UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

Building Performance Evaluation: A Dutch Perspective in Thermal Comfort and Energy Consumption

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André Fonseca Jorge Cardoso Leitão

Dissertação orientada por:
Prof. Dr. Guilherme Carrilho da Graça

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Abstract

Published works have shown that buildings often consume more energy, than is necessary for occupant comfort. The building sector is accountable for 40% of EU's final energy use and responsible for 36% of EU's CO_2 emissions, directly related to energy consumption. Researchers say that there is a huge potential for energy savings in this sector, because the available technology is currently highly cost-effective, which could help to mitigate global energy use by the building sector. This study focuses on building performance aspects of an office building at TU/e, such as energy consumption and thermal comfort. *EnergyPlus* is used as a simulation tool to investigate energy-efficient opportunities, during the later phases of design process, and to research innovative applications for design support. However, buildings do not always perform as well as predicted. This performance gap may result from a number of reasons, but the most representative causes are introduced by uncertainties within the model design. For this reason, in recent years, the calibration of building simulation models has been of growing interest, mostly due to the lack of a recognizable approach to take during the entire calibration process.

This paper presents a methodology to apply during model development and calibration optimization, for tuning a set of parameters, while highlighting the effects of uncertainty in the calibration process. The goal is to minimize the difference between predicted (simulated) energy performance and actual measured energy use. To assess the accuracy of the model, two statistical indices are calculated: the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), which were found to be consistent with ASHRAE guideline 14 limits.

After the model has been successfully calibrated and validated, other analyses may proceed. In this research, besides the building's energy consumption assessment, the thermal comfort of the occupants is also evaluated in relation to Dutch guidelines, which are based on the ATG-method. The analysis conducted confirmed a "good" level of thermal comfort in the test case building, with less than 10% of its users experiencing discomfort.

Keywords: Building performance, simulation model, *EnergyPlus*, Performance gap, Calibration, Uncertainty, Thermal comfort.

Resumo

Trabalhos publicados mostraram que os edifícios normalmente consomem mais energia do que o necessário para o conforto dos ocupantes. O setor dos edifícios é responsável por 40% do consumo de energia final na EU e responsável por 36% das emissões de CO_2, diretamente relacionadas com o consumo de energia. Investigadores dizem que existe um enorme potencial de poupança de energia neste setor, pois a tecnologia atualmente disponível é altamente económica, o que poderá ajudar a mitigar o uso global de energia pelo setor de edifícios. Este estudo centra-se em aspectos relacionados com o desempenho energético de um edifício de escritórios na TU/e, tais como o consumo de energia e o conforto térmico. O *EnergyPlus* é usado como ferramenta de simulação para investigar oportunidades energeticamente eficientes, após a período de ocupação de um edifício. No entanto, os edifícios nem sempre se comportam energeticamente tão bem quanto o previsto. Esta discrepância no desempenho pode ter uma série de razões, mas as causas mais representativas são introduzidas por incertezas referentes ao design do modelo de simulação. Por esse motivo, durante os últimos anos, a calibração dos modelos de simulação tem sido de crescente interesse, principalmente devido à falta de uma abordagem reconhecida a ser tomada durante o processo de calibração.

Este trabalho apresenta uma metodologia a aplicar durante as técnicas de desenvolvimento e calibração do modelo de simulação, ajustando um conjunto de parâmetros, enquanto destaca os efeitos das incertezas no processo de calibração. O objetivo é minimizar a diferença entre o consumo de energia previsto (simulado) e consumo de energia medido. Para avaliar a precisão do modelo, dois indicadores estatísticos são calculados: o erro quadrático médio (MBE) e o coeficiente da raiz de variação do erro quadrático médio(CV(RMSE)), que foram considerados consistentes com os limites impostos pela norma 14 do ASHRAE.

Após o modelo ser calibrado e validado com sucesso, outras análises poderão ser conduzidas. Neste estudo é também avaliado, além dos consumos energéticos, o conforto térmico dos ocupantes do edifício em relação à legislação holandesa, que se baseia no método ATG. A análise realizada confirmou um "bom" nível de conforto térmico no edifício em estudo, com menos de 10% de seus ocupantes a sentirem desconforto.

Palavras-chave: Desempenho energético, Modelo de simulação, *EnergyPlus*, Discrepância no desempenho, Calibração, Incertezas, Conforto térmico.

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Chapter 1 - Introduction

Buildings are one of the major consumers of energy among the entire sectors of the economy. In 2015, the building sector accounted for almost 40% of final energy consumption and 36% of CO_2 emissions in Europe [1], figure 1.1. Moreover, this energy was provided mostly from electrical and fossil fuel sources. To address this issue, many countries have implemented building energy regulations to establish a method of assessing, rating and certifying the sustainability of buildings.

Despite significant policy efforts to improve energy efficiency, buildings energy use has risen by 20% compared to 2000 values [2]. In addition, about 35% of the EU's buildings are over 50 years old [3]. Consequently, there is an elevated potential for cost-effective energy savings of up to 50-90% [4], hence the building sector has become a priority for the European Union trying to meet its ambitious climate and energy targets for 2020 and 2050.

The 2012 EPBD's (Energy Performance Building Directive) furthered the importance of ensuring that building construction continually improves its energy performance. It established goals to cut energy use by 20% [5], by introducing new minimum energy performance requirements for buildings, building elements or systems. Also gave recommendations and strategies to promote the transition towards nearly Zero-Energy Buildings (nZEBs).

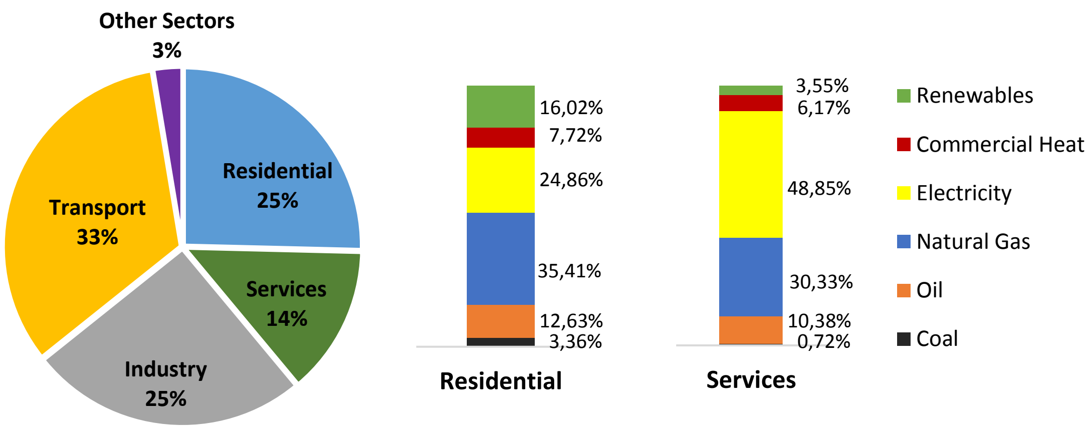


Figure 1.1: EU final energy consumption by sector and buildings energy mix in 2015. Adapted from: [1].

EU's targets confront the building industry with new challenges, leading to the need for the engineers and academics to consider in more detail the main driving factors for energy demand, while searching for solutions and new building concepts that contribute to achieve these objectives. For instance, the increasing awareness on thermal indoor climate and air quality has proven that a well-designed indoor thermal environment helps to maximize the building occupants' productivity [6].

Focusing on the EU's services sector, approximately 60% of the annual energy demand in commercial buildings has heating and cooling as the main final energy end-use [7], [8]. Moreover, occupant expectation for new levels of comfort associated with the building sector leads, ultimately, to an increase in energy use. In the end, it is relevant the study of measures that promote the reduction of consumption, by raising the levels of energy efficiency. Building

Performance Evaluation (BPE) is an innovative approach to systematically assess quantitively and qualitatively the sustainability of a building, considering its impact on the environment and users during all phases of the life-cycle. By using such a process, decision-makers can make better and more informed user-oriented design decisions.

BPE is a mechanism generally applied in later stages of design, often to address two topics. First, an analysis is carried as a method to fully recognize a building energy flows based on real operating conditions and compared against expected design criteria. In other words, through a detailed evaluation of energy, water and indoor air quality an assessment can be made relative to the building's performance. Secondly, a number of energy conservation measures are selected using the knowledge obtained from the building behaviour and the interactions between weather conditions, user occupancy and operating systems. Then, the savings potential of the most cost-effective improvements are estimated according to occupant concerns and needs.

In this context, computer-based simulation models appeared as a tool to effortlessly predict a building behaviour, given system properties and conditions. Buildings energy models use heat and mass detailed calculations to determine the response of a complex interdependent system under specific external conditions. Building Performance Simulation (BPS) emerged has a design support tool for its proven capabilities to accurately estimate annual energy consumption and thermal comfort in buildings, as well as an instrument that can be used to predict cost-saving renovations.

Table 1.1 lists the main influencing factors on the total building energy use. A detailed comparative analysis on building energy data, concerning those parameters provides an essential guidance to identify opportunities to save energy and reduce greenhouse gases.

Table 1.1: Building performance main influential factors. Source: [9]

Building Performance	**User behaviour**	- Indoor quality provided; - Occupant activities; - Behaviour patterns.
	Physical properties	- Envelope & Services; - Operation & Maintenance; - Energy systems.
	External conditions	- Climate.

However, an analysis and evaluation method suffers from two sources of modelling inefficiencies: lack of information on the exact properties of the building and simplifications/assumptions introduced in the development of the model. Thus, one cannot completely predict actual energy consumption, since there is a risk in the assessment of model parameters, which cause uncertainties pertaining to building demand. Despite, nearly 40 years of research and development, methods for the design assessment are yet costly to implement, time-consuming or not applicable [10]. It is therefore necessary to constantly face this complexity and improve the ability to predict the impact of changes in the building model to make better decisions and provide optimal solutions with the help of BPS.

The scope of this work will be to support any building simulation based environment into applying a clear strategy, for design support during the later phases of the design process, for the study of an office building's energy use and thermal comfort. Furthermore, it has the goal to present an optimized-based approach to facilitate the improvement of the model accuracy, through easy and simple techniques, taking into account the influence of uncertainties within a model.

1.1.Problem Definition

Building simulation offers a unique perspective to gauge and evaluate how energy is currently consumed. For this analysis, it is fundamental the collection of data pertaining to the building under study (energy consumption, usage profile, building systems, envelope characteristics, etc). Through the exercise of a variety of simulation techniques and procedures it is possible to predict real physical conditions in a building and perceive how energy performance can be promoted.

BPS tools are based on dynamic models that use numerical methods to calculate an approximate solution of a realistic building. In order to have accurate results and make simulation predictions match closely with real demand, there are major challenges to overcome on dealing with difficulties related to large diversity of parameters and complexity of factors. The information needed to guide the decisions, while constructing the simulation model will require the exact specification of systems and the selection of all parameters relevant for the design. In spite of recent boom and mainstream application of BPS tools in post-construction stages, a significant discrepancy has been often found between the designed and real total energy use in buildings. This is often addressed as “the performance gap” [11].

Several studies [12]–[14] have highlighted and addressed the issue about the significant differences between predicted BPS models and the actual metered building energy use. Even, the most recognized BPS tools used currently, show some level of discrepancies. To illustrate this *P. de Wilde* [11] reports that the “ measured energy can be as much as 2.5 times the predicted energy use”. So, it is necessary that the simulation model closely represents the actual behaviour of the building, to the extent of not undermining the confidence in the simulation results. To properly reduce these disparities and increase reliability in BPS, the model must go through a process of calibration focused on the physical uncertainties of the model. This mechanism comprises essentially, technical and operational adjustments of the computer model to have a more realistic representation of the building performance. One reason for this discrepancy could be limited information on the building’s thermal envelope and installations. Hence, this problem of imprecision requires an evaluation of the effects of different input variables values in terms of the system response, towards finding the optimal estimate.

In the end, a simulation model is only valid if the model has gone through an accurate calibration, thus becoming an essential part of every building simulation to integrate the issues related to risk and uncertainty in design. However, a BPS calibration involves thousands of input parameters resulting in a wide range of multiple solutions that depend on the building under investigation. Therefore, resulting into the nonexistence of an uniformized methodology to properly calibrate a BPS model.

This thesis focuses on a simplified methodology for conducting a building performance evaluation of a building at TU/e (Vertigo). It uses the *EnergyPlus* simulation tool, emphasising on the current practices used in the Netherlands. The main goal is to present a simulation-based optimization approach for calibrating any dynamic energy model based on monitored data. It is proposed an easy and effective method to handle the different sources of model uncertainty, intrinsic to some degree to every simulation, by manual tuning the building input data to obtain the optimal solution with minimum computation time.

The case study presented is based on an office building with respect to various performance indicators. Even though, the aim is not to quantify the uncertainty in the model calculations, the intention is to show how the application of a simulation-based optimization enhances energy consumption predictions (annual heating and cooling). After a successful calibration and consequently validation, further analysis can pursue.

Finally, this thesis also has the objective to analyse the building occupants' thermal comfort level based on the Dutch guidelines. Legislation requires the maintenance of conditions of thermal comfort in the workplace appropriate to the human body, taking into account the methods of work and the imposed physical constraints. The determination of the state of thermal environment and the measures to be taken may only be made by assessing the factors determining it, since thermal comfort may affect largely the occupant's behaviour, which ultimately relates to energy consumption. Netherlands formulated a standard for the indoor climate conditions in office spaces (ISSO 74:2014) based upon the adaptive approach (ATG method), which can provide a method to support a clear and straightforward communication with customers and other stakeholders.

1.2.Thesis outline

This thesis is structured in nine chapters and four complementary annexes, where is included the introduction, which makes an initial approach to the topic being debated, pointing out the goals that are to be met throughout this work.

The second chapter gives an overview of the concepts related to an energy performance evaluation. Discusses the importance of assessing the energy demand in dwellings and commercial buildings. In addition, gives an insight to the current design guidelines and rating systems.

Chapter three describes the computer simulation tool used during the research study, *EnergyPlus*, for the evaluation of building energy consumption and occupants' thermal behaviour. Brings out the relevance of employing a simulation tool in the energy assessment strategy.

Chapter four defines the necessary steps towards verifying and validating a simulation model. It is fundamental an understanding in design simulation tools and optimization techniques before developing the ideas of how to improve the current use of BPS.

In chapter five is accomplished a general framework of the present Dutch legislation, regarding the energy performance of building and occupants' thermal comfort.

The chapter six presents the test case building and all its pertaining information gathered, relevant for the design of the simulation model. Explains in detail the building under analysis, as wells as, the data collected concerning the systems operation.

Chapter seven proposes a methodology to implement during a building performance evaluation. Additionally, a simulation-based optimization approach for calibrating building energy model, using monitored data is recommended. The applicability of the validation technique in current building performance simulation is shown.

Chapter eight presents the results of the simulation model compared with the metered data, before and after the calibration process, recognizing the benefits it brings to the accuracy of the designed model and enabling a precise assessment of the occupants' thermal comfort.

Chapter nine summarizes and concludes this research; furthermore, it identifies directions for future research opportunities.

Chapter 2 - Building Performance Evaluation (BPE)

Building Performance Evaluation (BPE) is a tested and defined method that can be adopted to continuously measure and monitor building performance before, during and after building being commissioned. It is used to assess the building's performance in terms of design goals or other specific performance criteria. This includes not only occupant satisfaction, but also resource consumption, both water and energy use. A building design process using feedback from ongoing evaluation will tend to lead to better informed design assumptions, and ultimately, to better solutions. By employing a rigorous and systematic procedure, decision-makers can make more competent user-oriented design decisions, in terms of cost-effectiveness, productivity and sustainability.

2.1. Role of BPE

Presently, there is a significant and growing evidence that buildings do not perform as anticipated at their project design stage, this is referred as "performance gap". BPE provides the means of quantifying any performance gap and gives the key insights into its root causes. It provides guidance on how and why buildings perform, identifying opportunities for improvements in the design, systems or in control strategies [15]. This contributes for an overall energy efficiency and occupant satisfaction in the building. The techniques and approaches will depend on the project environment within which it is being applied, focusing on a range of technical performance requirements, and whether the evaluation is being conducted on a domestic or non-domestic building.

Ideally, when commissioning a building there are four different stages to ensure that the transition from construction to occupation, occurs with the least possible problems, while operational performance is optimized [16]. This transition needs to be considered throughout the development of a project, not just at the point of handover. The four key periods are defined as, figure 2.1:

- Concept and design: in this initial phase, there is the need of ensuring that the client's needs and requirements are clearly clarified. At this point, occurs the planning, programming and design of the building;
- Construction development and review: reviewing comparable projects and assessing proposals in relation to facilities management and building users;
- Pre-occupancy: at a pre-handover stage, operators must properly understand systems before occupation, so that the initial aftercare may start with the least mistakes possible for the stationing project team on site to receive feedback, fine tune systems and prepare operation;
- Extended aftercare and post occupancy evaluation: it is suggested that this period last for three years. In year 1, problems are identified, training provided and systems adjusted, with regular previews. In year 2 and 3, performance is reviewed, and post occupancy surveys carried out, but with reviews becoming less frequent.

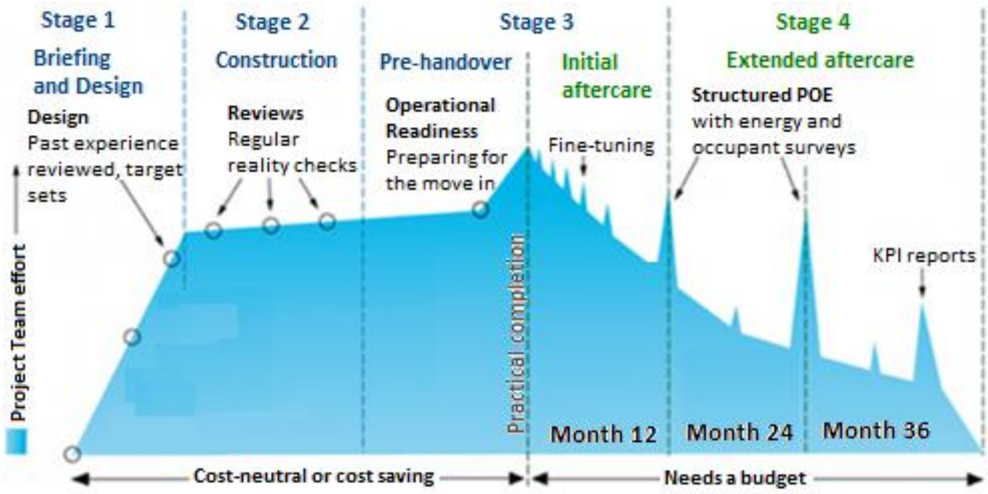


Figure 2.1: Diagram representing the four different stages during a BPE. Adapted from [15].

Nonetheless, most BPE are conducted only after the building is occupied. Hence, disregarding potential energy savings measures during other periods of the building life-cycle. In order to a BPE work effectively, data-gathering and analysis activities are necessary at every stage. Future post-occupancy evaluations (POE) will thus benefit from methodical accumulated information, regarding the building performance.

Quantitative and qualitative building performance criteria that represent the expected outcome, are at the centre of the model. The challenge is then to translate these performance indicators into useable benchmarks and to establish a methodology, with which is possible to measure easily and regularly the performance of the building in relation to those indicators. The actual performance of the building can be evaluated systematically over its lifetime, and compared to the more general benchmarks available, to determine the extent to which the building's energy efficiency goals have been met.

A performance indicator is described as a performance metric, which simplifies complex information and points to a general state of the building. Performance indicators are accessible numeric metrics of energy usage or observed building characteristics, that indicate a certain aspect of the performance. They are intended to yield the best information for the least cost and time, using the available metered data and observable characteristics. Normally, the most common performance indicators for office buildings, take into consideration the energy consumption of the building, both for heating and cooling, building size, operating hours, wind exposure, internal temperature and humidity.

The use of a set of performance indicators will hence provide an assessment of whether or not the building is efficiently running. Benchmarking drives facilities to continually review the energy performance, by measuring and comparing it against standard benchmarks and other peer buildings. This will serve as a starting point for pre- and post-evaluation on capital improvements aimed at increasing operational efficiency and reducing costs. The European Union has perhaps the most advanced benchmarking policies for building sustainability in the world, manifested in wide-ranging legislation that is beginning to affect a number of sectors. This includes the European Building Directive which, from 2007 onwards, requires every house to have a performance certificate issued at point of sale, and every public building in Europe to have an annually renewed Performance Certificate.

2.2. Building Benchmarking

Benchmarking models based on energy-efficient indicators are valuable assessment tools for both governmental and private sectors in managing energy consumption. Various rating systems have been developed by organizations around the world, that strive to indicate how well a building meets prescribed requirements and to determine, whether a building design is efficient and to what level. Benchmarking is a mechanism whose main objective is to promote higher energy performance standards than the regulated ones [17], through the practice of comparing the measured performance over time of a single facility to itself, its peers, or established norms. The goal is to inform and motivate performance improvements, by providing a clear and detailed information about the building’s energy performance (energy labelling), allowing for the straight comparison between buildings. A well-implemented benchmarking certification must promote a clear quantification of design concepts, by assessing the most effective opportunities for energy efficient renovations, as well as a mean to quantify/verify energy savings [18].

To have a wider understanding about the benefits and performance of high-efficient buildings, detailed data and information is needed regarding building characteristics and operation. Therefore, qualitative information, as well as quantitative measures off environmental impacts and resources use, such as energy use, water consumption and waste generation must be collected. Used in these ways, benchmarks can promote efficiency in buildings and help accelerate market transformation.

A consistent and systematic evaluation of a building performance, enables future building design and may also help to “close the loop” in building delivery and management process. Besides, performance data can be used to set and report against targets as well as benchmark performances, and over time, against industry benchmarks or comparable buildings. The rating and certification systems and tools are intended to promote more sustainability during building design, construction, operation, maintenance, and disassembly or deconstruction by encouraging and enabling a better integration of environmental, social, functional, and financial concerns with other traditional decision criteria [19].

There are two major voluntary building rating and certification systems that provide the basis for the other approaches used throughout the world: the Building Research Environmental Assessment Method (BREEAM), which was developed in the U.K. and the Leadership In Energy and Environmental Design (LEED), created by the U.S. Green Building Council. These systems and tools can both be used to support the sustainable design, since they transform the sustainable goal into specific performance objectives to evaluate the overall performance.

Schwartz *et al.*, [20] made a comparative overview between BREEAM and LEED, in which illustrates the differences and benefits of each benchmarking scheme. There are different perspectives in different sustainable building rating and certification approaches, but they have certain points in common. In general, these systems and tools deal, in one way or another, with the same categories of building design and life cycle performance: site, water, energy, materials, and indoor environment. Benchmarking is a crucial element of a commercial building’s energy management strategy as a method to control the energy performance, through ongoing measures, ensuring a cost-efficient operation. Across many commercial building markets, the practice has become standard operating procedure, as energy costs and associated environmental and sustainability issues have raised awareness around the importance of energy management.

Chapter 3 - Building Performance Simulation (BPS)

Building performance simulation (BPS) is a method that uses a dynamic thermal model meant to predict the performance of a building, regarding energy consumption and thermal comfort. In other words, it aims to provide an approximate solution of a realistic building. It is important to compare these predicted results with the experimental ones, in order to validate the accuracy of the modelling.

The primary purpose of an office building is to provide a comfortable environment to its inhabitants, which will ensure their productivity. As a way to fully take advantage of Building Performance Simulation (BPS) tools, it is essential at first to understand the heat transfer mechanisms within a building. Hence, a building's thermal load is the amount of energy that must be removed or added to the system, to maintain a constant air temperature inside a room.

The combination of these aspects has originated some models. Firstly, the heat-mass balance model (maybe the most accurate) ensures that all energy flows, in each zone, are balanced and involve the solution of a set of energy balance equations for the zone air, as well as, to the interior and exterior surfaces. The second class are thermal network approaches, which are a form of heat balance models with the discretization of the building in a network of nodes. The third class corresponds to the transfer function methods that use transfer functions or response factors to relate current value of heating and cooling load, to past values of either demand or heat gains. To have an accurate simulation, it is also required apart from the control of the above-mentioned aspects, to take into account the weather data, time of the day, building geometry, construction type and occupancy. Besides, the decision related to the right time steps is crucial for the simulation because decreasing the time step not always improves the accuracy.

3.1. Energy Balance in Buildings

As a starting point, for any building evaluation it is fundamental to review concepts about heat transfer in buildings. The recent interest in this field, due to increasing demand and thermal comfort needs, requires an in-depth study of the energy balance of a building, in terms of the thermal losses and gains that occur through its surroundings. Therefore, enabling building performance evaluations to make the methods of forecasting more reliable.

The law of conservation of energy in stationary conditions states that, for a certain instant *dt*, the energy balance in any frontier controlled volume is always null. The energy conservation in a zone is an analysis, which allows to quantitatively compare the main flows and sources of energy that characterize a thermal zone. There is a number of possibilities to use the energy conservation equation, but in stationary regime it is only possible to solve one variable at a time. For example, one can predict the inside temperature for a determined scenario without air conditioning or one can impose a fixed inside temperature, in order to estimate the air conditioning load. When performing a building's heat balance, it is important to first understand which are the key factors that contribute for the building's gain or loss of heat, as are some described in figure 3.1. In any energy balance, one needs to keep in mind that the rate of gains in a building equals the rate of losses, as equation 3.1 translates.

$$\boldsymbol{Q_{gains} = Q_{losses}} \tag{3.1}$$

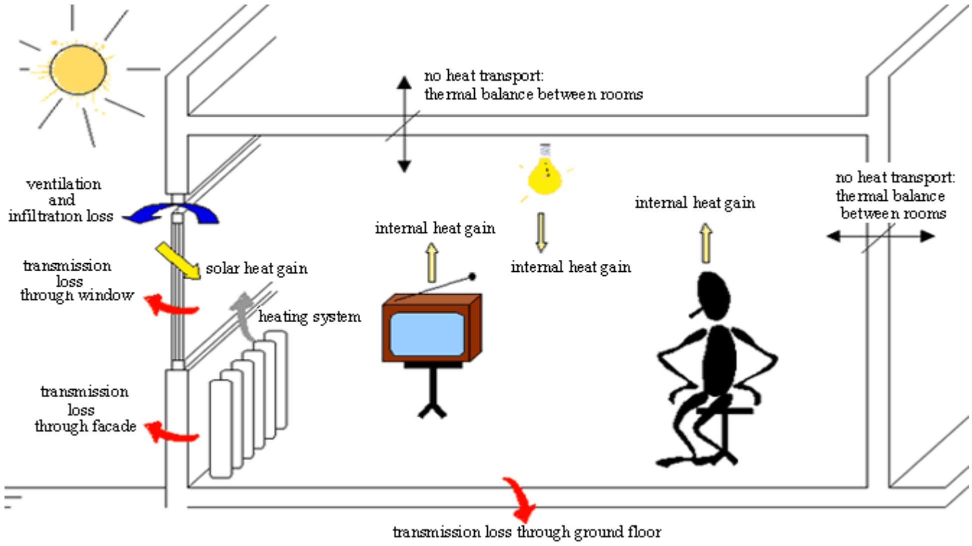


Figure 3.1: Flows of energy in a thermal zone. Source: [21]

A building's envelope is a critical component, since it both protects the building occupants while plays a role in regulating the indoor environment, controlling the flow of energy between the interior and exterior. With respect to gains, the main aspects which will have effect on a building's heat balance can be divided in either internal and external. Internal gains are due to the presence of people and/or electric equipment, the usage profile and equipment's power may cause a significant increase of heat inside the building, consequently affecting the thermal load. External gains like solar radiation that pass through glazed construction are also a key factor for the increase of thermal energy.

Regarding the losses of heat in a building, they may occur by four different processes. One is by filtration losses, which are related to the air tightness of the building. Other is by ventilation losses, due to mechanical or natural ventilation. The third pertains to the influence of building's thermal mass, which will greatly affect the amount of stored heat depending on the temperature gradient. The last concerns the transmission losses. They can have a major impact, since they are the most common losses of heat in a building. Transmission losses must be divided in several components considering that they can occur by three different forms: through building elements such as walls, doors, internal floors and ceilings, windows and others; along thermal bridges and over ground-coupled elements such as floors and basements.

With all this information, one can establish a relationship between all these factors previously discussed, and easily establish an expression of heat balance in stationary regime for a typical room, with inside constant temperature, as presented in equation 3.2:

$$\boldsymbol{G_{ig} + G_s + G_v + G_{ac} = \rho . C_p . V_s . \frac{(T_{sup} - T_i)}{\partial t} + \sum_{n=1}^{k} A_n . U_n \times (T_i - T_{s_n})} \tag{3.2}$$

where, G_{ig} is the internal gains due to occupants' activity, electric equipment and lighting [W]; G_s is the solar gains which pass through transparent surfaces [W]; G_v is the gains due to ventilation, resulting from outside air intake, mainly through infiltration [W]; G_{ac} is the air-conditioning load needed to maintain a constant inside temperature [W]; $\rho . C_p . V_s . \frac{(T_{sup} - T_i)}{\partial t}$ are the gains due to energy stored within air itself [W]; $\sum_{n=1}^{k} A_n . U_n \times \left(T_i - T_{s_n}\right)$ is transmission losses through the surroundings [W], T_{sn} is the temperature of the surface "n", ρ is the density of air [kg/m^3], C_p is the specific heat of air [J/Kg.K], V_s is the volume of the room, A_n is the area of the surface [m^2], U_n is transmission heat coefficient of the surface "n" [W/(m^2.K)];

To properly calculate equation 5, one needs to first understand how to determine the other variables. Thus, to calculate the solar gains from transparent surfaces there is a correlation that can approximately estimate, as expressed in equation 3.3:

$$\boldsymbol{G_s = A_g . F_s \times \left(R_{dir}. Cos(height). Cos(azimuth) +. R_{dif}\right)} \tag{3.3}$$

where, A_g is the area of the transparent surface [m^2], F_s is the solar factor, R_{dir} is the direct radiation [W/m^2], R_{dif} is the diffuse radiation [W/m^2], solar height [º] and azimuth in [º].

Finally, there are gains from ventilation and air-conditioning, which are very similar to calculate, equation 3.4 and 3.5 can respectively translate these gains:

$$\boldsymbol{G_v = \rho . C_{p.} \dot{V} . (T_{ext} - T_i)} \tag{3.4}$$

$$\boldsymbol{G_{ac} = \rho . C_p . \dot{V} . \left(T_{sup} - T_i\right)} \tag{3.5}$$

where, $\dot{V}$ is the volumetric flow of the air-conditioning system [m^3/s], T_{ext} is the outside temperature [ºC], T_{sup} is the supply air temperature used to heat the space [ºC], T_{int} is the inside temperature [ºC].

3.2. Dynamic Simulation in Buildings

Nowadays, computational modelling and simulation is one of the most powerful and commonly used analysis technique by the scientific community, because of the simplicity for the user to fully comprehend the heat transfer mechanisms within a building. Throughout the recent years, it has been widely recognized inside the building industry, that predicting and analysing future building behaviour in advance is far more efficient and economical, than fixing problems when the building is in the use phase.

BPS tools use numerical approximation of partial differential equations to solve spatial and temporal discretization. The accuracy of a building simulation is based on the number of network nodes and the associated thermal capacities. If the number of nodes used is big enough to assure some level of accuracy, on the other hand it also demands a large computational effort. However, the accuracy of the model does not only depend on the number of nodes, but also on the discretisation scheme. A reduced time step usually means a more accurate solution [22].

Whole building energy simulation tools, allow the detailed calculation of the energy required to maintain specified building performance criteria under the influence of external inputs, usually during the course of a full year. The energy performance of a building is mostly driven by six key factors: climate, building envelope, building equipment, operation and maintenance, occupant behaviour and indoor environmental conditions.

In building design while using simulation approaches, analysis often must deal with uncertainty during various steps of the optimization, resulting in uncertain optimal solutions. These uncertainties generally may arise, as described by *de Wit* [23], from modelling uncertainties, numerical uncertainties and input uncertainties. So, the choice of the program should always depend on the question that needs to be answered.

A good building performance simulation tool depends on the tool's capabilities for building design optimization and on the availability of advanced building control strategies. Over the past 50 years a wide range of building performance simulation tools have been developed to assist engineers in accessing a building's performance. An overview of the most used BPS tools, like for example: *EnergyPlus*, *ECOTECT*, *Esp-r*, *HAP*, *TRNSYS*, *IES<VE>*, is provided by Crawley *et al*., [24], as well as, a comparison of the capabilities of each simulation program.

3.2.1. *EnergyPlus* Simulation Tool

During this thesis, the BPS tool selected to make an evaluation of a building's energy consumption and assessment of its occupants' thermal comfort is *EnergyPlus 8.5*. This software program was chosen for the reason of being one of the most used energy analysis and thermal load simulation programs. But, mostly, for its free availability and capabilities as an open source BPS tool.

EnergyPlus is the combination of two software programs developed in 70s and 80s, *BLAST* and *DOE-2*. It is based on a user's description of a building from its physical aspects, mechanical systems and behaviour patterns [25]. *EnergyPlus* has the ability to calculate the heating and cooling loads of a building necessary to maintain certain set-points, the energy consumption of the building's system and equipment, and other simulation details that user may seem necessary to estimate. *EnergyPlus* was first released in 2001 and has been constantly updated, seeking to improve itself while adapting to the demands of present and future projects.

EnergyPlus is not a user interface. It is intended to be the simulation engine around which a third-party interface can be wrapped. In this research, the cross-platform employed is *Openstudio plug-in* for *Google SketchUp*, figure 3.2, which is intended to support whole building energy modelling using *EnergyPlus*. *Openstudio plug-in* for *SketchUp* is an open source software with the goal to facilitate the creation of the building's geometry in *EnergyPlus*. It is a fully graphical application, unlike *EnergyPlus*, making it more user-friendly.

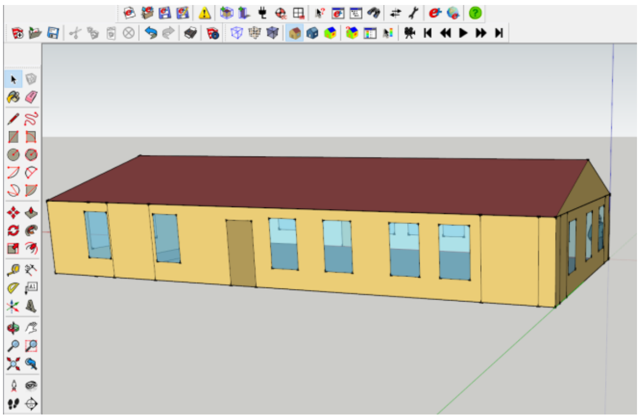


Figure 3.2: Interface example of Google SketchUp with Openstudio plug-in.

The simulation building process can be separated into four phases, as a general guide to create an *EnergyPlus* model. The first step consists of observing the real system and the interactions among its various components and of collecting data on the building behaviour. Therefore, is necessary to obtain meteorological information from the building site and, most important, it should be selected a weather file that best represents the climate region. *EnergyPlus* website has a database for more than 2100 location, where one can find weather data for virtually every region in the world. After obtaining sufficient building information the next step can be started.

In step two, one must begin by constructing the geometric representation of the building, dividing it in thermal zones that properly illustrates the shape and the partitions of the building. This stage is developed with *SketchUp* software and with *Openstudio plug-in*, because of its simplicity for the user, during the conception of the model. After completing the 3D modelling, the building model has to be converted into an IDF file, where all the geometric parameters are specified. Then, it is time import the file into the *EnergyPlus-Launch* engine and begin modelling the building characteristics. In *IDF Editor* one will be able to define the materials that compose the several construction elements like the floors, roof, walls and windows.

The third step involves the configuration of the behaviour patterns, internal gains and all the other parameters that may have an influence on the inside environment (ground temperature, shadowing, occupation schedules, lighting, electric equipment, infiltration, temperature set-points, etc.). In some cases, it is not possible to collect all the data pertaining to building (for example, usage profile) and in the end, it will be necessary to apply a probability distribution to estimate the input parameter.

The last step regards building’s mechanical system description. At this point, the heating, cooling and ventilation systems of the building are modelled according to the data collected. Finally, with all the building’s parameters and characteristics defined in *EnergyPlus* engine, the simulation is ready to be started. The verification and validation of the building model is followed to assess the validity of results.

The simulation in *EnergyPlus* occurs simultaneously in two major stages, building simulation heat balance module and systems simulation module [26]. Firstly, the simulation starts by doing surfaces heat balance considering the conduction, convection and radiation heat flows. These heat balances, will have an impact on the internal air heat balance in each zone, which handles with heat exchange air derived from ventilation, exhaust air and infiltrations. Thus, in this primary stage, the results obtain from each zone heat balance will work as input for the systems simulation module, that is responsible for determining the heating and cooling loads for the defined timestep. Next, this information will be forwarded again as an input for the building simulation module, leading to update the conditions of each zone for the following timestep, and so on like this until the end of the simulation.

Equation 3.6 translates how *EnergyPlus* calculates the heat balance on the zone air for timestep z:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{Nsl} \dot{Q}_i + \sum_{i=1}^{Nsurfaces} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{Nzones} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \tag{3.6}$$

where:

$C_z \frac{dT_z}{dt}$ – energy stored in the zone air;

$\sum_{i=1}^{Nsl} \dot{Q}_i -$ sum of the convective internal loads;

$\sum_{i=1}^{Nsurfaces} h_i A_i (T_{si} - T_z)$ – convective heat transfer from the zone surface;

$\sum_{i=1}^{Nzones} \dot{m}_i C_p \, (T_{zi} - T_z)$ – heat transfer due to interzone air mixing;

$\dot{m}_{inf} C_p (T_\infty - T_z)$ – heat transfer due to infiltration of outside air;

$\dot{Q}_{sys} \; = \; C_p \left(T_{sup} - T_z\right) -$ HVAC thermal load introduced into the area.

Chapter 4 - Verification and Validation of Simulation Model

Simulation models are used to evaluate the performance of a real system, concerning its operating characteristics. Since a BPS has the goal of producing an accurate and credible model, the output data from a simulation should directly correspond to the outputs recorded from the actual building. However, during the building modelling a collection of simplifications about the components and the structure of the system, plus assumptions made while estimating input parameters, decrease the level of confidence in the results obtained from the simulation.

In this context, verification and validation are essential iterative processes to conduct throughout the development of the model, until the model accuracy is considered accepted. Verification pertains to computer simulation software used to model the building. It is a procedure of confirming that the computer simulation is correctly implemented, with respect to the conceptual model. The objective of model verification is to ensure that the implementation of the model is correct. If the input parameters and logical structure of the model are correctly represented in the model, verification has been completed. For the most part, common sense is used in completing this step.

Verification and validation, although theoretically different, typically are simultaneously performed. Validation is the overall procedure of comparing the model and its behaviour to the actual building [27]. Once developed and validated, a model can be used to investigate a wide variety of aspects regarding the building (thermal comfort, cost-efficient opportunities, etc).

4.1. Validation

Validation of a model consists on making sure that the model simulations are providing accurate and reliable results about the building’s performance. It is a process of assessing, by independent means, the quality of the data products derived from the system outputs, which is related to the simulation algorithms accuracy and correctness. Typically, exists three types for validation of a building performance simulation software. The first is called comparative testing, in which a program is compared to itself or to other programs. The other two techniques are: analytical validation and empirical validation [28].

In the analytical verification, the outputs from a program or algorithm are compared to the results from a known analytical solution for isolated heat transfer mechanisms, under very simple boundary conditions. In other words, it tests the numerical solutions of a software, but does not test the simulation model. It is based on very simple physical processes which are already pre-established and well-known, making it only applicable to a limited number of situations, and if the results obtained with the software are correct they can be extrapolated to more complex cases, given its simplicity it provides an exact standard for comparison. This method enables an easy and inexpensive way to understand correctly the basic physics of a situation, but for the more complex models, where multiple building parameters and aspects need to be modelled, this technique is not useful.

In the Empirical validation, the calculated results from a program or software are compared to monitored data from a real structure or building. This technique requires high quality detailed measurements, which make the gathering and monitoring of the data too much demanding in time and very expensive. The characterization of some of the more complex physical processes (heat transfer with the ground, infiltration, indoor air motion and convection) treated by simulation operating systems are often excluded, due to measurement difficulties and uncertainties. Because of these disadvantages only a limited number of cases are economically practical. But at the same time, it also provides a rigorous and accurate test of the model and the solution process, making it applicable to any level of complexity.

The research presented intends to check the accuracy of a building simulation model through an empirical validation. Consequently, optimization techniques must be integrated into simulation analysis. The whole process of validation consists of comparing the results with what is expected based on utility data. Therefore, a base model should be created and calibrated so that it matches the expected performance. The calibrated model should then be verified to ensure that the model is operating as anticipated based on the input transformations. In the end, validation can only be achieved through model calibration.

Hence, model calibration is the iterative process of comparing the model to the real system, adjusting the input of each variable to see the effect on the design objectives while other variables are kept unchanged. This method is often time-consuming and is repeated until model accuracy is deemed acceptable. To validate the results produced from the BPS, statistical techniques are employed as a method to assess the accuracy of outputs and the consistency of the same.

Although sometimes ignored in BPS, it is very important to perform an uncertainty and sensitivity analysis to confirm that the accuracy of the results is properly understood, by quantifying and characterizing the uncertainties of the model for design information and quality assurance. Both these methods can provide information about reliability towards design parameters, with respect to the overall design. UA (uncertainty analysis) and SA (sensitivity analysis) are applied in several approaches for parameter screening with the aim of assessing the robustness of the model and as a powerful technique for model validation.

The verification and validation phases often detect bugs that require further debugging, or incorrect assumptions that need significant model modifications and then further model re-verification and re-validation. It should also be noted that no model is ever 100% verified or validated. Validation is not an absolute method. Any simulation model is a representation of a system, and the model's behaviour is at best an approximation to the system's behaviour.

4.2. Model Calibration

Calibration is a crucial technique during building simulation to ensure the maximum accuracy of results. It consists on a process of quantitatively defining the system responses to known, controlled signal inputs. It is meant to evaluate the accuracy of the predicted building performance simulation outputs, according to a set of parameter modifications (new insulation materials, variation in the shading devices, optimization of HVAC systems), by comparing to the actual measured data from the building. This procedure has the goal to diminish the gap between the known results from the building's data and the values obtained from the model simulation.

Kaplan *et al.,* [29], [30] defined calibration as the process of adjusting the parameters of a model through several iterations, until it agrees with recorded data within some predefined criteria. The definition of these criteria is a complex issue and, to date, it is impossible to determine how close a tolerance needs to be to fulfil the calibration process. The calibration of a BPS model comprises two ideas towards quantitatively define the systems response to known, controlled parameters: Calibration Signature and Characteristic Signature.

Characteristic Signature, equation 4.1, consists on the comparison between baseline uncalibrated performance simulation results and a modified baseline simulation, usually by a normalized plot that easily demonstrates the difference between them. The baseline uncalibrated model is based on information known about the building design construction, occupancy profiles and systems control and management, which may introduce some inaccurate results. These inputs are tested and changed (increased or decreased) one at a time, and two characteristic signature plots are generated for cooling and heating energy demand as a function of the ambient air temperature. The main limitation of this method is that some parameters are independent of ambient temperature and may not change accordingly, but still may have an important role in the building energy needs.

$$Characteristic\ signature = \frac{Change\ in\ energy\ consuption}{Maximum\ energy\ consumption} \times 100 \tag{4.1}$$

where the change in energy consumption represents the difference between the modified simulation value and the baseline uncalibrated simulation value.

Similarly, Calibration signature, equation 4.2, shows the difference between measured data results and the modified baseline model simulation, by a normalized plot with the simulated energy consumptions as a function of the outside temperature. The objective is to verify the difference in input parameters with several model simulations, in order to understand where the discrepancies in the building's performance lay. This process has the advantage to perform faster calibrations because the users have a better idea about which parameter needs to be altered, instead of a trial and error technique that may take much longer [31]. Calibration signature output results are a clear demonstration of how much error is inserted into the building model simulation, enabling a rapid assessment pertaining to the accuracy of the predictions.

$$Calibration\ signature = \frac{-Residual}{Maximum\ measured\ energy} \times 100 \tag{4.2}$$

where,

$$Residual = Simulated\ Consumption - \ Measured\ Consumption \tag{4.3}$$

To have a broader understanding of the accuracy of the model and to minimize the compensation effect, whereby over-estimations cancel out under-estimations, researchers proposed the adoption of a standardized statistical indices as mean of comparing the errors between simulated and measured data, which better illustrate the performance of a BPS model. These two indices are the Root Mean Square Error (RMSE) and Mean Bias Error (MBE). When analysing a building's parameter, the RMSE can give an important help because it represents the standard deviation of the differences between the model simulated and the measured data, thereby measuring the variability of the data as defined in formula 4.4:

$$RMSE = \sqrt{\frac{\sum_{t-1}^{n} Residual_t^2}{n-2}} \tag{4.4}$$

where n is the number of data points. Towards a better measurement of the overall prediction accuracy of the model a relevant index associated with RMSE is used to closely reflect the accumulated magnitude of error. The Coefficient of Variation of Root Mean Square Error, CV(RMSE), is a measure of accumulated error normalised to the mean of the measured values, allowing to efficiently determine how well a BPS model fits the data by capturing offsetting errors between measured and simulated data, as defined in formula 4.5:

$$CV(RMSE)(\%) = \frac{\sqrt{\frac{\sum_{t-1}^{n} Residual_t^2}{n-2}}}{\bar{m}} = \frac{RMSE}{\bar{m}} \tag{4.5}$$

where $\bar{m}$ represents the average of measured consumption data. In contrast with the RMSE, the Mean Bias Error (MBE), equation 4.6, is an overall measure of how influenced the data is and is also a good indicator of how much error will likely be introduced in the annual energy consumption estimates, since positive and negative errors will cancel each other out.

$$MBE = \frac{\sum_{t-1}^{n} Residual_t}{n} \tag{4.6}$$

Similarly, to CV(RMSE) a normalised non-dimensional bias measure between measured and simulated data, NMBE, is a good indicator of the model overall bias. Equation 4.7 defines a quick and easy estimate to accomplish it.

$$NMBE\ (\%) = \frac{\sum_{t-1}^{n} Residual_t}{\sum_{t-1}^{n}(m_t)} \tag{4.7}$$

where m_t is the respective measured data point. The calibration and corresponding BPS validation, both for heating and cooling energy consumption, is based on a model’s compliance with standard criteria as shown in table 4.1 by means of using the previous defined indices, and generally the models are considered calibrated if they are in agreement with ASHRAE Guideline 14 [32]. The criteria may vary depending the type of data one is working with, hence models can be calibrated accordingly to monthly or hourly measured data.

Table 4.1: Acceptance criteria for calibrating BPS models.

Standard/guideline	Monthly criteria (%)		Hourly criteria (%)	
	MBE	CV(RMSE)	MBE	CV(RMSE)
ASHRAE Guideline 14 [32]	5	15	10	30
IPMVP [33]	20	-	5	20
FEMP [34]	5	15	10	30

However, calibration is not an exact science, after all the same exact building can have numerous models to be considered calibrated in accordance to the standard criteria, therefore calibration does not have a unique solution. Meaning that when there is reasonable agreement between measured and simulated data, the BPS model may be deemed calibrated. The whole process of calibration demonstrated in a simplistic way in figure 4.1, shows how it is going to be conducted during this research study.

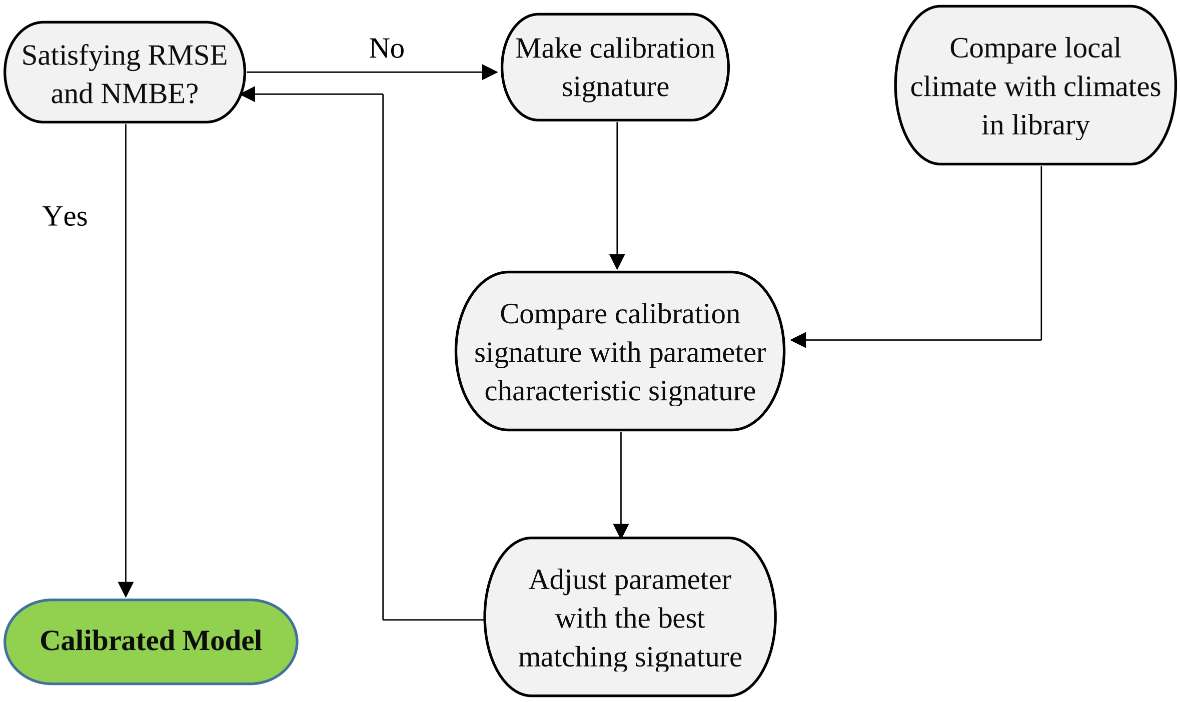


Figure 4.1: Methodology process for calibrating a simulation model. Source: [31]

As a complement to the former indices, one may consider to assess the total error of a BPS model calibration. In the attempt to minimize the total error of the model, one may arbitrarily combine the root mean square heating and cooling with mean bias heating and cooling in algebraic combination to have a measure of error as defined in formula 4.8:

$$\begin{aligned} ERROR_{TOTAL} &= [RMSE^2_{TOTAL} + MBE^2_{TOTAL}]^{1/2} \\ &= [(RMSE^2_{CLG} + RMSE^2_{HTG}) + (MBE^2_{CLG} + MBE^2_{HTG})]^{1/2} \end{aligned} \tag{4.8}$$

In addition, another aspect to emphasize is that the current calibration methodology relates solely to predicted energy consumption, and does not account for uncertainties of building software environments.

4.3. Uncertainty and Sensitivity Analysis

The aim of a UA/SA (Uncertainty and Sensitivity Analysis) study is to support the design process by providing additional information of the parameters chosen. The different sources of uncertainty that play a role in the design of the BPS must be considered throughout the modelling, but especially during model calibration. The model does not need to represent as it is architecturally, but rather its thermal behaviour. *De Wit* [35] stated that modelling uncertainties arise from commonly applied physical assumptions and simplifications in a computer model. Thus, a major challenge in simulation tools is how to deal with difficulties through a large variety of parameters and complexity of factors.

Risk in the assessment of a BPS model can be categorized in different types of uncertainty, according to *Hopfe* [10]:

- Physical;
- Scenario;
- Design parameters.

Firstly, during the construction of the building, deviations from the design specifications may occur due to incomplete specification of all relevant properties of the building. Physical uncertainties refer to the material properties such as thickness, density or even wall, roof and floor characteristics. This is the most common source of uncertainty within a building, since one can be completely aware of the exact properties of a material and the designer as no influence on this type of uncertainty. Taking these uncertainties into account will considerable affect the quality assurance of the building model.

Secondly, uncertainties may be introduced in the scenario, trough external conditions imposed to the building, which involves the wide range of different possible usages. They are related to the influence of infiltration rate, outdoor climate conditions and occupant behaviour that may be unpredictable to determine and may change during the building life time.

Finally, uncertainties in design parameters can be described as design variations that occur during the modelling process. Even if a model is developed on the basis of a complete description of all appropriate building properties, the introduction of assumptions and the simplifications of physical processes bring uncertainty into the model. For instance, in the conceptual design of the building, aspects like the thermal zone geometry or glazing dimensions can have a substantial influence on the accuracy of the model. In addition, numerical errors and numerical approximations also represent a source of uncertainty. It is assumed that choosing the appropriate discretization scheme and time step can help to minimize the numerical uncertainty of the model, hence this uncertainty will not be addressed during this study.

The goal of integrating UA/SA into a simulation analysis, is to establish the impact that uncertainties have on the predicted energy use [10]. Uncertainty analysis is aimed to show the effect that uncertainty has on the outcome. While sensitivity analysis is to find a limited set of parameters, which account for most of the uncertainty in the model output [23].

Uncertainty analysis investigates the uncertainty of variables that are used during the design of the model, and then quantifies its propagation through the simulation. Uncertainty refers to the range of variation of a physical property, represented by a probability distribution. So, an uncertainty analysis (UA) takes into account uncertainties related to simplifications assumed during the development of the model and lack of information with respect to the input data. A common approach to conduct UA is to use a deterministic model, but assign probability distributions to the uncertain input parameters. This distribution is described as degree of belief as where possible values of each variable are located.

On the other hand, sensitivity analysis (SA) consists on modifying model inputs, in order to see their effects on model outputs. In other words, SA supports the decision maker in identifying the most sensitive parameters improving building performance understanding. *De Wit* [35] proposed an approach to conduct a sensitivity analysis consisting of two steps:

1. Parameter screening: at first rank the most important parameters considering their contribution to the uncertainty in the model results;
2. Validation: verification of the set of parameters screened to determine the impact of a variable.

UA and SA are usually applied to assess the risk of different energy conservation measures, helping to support decision-making. For instance, both analysis can provide information about reliability towards design parameters, which can respectively have an effect to the overall design [10]. To summarize, UA/SA are applied as a method to test the robustness of a simulation model in the presence of uncertainty, with the goal of uncertainty reduction.

Chapter 5 - Dutch Building Decree

Under the Energy Agreement for Sustainable Growth [36], the Netherlands has set goal for a sustainable energy supply system by 2050. The overall building targets, which the Netherlands is committed to achieve in the Agreement, establishes detailed building sector goals, regarding a specific number of buildings to be renovated by 2020 and an increase in energy labelling for the existing building stock, by at least two label steps. By 2030, the average for the existing building stock is targeted to be a label A (or better). The core feature of the Agreement is a set of broadly supported provisions regarding energy saving, clean technologies, and climate policies. Implementing these provisions is intended to result in an affordable and clean energy supply, jobs, and opportunities for the Netherlands in the market of energy effieciency. Alongside, the Dutch government is trying to reduce the burden that several Dutch regulations create on the developers of building projects.

The Dutch Building Act 2003 or "Bouwbesluit 2003 " [37] was the first decree in The Netherlands related to the building industry. Contains provisions on the building and demolition of buildings, the state and the use of existing buildings, yards and open fields and on safety measures during construction and demolition. It sets rules relating to the construction of structures in terms of safety, health, usability, energy efficiency and environment. These are the requirements to ensure the minimum necessary quality of the buildings.

The objective of merging the regulations in a single new act is to increase coherence within the building regulations, reduce the regulatory burden and improve accessibility. This relates mainly to the standardization of the methodology and concepts, simplifying regulations, harmonization with other regulations, the experience in the application of the current rules, both the European and Dutch regulations.

5.1. Building Thermal Code

The Dutch Building Decree, Bouwbesluit [37], suffered a renovation in 2012 and is divided in five chapters relating to safety, health, usefulness, energy-saving; and "the environment". Especially, chapter 5 (NEN 7120:2011) has significant importance because it concerns the building regulations in the Netherlands, making it the focus of this thesis. It explains in some detail government regulations during the use phase of a dwelling or commercial building. According to it, the energy performance is expressed by EPC or "energy performance coefficient" for new buildings and in the case of extensive renovations. On one hand, residential buildings built after 2012 the EPC is 0.6 and will be lowered to 0.4 in 2015, with the intention of reducing the energy consumption of new buildings over time. On the other hand, commercial buildings vary on EPC depending on the type of function in which the buildings are used, Table 5.1, [37].

Table 5.1: Energy performance coefficients (EPC) requirements by type of building. Source: [37]

Type of Building	EPC
Healthcare	0.8
Office	0.8
Education	0.7
Sports	0.9
Store	1.7

However, Dutch building decree does not specify how to calculate the energy performance coefficients. Only accessing NEN 7120 and/or NEN 2916 (NEN stands for Nederlands Normalisatie-Instituut), would enable the possibility of determining the EPC. Since it would be required to buy the norm for a substantial amount of money, this topic will not be addressed during this research, even though it would be a plus to this work for being the overall score of how efficiently is performing a building.

Nonetheless, it is essential and necessary to highlight the code regulations in the Netherlands. A better performance than the minimum level cannot be required, but both parties, engineers and clients, may agree on higher performances on a voluntary basis. The decree [37] requires a global thermal insulation, R_c, for commercial buildings of at least :

- Roof – 6.0 m^2.K/W
- Wall – 4.5 m^2.K/W
- Floor – 3.5 m^2.K/W

While for windows and doors, the regulation establishes that heat transfer coefficients should be between 1.4 to 6 W/(m^2.K).The Decree also contains some provisions related to building's internal heat productions: lighting, people and equipment. Regarding lighting, the NEN 7120 alongside with ISSO 32 [38] (where ISSO stands for Instituut voor Studie en Stimulering van Onderzoek) states that the lighting power is related to the use functions in the building:

- Dwellings – during daytime there is no lighting and at night 15 W/m^2 in living room and kitchen;
- Schools – 10 W/m^2;
- Offices – The values for the power per sqm can be obtained in table 5.2.

People internal heat productions covered by ISSO 8 [39] and ISSO 32, expresses that people power is calculated on the basis of the specified clothing and MET (the Metabolic Equivalent of Task) values. The standard clothing value used in the Netherlands, citing ISSO 19 [40], during Summer time is 0.7, considering that 1 clo = 0.155 m^2.K/W. On the other hand, standard clothing during Winter is 0.9. Table 5.3 describes typical clothing insulation values conform Netherlands legislation. MET is the physiological measure that describes the energy cost of physical activities, where an average adult has 1.8 m^2 of surface area (skin) and 1 MET = 58.2 W/m^2.

Table 5.4 shows physical activities in consonance with its MET equivalent. The standard value used during building design phase and BPS is 1.20 MET for most common type buildings. Lastly, equipment internal gains will vary depending on the usage of the building, as a result table 5.5 exemplifies recommended values for equipment used in houses and offices.

Table 5.2: Installed power for lighting systems. Source: [38]

Lighting system	Type of switching device	Average installed power in W/m2
Surface-mounted luminaires with standard fluorescent lamps	conventional electronic	14.5 11.5
Surface-mounted luminaires T5 fluorescent lamps and high-performance mirror optics	conventional electronic	11.5 8
Surface-mounted luminaires with compact fluorescent lamps	CFL	15/16
General lighting with built-in / surface-mounted luminaires for indirect lighting via reflector in fixture		15/16
Indirect general lighting with pendant luminaires features (compact) fluorescent lamps	TRY	11.5
Limited indirect general lighting with pendant luminaires, locally supplemented by workplace luminaires		9.5
Limited indirect general with additional local lighting with standing luminaire		15/16
Limited indirect general lighting and additional local lighting with pendant luminaires in combination with standing luminaries		12.5

Table 5.3: Values for standard clothing. Source [41]

Type of Clothing	CLO units
Nude	0
Only shorts	0.1
Standard skin suits (skirt, shorts, shirt with open collar and short sleeves or T-shirt, thin socks and sandals)	0.3
Light summer suit (slip, light trousers, shirt with open collar and short sleeves, thin socks and shoes)	0.5
Light suit (underwear, cotton work shirt with long sleeves, long trousers, woollen socks and shoes and panties, petticoat, stockings, dress and shoes)	0.7
Winter clothes indoor (underwear, long sleeved shirt, long pants, long-sleeved sweater, thick socks and shoes and panties, stockings, blouse, long skirt, jacket and shoes)	1.0
Winter clothes outdoor (cotton underwear with long sleeves and trousers, shirt, suit with long pants, jacket and vest, wool socks and heavy shoes)	1.5

Table 5.4: Adopted activities and respective MET Values. Source: [38], [39]

Activity	MET value	Total Power [W]
Resting	0.81	85
RGD BIM Standard	1.20	126
Sedentary office work	1.24	130
Typing	1.52	160
Light active sedentary work	2.00	210
Light active standing work	2.86	300
Active sports	3.81	400
Heavy sports	4.76	500

Table 5.5: Recommended values for power equipment in office and homes. Source: [38]

Device	Power (standby) [W]
Desktop computer	200
Flat screen TV with 17 "	25
Flat screen TV with 19 "	30
Flat screen TV with 22 "	55
Large graphic display	150
Laptop	30
Mini-notebook	15
Printer	50 (10)
Laser Printer	400 (10)
Plasma TV	300 (15)
LCD TV	125 (5)

Infiltration is defined as all air entering the building in a different way than mechanical means or by ventilation features. According to ISSO 51 [42] and ISSO 57 [43], included in the 2012 Building Decree, the airtightness value for non-residential building relies on the volume of the building. Hence, for buildings built after 1992, infiltration varies from 0.2 to 0.4 air changes per hour. Similarly, in ISSO 53 [44] there is a guideline for determining infiltration for offices, which describes that the infiltration rate is 200 dm^3/s per 3000 m^3, corresponding to 0.24 air changes per hour.

The standard design temperatures for heating and cooling for occupied areas in residential, office and education buildings are 20ºC and 24ºC, correspondingly [42], [43]. Nevertheless, this temperature set-points may be different depending on occupant's preference or concerning the operation of the building management system.

According to Building Decree 2012, ventilation during building design phase is considered based on the number of people present in a room or area. For a building with an office function, the minimum requirement of people present in an occupied area is 0.05 people per m^2. Further, for educational buildings consisting mainly of classrooms the requirement is of 0.12 people per m^2. From this information, it can now be obtained the minimum requirement of designed outdoor supply air for buildings with office function which corresponds to 6.5 dm^3/s per person. Moreover, buildings comprising mainly on classrooms with educational purposes have a ventilation requirement of 8.5 dm^3/s per person. Annex A contains additional information on ventilation rate regulation. All the guideline data formerly mentioned will be crucial during the BPS model discussion in chapter 7.

5.2. Thermal Comfort Guideline for the Netherlands

In the mid-70s, Netherlands started to develop the first guidelines and strategies relative to thermal comfort in buildings. They were primarily based on the PMV-PPD model developed by P.O. Fanger and later on ISO-EN 7730 [45]. Both presented a theory to predict whether a particular circumstance experienced by building users will be perceived as "cold", "neutral" or "hot". Over the years, the Netherlands adopted three consecutive methods to assess thermal comfort for the design and simulation of buildings, and they respectively are:

- Overheating Hours (TO);
- Weighted Overheating Hours (GTO);
- Adaptive Temperature Limits (ATG).

PMV was developed to be used in steady-state conditions. Then, it is important to take into account that only TO performance indicator is suitable for these cases only. Consequently, for naturally ventilated spaces, which often have high levels of air movement, were developed empirical methods of thermal comfort, such as GTO and ATG. The Overheating Hours (TO) method was first presented in 1979 by the Netherlands government. It is the simple and quickest technique to evaluate a certain indoor environment in terms of comfort for its occupants. The standard ISO 7730 establishes that for a space to present "good" conditions of thermal comfort must comply with the limits of $0.5<PMV<0.5$ and no more than 10% of its occupants may feel uncomfortable. TO defines that the number of hours at which temperature levels are superior to 25ºC and 28 ºC, should not exceed 100 and 10 to 20 hours, respectively, during the course of a full year. However, one disadvantage of this indicator is that does not provide information about how long the overheating hours last and it does not take into consideration other aspects than temperature.

Afterwards, the TO method evolved into the so-called Weighted Overheating Hours (GTO) method and was initially introduced in the Guidelines for Governmental Buildings in 1989. The GTO is supported by the theory developed by Fanger. This performance index relates the hours in which a predicted mean vote (PMV) exceeds +0.5 or -0.5 the comfort boundaries with weighting criteria proportional to PPD values. The sum of these hourly factors over the year result in the GTO. In case the system is improperly sized, the number of weighted overheating hours can be seen to be rather high, in some cases even higher than the number of operation hours. When the number of weighted overheating hours remain below 150 hours per year, the indoor conditions are considered to be in an acceptable range.

This method however, has some important drawbacks. To begin with, thermal comfort results obtained through this method are not intuitive, and therefore it may be difficult to present them to people untrained on this subject. Secondly, as the GTO is based on the occupants' thermal comfort perception, this method may not be suitable for buildings in which occupants take different actions, in order to adapt themselves to the changing thermal environment. For buildings with degree of adaptive opportunity the TO and GTO thermal comfort models were found to have major obstacles.

Following this, in 2004 a new method to access thermal comfort was adopted [46], in which a distinction between sealed centrally air-conditioned buildings and buildings with free running conditions and possibility to control room temperature is made. In an effort to overcome these complications the terms Alpha and Beta, were introduced to characterize the different climate/building types.

The Adaptive Temperature Limits (ATG) thermal comfort model, described in detail in ISSO 74 [47], is based on the relationship between the indoor comfort and outdoor climate. It considers the human occupant as being able to adapt himself to different temperatures during the seasons of the year. The maximum indoor temperature is higher for Alpha buildings rather than for Beta buildings, though the minimal values are equal in both building types. Alpha buildings are categorised by the existence of natural ventilation, free-running conditions or climate control conditions by the user himself in terms of having at least one operable window and/or temperature adjustment. In opposition, Beta buildings are characterized for having a closed façade and air conditioning with centrally regulated climate.

The main advantage of this method is that allows the distinction between two types of buildings. ATG method tolerates a wider temperature range for natural ventilated buildings and simultaneously, facilitates the communication with the client about the thermal comfort assessment. One should take in mind, that the comfort perceived by occupants differs, when comparing office buildings to dwellings. When one is at home, usually, wears a more comfortable clothing to relax, whereas at work the main requirement is to feel comfortable, in order to be productive. Moreover, office buildings distinguish from dwellings in terms of occupancy times. With this method, the occupant's thermal comfort can be easily determined by means of a simple, clear and objective chart. In addition, the ATG method also takes into account the different building configurations, operational approaches, inside and outside temperatures and people behaviour, unlike the other methods.

In 2014, a new version was elaborated of the ISSO 74:2004 guideline, making it the current Dutch Adaptive Thermal Comfort Guideline [48], [49] used when designing a new or refurbishing a building. To determine the limits that one as to use for the operative temperature, two very important features must be examined initially for every building:

- Whether the situation is type α or a type β (room or building);
- The classification level pretended (Class A, B, C or D).

For cases where the building or room is in free-running conditions during summer, with operable windows and other adaptive opportunities for the occupants, the operative temperature limits are type α. Whereas, type β refers to situations where the operative temperature limits to consider are based on a building or room that depends on centrally-controlled cooling.

After determining what type of building it matches, the known temperature limits should be used as a threshold value, so that measurements can be made or can be ascertained by a computer simulation to estimate the inside operative temperatures. Every time that is made a reference to operative temperatures, this implies that also radiant temperature effects are taken into consideration.

The classification level should be applied given the situation intended. Class A is projected when exists a high level of expectation. This category is a reference when designing spaces for people with limited load capacity (extra sensitive people namely ill people) or when extra luxury is asked for. Class B is the most common level of expectation; it is a reference when designing or measuring new buildings or in case of extensive renovations. When measuring older existing buildings, the most common anticipated thermal comfort class is C. For a low level of thermal comfort, the classification level is D, normally can be used as a reference in the case of temporarily buildings or with limited use. The temperature boundaries are presented in table 5.6, as well as, in figure 5.1 are demonstrated the corresponding adaptive temperature limits for each level of classification.

Table 5.6: Description of the four classification levels. Adapted from: [48]

Class (bandwidth)	**Requirements indoor operative temperature (ºC)**				**Percentage Dissatisfied (%)**	**PMV analogy (bandwidth)**
	Setpoint limit	**Winter**	**In-between-seasons**	**Summer**		
General	Setpoint line	21		24.5		
A	Upper limit	Same as class B (requires options available for occupant control with ± 2 K)			Max. 5%	-
	Lower limit	Same as class B (requires options available for occupant control with ± 2 K)				
B	Upper limit	24	$18.8+0.33*T_{out}+1$	Type β:26 Type α: $18.8+0.33*Tout+1$	Max. 10%	$-0.5 < PMV < +0.5$
	Lower limit	20	$20+0.2*(T_{out}-10)$			
C	Upper limit	25	$18.8+0.33*Tout+2$	Type β:27 Type α: $18.8+0.33*Tout+2$	Max.15%	$-0.7 < PMV < +0.7$
	Lower limit	19	$19+0.2*(T_{out}-10)$			
D	Upper limit	26	$18.8+0.33*Tout+3$	Type β:28 Type α: $18.8+0.33*Tout+3$	Max. 25%	$-1.0 < PMV < +1.0$
	Lower limit	18	$18+0.2*(T_{out}-10)$			

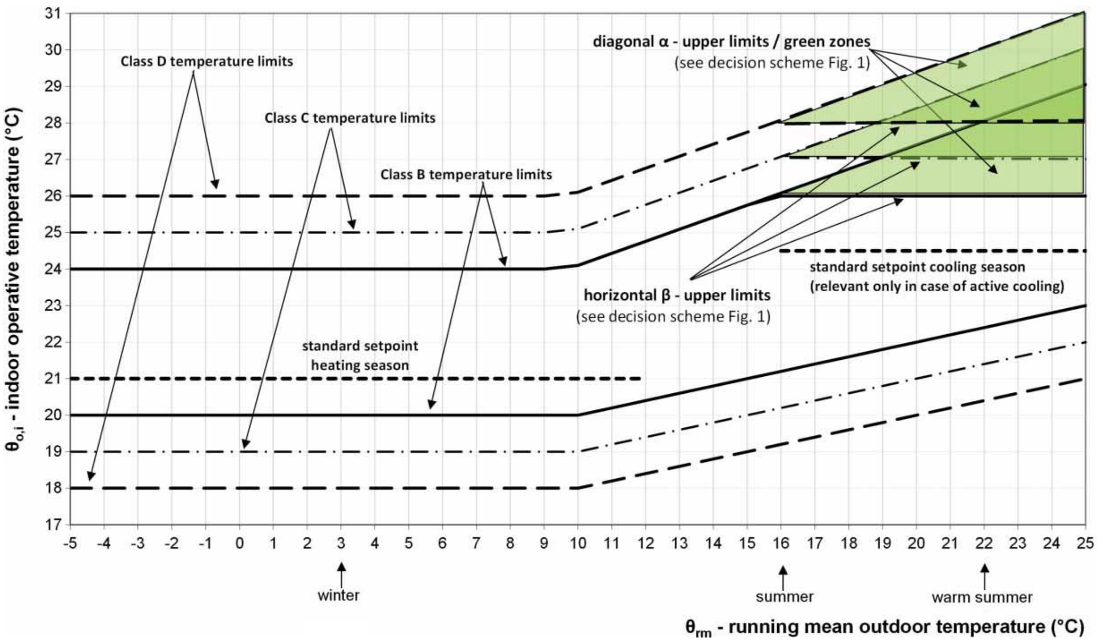


Figure 5.1: Adaptive Temperature Limits (ATG) chart. Source: [50].

This study gives guidance on how to apply the new guideline in practice and the applicability of this new method into the building performance evaluation. The compliance verification with the new ISSO 74 guideline, thus allows to confirm whether a building's thermal performance is operating as expected, either in the design phase or throughout the occupancy phase. The temperature limit boundaries from each class is also a good measure of how comfortable the occupants are, since this temperature limits derive from the thermal comfort model proposed by Fanger and ISO 7730. Figure 5.2 provides an expected output result of a thermal comfort assessment while using a BPS tool.

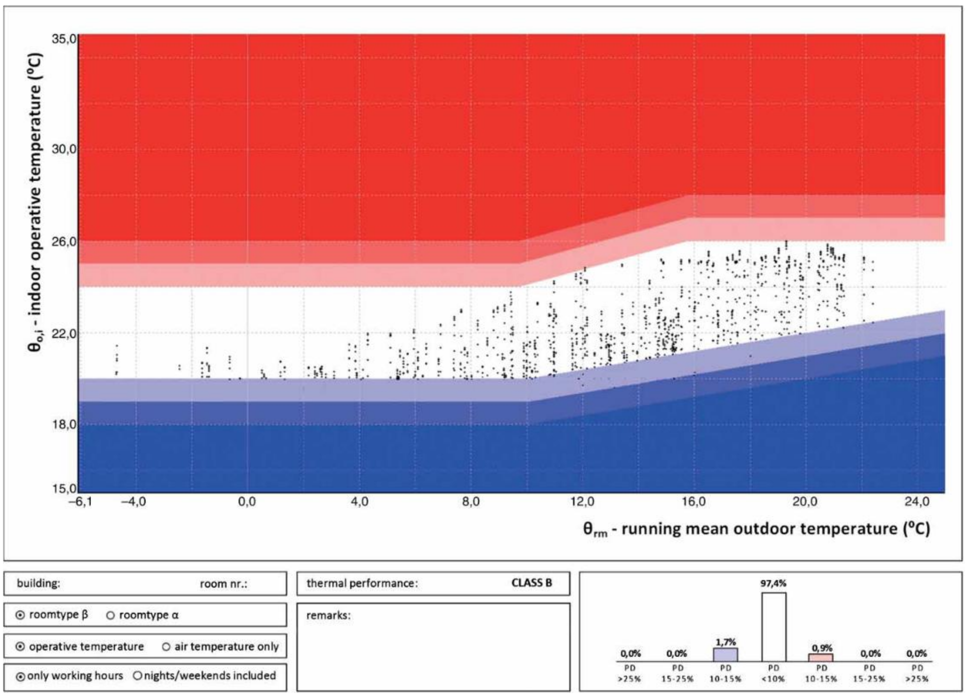


Figure 5.2: Example of simulation results for a type α building. Source: [50].

Chapter 6 - Case Study

6.1. Data collection

The first stage of this research consists in the collection of data, as detailed as possible, regarding the characteristics and operating systems of the building under evaluation. To achieve these objectives, several inspections were made to the case study building. The Vertigo Building on the campus of the Eindhoven University of Technology (TU/e) in Eindhoven, the Netherlands, was chosen as a test case. Most of the collected information was provided by TU/e Real Estate department. The following points indicate all material collected:

- Floorplans, blueprints and glass façade constructive details;
- Inspections to the building enabled the collection of information relative to the use of spaces: occupation, lighting, equipment;
- Annual energy consumption measurements from 2009 until 2012;
- Annual energy use reports.

Although, it was possible to gather relevant data concerning the building and its operations, it is important to mention that it was not possible to obtain a complete description of the construction materials, as well as of the entire air-conditioning system. Nevertheless, in some parts of the building, monitoring systems were installed. These can record hourly consumption, which allows to establish an hourly comparison between simulation results and measured data. The metering information is divided in:

- Six electrical meters: constant load representing lighting, semi-fluctuating load representative of equipment used in the building, two sensors in the mechanical system transformers, one sensor in the emergency circuit and other one in the heat pump),
- One gas meter
- Two meters assessing the amount of thermal energy delivered by de ATES (Aquifer Thermal Energy Storage) system (one for Warm and another for Cold).

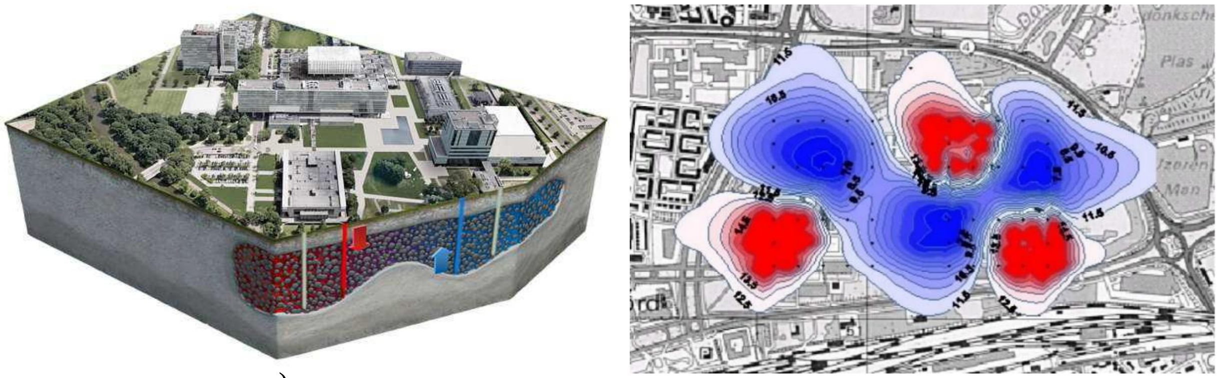
Regarding the occupancy data, information was collected on the basis of users' descriptions and reports. Due to the educational purposes of this office building, it has free access to all the academic staff. Thus, it is difficult to estimate exact values, because the turnout in this building changes on hourly and monthly basis, according to unidentifiable factors.

6.2. Building description

The case study is an office building located in the Eindhoven University (TU/e) campus, usually called as The Vertigo, heading the Faculty of Architecture, Building and Planning. TU/e has a heating and cooling infrastructure based on a large-scale Aquifer Thermal Energy Storage (ATES) spread throughout the university campus, making it one of the largest ATES systems in Europe, see figure 6.1a).

The ATES system supplies direct cooling in summer as well as low-temperature heating during winter into the evaporators of the heat pumps [51]–[53]. As a mean to charge enough cold in winter and due to higher annual cooling then heating demand, cooling towers are used to charge additional cold. Nowadays, energy demand is supplied to approximately 20 buildings, with a target of *Campus 2020* to reach 30 buildings.

The system consists of a large open circuit system created by two distribution rings, one warm and one cold, to which 16 cold wells and 16 warm wells divided over 6 clusters (3 cold and 3 warm) are connected to the Vertigo and other buildings, as in figure 6.1b). The total capacity of the system is 25 MW_t and to every building there is a delivery system, where is included a heat exchanger and several mechanical components, to exchange cold and heat with the main distribution network. Cold and low temperature heat are available all year around.



a) b)

Figure 6.1: a) ATES system in TU/e campus; b) ATES warm and cold clusters in Tu/e. Source: [53][53]

With all the previous information, one can now focus on the target building under evaluation. The Vertigo building was constructed on 1965 and underwent a major renovation from 1998 until 2002 [54], [55]. The building envelope is made of a sandblasted concrete carcass, rearranged and coated with a glass curtain wall (façade), with an average ratio 30/70, respectively [56], see figure 6.2. This building is a 23,000 m^2 with a total of 12 floors. It is comprised by a high-rise seven-floor section, a three-story section with a larger floor plan and two below ground floors.

The top five floors contain office spaces sharing a central atrium, which can be described as an open area. The rest of the top floors and the lower floors of the building consist of a mixture of small and large work rooms, open workplaces, meeting rooms, offices, and laboratories. The below ground level floors house the mechanical systems. It has approximately 16,500 m^2 of usable floor space area and a floor height of 5.40 m. The building façade comprises a curtain wall framework, built in with clear double glass and silk-screen glass. Vertigo building is usually occupied from 08:00 till 18:00 on weekdays and is vacant on weekends.

Figure 6.2: Picture of the Vertigo building at TU/e.

6.3. Building Systems

Heating and cooling is mainly provided by a district aquifer thermal energy storage (ATES) system connected to a heat pump. The basic idea of this storage system is to use the accumulated cold and/or warm water, to cool and/or heat the building and to store back the rest of warm/cold water, in the underground storage for later use (mostly to use in the next season).

The primary mechanical system consists of a water source heat pump located in the basement and two hot water natural gas boilers located on the roof, figure 6.3. Since the end of the renovation in 2002, the building has suffered up until 2008/2009 constant tweaks in its mechanical system, seeking the most energy efficient load, regarding the building's occupancy and energy consumption profile.

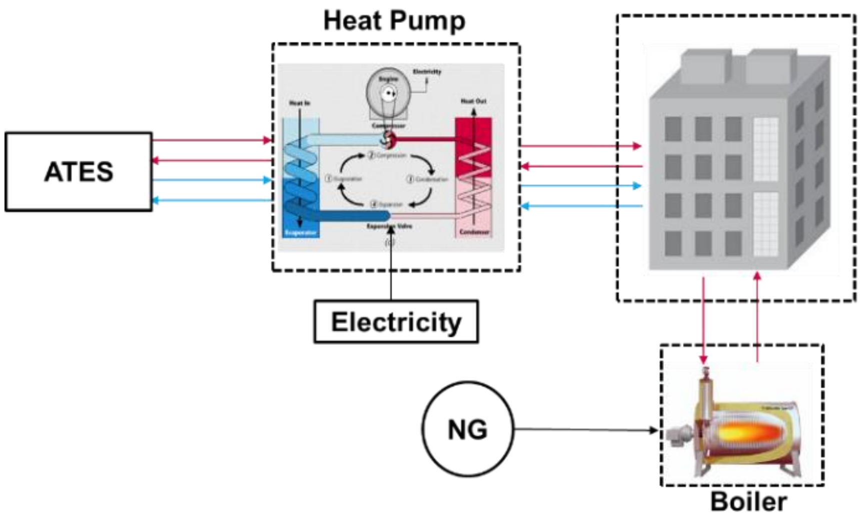


Figure 6.3: Vertigo's mechanical system overview

Due to climate conditions, heating demand is higher than cooling for the Vertigo building during most time of the year. The temperature in the heat storage is too low to be directly connected to the heating circuit [57], resulting in a need to complement the whole district with heat pumps and boilers. The source of the entire system is water, a relevant aspect to highlight is the fact that warm water from the ATES comes at roughly 15 ºC. Hence, the ATES system acts as a pre-heater of the water to be utilized by the heat pump as a source. On the other hand, the water stored in the cold ring has a maximum temperature of 8 ºC.

However, the ATES system is not precisely coupled to the building. Instead, a heat exchanger is used as an interface that allows to transfer thermal energy between the primary system (ATES) and the secondary system (heat pump). As a result, heat from ATES' warm ring is transferred to the building, returning as cold water back into the ATES' cold storage.

In the case where there is a need of heating, warm water in the heat exchanger is redirected to the heat pump evaporator, turning back as cold water to the heat exchanger. While, the heat is transferred to the evaporator and the water cools down, the refrigerant from the heat pump evaporates. This fluid, now in its gaseous state, is pressurized and circulates through the heat pump system by a compressor. At this stage, the hot and highly pressurized vapor goes into the condenser and is used to heat up the water on the building side. During that period, the refrigerant cools down in the condenser restarting the cycle all over again.

Nonetheless, when there is a need of cooling the temperature level in the cold storage is designed to be directly used to cool down the water from the building side [58]. This all happens through the heat exchanger, whom redirects the cold water from the cold ring into the evaporator, to be used then for cooling by HVAC equipment in rooms and air handling units. Figure 6.4 simplifies and outlines the working process of a reversible heat pump intended to provide heat and cold to the inside of the building.

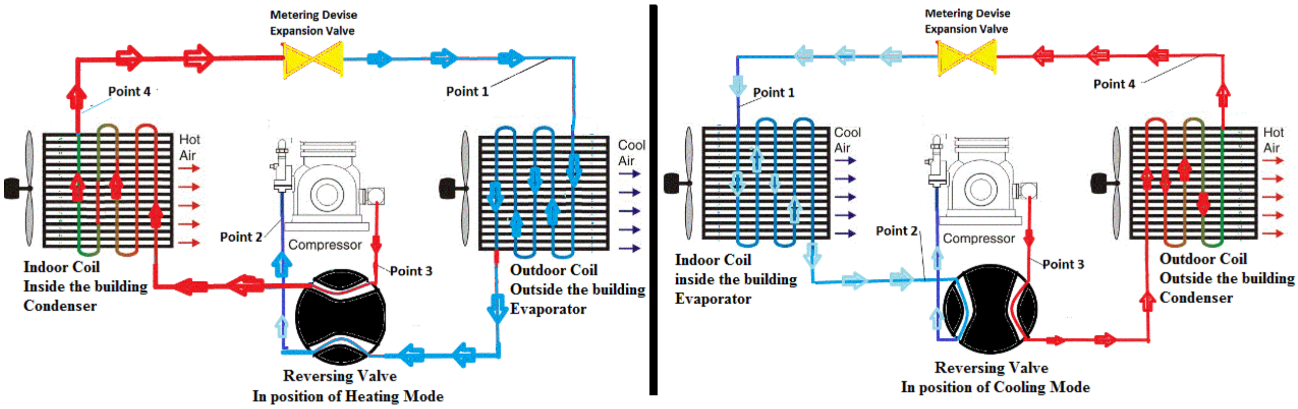


Figure 6.4: Diagram describing the heating and cooling mode of a reversible heat pump.

Subsequently, the heat pump is designed to heat up the water only up to 50 ºC, that corresponds approximately to the heating demand at 5 ºC ambient temperature, for which the equipment is sized. When the heating demand is higher, the boiler that is connected in parallel is switched on and heats up, to the point that corresponds to the specified set point temperature, depending on the ambient conditions. The second boiler is turned on solely if one boiler is not sufficient.

The space conditioning throughout the Vertigo is performed by a combination of: four air handling units providing ventilation air; convective radiators with hot water coil along the perimeter of the building; a four-pipe climate ceiling in the office spaces, where the user is allowed to set the temperature, at approximately three degrees higher or lower than the common set point and ten fan coil units in unique spaces, with high internal gains [59].

The air handlers' heating is commanded off when the outdoor temperature exceeds 16°C. The convective radiators are organized and controlled by two-way valves set to maintain a room temperature of 22°C throughout the building. The radiators are commanded off when the ambient temperature exceeds 14°C. The climate ceilings located in the offices are locally controlled to maintain the room set-point pretended.

Due to lack of sufficient information about the heat pump operation, rather than the one formerly presented, either about the heating or cooling mode, it was assumed that when the ambient temperature is below 15 ºC the heat pump is heating and when is above the heat pump is cooling. This assumption was based on the set-points for the heating-off command of the air handlers and the radiators.

Chapter 7 - Methodology

In this chapter, it is described the case study, in addition to the simplified methodology proposed for the implementation of this research. For model based methodologies, there are two general approaches, known as bottom-up and top-down. The bottom-up focuses on the component or subsystem level to identify reference building parameters. In this case, a model is used to compare a real physical element to ideal operation conditions, in order to detect the fault of a particular system component [59].

Contrarily, top-down approaches define a baseline for policy decision makers and energy efficiency improvements. Top-down methodologies are based on whole building level analysis, describing the change of energy use, as well as, an evaluation technique to determine the sum of energy savings, through the study of energy consumption patterns [60]. With this method, a BPS model is used to compare the real-time measurements against its ideal operation conditions, just as in the bottom-up approach. The advantage of top-down approach is that the whole building analysis, typically does not require large amounts of information, regarding the operation of the building.

The methodology proposed is based on a post-occupancy evaluation by means of a top-down approach, in which building computer simulations are implemented, using *EnergyPlus* for the assessment of energy performance of a non-residential building. This simulation tool complies with ASHRAE 140-2004 standard [61], as the regulation obliges to. Additionally to the *EnergyPlus* software, *Openstudio* is also used to assist and to support the whole building energy modelling, because it includes graphical interface that facilitates users while programming.

The implementation of the proposed strategy follows a research-based methodology. This process can be broken down into the following steps, figure 7.1:

1. Analysis of the system and survey of operational variables. This step requires the description of the building's equipment or sub-systems in their interaction with the building. The conditions of the system's usage and the operational requirements must be evaluated, including the analysis of the variables with the largest influence;
2. Creation of dynamic model that satisfactorily represents all the involved phenomena and description of all related variables, with a significant influence on the analysed process. At this stage, the model is uncalibrated, considering the physical and design parameters known at the time;
3. Evaluation of the accuracy of the predicted building model, by means of calibration and validation of the system outputs. The process will focus on the model parameters uncertainties by manual tuning the unknown variables according to the metered data;
4. After successfully calibrate the building simulation model, make an analysis of the building's heating and cooling loads;
5. Evaluation of the occupants' thermal comfort in accordance to the Dutch guidelines.

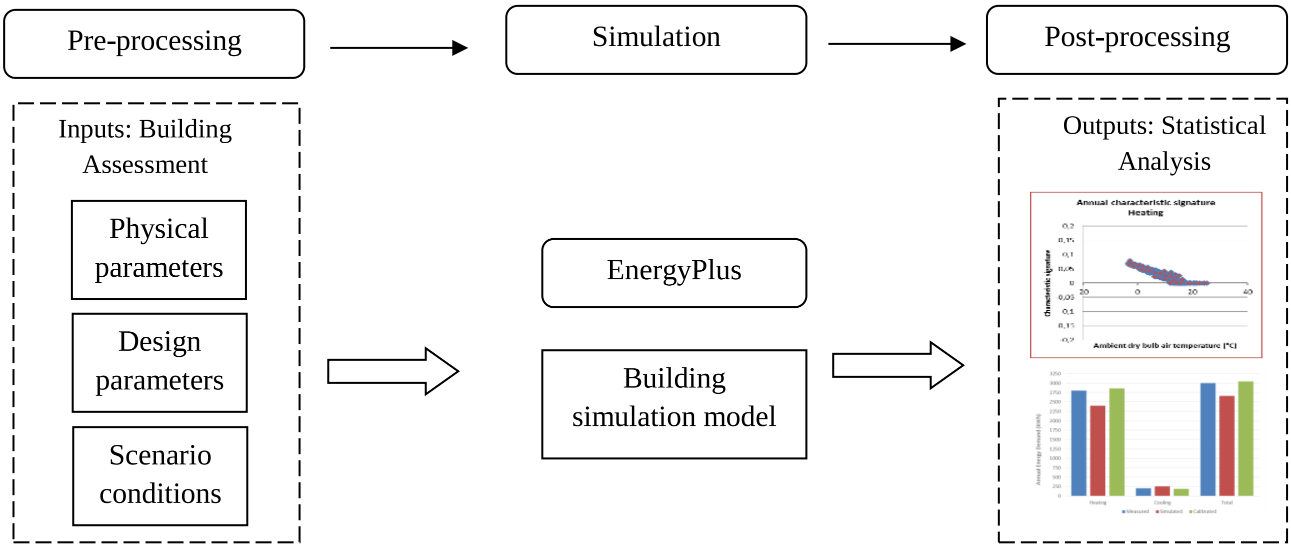


Figure 7.1: Overview of methodology process

In what regards the proper creation of an accurate representation of the test case building, it is necessary to first gather and record the building geometry data, environmental and weather data, HVAC system specifications and operating schedules over time. This will continue until all available sources of building information have been exhausted. Using the information collected in step 1, mainly the floorplans of the target building, will enable the creation of an initial 3D geometric model. At this period, one begins to make interactive changes to the model based on the initial building database, along with information acquired on continuous monitoring, in order to appropriately determine actual occupancy and equipment load schedules.

This model will serve as a starting point for the basis of calibration in step 3. Aside from the methodology previously presented for assessing a building's performance, this research also proposes an analytical optimized approach for the calibration of detailed energy simulation models, discussed in the next subchapters.

Several studies [11], [62]–[66], have underlined the importance of a calibrated simulation approach for every building energy assessment, carried out by means of a dynamic energy simulation tools. They have defined calibration as a process of optimization, which involves fixing the ranges of variability of continuous parameters, towards finding the parameters optimal values for a better simulation model, thus matching with the measured data as close as possible. As said before in chapter 3, when simulating in *EnergyPlus* a specific class function is used to estimate, in a time efficient manner, the heating and cooling demands of the building. Calibration process will focus on adjusting the load calculations from *EnergyPlus* outputs against metered data. To complete this process several simulations will be run, to ensure the model's accuracy and reliability.

After model calibration, energy consumption and occupant's thermal comfort can be evaluated alongside. Following the Dutch thermal comfort guidelines and with the *EnergyPlus* output, *Zone Operative Temperature*, the final goal of the building's evaluation is to determine the building's thermal comfort classification level only during occupation hours.

7.1. Simulation Modelling Approach

The number of independent variables during building optimization should be limited, since simulation of detailed building models may take several minutes in building energy simulation. Unlike computational fluid dynamics (CFD), where simulations may take several hours to complete. Simulation-based optimization techniques often require hundreds or thousands of simulation evaluations. To overcome this, some simplifications are regularly assumed. Simulation modelling approach refers to how the information was processed and analysed to be used as inputs during the construction of the BPS model.

As mentioned in previous chapters, the building is modelled with the whole building performance simulation tool *EnergyPlus*. In order to simulate, there are some simplifications of physical processes and assumptions made in the design of the model, caused by unknown, uncertain or incomplete parameter values. Measurement data will be used to compare results of the simulation detailed tool. The first simulation will serve as an uncalibrated version of the model, which will then be subjected to calibration optimization techniques. Through this methodology, it is possible to ensure more accurate results in relation to the sub-meters measured energy consumption.

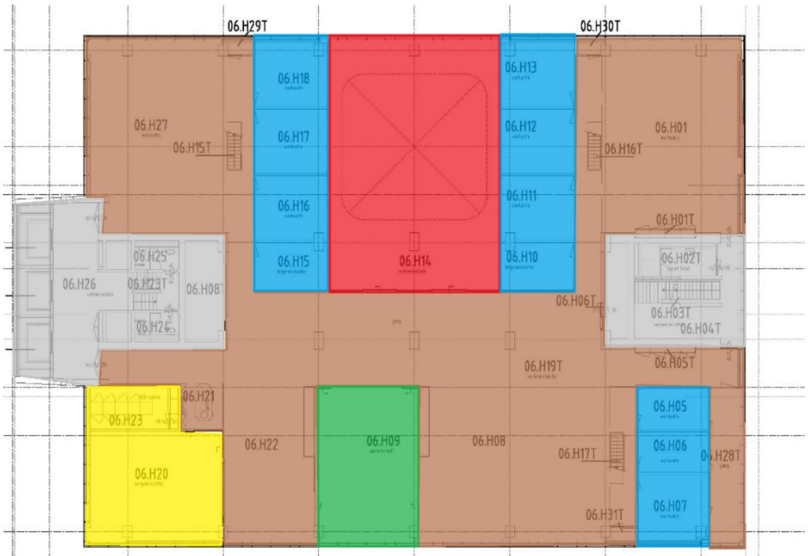
The calibration methodology will demand several simulations to adjust the most influential input parameters, seeking the most optimized solution for uncertain or unknown input values. The simulations are performed for the duration of one year, starting January 1st and ending December 31st. 2011 was chosen to make the building energy assessment, because it was the year with the most viable metered data, when comparing to others. In fact, the hourly measurements of 2009, 2010 and 2012 contained several errors, particularly due to failures while reporting.

From Real Estate Management Department, it was also retrieved the building's blueprints and schematics, see example in figure 7.2. This enabled through *Google SketchUp* an easier and proper 3D representation of the Vertigo geometry. Then, the information about the building's surfaces and thermal zones geometry can be imported easily into *EnergyPlus,* as input parameters. Annex B has all the Vertigo floorplans retrieved from the Real Estate Department that were employed during the model geometry conception.

Figure 7.2: Vertigo Floorplan.

7.1.1. Thermal Zones

Thermal zones are defined as air volumes with identical features and thermal behaviours, bounded by heat transfer surfaces. Thermal zoning criteria is part of the first set of decisions made, while modelling which can have an impact in the building's thermal performance. The strategy used during zoning is based on different spatial activities and building usage. Whenever the same space type usage was identified in the adjacent areas with the same orientation, was defined as a rule to group those zones into a single thermal zone. As an example, figure 7.3 illustrates how zoning was conducted from 6th to 9th floor. Considering the resemblance of the four top floors, the thermal zone division is similar from floor to floor. The different colours represent the space function of each thermal zone.



Teachers and PhD students' offices
Work room/Meeting room
Open space with working areas
Top Floors Atrium
Department office
North and Main stairs with lifts

Figure 7.3: Vertigo blueprints from 6th to 9th floor with thermal zoning illustration.

The approach taken while zoning was to limit the number of zones of the Vertigo, since it is a 23.000 m^2 building with 12 floors. This is important while modelling the model in *EnergyPlus*, because it will become difficult to introduce all the appropriate inputs with a greater number of zones and surfaces. Furthermore, the time consumed by a simulation increases with the number of zones of a building model, but precaution is needed to avoid making gross simplifications since some misrepresentations might lead to inaccurate results.

For instance, north stairs and lifts areas are two distinguished thermal zones that expand from the basement to the top floors, making them different from the rest of the others zones which are independent from floor to floor. Another exception is the Top Floors atrium thermal zone that spreads from the 6th to 9th floor.

In the end, thermal zones are created accordingly to individual spaces, in combination of adjacent similar areas. It might even happen in some cases, where zones, in result of their size, present obvious asymmetries (internal gains distribution, solar exposure and others) and it is required to split in more than one thermal zone. Every zone and surface is named appropriately, to make it easier while editing in *IDF Editor* in *EnergyPlus*. Overall, the 3D geometric model was divided in 76 thermal zones, figure 7.4.

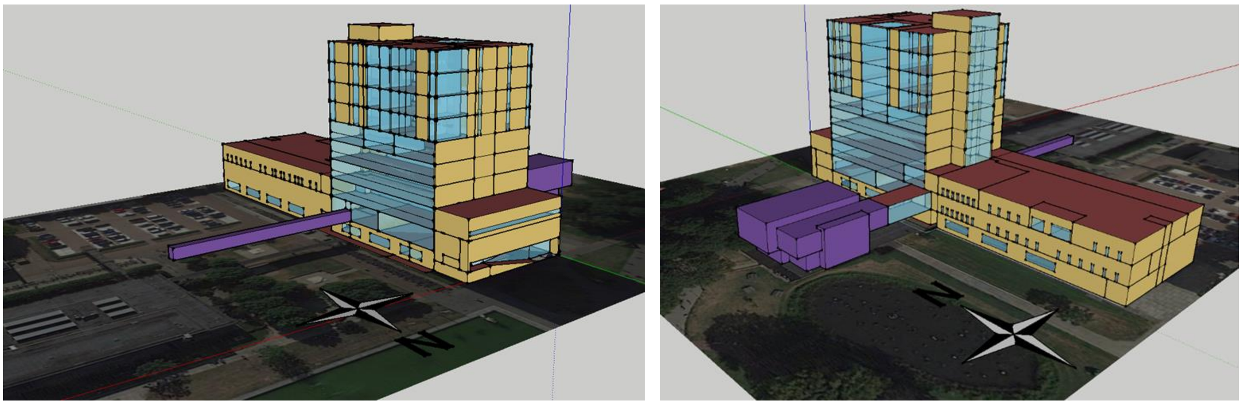


Figure 7.4: Left) North and West side display of the 3D model in Google SketchUp; Right) East and South side display of the 3D model in Google SketchUp.

7.1.2. Building Site

Apart from an IDF file, another relevant aspect during simulation, which will have a determining effect in the accuracy of the model, is a rigorous weather data file. *EnergyPlus* website offers a range of locations worldwide [67], where can be found detailed weather data information to use in energy simulation programming. Typically, these weather files come with a time step of an hour in an EPW format, containing basic location features such as name, latitude, longitude, time zone, elevation, ground temperatures and others. The time step data includes dry bulb and dew point temperature, relative humidity, atmospheric pressure, solar radiation, illuminance, wind direction and speed, sky cover.

EnergyPlus website does not have an available weather file correspondent to Eindhoven. So, the next best action to take, was to choose other location from The Netherlands. Where is possible to acquire a weather file with an EPW format and is, at the same time, located geographically close to Eindhoven, in order to ensure similar climatic conditions. Thus, Beek was selected for being a location at 75 km from Eindhoven. Beek weather file data comes from a Weather Meteorological Organization (WMO) station located at this site and the file information follows ASHRAE design conditions. The data is carefully generated from a period of record, typically 30 years, to be representative of a typical year of the location. In the end, it is mostly suitable for use in heating/cooling load calculations.

Other relevant aspect, from the weather file is the ground temperatures. They will be crucial to model ground heat transfer with the building. In *EnergyPlus*, to modulate the surfaces in contact with ground, there are several approaches that one can take, as described in [68], or even by simply inserting the ground temperatures monthly average. But, in respect to this case study an alternative method is required. Since, the monthly ground temperatures are not correctly known and the building target has two kinds of surface in contact with the ground: slab and basement, it must be considered the effect of soil temperature changing, in relation to depth. *EnergyPlus* has objects that can ascertain the ground temperatures, but due to their complexity it will instead be determined the boundary conditions for the outer plane of the mass walls in contact with ground ($T_{s,e}$). In the end, this approach present similar results if modelling the ground temperature with other objects and enables, at the same time, a simpler method to determine ground temperatures with low computing time

Based on the correlation developed by Kusuda T. and P. Achenbach [69], one can easily determine the undisturbed ground temperatures of the building site, as a function of depth and time. In *EnergyPlus*, there is an object that can specifically calculate this factor, named *Site:GroundTemperature:Undistirbed:KusudaAchenbach*. First of all, it is necessary to know the properties of the soil. Dutch soil characteristics can be found in [70], where:

- k = 1.9 [W/m.K]
- ρ = 1700 [Kg/m3]
- Cp = 1200 [J/Kg.K]

Secondly, to use Kusuda's function it is also required to establish a simple analysis of the weather temperature data statistics, mainly the determination of: the average air temperature, the average difference between maximum air temperature and minimum air temperature and the day of the year, in which it is recorded the minimum air temperature. To simplify this process, *EnergyPlus* comes with an auxiliary program to precisely calculate these three variables, designated as *CalcSoilSurfTemp*. This utility program only requires the weather data file to calculate those three input parameters.

After introducing all the correct inputs of Kusuda's function, one can start to define the two types of ground surface: slab and basement, since both cases of ground contact must be considered simultaneously in this type of building, as demonstrated in figure 7.5. *EnergyPlus* has two distinguished input objects to use in this situations, thus allowing, by utilizing the *SurfaceProperty:OtherSideConditionsModel* object, to simulate ground coupled heat transfer with underground zones (*Site:GroundDomain:Basement*) and with horizontal building surfaces (*Site:GroundDomain:Slab*).

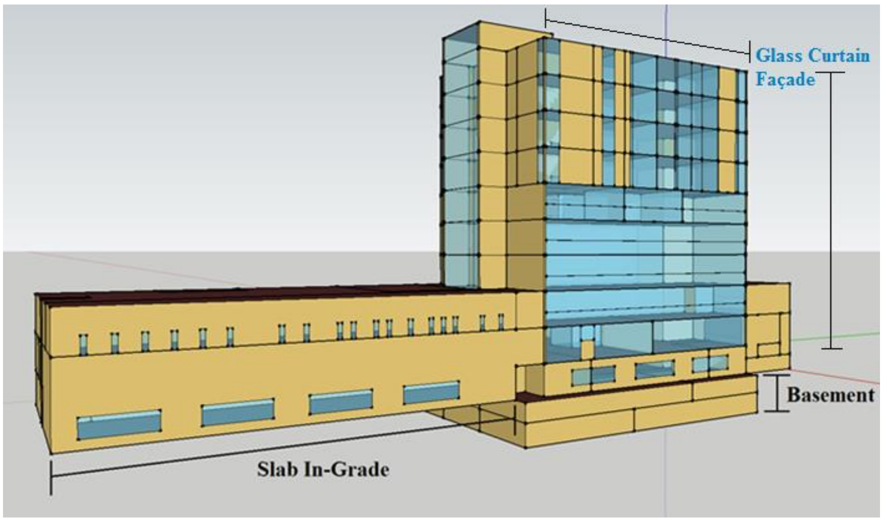


Figure 7.5: Building demonstration on Google Sketch up of slab and basement constructions.

By referencing *Other Side Conditions Model* object (OSCM), the boundary conditions values are resolved for the outer plane of the mass wall dynamically, by the *EnergyPlus*. It uses heat transfer calculations for, in this case, ground coupled surfaces, which are in contact with ground domain objects [71]. Mostly, there are two types of situations for which *Site:GroundDomain:Slab* can be equipped in a case study model: in-grade slab and on-grade slab. The on-grade slab option is applied to simulate scenarios when the lower slab surface is near the ground surface level, therefore the whole floor must be included within the floor construction object. In this case study, must be applied the in-grade slab option, since it is used for circumstances when the upper slab surface is near the ground level, see figure 7.6a). So, for this situation, the slab upper surface must connect with the zone via an OSCM boundary condition, previously explained.

In addition to the slab construction, this building also has a basement structure. In *EnergyPlus* the interaction between the basement zone surfaces is possible with *Site:GroundDomain:Basement* object by using two distinct OSCM objects. These two objects are required for the basement horizontal surfaces and vertical surfaces, as in figure 7.6b). The basement floor and wall surfaces are constructed as any other surface with *Google SketchUp*, but having the difference of the vertical wall surfaces interacting with the *OSCM-BasementWall*, while the horizontal floor surfaces will be modelled with *OSCM-BasementFloor*. Both objects are created specifically for the basement modulation, in order to determine the outside boundary condition.

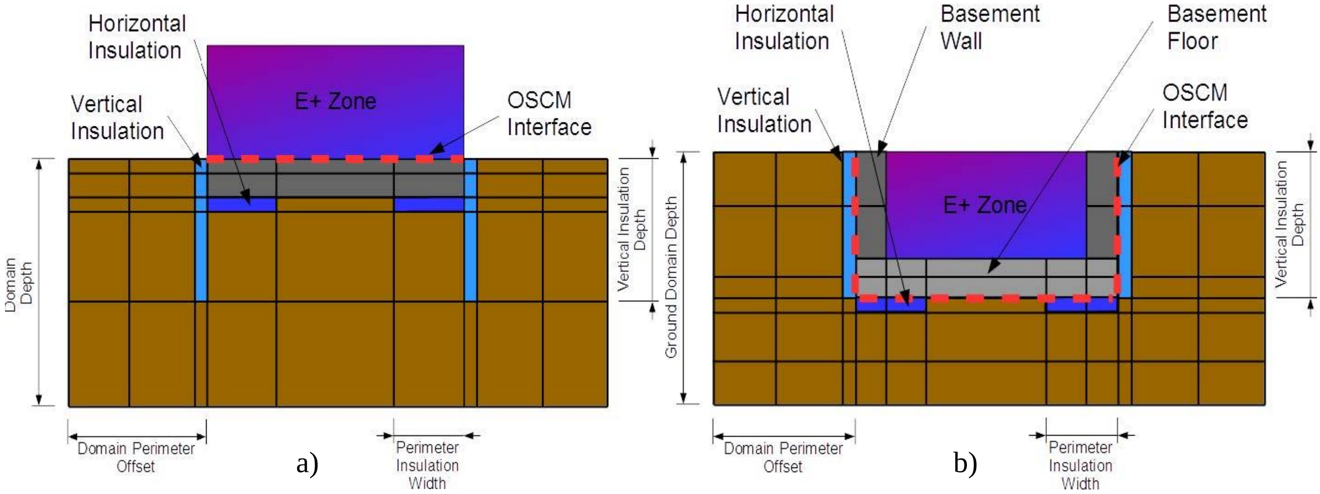


Figure 7.6: a) Slab in-grade configuration; b) Basement configuration. Source: [71]

7.1.3. Building Envelope

Faculty of Architecture, Building and Planning bares a concrete skeleton refurbished with a glass curtain façade that strikes a balance between massiveness and transparency. The smooth glass skin is a low-tech energy façade sealed for nearly 70% of the building. According to the TU/e's Real Estate Department, exists only a simple estimation about the construction sections overall heat transfer coefficients, as described in table 7.1. Besides, there is no detailed information available regarding the description of the different building materials of roof, walls, windows and floors. Thus, for the purpose of an accurate simulation, this situation poses a challenge and a source of uncertainty, which will demand an extra effort during the model calibration approach.

Table 7.1: Main characteristics of the building envelope

Construction	U-value (W/m^2.K) (overall air-to-air)
External walls	0,4
Floor	0,4
Roof	0,25
Windows	1,4

Nevertheless, before calibration, *EnergyPlus* requires the assignment of the building materials of each section, with a complete description of their thermal properties. However, detailed information on construction elements for the Vertigo building could not be obtained, since it was inexistent. For this reason, one had to resort to local observation, while, at the same time, taking into account the Dutch Building Decree, the most common building elements in Netherlands [72], [73] and the information collected, already described in chapter 6.

The building elements assumed during *EnergyPlus* simulation are described in table 7.2. One needs to keep in mind that the elements described in table 7.2, must comply with the U-values of each construction section, as defined in table 7.1. Recalling that the most important for calculation purposes is not the complete description of materials in particular, but the overall air-to-air U-values.

Table 7.2: Constructive characteristics of the Vertigo building

Construction Section	**Construction Materials (Outside layer to Inside layer)**
Exterior walls	Concrete, Vertical air wall, XPS (insulation foam), Aerated Concrete, Concrete
Floor Ground	Slab, XPS, Concrete
Roof	Asphalt shingle, Roof insulation, Roof membrane, XPS, Concrete
Interior Floors	Concrete, XPS, Concrete
Interior Walls	Concrete, XPS, Concrete
Basement Floor	XPS, Concrete, Aerated Concrete, Concrete
Basement Wall	Concrete, Vertical air wall, XPS, Aerated concrete, Concrete

After some research, the glazing materials description was retrieved from Tu/e Real Estate Department. The Vertigo’s glass curtain wall is formed by two types of windows: double glazed and green silk screen-printed double glazed. Information regarding interior glazing could not be found, therefore assumptions were made. All the interior glazing is perceived to have the same glass material, attributable to the fact that all interior glazing is single glazed. Table 7.3 as all the data obtained relative to glazing description.

In the Netherlands, the most common U-values and g-values for typical windows according to the current legislation can be verified in detail at [74]. The typical method to model windows in *EnergyPlus*, compels the user to enter the thermal and optical properties in the input objects *WindowMaterial:Glazing* and *WindowMaterial:Gas* or *WindowMaterial:GasMixture* to properly estimate the internal gains associated with them. For this reason, *Window 7.4* was used due to its large database capabilities concerning glasses thermal and optical properties. *Window 7.4* was found a very useful and simplistic tool to quickly access the necessary input parameters.

Table 7.3: Fenestration description

Window Type	**Window Material**	**Thickness (mm)**	**U-Value ($W/m^2.K$)**
Clear Double Glazed	SGG COOLITE SKN 165 [75]	8-16-8	1.4
Green Silk Screen-Printed Double Glazed	Ariño Duglass – Ariplak DAG 66/38 [76]	8-16-8	1.4
Clear Single Glazed	SGG STADIP SILENCE [77]	8.4	5.7

Concerning windows blinds and shades, they were not taken in consideration, during simulation. This decision was mainly taken because information regarding this was not available, and also due to the fact that this building is located in a northern country of Europe with limited sunlight and low temperature conditions, during most part of the year. Hence, BPS model without this input parameter will have a reduced outcome and insignificant influence on the building's thermal loads.

Regarding building shading conditions, there are glazed halls that connect the Vertigo to others buildings on the East and West side. The glazed hall on the West connects to a Cafetaria/Bar which is adjacent to the Vertigo. On the East is located a two-story building connected to the Vertigo through a glazed hall, but on the account of being at a substantial distance, there were no reasons to considered shading influences from the East side building, apart from the extensive hall. Both these shading elements are defined using *OpenStudio Sketch Up Plug-in* by creating a new Shading Group thermal zone.

7.1.4.Building Internal Gains

In accordance with the information already expressed in previous chapters, the next stage in creating the BPS model is to characterize the internal gains within the building. In *EnergyPlus*, internal gains are divided in three main object classes: people, lights and electric equipment. And for each class is required to state a predefined schedule for the input parameters occupancy profile, in order to set the 24-hour daily cycle during the period of a year. And to do so, three type of object schedules are used: *Schedule:Day:Hourly*, *Schedule:Week:Daily* and *Schedule:Year*. Due to the relevance of internal gains in a building's thermal load, occupancy profiles will have a determining factor in the accuracy of the model, thus they must be properly estimated and accounted for. Plus, TU/e school calendar is subjected to examination, to take into consideration vacant days and holidays.

Vertigo's occupancy schedule for the building was assumed to be between 8 a.m. until 18 p.m., from Monday to Friday and vacant on weekends. Information relative to Vertigo's gains were calculated in a particular and different way, rather than the standard method usually applied. In spite of counting every single lighting system and electric equipment existing in every single zone, a yearly average estimate was determined based on a probability distribution for a typical week, using the hourly sub-meters for lighting and electric equipment. Being aware at the same time, if the Dutch Building Decree requirements are being respected. The advantage of this technique is that requires less time computing all the involved inputs parameters.

Most of the lighting system is composed of pendant luminaries with fluorescent lamps, locally supplemented by workplace luminaries. When analysing the lighting sub-meter data for a typical week in Summer and Winter, it can be easily determined the lighting power density of the building. From the regulation requirements and measured data, one can extrapolate that the building has an average lighting power density of 9.5 W/m^2, where was considered the value of 37% for radiant fraction [71]. Moreover, the defined lighting schedule is based on Summer and Winter typical week profiles.

Equally to lighting, electric equipment is predicted using the metered data. The electric equipment for this building includes several appliances, which are completely different from each other. The data obtained from sub-meters does not differentiate the appliances used in the Vertigo (such as elevators, TV's, kitchen, PC's, printers, snack machines and others). In the faculty, there are several tools at the disposal of students and researchers like for example the 3-D concrete printer and numerous electric tools at the architectural workshop. A survey was conducted with the intention to detect the type of appliances, but became problematic to quantify and even identify them all.

Due to the magnitude of the building and the large diversified appliances in laboratories, workshops, work rooms and offices, it became more reasonable for modelling purposes a simple analysis of a typical week in Summer and Winter to access the average electric power density. Through this method, all the electric equipment is considered and is not even disregarded, the thermal convective gains associated with the air handling units and fan coils, which are also considered in this input object. It is important during this analysis to take a special look to the daily consumption pattern, seeking to establish the electric equipment schedule as similar to the reality as possible, distinguishing Summer consumption pattern from Winter. After the evaluation of the measured results, was determined an average electric equipment density of 15 W/m^2. For the equipment, a radiant fraction of 30% [71] was assumed for the BPS model.

Occupancy behaviour has a major role in building performance, caused by the presence of occupants in the building and due to the actions, they take to influence the indoor environment. In BPS, occupant behaviour is modelled using predefined occupancy profiles. From Real Estate Department and Bynum [78] occupancy patterns were presumed to have average 650-700 people comprised by students, researchers, teachers and faculty employees. The building top floors have usually more occupants than lower floors, resulting in occupancy profiles divided from floor to floor, without disregarding the Dutch Building Decree where it demands a minimum of 0.05 people/m^2 (Annex A, building education function – office space). This value is defined as the lowest occupant density. And the maximum value defined is 0.125.

In addition, the clothing insulation value (clo) has a strong impact on the calculated comfort. ISO 7730 proposes a value of 0.5 for Summer and 1.0 for Winter, whereas Netherlands standard values suggest 0.7 clo during Summer and 0.9 clo in Winter. Consequently, the Summer value selected for the BPS model is the mean value between ISO 7730 and the Netherlands standard value, 0.6 clo. While the Winter value defined is slightly lower than the standard value, because people in the Vertigo do not wear jackets during work, but instead wear long sleeves, thus the value assumed is 0.85 clo. The activity level considered is equivalent to office work and, in the Netherlands, the standard value usually adopted is 126 W/person.

The main operating conditions related to internal gains are summarized in table 7.4, they represent the considered values used, while modelling the uncalibrated simulation. This model will serve as reference case for future optimization adjustments within the BPS model.

Table 7.4: Internal gains assumed in BPS model

Main Input Parameters		
Occupancy hours	8-18h	Monday to Friday
Lighting power density	9.5	W/m2
Electric equipment power density	15	W/m2
Average density of occupation	0.05-0.125 (lower floors to higher floors)	People/m2
Clothing insulation	0.60/0.85 (Summer/Winter)	clo
Metabolic rate	126	W/person

7.1.5. HVAC System and Infiltration

As described before, the Vertigo's mechanical system has a very complex configuration. Heating and cooling is provided through a ATES system (district heating and cooling) connected to a heat pump, and for additional heating two boilers may be activated when needed. The building HVAC system comprises AHU (air handling units), convector radiators, fan coils and four-pipe climate ceiling. To insert all this parameters into the *EnergyPlus* input classes, would involve massive modelling time and considerable know-how, regarding the complex mechanisms of the software about the design and control functions of the entire HVAC system. Besides, there is no amount of data available about the energy systems, for a precise *EnergyPlus* modulation. Due to the fact it would require a vast collection of data, rather than the limited information previously mentioned in chapter 6.

For these kind of situations *EnergyPlus* has an object where the user can easily study the performance of a building, without modelling a full HVAC system. Through this way the whole process of simulation is simplified. In such cases, the object to use as the sole air-conditioning object is HVACTemplate:Zone:IdealLoadsAirSystem, where the user does not need to specify air lops, water loops and all the other components. All that is necessary are the heating and cooling controls, operating schedule and the supply air flow rate.

This component can be perceived as an ideal unit that mixes air and then, adds or removes heat and moisture at 100 % efficiency, in order to produce a supply air stream at the specified conditions. This way, it is guaranteed that, for each iteration, the object uses the flow rate and the power required to meet comfort temperatures. The key disadvantage consists on the assumption that there is no energy consumption by the building's mechanical system, while allowing effortlessly to evaluate the load components of a building.

Conform the Dutch Building Decree (see Annex A), educational buildings with office function have a minimum requirement of fresh air supply of 6.5 dm^3/s.person (23.4 m^3/h.person). This value is defined only during occupied periods, seeing that the HVAC system is always working. The HVAC system temperature set-point is 20 ºC for heating and 24 ºC for cooling, in consonance with the legislation in the Netherlands.

Infiltration is defined as the introduction of outside air into the building. Air from outside flows into the building, through openings in windows or grilles, and also through cracks in the envelope, essentially at the junction of components. The passage between building zones through doors, also account as another factor for air leakage within thermal zones. In many countries, building regulation set maximal values for infiltration air flow rates. For instance, the Netherlands suggests that the infiltration air flow rate should not exceed 0.24 ACH. An exception is made in the simulation model for north entrance zones, considering they correspond to the main entrance and exit of the Vertigo. Thus, 1.5 ACH was defined during occupied periods and 0.4 for unoccupied situations.

7.2. Calibration Approach

The main aim of this study is to present a simplified and clear approach to be conducted for every building energy assessment, towards providing insight into a building's thermal load using utility bill data. Monetti *et al.,* [79] defined calibration as a four-stage methodology. In stage 1 of calibration, formerly described in chapter 7.2, the model designed is at this point uncalibrated and constructed, based on the gathered design data information and on pre-defined assumptions. The following stages of calibration split into Pre-processing, Optimization and Post-processing and Validation.

Stage 2, "Pre-Processing, is in fact the first step of the process of calibration, since from now on one begins to accomplish an analysis on the metered data and on the building model input data. In addition, meteorological data measured by the local weather station is used to create a real-time weather file for the BPS, instead of using a representative meteorological weather file which, brings inaccuracy in the simulation analysis.

Typically, when calibrating a building model, this involves the presence of different sources of uncertainty that must be considered, since they can have a representative impact on the accuracy of the simulation. Thus, the common approaches taken to overcome the lack of detailed information are achieved by means of sensitivity and uncertainty analysis. Due to the large computational time spent related to the use of a dynamic energy simulation tool, sensitivity and uncertainty analyses in this research work will not be carried out. But, would undeniably bring more reliability to the energy performance assessment.

Based on a detailed literature review, best-guess estimations and probability functions, a set of parameters are defined for being the most prominent, to have a significant effect on the building energy consumption. Each critical parameter is circumscribed to a range of variability with delimited upper and lower bound, representing the uncertainty domain and categorized into four classes depending its role: site, building envelope, internal gains and HVAC system and infiltration. The optimization objective is targeted on the building heating and cooling energy consumption.

In stage 3, "Optimization", the calibration approach addresses the difference between measured and simulated values. The building model parameters are systematically varied within specified ranges, until the optimization problem is solved. Characteristic and calibration signature charts are a method to quick and easily detect deviations between uncalibrated simulation model and measured data. The most influential parameters selected in the energy model are tested individually between each run the (e.g. internal gains, building envelope features, etc), as well as their repercussions on the energy demand.

Consequently, every simulation run will generate two characteristic signature plots (for heating and cooling consumption), and two calibration signature plots. In order to determine calibration best estimates, and whether the input value ought to increase or decrease, several optimization simulations are performed. Two model evaluation statistics, RMSE/CV(RMSE) and MBE, are used to report error between predicted and measured values. The calibration stops, when simulated heating and cooling consumption of the case study matches closely the monitored data.

Lastly, in stage 4 each parameter optimal value is carefully chosen on the matter of their impact to accurately calibrate the model. All the individually compared parameters, considered critical for the reliability on the outputs of the model, are then inserted as a global in the final simulation run. The post-processing optimization results are then used to plot the characteristic and calibration signatures, to verify if the model is in accordance with the expected outcome. Secondarily, is calculated the final RMSE/CV(RMSE) and MBE, in order to confirm if the model is consistent with the guideline limits from table 2, respectively 30% and ±10% on hourly basis. This will act as the final validation procedure to verify the compliance of BPS model with the monitored data consumption pattern.

7.2.1. Pre-processing – Metered data

Vertigo has a number of sensors that enable the monitorization of the building's operation. Aside from the electrical sub-meters for lighting and equipment, there is also the electrical output for the heat pump, a natural gas consumption meter and an ATES heat/cold thermal energy meter. The base load for heating is provided by the ATES via heat pump. Then, when demand is high, natural gas-fired boilers are triggered. Cooling is delivered directly through the ATES system and if, extra cooling is needed, the heat pump can act in reverse mode.

To be able to make a comparison between predicted (simulation model) and measured values, a sort of data modification is required on the utility bill data retrieved from Real Estate Department. This is justified, since the heating supplied to the building comes from two distint types of sources (heat pump - electrical energy; natural gas boiler/ATES – thermal energy), obstructing a direct approach of analysis. As a process of simplification, during this energy assessment, it will be estimated the actual heating and cooling provided, concordantly to the hourly measurements of the heat pump, gas boiler and warm/cold ATES. This, will serve as basis for the evaluation of the BPS model energy demand. Through this way, it is expected to speed up the process of calibration with a low margin of error.

The total amount of heat and cold demand was obtained from the hourly measured data. It can be divided into three main categories: gas consumption, ATES load and electrical load. The next paragraphs discuss the method applied to determine thermal energy demand from hourly measurements.

To begin with, natural gas usage comes from a sub-meter that reports the hourly m^3 consumption. To estimate the amount of thermal energy released, during the combustion of gas, two factors are essential: the gas calorific value and the boiler efficiency. The Dutch gas has a higher calorific value (HCV) of approximately 35.17 MJ/m^3 [80], [81]. From the information retrieved at Real Estate Department, the Vertigo's boiler has an average efficiency of around 85%. Consequently, 1 m^3 of gas corresponds to nearly 8.304 kWh_t.

Secondly, the total amount of heat and cold delivered by the ATES system is already in thermal energy units and no conversion is needed. It is necessary only a rapid confirmation of values to ascertain the validation of the data measured.

Thirdly, the process to determine the heating and cooling from the electrical output of the heat pump is a bit trickier. The heat pump sub-meter does not distinguish electrical consumption when, it is in the heating or cooling mode. However, the air handling units are commanded off when outside temperature is over 16 ºC and the radiators are set-off when is over 14 ºC. For this reason, one can extrapolate for thermal energy assessment purposes that, when the ambient temperature is below or equal to 15 ºC, the heat pump is in heating mode. Oppositely, when is superior, the heat pump works in cooling mode.

To accurately quantify the heating and cooling loads, the heat pump electrical consumption must be multiplied by its COP. Besides that, thermal distribution losses are taken into consideration. The COP and EER, respectively for heating and cooling, are defined by the formulas 15 and 16 [82]:

$$COP = \psi \times \frac{T_{Cond}}{T_{Cond} - T_{Evap}} \tag{7.1}$$

$$EER = \psi \times \frac{T_{Evap}}{T_{Cond} - T_{Evap}} \tag{7.2}$$

where COP, designates the heat pump coefficient of performance for heating and EER the energy efficiency ratio for cooling, T_{Evap} and T_{Cond} represent the evaporation and the condensation temperatures, respectively and in K. Ψ, characterizes, the technical efficiency to achieve heating/cooling with the theoretically minimal work required compared to the actual work. In other words, it is the ratio between the actual coefficient of performance of the heat pump and the theoretical Carnot engine [83]. The correction factor used for large size heat pumps is generally 50% [84], [85]; therefore this value was chosen during this study.

Moreover, the heat pump water distribution temperature (T_{Dist}) is another aspect worth to take into consideration. Such variable is not a fixed value, but instead a mutable parameter that depends on the outside temperature. Furthermore, the heat pump is used to heat the water only up to 50 ºC for which the equipment is sized. Annex C contains supply water temperature control plot that will aid during heat pump thermal energy assessment, fundamental to accurately determine the T_{Dist} either for heating or coooling. All the required parameters are presented in next table (table 7.5).

Table 7.5: Parameters used in calculation of heating and cooling thermal energy load.

	Heating	Cooling
T_{Dist}	y = -0.6667x + 53.333	y = -0.1143x + 12
T_{Cond}	T_{Dist} + 10	$T_{Cold\ ring}$ + 10
T_{Evap}	$T_{Warm\ ring}$ - 10	T_{Dist} -10
$T_{Warm\ ring}$	15 ºC	
$T_{Cold\ ring}$	8 ºC	
Ψ	50 %	
Distribution Losses	10 %	

The final stage consists of adding the previously described loads either into global heating or cooling. The total amount of heating demand of the building is estimated by summing the natural gas thermal energy, the warm ATES thermal energy delivered and the thermal energy produced by the heat pump while on heating mode. On the other hand, the totality of cooling is purely formed by the sum of cold ATES thermal energy and the thermal energy produced for cooling. From this four-step process, it can be started the calibration simulation assessment, by comparing real measured values with simulated values.

7.2.2. Pre-processing – Weather file

To approximate the actual climatic conditions recorded in Eindhoven during the experimental campaign and the Beek weather file data used during the uncalibrated simulation, a sort of weather file modification is a vital requirement to have a proper model calibration. The weather file extracted from *EnergyPlus* website is a typical year with the goal to represent an entire year. It is a IWEC data file based on hourly weather data information derived from up to 18 years (1982-1999), most suitable to use in building energy simulation programs. A weather file with real arrangements from the period sub-meter measurements was taken. Then, an even greater accuracy of the BPS model will be ensured in relation to the hourly metered data, minimizing possible miscalculations.

Initially, the process focused on analysing the data that was within the weather from *EnergyPlus* website. Then, it was compared with the Royal Netherlands Meteorological Institute (KNMI) [86] data of the year 2011 for the city of Eindhoven, where is located a permanent monitoring station. The file collected from KNMI is composed of hourly monitored data of several climatic parameters. The most significant elements from KNMI meteorological station which form the basis for an *EnergyPlus* simulation, and therefore required a replacement in the values were: dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, global horizontal radiation, wind direction, wind speed, cloud cover and precipitation.

To be able to make a change in the estimates from EnergyPlus to real measurements, EnergyPlus has an utility program named *Weather Converter* [87]. This program is mainly use to convert the EnergyPlus weather file format (.epw file) to excel format (.csv file) and vice-versa. Hence, from downloaded EPW file from Beek, the first thing to do is to convert it into Excel format. Then, one must modify the parameters according to the KNMI climatic file, and all the other unknown variables are set as missing values (in *EnergyPlus* this is done by defining as 9999). Additionally, the location is changed from Beek to Eindhoven by altering the latitude, longitude and elevation. For solar radiation calculations *EnergyPlus,* uses solely direct normal and diffuse horizontal radiation. When only exists information relative to global horizontal radiation, *Weather Converter* software detects when solar values are missing from the incoming data and uses a mathematical model, the Perez split [88], [89]; to separate the global into direct normal and diffuse horizontal radiation values. Alongside, horizontal infrared radiation intensity is determined using sky cloud cover and dry and dew point temperatures [87].

Finally, after altering all the identified parameters from Excel format one must convert the file back into EPW format. By doing this, the weather file used through the process of calibration, takes into consideration real measured weather data from Eindhoven station, in each hour of the year.

7.2.3. Pre-processing – Parameter optimization

During calibration process, it is quite common to use a "trial and error" method, given the large number of parameters involved. Before starting the entire calibration assessment, a decision regarding the possible most significant input parameter elements must be made. Heo [90] identified within the building physics domain the four main categories, table 7.6, to be the sources of uncertainties in building models, when carrying out building energy evaluations. Their identification has a great impact on the model reliability.

Table 7.6: Source of uncertainty in building energy models. Source: [90]

Category	Factors
Scenario uncertainty	Outdoor weather conditions Building usage/occupancy schedule
Building physical/operational uncertainty	Building envelope properties Internal gains HVAC systems Operation and control settings
Model inadequacy	Modelling assumptions Simplification in the model algorithm Ignored phenomena in the algorithm
Observation error	Metered data accuracy

The first category, scenario uncertainty, concerns the external environment and the building use. Generally, the use of a real weather file to be employed in a building simulation can address this question, which was already discussed in the previous sub-chapter. The second and third categories refer to uncertainties in the building model and assumptions/simplifications that may arise from model approximation as a physical representation of a real building. The last category mentions the problem of data quality in the measured data. This issue was minimized by selecting the hourly metered data from 2011, that was found to have the least errors relating to the monitoring of measured values. Therefore, some minor uncertainties in measured data have thus to be taken into account.

Firstly, the large number of candidate model parameters was reduced to a certain extent via literature review based considerations. This detailed energy model is highly complex due to the magnitude of the building, resulting in many assumptions on the building characterization with a direct impact on the simulation results. Consequently, the input parameter values optimization concentrated on assumptions made during the design of the building model.

The set of parameters considered as the most influent on the building energy consumption for this case is presented in table 7.7. For each parameter, a constraint, with a lower and an upper bound was defined. Furthermore, internal gains occupancy schedules were optimized to make the simulated energy closely match to the measured ones.

Table 7.7: Input parameters changed during simulation optimization.

Input Parameters	Min. Value	Max. Value
Materials' thickness	-20%	+20%
Lighting density	8 W/m^2	11 W/m^2
Equipment density	12 W/m^2	18 W/m^2
Equipment radiant fraction	0.15	0.45
People density	0.01 person/m^2	0.130 person/m^2
Heating set-point	19.5 ºC	24 ºC
Cooling set-point	21.5 ºC	26 ºC
Infiltration rate	0.2 ACH	1 ACH
Fresh air supply	6 m^3/s.person	9 m^3/s.person

Chapter 8 - Results and Discussion

In this chapter, the results will be introduced according to the order already presented in the methodology. However, only the results considered relevant are presented, due to the large volume of data. Therefore, simulation output data of the uncalibrated model will be compared and discussed against the final calibrated version of the BPS model. The simulations were performed for the entire year of 2011. Aside from that, a thermal comfort analysis on the final calibrated model will be conducted, to evaluate how the occupants feel when they are inside the building.

8.1. Uncalibrated BPS model

After collecting all the necessary data, it was processed and the corresponding simulation was carried out. The first simulation presents itself as the uncalibrated model, some of the input parameters are the product of best-guess values and simplifications made during the design of the model, as explained in previous chapters. Results shown from simulation are compared with metered data. The weather file used for the initial simulation is from Beek, obtained from *EnergyPlus* weather data centre. It seemed convenient to expose daily and monthly outputs as a mean to compare them against the calibration process before and after, as well to assess if they are in accordance with the guidelines accuracy criteria. Daily results describe a consumption pattern with greater detail, while monthly results show a broader arrangement of the load trend during the year.

First, simulation products are displayed in daily and monthly results both for heating, figure 8.1 and 8.2, and cooling, figure 8.3 and 8.4. It is worth to note that a dynamic energy simulation model is a physical representation and, ultimately, an approximation to real performance of a building. Also, it is not always at the first attempt that the results are the ones expected. Consequently, these first results will serve as a baseline version of the model for future calibration adjustments.

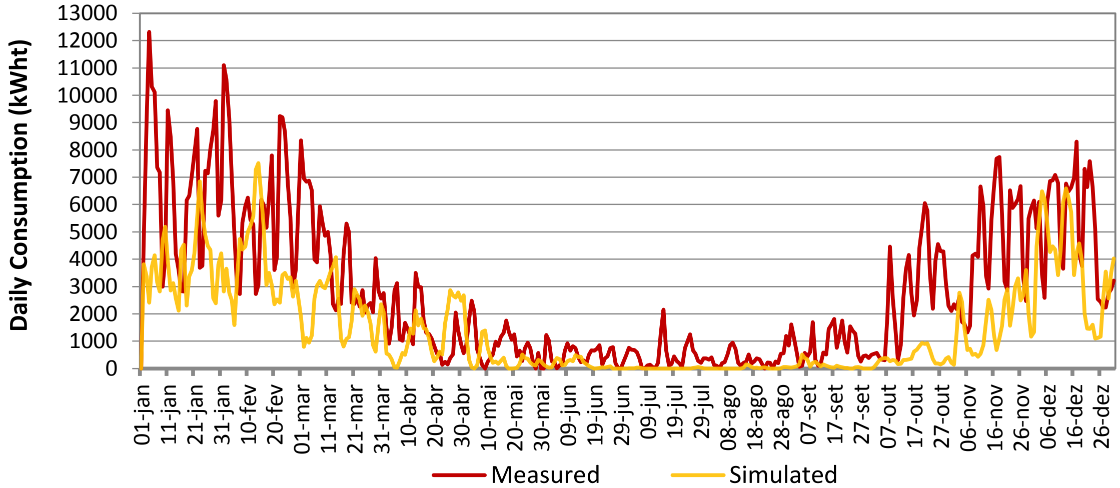


Figure 8.1: Vertigo uncalibrated BPS model hourly heating consumption comparison.

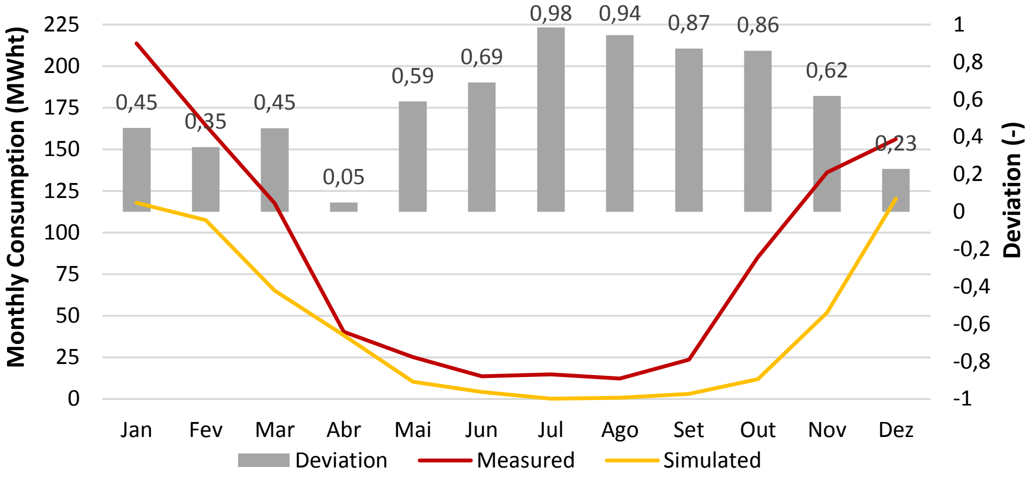


Figure 8.2: Vertigo uncalibrated BPS model monthly heating consumption comparison.

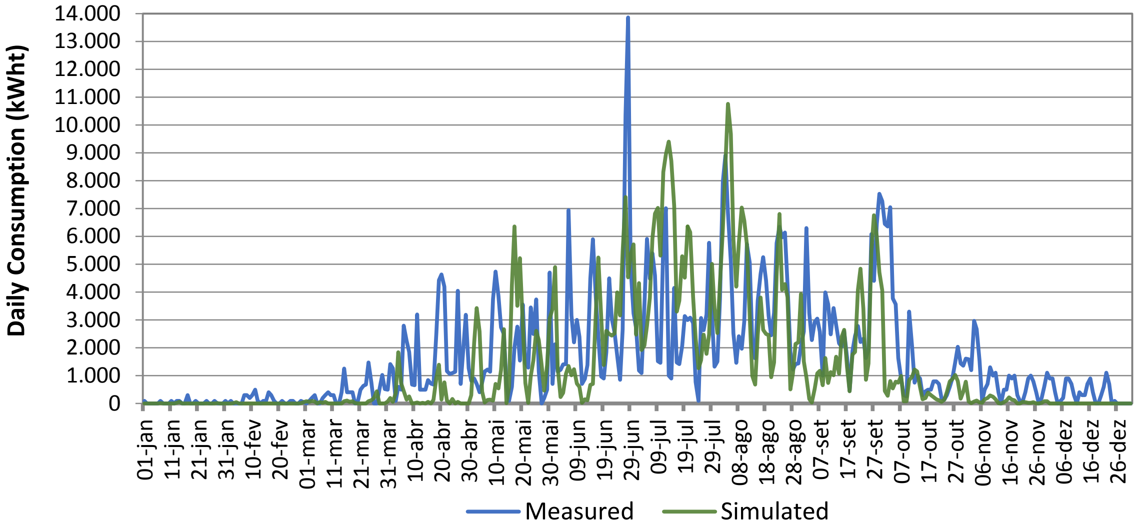


Figure 8.3: Vertigo uncalibrated BPS model hourly cooling consumption comparison.

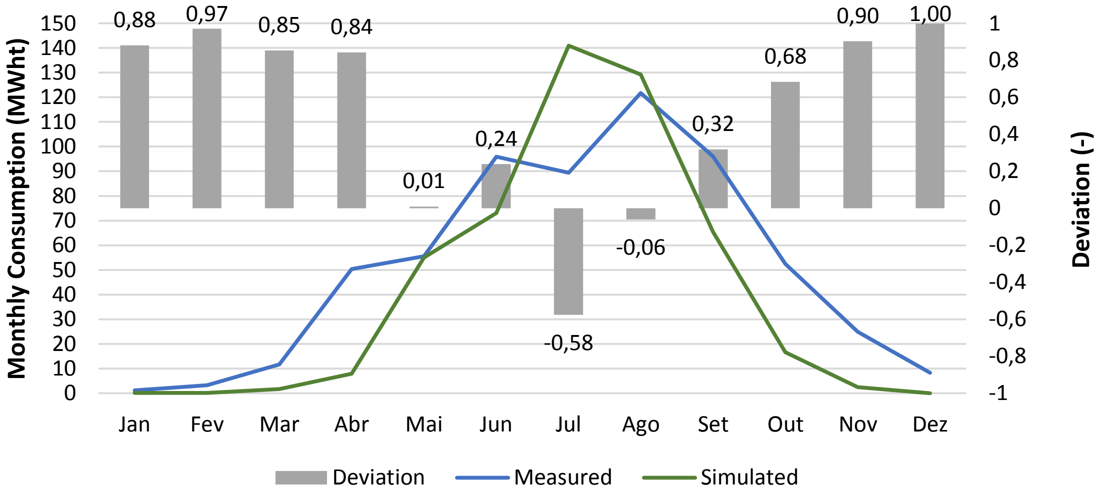


Figure 8.4: Vertigo uncalibrated BPS model monthly cooling consumption comparison.

From figures above exhibited, both the daily heating and cooling consumption have a clear discrepancy in their results throughout the year. But even so, from the monthlies thermal consumption behaviours, it can be detected a quite similar pattern from simulated and measured values. Hence, a simulated calibration might have the potential to diminish the gap between these results. In addition, figures 8.5 and 8.6, respectively, the heating and cooling calibration signatures illustrate the error associated between the daily measured and the predicted energy performances in the uncalibrated version of the model. The greater the error (calibration residual) the bigger the difference between the simulation and the monitoring data. Using the hourly and monthly statistical indices displayed in table 8.1, an analysis on the uncalibrated model can be made. All these outputs will help to make a decision on which input parameters should be optimized during calibration approach.

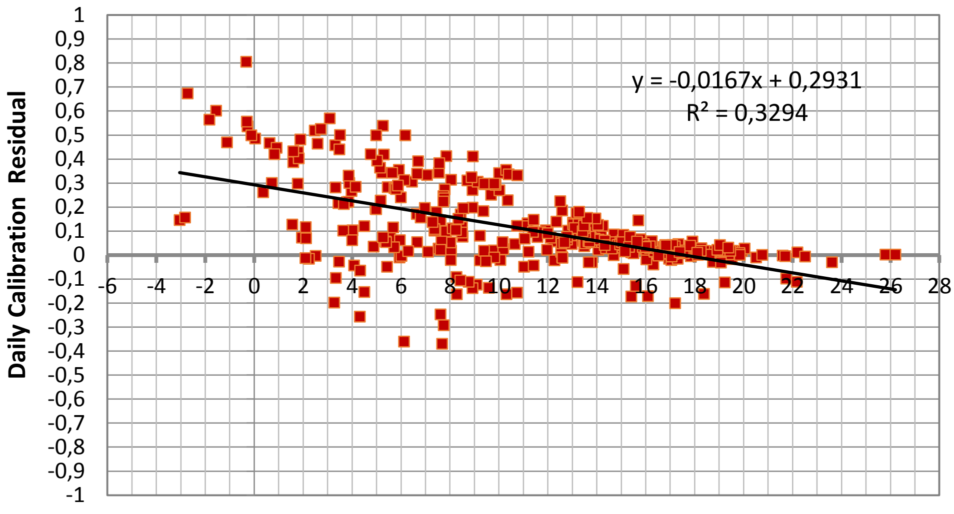


Figure 8.5: Uncalibrated model heating calibration signature.

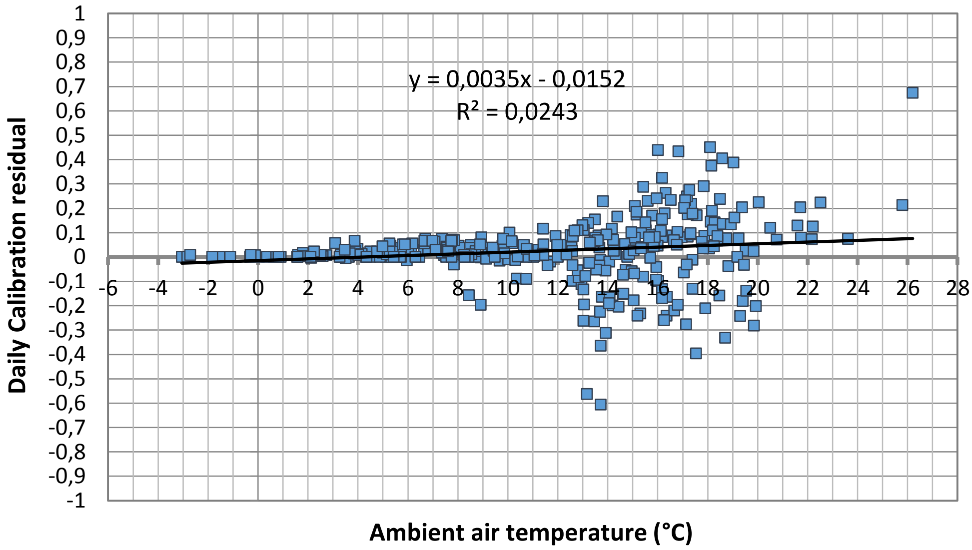


Figure 8.6: Uncalibrated model cooling calibration signature.

Table 8.1: Statistics of the BPS model before the calibration approach.

	Heating	Cooling
Total measured consumption (kWht)	1,003,037	613,494
Total simulated consumption (kWht)	531,282	492,672
RMSE hourly (kWh_t/hourly)	103	76.69
MBE hourly (kWh_t/hourly)	-53.85	-13.82
ERROR Total hourly (kWh_t/hourly)	139.93	
CV(RMSE) hourly (%)	89.95	66.98
NMBE hourly (%)	-1.96	-0.82
RMSE monthly (MWh_t/monthly)	54.81	25.75
MBE monthly (MWh_t/monthly)	-39.31	-9.857
ERROR Total monthly (MWh_t/monthly)	72.87	
CV(RMSE) monthly (%)	65.58	30.8
NMBE monthly (%)	-47.03	-19.37

The calibration signatures come to confirm the daily consumption charts by signalling, with respect to the heating energy demand, an overall underestimation when compared to the utility bills. Concerning the cooling load, there is an equal overestimation as well as an underestimation throughout the year. So, there is an evident connection amongst the assumptions made during the design of the model and the energy values mismatches. The CV(RMSE) of nearly 90% for heating and 67%, for cooling just comes to prove that the model needs undoubtedly a calibration procedure. And moreover, by looking to the heating total measured consumption and simulated consumption there is almost 50% difference between energy values. Therefore, from the first simulation, it can be concluded that the heating demand suffered a higher divergence in its results when confronted with the cooling. Nevertheless, calibration process shall attend both loads in order to improve the overall accuracy of the model, in relation to measured consumption. This uncalibrated simulation demonstrated that the uncertainty in some input parameters caused simplification issues in the model and a calibrated simulation focused in optimizing the uncertain variables will contribute to reduce the gap between energy loads and identify all the unknown parameters in the model.

8.2. Calibrated BPS model

The entire process of calibration is a highly undetermined problem where does not exist a non-unique solution. Considering all the uncertainties concerning this model, one simulation run is not sufficient. Numerous runs were required in a trial and error effort, in order to discover the optimal value for all the unknown variables evaluated. For each simulation run, it was analysed the effect of the respective individual parameter change, through a calibration signature and a characteristic signature. The initial moment of the calibration focused on developing a real weather file for Eindhoven and an examination of the consequences it brought, into the accuracy of the model. The following simulations are concentrated on finding the variables optimal value and the corresponding occupancy schedules. Final calibrated simulation culminated on grouping every parameter optimal value into the design of the model. The optimized values of the calibration variables are given in table 8.2. Additionally, annex D shows the adjusted materials' thickness and subsequently the construction elements description. Figures 8.7 and 8.8 show heating energy demand for the final calibrated simulation of the BPS model and on the other hand figures 8.9 and 8.10 present the cooling energy demand.

Table 8.2: Optimized values during calibration of the BPS model.

Input Parameters	Initial Value	Final Value
Lighting density (W/m^2)	9.5	9
Equipment density (W/m^2)	15	16
Equipment radiant fraction	0.3	0.2
People density (person/m^2)	Lower floors (-2nd to 4th): 0.05 Top floors (5th to 9th): 0.1	Lower floors (-2nd to -1st): 0.01 – 0.04 Mid floors (0th to 3rd): 0.05 – 0.09 Top floors (4th to 9th): 0.09 – 0125
Heating set-point (ºC)	20	23
Cooling set-point (ºC)	24	24
Infiltration rate (ACH)	Unoccupied period: 0.24 Occupied period: 0.24	Unoccupied period: 0.24 Occupied period: 0.6
Fresh air supply (m^3/s.person)	6.5	7.5

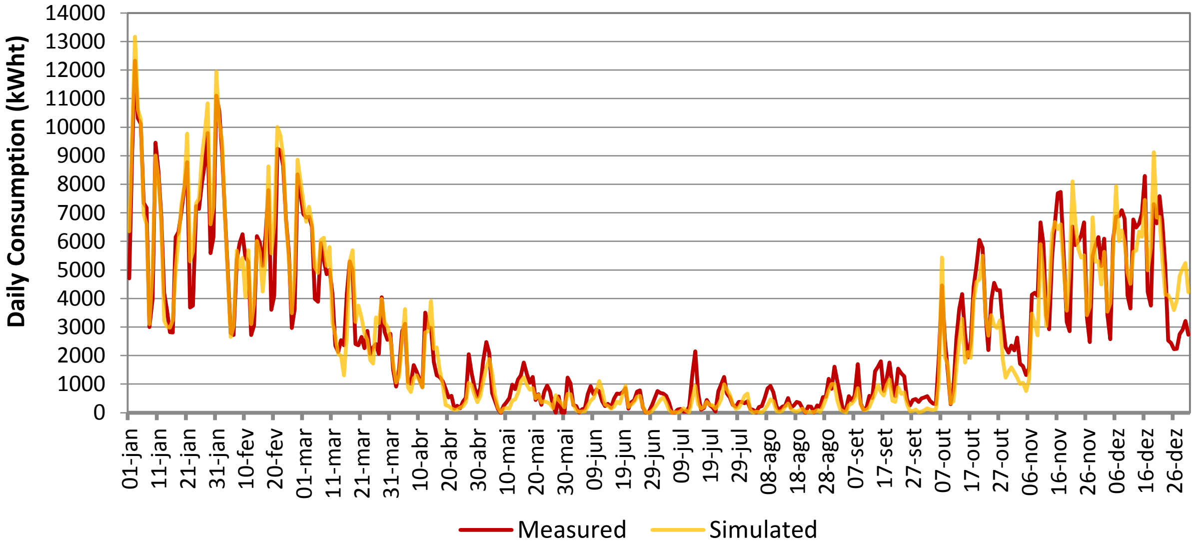


Figure 8.7: Vertigo calibrated BPS model hourly heating consumption comparison.

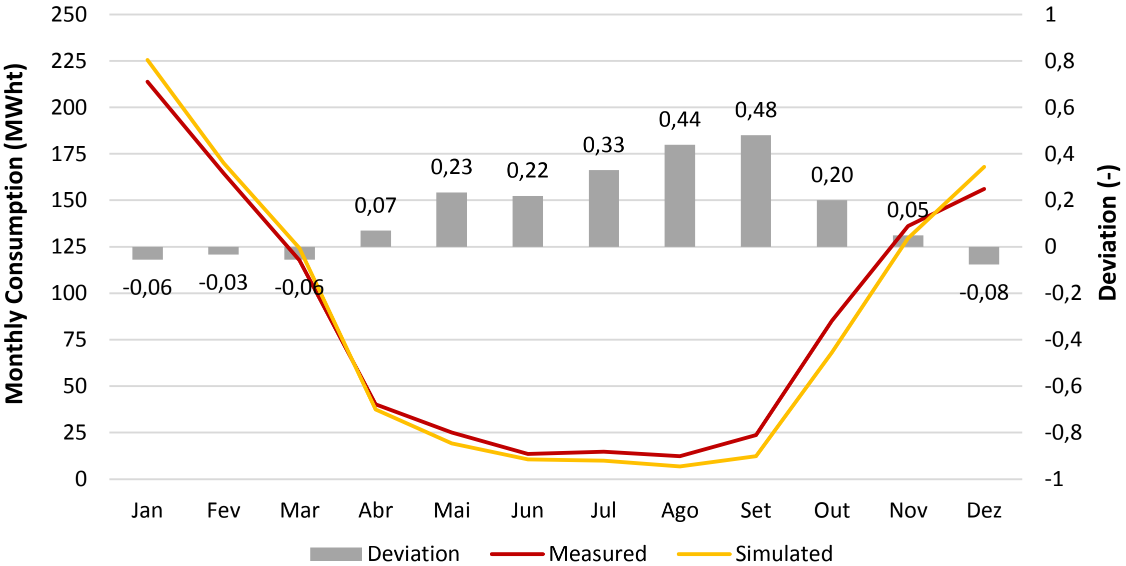


Figure 8.8: Vertigo calibrated BPS model monthly heating consumption comparison.

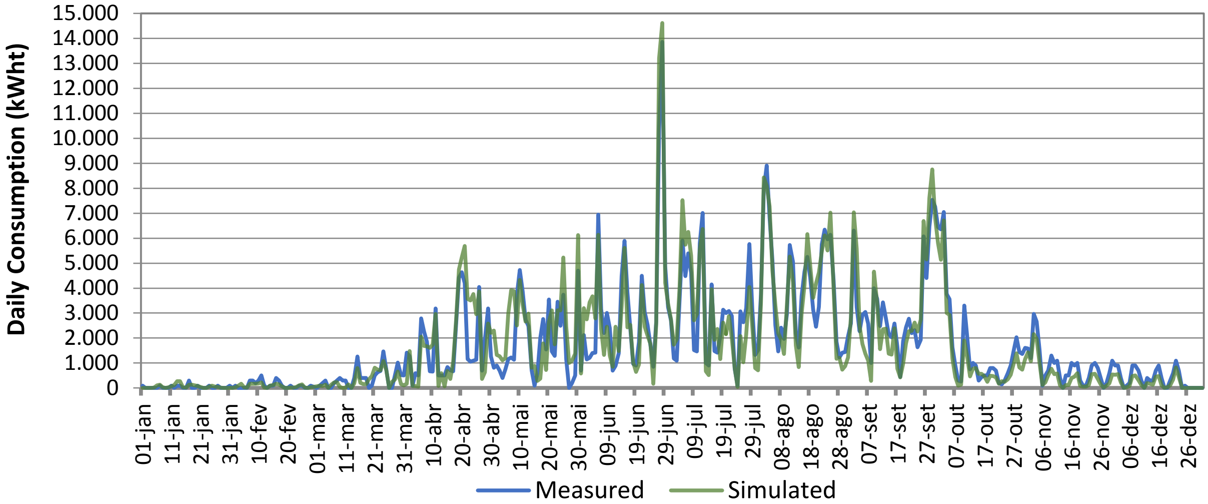


Figure 8.9: Vertigo calibrated BPS model hourly cooling consumption comparison.

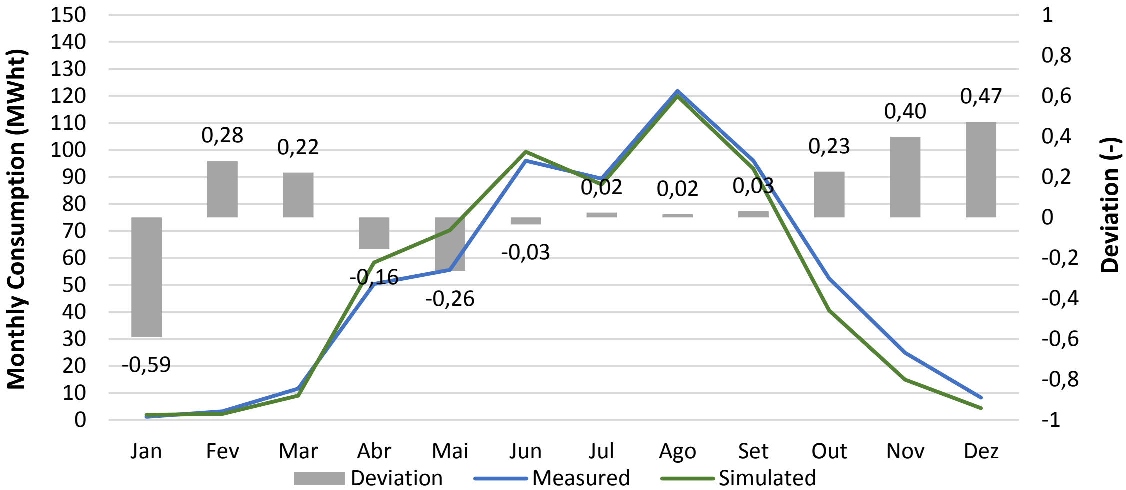


Figure 8.10: Vertigo calibrated BPS model monthly cooling consumption comparison.

Already from the start, the differences between the uncalibrated version of the model and the final calibrated simulation can be quite noticeable. From the daily consumption charts, it is visible some slight disparities among energy demands, by not corresponding precisely with the metered data, but nonetheless the energy demand either for simulated heating or cooling, resembles to some extent throughout the entire year. Furthermore, the monthly consumption plots also translate the correction implemented by the calibrated simulation.

It is worth to note the occurrence in the monthly heating demand a higher deviation, regarding the measured values in the summer period, whereas the cooling demand has a greater deviation during the winter. In contrast, the heating in the winter and the cooling in the summer seasons have negligible asymmetries concerning the deviation of results. Even as it may be, the final calibrated model monthly results have a significant improvement when compared with the uncalibrated simulation, without disregarding some minor discrepancies. Figures 8.11 and 8.12, respectively, heating and cooling calibration signatures point out how much error the calibrated simulation energy values have in relation with the measured data. NMBE and CV(RMSE) were calculated to verified if they were consistent with thresholds limits recommended by the ASHRAE guideline. Table 8.3 reports the results of the whole calibration process.

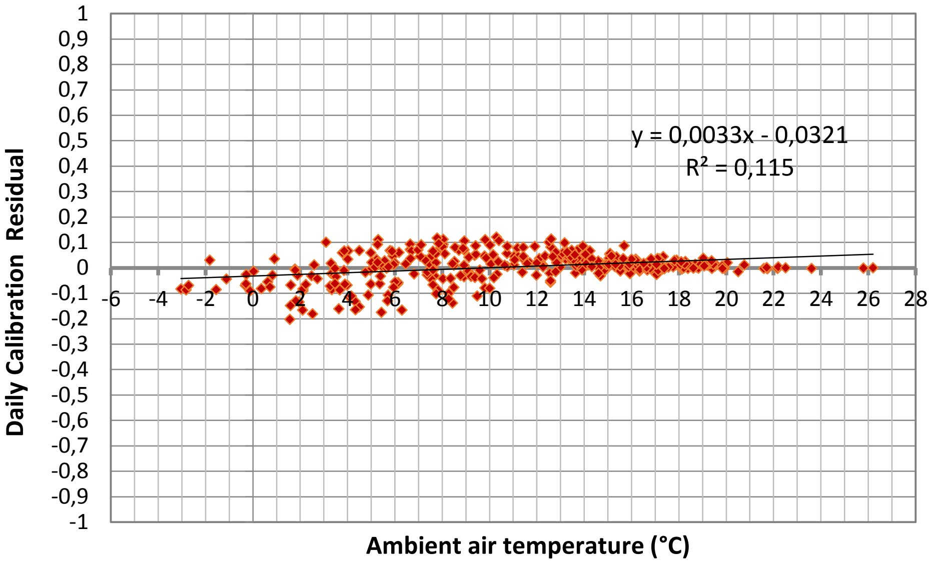


Figure 8.11: Final calibrated BPS model heating calibration signature.

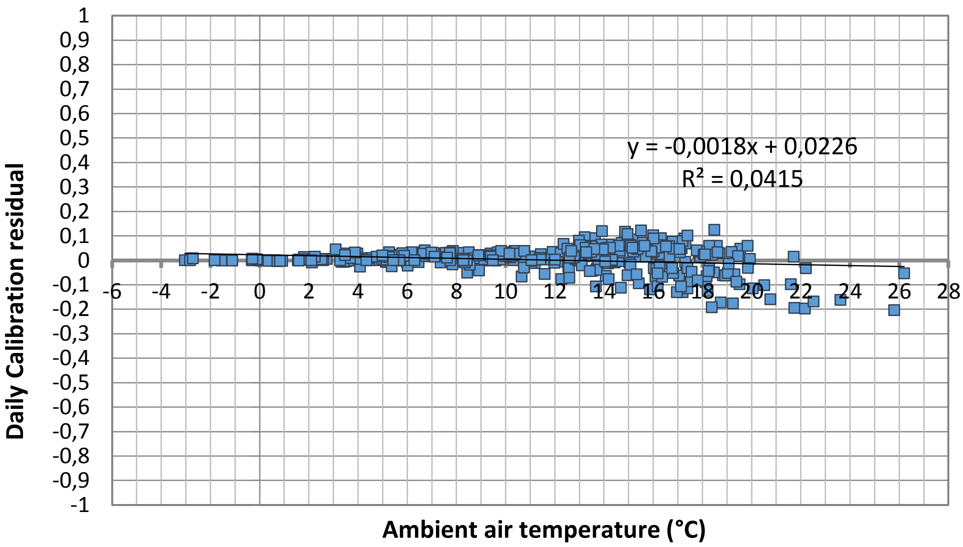


Figure 8.12: Final calibrated BPS model cooling calibration signature.

Table 8.3: Statistics of the BPS model obtained from the final calibrated simulation.

	Heating	Cooling
Total measured consumption (kWht)	1,003,037	613,494
Total simulated consumption (kWht)	982,014	602,892
RMSE hourly (kWh_t/hourly)	29.07	30.30
MBE hourly (kWh_t/hourly)	-2.40	-1.21
ERROR Total hourly (kWh_t/hourly)	42.07	
CV(RMSE) hourly (%)	25.38	26.46
NMBE hourly (%)	-0.09	-0.07
RMSE monthly (MWh_t/monthly)	9.60	6.87
MBE monthly (MWh_t/monthly)	-1.75	-0.80
ERROR Total monthly (MWh_t/monthly)	11.97	
CV(RMSE) monthly (%)	11.49	8.22
NMBE monthly (%)	-2.09	-1.56

When comparing the errors from the calibration signature plots of the uncalibrated and the calibrated simulation, the only thing that stands out is the massive reduction in the calibration residual between predicted and measured values. Confirming that a calibration approach is an imperative method, to provide reliable predictions of a building's energy demand and other performance indicators. Furthermore, the statistical indices have also dramatically improved, where both the hourly and monthly NMBE and CV(RMSE) were within limits of ASHRAE guideline. Then, if a BPS model is calibrated in compliance with these limits, it is sufficiently close to the physical reality that it is intended to simulate and further assessments relative to the building operation can be made (e.g. occupants' thermal comfort, room temperatures, energy efficient upgrades, …).

It should be mentioned, it was found for this case that the most contributing factor for the improvement of the BPS model, during calibration, was the usage of a real weather file that statistically represents the location of the building and the time period, from when the monitored data was obtained for the building performance evaluation. The following calibrations managed to adjust each input parameter to its optimal value, in order to enhance the quality prediction of the model, by shortening the gap between predicted and measured energy demand.

In conclusion, the total heating simulated consumption (982 MWh_t) has a difference of just 2.1% when compared with the total heating measured consumption (1003 MWh_t), while the total cooling simulated (602 MWh_t) and measured (613 MWh_t) energy demand when confronted between each other have a deviation of only 1.7%. Overall, with an hourly heating CV(RMSE) of 25% and a cooling CV(RMSE) of 26% the BPS model can be considered at this stage calibrated.

8.3. Thermal Comfort

Having a fully calibrated model, one can start to make some assessments regarding the building under evaluation. Another objective of this paper is to analyse the perception of thermal comfort that occupants of the Vertigo have. As describe in previous chapter, the examination will follow Dutch guidelines to estimate this indicator. The ATG method is generally suitable for buildings with lots of users with little influence and for practical predictions of thermal comfort in buildings. To first evaluate the thermal performance of the building, one must determine the category of building that the Vertigo belongs to.

From the model design, already described earlier, there is no natural ventilation or free-running conditions and only climate control in a few unique spaces (offices from the 6^{th} to 9^{th} floor). Since, the Vertigo has a closed façade and air-conditioning with centrally regulated climate, it is classified as a type β climate building. Then, using the operative temperatures reported by the simulation, the results are put through a simple and clear chart that easily translates indoor comfort level. The building class is weighted depending on the operative temperature range of results compared with the adaptive temperature limits.

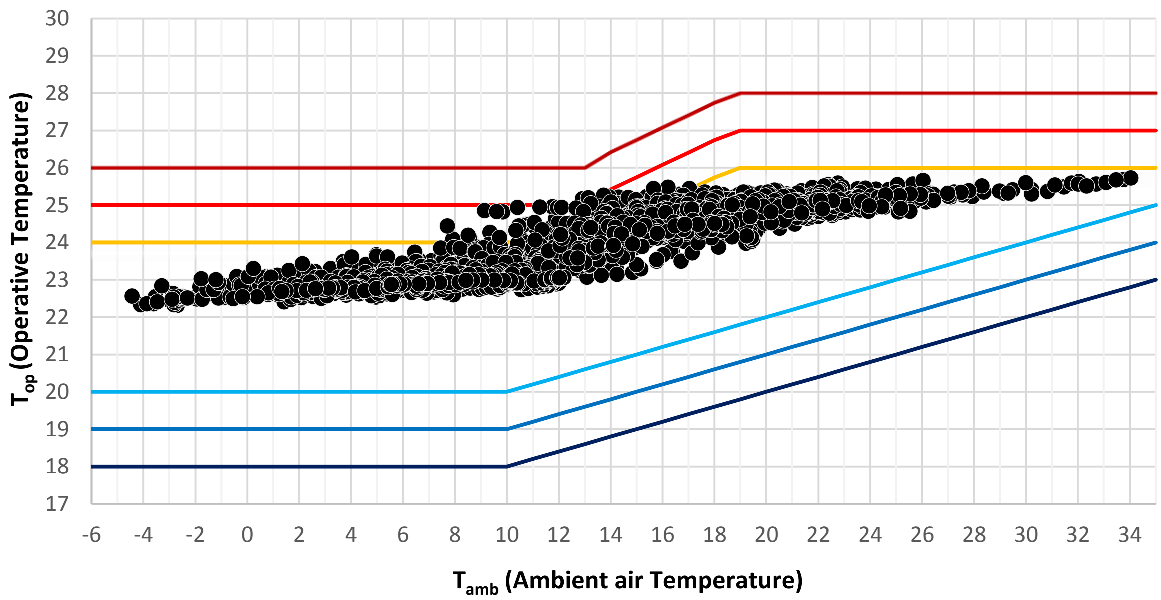
In accordance with ISSO 74:2014, the conformity between simulation outputs and the adaptive limits categorizes the occupants' thermal comfort perception based on the following classification:

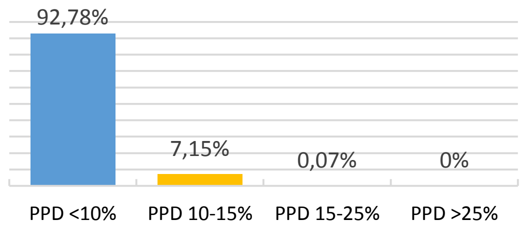
- Class A: comfortable 95% of the time;
- Class B: 90%;
- Class C: 85%;
- Class D: 75%.

If the operative indoor temperatures, during working time or use time, to a large extent are outside the Class D, building performance is to be labelled as “Bad”. Note that the temperature limits for Class A and Class B are the same, the difference between them is that for Class A it is additionally required a possibility for the user to influence:

- The operative temperature (with ± 2 ºC around setpoint Summer/Winter); and or
- The air velocity (between 0.2 and 1.5 m/s).

Since, there is no option to control the temperature in most areas of the building, except in offices, and there is no opportunity to open windows within the building, the limits criteria will be circumscribed to a maximum rating of B. Furthermore, seeing that the building is an office used in weekdays for educational purposes, the thermal comfort assessment is only done during the occupied periods. Moreover, the building model design was divided in 76 thermal zones, hence it would not be time-effective to carry out the ATG method for all those zones. Consequently, it was decided to conduct an evaluation for a typical zone and for the building as a whole. Figure 8.13, shows the ATG chart for the open space zone of the 5th floor, as well as the average predicted percentage of dissatisfied people and the number of hours corresponding to each class limit.



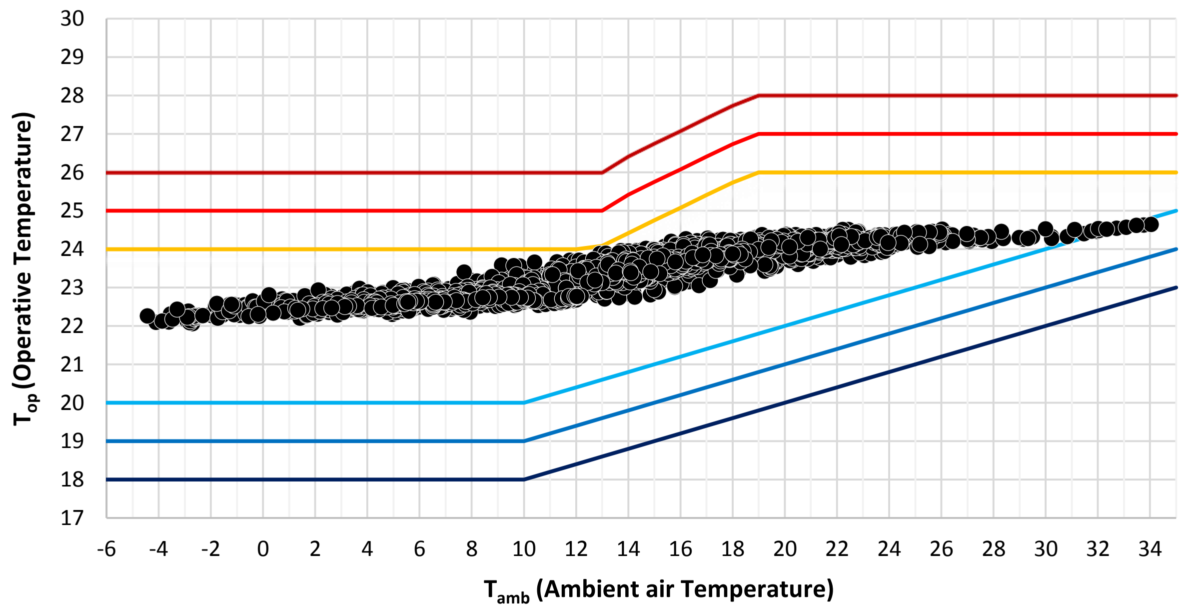


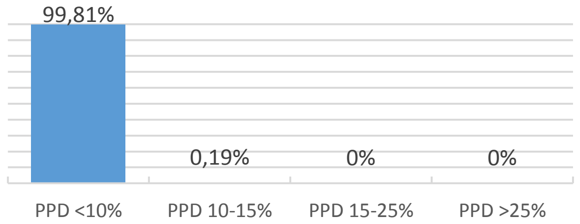
Class Bandwidth	Number of hours	% of time
Class B	2480	92,78
Class C	191	7,15
Class D	2	0,07

Figure 8.13: Vertigo 5th floor open space occupants thermal comfort perception using the ATG method.

From the figure above is quite natural to perceive the occupants' indoor thermal comfort. During more than 90% of the year, less than 10% of the building users are dissatisfied with inside temperature. The operative temperatures are most of time within the comfortable limits, assuring through this way an increase in productivity by the Vertigo occupants. The 5th floor open space area is classified regarding its thermal comfort performance as "good" – Class B. With the attribution of this classification, can be deduced a predicted mean value (PMV) for this zone of -0.5<PMV<0.5.

To inspect the thermal comfort of the entire building an area weighted average is applied in order to achieve a mean operative temperature in the building throughout the year. Even though its representation may not be completely accurate, it gives a global perspective of the thermal perception in the totality of the building. Figure 8.14 presents the ATG method, for the whole building, as a way to effortlessly categorize the thermal comfort indoor conditions of the Vertigo.





Class Bandwidth	Number of hours	% of time
Class B	2668	99,81
Class C	5	0,19
Class D	0	0

Figure 8.14: Vertigo occupants thermal comfort perception using the ATG method.

These results just come to prove that the Vertigo has "good" thermal performance throughout the building. It can be seen that the operative temperature outputs are always within the limits during more than 99 % of the year with less than 10% of its users thermally dissatisfied. To conclude, the results obtained from the evaluation of the typical zone, along with results from figure 36 corroborate the thermal comfort performance as Class B for the Vertigo, with an anticipated PMV between -0.5 and 0.5. Hence, this building ensures the maximum work productivity by its occupants with negligible thermal displeasures.

Chapter 9 - Conclusions and Future Work

The Netherlands set standards for building optimization and is one of the most advanced countries in monitoring and predict building behaviour. One of the most challenging barriers in achieving a considerable amount of energy efficient improvements is the lack of knowledge regarding the factors which determine the energy usage. Netherlands ambitious policies goals of achieving building neutrality by 2020, has given room to a rising concern in building operational performance, in particularly, at TU/e. The case study presented in this paper, which is focused on the occupant comfort and energy consumption of an existing building, is a remarkable example of the difficulties encountered by design teams to analyse the performance of a building pre-and post-construction. Simulation tools were found to greatly benefit the design, analysis and optimization of complex systems, such as a building, during all stages of the building life-cycle.

However, this study has also appointed the fact of a performance gap, partly caused by uncertainties during the design stage, which are very difficult to model. These discrepancies found between simulated and measured energy consumption, undermines confidence in building simulation tools and in their predictions. This is why it is important to start a building performance evaluation in the initial stages of conception. Smart metering technologies offer a superior insight to actual and real-time consumption values, during post occupancy evaluations that within a calibrated model, facilitate energy conservation measures and optimisation studies. Simulation-based optimization is undoubtedly a promising approach to achieve many building design targets, opening a new era of design to architects and engineers. Nevertheless, existing energy simulation tools fail to meet the needs of architects and building designers at the early stages of design due to the excessive complexity of the tools and required technical knowledge.

Calibration aims to minimise disagreements between measured building energy consumption and predicted energy consumption, by building energy simulation programs. In this research, it is proposed an optimized calibration approach to assist during a building performance evaluation study of an office building. Despite the growing awareness of a calibrated simulation, there is still the absence, as well as the need of a recognized standard method to perform calibration of a building energy model, that can be used generically in a wide variety of buildings. Therefore, one of the main objectives of this work is to investigate the methodologies and techniques for simulating total energy use in an office building, in order to demonstrate how the resulting information can be used to provide meaningful advice for better building energy performance.

In this case, an *EnergyPlus* simulation model was used to conduct a building performance evaluation. The current work was carried out using actual hourly data over annual/monthly energy cycles, ensuring greater confidence in the accuracy of model based assessments. To verify the accuracy of the model, actual energy consumption was compared with calculated heating and cooling loads. The comparison between these two sets of values showed very similar results, and the validation of the building model was based on the hourly threshold limits of the MBE and CV(RMSE), which were considered within ASHRAE acceptance criteria of ±10% and <30%, respectively. Thus, a model calibrated around these limits can more confidently predict actual room temperatures within the building. To this extent, the dynamic energy model from *EnergyPlus* simulation can be considered validated and the promising results encourage further studies to be pursued. Besides, the conclusions of this paper demonstrated that real weather files characterized by actual climate conditions, should be obtained and used for a model to be considered calibrated, in consideration of the consequences it can bring to guaranty a superior model precision.

Netherlands increased awareness in occupants' thermal comfort of having the ability to influence workers' productivity, led to establish one of the most advanced guidelines within this area. Therefore, another target goal of this thesis was to examine the Vertigo users' thermal behaviour. The ATG results come to confirm a good level of satisfaction regarding the building indoor temperatures, where for more than 90% of the year the room temperatures are within the adaptive limits. Hence, Vertigo class B thermal performance certifies that is provided a comfortable environment to work to everyone inside the building.

There is an undeniable capacity for further improvements to refine the calibration process. Contrary to the manual approach taken to change more than one parameter, it is suggested that for further studies an automated approach is preferable to test and simultaneously modify an even higher number of parameters. This strategy can be implemented using *GenOpt* software coupled with *EnergyPlus,* for optimizing the uncertain parameters to make the simulated energy match measured one. In addition, an uncertainty and sensitivity analysis would have a significant effect to determine the robustness of the Vertigo building and to detect the most influent model parameters, as a mean to close the gap between predicted and measured energy values. Furthermore, as a future work, analyses can be made to identify possible energy efficient actions to take as a process to reduce the overall energy demand of the Vertigo, by maintaining at least the same level of comfort.

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Chapter 11 - Annexes

11.1. Annex A – Building Legislation for Ventilation

The ventilation rate is considered based on the Building Decree 2012, but to be able to make this assessment first, it is necessary to know the minimum requirement of people for each type of building, since this key parameter will be fundamental while designing any type of building. Table 11.1 shows both minimum requirements to hold people according to building's use function and ventilation rate.

It is also appropriate to have a general understand about the meaning of each type of building according to the Netherlands Building Decree:

- Meeting function: used for bringing people together for art, culture, religion, communication, childcare, watching sports providing consumption for on-site use;
- Office function: used for administration purposes;
- Cell function: used for people forced stay;
- Health function: used for medical examination, nursing, care or treatment;
- Bed function: used for providing recreational stay or temporary shelter for people;
- Educational function: used for teaching purposes;
- Sports function: used for practicing sports;
- Industrial function: used for business editing or storage of materials and goods or for agricultural purposes;
- Store function: used for the trade of material, goods or services.

Table 11.1: Minimum people for each building function and respective ventilation rate according to Building Decree 2012. Source: [37]

Building Use Function	Ventilation minimum required		
	New building		Existing Building
	dm^3/s.person	Minimum require to hold people per m^2	dm^3/s.person
Meeting Function			
a. Dining area	4	0.125	2.12
b. Bar	4	0.125	2.12
c. Company restaurant	4	0.125	2.12
d. Canteen	4	0.125	2.12
e. Spectators space	4	0.125/0.3	2.12
f. Library	4	0.125	2.12
g. Museum	4	0.125	2.12
h. Cinema	4	0.125	2.12
i. Music hall	4	0.125	2.12
j. Theatre	4	0.125	2.12
k. Casino	4	0.125	2.12
l. Meeting space	6.5	0.05	3.44
Cell Function			
a. Cell not having day and night accommodation	12	0.05	6.4
b. Cell with day and night accommodation	12	0.05	6.4
c. Other area	6.5	0.125/0.05	3.44
Health functions			
a. Patient rooms	12	0.125	3.44
b. Intensive care room	12	0.125	3.44
c. Operating room	12	0.125	3.44
d. Research area	6.5	0.05	3.44
e. Physioterapy	6.5	0.05	3.44
f. Section space	6.5	N/A	3.44
Industrial Function			
a. General industry	6.5	N/A	3.44
b. Paint spraying device	6.5	N/A	3.44
c. Battery bay	6.5	N/A	3.44
Office Function			
a. Office space	6.5	0.05	3.44
b. Front desk	6.5	0.05	3.44
Bed Function			
a. Room	12	0.05	6.4
Education Function			
a. Classroom	8.5	0.125	3.44
b. Workshop	6.5	0.125	3.44
c. Office space	6.5	0.05	3.44
d. Gym	6.5	N/A	3.44
e. Auditorium	6.5	0.125	3.44
Sports Function			
a. Gym	6.5	N/A	3.44
b. Bowling area	6.5	N/A	3.44
c. Swimming pool	6.5	N/A	3.44
Store Function			
a. Pharmacy	4	N/A	2.12
b. Beauty shop	4	N/A	2.12
c. Library	4	N/A	2.12
d. Florist	4	N/A	2.12
e. Hair stylist	4	N/A	2.12
f. Post office	4	N/A	2.12
g. Convenience store	4	N/A	2.12
h. Department Store	4	N/A	2.12
i. Butchery	4	N/A	2.12
j. Salesroom	4	N/A	2.12
k. Laundry	4	N/A	2.12
Other functional unit	-	N/A	-

11.2. Annex B – Vertigo Blueprints

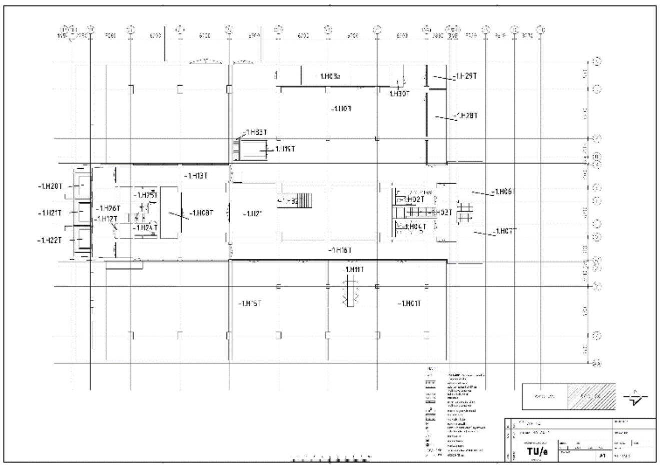

Figure 11.4: Floorplan of -1st floor of the Vertigo.

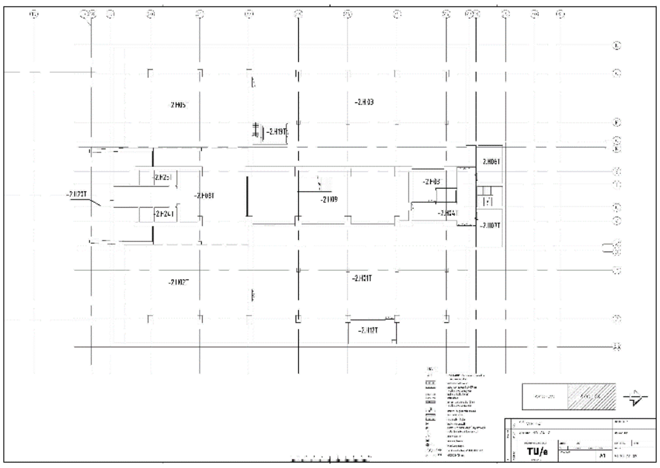

Figure 11.2: Floorplan of -2nd floor of the Vertigo.

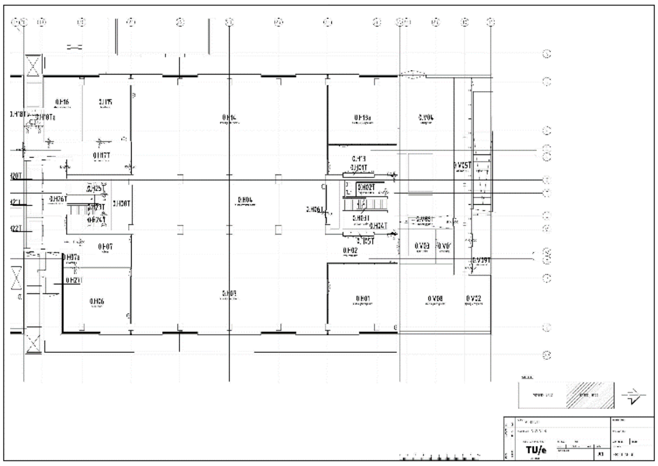

Figure 11.5: Floorplan of 0th floor North side of the Vertigo.

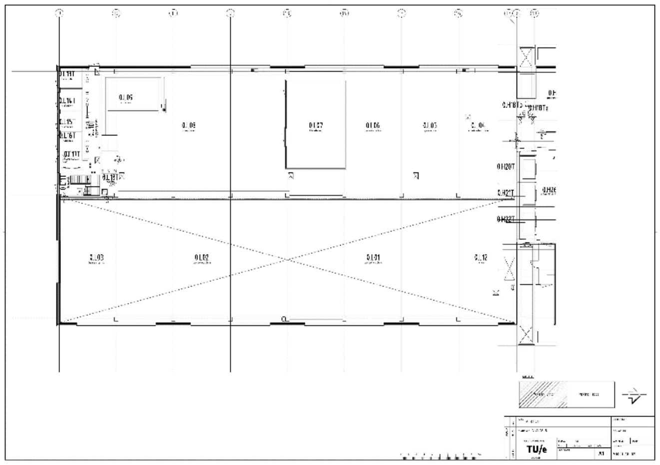

Figure 11.3: Floorplan of 0th floor South side of the Vertigo.

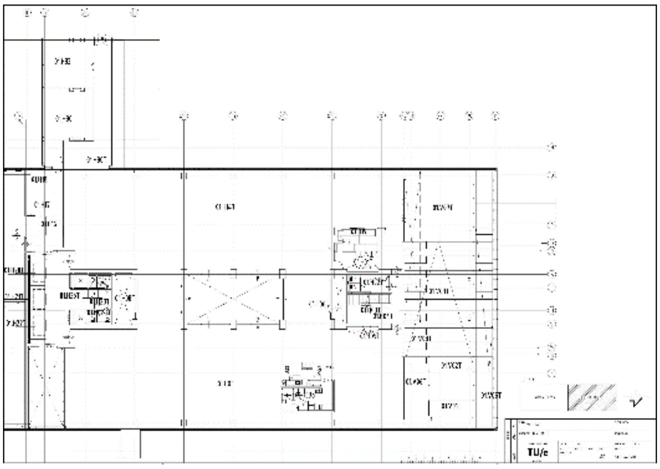

Figure 11.6: Floorplan of 1st floor North side of the Vertigo.

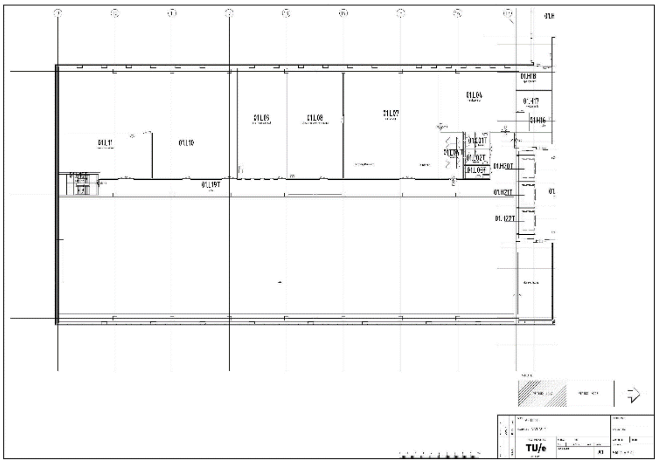

Figure 11.1: Floorplan of 1st floor South side of the Vertigo.

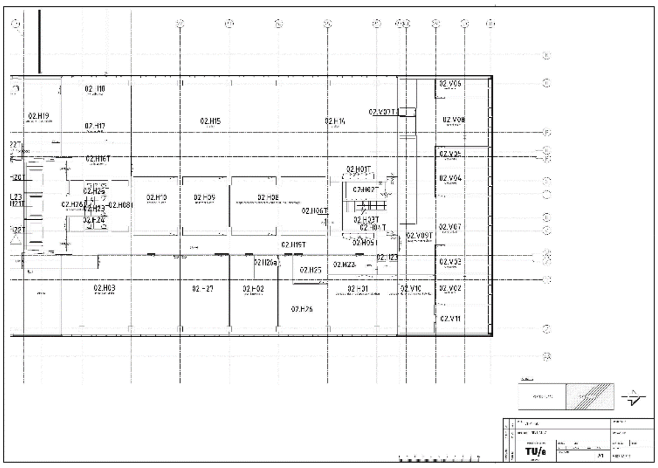

Figure 11.10: Floorplan of 2nd floor North side of the Vertigo.

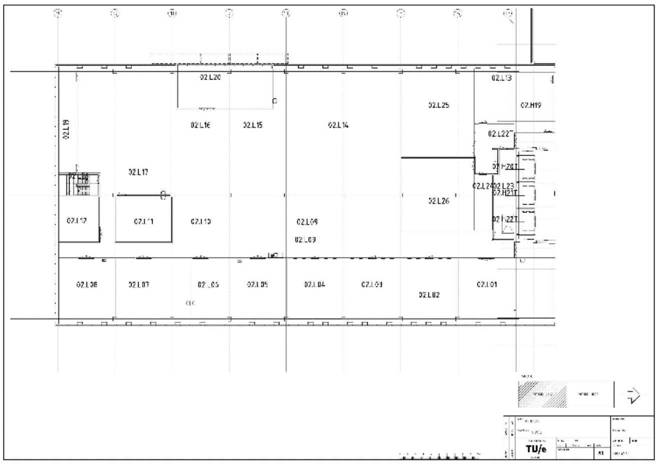

Figure 11.9: Floorplan of 2nd floor South side of the Vertigo.

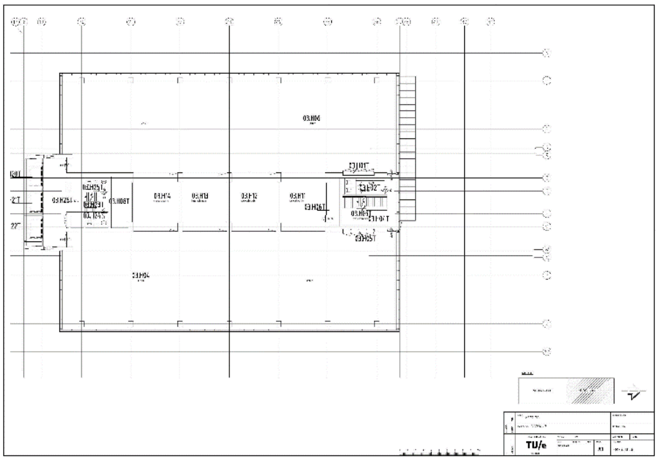

Figure 11.8: Floorplan of 3rd and 4th floor of the Vertigo.

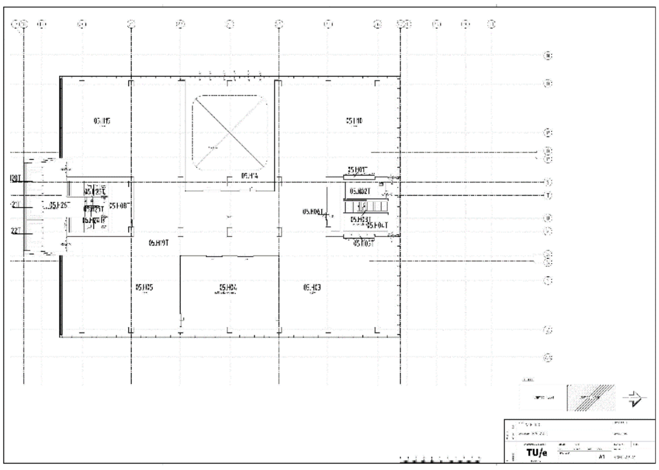

Figure 11.7: Floorplan of 5th floor side of the Vertigo.

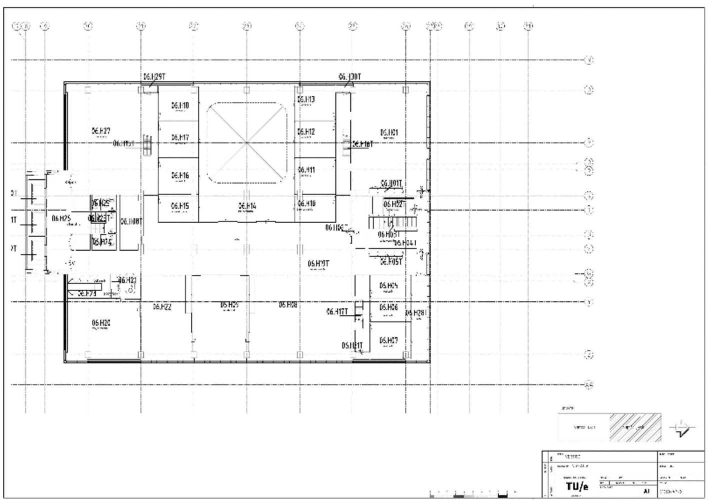

Figure 11.11: Floorplan of 6th – 9th floor of the Vertigo.

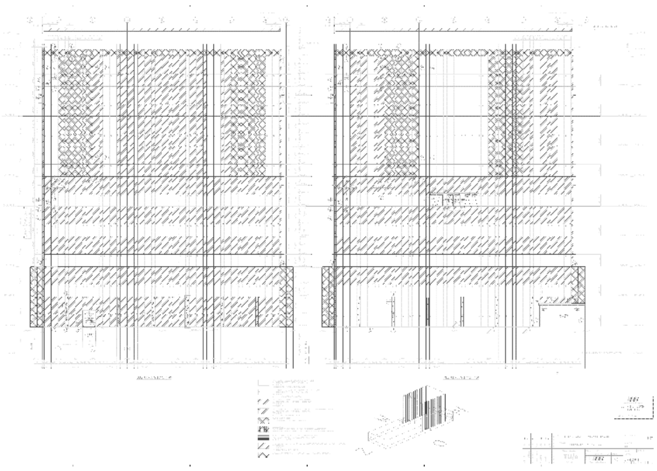

Figure 11.13: Vertigo glass façade.

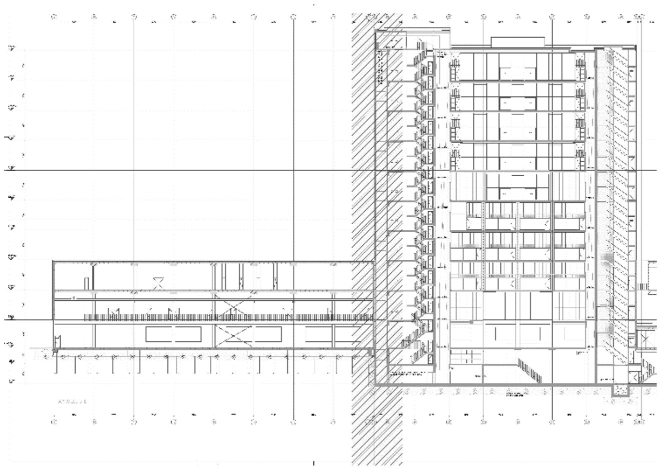

Figure 11.12: Vertigo layout.

11.3. Annex C – Heat Pump Supply Water Temperature

The Vertigo’s heat pump has a linear correlation for the supply water temperature both for heating, figure 11.14, and cooling, figure 11.15. Both these elements are crucial for a precise estimation of the hourly measured heating and cooling loads. Therefore, through this method one can accurately determine the water distribution temperature depending on the ambient temperature at any given moment.

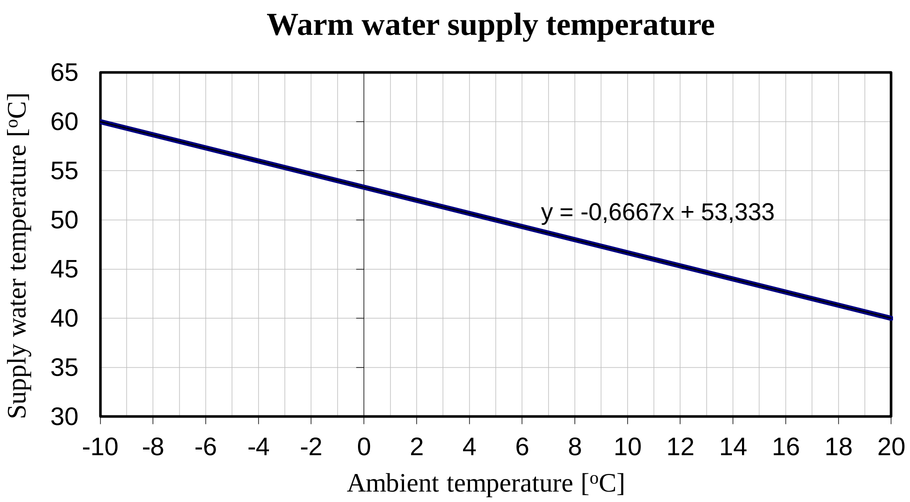

Figure 11.14: Changes in hot water supply temperature depending on the outdoor temperature

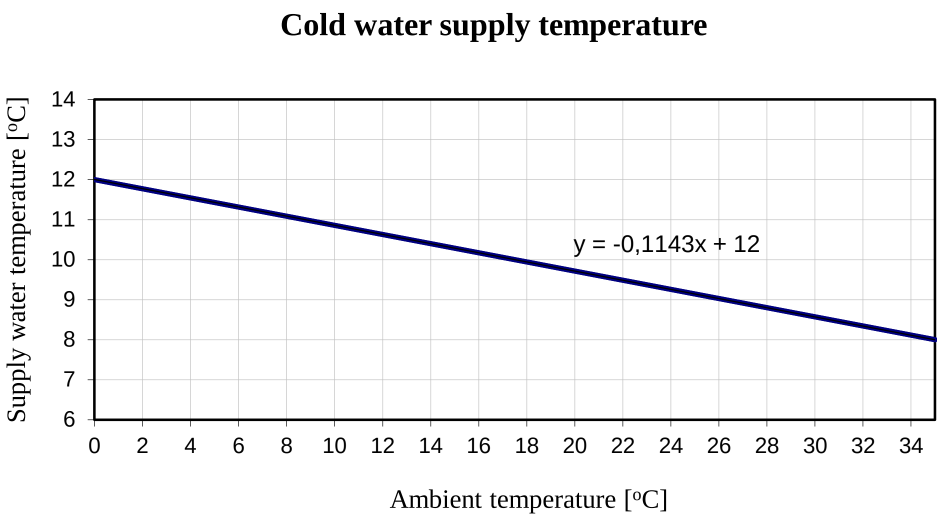

Figure 11.15: Changes in cold water supply temperature depending on the outdoor temperature

11.4. Annex D – Building Envelope Properties

Description of the materials that make up each construction element associated with the building envelope. From the outside layer to inside layer.

Exterior Wall:

Material	Thickness (m)	Conductivity (W/m.K)	Density (Kg/m^3)	Specific Heat (J/Kg.K)	Thermal Resistance (m^2.K/W)
Concrete	0.1	1.831	1700	840	0.055
Vertical air wall	0.025	-	-	-	0.16
XPS (Extruded Polystyrene)	0.051	0.027	35	1450	1.889
Aerated concrete	0.045	0.141	1000	500	0.319
Concrete	0.1	1.831	1700	840	0.055
Total Thickness (m)					0.321
Total Thermal Resistance (m^2.K/W)					2.478
Heat Transfer Coefficient (W/m^2.K)					0.4

Interior Wall:

Material	Thickness (m)	Conductivity (W/m.K)	Density (Kg/m^3)	Specific Heat (J/Kg.K)	Thermal Resistance (m^2.K/W)
Concrete	0.075	1.831	1700	840	0.041
XPS	0.065	0.027	35	1450	2.407
Concrete	0.075	1.831	1700	8400	0.041
Total Thickness (m)					0.215
Total Thermal Resistance (m^2.K/W)					2.489
Heat Transfer Coefficient (W/m^2.K)					0.4

Basement Wall:

Material	Thickness (m)	Conductivity (W/m.K)	Density (Kg/m^3)	Specific Heat (J/Kg.K)	Thermal Resistance (m^2.K/W)
Concrete	0.1	1.831	1700	840	0.055
Vertical air wall	0.025	-	-	-	0.16
XPS	0.051	0.027	35	1450	1.889
Aerated Concrete	0.045	0.141	1000	500	0.319
Concrete	0.1	1.831	1700	840	0.055
Total Thickness (m)					0.321
Total Thermal Resistance (m^2.K/W)					2.478
Heat Transfer Coefficient (W/m^2.K)					0.4

Floor Ground:

Material	Thickness (m)	Conductivity (W/m.K)	Density (Kg/m^3)	Specific Heat (J/Kg.K)	Thermal Resistance (m^2.K/W)
Slab	0.05	1.8	2400	750	0.028
XPS	0.065	0.027	35	1450	2.407
Concrete	0.1	1.831	1700	840	0.055
Total Thickness (m)					0.215
Total Thermal Resistance (m^2.K/W)					2.49
Heat Transfer Coefficient (W/m^2.K)					0.4

Interior Floors:

Material	Thickness (m)	Conductivity (W/m.K)	Density (Kg/m^3)	Specific Heat (J/Kg.K)	Thermal Resistance (m^2.K/W)
Concrete	0.075	1.831	1700	840	0.041
XPS	0.065	0.027	35	1450	2.407
Concrete	0.075	1.831	1700	840	0.041
Total Thickness (m)					0.215
Total Thermal Resistance (m^2.K/W)					2.489
Heat Transfer Coefficient (W/m^2.K)					0.4

Roof:

Material	Thickness (m)	Conductivity (W/m.K)	Density (Kg/m^3)	Specific Heat (J/Kg.K)	Thermal Resistance (m^2.K/W)
Asphalt shingle	0.015	0.082	1121	1256	0.183
Roof insulation	0.1	0.049	265	836.8	2.041
Roof membrane	0.03	0.16	1121	1460	0.187
XPS	0.042	0.027	35	1450	1.55
Concrete	0.05	1.831	1700	840	0.027
Total Thickness (m)					0.237
Total Thermal Resistance (m^2.K/W)					3.988
Heat Transfer Coefficient (W/m^2.K)					0.25

Fenestration:

Clear Double Glazed Window				
Material	**Thickness (m)**	**Total Visible Transmittance (%)**	**Total SHGC (%)**	**Total Heat Transference Coefficient ($W/m^2.K$)**
SGG Coolite SKN 165	0.008	0.446	0.26	1.4
90% Argon/10% Air	0.016			
SGG Coolite SKN 165	0.008			

Green Silk Screen-Printed Double Glazed Window				
Material	**Thickness (m)**	**Total Visible Transmittance (%)**	**Total SHGC (%)**	**Total Heat Transference Coefficient ($W/m^2.K$)**
Ariplak DAG 66/38	0.008	0.54	0.32	1.4
Air	0.016			
Ariplak DAG 66/38	0.008			

Clear Single Glazed Window				
Material	**Thickness (m)**	**Total Visible Transmittance (%)**	**Total SHGC (%)**	**Total Heat Transference Coefficient ($W/m^2.K$)**
SGG STAPID SILENCE	0.0084	5.7	0.83	5.7