EPC1.

Zones	Fresh air supply [m³/h]	Transfer [m³/h]	Extraction [m³/h]	Fine [€]
Living	150	144	75	0
BR-PARENTS	**53**	28,8	0	**0,98**
BR-1	**36**	28,8	0	**55,15**
BR-2	**36**	28,8	0	**55,15**
HALL DOWN	0	115,2	0	0
VESTIAIRE - ENTREE	0	57,6	0	0
HALL UP	0	201,6	0	0
LT	0	86,4	50	0
SDB	0	28,8	75	0
LT-2	0	28,8	50	0
WC	0	28,8	75	0

Where the ventilation rates regarding the fresh air supply of the bedrooms are too low according to the current norms (NBN D50-001), this simulation model (EPC1) has the following value of indicators illustrated in Figure-4.1. Compared to the nZEB standards indicators defined by the Walloon Region (cf. chapter 2), a slight difference is observed.

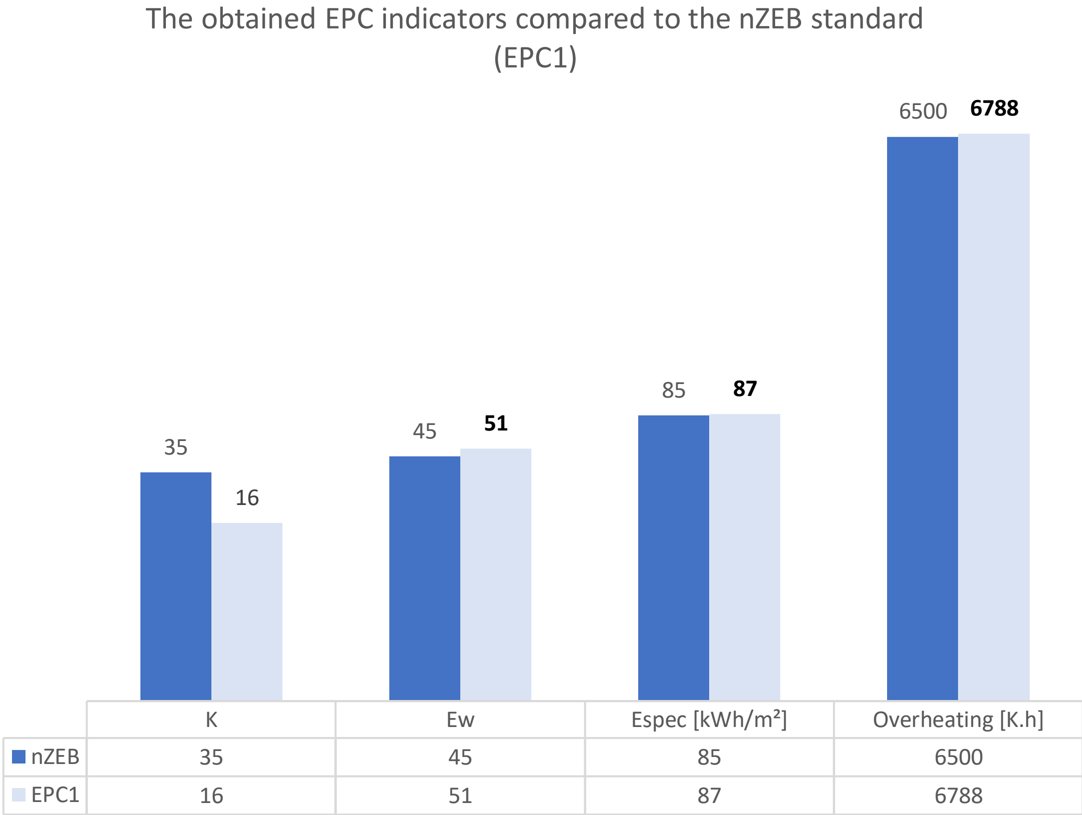


Figure 4.1-The obtained EPC1 indicators compared with the nZEB standard.

The obtained indicators from the EPC1 simulation model differs from the required indicators of the nZEB standard in three values (E_w, E_{spec} and the Overheating indicator).

These indicators result in a simulation model that is classified as "PEB B", which is characterized by an E_{spec} value comprised between ($85kWh/m^2 < E_{spec} \leq 170kWh/m^2$).

The classification of the model is mainly based on its E_{spec} value that is a result of the total characteristic primary energy consumption, which is resumed within EPC1 in the following Table-4.2.

The primary energy consumption is calculated based on the ratio between the annual consumption of primary energy of a single unit to the total surface of the heated or cooled floor, corresponding to an annual primary energy consumption of 12 525 kWh to a total heated floor surface of 144 m^2.

Table 4.2-Detailed monthly distribution of the characteristic primary energy consumption in EPC1.

Calculation	Characteristic consumption of PE (kWh)	Reduction of PE-cogeneration(kWh)	Consumption of PE-auxiliary (kWh)	Reduction of PE-solar panels (kWh)	Consumption of PE -DWH (kWh)	Consumption of PE - active cooling (kWh)	Consumption of PE-Heating (kWh)
Jan	2.387,29	-	-	-	547,14	-	1.840,15
Feb	1.810,03	-	-	-	437,27	-	1.372,77
Mar	1.432,94	-	-	-	407,72	-	1.025,22
Apr	736,46	-	-	-	308,17	-	428,29
May	324,52	-	-	-	247,10	-	77,42
June	224,02	-	-	-	224,02	-	-
July	250,23	-	-	-	250,23	-	-
Aug	273,65	-	-	-	273,65	-	-
Sept	322,63	-	-	-	322,63	-	-
Oct	712,09	-	-	-	434,95	-	277,14
Nov	1.647,45	-	-	-	506,49	-	1.140,96
Dec	2.404,06	-	-	-	563,83	-	1.840,23
Total	**12.525,37**	-	-	-	4.523,19	-	8.002,18

EPC1 has a calculated overheating indicator value of 6 788 [K.h], which is 4% higher than the required amount to meet the nZEB standard. This overheating indicator value implies that there is a 100% potential for active cooling (P_{cool}=1), shown in Figure-4.2.

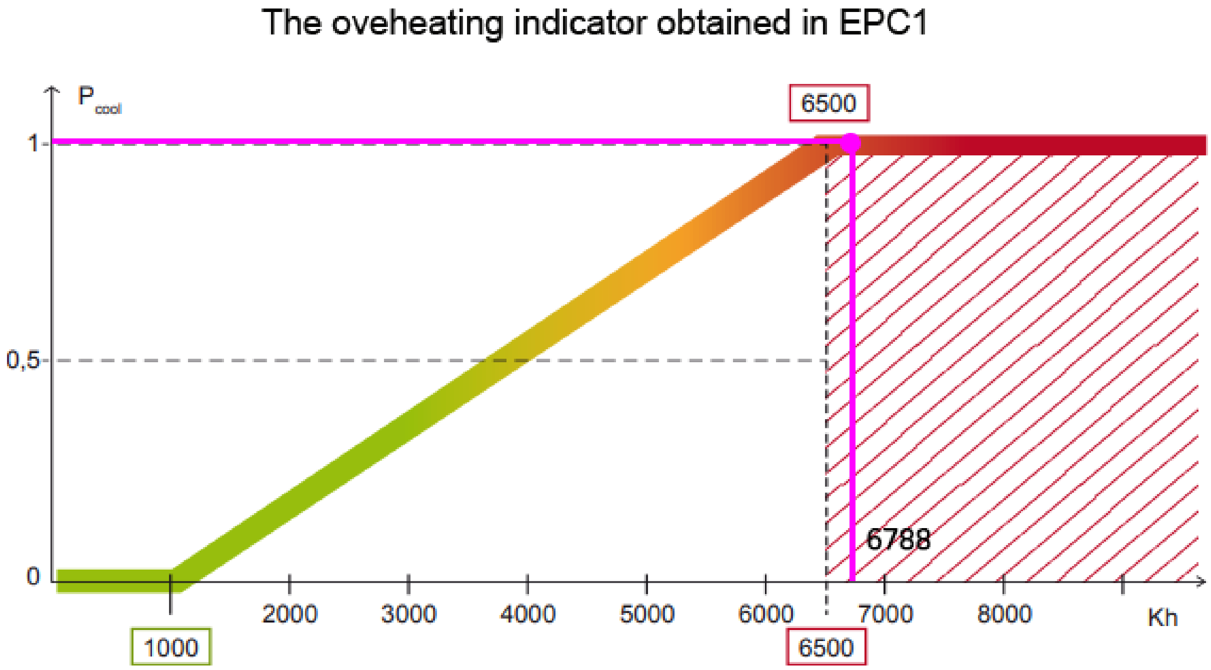


Figure 4.2-The overheating indicator in EPC1.

This P_{cool} is translated into a "fictive" active cooling system within the PEB simulation model that introduces additional characteristic primary energy consumption within Table-4.2, causing the downgrade of the classification of the model with a value of 5 to 10 on the E_w indicator depending on the P_{cool} value (CSTC, 2011).

As mentioned in the validation section, the initial EPC simulation model (EPC1) is adapted to meet the current norms regarding the ventilation rates (NBN D50-001) that lead to a modified EPC simulation model (EPC2), characterized by the following ventilation rates illustrated in Table-4.3.

Table 4.3-The ventilation rate of the zones in EPC2.

Zones	Fresh air supply [m³/h]	Transfer [m³/h]	Extraction [m³/h]	Fine [€]
Living	150	144	75	0
BR-PARENTS	**75**	28,8	0	**0**
BR-1	**50**	28,8	0	**0**
BR-2	**50**	28,8	0	**0**
HALL DOWN	0	115,2	0	0
VESTIAIRE-ENTREE	0	57,6	0	0
HALL UP	0	201,6	0	0
LT	0	86,4	50	0
SDB	0	28,8	75	0
LT-2	0	28,8	50	0
WC	0	28,8	75	0

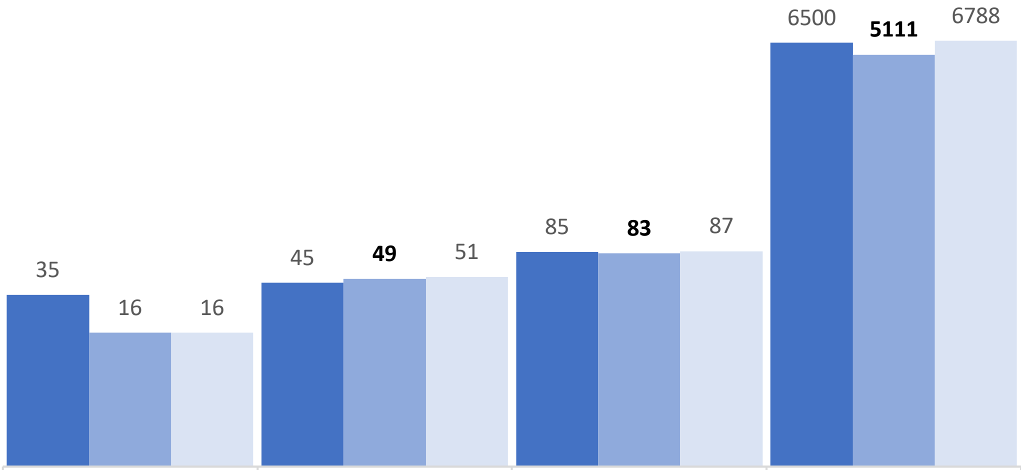
The applied modification is based on meeting the general requirement defined previously as 3,6 m³/h per m² of floor surface, obtaining an improvement in the flow rates illustrated in Table-4.4.

Table 4.4-The improvement in the ventilation within the EPC software.

Zones	Fresh air supply EPC1 [m³/h]	Fresh air supply EPC2 [m³/h]	Improvement [%]
Living	150	150	0
BR-PARENTS	**53**	**75**	**41**
BR-1	**36**	**50**	**38**
BR-2	**36**	**50**	**38**
HALL DOWN	0	0	0
VESTIAIRE - ENTREE	0	0	0
HALL UP	0	0	0
LT	0	0	0
SDB	0	0	0
LT-2	0	0	0
WC	0	0	0

This improvement in the EPC2 ventilation rates leads to the following indicators illustrated in Figure-4.3, which are compared with the nZEB indicators and the indicators obtained in EPC1.

Comparison of the EPC2 indicators to the EPC1 and the nZEB indicators



	K	Ew	Espec [kWh/m²]	Overheating [K.h]
NZEB	35	45	85	6500
Case A2	16	49	83	5111
Case A1	16	51	87	6788

Figure 4.3-The obtained EPC2 indicators compared with EPC1 and the nZEB standard..

The different indicator values obtained within EPC2 corresponds to the nZEB standards. Still, with a slight difference regarding the E_w value, which is 8% higher than the requirement, however, this value was considered acceptable in this research, since the ventilation system can improve it.

The nZEB standard is characterized in the EPC software by a characteristic primary energy consumption value that is lower than $E_{spec} \leq 85$ kWh/m² (cf. Chapter 2). As in EPC1, the E_{spec} is the result of the annual characteristic primary energy consumption illustrated in Table-4.5 and with a value of 11 919 kWh to a total heated floor surface of 144 m².

Therefore, since EPC2 is considered as an nZEB building, it corresponds to a maximum number of overheating hours criteria that should not surpass 5% of the total hours of a year (cf. chapter 2), which is equal to 438 hours per year.

Table 4.5-Detailed monthly distribution of the primary energy consumption in EPC2.

Calculation	Characteristic consumption of PE (kWh)	Reduction of PE-cogeneration(kWh)	Consumption of PE-auxiliary (kWh)	Reduction of PE-solar panels (kWh)	Consumption of PE -DWH (kWh)	Consumption of PE - active cooling (kWh)	Consumption of PE-Heating (kWh)
Jan	2416	-	-	-	492	-	1923
Feb	1764	-	-	-	394	-	1371
Mar	1326	-	-	-	367	-	959
Apr	572	-	-	-	277	-	294
May	241	-	-	-	222	-	19
June	202	-	-	-	202	-	-
July	225	-	-	-	225	-	-
Aug	246	-	-	-	246	-	-
Sept	290	-	-	-	290	-	-
Oct	560	-	-	-	391	-	168
Nov	1606	-	-	-	456	-	1150
Dec	2471	-	-	-	507	-	1964
Total	**11919**	-	-	-	4071	-	7848

The obtained value of the overheating indicator in EPC2 corresponds to 5 111 K.h, which is 21% lower than the upper limit of the nZEB overheating indicator required in the EPC. This overheating indicator leads to a potential of active cooling with a value of P_{cool} = 0,78, as illustrated in Figure-4.4.

The oveheating indicator obtained in EPC2

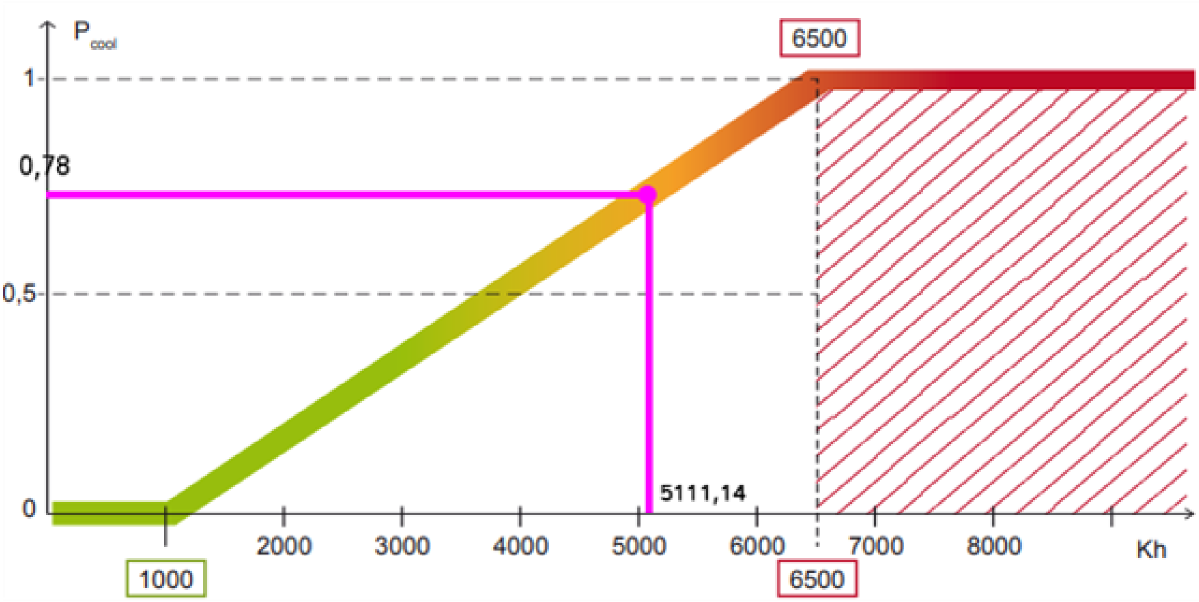


Figure 4.4-The overheating indicator in the adapted PEB simulation model.

Following these two simulations is establishing the comparison between the EPC simulation model (EPC2) and the initial DesignBuilder simulation model (DB1) to compare their overheating hours.

The simulation results of DB1 illustrated in the following figure (Figure-4.5), indicates the number of hours surpassing the chosen comfort temperature. Where in the case of the DesignBuilder simulation model, the upper limit of this comfort temperature is set at an indoor operative temperature of 26 °C (cf. 3.1).

Therefore, the simulation result of DB1 has 1386 hours, which is considered within the overheated conditions. This number of hours corresponds to 15,86 % of the total number of hours of a year, which is 10% higher than the required limit.

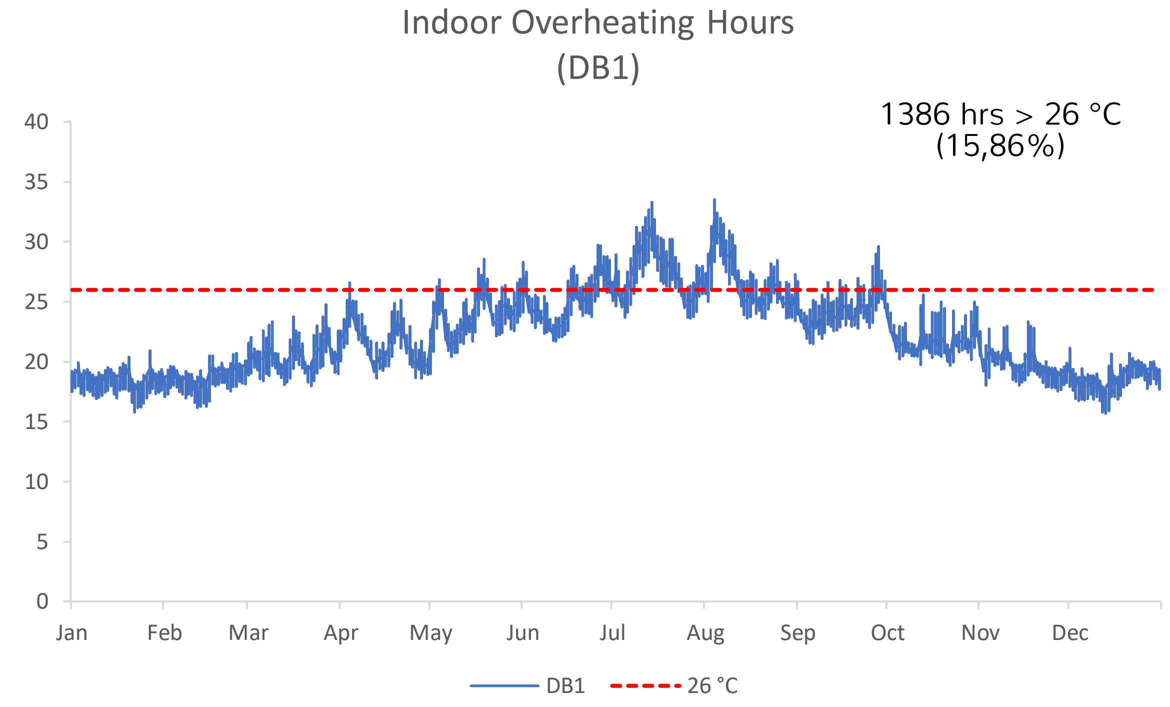


Figure 4.5-The overheating hours in Case B1.

By comparing the total number of overheated hours of both simulation models (EPC2 and DB1), we obtain Figure-4.6 that illustrates the differences regarding nZEB/passive standards and both simulation models.

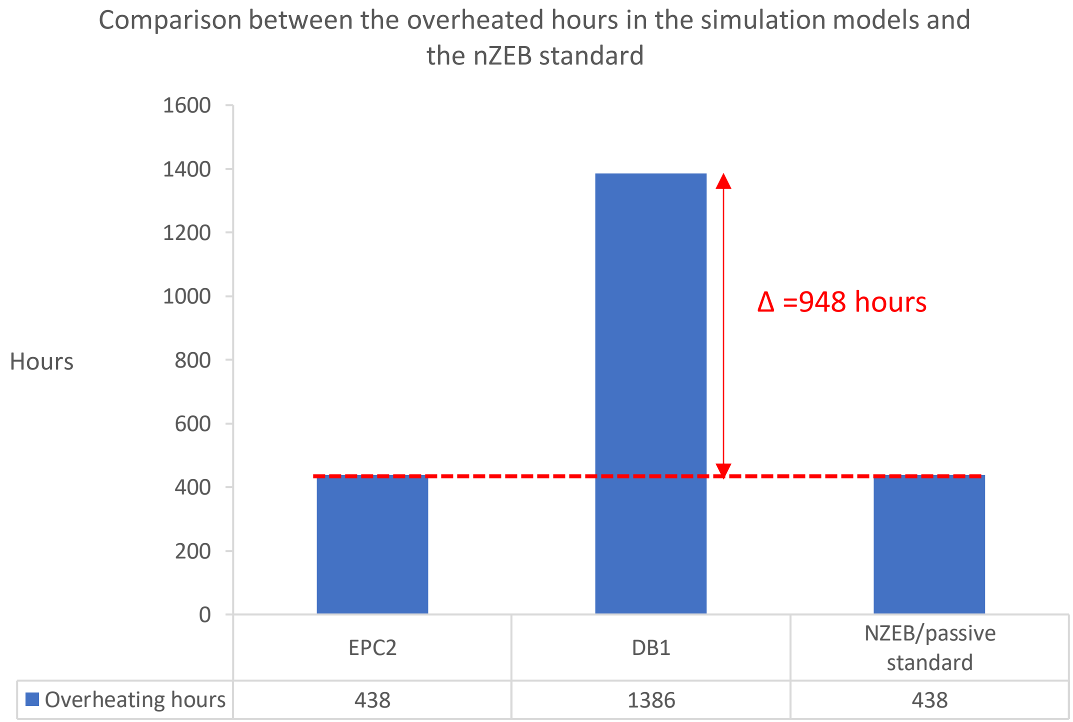


Figure 4.6-Comparison between the obtained overheated hours in both models and the nZEB.

While the simulation model obtained from the EPC software (EPC2) is conform with the nZEB standard, the simulation model derived from the DesignBuilder software surpasses the overheating hours' requirements of this standard. Therefore, having an initial difference of 948 hours between them.

The adopted long-term indicators are applied to the DB1 simulation model To understand the severity of the obtained overheated hours its sensitivity towards climate change. Starting with the Ambient Warmness Degree (AWD) illustrated in Figure-4.7.

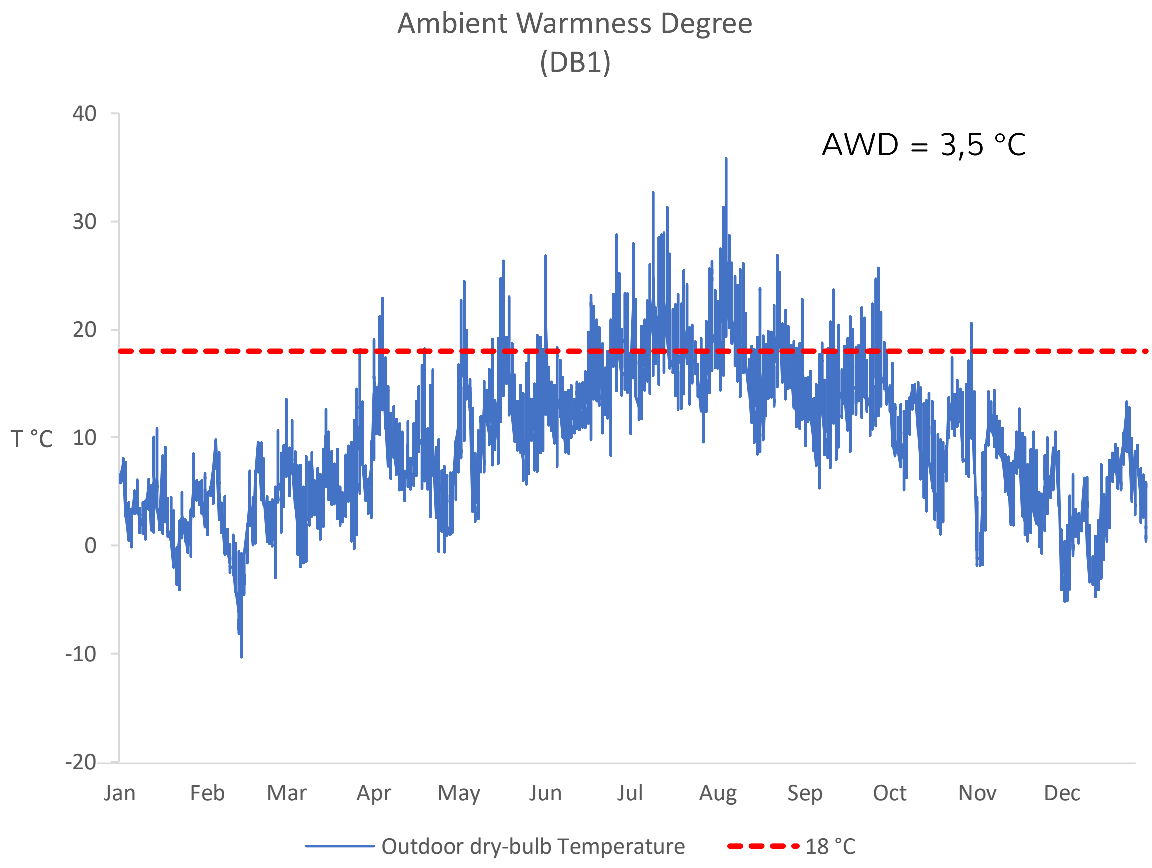


Figure 4.7-The Ambient warmness degree obtained in DesignBuilder.

Where, as defined in chapter 3, the Ambient Warmness Degree is a function of the outdoor dry-bulb temperature. Within the simulation model of Case DB1, it has a value of 3,5°C based on a reference temperature of 18°C (cf. 3.1.), which will remain constant regardless of the changes that will occur on the DesignBuilder simulation model.

The following indicator calculated is the Indoor Overheating Degree (IOD), which is a function of the obtained indoor operative temperature regarding the chosen thermal comfort limit, which, as described previously, is set at 26°C.

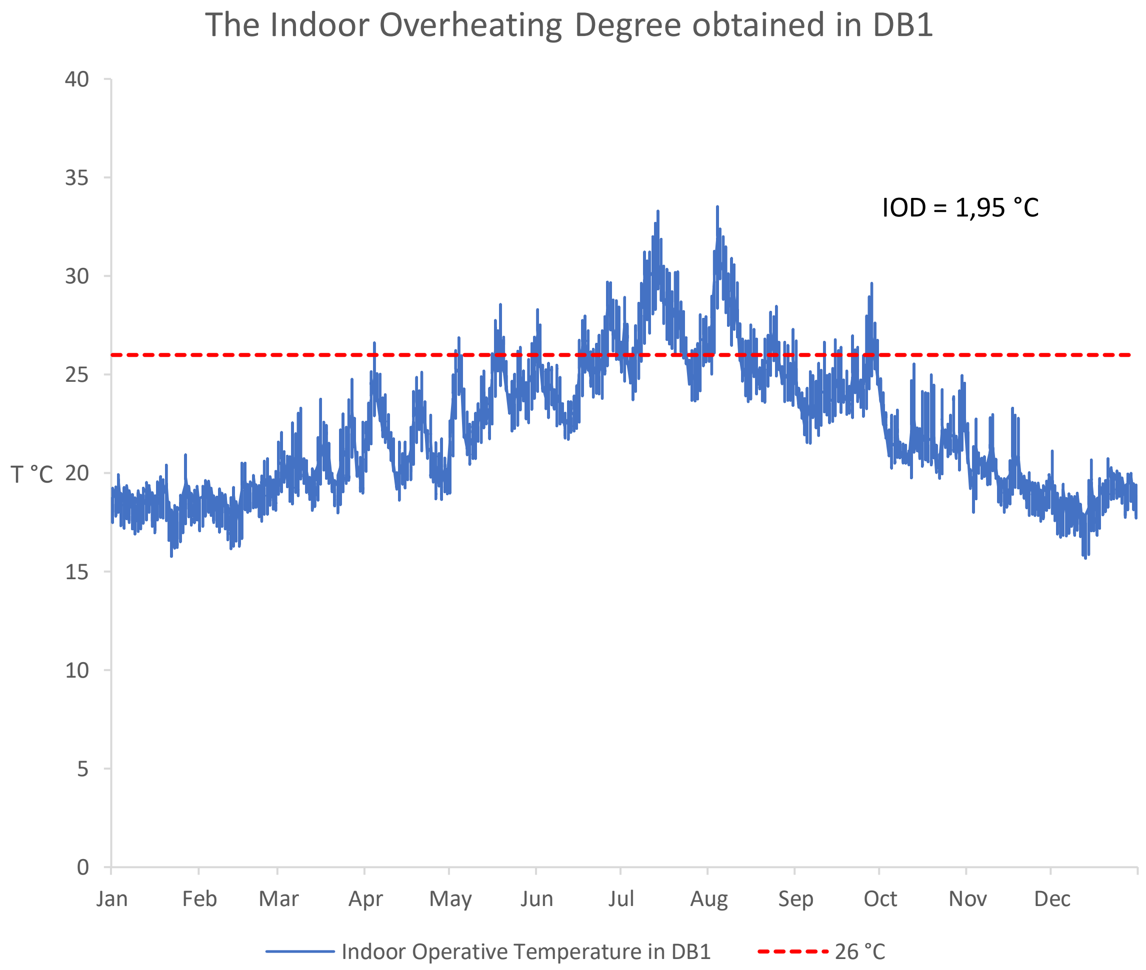


Figure 4.8-The indoor overheating Degree obtained in DB1.

Figure-4.8 illustrates the obtained Indoor overheating degree from the initial DesignBuilder simulation model (DB1), quantifying the intensity and frequency of the overheating risk and has a value of IOD = 1,95 °C.

The previous two indicators (AWD, IOD) lead to the following Overheating Escalation factor indicator (α_{IOD} = 0,56). This (OEF) indicator represents the relation between the AWD and the IOD, describing the sensitivity of the obtained indoor operative temperature to change regarding outdoor temperature changes.

4.2. Potential of free cooling

The second stage of the assessment takes into account the integration of the passive solutions within the DesignBuilder simulation model, obtaining a modified DesignBuilder simulation model (DB2).

These passive solutions are translated as specific air change rates according to the different activity schedules (c.f. 3.1.), improving the thermal conditions.

The newly obtained indoor operative temperatures are illustrated in Figure-4.9, highlighting the differences obtained compared with the initial DesignBuilder simulation model (DB1).

The differences in the indoor operative temperatures obtained from DB2 are manifested by a lower number of hours surpassing the comfort limit temperature of 26 °C, with a total of 767 hours per year, which slightly differs from the nZEB standard by 3,7 %.

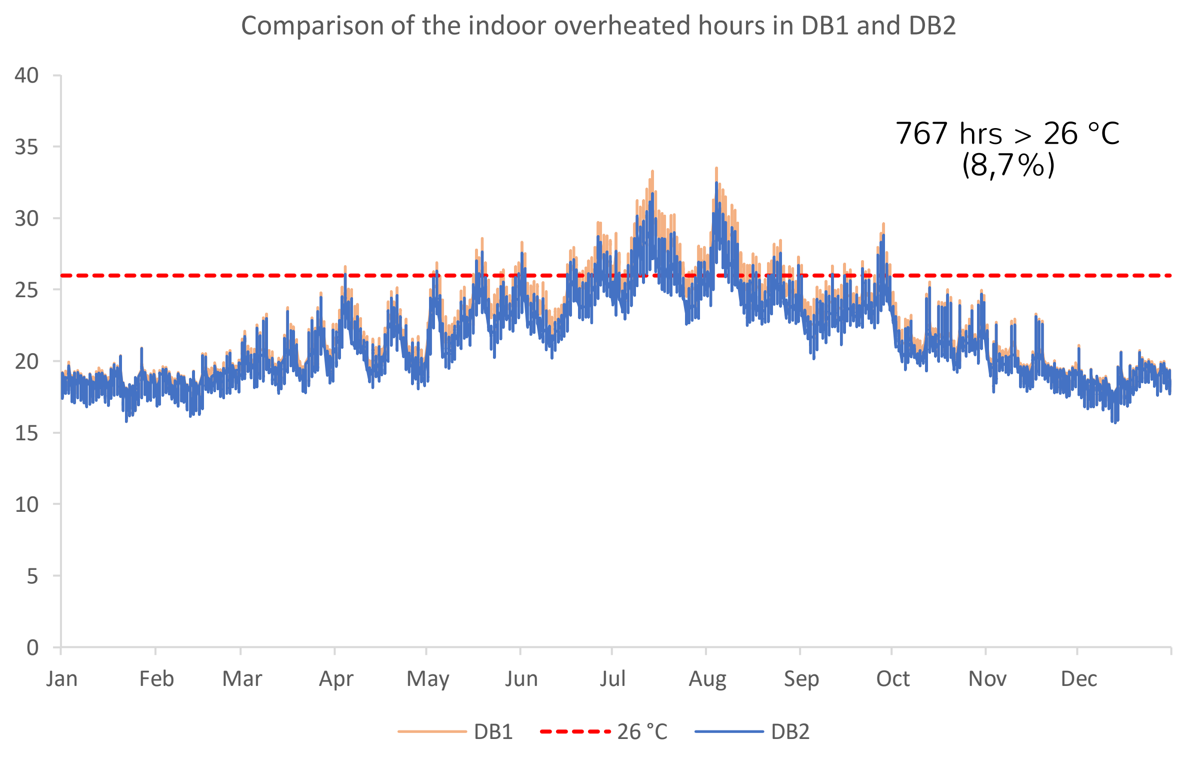


Figure 4.9-Comparison between the overheated hours in DB1 and DB2 .

These updated values of the indoor operative temperatures result in different values for the set of the indicators (IOD, OEF), starting with the Indoor Overheating Degree (IOD) illustrated in Figure-4.10, and with a value of IOD = 0,36°C. This IOD value is 1,59 °C lower than the value obtained within DB1.

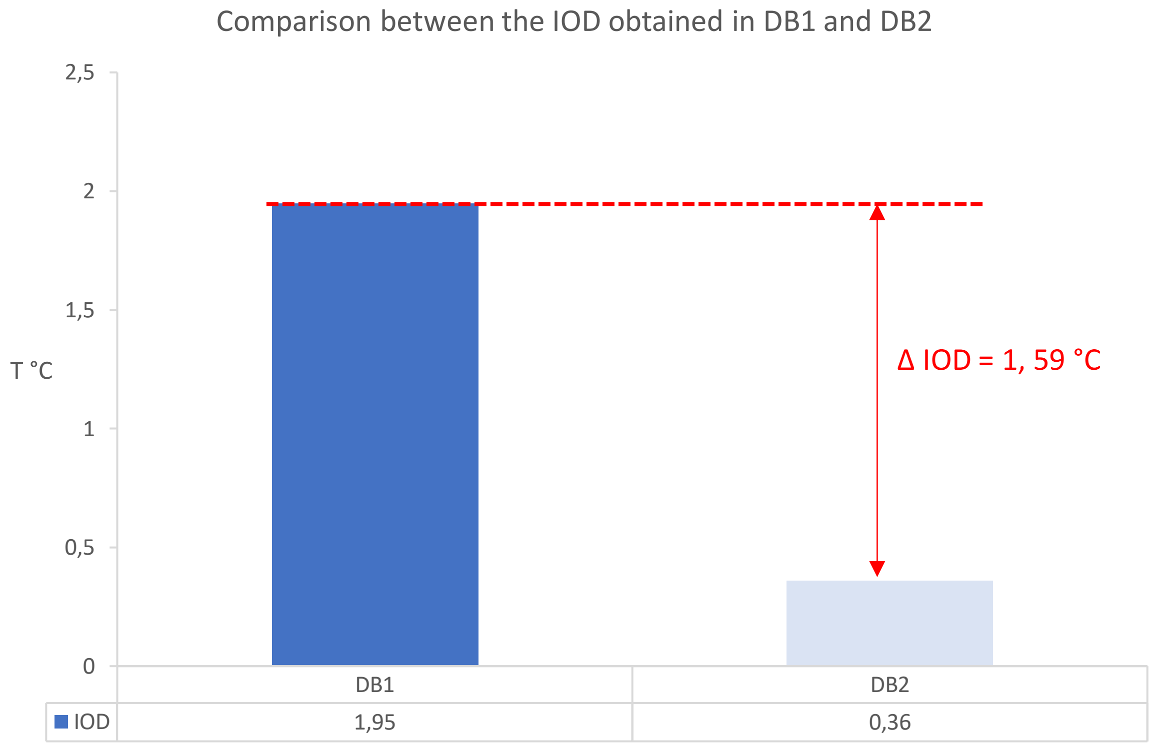


Figure 4.10-Comparison between the IOD obtained in DB1 and DB2.

Based on the updated indicators (IOD, AWD) within the simulation model (DB2), the overheating escalation factor indicator (OEF) is calculated and has a value of 0,10, which is 46% lower than the initial state (DB1) as illustrated in Figure-4.11.

However, it is essential to cite that the values of the OEF escalation factor are both within a range that is lower than 1,0. This significance is interpreted later on within the discussion.

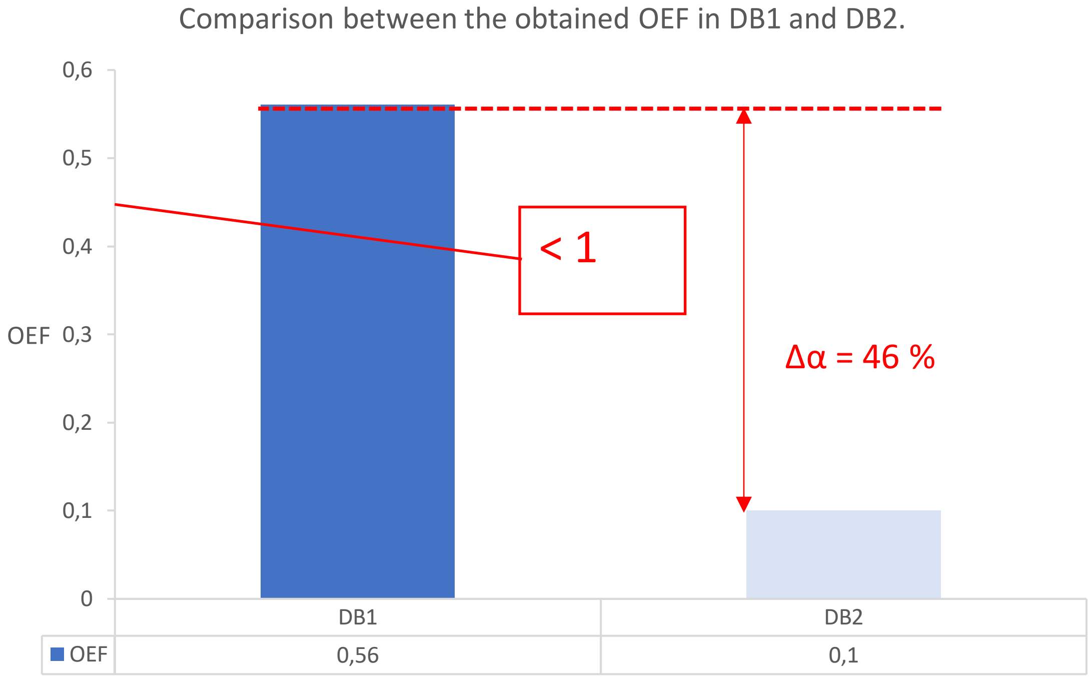


Figure 4.11-The Overheating escalation factor of Case B2.

The established Figure-4.12 compares the different overheated hours between the simulation models of the different softwares with the nZEB standard.

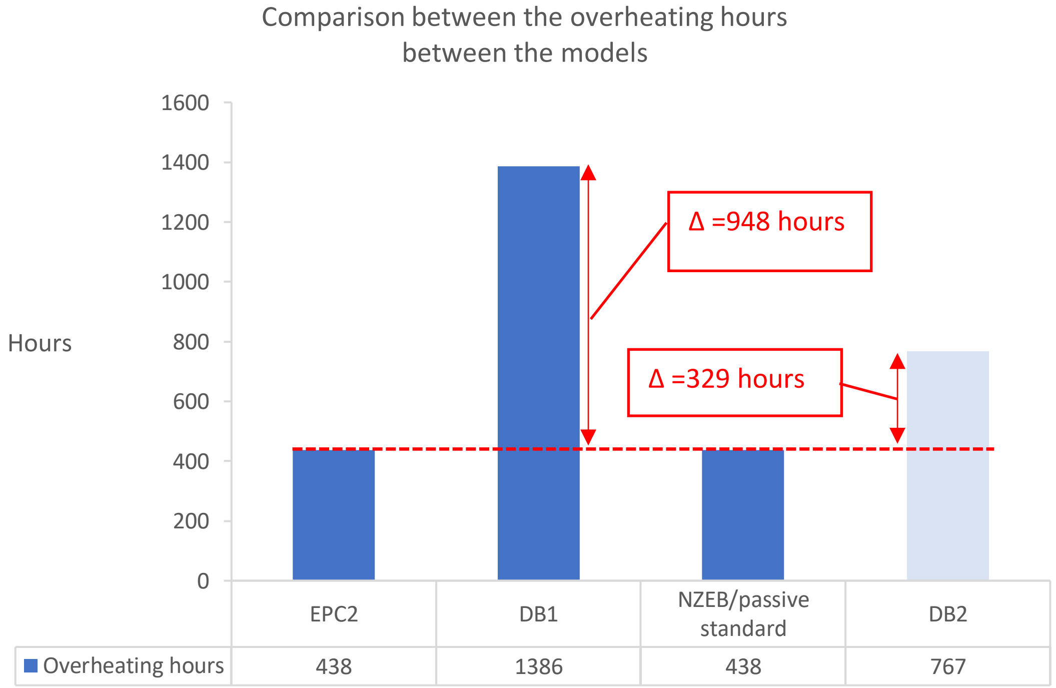


Figure 4.12-Comparison of the overheating hours between the different models.

This comparison points out the impact of the applied passive solutions regarding the number of the overheating hours' aspect where the number of overheated hours significantly improve from DB1 and has a value of 767 hours per year. However, this value is still higher than the requirements and surpasses the limit by 329 hours.

Figure-4.12 illustrates the difference between the degree of accuracy of the softwares and the improvements resulting from the passive solutions.

Finally, to accurately assess the potential of free cooling as a mitigation strategy, the last set of long-term indicators is applied, as mentioned previously, which are the Contribution of Ventilation ($C_{ventilation}$) and the Potential of adaptation ($P_{Ventilation}$).

Starting with the contribution of ventilation that quantifies the relative effectiveness of the adopted passive solution, and is calculated based on the difference between the obtained IOD (Figure-4.10) in minimum and maximum ventilation cases (DB1 and DB2). The obtained value regarding the contribution of ventilation is equal to a value of $C_{ventilation}$ = 1,59 °C.

As a final result of the analysis, the calculated potential of ventilation ($P_{ventilation}$) as an adaptation tool has a value of 82% as a capacity of adaptation, since the IOD values decreased significantly from the initial state (DB1).

The contribution of ventilation is also quantified in the EPC software by the decrease in the overheating indicator after changing the ventilation rates in both simulation models (EPC1, EPC2).

This contribution is illustrated in Figure-4.13 and presents a reduction of 26% of the value of the overheating indicator.

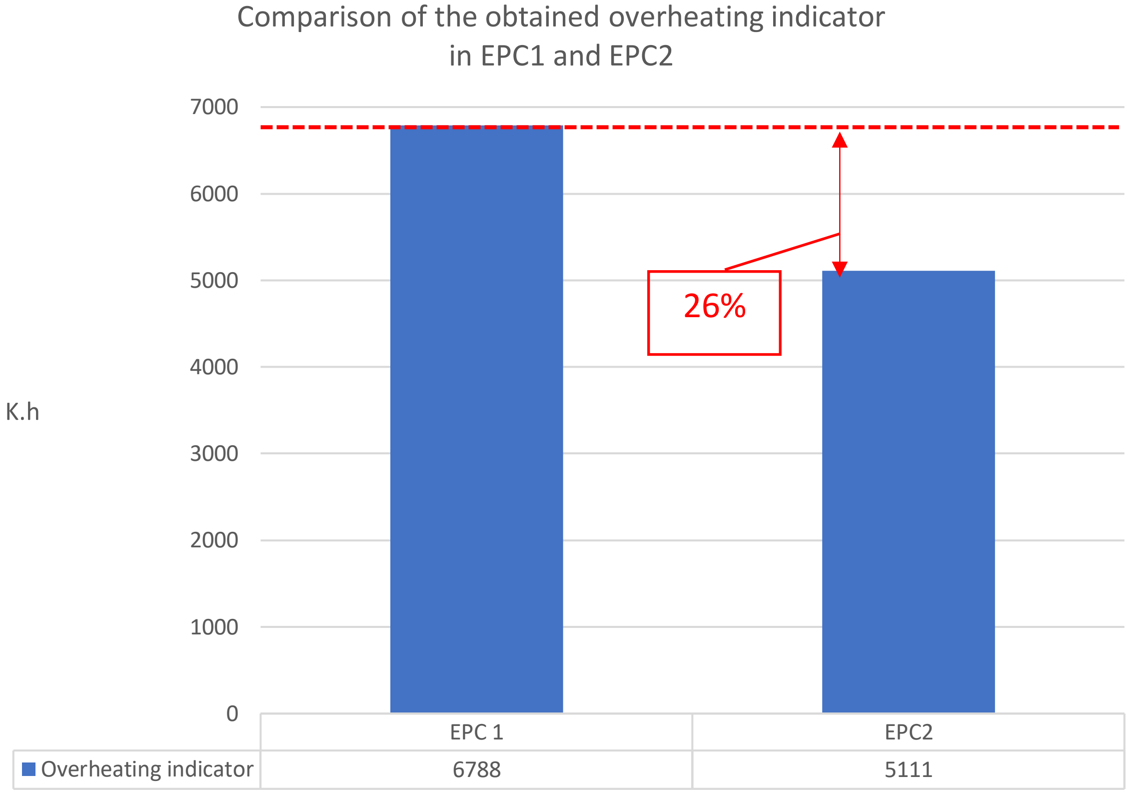


Figure 4.13-Comparison of the obtained overheating indicators in EPC1 and EPC2.

Based on these results, the evaluation of the overheating and the ventilative cooling will take place, responding to the research questions and highlighting its significance regarding existing theories and researches.

Chapter 5: Discussion

Within this chapter, the results obtained from the research methodology will be discussed, highlighting and interpreting the obtained results, providing insight into the meaning and importance of the proposed research.

5.1 Key findings and recommendations

- **Key findings**

The study confirms the difference related to the degree of accuracy of an energy simulation model, starting with the obtained overheating risk that is manifested by the total number of overheating hours. This difference is illustrated in Figure-4.6 and results with a difference of 216% compared with the EPC software.

The obtained difference confirms the previous research conducted by (Vanderavero, 2019), where a difference between the EPC software and TRNSYS is obtained regarding the overheating risk in a residential apartment.

However, the obtained difference of 216 % of the proposed research largely surpasses the 14% difference obtained in the study conducted by Vanderavero. This could be caused by numerous reasons and triggers future research regarding the topic.

The difference obtained in the overheating hours is one of many reasons why the quality of the indoor environment of most energy certified buildings doesn't correspond to its predictions calculated within the preliminary stages of the design. On the other hand, both research results contradict the hypothesis provided by the research of (Monfils & Hauglustaine, 2016) that proves that the standardized human behavior in the EPC software overestimates the final energy consumption.

This could be the case in old existing buildings but not in high-efficiency buildings and more specifically on the overheating aspect, where that same human behavior can introduce additional risk and cause the downgrade of the EPC model.

This gap between theoretical values and realistic values is highlighted in many Post Occupancy Evaluation (POE) studies, such as the study conducted by (Pastore & Andersen, 2019), which is a POE study conducted on four energy certified office-buildings. The study demonstrated that the occupant satisfaction rate regarding temperature and air quality was never higher than 50%, which doesn't correspond to the 80% satisfaction threshold, in addition to many other studies concerning the end-user field.

The study also demonstrates the importance of the adopted long-term indicators, starting with the Indoor Overheating Degree indicator (IOD). This IOD enables us to understand and quantify the severity and frequency of the indoor overheating state by comparing them with numerous studies that assess the overheating sensation of the occupants.

Where in the case of initial DesignBuilder simulation model (DB1) the IOD has a value of 1,95 °C as illustrated in Figure-4.10, and by applying the results of the study conducted by (Lomas & Porritt, 2017), this indoor overheating degree is within the sensation of the thermal comfort temperature for occupants within urban areas (less than 2,45°C temperature difference). In contrast, occupants within rural areas have an overheating sensation (larger than 1,32°C temperature difference).

However, by applying the passive solutions to the DesignBuilder model (DB2), this indoor overheating degree is lower than the thermal temperature threshold, therefore, minimizing the overheating sensation on the occupants regardless of the building area typology.

The study also demonstrates and quantifies the relationship between the indoor thermal environment and the outdoor conditions regarding the case study's sensitivity to overheating concerning outdoor climate, which is done by the introduction of the Overheating Escalation Factor (OEF).

OEF is a practical indicator when it comes to the evaluation of the effect of climate projections on the variation of the indoor operative temperature, which is a primary focus of multiple studies that are concerned with the impact of climate change on dwellings such as the work of (Gobin, 2016).

Where in the DB1 simulation model, the OEF has a value of 0,56, which is translated to a 44 % chance that the case study can suppress the effects caused by climate change.

However, in DB2, the OEF has a value of 0,1, which is translated into a 90% chance that the case study can suppress the effects caused by climate change, providing insight on the importance of ventilative cooling.

The translation of the indicator is based on the definition provided by (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017), that defines the sensitivity of the dwelling regarding climate change when it surpasses and OEF > 1, meaning that the indoor thermal conditions will get worse compared to the outdoor thermal conditions

Adopting these indicators within the Belgian legislative context allows the assessment of the existing building stock, characterizing them based on their efficiency, thermal comfort conditions, and their capacity of adaptation. This point is emphasized by the work done by (Singh, Attia , Mahapatra, & Teller, 2016), that argue that modern comfort standards have failed to estimate the comfort level in existing buildings.

Another aspect confirmed by the analysis was the contribution of ventilation as a passive solution. This contribution is observed within both simulation models, wherein the case of the EPC simulation model, a slight improvement in the ventilation rates illustrated in (Table-4.4) resulted in a 26% improvement regarding the overheating indicator (Figure-4.13).

In the case of the DesignBuilder simulation model, the contribution of ventilation was quantified based on the difference between the obtained IOD indicators within DB1 and DB2.

The results of the potential of ventilation (P_{vent} = 82%) illustrated in Figure-X indicate that the adopted passive solution has an effective measure to reduce the domestic overheating and mitigate its effects regarding climate change.

Therefore, confirming the results of the research conducted by (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017) indicating that an 5 ac/h ventilation rate has an average value of 80 – 90% depending on the severity of the outdoor temperature.

In addition to that, the obtained result and potential indicator came as a successive research study that provides an insight into the previous studies conducted on this particular case study and, more precisely, the work of (Gobin, 2016), where the potential of passive solutions was still undetermined.

- **Recommendations**

The main focus of the study is on a single case; therefore, it is recommended to reproduce the applied methodology in many instances to obtain a more reliable comparison that is based on statistical analysis.

The reproduction of the study within a larger scale can be the first step towards the introduction of a correction coefficient applied to the Walloon legislative framework.

Further researches must be conducted on the efficiency of passive solutions. For example, within the context of the study, only one method was applied, which consisted of free cooling. However, numerous other solutions can be used, such as chromogenic windows, double-skin façades, cogeneration, thermal mass, etc.

The applied methodology can be used to compare the different results obtained (mainly the differences between the IOD values) from each type of solution and present an insight towards the most efficient method.

Future studies should take into account the impact of the introduced indicators and, more specifically, their impact on the total primary energy consumption, where actual buildings are becoming more and more restricted when it comes to energy consumption.

A high value of the OEF is translated into the necessity of integrating active cooling within the near future, therefore adding additional primary energy consumption that, in some cases, might affect the integrity of the design itself.

5.2 Strengths and limitations

- **Strength of the study**

As is the case of all proposed researches, each study has its strong points and its limitations, and one of the main strengths of the study was the chosen case study.

This case study is a certified passive house that has undergone multiple studies and researches, representing a popular typology of buildings within the Belgian context. The fact that this case study is certified and was the center of numerous studies minimizes the assumptions and hypotheses regarding its different details.

In addition to the case study being verified, it has undergone a previous simulation modeling within DesignBuilder, which provided the specific details that need to be programmed within the software.

The fact that this case study is verified enabled calibrating the simulation model in DesignBuilder, given the availability of the data regarding the annual consumption of biomass and electricity.

Another strength point was the choice of the comparing software, which is an EnergyPlus based software that has undergone numerous verifications and accreditation processes, such as the BESTEST validation process.

Not only is this software verified, but it runs its simulation based on 1-hour interval calculations making its degree of resolution multiple times better than the PEB software, which, as proven within the study, resulted in a difference of 216%.

The adopted long-term indicators are based on hourly calculation, therefore applying them on DesignBuilder didn't require specific modifications and alterations within the equations, hence, keeping their accuracy and reliability intact.

The adopted methodology is well designed that it enables the findings to be generalized and reproduced in similar contexts, given the fact that the obtained data is transparent, representative and doesn't require assumptions or subjective interpretations.

Finally, the relevance of the research study with current problems and challenges facing the construction sector signifies its importance and contribution to the industry.

The research doesn't only serve as an assessment of the current legislative framework of the Walloon Region. Still, it provides an insight on what can be defined as the potential of multiple reasons that can affect the integrity of the indoor environmental quality of a building, but also the satisfaction and well-being of the occupants.

Meaning that the introduction of these long-term indicators takes into account the future projections and capacity of a building, where within current takes, only the actual state of a building is taken into account without any relevant future considerations

- **Limitations**

It is necessary to cite the limitations of this research, which is mainly manifested by the sample size. This limitation implies that the obtained values can't be generalized unless the methodology is reproduced on a larger scale providing a representative statistical value or a correctional coefficient.

Within the limitations of the sample size, we can cite that only one weather data file is used in running the simulation, which implies that there could be a slight variation within the obtained values.

However, this limitation is compensated by the level of detail taken into account within the programming process and choosing a representative weather file.

Another limitation is the fact that the case study has never been programmed as a simulation model within the PEB software, implying that within individual specifications, either the default value is used or the current best practices and norms where programmed. This limitation has a slight downgrading value regarding the overall performance of the simulation model. However, this limitation doesn't affect the integrity and reliability of the research.

The final limitation of the research was the fact that it focuses on the sole point of overheating. In contrast, the building functions as a whole and has multiple other aspects that need to be taken into consideration. Such as total energy consumption, lighting comfort, etc. Which if taken into account, wouldn't have enabled thorough analysis of all these aspects and would have led to broader questions that don't meet the requirements of this study but could be the focus of future studies.

5.3 Implication on practice and future research

The outcomes of the research provide a new insight that highlights some limitations regarding the actual state of the legislative framework adopted by the Walloon Region.

It is illustrating the importance of adapting the current EPC software for it either to be based on more fine calculations and eventually seek hourly weather simulations. Or to adopt the introduced set of long-term indicators to classify the building, not only on its actual state but also on its capability to adapt to future climate changes.

The importance of the degree of accuracy is justified by the study conducted by (Reiter & Nguyen, 2014), where the total discomfort hours is reduced as high as 86,1% by applying simulation-based optimization methods.

Another essential aspect that is introduced in this paper is the high potential of the adopted passive solution, therefore, encouraging future studies to assess the efficiency of each type of solution based on the proposed indicators.

As for the practical domain of architecture and building performance engineering, based on the obtained results from the research, the paper emphasizes the necessity to not only rely on an established simulation model to classify a building. But also integrate the post-occupancy aspect to verify whether the designed building corresponds to the expectations calculated within the early stages.

The POE will allow the continuous improvement of the energy simulation models and verifies their accuracy regarding actual states, leading to adopting specific methods or softwares and having a more extensive overview rather than relying solely on one simulation software.

Regarding the scientists and, more specifically, the building performance engineers, the data obtained from the paper strongly highlight the necessity to have more adaptable definitions regarding specific building standards.

I.e., when the overheating hours surpassed the allowed regulations, it is inevitable to integrate active cooling as a solution if passive solutions weren't designed from the start. This additional energetic load will deviate the building from its initial balanced state, therefore, no longer complying with its initial principles (e.x. the nZEB standard).

Therefore, it is inevitable to define clear definitions that take into account future adaptations of the performance of a building and perhaps translate this definition in the legislative context of the Walloon Region. Where, after conducting the literature review, there is still a lack of a clear description of this nZEB standard that will be shortly adopted as the norm for new and renovated buildings.

An approach that could enable adopting more specific standards, specifically within the Belgian context, is establishing benchmark models for these concepts that can be referred to and used as clear base points within the different simulation tools. Such as the work of (Attia, Shadmanfar, & Ricci, 2020), that developed two benchmark models for nZEB schools based on statistical data obtained from 30 representative schools.

Future research is needed to enhance further the EPC software to account for future changes, either by adopting the proposed long term indicators or by applying a more accurate calculation that differs from the actual method that is based on typical days (cf.Chapter 2).

Chapter 6: Conclusion

- **Summary of the research**

The research uses a chosen verified case study of a passive house in Belgium, that represents a popular building typology, as an assessment tool that allows answering specific issues recognized within the current state of the construction sector in Belgium.

From these issues, we can clearly state the unclarity of the overheating degree of accuracy of the EPC tool, which is adopted by the Walloon Region as a certification and classification tool.

In addition , the research also assesses the sensitivity of high energy efficiency buildings by applying long-term indicators that numerically quantify this risk.

As a final contribution of the research, the impact of ventilative cooling is assessed to verify whether it is efficient as a mitigation strategy for future climate projections.

The objective of this research is summarized as creating energy simulation models of this case study in the EPC software tool and a state-of-the-art energy simulation software DesignBuilder.

This DesignBuilder software runs its simulation on an hourly based calculation using the EnergyPlus engine that has undergone standardized validation procedures (BESTEST procedure).

After the creation of the simulation models, a comparison between the obtained hours of overheating takes place to evaluate their degree of accuracy. And based on the obtained results, a difference of 216% between both software is identified.

The sensitivity of the chosen case study regarding overheating due to climate change is quantified based on the adopted long-term indicators introduced by (Hamdy, Carlucci, Pieter-Jan, & Jan L.M., 2017). By applying these indicators on the indoor operative temperature of the DesignBuilder simulation model, the capacity of the case study to resist climate change is quantified as a 44% chance of resistance.

As for the efficiency of ventilative cooling, it is quantified by applying the passive solution to the DesignBuilder simulation model and reassessing the long term indicators. And based on the obtained results, the efficiency of ventilative cooling as a mitigation strategy is quantified as an 82% effectiveness.

- **Recommendations and contribution to the knowledge**

The proposed research clarifies uncertainties regarding the accuracy of the overheating risk within current regulations, and it quantifies the possibility of overheating risk by applying long-term indicators.

The research results highlight the importance of integrating appropriate overheating indicators to the current legislative framework.

As for the capacity of passive methods to be one of many solutions that can be applied to these high energy efficiency concepts, the results of the research present a high potential and probability of adaptation, hence, supporting the existing arguments and theories.

- **Self-reflection on the research**

Within a sector where pre-construction estimation and calculations are becoming more and more the norm, such research must inevitably be conducted in addition to many others.

These research back up and evaluate the reliability of the used tools and provide insight on lacking points that need periodical improvement, which correspond to the never-ending evolving building sector.

However, specific standards are becoming more and more challenging to satisfy unless the adopted method becomes more and more accurate and takes into account all the variables. And at a certain point, the question must be asked whether these standards are that efficient? And if yes, on what cost? Is it on the cost of the occupant's comfort? Or on the cost of energy consumption?

As a final reflex, it is essential to acknowledge that this research is only the first step in the path of evaluating the reliability of the energy simulation software and standards facing climate and environmental changes.

Also, the lack of availability of data, manifested by the sample size, restricts the dependability of the research, Necessiting its reproduction on a larger scale, to adopt more accurate indicators, that can be applied within the construction sector of Belgium.

Bibliography

Alensis. (2015, January 01). *DesignBuilder Sofware*. Retrieved from Altensis-Managing Sustainability: https://www.altensis.com/en/services/designbuilder-software/

ASHRAE. (2014). *ASHRAE Guidline 14 - Measurement of Energy, Demand and Water Savings.* Atlanta: ASHRAE.

Attia, S., & Gobin, C. (2020, January 01). Predicting the impact of climate change on thermal comfort in a naturally-ventilated nearly zero energy building. *Energy Reports*, pp. 35, 125.

Attia, S., Shadmanfar, N., & Ricci, F. (2020, January 01). Developing two benchmark models for nearly zero energy schools. *Applied Energy*, pp. 1-16.

Biebaut, G.-J., & De Saedeleer, I. (2107). *Nearly Zero-Energy Buildings: An Economic Analysis.* Ghent: Faculty of Ecnonomics and Business Administration - Ghent University.

CIBSE. (2015, January 01). *GVA/15 CIBSE Guide A: Environmental Design 2015*. Retrieved from CIBSE - CHARTERED INSTITUTION OF BUILDING SERVICES ENGINEERS: https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I79JAAS

CSTC. (2011, February 01). *PEB - Systèmes de refroidissement actifs*. Retrieved from CSTC.be: https://www.cstc.be/homepage/index.cfm?cat=publications&sub=infofiches&pag=48&art=8&lang=nl#c2

De Meester, T. (2008). *Etude du comportement thermique et énergétique.* Louvain-la-Neuve: UNIVERSITE CATHOLIQUE DE LOUVAIN.

DesingBuilder. (2019, January 01). *EnergyPlus Hourly Weather Data*. Retrieved from DesingBuilder: https://designbuilder.co.uk/helpv4.5/Content/EnergyPlus_Hourly_Weather_Data.htm

Energie Plus. (2007, September 25). *Confort thermique : généralité*. Retrieved from Energieplus: https://energieplus-lesite.be/theories/confort11/le-confort-thermique-d1/

Energie Plus. (2014, January 30). *Norme NBN EN 15251:2007 : Critères d'ambiance intérieure*. Retrieved from Energie Plus - Le site: https://energieplus-lesite.be/reglementations/confort44/norme-nbn-en-15251-2007-criteres-d-ambiance-interieure/#Evaluation_et_classification_de_l'ambiance_interieure

EnergiePlus. (2014, January 30). *Ventilation intensive mécanique d'été*. Retrieved from EnergiePlus: https://energieplus-lesite.be/techniques/ventilation8/ventilation-intensive/ventilation-intensive-mecanique-d-ete/

Energuide.be. (2020, January 01). *Quels sont les systèmes de ventilation existants?* Retrieved from energuide.be: https://www.energuide.be/fr/questions-reponses/quels-sont-les-systemes-de-ventilation-existants/746/

enregywatch. (2020, January 01). *What is ASHRAE Guidline 14?* Retrieved from enregywatch - energy economics simplified: https://energywatch-inc.com/ashrae-guideline-14/

EPB Center. (2020, January 01). *The Energy Performance of Buildings Directive (EPBD)*. Retrieved from EPB Center: https://epb.center/epb-standards/energy-performance-buildings-directive-epbd/

EUR-Lex. (2018, August 08). *Summaries of EU Legislation*. Retrieved from EUR-Lex Access to European Union Law: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Aen0021

European Commission. (2014, July 31). *Certificates and inspections*. Retrieved from European Commission: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/certificates-and-inspections_en

European Commission. (2019, May 16). *Energy Performance of Buidlings Directive*. Retrieved from Euroean Commission: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

European Union. (2012). *Belgian National Plan-Nearly Zero Energy Buildings.* Brussels: European Union.

Gobin, C. (2016). *Bâtiment d'aujourd'hui, Climat de demain : Evaluation de l'impact du réchauffement climatique sur le confort thermique et l'efficacité énergétique d'un bâtiment résidentiel passif existant en Belgique.* Liege: University of Liege.

Haak, A. (2012). *Climate change and heat stress in residential buildings: Evaluation of adaptation measures.* Eindhoven: Eindhoven University of Technology.

Hamdy, M., Carlucci, S., Pieter-Jan, H., & Jan L.M., H. (2017). The impact of climate change on the overheating risk in dwellings-A Dutch case study. *ELSEVIER*, 307-323.

Hecq, W., Kris, B., Pirotton, M., Meire, P., & De Sutter, R. (2006). *General study and evaluation of potential impacts of climate change in Belgium.* Brussels: CEESE - Centre for Economic and Social Studies on the Environment.

Holt, J. (2020, March 18). *Thermal mass and Energy Savings*. Retrieved from Wells: https://www.wellsconcrete.com/blog/thermal-mass-and-energy-savings/

IPCC. (2018). *Global warming of 1.5°C.* Switzerland: IPCC - Intergovernmental Panel on Climate Change.

JRC - European Commission. (2016). *Synthesis Report on the National Plans for Nearly Zero Energy Buildings (nZEBS).* Italy: European Union.

Kamal, M. A. (2012). An Overview of Passive Cooling Techniques in Buildings: Design Concepts and Architectural Interventions. *Acta Technica Napocensis: Civil Engineering & Architecture*, 84-97.

Lomas, K., & Porritt, S. (2017, November 30). Overheating in buildings : lessons from research. *Building Research & Information*, pp. 1-18.

Monfils, S., & Hauglustaine, J.-M. (2016). Introduction of Behavioral Parameterization in the EPC Calculation Method and Assessment of Five Typical Urban Houses in Wallonia, Belgium. *Sustainability*, 1-23.

Oleson, B., & Parsons, K. (2002, January 01). Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730. *Energy and Buildings*, pp. 537-548.

Passive House Institute. (2016). *Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard.* Darmstadt: Passive House Institute.

Pastore, L., & Andersen, M. (2019, January 07). Building energy certification versus user satisfaction with the indoor environment: Findings from a multi-site post occupancy evaluation (POE) in Switzerland. *Building and Environment 150*, pp. 60-74.

Reiter, S., & Nguyen, A. (2014). The efficiency of different simulation-based design methods in improving building performance. *WIT Transactions on Ecology on The Built Environment, vol. 142*, 139-149.

Service public fédéral Chancellerie du Premier Ministre. (2009). *MONITEUR BELGE − 30.12.2009 − BELGISCH STAATSBLAD.* Brussels: Service public fédéral Intérieur.

Singh, M. K., Attia , S., Mahapatra, S., & Teller, J. (2016, January 01). Assessment of thermal comfort in existing pre-1945 residential building stock. *Energy 98*, pp. 122-134.

Sofia Energy Centre. (2009). *Passive cooling and summer friendly design and engineering.* Bulgaria: European Union.

SPW - Wallonie Energie. (2017). *EPBD implementation in Belgium - Wallon Region.* Jambes: Public Service of Walloon Region.

SPW - Wallonie énergie. (2018). *Le Guide PEB.* Jambes: SPW Energie.

SPW. (2020, January 01). *Bâtiments Quasi Zéro Energie (Q-ZEN)*. Retrieved from SPW - Wallonie Energie: https://energie.wallonie.be/fr/q-zen.html?IDC=8729

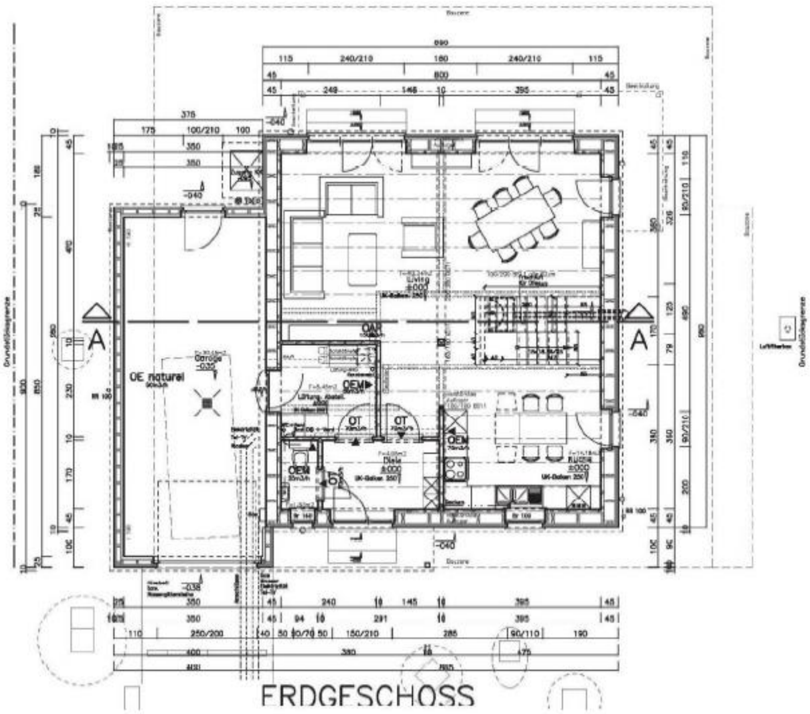
SPW Energie. (2015, May 07). *La certification PEB des bâtiments*. Retrieved from Service Public de Wallonie: https://energie.wallonie.be/fr/certification-peb.html?IDC=7506

Vanderavero, L. (2019). *Comparaison des résultats du logiciel PEB avec une simulation thermodynamique pour un bâtiment résidentiel.* Liege: University of Liege.

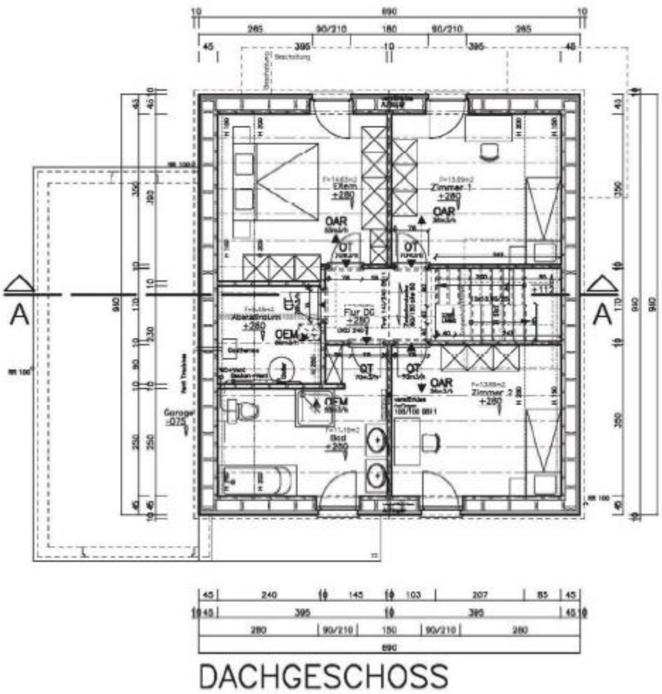
Walloon Government. (2018). *Annexe A1-Méthode de détermination du niveau de consommation d'énergie primaire des unités residentielles.* Namur: Wallon Gouvernment.

Annex:

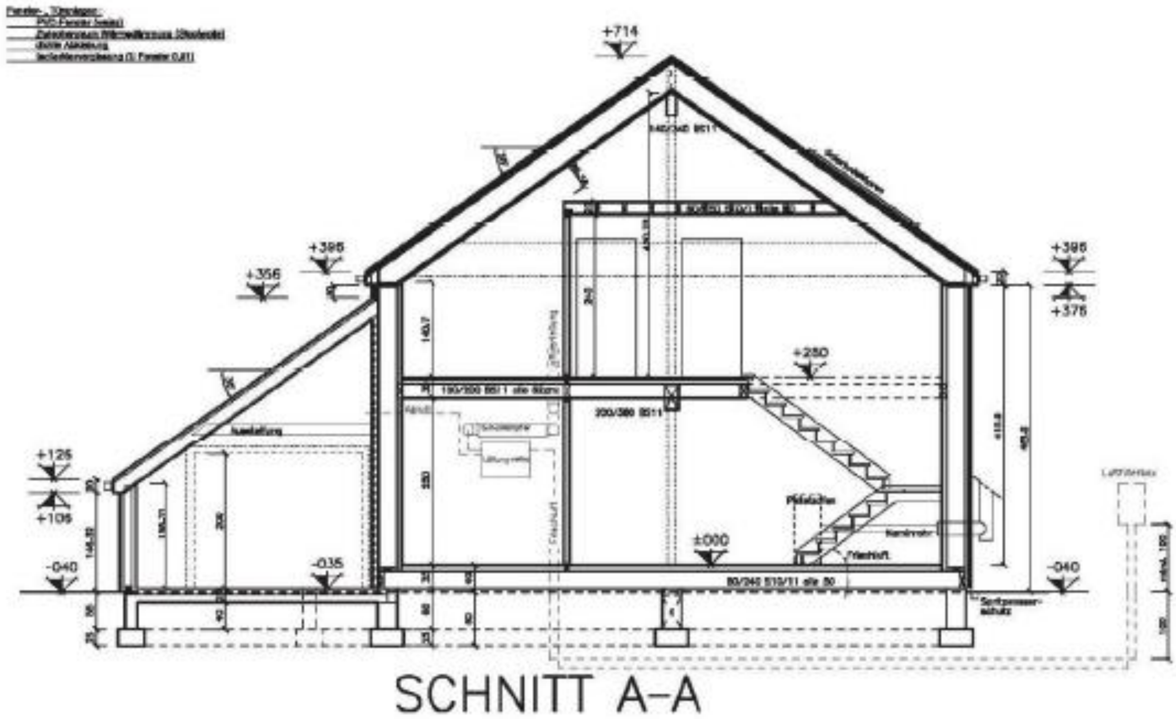
4.1. Annex-1: The detailed geometry, envelope compositions, and systems



Ground Floor Plan

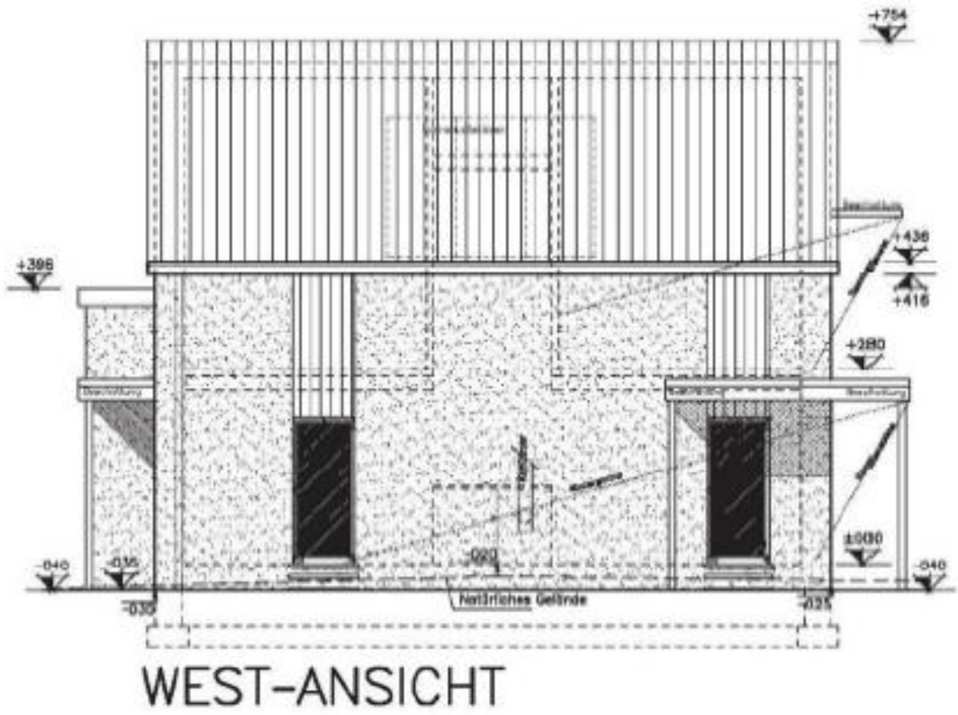


First Floor Plan

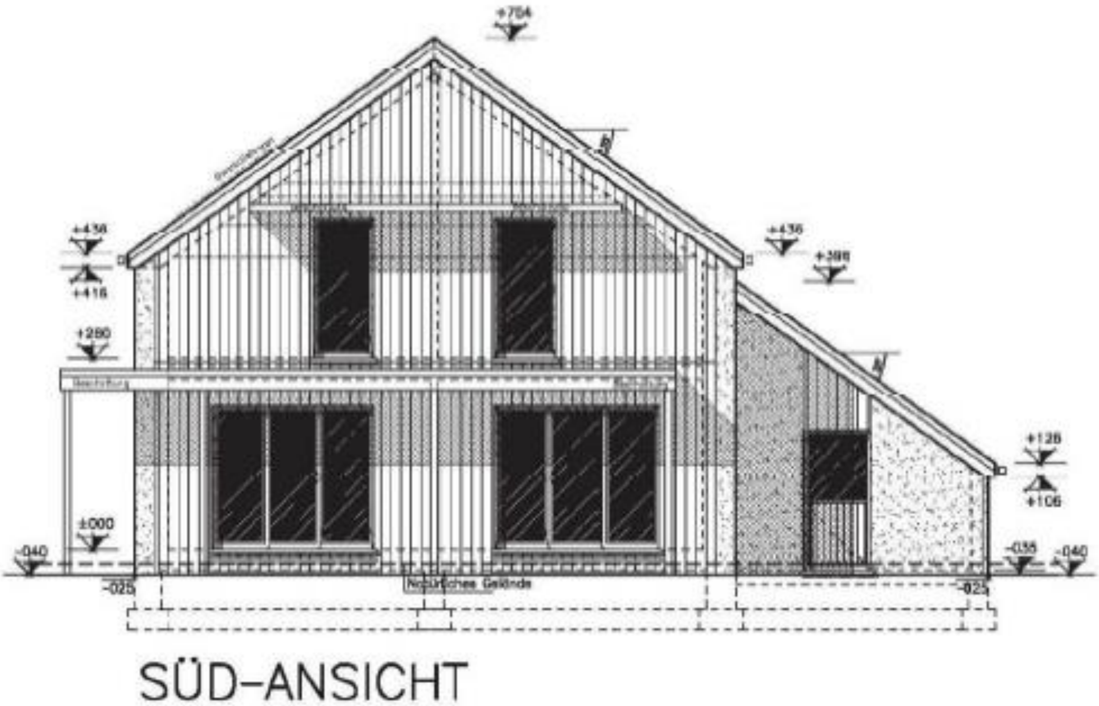


Section A-A

North Elevation

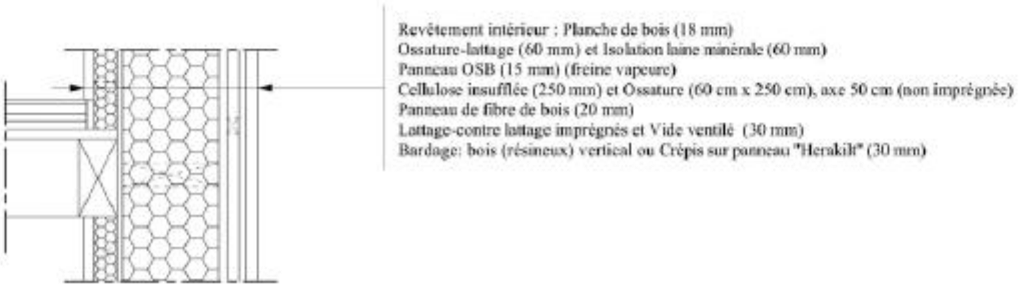


West Elevation



South Elevation

MUR EXTERIEUR (45 cm)	Epaisseur e [mm]	Conductivité thermique λ [W/mK]	Conductivité thermique λ [kJ/hmK]	Capacité thermique c [kJ/kgK]	Densité ρ [kg/m³]	Résistance thermique R [m²K/W]
Revêtement int : Planche de bois	18	0,13	0,47	1,88	600	0,014
Isolation laine minérale	60	0,04	0,144	0,84	80	1,500
Ossature-lattage	60	0,13	0,468	1,88	800	0,462
Panneau OSB	15	0,13	0,468	1,88	650	0,115
Cellulose insufflée	250	0,04	0,144	0,84	110	6,250
Ossature 60/250	250	0,13	0,468	1,88	800	1,923
Panneau de fibre de bois	20	0,045	0,162	1,88	110	0,444
Lattage-contre lattage	30	0,13	0,468	1,88	800	0,231
Vide ventilé	30	0,163	0,587	1,017	1,25	0,184
Bardage: bois (résineux) vertical	30	0,163	0,587	1,88	600	0,184



Exterior Wall Composition

	W/m²K	dB
Fenêtre	0,81	33
Vitrage	0,5	32

Windows specifications

TOIT (48cm)	Epaisseur e [mm]	Conductivité thermique λ [W/mK]	Conductivité thermique λ [kJ/hmK]	Capacité thermique c [kJ/kgK]	Densité ρ [kg/m³]	Résistance thermique R [m²K/W]
Revêtement int : planche de bois	18	0,13	0,47	1,88	600	0,138
Laine minérale	60	0,04	0,144	0,84	80	1,500
Lattage 40/60	60	0,13	0,468	1,88	800	0,462
Faite en LC 140/340		0,13	0,468	1,88	800	
Cellulose insufflée	300	0,04	0,144	0,84	110	7,500
Chevron 6/30	300	0,13	0,468	1,88	800	2,308
Panneaux de bois	22	0,13	0,468	1,88	650	0,169
Lattage - contre lattage	50	0,13	0,468	1,88	800	0,385
Vide ventilé	50	0,271	0,976	1,017	1,25	0,185
Tuiles	20	1,4	5,04	0,84	2000	0,014

Roof Composition

MUR INT	Epaisseur e [mm]	Conductivité thermique λ [W/mK]	Conductivité thermique λ [kJ/hmK]	Capacité thermique c [kJ/kgK]	Densité ρ [kg/m³]	Résistance thermique R [m²K/W]
Planche en bois	20	0,13	0,468	1,88	650	0,154
Ossature 60/60	60	0,13	0,468	1,88	800	0,462
Isolation laine minérale	60	0,04	0,144	0,84	80	1,500
Structure poteau poutre intégré en LC	18	0,13	0,468	1,88	650	0,138

Interior wall Composition

PLANCHER DU REZ-DE-CHAUSSEE	Epaisseur e [mm]	Conductivité thermique λ [W/mK]	Conductivité thermique λ [kJ/hmK]	Capacité thermique c [kJ/kgK]	Densité ρ [kg/m³]	Résistance thermique R [m²K/W]
Carrelage	30	1,2	4,32	0,84	2000	0,025
Chape	60	1,44	5,2	0,84	2200	0,042
Panneau OSB	22	0,13	0,468	1,88	650	0,169
Cellulose insufflée	250	0,04	0,144	0,84	110	6,250
Gitage 60/250	250	0,13	0,468	1,88	800	1,923
Panneau fibre-ciment	10	1,25	4,5	0,84	2000	0,008

Ground Slab Composition

Plancher (étage)	Epaisseur e [mm]	Conductivité thermique λ [W/mK]	Conductivité thermique λ [kJ/hmK]	Capacité thermique c [kJ/kgK]	Densité ρ [kg/m³]	Résistance thermique R [m²K/W]
Plancher en bois	15 - 18	0,13	0,47	1,88	600	0,115 - 0,138
Isolation phonique	20 - 40	0,04	0,144	0,84	110	0,5 - 1
Planches de bois	24	0,055	0,2	1,88	300	0,436
Gîtage en LC 10/20	20 - 20	0,13	0,468	1,88	800	
Poutre principale LC 200/380	200/380	0,13	0,468	1,88	800	

First Floor slab Composition

Valeur calorifique	5,3 kWh/kg
Densité	700 kg/m³
Teneur en humidité	8% du poids au max
Part de cendres	1% du poids au max
Diamètre	5 - 6,5 mm
Longueur	30 mm au max
Contenu	100% de bois non traité et sans adjonction de produit liant (part d'écorce 5% au max.)
Emballage	en sacs, composés de plastique neutre pour l'environnement, biodégradables ou en papier (2 - 3 couches/similaire à un sac de ciment)

Tableau 2.3 : Spécification des pellets

Heater Specifications

Le boiler et les capteurs solaires

Le boiler est couplé à un système de capteur solaire (6m²) qui vont permettre de préchauffer l'eau chaude sanitaire. Le boiler de marque Sieger a besoin d'un appoint, au gaz dans ce cas-ci.

Ces panneaux solaires sont placés sur le toit, exposés au sud et inclinés à 35°C. Notons que l'inclinaison de 45°C est plus avantageuse comme ont pu le démontrer de précédents travaux[19].

Boiler and Solar panel properties

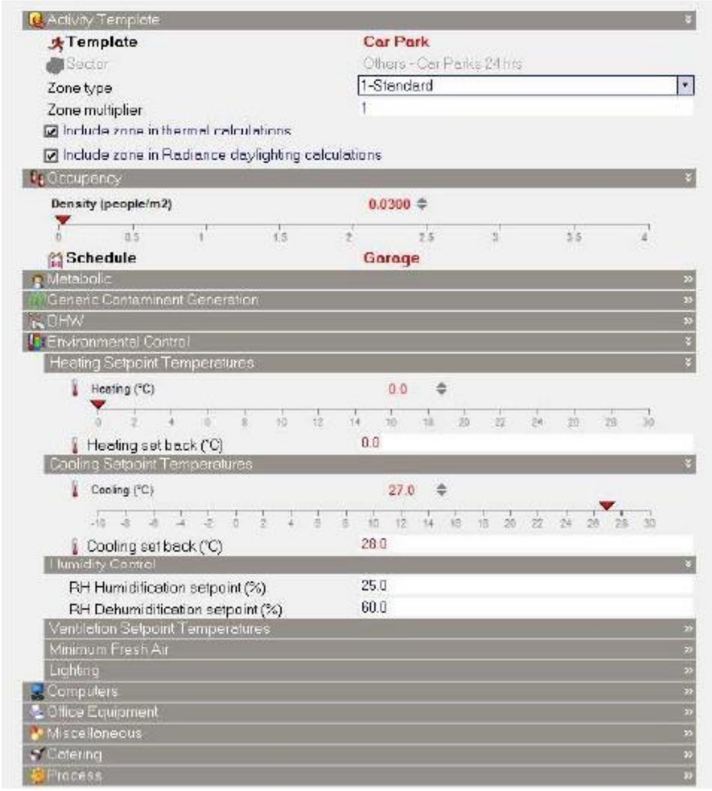
L'étanchéité à l'air de la maison Kettenis a donc été calculée lors du test d'étanchéité à l'air sous 50 Pa, le Blowerdoor (Figure 2.16). Le renouvellement d'air sous une différence de pression de 50 Pascal (n_{50}) entre l'intérieur et l'extérieur est de 0,5 vol/h. Rappelons que la norme exige 0,6 vol/h pour une maison passive. Concrètement, il faut considérer l'atmosphère sous 2 Pa ce qui nous permet d'établir l'hypothèse que les infiltrations sont de 0,02 vol/h, en considérant une relation linéaire. Cela correspond pour un volume total annoncé de 536 m^3 à « 10,72 m^3/h » (et 268 m^3/h sous 50 Pa) ce qui est très performant !

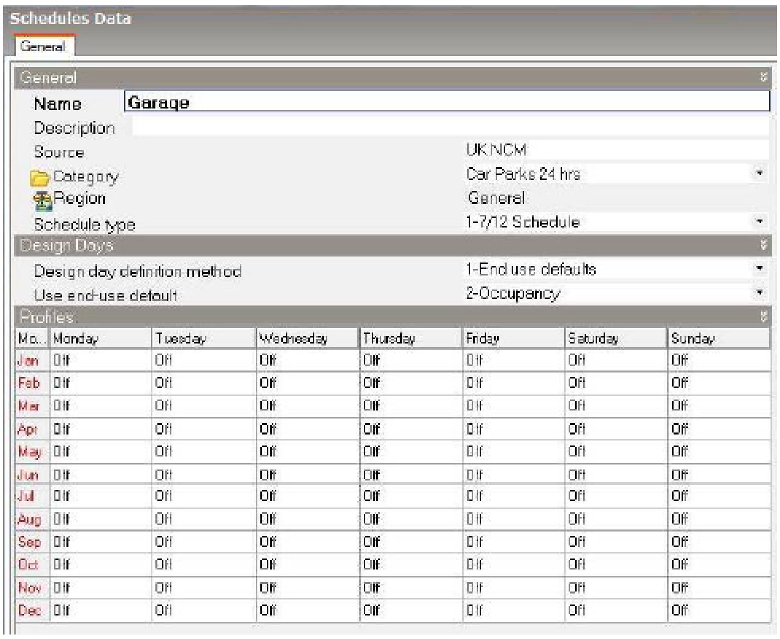
Air tightness

Zonage	Zone11	Zone12	Zone13	Zone14	Zone22	Zone23	Zone24	Zone25	Zone26
Pièce	**Living**	**Local technique**	**Hall d'entrée**	**Vestiaire**	**Ch. Parent**	**Ch. Enfant Sud**	**Ch. Enfant Nord**	**Salle de bain**	**Local technique**
Surface au sol	57,93	5,52	4,95	1,60	14,79	13,83	13,83	11,33	5,52
Volume	144,84	13,80	12,37	4,00	39,47	38,81	38,81	29,17	23,21
Débit de ventilation nominale m³/h/m²	3,60	3,60	3,60	3,60	3,60	3,60	3,60	3,60	3,60
Débit de ventilation calculé (m³/h)	208,56	19,87	17,81	5,75	53,23	49,77	49,77	40,77	19,87
Choix des débits en fonction de la réglementation (min ou max)	Min 75 m3/h et max 150 m3/h + Reprise dans la partie cuisine	du living	Zone de transfert d'air	Reprise d'une partie des débits venant du hall (pour wc : min 25 m³/h)	Min25 m3/h et max 36 m3/h par personne	Min25 m3/h et max 36 m3/h par personne	Min25 m3/h et max 36 m3/h par personne	Min 50 m3/h et max 75 m3/h reprise d'une partie des débits du premier étage	Reprise d'une partie des débits du premier étage
Débit (m³/h) (« vitesse 3 »)	**150 + (-75)**	**-50**	**(75)**	**-25**	**53**	**36**	**36**	**-75**	**-50**
Débit actuel (m³/h) (« vitesse 1 »)	**60 + (-30)**	**-20**	**(30)**	**-10**	**21,20**	**14,40**	**14,40**	**-30**	**-20**
Renouvellement de l'air (1/h) selon la réglementation	1,036	3,623	6,064	6,258	1,343	0,928	0,928	2,571	2,154
Renouvellement de l'air (1/h) selon la réalité (« vitesse 1 »)	0,414	1,449	2,426	2,503	0,537	0,371	0,371	1,028	0,862

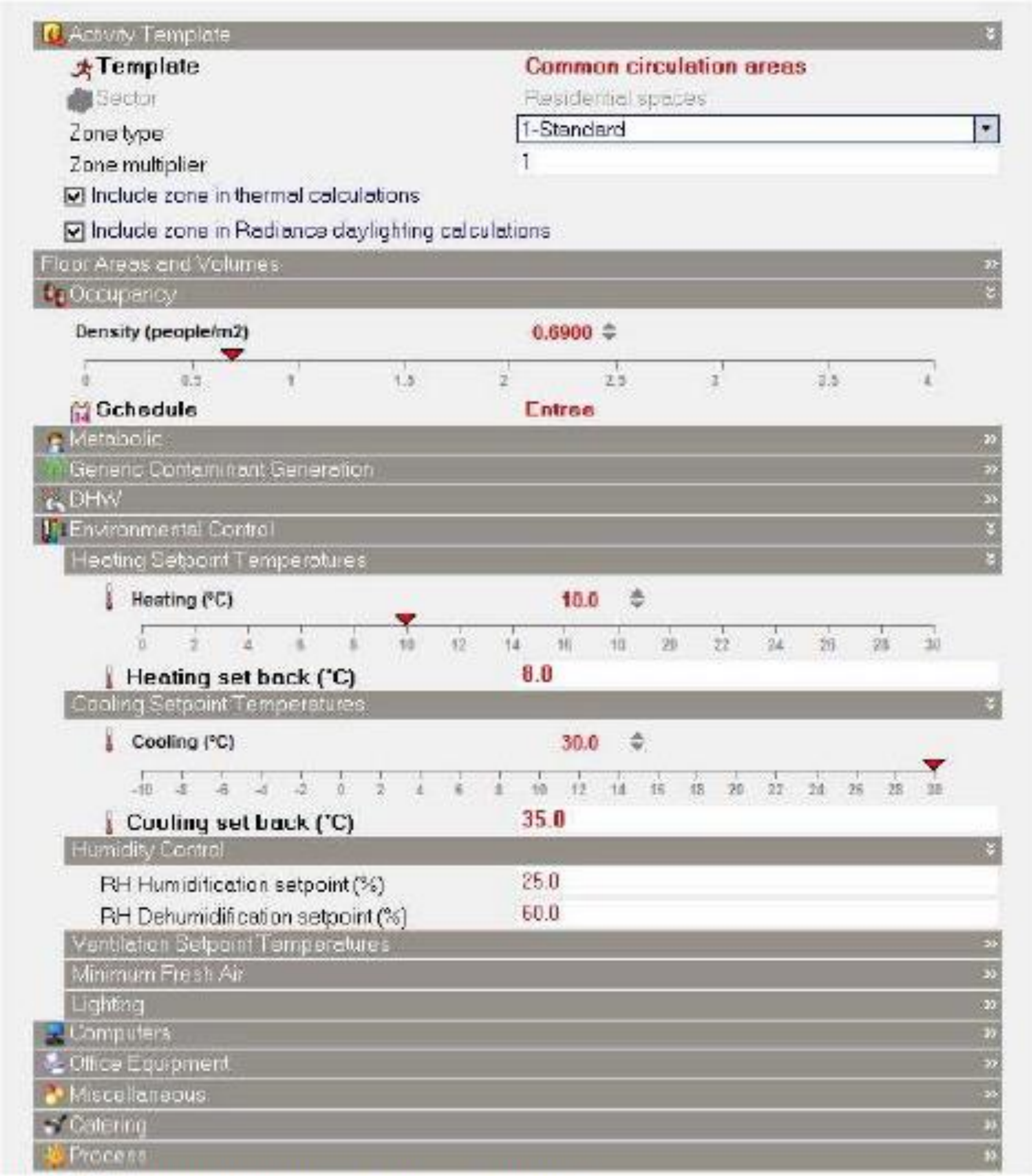
Ventilation rates

4.2. Annex-2: The activity schedule and minor details required for DesignBuilder





Activity data – garage



igure 61 : DesignBuilder - Activity – Entrée

Mo..	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Feb	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Mar	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Apr	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
May	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Jun	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Jul	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Aug	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Sep	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Oct	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Nov	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Dec	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30

Activity data – Entrance

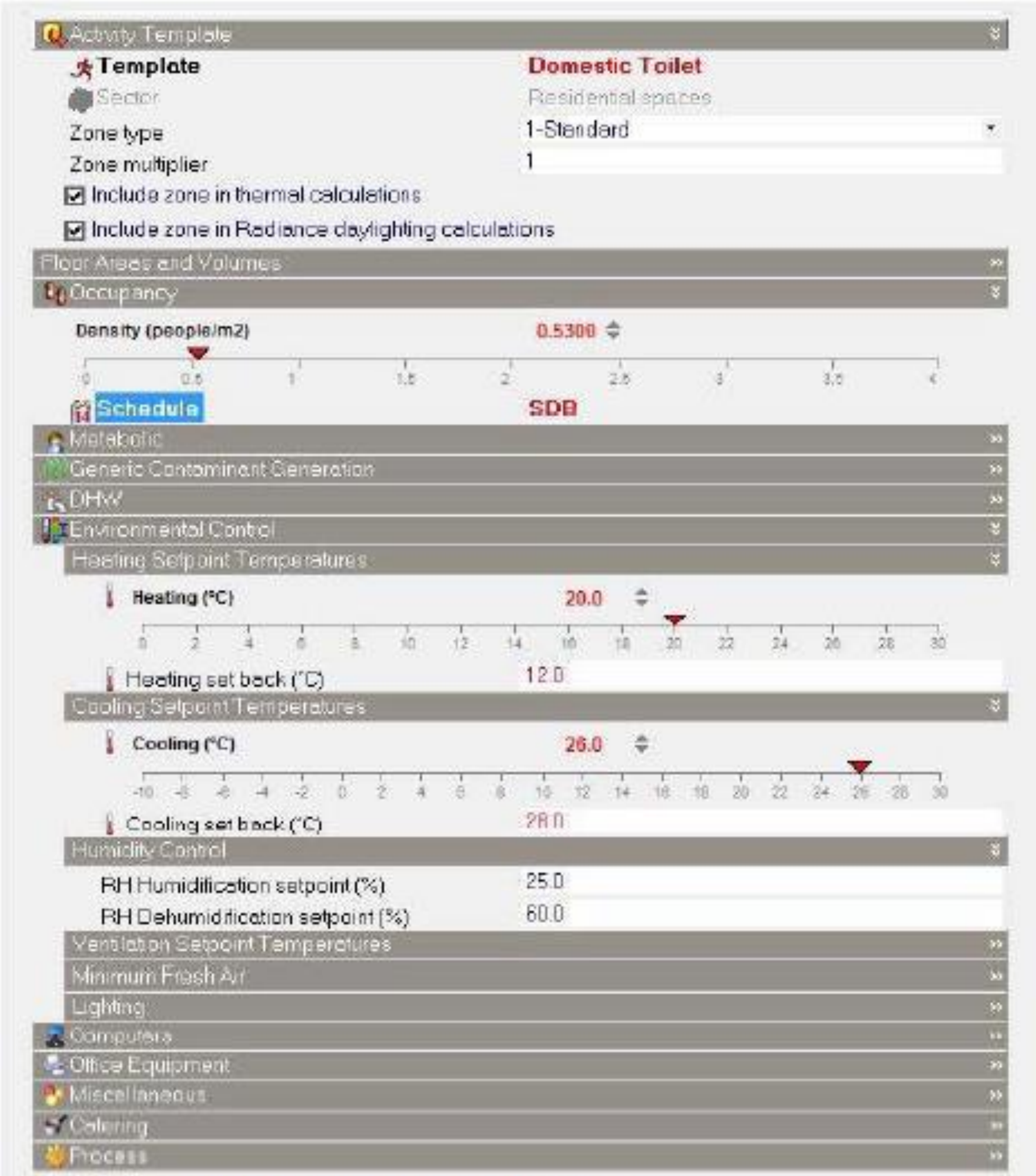


Figure 63 : DesignBuilder - Activity - Toilettes

Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Feb	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Mar	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Apr	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
May	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Jun	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Jul	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Aug	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Sep	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Oct	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Nov	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Dec	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30

Activity data – Toilets

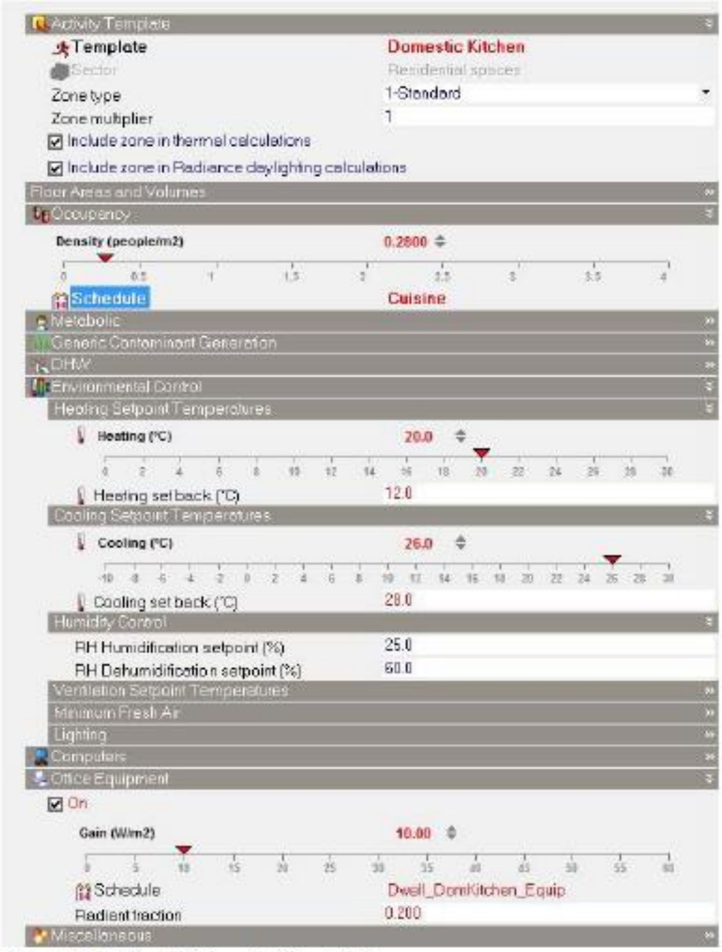
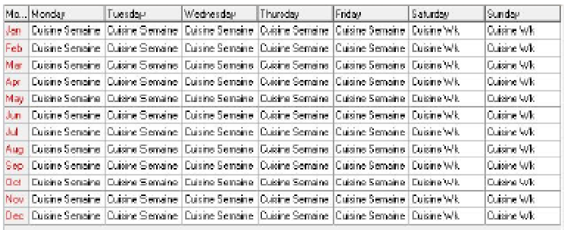


Figure 65 : DesignBuilder - Activity - Cuisine



Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Feb	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Mar	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Apr	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
May	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Jun	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Jul	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Aug	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Sep	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Oct	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Nov	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk
Dec	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Semaine	Cuisine Wk	Cuisine Wk

Figure 66 : DesignBuilder - Activity - Planning Cuisine

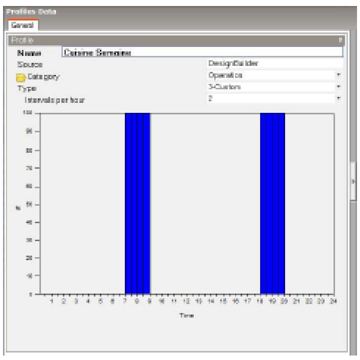


Figure 67 : DesignBuilder - Activity - Planning Cuisine Semaine

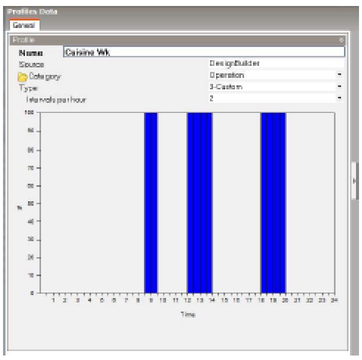
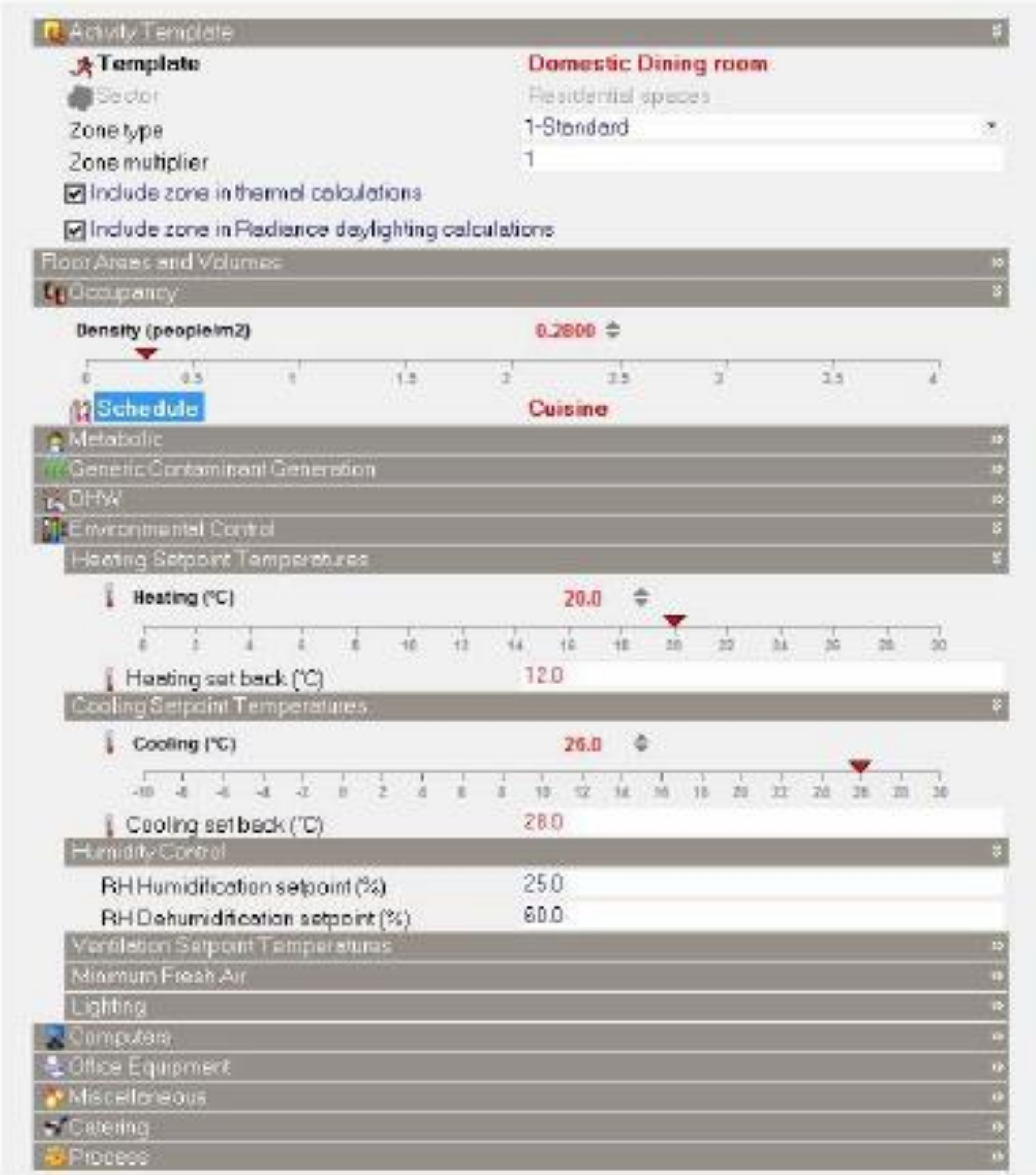


Figure 68 : DesignBuilder - Activity - Planning Cuisine Week-End

Activity data – Kitchen



Activity data – Dining room

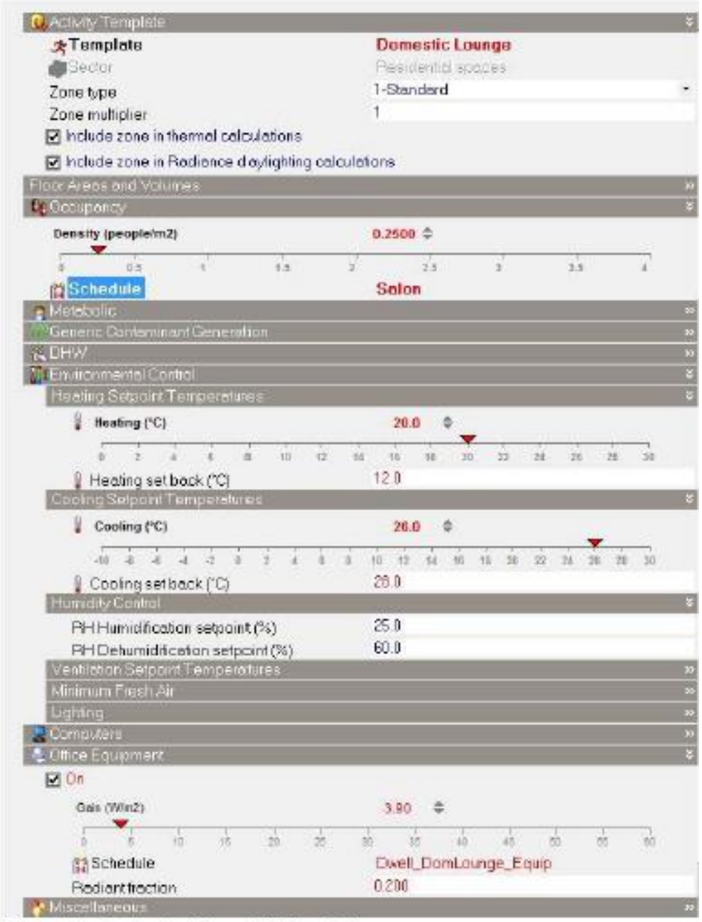


Figure 70 : DesignBuilder - Activity - Salon

Mo..	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Feb	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Mar	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Apr	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
May	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Jun	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Jul	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Aug	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Sep	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Oct	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Nov	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk
Dec	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Semaine	Salon Wk	Salon Wk

Figure 71 : DesignBuilder - Activity - Planning Salon

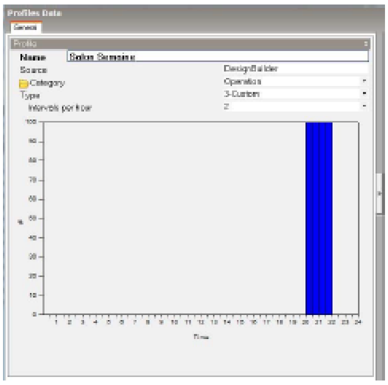


Figure 72 : DesignBuilder - Activity - Planning Salon Semaine

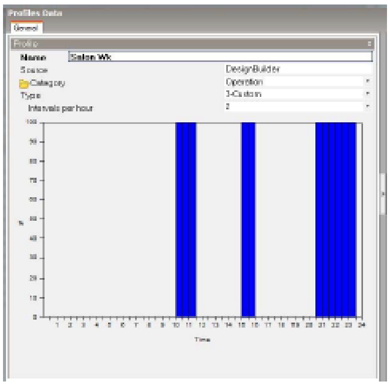


Figure 73 : DesignBuilder - Activity - Planning Salon Week-end

Activity data – Living room

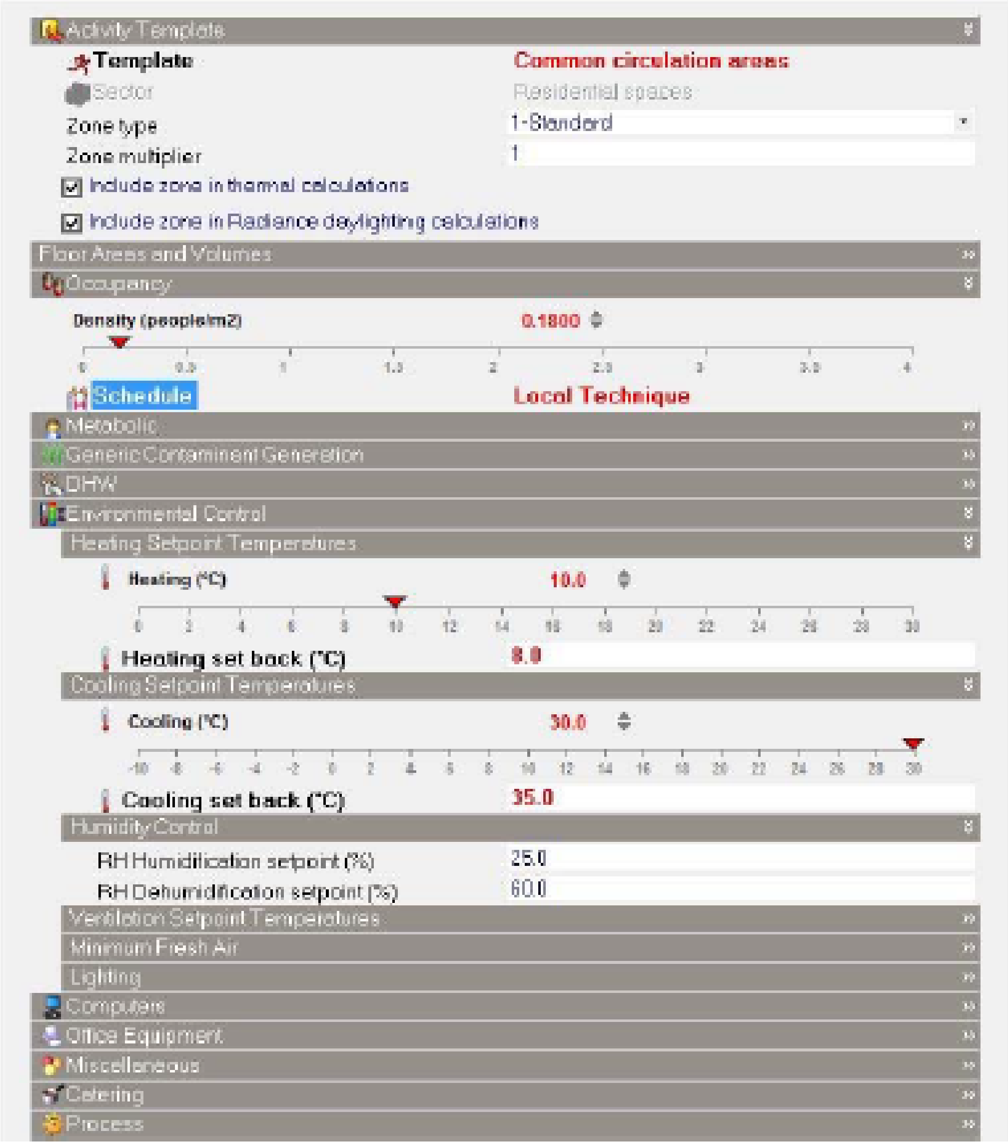


Figure 74 : DesignBuilder - Activity - Locaux Techniques

No.	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	Off	Off	Off	Off	Off	Off	Off
Feb	Off	Off	Off	Off	Off	Off	Off
Mar	Off	Off	Off	Off	Off	Off	Off
Apr	Off	Off	Off	Off	Off	Off	Off
May	Off	Off	Off	Off	Off	Off	Off
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	Off	Off	Off	Off	Off	Off	Off
Sep	Off	Off	Off	Off	Off	Off	Off
Oct	Off	Off	Off	Off	Off	Off	Off
Nov	Off	Off	Off	Off	Off	Off	Off
Dec	Off	Off	Off	Off	Off	Off	Off

Figure 75 : DesignBuilder - Activity - Planning Locaux Techniques

Activity data – technical rooms

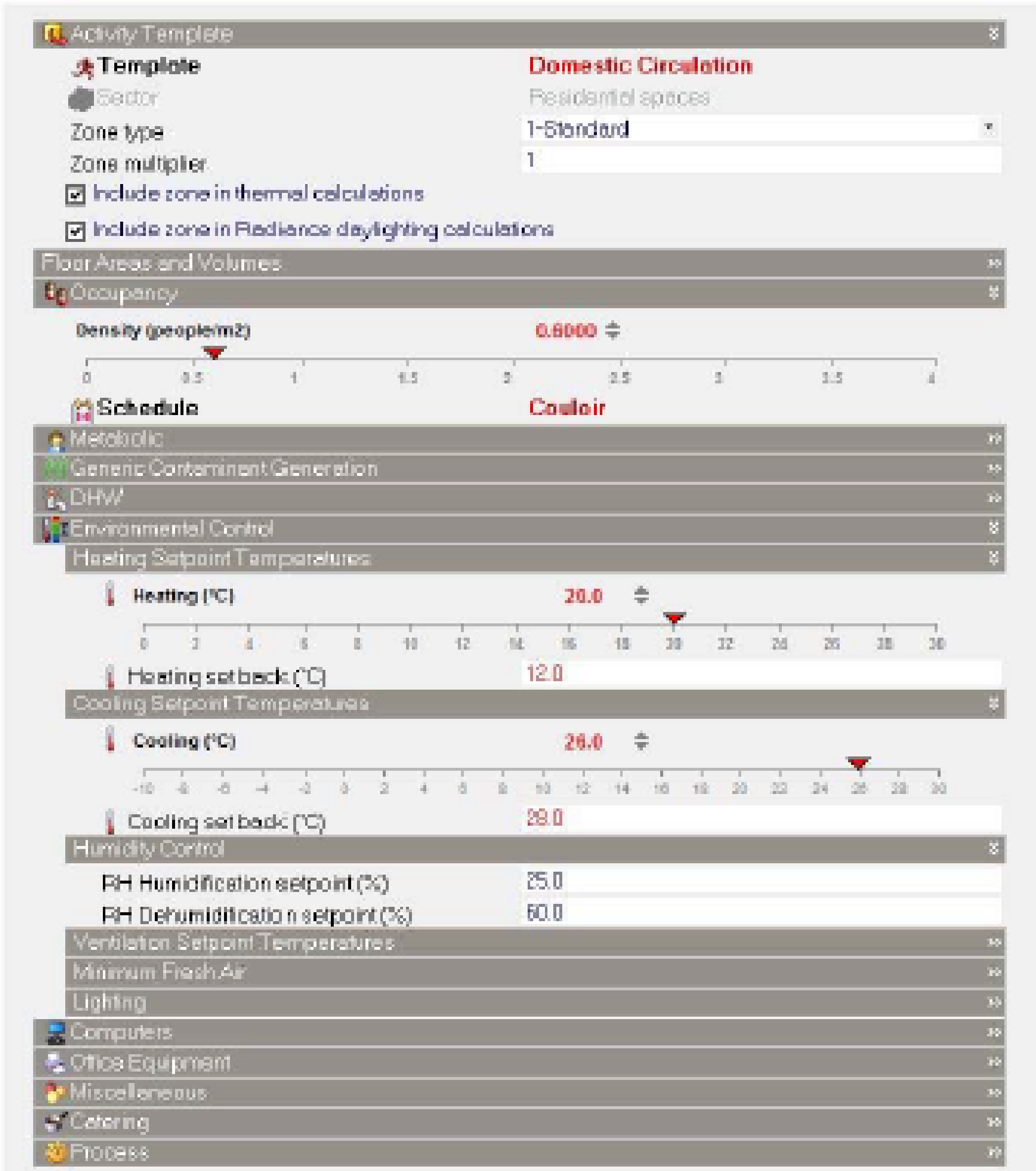


Figure 76 : DesignBuilder - Activity - Circulations

Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Feb	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Mar	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Apr	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
May	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Jun	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Jul	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Aug	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Sep	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Oct	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Nov	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Dec	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30

Figure 77 : DesignBuilder - Activity - Planning Circulations

Activity data - Circulation zones

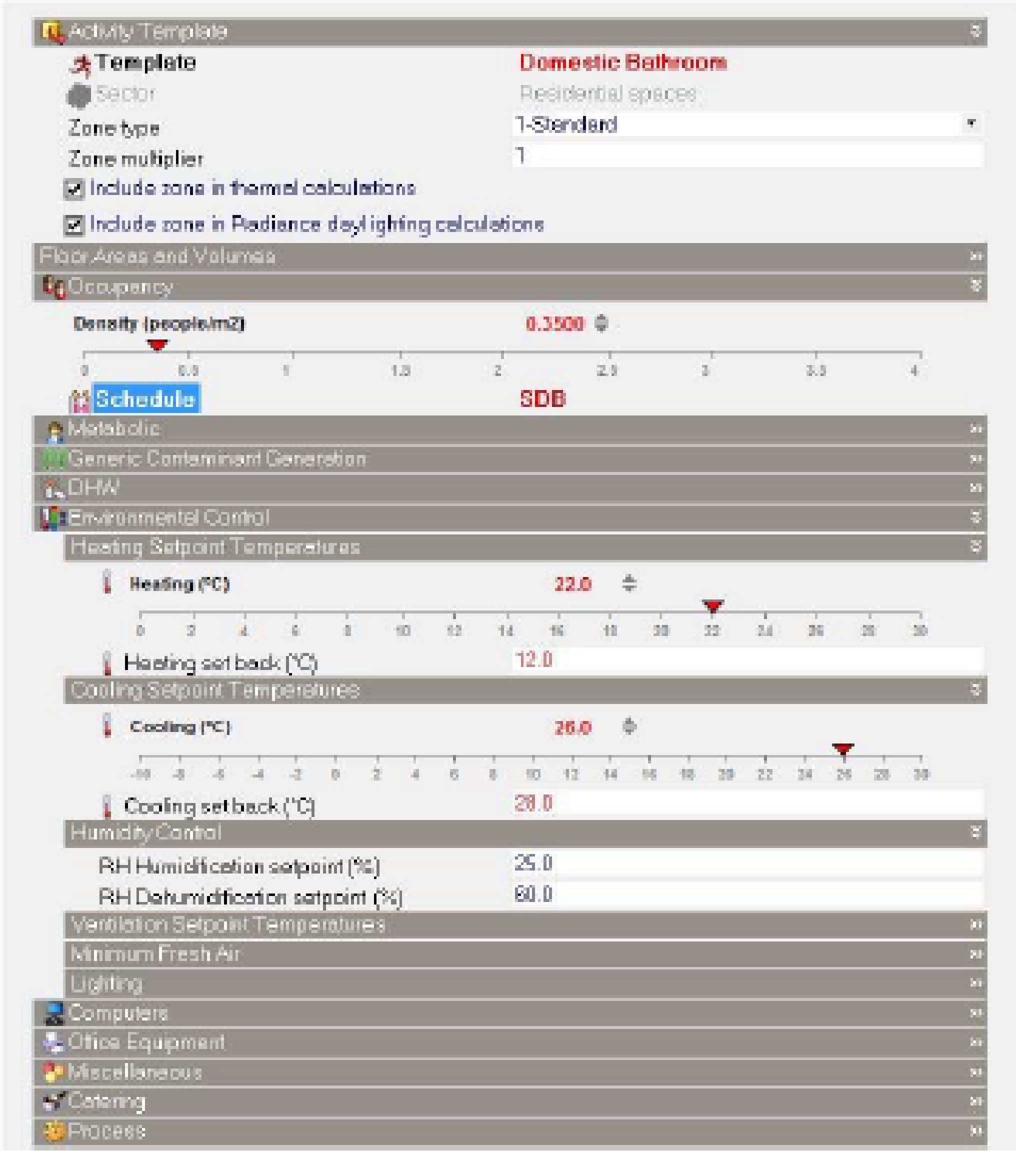


Figure 78 : DesignBuilder - Activity - Salle de Bain

Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Feb	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Mar	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Apr	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
May	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Jun	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Jul	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Aug	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Sep	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Oct	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Nov	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30
Dec	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30	12:30 - 13:30

Figure 79 : DesignBuilder - Activity - Planning Salle de Bain

Activity data -Bathroom

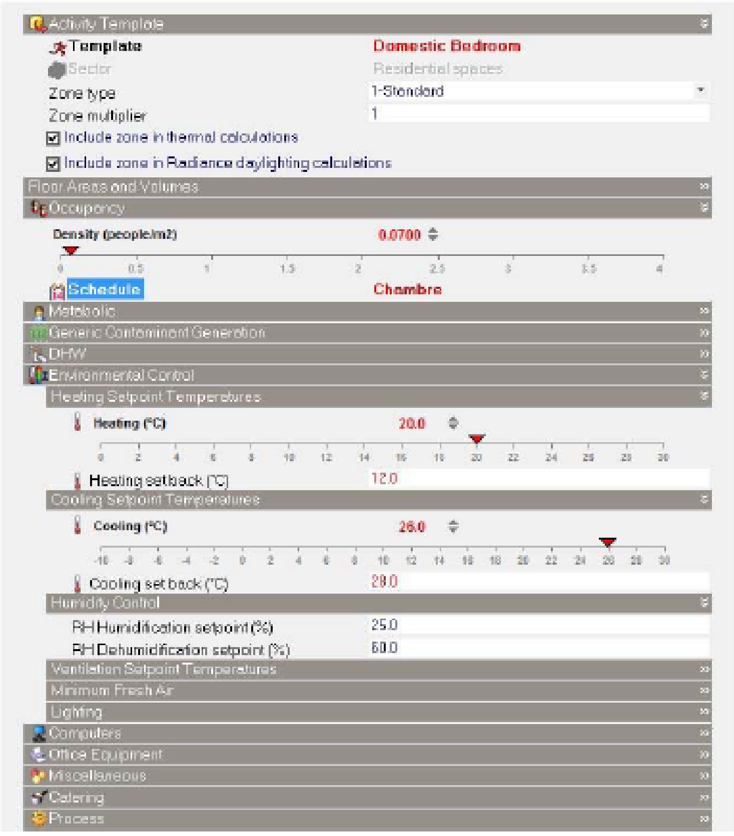
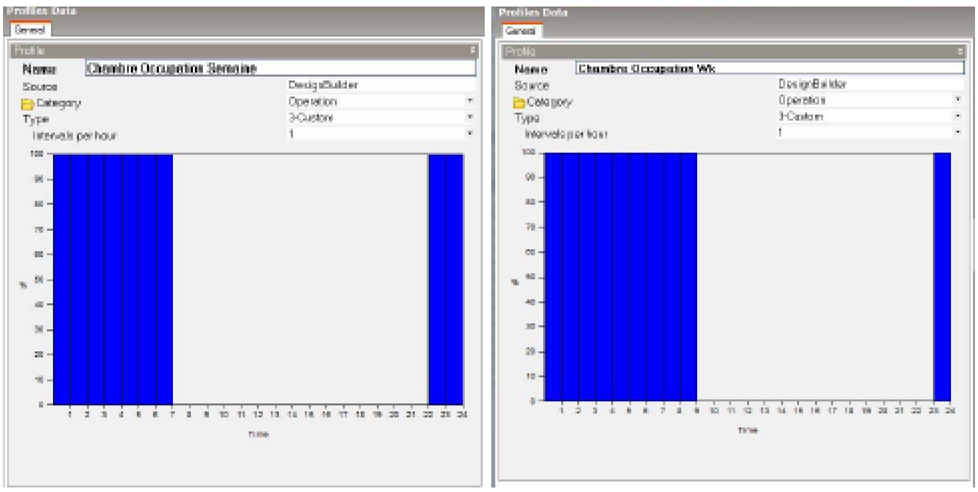


Figure 80 : DesignBuilder - Activity - Chambres

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Feb	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Mar	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Apr	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
May	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Jun	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Jul	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Aug	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Sep	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Oct	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Nov	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...
Dec	Chambre Occupation Semaine	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occ...	Chambre Occupation Wk	Chambre Occ...

Figure 81 : DesignBuilder - Activity - Planning Chambres



Activity data – Bedroom

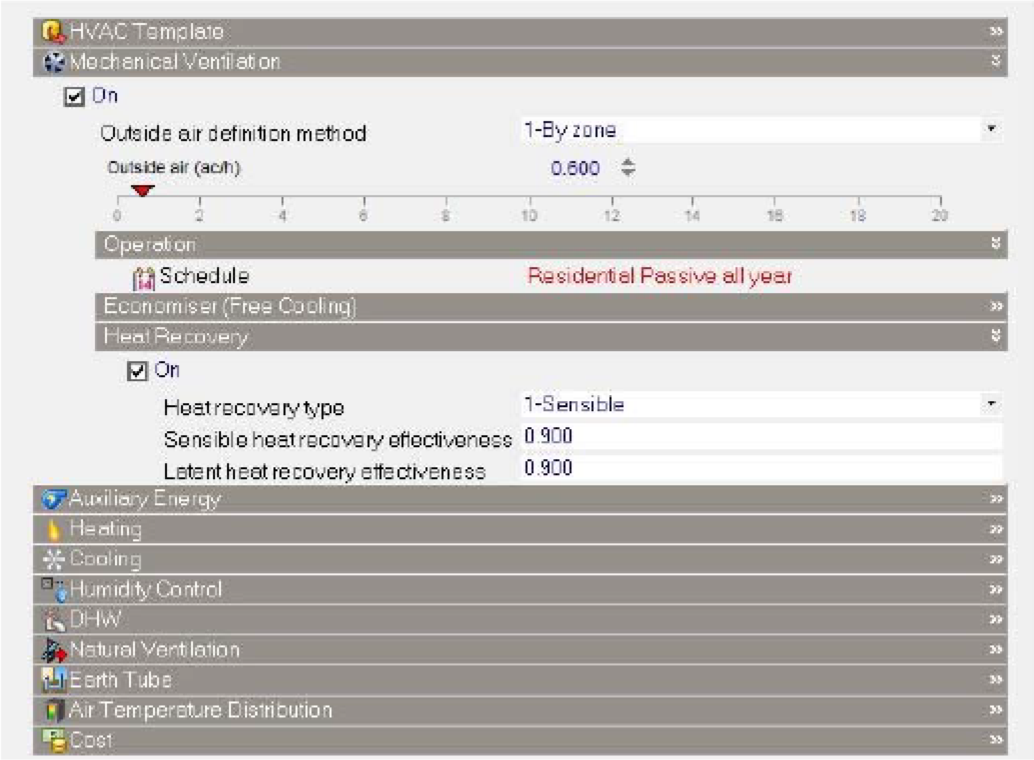
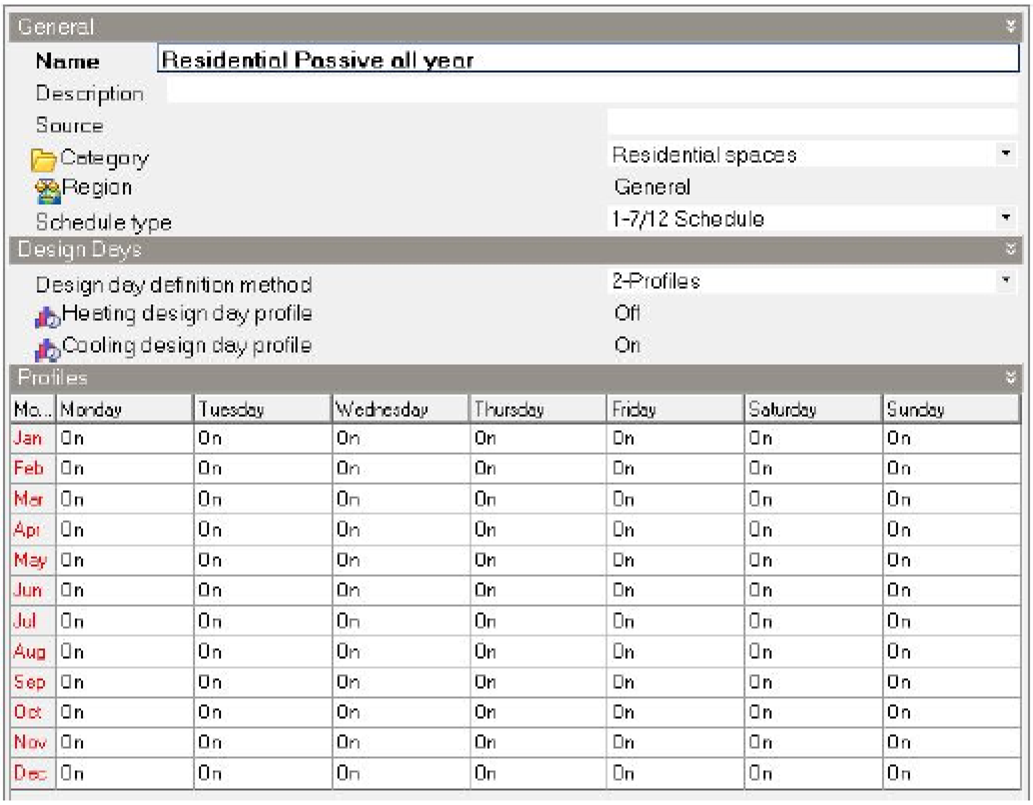


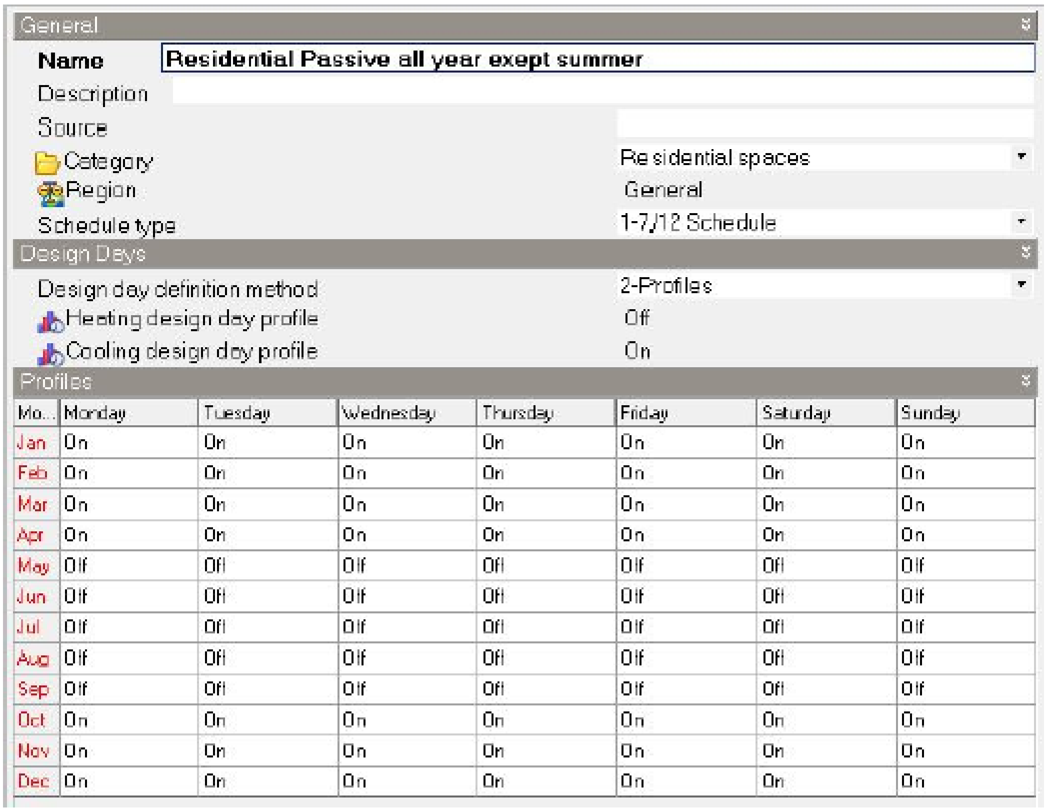
Figure 87 : DesignBuilder - HVAC - Ventilation mécanique



Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	On	On	On	On	On	On	On
Feb	On	On	On	On	On	On	On
Mar	On	On	On	On	On	On	On
Apr	On	On	On	On	On	On	On
May	On	On	On	On	On	On	On
Jun	On	On	On	On	On	On	On
Jul	On	On	On	On	On	On	On
Aug	On	On	On	On	On	On	On
Sep	On	On	On	On	On	On	On
Oct	On	On	On	On	On	On	On
Nov	On	On	On	On	On	On	On
Dec	On	On	On	On	On	On	On

Ventilation System data

Figure 89 : DesignBuilder - HVAC - Chauffage et Refroidissement



Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	On	On	On	On	On	On	On
Feb	On	On	On	On	On	On	On
Mar	On	On	On	On	On	On	On
Apr	On	On	On	On	On	On	On
May	Off	Off	Off	Off	Off	Off	Off
Jun	Off	Off	Off	Off	Off	Off	Off
Jul	Off	Off	Off	Off	Off	Off	Off
Aug	Off	Off	Off	Off	Off	Off	Off
Sep	Off	Off	Off	Off	Off	Off	Off
Oct	On	On	On	On	On	On	On
Nov	On	On	On	On	On	On	On
Dec	On	On	On	On	On	On	On

Heating System data

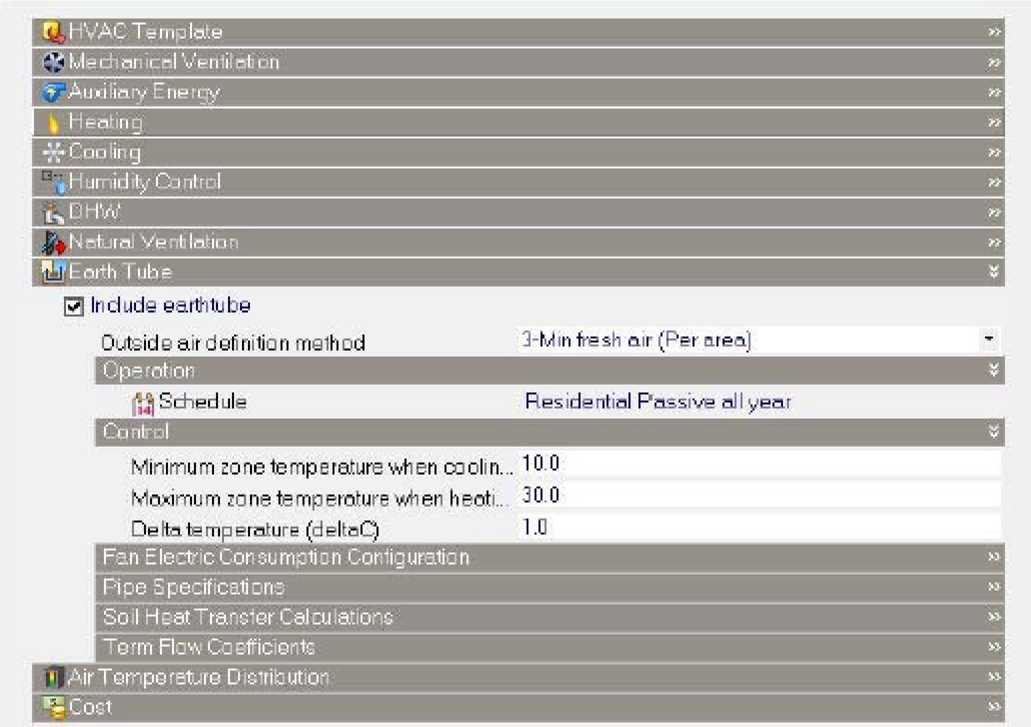
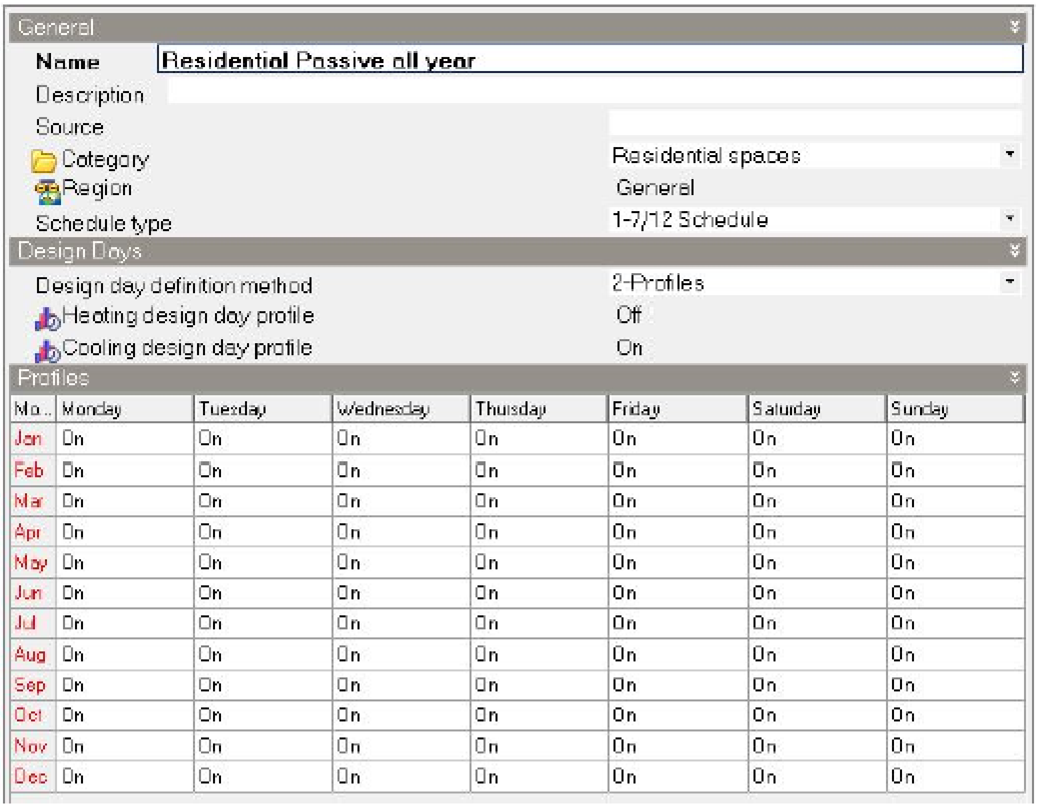


Figure 93 : DesignBuilder - HVAC - Puits canadien


General

Name Residential Passive all year

Description

Source

Category: Residential spaces

Region: General

Schedule type: 1-7/12 Schedule

Design Days

Design day definition method: 2-Profiles

Heating design day profile: Off

Cooling design day profile: On

Profiles

Mo...	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Jan	On	On	On	On	On	On	On
Feb	On	On	On	On	On	On	On
Mar	On	On	On	On	On	On	On
Apr	On	On	On	On	On	On	On
May	On	On	On	On	On	On	On
Jun	On	On	On	On	On	On	On
Jul	On	On	On	On	On	On	On
Aug	On	On	On	On	On	On	On
Sep	On	On	On	On	On	On	On
Oct	On	On	On	On	On	On	On
Nov	On	On	On	On	On	On	On
Dec	On	On	On	On	On	On	On

Earth tube data

4.3. Annex-3: The report exported from the PEB software

**Performance énergétique
et climat intérieur des bâtiments**

Rapport PEB

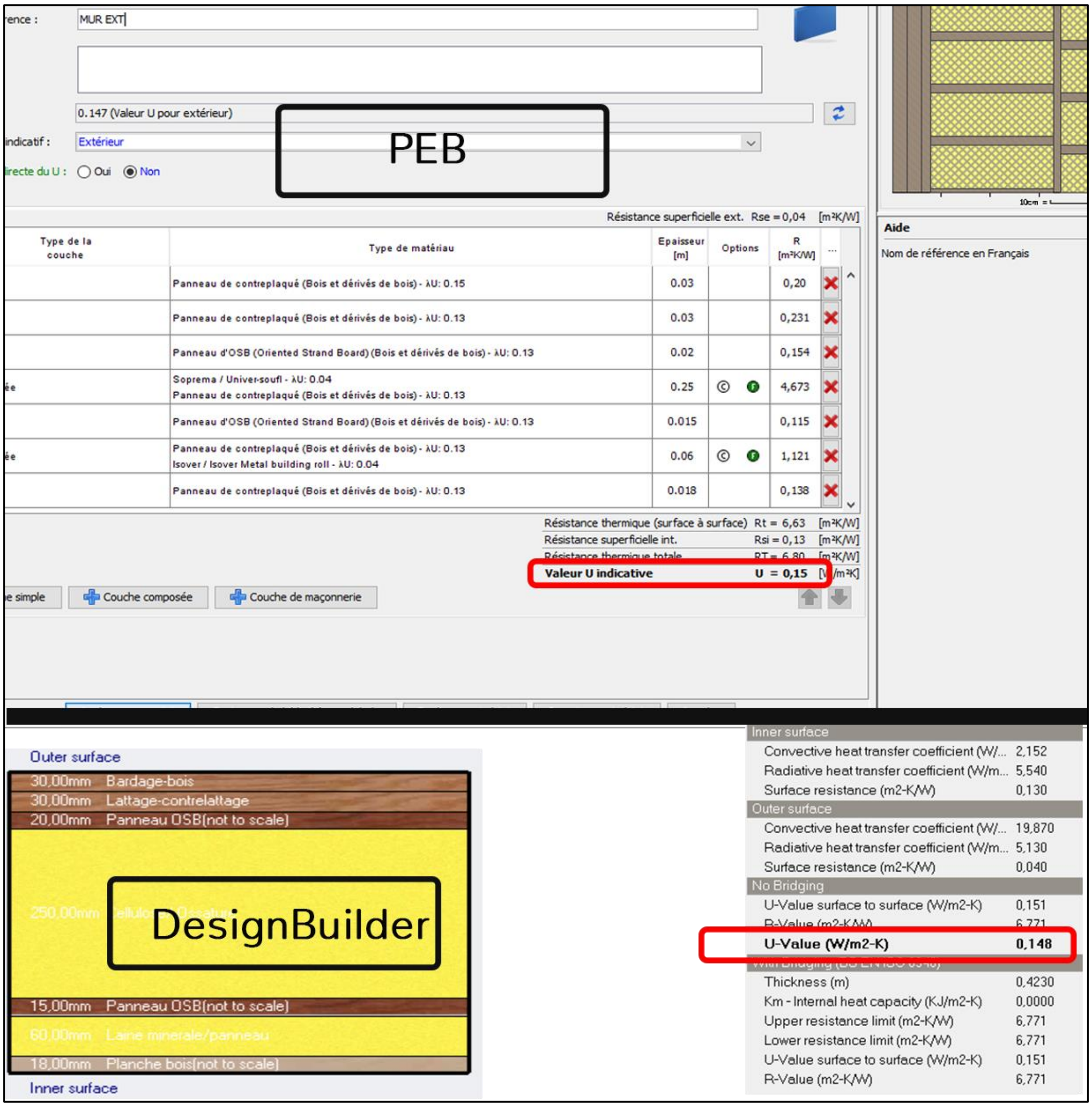
Données administratives du projet

Nom du Projet	**La Maison Kettenis**		
Rue		Numéro	
Localité	**Eupen**	Code Postal	**4700**
Référence cadastrale			

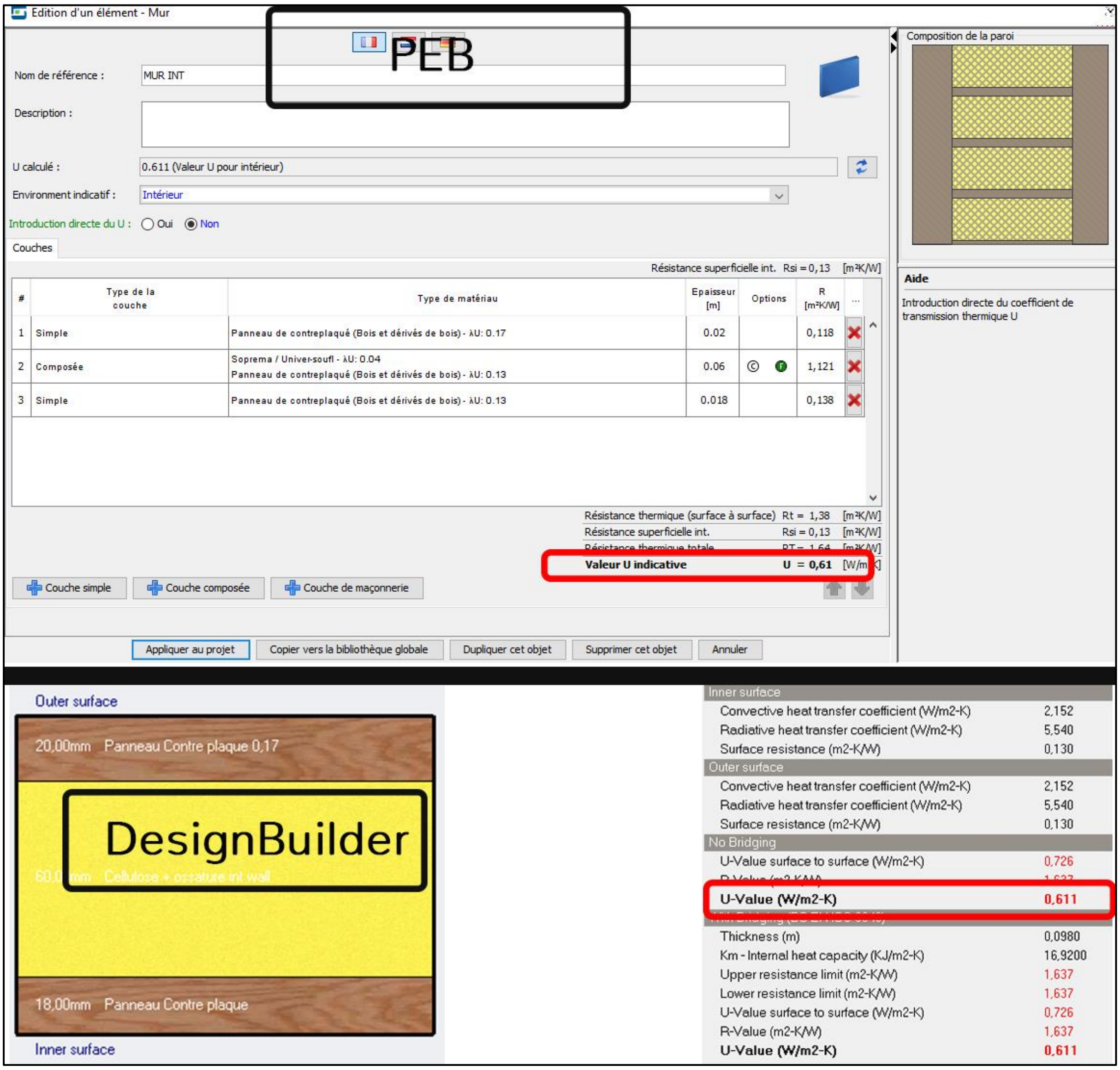
Produit par le logiciel PEB v10.5.3 le 04/04/20 18:20 Page 1

05ee-39f2-0d83-1cf8

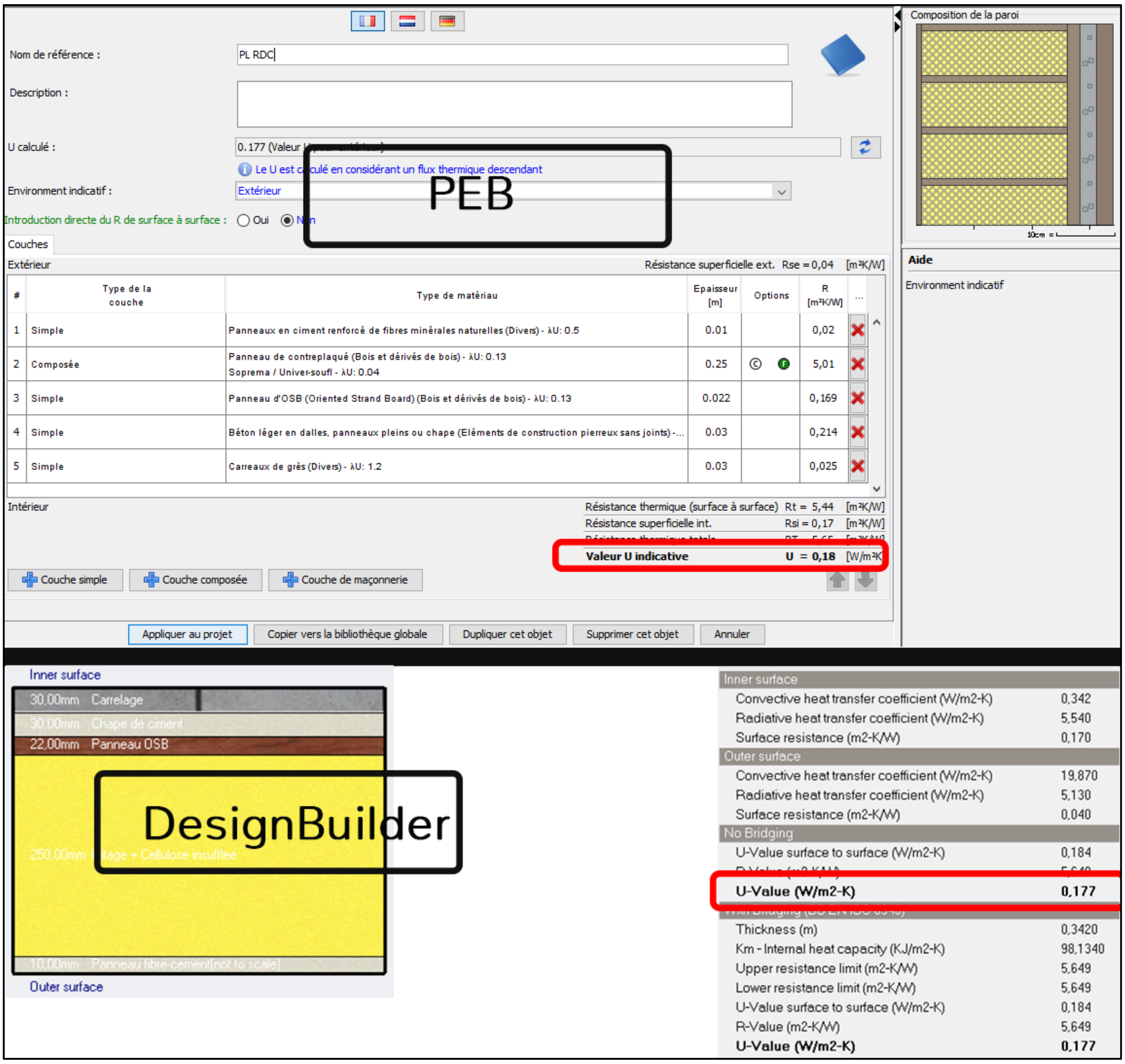
4.4. Annex-4: Details of both simulation models in different software.



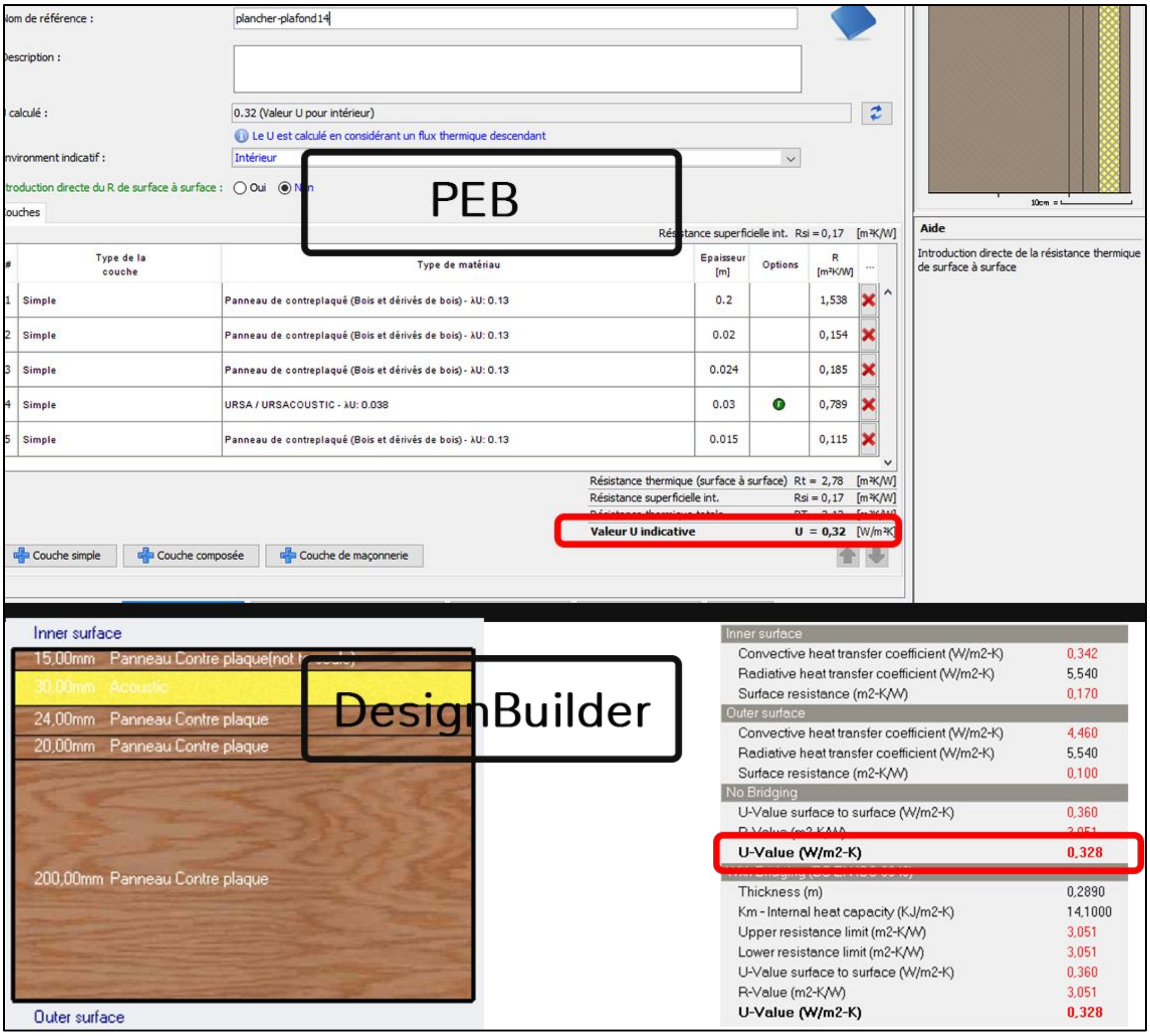
The composition of the exterior wall



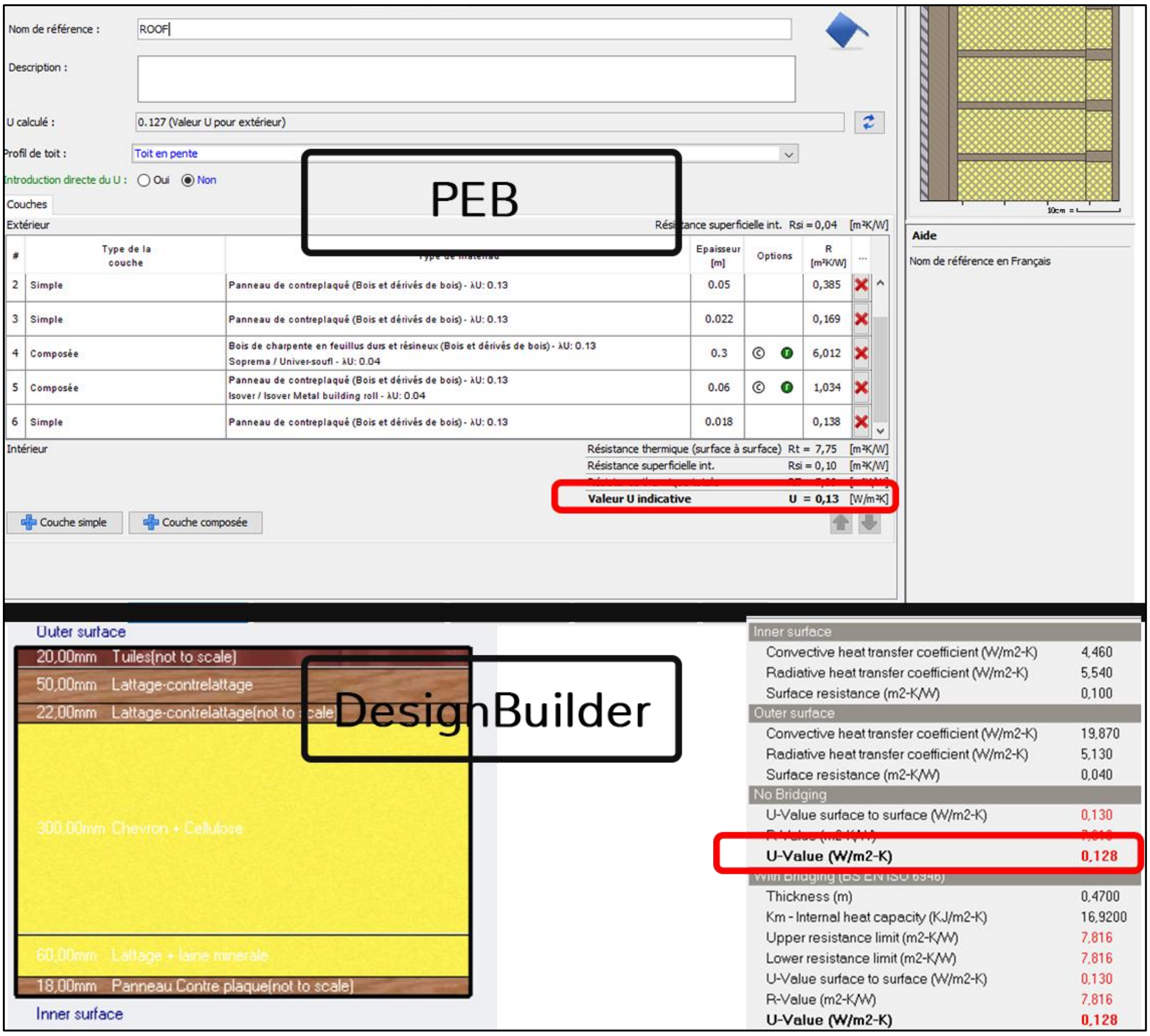
The composition of the interior wall



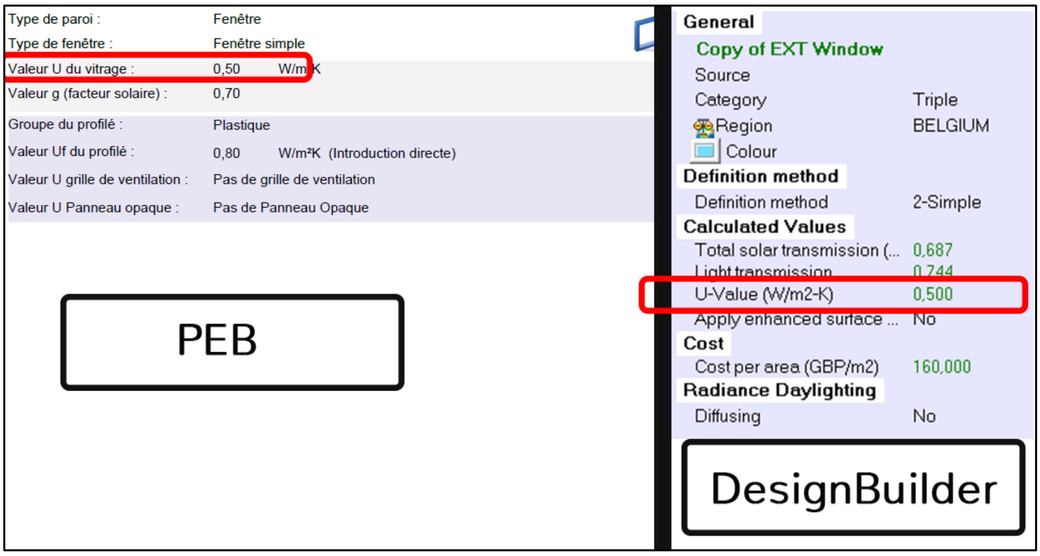
The composition of the ground floor



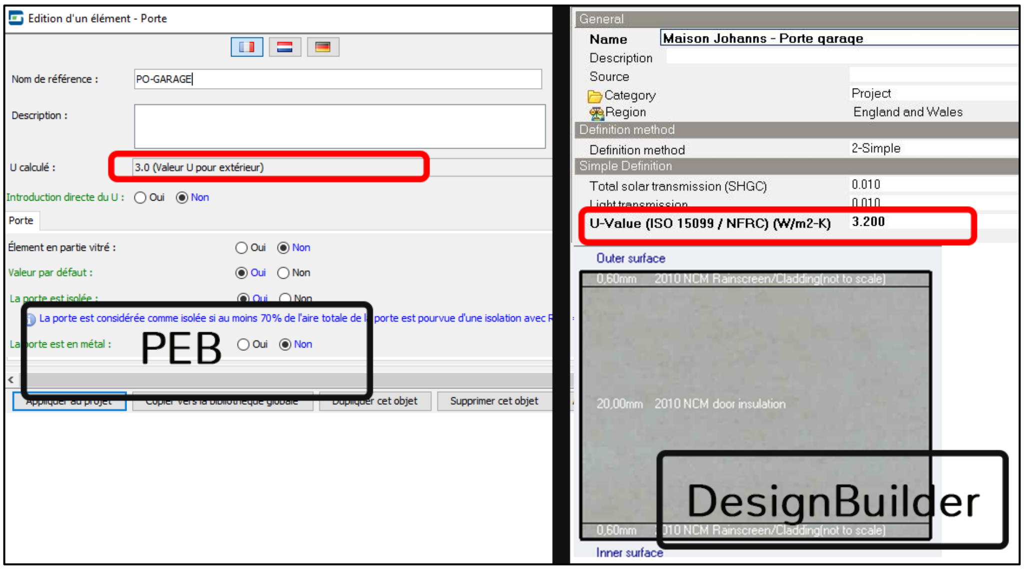
First floor slab



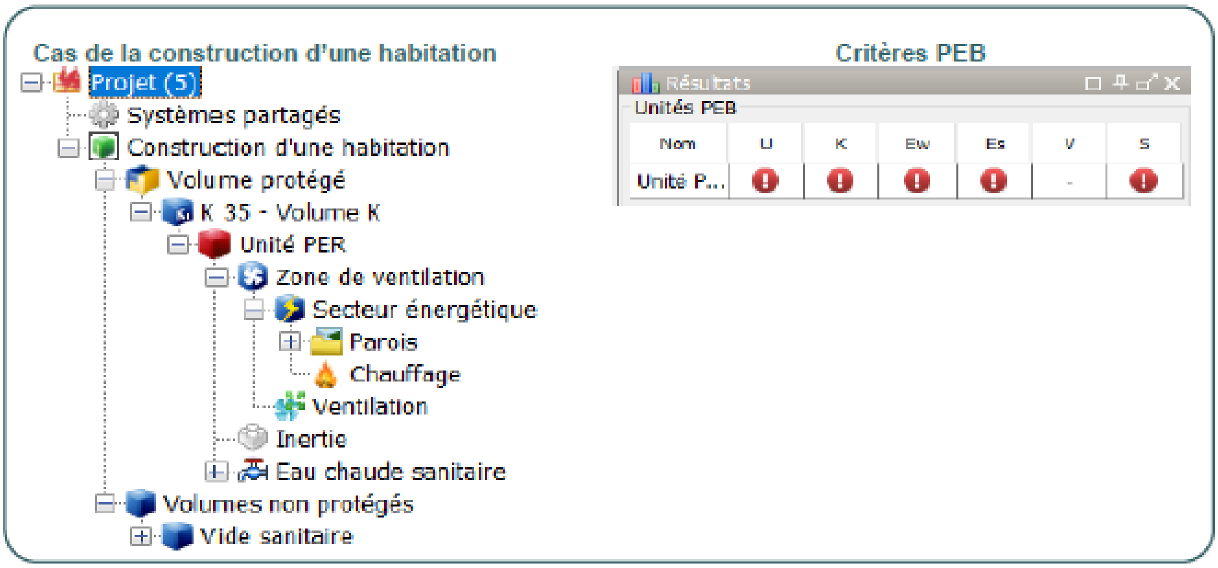
The composition of the roof



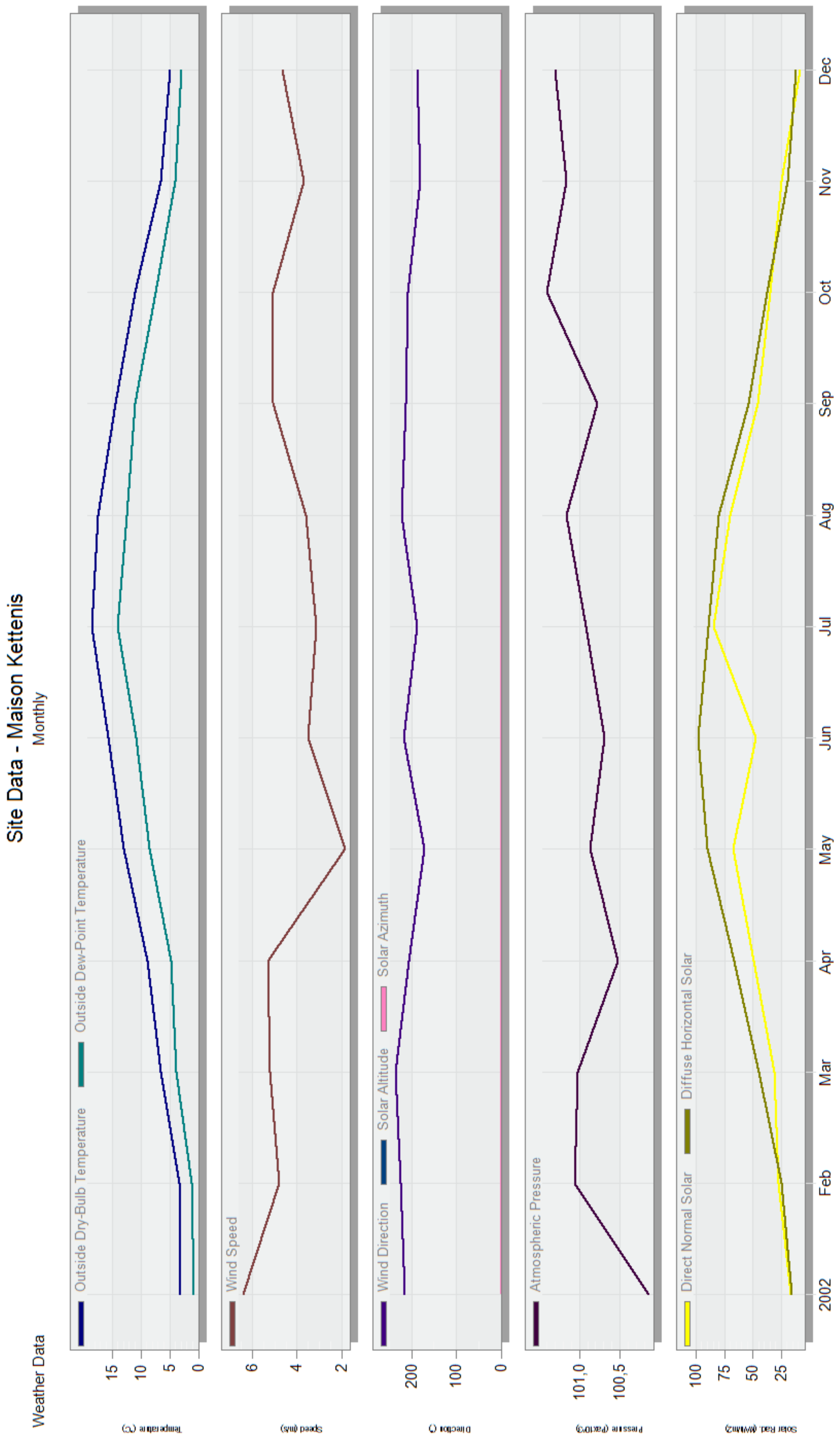
The characteristic of the windows



The characteristics of the exterior doors



The subdivisions in the EPC software



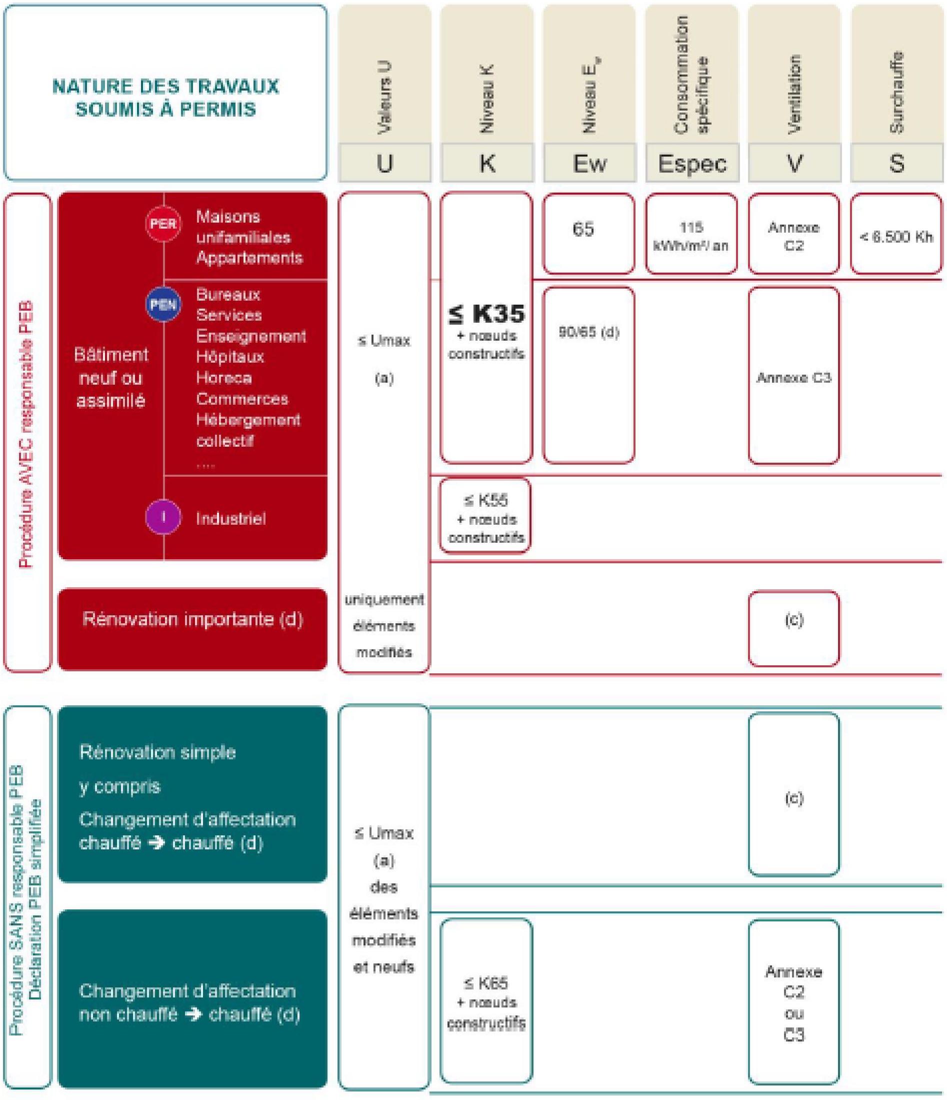
Annual representation of the hourly weather data used in DesignBuilder

4.5. Annex-5: PEB regulations.

TABLEAU DES VALEURS U_{MAX} EN VIGUEUR DEPUIS LE 1ER JANVIER 2017, CALCULÉES SELON L'ANNEXE B1-DRT

ELÉMENTS DE CONSTRUCTION	U_{MAX} [W/m²K]
Parois délimitant le volume protégé (VP)	
Toitures et plafonds	0.24
Murs[18]	0.24
Planchers	0.24
Portes et portes de garage	2.00
Fenêtres :	
• Ensemble châssis et vitrage	1.50
• Vitrage uniquement	1.10
Murs-rideaux :	
• Ensemble châssis et vitrage	2.00
• Vitrage uniquement	1.10
Parois transparentes/translucides autres que le verre :	
• Ensemble châssis et partie transparente	2.00
• Partie transparente uniquement	1.40
(ex : coupole de toit en polycarbonate…)	
Briques de verre	2.00
Parois entre 2 volumes protégés situés sur des parcelles adjacentes [19]	1.00
Parois opaques à l'intérieur du volume protégé ou adjacentes à un volume protégé sur la même parcelle [20]	1.00

The U-Values to be respected



The values of the indicators to be respected in the PEB (2017)

$$E_{W,PEN} = \frac{\sum_f A_{ch,fct\,f} \cdot E_{W,fct\,f}}{A_{ch}}$$

Avec :

$E_{w,PEN}$ le seuil à respecter pour le niveau Ew de l'unité PEN étudiée [-]

$A_{ch,fct,f}$ la surface totale de plancher chauffée de chaque fontion f présente dans l'unité PEN [m²]

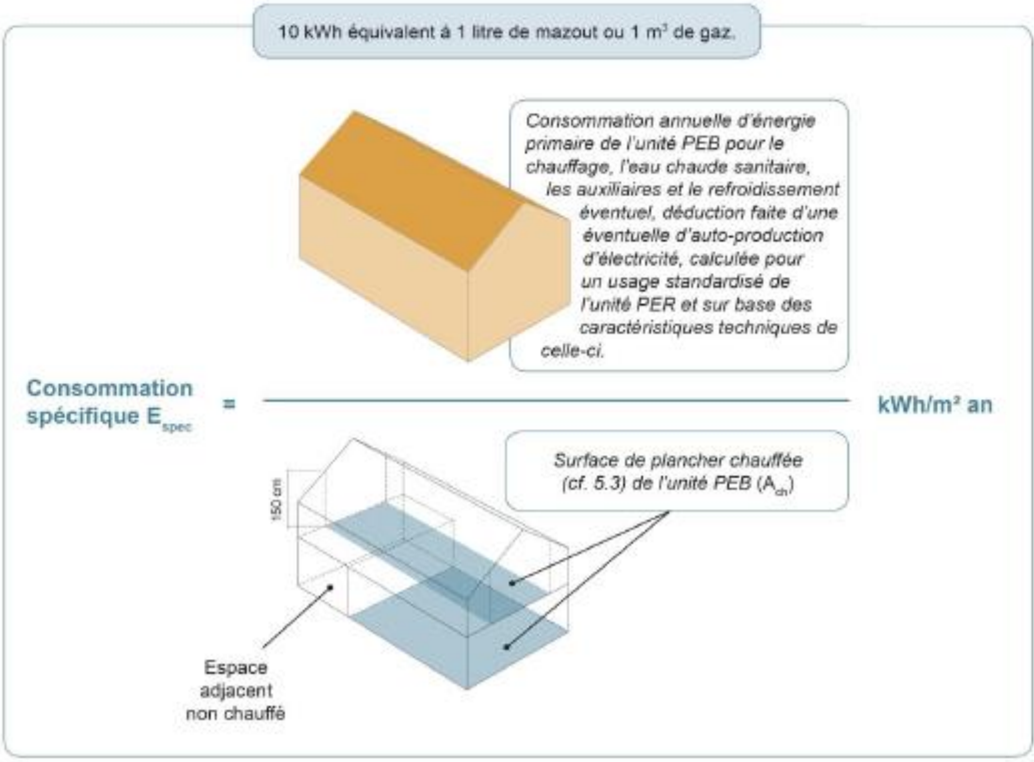
$E_{w,fct,f}$ le niveau d'exigence par fonction, pour chaque fonction f présente dans l'unité PEN [-]

A_{ch} la surface totale de plancher chauffée de l'unité PEN étudiée [m²]

Les valeurs des niveaux d'exigence par fonction, $E_{w,fct\,f}$, sont définies dans le texte de l'AGW PEB recast et sont reprises dans le tableau ci-dessous :

FONCTION		NIVEAU $E_{W,FCT\,F}$
Hébergement		90
Bureaux		65
Enseignement		65
Soins de santé	Avec occupation nocturne	90
	Sans occupation nocturne	90
	Salle d'opération	90
Rassemblement	Occupation importante	90
	Faible occupation	90
	Cafétéria / Réfectoire	90
Cuisine		90
Commerce / Services		90
Sport	Hall de sport / Gymnase	90
	Fitness / Danse	90
	Sauna / Piscine	90
Locaux techniques		90 ou 65
Communs		90 ou 65
Autre		90
Fonction inconnue		90

The details of the calculation of E_W



The details for calculating the E_{spec}

6.16 Ventilation PER

À l'exception des unités industrielles, la réglementation PEB prévoit des exigences de ventilation pour tous types d'unités PEB quelle que soit la destination (résidentielle ou non-résidentielle) et la nature des travaux applicables.

DESTINATION	NATURE DES TRAVAUX				RÉFÉRENCE RÉGLEMENTAIRE
	Neuf et assimilé	Changement de destination	Rénovation simple	Rénovation importante	
PER Résidentiel	Mise en place d'un système de ventilation complet, soit : • A - Alimentation et évacuation naturelles ; • B - Alimentation mécanique, évacuation naturelle ; • C - Alimentation naturelle, évacuation mécanique ; • D - Alimentation et évacuation mécaniques. Les dispositifs de ventilation installés doivent permettre • d'assurer les débits requis : o en alimentation dans les locaux secs ; o en évacuation dans les locaux humides ; • une circulation de l'air des locaux secs vers les locaux humides via des ouvertures de transfert.		Pour les **locaux existants où des châssis de fenêtres ou de portes extérieurs sont placés ou remplacés**, seules les exigences de ventilation relatives aux amenées d'air sont applicables. Pour les **locaux situés en extension,** mise en place de dispositifs de ventilation permettant • d'assurer les débits requis : o en alimentation dans les locaux secs ; o en évacuation dans les locaux humides ; • une circulation de l'air des locaux secs vers les locaux humides via des ouvertures de transfert. *NB : Il est permis de faire mieux que la réglementation en prévoyant un système de ventilation complet.*		Annexe C2 - VHR de l'arrêté qui fait référence, notamment, à la norme **NBN D 50-001.**

The ventilation requirements

<table>
<tr><th>Risque de surchauffe négligeable</th><th>Risque de surchauffe modéré à élevé</th><th>Risque de surchauffe trop élevé</th></tr>
<tr><td>Critère respecté</td><td>Critère respecté</td><td>Critère non respecté</td></tr>
<tr><td>Lorsque p_{cool} = 0, la probabilité conventionnelle d'installer un système de refroidissement actif est nulle.</td><td>Lorsque p_{cool} est compris entre 0 et 1, la probabilité conventionnelle d'installer un système de refroidissement actif est comprise entre 0 et 100%.</td><td>Lorsque p_{cool} = 1, la probabilité conventionnelle d'installer un système de refroidissement actif de 100%.</td></tr>
<tr><td colspan="2">Si aucun système de refroidissement actif n'est prévu dans l'unité PER :</td><td rowspan="2">Si aucune mesure n'est prise pour ramener l'indicateur de surchauffe en-dessous de la valeur maximale admise :
• exigence non respectée ;
• et amende administrative sur base de la déclaration PEB finale.</td></tr>
<tr><td>→ pas de comptabilisation de consommation de froid dans son bilan énergétique</td><td>→ comptabilisation d'une consommation d'énergie fictive pour le refroidissement proportionnelle à p_{cool} dans son bilan énergétique</td></tr>
<tr><td colspan="2">Si un système de refroidissement actif est prévu dans l'unité PER :</td><td rowspan="2">Qu'une installation de refroidissement actif soit prévue ou non dans l'unité PER, le bilan énergétique comptabilise 100% de la consommation d'énergie pour le refroidissement</td></tr>
<tr><td colspan="2">→ sa consommation est comptabilisée dans le bilan énergétique de l'unité PER, quelle que soit la probabilité.</td></tr>
</table>

The overheating regulations

Eq. 62 $$I_{overh,sec\ i} = Q_{excess\ norm,sec\ i,a} = \sum_{m=1}^{12} Q_{excess\ norm,sec\ i,m}$$ (Kh)

avec :

Eq. 63 $$Q_{excess\ norm,sec\ i,m} = \frac{\left(1 - \eta_{util,overh,sec\ i,m}\right) \cdot Q_{g,overh,sec\ i,m}}{H_{T,overh,sec\ i,m} + H_{V,overh,sec\ i,m}} \cdot \frac{1000}{3,6}$$ (Kh)

et avec :

Eq. 64 $$Q_{g,overh,sec\ i,m} = Q_{i,sec\ i,m} + Q_{s,overh,sec\ i,m}$$ (MJ)

Eq. 65 $$\eta_{util,overh,sec\ i,m} = a_m/(a_m + 1) \text{ pour } \gamma_{overh,sec\ i,m} = 1$$

$$\eta_{util,overh,sec\ i,m} = \frac{1 - \left(\gamma_{overh,sec\ i,m}\right)^{a_m}}{1 - \left(\gamma_{overh,sec\ i,m}\right)^{a_m+1}} \text{ pour les autres cas}$$ (-)

avec :

Eq. 66 $$\gamma_{overh,sec\ i,m} = Q_{g,overh,sec\ i,m}/Q_{L,overh,sec\ i,m}$$ (-)

Eq. 67 $$a = 1 + \frac{\tau_{overh,sec\ i,m}}{54000}$$ (-)

Eq. 68 $$Q_{L,overh,sec\ i,m} = Q_{T,overh,sec\ i,m} + Q_{V,overh,sec\ i,m}$$ (MJ)

Eq. 69 $$Q_{T,overh,sec\ i,m} = H_{T,overh,sec\ i,m} \cdot \left(23 - \left(\theta_{e,m} + \Delta\theta_{e,m}\right)\right) \cdot t_m$$ (MJ)

Eq. 70 $$Q_{V,overh,sec\ i,m} = H_{V,overh,sec\ i,m} \cdot \left(23 - \left(\theta_{e,m} + \Delta\theta_{e,m}\right)\right) \cdot t_m$$ (MJ)

Eq. 71 $$\tau_{overh,sec\ i,m} = \frac{C_{sec\ i}}{H_{T,overh,sec\ i,m} + H_{V,overh,sec\ i,m}}$$ (s) avec :

$\eta_{util,overh,sec\ i,m}$	le taux d'utilisation des gains de chaleur mensuels du secteur énergétique i, pour l'indicateur de surchauffe, (-) ;
$Q_{g,overh,sec\ i,m}$	les gains de chaleur mensuels par ensoleillement et production de chaleur interne dans le secteur énergétique i pour l'indicateur de surchauffe, en MJ ;
$Q_{i,sec\ i,m}$	les gains de chaleur mensuel par production de chaleur interne dans le secteur énergétique i, en MJ, déterminé selon le § 7.9.2 ;
$Q_{s,overh,sec\ i,m}$	les gains de chaleur mensuel par ensoleillement dans le secteur énergétique i pour l'indicateur de surchauffe, en MJ, déterminé selon le § 7.10 ;
$\gamma_{overh,sec\ i,m}$	le rapport entre les gains de chaleur mensuels et les déperditions de chaleur mensuelles dans le secteur énergétique i pour l'indicateur de surchauffe, (-) ;
$Q_{L,overh,sec\ i,m}$	les déperditions de chaleur mensuelles du secteur énergétique i par transmission et par ventilation pour l'indicateur de surchauffe, en MJ ;
a_m	un paramètre numérique ;
$Q_{T,overh,sec\ i,m}$	les déperditions de chaleur mensuelles par transmission du secteur énergétique i pour l'indicateur de surchauffe, en MJ ;
$Q_{V,overh,sec\ i,m}$	les déperditions de chaleur mensuelles par ventilation du secteur énergétique i pour l'indicateur de surchauffe, en MJ ;
$\theta_{e,m}$	la température extérieure moyenne mensuelle, en °C, voir le Tableau [1] ;
$\Delta\theta_{e,m}$	une hausse de la température extérieure moyenne mensuelle pour le calcul du besoin net en énergie pour l'indicateur de surchauffe, égale par hypothèse à 1°C ;
$H_{T,overh,sec\ i}$	le coefficient de transfert thermique du secteur énergétique i par transmission pour l'indicateur de surchauffe, en W/K, tel que déterminé ci-dessous ;
$H_{V,overh,sec\ i,m}$	le coefficient de transfert thermique mensuel du secteur énergétique i par ventilation pour l'indicateur de surchauffe, en W/K, déterminé selon le § 7.8.2 ;
$\tau_{overh,sec\ i,m}$	la constante de temps mensuel du secteur énergétique i pour l'indicateur de surchauffe, en s ;
$C_{sec\ i}$	la capacité thermique effective du secteur énergétique i, en J/K, déterminée selon le § 7.6 ;
t_m	la longueur du mois considéré, en Ms, voir le Tableau [1].

$H_{T,overh,sec\ i}$ est déterminé selon le § 7.7.2. Toutefois si l'influence des nœuds constructifs est calculée de manière forfaitaire (selon l'option C de l'annexe B.2 au présent arrêté), ce supplément forfaitaire n'est pas pris en considération dans le calcul de l'indicateur de surchauffe.

The detailed calculation of the overheating indicator