# Dynamic energy simulation for a sustainable design of buildings

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# DYNAMIC ENERGY SIMULATION FOR A SUSTAINABLE DESIGN OF BUILDINGS

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# Publications list

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Erminia Attaianese, Francesca Romana d’Ambrosio Alfano, Boris Igor Palella, Daniela Pepe, and Roberto Vanacore. An Integrated Methodology of Subjective Investigation for a Sustainable Indoor Built Environment. The Case Study of a University Campus in Italy. Atmosphere, 2021, 12,1272; doi: 10.3390/atmos12101272.

Francesca Romana d’Ambrosio Alfano, Bjarne Wilkens Olesen, Boris Igor Palella, Daniela Pepe. The prediction of energy use and indoor temperatures in building simulation tools. Submitted to Journal of Building Engineering.

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# Summary

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# Abstract

The combined study of energy efficiency of buildings and Indoor Environmental Quality (IEQ) is a new strategy to achieve a sustainable design of one of the highest consumption sectors, such as that of construction.

The Energy Performance Building Directive EPBD 844/2018 with technical reports as the EN 16798-1:2019 Standard and CEN/TR16798-2:2019 are specific references for the design and assessment of buildings' energy performance.

For this aim, dynamic energy simulation is an instrument to simulate building behaviour according to the variation of boundary conditions over time.

The thesis describes the role of dynamic energy simulation for the control and optimization of thermal comfort, which is one of the IEQ aspects strongly correlated with the energy efficiency of buildings.

Starting with a study on the limits of the Standard reference for building design and, on the determination of input parameters for thermal comfort assessment according to the Standard, the thesis shows a comparison of dynamic simulations performed by Energy Plus and IDA ICE, two building simulation tools used by designers and researchers. From the comparison the necessity emerges to deepen the analysis of some parameters of which determination affects building behaviour for the evaluation of energy use and thermal comfort: the U-value and the mean radiant temperature. The thesis deals with the calculation methods to determine these parameters, identifying differences and assumptions at the base of the simulation tools.

The results demonstrate how different software can carry out unlike estimation of thermo-energy behaviour caused by the several assumptions at the base of the calculations, affecting the modelling procedure. For this reason, the designer should know the specific software for the dynamic simulation, manage the multiple input data required and analyse having a critical approach to the obtained results.

# Introduction

The growing attention to issues relating to energy sustainability has led to the need to combine the energy efficiency of buildings with internal environmental quality, changing the building design for some years now.

From a legislative point of view, the Directive (EU) 2018/844 of the European Parliament prescribes that energy efficiency must combine with Internal Environmental Quality (IEQ), both in new and existing buildings. From a regulatory point of view, the EN 16798-1: 2019 Standard and the technical report CEN TR16798-2: 2019 prescribe internal environmental input parameters for the design and evaluation of the energy performance of buildings.

To deal with two aspects of the design studied separately so far, it is necessary to use dynamic energy simulation, which provides a complete picture of the energy behaviour of the building and the quality level of the internal environments. Dynamic energy simulation allows following the evolution of the energy behaviour of the building as internal and external conditions vary, such as microclimatic variables, thermal loads, occupancy levels, etc.

The dynamic simulation tools are powerful instruments capable of carrying out an energy design and studying the internal climatic conditions according to the Standards. Unfortunately, they can give wrong results if the user does not know their operating logic and the boundary conditions on which the calculation is based.

The thesis aims to identify the role of dynamic energy simulation in the control and optimization of thermal comfort, which is one of the IEQ aspects strongly correlated with the energy efficiency of the buildings, considering a critical approach in the use of simulation tools which detect the building performance over time.

Are the IEQ aspects strongly correlated with the energy efficiency of buildings? How to evaluate the building's performance? Why is it important correctly use dynamic simulation tools? What about the reliability of these instruments? These are the main research questions that the PhD thesis answer dealing with several issues encountered in the analysis of building performance evaluation through dynamic simulation tools.

To reach the main objective additional sub-objectives are dealt with:

understand how to evaluate building performance, according to indications of the European standards; compare results of two different building simulation tools, in terms of energy use and thermal comfort; analyse the calculation of critical parameters in the buildings' thermal-energy behaviour: U-value and mean radiant temperature. So, the first three chapters of the thesis concern theoretical aspects of the energy efficiency of buildings, thermal comfort evaluation, and the use of dynamic energy simulation to predict buildings' behaviour. The following chapters are focused on specific topics about specific aspects of dynamic energy simulation.

Chapter IV deals with the assessment of thermal comfort and energy consumption in a residential building carried out with a dynamic energy simulation tool, applying the EN 16798-1 and -2 Standards. This study worked out during the research period at Denmark Technical University.

Chapter V concerns the comparison between two commercial dynamic energy simulation software. The goal is to analyse the different outputs in terms of energy consumption and thermal comfort. This aspect is very important, for example in the choice of a tender assignment. Based on the obtained results in Chapter V, the difference in the classification of the thermal environment is evaluated in Chapter VI.

Finally, Chapters VII and VIII analyse two critical aspects of the simulation tools: the U-value calculation, which influences the heat transfer through the envelope, and the calculation of the mean radiant temperature, which affects the PMV index value. The theoretical analysis is then applied to specific studies.

# Chapter I
# The energy efficiency of buildings

## I.1 Introduction

The attention to sustainability starts in 1987 when the United Nations Brundtland Commission defines sustainable development as progress able to «meet the needs of the present without compromising the ability of future generations to meet their own needs» [1]. In this way the Brundtland report *Our common future*, introduces the concept of sustainability, setting the theoretical bases for the Rio Conference, in 1992, where the United Nations Framework Convention on Climate Change-UNFCCC was signed, and for the Kyoto Conference, where the basis of Kyoto Protocol was laid.

In this contest Climate change is one of the most urgent global issues, humanity continues a dependence on fossil fuels and energy sources such as coal, oil and natural gas represent the largest part of the energy used in the world. As visible in Fig. I.1 oil is the most employed energy source in the world and renewable energy sources are less used even if the use has increased in the last years (Dale, 2021). In December 2015 the Paris Agreement at COP21 represents the latest arrangement to limit global warming to reduce the temperature rise. To meet the Paris Agreement goal, the global economy should aim to achieve net zero $CO_2$ emissions by 2050. It will be necessary to intensify urgent action to reduce emissions and the decarbonisation process becomes a must.

On the same note, the 2030 Agenda for Sustainable Development is an action program for people, the planet and prosperity signed in September 2015 by the Governments of the 193 UN member Countries. The 17 Sustainable Development Goals described in the 2030 Agenda (Fig. I.2), to achieve within 15 years, are a universal call to action to end poverty, protect the planet and improve the lives and prospects of everyone, everywhere.

This thesis deals with a very important aspect of sustainability: energy sustainability. Indeed the energy interacts with goals 3, 7, 9, 11, and 12. Not surprisingly, Europe has worked a lot on energy sustainability in recent years. The reduction of energy demand through the adoption of an energy efficiency policy is a key element of energy strategy.

The European "Green Deal" was presented in December 2019 to provide a roadmap with actions for efficient use of resources, operating through a clean, circular economy and stopping climate change, reverting biodiversity loss and cutting pollution. The deal presents investments needed and financing tools available to achieve the sustainable objectives and transform the EU into the world's first climate-neutral continent by 2050 covering all sectors of the economy, notably transport, energy, agriculture, buildings, and industries such as steel, cement, ICT, textiles and chemicals [2]. Fig. I.3 shows a scheme that summarizes the main contents of the Green Deal. The Green Deal is an integral part of the Commission's strategy to implement the 2030 Agenda of the United Nation and the Sustainable Development goals [3].

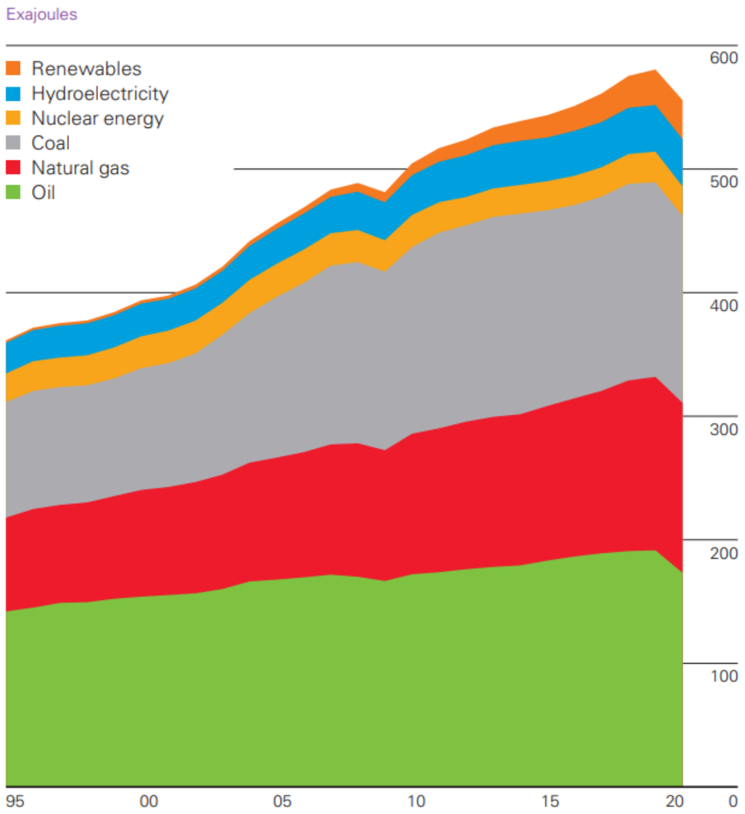


**Figure I.1** *World consumption during years (Dale, 2021)*

**Figure I.2** *The 17 Sustainable Development Goals*

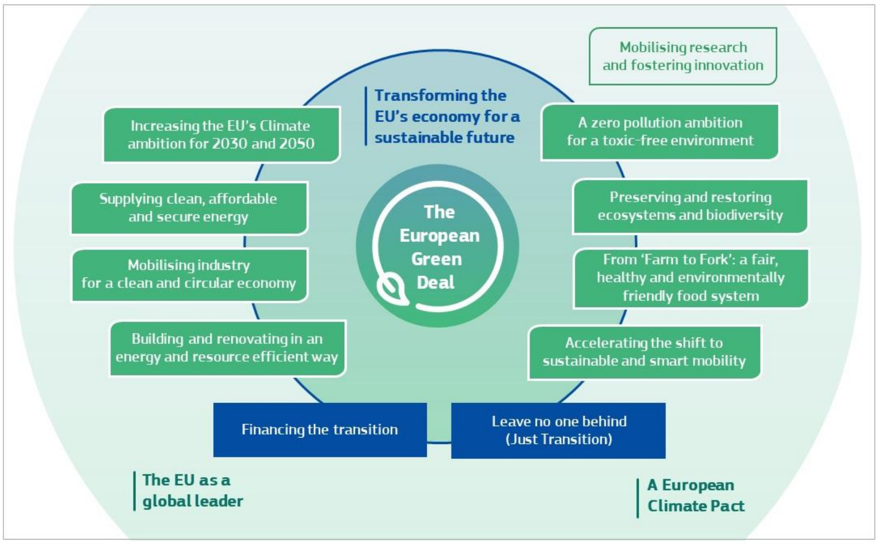


**Figure I.3** *The European Green Deal scheme [2]*

As part of the Green Deal, the European Commission launched 2020 policy strategies to reach the target of 2050 among which the “2030 Climate & Energy framework” to reach a 55% of reduction of greenhouse gas emissions by 2030 compared to 1990. For renewable energies and improvements in energy efficiency, the scenarios aspire to increase by about 30% [4].

Another act introduced by Green Deal was the “European Climate Pact” which is aimed to involve not only Member States' governments but citizens, communities and organizations who play an important role in the energy transition, through the spread of information about climate change and environmental degradation, and how they tackle these existential threats, with propose grassroots activities and share solutions [5].

Because of intensive activity in the construction sector, an essential action singled out in the European Green Deal was the strategy "Renovation wave" with aim to double the annual rate of energy renovation of buildings in the next 10 years. The plan aims to tackle energy poverty by encouraging the renovation of worst-performing buildings, public buildings, and social infrastructure [6].

In this framework, the energy efficiency of buildings is a current and relevant topic at the National, European, and International level. The use of fossil fuels and human activities have produced devastating effects on the environment and on the climate, with the emission of pollutants and of Green House Gases-GHG, responsible for global warming and environmental changes.

Energy use in the building sector is still around 40% of the total energy use, despite the decline in energy due to the change in the way to use existing buildings during the last critical pandemic phase. In fact, COVID-19 had a very high impact on the global buildings and construction sector in 2020. It has been estimated that the average annual growth rate in buildings decreased by 4% in 2020 compared to 2019. The main reason for this decline in market growth is the impact of a global pandemic on construction activities which comported a limited demand for new buildings and the stop of several sectors connected to the construction chain [7].

Statistic data also estimate a decrease in global energy demand by 4.5% in 2020 COVID-induced with a consequent reduction in $CO_2$ emissions, as shown in Fig. I.4 (Dale, 2021). Indeed, the pandemic changed the way to occupy buildings and energy demand shifted from the commercial and retail sectors to the residential sector with a quick transition to remote smart working arrangements, while many public buildings closed for significant periods. Fig. I.5 shows how the highest percentages of $CO_2$ emissions are related to the building and construction sector compared to other sectors. The challenge is now to maintain this level of emissions of $CO_2$ in the future, when the world economy recovers, returning to the previous way of occupying buildings.

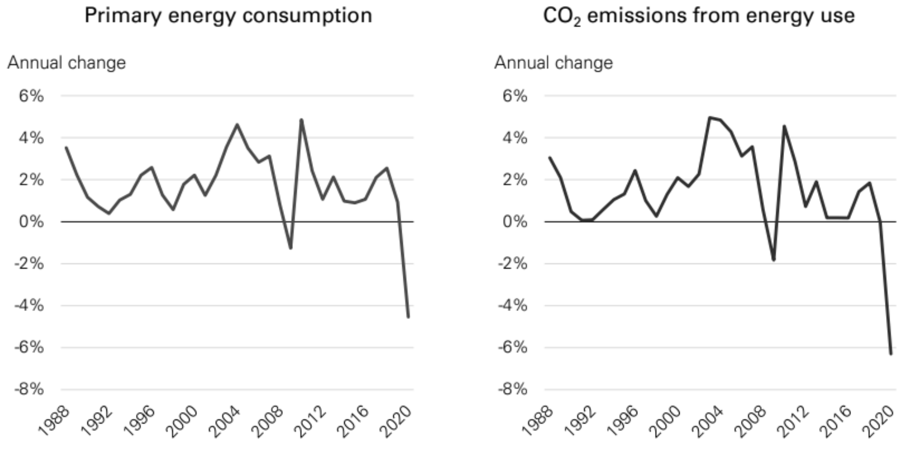


**Figure I.4** *Energy consumption and $CO_2$ emissions (Dale, 2021)*

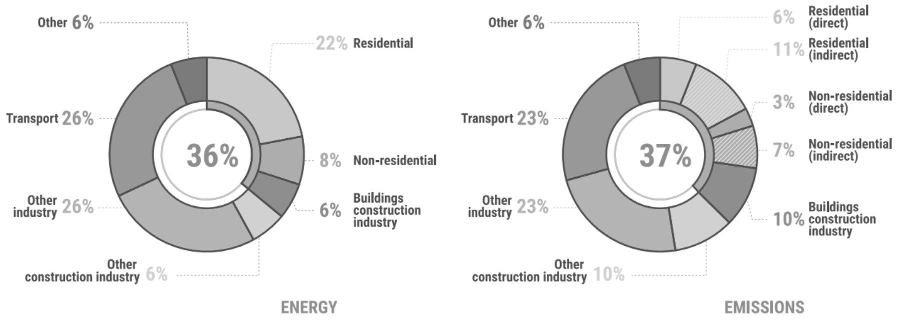


**Figure I.5** *Share of Buildings and Construction of global final energy and energy-related $CO_2$ emissions [7]*

The European Union has adopted policies and programmes to improve energy efficiency in the building sector. In November 2016 the European Commission published the “Clean and Secure Energy for All Europeans” or the so-called “Winter Package” [8] to implement the Climate Package 2020 [9] set by the EU in 2007 which included a set of laws to ensure the EU meets its climate and energy targets for the year 2020 (referred to 1990 levels): 20% cut in greenhouse gas emissions, 20% of EU energy from renewables and 20% improvement in energy efficiency. With Winter Package, the EU wanted to facilitate the transition to a clean energy economy and encourage the European community to continue the path of decarbonisation. It is designed to establish goals for the coming decades to find a governance mode to push the Member States in the direction of more ambitious and better-coordinated climate and energy policies (Ringel and Knodt, 2018).

Energy policies, progressively modified over the years, encourage measures of energy efficiency in new and existing buildings.

Investment in building energy efficiency has increased by 40 per cent since 2015 but the actions are too few to provide a radical change. Most of the improvements in energy efficiency came from a small number of European countries and there is a lack of ambitious decarbonization targets in NDCs (Nationally Determined Contributions) which define actions for addressing buildings-related emissions or improving energy use, under the Paris Agreement.

Looking at the policies for Energy Efficiency in buildings, there is no single policy that alone can achieve a substantial transformation of the existing building stock and significantly reduce energy consumption: over the years action plans, directives, and decree laws have been implemented in this direction (Economidou et al., 2020).

## I.2 Energy Performance Building Directive (EPBD)

The major steps taken by the EU to increase energy efficiency derive from the Energy Performance Building Directives - EPBDs. The EPBD represents the first cohesive European legal act on energy policy in buildings to improve the security of energy supply, increase employment and eliminate large differences observed between the Member States.

The Directive 2002/91/EC of 16th December 2002 on Energy Performance of Buildings [10], introduced an energy performance calculation methodology for buildings where the energy performance represents the amount of energy consumed or estimated to produce heating, hot water heating, cooling, ventilation and lighting.

The main actions indicate by the Directive are:

- Specify national minimum requirements and opportunities for energy performance measures for new buildings and large existing buildings undergoing a major renovation.
- Identify national minimum requirements and specific energy performance measures for new buildings and large existing buildings undergoing a major renovation.
- Review conditions for the inspection of boilers and heating/cooling systems, made by qualified and accredited experts.

Finally, the EPBD introduces a new instrument in the Art. 7 to describe buildings' performance: “The energy performance certificate for buildings shall include reference values such as current legal standards and benchmarks to make it possible for consumers to compare and assess the energy performance of the building. The certificate shall be accompanied by recommendations for the cost-effective improvement of the energy performance” [10].

After some years of implementation, the Commission started to evaluate the Directive considering the experience gained during its application. The evaluations of the Commission led to clarifying the EPBD by introducing new criteria and indications related to improving the energy performance of buildings. The result was the adoption of the EPBD recast 2010/31/EU, which requires the Member States to identify and submit to the Commission, national financial measures to expand energy efficiency.

The EPBD recast at Art. 9 introduced nearly zero-energy building-NZEB, defined in Art. 2 as "*a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*" [11]. In Fig. I.6 the concept of NZEB is shown.

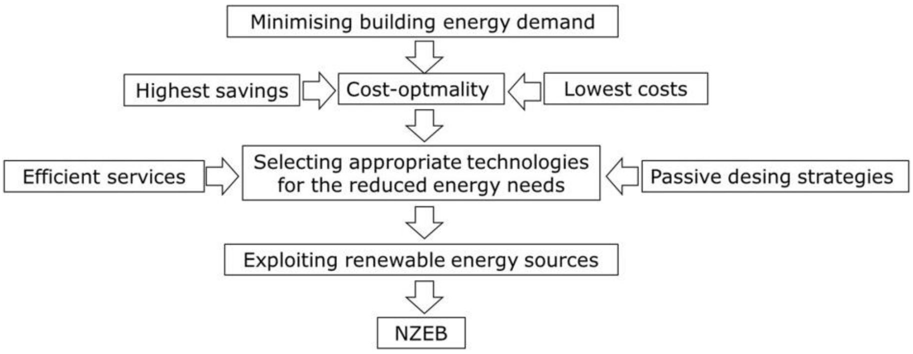


**Figure I.6** *The concept of NZEBs (D'Agostino and Mazzarella, 2019)*

Another important new introduced in EPBD Recast is the cost-optimal methodology as a guiding principle for the definition of building energy requirements. It consists of a comparative method to the determinate energy performance of buildings considering the economical aspect involved in energy performance evaluation and, to identifying the cost-optimal level. This is because some national standards were not ambitious enough in the definition of minimum energy performance requirements. The cost-optimal methodology was intended to guide the Member States in the definition of minimum energy performance requirement and to ensure that they had similar ambition levels in terms of energy savings and greenhouse gas emissions reduction, achieving a balance between the investments involved and the energy costs saved through the lifecycle of the building.

After new objectives contained in the Winter Package (2016), the Directive (UE) 2018/844 [12] was published. It provides changes not only to Directive 2010/31/EU but also to the Energy Efficiency Directive [13] which is focused on the field of energy efficiency. Directive 844/2018 introduces targeted amendments to accelerate the cost-effective renovation of existing buildings, implement the decarbonization of building stock by 2050 and the mobilization of investments to reach the goals. The revision supports the promotion of electromobility and appropriate proposed measures in that regard through infrastructure deployment in buildings' car parks (Economidou et al., 2020).

Directive 844/2018 also introduces the Smart Readiness Indicator"-SRI of the buildings. It measures the ability of buildings to adapt energy consumption according to the real needs of the inhabitants, through intelligent and interconnected devices. Buildings can be controlled by automation systems that permit the regulation of indoor environmental parameters and guarantee comfort conditions and energy efficiency.

Last, but not least, 844/2018 states that «Member States shall encourage, about buildings undergoing a major renovation, high-efficiency alternative systems, in so far as this is technically, functionally and economically feasible, and shall address the issues of healthy indoor climate conditions, fire safety and risks related to intense seismic activity». In this way the Art. 7 introduces as a crucial point of the energy performance the satisfaction of the objectives of the Indoor Environmental Quality (IEQ) ensuring the safety of the occupants and dealing with safety in the event of fires and problems associated with seismic activity.

Therefore, energy efficiency must be achieved considering the IEQ Indoor Environmental Quality, which includes air quality, thermal, acoustic and visual comfort, as discussed in the next paragraph.

## I.3 Energy performance of the building and indoor environmental quality

While over the last ten years, research has devoted a lot of resources to IEQ, studying the four aspects separately, for some years, the relationship between energy efficiency and IEQ is one of the main themes of research in the field of Environmental Technical Physics.

Regarding IEQ, the EN 16798-1 standard (CEN, 2019a) prescribes the values of the parameters to be used for the design and evaluation of the energy performance of buildings considering precisely the aspects relating to IEQ. EN 16798-1 Standard replaces EN 15251 Standard (CEN, 2007): the central standard of the CEN Mandate M/480 [14], referring to EPBD recast 2010/31/EU [11]. This standard presents classification and certification of the internal environment, highlighting that, as required by Directive (EU) 844/2018, the information on the indoor environment must be contained in the energy certificate to estimate the total performance of the building not only in terms of energy but also of comfort. For this reason, it is necessary to draw up a general classification, indicative of the overall quality of the internal environment. Due to the lack of knowledge of the combined influence of the IEQ parameters, the standard recommends making a general classification of the indoor environment based only on thermal comfort and air quality through annual simulations or measurements. The goal of simulations is to evaluate the percentage of time in which the parameters of the two aspects are included in the four categories of expectation (CEN, 2019b).

Even the sustainability certifications, such as LEED [15] and ITACA [16] include IEQ among the evaluation criteria, confirming that this aspect is of fundamental importance to achieving goals for sustainable building.

Finally, energy efficiency in buildings and the achievement of acceptable IEQ conditions represent two focal elements of the European strategies for the fight against climate change and the sustainable design of the building.

# Chapter II
# Dynamic simulation

## II.1 Introduction

An energy design operating through sustainable strategic choices needs calculation tools that predict and control the behaviour of the building as the boundary conditions vary, such as the climate, the availability of energy sources, the occupant comportment, and the management of plant systems. In this way, it is possible to achieve better performance objectives.

The building sector still has a high impact on the environment. So, the necessity to reduce energy consumption, integrate clean energy supplies and mitigate environmental impacts, are required all while meeting expectations for human well-being and economic growth.

«Simulation of building thermal performance using digital computers has been an active area of investigation since the 1960s, with much of the early work focusing on load calculations and energy analysis. Over time, the simulation domain has grown richer and more integrated, with available tools integrating simulation of heat and mass transfer in the building fabric, airflow in and through the building, daylighting, and a vast array of system types and components. At the same time, graphical user interfaces that facilitate the use of these complex tools have become more and more powerful and more and more widely used» (Spitler, 2006). With this description, Spitler has defined the evolution of Building Performance Simulation.

The approach of BPS can be used to verify the achievement of adequate levels of comfort and indoor air quality, to devise energy efficiency and demand management solutions, to embed new and renewable energy technologies, to lessen environmental impact, to ensure conformance with legislative requirements, and to formulate energy action plans at any scale.

The planning of design is an instrument to delineate best practices where the performance of the building, the environmental impact and the health of users are managed in an interconnected process. It is a rational process which enables the gradual evolution of the problem description and with a consequent progressive design stage (Clarke and Hensen, 2015).

The development of various performance assessment tools is where most effort has been made to follow a design process aimed at the energy efficiency of buildings.

Moving from simple steady-state normative calculation engines to highly complex dynamic software, Building Performance Simulation Tools (BPST) can provide an accurate estimation of the performance of a building. The simulation tools are used by users who want to have a prevision of the behaviour of buildings and their environment during the short and long time under specific conditions of the external climate and of the operation of building systems. It is increasingly necessary to have an accurate knowledge of the management of these sophisticated tools to get a more realistic vision.

The increasing use of simulation tools in recent years is supported not only by interest in the evaluation of building energy performance but also by the advantages deriving from an initial investment in the design phase rather than higher costs during the execution phase. Performing an evaluation of the optimization iterations of the building at the start of design rather than at the end, helps save on design and development costs of the project (Ghiassi, 2013).

Fig. II.1 displays a synthetic scheme of a building performance assessment process which consists of a flow of data required by a building performance simulation software. The data are organized as input files or information to select. The enormous amount of data to manually enter some simulation tools without a user-friendly interface could in many cases result in irretraceable errors with a consequent unrealistic estimation of performance.

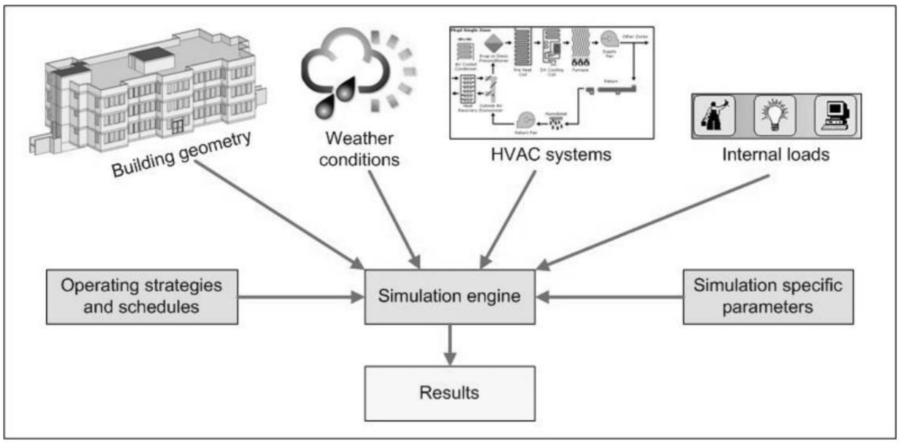


**Figure II.1** *Scheme of a building performance assessment process (Maile et al., 2007)*

An important investment factor of computational modelling is the time needed for learning and using the software. In fact, the effort to understand, master and use a computational building evaluation tool, is not to be underestimated.

A study demonstrates that the portion of this time spent on creating the building model is higher than other operations, such as running the simulations and documenting the results (Mahdavi and El-Bellahy, 2005).

According to prof. Jan Hensen, past president of IBPSA (International Building Performance Simulation), the information based on simulations has the enormous potential to increase competitiveness, productivity, quality and efficiency of the construction sector, and at the same time to facilitate future innovation and the technological process (Hensen and Lamberts, 2011). Prof. J.A. Clarke, another past president of IBPSA, supports that the simulation allows users to understand the interrelationships between design and performance parameters, to identify potential problem areas, and thus to implement and test appropriate design solutions. In this way, it is possible to have a more energetically conscious design and obtain higher levels of comfort and air quality (Clarke, 2001).

In the United States, the U.S. Department of Energy makes the following classification of the building simulations applications, distinguishing between:

- Generic analysis of the building which concerns the determination of the thermal loads for the design of air conditioning systems and energy simulation aimed at project optimization, retrofit analyses, evaluation of renewable energy and sustainability.
- Analysis of materials and systems with the evaluations of opaque and transparent envelope components and of air conditioning, lighting, and ventilation systems.
- Other applications include analysis of the outdoor environment (climate, air pollution, solar radiation) and indoor environment quality (Filippi and Fabrizio, 2012).

### *II.1.1 Modelling approach*

The buildings performance simulation permits modelling according to a specific mathematic model which is composed of three elements: input variable, proprieties of the system to describe and output variable. With mathematic modelling the aim is to determine one of three components, knowing the other two. Two approaches are prosecutable:

- Forward modelling where is assumed a deep knowledge of input data, characteristics of the materials and operation of the system.
- Inverse modelling where modelling consists of the measurement of the input and output quantities of the system to derive a calibrated model and to forecast future developments.

The main dynamic simulation codes work on the forward approach (Hensen and Lamberts, 2011).

### II.1.2 Stationary, semi-stationary and dynamic simulation

The calculation of building performance consists in making balance on the building by studying the flows of energy into and out of its boundaries.

Energy calculation methods differ in three types, based on the time unit used to investigate the phenomenon.

- The stationary model considers the heating or cooling season.
- The semi-stationary model considers the month.
- The dynamic model considers the hourly or sub-hourly unit.

In Italy the semi-stationary method was particularly used to verify conformity with the limits imposed by Standards series UNI TS 11300 which suggests a methodology for the determination of energy building performance.

The limit of this type of calculation is that parameters such as the outdoor temperature are considered as the monthly average, resulting in a simplification in the calculation and in the consequent determination of the performances moving away to the real building behaviour.

As a result of a simulation in a semi-stationary regime, a purely theoretical performance value to be compared with the standard limit and useful for energy classification is obtained. Unfortunately, it is not representative of the real consumption of the building.

Born in the 1980s within the academic sector, dynamic simulation is an emerging discipline in the field of energy design aimed at reproducing a more realistic building behaviour. A more detailed calculation, where a lot of input data returns a lot of output results, giving back a high amount of information.

Switching from semi-stationary to dynamic computation was not easy. Professionals, researchers, and all users who work in energy design approached the new calculation engines: codes developed mainly by international research institutes, with great computing power but often not very user-friendly (Pifferi and Subazzoli, 2013).

### II.1.3 Regulations

The complexity of the simulation tools has long been a brake on the spread of their use. The growing attention to building design with dynamic simulation tools is driven by the spread of voluntary environmental certifications such as that LEED (Leadership in Energy and Environmental Design) and by European Directives on the energy performance of buildings.

The use of dynamic tools permits to carry out of appropriate evaluations in cost-optimal methodology introduced by EPBD recast 2010/31/EU with the determination and comparison of the *reference building*.

As defined in the Directive, a reference building is representative of the design building, reproducing the same geometry, functionality, and geographic location, including indoor and outdoor climate conditions of the design building. The concept of "reference building" is also required by the LEED protocol based on ASHRAE 90.1 (Kim et al., 2013). The LEED protocol defines a score for improvements in the energy performance index of the design building with respect to the energy consumption of correspondence reference building (Pifferi and Subazzoli, 2013).

The LEED certification system considers energy simulation as a tool to evaluate the performance of a building attributing a maximum of 19–21 points based on the type of building (Ryu and Park, 2016).

Considering the energy efficiency targets required by the nZEB, dynamic energy simulation software is a key device for design in terms of evaluation of energy performance and of the forecast of perceived thermal comfort.

In Italy, the dynamic simulation was introduced with Presidential Decree 59/2009 which, in the context of the definition of methodologies for energy performance calculation, in art. 4 par. 27 let. o) prescribes that "in the calculation of building energy performance need to be considered for new buildings in the tertiary sector with volumes greater than 10.000 $m^3$, the influence of dynamic phenomena, through the use of appropriate simulation models, unless it is possible to demonstrate the scarce relevance of such phenomena in the specific case " (President of Italian Republic, 2009).

### II.1.4 Opportunity and disadvantages of dynamic simulation

Dynamic simulation offers the possibility to perform various analyses with a bigger detailed degree. The main uses are listed below:

- Determine the heating and cooling loads of the building for the design and dimensioning of building systems.
- Determine the energy consumption for heating and cooling in compliance with the performance values set by law and performance values, such as assigning a score in the sustainability protocols.
- Check the performance of thermal comfort and air quality inside the rooms, in connection with the required energy consumption.
- Evaluate electricity consumption for lighting and the exploitation of free solar contributions.
- Estimate the emissions of pollutants in the atmosphere produced during operation by the energy systems present in the building.
- Compare different design hypotheses relating to the envelope (insulation, windows, shading and orientation).

- Compare several plant systems and their interactions with Renewable Energy Sources.
- Identify malfunctions of plant systems by comparing simulated and real consumptions.
- Develop energy-efficient control strategies.
- Develop strategies for control of IEQ.

To meet the needs of the designer, specific commercial calculation software is available for each area of analysis, or it is possible to use a single calculation tool for all types of analysis.

The results that derive from a dynamic simulation are many and the designer should have adequate skills to manage the amount of data and interpret them.

With dynamic simulation, the design approach does not consist only of the evaluation of alternative solutions but a true process of optimization of the whole design is undertaken.

The major hurdle in the use of these tools is the availability of variable input data at an hourly step, whether they are outdoor climatic parameters (temperature, relative humidity, solar radiation, etc.) or user occupancy profiles. The problem of the input data is not only related to the high number of data required but to the reliability of the data retrieved. In fact, uncertain input data can generate unreliable results and the objective to reach is that the level of uncertainty could be reduced to such an extent, that it does not affect the design choices.

Furthermore, the simulations are based on several basic assumptions that affect the results and, the calculated parameters could significantly differ from real performance (Fabi et al., 2011). For this reason, it is necessary to apply uncertainty intervals to the input data and calibrate the model based on real measurements.

Another aspect to consider is the deviation between calculated and measured performance. For existing buildings, this happens when it is not possible to define the effective behaviour of the occupants (time of occupation, management of window openings, clothing) and the surrounding conditions that are not known or measured, such as the ground temperature. In these cases, the dynamic thermo-energy simulation requires a careful and laborious preliminary calibration process.

Moreover, if the dynamic simulation is used to compare multiple design options, decisions can often be inadequate due to a poor understanding of which input data affects the result the most.

## II.2 Simulation tools

The capacity to estimate building behaviour is a fundamental instrument to support designers and make the best decision-making measures for both new and existing buildings also in terms of costs.

Many building performance simulation tools are widely used in energy refurbishment and energy efficiency of buildings. Each software presents different characteristics which comport advantages and disadvantages for the user affecting the accuracy of the simulation (Vadiee et al., 2018).

Some studies compare the software together with other simulation tools by analysing the differences related to the main features of the software (Crawley et al., 2008); their capabilities of calculating a significant number of variables (Sousa, 2012); the procedure for calculating heating demand and operative temperatures (Vadiee et al., 2018); the way of heat exchanges between the envelope and the indoor and outdoor environment (Mazzeo et al., 2020).

Although several studies have been done on the comparison between the simulation tools, there is no deepen study describing the modelling procedure, inputs, outputs and validity of the tools compare to each other (Johari et al., 2019). Some tools are more flexible but with a low execution speed and tools mainly solve standard problems but with a high execution speed (Mazzeo et al., 2020). In addition to classifying a calculation tool based on the mathematical model used in the heat exchanges, it is possible to distinguish two types of simulation software based on source code access and modification mode, and simulation control capability.

The choice of using one tool over another depends on its application, the number of times it will be used, the experience of the user, type of hardware available to run the simulation and to describe and reproduce a particular phenomenon (Harish and Kumar, 2016).

Three simulation tools used in the field of dynamic simulation and in the present PhD thesis work are described below: IDA ICE, Energy Plus and Design Builder.

### *II.2.1 Calculation algorithms*

The algorithms of calculation of dynamic simulation tools are based on two different models: “transfer functions” and “finite differences” or “finite volume method”.

The *transfer function method* (TFM) was developed in 1960 by ASHRAE based on the theories of Stephenson and Mitalas and it is the most widely used (Hui and Cheung, 1998). The method links the stresses (e.g. temperatures and heat flows) induced on the system with the response of the system itself. Based on the type of evaluation, there are different transfer functions used:

- "Wall transfer functions" (CTF, Conduction Transfer Function) to calculate the heat flow transmitted by conduction inside the envelope walls.
- "Room transfer function" (RTF) to evaluate the convective heat flow supplied to the ambient air.

- "Space air transfer functions" (SATF) to evaluate the heat flow provided by the air conditioning system.

Afterwards, the transfer function method (TFM) was replaced by only the CTF (Conduction Transfer Function) function and the "air heat balance" (AHB) was introduced to determine the thermal flow in the environment.

The *finite volume method* considers the domain divided into portions and assigns to each of them a series of balance equations to execute, for example conservation of mass, and conservation of energy laws. Another possibility is to improve the solution by increasing the degree of detail of the domain for example dividing in multiple controls volume, as in the case of a thermal stratification study where the user can calculate temperatures and energy flow within the wall (Filippi and Fabrizio, 2012).

### ***II.2.2 Modelling process***

Typically, modelling in a dynamic simulation tool consists of 4 main phases:

- Determination of the geographical location makes use of standard weather data sets.
- Geometric construction of the building can be done by drawing the building from the beginning or by importing a geometric model in a format compatible with the chosen simulation software. Then the identification of the materials and the stratigraphy of each component follows.
- Definition of the variables to consider in the simulation and the run of the simulation. In this phase the type of building (office, residential, commercial, etc.), the type of activity carried out by users and their occupancy profiles, the characteristics of equipment, the HVAC system, and the relative schedule operation are identified.
- Analysis of the results. In this phase, the software checks if there are errors in the variables set and the results are displayed in the chosen time step.

Based on the software used, the performance of the heat transfer by conduction, convection and radiation is evaluated and the main aspects are studied (Sousa, 2012):

- Physical Phenomena (hygrothermal behaviour, artificial/natural lighting, acoustics, ventilation and air distribution).
- Energy Systems (modelling energy, heating and cooling, thermal mass, cogeneration and renewable energy).
- HVAC Systems (thermal loads and its forecast for optimizing control of components, modelling and control systems, energy consumptions).
- Human Factors (aspects of IEQ - Indoor Environmental Quality).
- Urban Simulation (sunlight and shadow effects).

### *II.2.3 Weather file*

In dynamic simulation software, weather files are a crucial reference in performance analysis to give information on the environmental conditions where the building is located. The weather file contains the typical and extreme conditions with a temporal resolution required by simulation packages (typically an hourly or higher resolution) and it expresses the effect of the urban micro-climate. The weather file influences the results of building energy simulations. For a typical residential building, the cooling and heating demand can differ by 50% or even 65% from the simulations based on the outdated weather file (Costanzo et al., 2020).

A typical weather year reflects the average trend of local long-term data and it is a typical year built based on the 12 months most representative of the peculiar conditions of each location (temperature, relative humidity, global irradiance on the horizontal plane and wind speed).

In the field of energy simulation of building three main procedures have been established to extract a typical weather year from a multi-year weather dataset:

- Typical Meteorological Year (TMY) was modified into the more recent formats called TMY2 and TMY.
- ASHRAE procedure, leading to the IWEC format (International Weather for Energy Calculations) and subsequently IWEC2.
- The procedure was introduced by the ISO 15927-4 Standard in 2005.

The twelve selected typical months, which do not necessarily belong to the same year, are then concatenated to create a typical year.

The weather files are developed by different survey stations, based on historic data observed for 20-30 years, depending on the data availability.

Each of the months of the typical year is entirely derived from one of the observed years. The choice of one month over another is made based on its representativeness (Mazzarella, 1997).

According to the different sources, the software includes several kinds of weather files. Tab. II.1 shows the most common weather files. Regarding format, the *.epw* format represents the more conventional file format employed by simulation tools (Herrera et al., 2017).

### *II.2.4 IDA ICE*

The software IDA Indoor Climate Energy - IDA ICE is based on mathematical models developed by the Royal Institute of Technology in Stockholm and the University of Technology of Helsinki within the framework of IEA SH&C Task 22 “Building Energy Analysis Tools”. In 1998 the first version of IDA ICE was released, and its last version 4.8 is commercially available and marketed by EQUA Simulation AB, a privately held Swedish company, founded in 1995.

IDA ICE permits the study of indoor climate and energy consumption in buildings. It is commonly used in European countries for research and consulting purposes.

The program is based on a general system simulation platform with a modular system and the base equation for modelling is Modelica or Neutral Model Format (NMF).

NMF is a program language for modelling dynamical systems by using differential-algebraic equations (Sahlin and Sowell, 1989).

IDA ICE is validated with ASHRAE 140-2004 Standard, and EN 15255:2007, EN 15265:2007 and EN ISO 13791 Standards [17].

The tool provides different levels of interfaces to be easily used by beginners and experts:

- Wizard level. The simplest mode is where the user fills a module and starts the simulation.
- Standard (or Phisical) level. The user uses the existing models taken from the library without any direct control over the mathematical model.
- Advanced level and NMF and/or Modelica programming for developers. In this interface, there is no physical model but using the language NMF, it is possible to write and edit the model.

**Table II.1** *Weather file type in various countries (Herrera et al., 2017)*

| Acronym | Complete name | Region | Sites | Period |
|---|---|---|---|---|
| RMY | Representative Meteorological Year | Australia | 69 | 1967-04 |
| CSWD | Chinese Standard Weather Data | China | 270 | 1982-97 |
| ISHRAE | Indian Typical Years from ISHRAE | India | 62 | 1991-05 |
| IGDG | Italian ‘Gianni De Giorgio’ | Italy | 68 | 1951-70 |
| SWEC | Spanish Weather | Spain | 52 | 1961-90 |
| UK TRY | Test Reference Year (CIBSE) | UK | 14 | 1984-13 |
| TMY | Typical Meteorological Year | USA and others | 1020 | 1991-05 |
| WYEC | Weather Year for Energy Calculation | USA/Canada | 77 | 1953-01 |
| IWEC | International Weather Energy Calculation | Worldwide | 3012 | 1991-05 |

The main aspects that IDA ICE consent to calculate are the following as described by Björsell et al. (1999):

- The zone heat balance, including contributions of sun, occupants, equipment, lighting, ventilation, heating and cooling devices.
- Solar flow through windows.
- Air and surface temperatures.
- Directed operative temperature for estimation of asymmetric comfort conditions.
- Comfort indices, PPD and PMV, at multiple arbitrary occupant locations.
- Daylight level.
- $CO_2$ concentration and moisture levels are both used also for control of vav system air flow.
- Air temperature stratification in displacement ventilation systems.
- Wind-driven airflows through leaks and openings with an integrated airflow network model.
- Power levels for primary and secondary system components.
- Total energy cost based on time-dependent prices.

In this program, the building is defined by one or more zones, which are identified by mean envelope components (roof, wall, floor). Connected to zones the systems of heating, cooling, ventilation, and lighting are active for working.

Detailed and simplified are two different zone models included in the library of software to study indoor climate. The first one is intended for design simulations while the second one is used for energy simulations.

Regarding outdoor environment conditions, there are two types of weather data used by software:

- "Design days": climate files based on the daily extreme wet and dry bulb temperatures, the wind direction and speed, and the reduction factor for the direct and diffuse sunlight.
- "Weather files": climate files with hourly measured data stored in a text format (*.prn*).

The weather files contain information about the air (dry bulb) temperature, relative humidity (RH), wind direction and speed, direct normal radiation, and diffuse (sky) radiation on a horizontal surface.

The outdoor pressure is not an available parameter in the weather file but the wind pressure on the external surfaces of the building is calculated considering different pressure coefficients in relation to the speed of the wind (Kalamees, 2004).

### *II.2.5 Energy Plus*

Energy Plus is one of the most used energy simulation software tools. It is an open-source building simulation software that concentrates on the analysis of thermal demand calculations in buildings. Energy Plus is a simulation engine with input and output text files and it uses Fortan90 as a programming language. So, graphical support can be used in modelling to have a user-friendly graphical interface.

The program was developed by the U.S. Department of Energy, and it presents a modular and structured code, based on the most popular features and capabilities of two software, DOE-2 and BLAST performed respectively by Department of Energy (DOE) and Department of Defence (DOD). Conceptually Energy Plus was founded in 1996 after a work finalized to merge the two programs.

Version 1.0 of Energy Plus was born in 2001 as an innovative program starting from two software (Crawley et al., 2001).

The actual version of the software consent to calculate the energy needs for the heating, cooling and ventilation services of buildings, as well as to evaluate the quality of the indoor environment.

The structure of the software (Fig. II.2) is composed of a *Simulation Manager* that controls the entire simulation process, the *Heat Balance Simulation* module to calculate thermal and masses loads and the *Building Systems Simulation* module that deals with the connection between the heat balance engine and HVAC water.

A specific module named WINDOW is available for total indices of window thermal performance (i.e. U-values, solar heat gain coefficients, shading coefficients, and visible transmittances) [18].

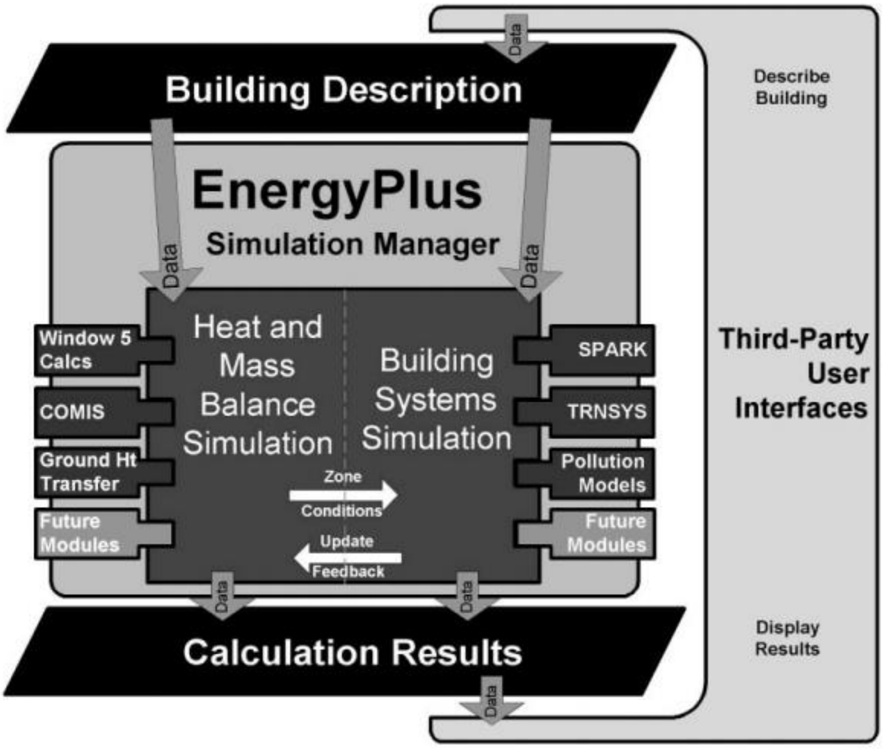


**Figure II.2** *Structure of Energy Plus (Crawley et al., 2000)*

Energy Plus is based on three modules to make the balance on the building envelope and the system plants:

- Surface Heat Balance Manager which simulates inside and outside surface heat balance, interconnections between heat balances and boundary conditions, conduction, convection, radiation, and mass transfer (water vapour) effects.
- Air Heat Balance Manager that deals with various mass streams such as ventilation and exhaust air, and infiltration.
- Building Systems Simulation Manager controls the simulation of HVAC and electric systems, equipment, and components to have a fully integrated simulation of loads and systems plant.

Other modules are connected to these three main modules with specific functions, as shown in Fig. II.3.

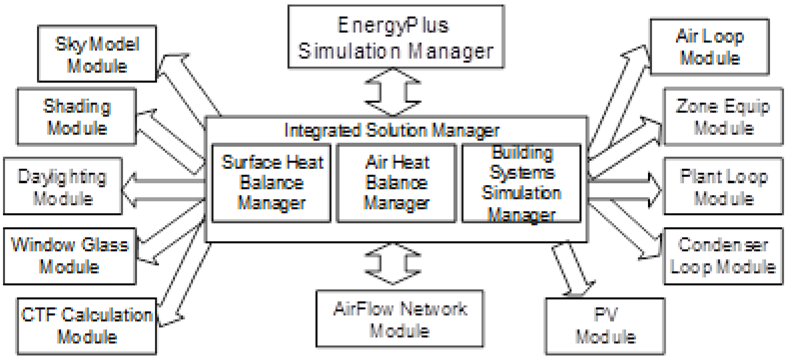


**Figure II.3** *Simulation modules of Energy Plus (Crawley et al., 2000)*

To create the model, the building is divided into thermal zones, each of which is defined by the surfaces that delimit them and each surface is characterized by its stratigraphy with specific material, as shown in Fig. II.4.

About Heat Balance Simulation, the scheme in Fig. II.5 summarizes the four processes simulated by the model:

- Outside face heat balance.
- Wall conduction process.
- Inside face heat balance.
- Air heat balance.

The hypothesis underlying the Air heat balance, is based on the following approximations:

- The air temperature is uniform, so the air in the space is mixed.
- The surface temperatures are uniform.
- The radiation is uniform.
- The conduction heat transfer is one-dimensional (Fabrizio, 2009).

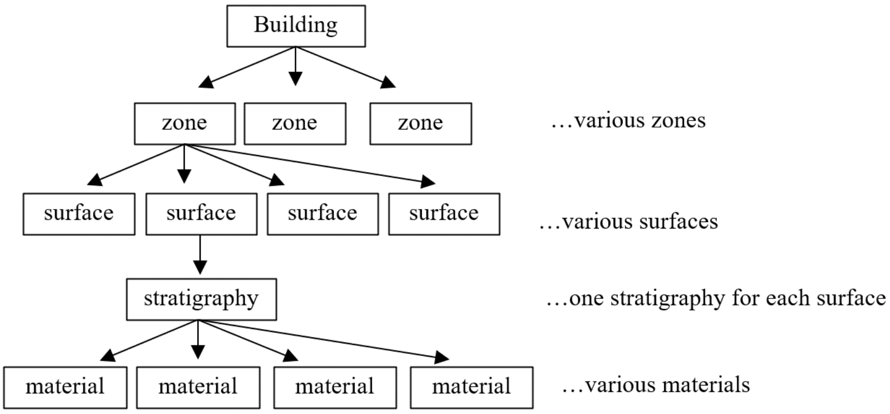


**Figure II.4** *Creation of model (modified from Filippi and Fabrizio, 2012)*

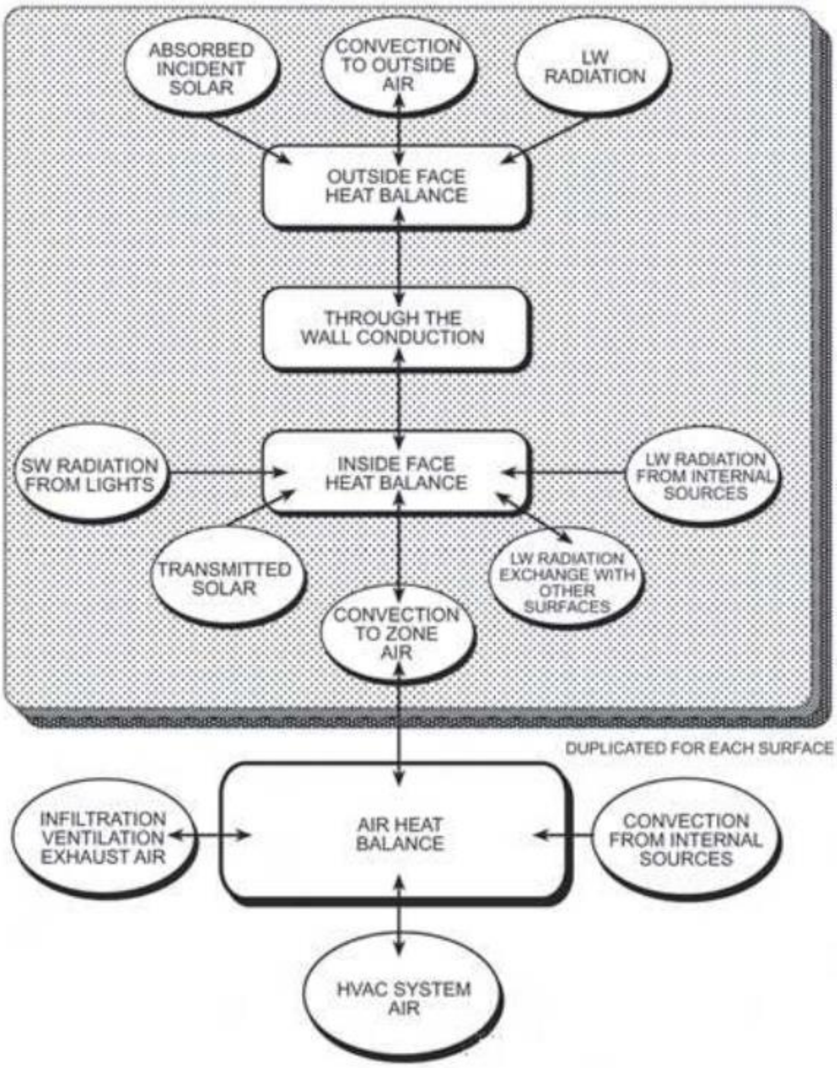


**Figure II.5** *Scheme of environment thermal model (Spitler, 2009)*

For weather files of Energy Plus, the *.epw* format is used. It is a text file that includes information such as location name, data source, latitude, longitude, time zone, elevation, peak heating and cooling design conditions, holidays, daylight savings period, and typical and extreme periods (Crawley et al., 2000).

### *II.2.6 Design Builder*

Design Builder is a simulation tool with Energy Plus integrated as a calculation engine. Design Builder is the first GUI (Graphical User Interface) of Energy Plus, able to perform easy building modelling [19].

Developed to simplify the process of building simulation of calculation engine Energy Plus, the software is useful to check building energy, $CO_2$ emissions, lighting and comfort performance. Design Builder is a standard in energy simulation and the user can compare the performances of buildings delivering results on time and budget. The process is also facilitated by the presence of templates available for model creation (Pawar and Kanade, 2018).

Design Builder manages a part of the available Energy Plus modules. Therefore, for complex configurations o deeply analysis, the graphic interface if on the one hand allows the designer to simplify the modelling, on the other hand, it does not fully exploit the potential of the integrated calculation engine.

The structure of the software is hierarchical type, as shown in Fig. II.6, permitting it to work on different degrees of detail. Higher level data is automatically assigned to lower levels as well so that the designer can define "Building" level settings that become active for the entire building or make changes to the "Zone" level.

The Design Builder screen, in Fig. II.7, consists of:

- Toolbar: to access a series of commands such as model settings, view, and program settings for calculations.
- Navigation panel: to access the various hierarchical levels.
- Modelling area: active at the Building level and where 8 tabs (Edit, View, Heating project, Cooling project, Simulation, CFD, Natural lighting, Costs and $CO_2$) permit to characterize the model.

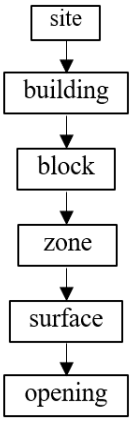


**Figure II.6** *Hierarchical structure in Design Builder*

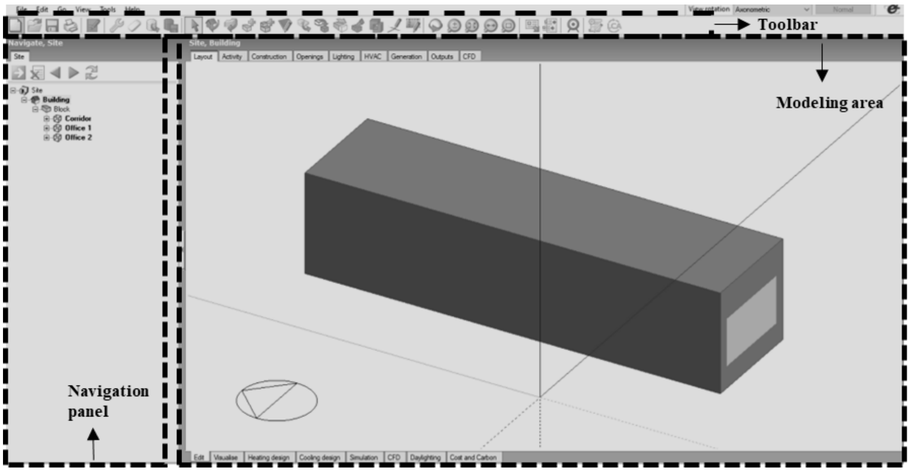


**Figure II.7** *Design Builder screen*

Regarding weather files, the software integrates the data of Energy Plus. For Italy, Design Builder uses the hourly climate files prepared by the CTI (Italian Thermotechnical Committee). The data are free available (official Energy Plus data, "G.DE GIORGIO") and they are obtained from a period of measurements ranging from 1951 to 1970. Thanks to the work recently carried out by the CTI (Italian Thermotechnical Committee), today there is the possibility to take advantage of recent official data released in 2015.

The work carried out concerns the conversion of the data of the typical years into files that can be used by the Design Builder and Energy Plus software. At the end of this procedure, the four necessary climate files are then obtained, with the extensions: *epw*, *.audit*, *.stat* and *.ddy*. The four elements are text files and all necessary for the use of the CTI hourly climate files in simulations. Most of the information, however, are in the *.epw* file, the other three contain statistical information useful for example to identify the summer and winter weeks of the project [20].

# Chapter III
# Standards on thermal comfort

## III.1 Introduction

The IEQ conditions are crucial, not only for people's well-being but for the achievement of productivity levels as well. Moreover, some studies demonstrate a key role of non-physical parameters in the whole-comfort perception of occupants representing an energy-saving opportunity (Castaldo et al., 2018). In fact, comfort perception depends not only on several parameters related to physical boundary conditions but also on the adaptation capability of occupants and other personal variables to measure, which are linked to socio-psychological and physiological factors. Combining measurable and physical aspects of the indoor environment quality with those concerning non-physical parameters permits a holistic approach to indoor built design. This permit to make more sustainable intervention strategies considering multidisciplinary skills synergically involved in improving the liveability of indoor environments (Attaianese et al., 2021).

Thermal comfort is one of the most relevant aspects of IEQ, together with indoor air quality.

ASHRAE defines thermal comfort as “the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE, 2020).

To assess thermal comfort also objective investigations looking at the human body as a thermodynamic system exchanging heat with the surrounding physical environment are needed. From the thermodynamic point of view, thermal comfort depends on six parameters: air temperature, $t_\mathrm{a}$, air velocity, $v_\mathrm{a}$, relative humidity, $RH$, mean radiant temperature, $t_\mathrm{r}$ and metabolic rate, $M$ and clothing thermal insulation, $I_{cl}$.

For the assessment of global thermal comfort indices PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) are used (CEN, 2005). The values of PMV and PPD can be calculated at the design level to simulate the behaviour of the indoor environment or in existing indoor environments to test the actual level of thermal comfort. The calculation of PMV and PPD can be made using *ad hoc* software based on EN ISO 7730 Standard (CEN, 2005).

Thermal comfort is also strongly connected to energy saving in buildings because achieving comfort conditions depends on thermo-physical characteristics of the building envelope and the HVAC system. Energy saving and safeguarding the conditions of indoor environment comfort play an important role in improving the performance of a building as expressed also by the Energy Performance Building Directives.

In line with goals of European Directive 2002/91/CE regarding design of indoor environmental quality, in 2007 the EN 15251 Standard (CEN, 2007) was issued which prescribed how to establish and define the main input parameters for building energy calculation and identify parameters for monitoring and displaying of the indoor environment. The EN 15251 Standard was superseded by EN 16798-1 Standard.

In this field, the normative is continuously evolving, as technical and scientific knowledge is rapidly developing. Over the years many documents have followed to regulate thermal comfort in confined spaces. Fig. III.1 presents a graphical timeline of the thermal comfort models in the regulatory document and Fig. III.2 summarizes general Standards for moderate thermal environments.

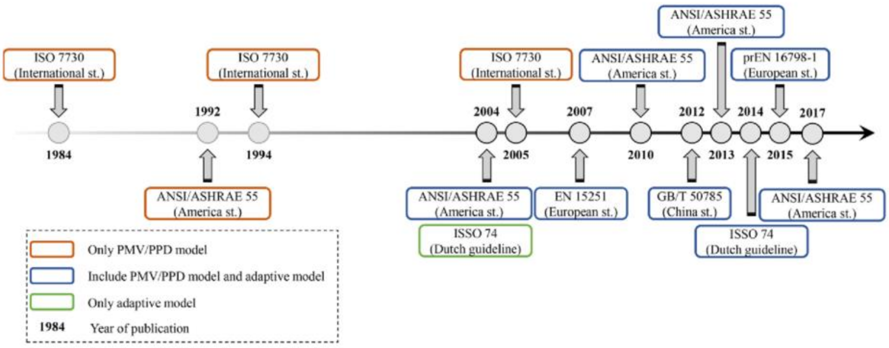


**Figure III.1** *Chronology of thermal comfort models in regulatory (Carlucci et al., 2018)*

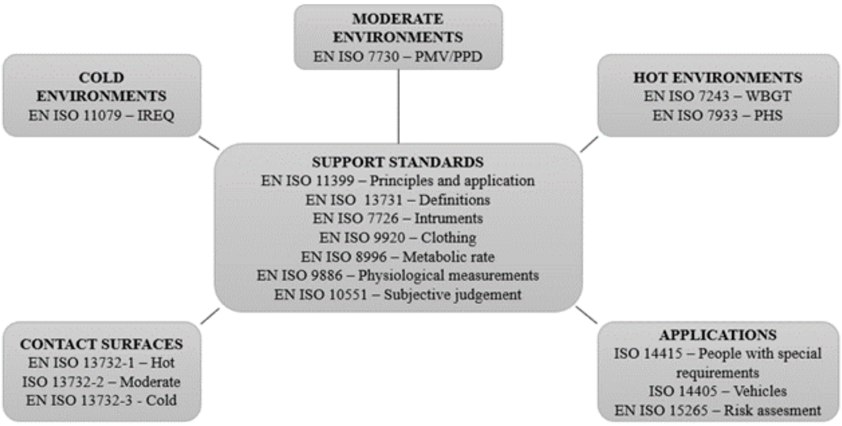


**Figure III.2** *Main ISO and CEN Standards for thermal comfort (modified from d'Ambrosio et al., 2014)*

## III. 2 Theoretical aspects

### *III.2.1 Energy balance on the human body*

The human thermal sensation is mainly related to the thermal balance of the human body which can be described with a model that exchanges energy with the surrounding environment. The Eq. (III.1) expresses the energy balance of the human body in moderate environments.

$$S=M - W - E - E_{res} - C_{ve} - C - R - K \qquad \text{(III.1)}$$

where:
$S$ = body heat storage rate, W/m$^2$;
$M$ = metabolic rate, W/m$^2$;
$W$ = effective mechanical power, W/m$^2$;
$E$ = evaporative heat flow at the skin, W/m$^2$;
$E_{res}$ = respiratory evaporative heat flow, W/m$^2$;
$C_{res}$ = respiratory convective heat flow, W/m$^2$;
$C$ = convective heat flow, W/m$^2$;
$R$ = radiative heat flow, W/m$^2$;
$K$ = conductive heat flow, W/m$^2$.

Generally, the terms of Eq. (III.1), refer to the surface area of the naked human body, $A_b$ which is calculated with the DuBois expression reported in the Eq. (III.2).

$$A_b = 0.202 \cdot W_b^{0.425} \cdot H_b^{0.725} \qquad \text{(III.2)}$$

where:
$W_b$ = body mass, kg;
$H_b$ = body height, m.

From Fig. III.3, for standard body measurements of 70 kg and 1.70 m, the body surface is 1.8 $m^2$.

By making explicit the terms of the energy balance, it appears that the Eq. (III.1) depends on six parameters, of which four are related to the environment:

- Air temperature, $t_a$ (°C).
- Air velocity, $v_a$ ($m \cdot s^{-1}$).
- Relative Humidity, *RH* (%).
- Mean radiant temperature, $t_r$ (°C)

and two linked to the person:

- Metabolic rate (depending on activity), *M* (met).
- Clothing thermal insulation, $I_{cl}$ (clo).

### *III.2.2 Thermal environment*

The thermal environment is the set of environmental parameters that determine the thermal sensation experienced by a person exposed to specific thermo-hygrometric conditions:

- Air temperature, $t_a$ (°C).
- Air velocity, $v_a$ ($m \cdot s^{-1}$).
- Relative Humidity, RH (%).
- Mean radiant temperature, $t_r$ (°C).

Thermal environments are divided into moderate environments, for which the goal is to achieve thermal comfort and severe environments (cold or hot) in which we are concerned with ensuring a state of safety to avoid risks that involve the individual.

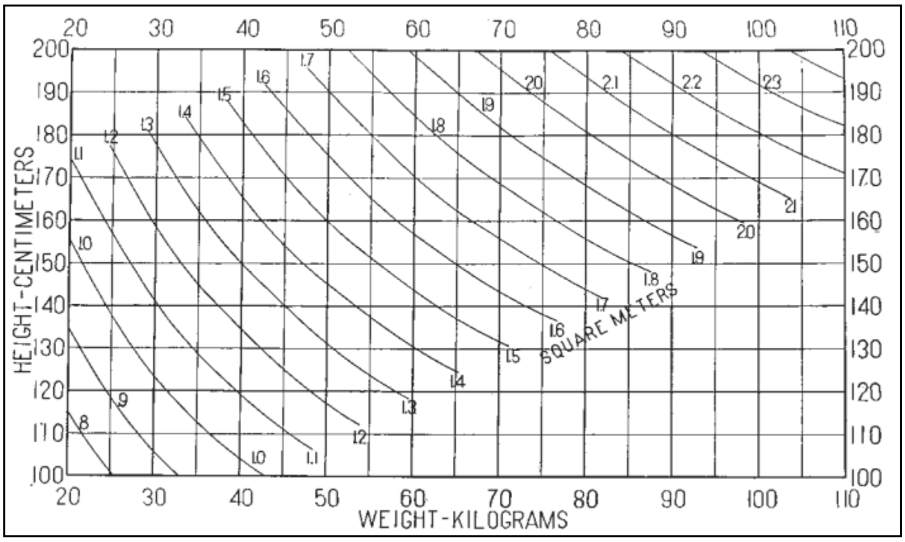


**Figure III.3** *Chart for determining human surface area from weight ($W_b$) and height ($H_b$) (Du Bois, 1916)*

## III. 3 EN ISO 7730 Standard

ISO 7730 Standard was first published in 1984, introducing the Fanger comfort model in standardization (CEN, 2005). This Standard contains the procedure to assess global and local comfort through *ad hoc* indices and introduces the classification of environments based on a range of these indices.

This Standard explicitly mentions other Standards for the measurement and assessment of parameters related to PMV and PPD (d’Ambrosio et al., 2011): ISO 7726 deals with instrumentation and measurement techniques of physical parameters relating to PMV and PPD; ISO 8996 provides methods for the measurement and evaluation of metabolism rate (M); ISO 9920 specifies methods for measurement and assessment of thermal clothing insulation ($I_{cl}$).

### *III.3.1 Overall thermal comfort*

The indices for overall thermal comfort are PMV and PPD.

The PMV (Predicted Mean Vote) represents the average vote of an individual exposed to a thermal environment. PMV has been formulated by Fanger based on experimental studies with people exposed to specific thermal conditions during tests in a controlled climatic room. The 1300 individuals exposed to the same conditions were asked to express a vote on the thermal environment referring to the 7-point scale shown in Tab. III.1.

Analytically, Fanger came to the definition of Eq. (III.3) that allows evaluating the PMV as a function of the six magnitudes of the thermal environment.

The Eq. (III.3) is derived from the comparison between objective and subjective data. The first term of the member on the right is the term of proportionality between the thermal load and the PMV, which takes into account the subjective responses. The thermal load is the difference between thermal energy generated in the human body that does not transform into mechanical energy and the thermal energy that the subject would disperse if he were in conditions of well-being with real value.

The PPD (Predicted Percentage of Dissatisfied) is representative of a state of dissatisfaction. Fanger defined the percentage of dissatisfied PPD correlated to PMV by means Eq. (III.4). The percentage of dissatisfaction is 5% for PMV equal to 0, it becomes 10% at the limits of the well-being interval (+0.50 and -0.50) and grows rapidly moving away from the comfort values as shown in Fig. III.4.

**Table III.1** *7-points ASHRAE thermal sensation scale*

| vote | sensation |
|---|---|
| +3 | hot |
| +2 | warm |
| +1 | slightly warm |
| 0 | neutral |
| - 1 | slightly cool |
| - 2 | cool |
| - 3 | cold |

$$PMV=\left[0.303\ exp(-0.036\ M)+0.028\right]\cdot \left\{\begin{array}{l} (M-W)-3.05\cdot 10^{-3}\cdot\left[5733-6.99(M-W)-p_a\right]-0.42\cdot\left[(M-W)-58.15\right] \\ -1.7\cdot 10^{-5}\cdot M\cdot\left(5867-p_a\right)-0.0014\cdot M\cdot\left(34-t_a\right) \\ -3.96\cdot 10^{-8}\cdot f_{\mathrm{cl}}\cdot\left[\left(t_{\mathrm{cl}}+273\right)^4-\left(t_{\mathrm{r}}+273\right)^4\right]-f_{\mathrm{cl}}\cdot h_{\mathrm{c}}\cdot\left(t_{\mathrm{cl}}-t_{\mathrm{a}}\right) \end{array}\right\} \tag{III.3}$$

$$PPD=100-95\ exp(-0.03353\cdot PMV^4-0.2179\cdot PMV^2) \tag{III.4}$$

where:

$M$ = metabolic rate, W/m$^2$;

$W$ = effective mechanical power, W/m$^2$;

$p_a$= water vapour partial pressure, Pa;

$t_a$ = air temperature, °C;

$f_{cl}$ = clothing surface area factor, 1;

$t_{cl}$ = clothing surface temperature, °C;

$t_r$ = mean radiant temperature, °C;

$h_c$ = convective heat transfer coefficient, W/m$^2$·K.

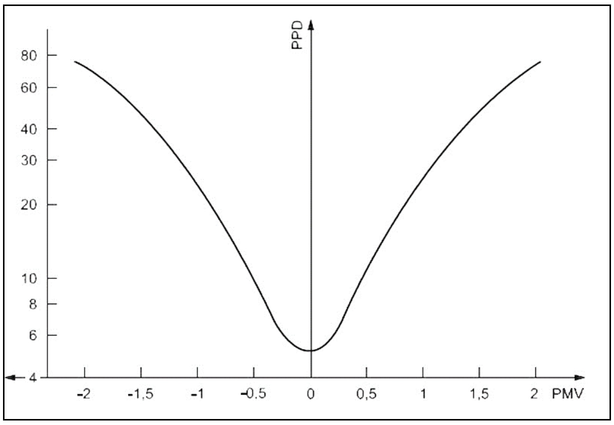


**Figure III.4** *Relationship between PMV and PPD (CEN, 2005)*

The dependence of the PMV on the air temperature and mean radiant temperature is traced back to a single variable, the operative temperature ($t_o$) defined by Eq. (III.5) (d'Ambrosio and Piterà, 2014).

$$t_o = \frac{h_r t_r + h_c t_a}{h_r + h_c} \tag{III.5}$$

where:
$t_a$ = air temperature, °C;
$t_r$ = mean radiant temperature, °C;
$h_c$ = convective heat transfer coefficient, W/m$^2$·K;
$h_r$ = radiative heat transfer coefficient, W/m$^2$·K.

The operative temperature corresponds to the actual temperature perceived by people and takes into account the radiative and convective heat transfer between the person and the environment. The Eq. (III.6) describes the simplified calculation of $t_o$ (d'Ambrosio and Piterà, 2014).

Tab. III.2 shows how changes the parameter "A" as a function of air velocity.

$$t_o = \mathrm{A}\ t_a + (1\text{-}\mathrm{A})\ t_r \tag{III.6}$$

**Table III.2** *Values of the parameter "A" as a function of the relative velocity expressed in m/s*

| $v_{ar}$ | $v_{ar} < 0.2$ | $0.2 < v_{ar} < 0.6$ | $0.6 < v_{ar} < 1$ |
|---|---|---|---|
| A | 0.5 | 0.6 | 0.7 |

Eqs. (III.5) and (III.6) underline that the higher the air velocity, that is to say, the convective thermal conductance, the greater the weight of the air temperature and the lower the mean radiant temperature (d’Ambrosio and Vio, 2010).

Another simplified procedure in the Eq. (III.7) for evaluation of operative temperature consists of the average between $t_a$ and $t_r$ values:

$$t_o = \frac{t_a + t_r}{2} \qquad \text{(III.7)}$$

This method is applicable when $v_{ar} < 0.2$ m/s and the absolute value of the difference between the radiant temperature and the air temperature is less than 4 ◦C. Using the Eq. (III.5) or Eq. (III.7) in the calculation of $t_o$, the results can have significant differences, affecting the evaluation of PMV and resulting in a shift of the category (d'Ambrosio et al., 2014).

## *III.3.2 Local discomfort*

To have a thermal comfort condition a further requirement is that there must not be local thermal discomfort. Thermal dissatisfaction can also be caused by four types of local discomfort.

- Vertical air temperature differences.
- Warm and cool floors.
- Draughts.
- Radiant asymmetry.

It is mainly people in light sedentary activity who are sensitive to local discomfort because they have a thermal sensation for the whole body close to neutral. At higher levels of activity, people are less thermally sensitive and consequently, the risk of local discomfort is lower.

### *III.3.2.1 Vertical air temperature difference*

The vertical air temperature difference is due to the high-temperature difference between the head and ankles. Fig. III.5 shows the percentage dissatisfied depending on the vertical air temperature difference.

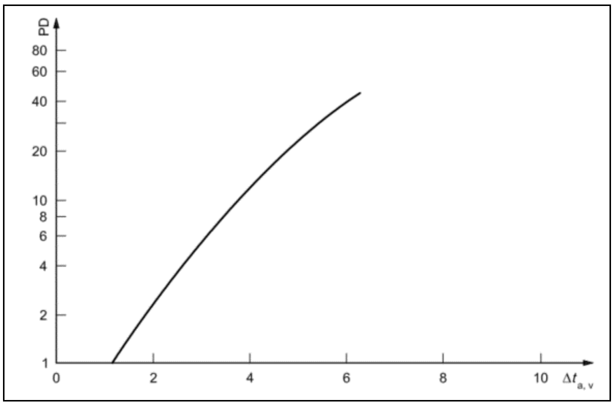


**Figure III.5** *Percentage of dissatisfied as a function of the vertical temperature difference (CEN, 2005)*

### *III.3.2.2 Warm or cool floors*

This kind of local discomfort depends on the too-warm or cool floor so that a person can feel an uncomfortable sensation at feet. Based on studies with people, Fig. III.6 shows the percentage dissatisfied as a function of the floor temperature.

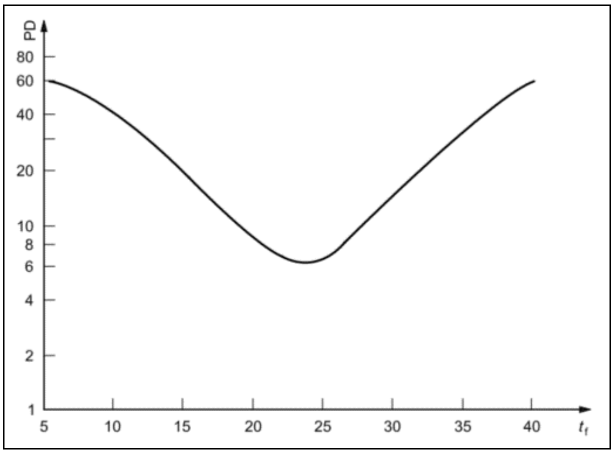


**Figure III.6** *Percentage of dissatisfied as a function of warm or cool floors (CEN, 2005)*

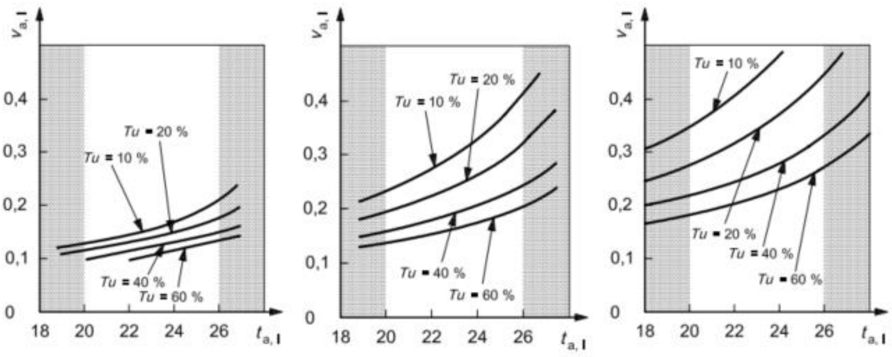
### *III.3.2.3 Draughts*

It is defined as an undesired effect of local cooling of the human body by air movement. The Draft risk is the percentage of dissatisfied obtained by Eq. (III.8) as a function of air conditions and of turbulence which represents the ratio of the "standard deviation" of air velocity fluctuations and means air velocity.

Fig. III.7 shows the maximum admissible values of the air velocity as a function of the air temperature and the turbulence intensity.

$$DR = \left(34 - t_a\right)\left(v_a - 0{,}05\right)^{0{,}62} \left(0.37 v_a T_u + 3.14\right) \qquad \text{(III.8)}$$

where:
*DR* = draft risk, %;
$t_a$ = ait temperature, °C;
$v_a$ = air velocity, m/s;
$T_u$ = turbulence, %.



**Category A: DR = 10 %** **Category B: DR = 20 %** **Category C: DR = 30 %**

**Figure III.7** *Admissible values of the air velocity as a function of the air temperature and the turbulence intensity (CEN, 2005)*

### *III.3.2.4 Radiant asymmetry*

The radiant asymmetry is defined as the difference between the plan radiant temperatures, $t_{pr}$, measured on the two opposite faces of a plane element. In the case of real non-isothermal environments, the radiant temperature depends on the position of the element face. Fig. III.8 shows the percentage dissatisfied as a function of the radiant temperature asymmetry caused by a warm ceiling, a cool wall, a cool ceiling or a warm wall.

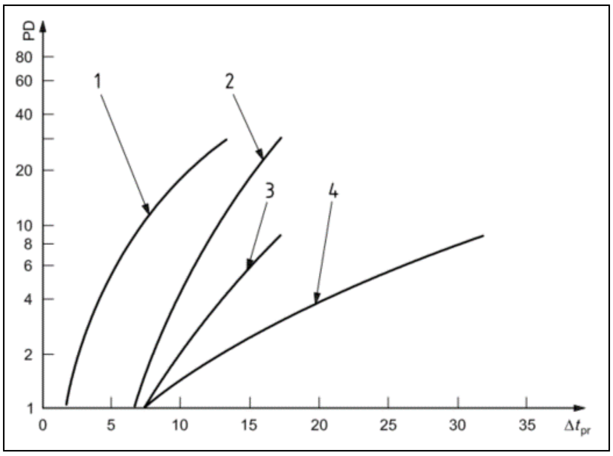


**Figure III.8** *Percentage of dissatisfied as a function of the radiant temperature asymmetry. 1) Warm ceiling. 2) Cool wall. 3) Cool ceiling. 4) Warm wall (CEN, 2005).*

## III.4 EN 16798-1 and -2 Standards

The EN 16798-1 Standard (CEN, 2019a) specifies indoor environmental input parameters for the design and assessment of energy performance of buildings addressing indoor IEQ aspects, whereas EN 16798-2 (CEN, 2019b) explains how to use EN 16798-1 by specifying additional information as:

- Input parameters for building system design and energy performance calculations.
- Methods for long-term evaluation of the indoor environment.
- Criteria for measurements can be used if required to measure compliance by inspection.
- Parameters to be used by monitoring and displaying the indoor environment in existing buildings (d'Ambrosio et al., 2020).

EN 16798-1 and -2 are part of a series of standards aiming at international harmonization of the methodology for the assessment of the energy performance of buildings, called “set of EPB standards”.

Considering that the energy consumption of buildings depends significantly on the criteria used for the design of the indoor environment and on the mode of systems operation, these standards specify different types and categories of criteria for the design and energy calculations of buildings and building service systems. The requirements of the thermal environment are described considering also design criteria for the local thermal discomfort factors. The European standard generally uses two types of buildings, such as residential and non-residential and also specifies occupancy schedules to use for energy calculations.

Another concept covered by the standard is the building low or very low polluting where predominantly very low-emitting materials and furniture are used and activity does not result in pollution of the building.

The polluting building is an important reference for the design of indoor air quality (IAQ).

These standards are characterized by two Annexes: Annex A, normative, in which each Country provides the national required input data, and Annex B, informative, which contains default values.

The criteria for the indoor environment provided by EN 16798-1 Standard, define sizing and energy calculations for the design of the building, air conditioning systems and lighting systems. The thermal criteria for example, PMV and PPD indices, are used as reference bases for the definition of input for heating and cooling load calculations, sizing of equipment and energy calculations.

Ventilation rates are defined for design, sizing and energy calculation for ventilation systems. About lighting, in addition to the design definition, the standard also includes the use of daylight lighting.

The default values of IEQ parameters utilized as input calculation of energy demand are referred to as occupied spaces.

The Standard establishes design criteria according to a procedure for heated and/or mechanically cooled buildings and for building without mechanical cooling (CEN, 2019a).

### *III.4.1 Heated and/or mechanically cooled buildings*

When the building is equipped with a mechanical cooling system, the criteria for the thermal environment are based on PMV-PPD indices assuming a specific level of activity and a typical thermal insulation clothing for seasons (winter/summer).In this case, the designer can use the corresponding design operative temperature interval or use directly the PMV-PPD index for dimensioning the heating and cooling system. In the last case, the effect of increased air velocity and the effect of dynamic clothing insulation can be considered.

Dynamic clothing insulation considers the influence of body movement.

As described also in the ISO 7730 Standard, the calculation of the correction factor from basic clothing insulation to dynamic clothing insulation requires the knowledge of the relative air velocity to consider the effects of body movements on convective heat exchange, but neither EN 16798-1 nor ISO 7730 report any equation for $v_{ar}$ which could be calculated using the most common Eq. (III.9) (d'Ambrosio et al., 2014):

$$v_{ar} = v_a + 0.0052\,(M - 58.2) \qquad \text{(III.9)}$$

where:
$v_{ar}$ = relative air velocity, m/s;
$v_a$= air velocity, m/s;
$M$ = metabolic rate M, W/m$^2$.

### *III.4.2 Building without mechanical cooling*

In buildings without mechanical cooling, EN 16798 recommends the adaptive comfort approach to define criteria for the design thermal environment (Brager and Dear, 1998; de Dear et al., 2013; de Dear and Brager, 1998; Nicol and Humphrey, 1998).

The adaptive thermal comfort approach is based on the thesis that occupants can constantly interact with the environment and adapt to it through easy access to operable windows to regulate thermal conditions in the space. Moreover, this method can only be applied to spaces where the occupants are engaged in mainly sedentary activities and without clothing policies, to allow people to freely adapt their clothing insulation. Finally, spaces may be provided by a heating system, but they must not be in operation.

The Standard defines ranges of indoor operative temperature as a function of outdoor running mean temperature, shown in Fig. III.9.

The outdoor running means the temperature is calculated using Eq. (III.10).

$$t_{rm} = \frac{1}{1+\alpha+\alpha^2}\left(t_{ed-1} + \alpha \cdot t_{ed-2} + \alpha^2 \cdot t_{ed-3}\right) \qquad \text{(III.10)}$$

where:
$t_{rm}$ = outdoor running temperature for the considered day, °C;
$t_{ed-1}$ = daily mean outdoor air temperature for the previous day, °C;
$\alpha$ = constant between 0 and 1 (recommended value is 0.8);
$t_{ed-i}$ = daily mean outdoor air temperature for the *i-th* previous day, °C.

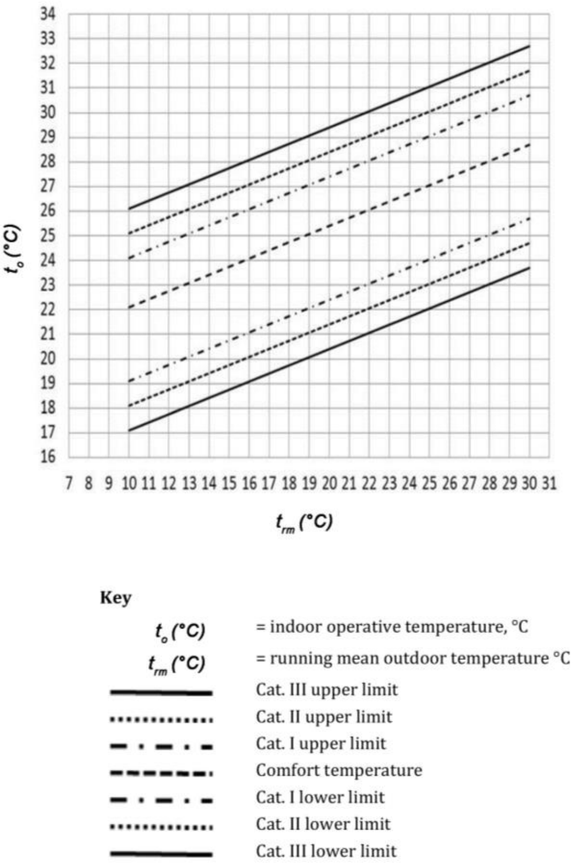


**Figure III.9** *Default design values of indoor operative environment depending on running mean of outdoor temperature (CEN, 2019a)*

## III.5 Classification of the thermal environment

The classes defined by EN 16798-1 Standard are three, which are a function of the level of expectation, Tab. III.3. The “Medium” is a normal level used for design and operation, the “High” may be selected for occupants with special needs (children, elderly, persons with disabilities, etc.), the “Moderate” corresponds to an acceptable environment in which some risk of reduced performance of occupants exists, the “Low” should only be used for a short time of the year or in spaces with a very short time of occupancy (CEN, 2019b).

According to the value of the PMV and the corresponding PPD, the Standard indicates the default category for the design of mechanical heated and cooled buildings (Tab. III.4).

Fig. III.10 shows the classification of the thermal environment according to the standards of thermal comfort.

**Table III.3** *Categories of indoor environmental quality (CEN, 2019a)*

| Category | Level of expectation |
|---|---|
| I | High |
| II | Medium |
| III | Moderate |
| IV | Low |

**Table III.4** *Default values for classification of the thermal environment (CEN, 2019a)*

| Category | PPD [%] | PMV |
|---|---|---|
| I | <6 | -0.2 < PMV < +0.2 |
| II | <10 | -0.5 < PMV < +0.5 |
| III | <15 | -0.7 < PMV < +0.7 |
| IV | <25 | -1.0 < PMV < +1.0 |

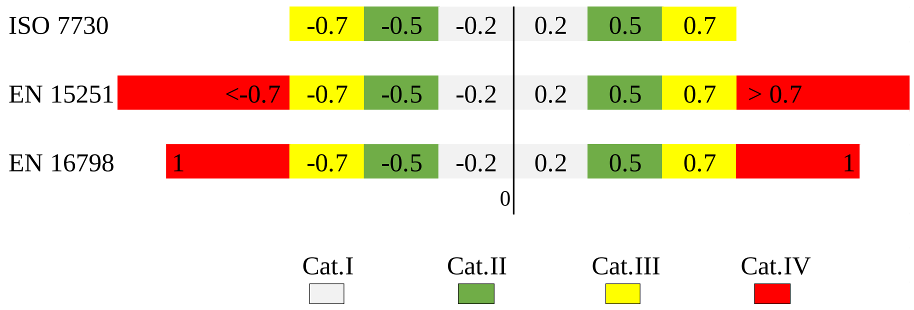


**Figure III.10** *Classification of thermal environment according to Standards*

# Chapter IV
# Thermal comfort and energy performance in a residential building using Standard ISO EN 16798-1 and -2

## IV.1 Introduction

In a sustainable design, a challenge is to be able to maximize occupant comfort and minimise energy use. The sustainable strategic decision for designing a building requires the use of calculation tools that forecast the behaviour of the building. In particular, the tools of dynamic simulations consent to creating a model of a building close to reality by working at a high degree of detail. In this way, it is possible to carry out an analysis of a building, understand its energy use, define energy-saving strategies and which parameters influence thermal comfort.

## IV.2 Objective

In this Chapter, the usefulness of dynamic simulation to estimate the energy use of a building and to outline the input parameters for the study of thermal comfort is presented and discussed. Another aspect investigated is the analysis of the standard limits for the heating and cooling season to understand if they are consistent with the requirements for achieving thermal comfort.

The specific software used is Energy Plus with the graphic Design Builder interface. The considered residential building is placed in two different geographical areas (Napoli and Copenhagen). By using hourly simulations of energy use the classification of the indoor environment for thermal comfort is estimated, according to EN 16798-1 Standard (CEN, 2019a). In this Chapter, only improvements related to the envelope are considered.

## IV.3 Method

The simulations are performed using Energy Plus (version 8.6) with graphical interfaces Design Builder (version 5.5). That allows simultaneous performance assessments of all building characteristics such as facade and wall construction, window glazing, HVAC systems, indoor air quality, thermal comfort and energy use.

A feature of Energy Plus makes it ideal for the study of thermal comfort. It is based on a heat balance procedure on the surface of the internal and external walls which permits the evaluation of the radiative effect of surfaces on thermal comfort.

The graphical interface Design Builder combines a rapid and easy building modelling simulation, but it has some limitations in the use of Energy Plus as it makes available partial use of the multiple potentialities of the calculation engine (Pawar and Kanade, 2018).

### *IV.3.1 Locations and meteorological data definition*

Simulations concern two European cities, each representing a different climate: Copenhagen and Napoli. The average monthly outdoor temperatures of the two locations are shown in Fig. IV.1.

The Typical meteorological year design data from International Weather Energy Calculation is used as input climate data in the software from the “Location” form (Fig. IV.2).

Dynamic simulations of each case are carried out throughout a whole year (from 1st January to 31st December, considering no holidays besides normal weekends) to compare the different effects of the two system control modes on the cooling and heating conditions.

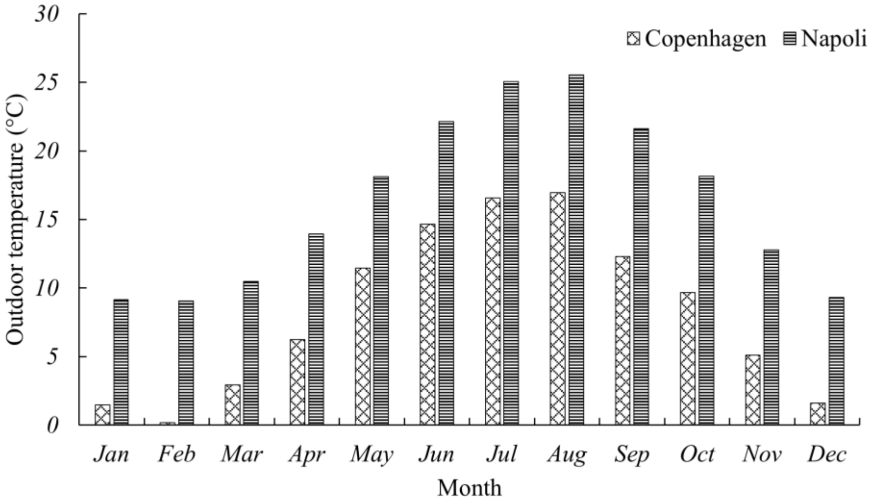
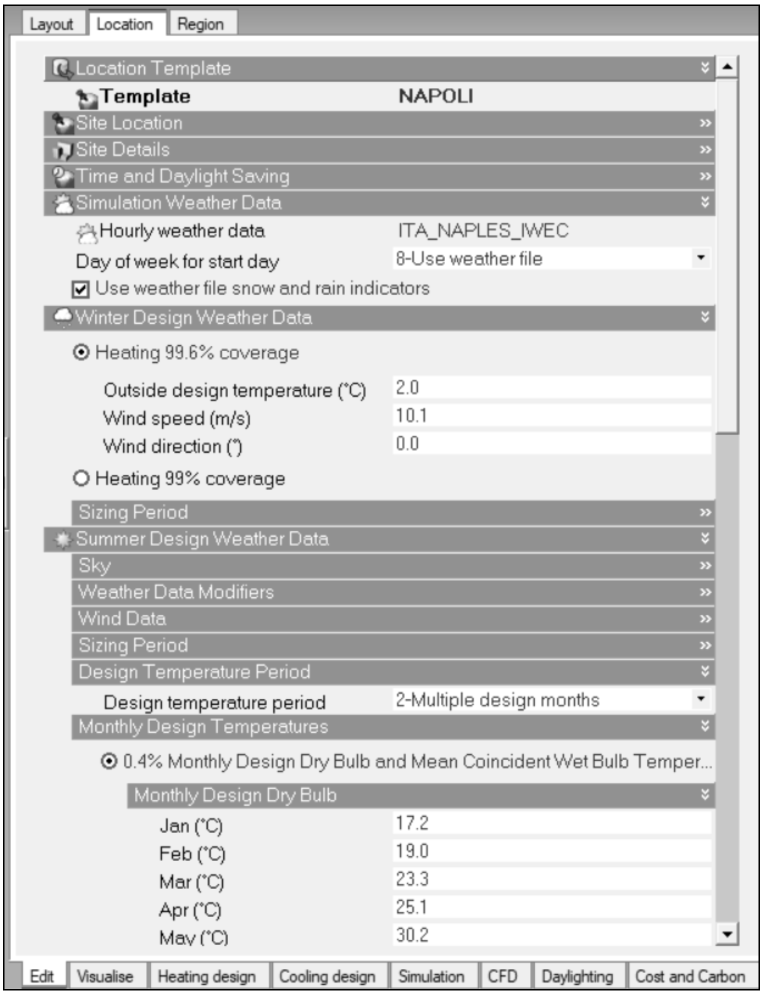


**Figure IV.1** *Average monthly outdoor temperatures*



| | |
|---|---|
| **Template** | NAPOLI |
| Hourly weather data | ITA_NAPLES_IWEC |
| Day of week for start day | 8-Use weather file |

☑ Use weather file snow and rain indicators

● Heating 99.6% coverage

| | |
|---|---|
| Outside design temperature (°C) | 2.0 |
| Wind speed (m/s) | 10.1 |
| Wind direction (°) | 0.0 |

○ Heating 99% coverage

| | |
|---|---|
| Design temperature period | 2-Multiple design months |

● 0.4% Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temper...

| | |
|---|---|
| Jan (°C) | 17.2 |
| Feb (°C) | 19.0 |
| Mar (°C) | 23.3 |
| Apr (°C) | 25.1 |
| May (°C) | 30.2 |

**Figure IV.2** *Location data – form of Design Builder*

### *IV.3.2 Building model description*

The building model shown in Fig. IV.3 is created *ad hoc*, representing a residential building module with a single zone. The building module, whose section is in Fig. IV.4, has a total floor area equal to 170.3 m$^2$.

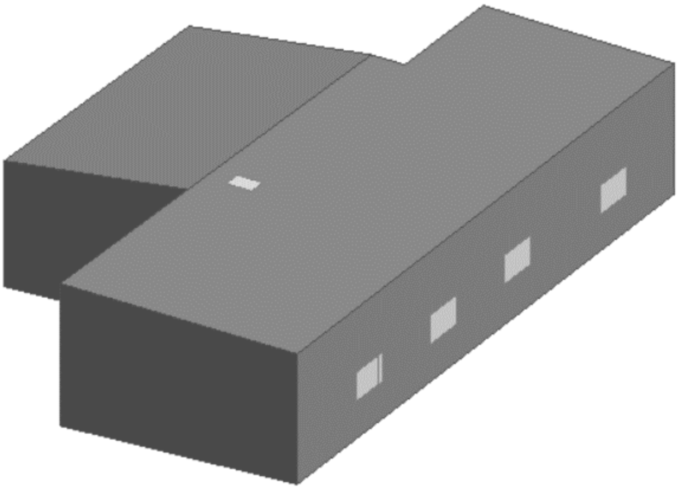


**Figure IV.3** *Building model*

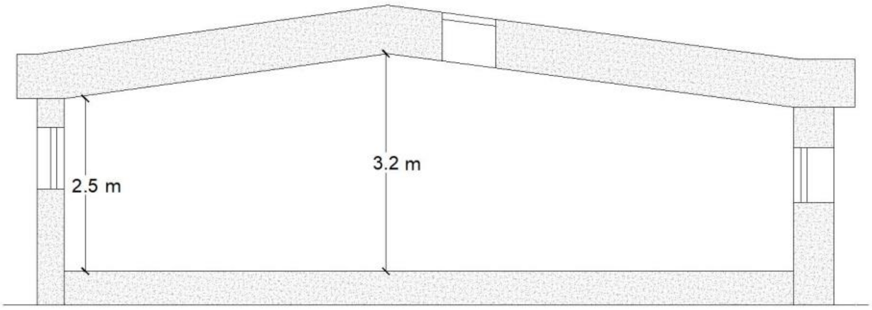
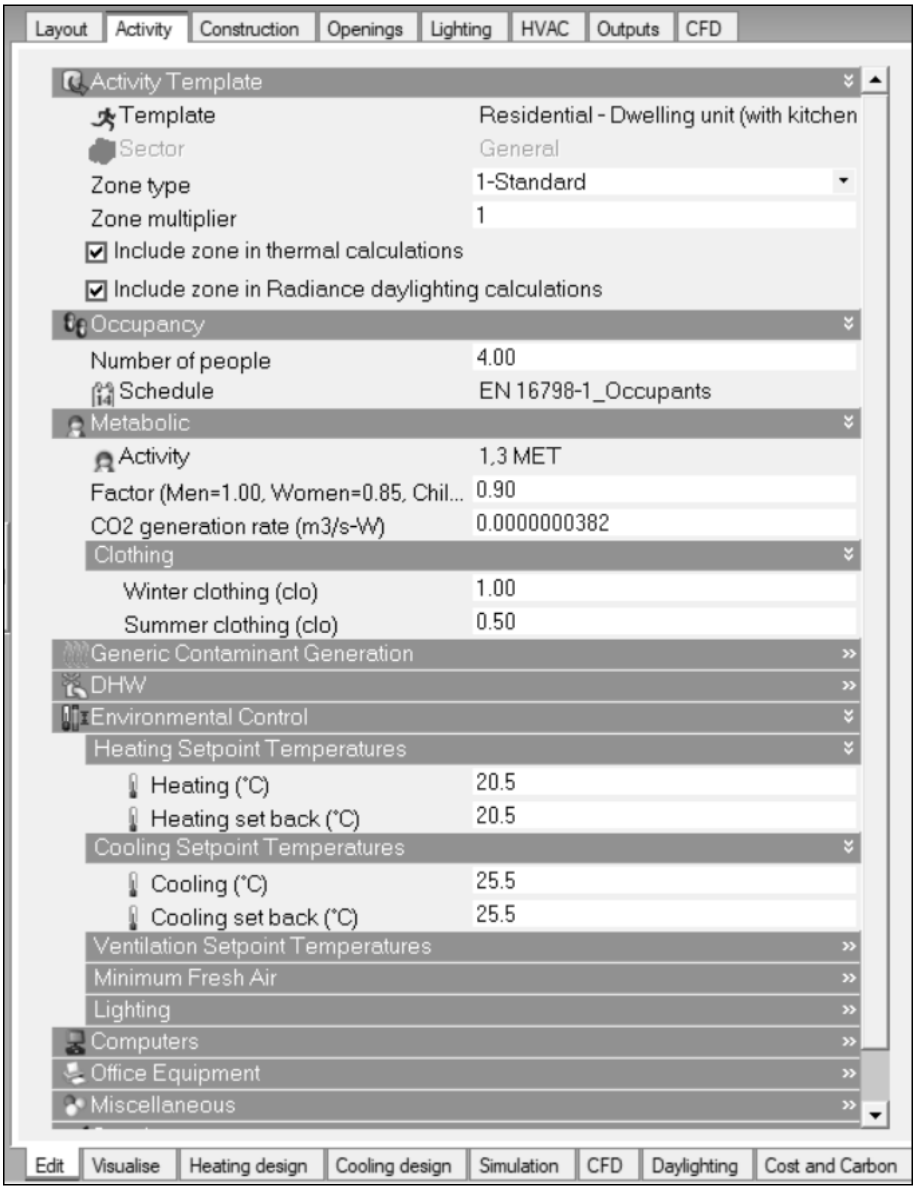


**Figure IV.4** *Section of building module*

The following sections show the definition of the model characteristics in the tabs of Design Builder.

The Activity tab (Fig. IV.5) consent to define information on the occupants (number of people, schedule, metabolic rate, clothing insulation), the setpoint temperature for heating and cooling systems and the equipment features.

In the Construction tab (Fig. IV.6) the stratigraphy of building components is assigned using the materials already present in the software library and modifying their physical properties based on the real values provided by the technical datasheets of actual materials. Finally, in this section it is possible set the airtightness value with a respective schedule for operation.



Activity Template
Template: Residential - Dwelling unit (with kitchen
Sector: General
Zone type: 1-Standard
Zone multiplier: 1
☑ Include zone in thermal calculations
☑ Include zone in Radiance daylighting calculations

Occupancy
Number of people: 4.00
Schedule: EN 16798-1_Occupants

Metabolic
Activity: 1,3 MET
Factor (Men=1.00, Women=0.85, Chil...: 0.90
CO2 generation rate (m3/s-W): 0.0000000382
Clothing
Winter clothing (clo): 1.00
Summer clothing (clo): 0.50

Generic Contaminant Generation
DHW
Environmental Control
Heating Setpoint Temperatures
Heating (°C): 20.5
Heating set back (°C): 20.5
Cooling Setpoint Temperatures
Cooling (°C): 25.5
Cooling set back (°C): 25.5
Ventilation Setpoint Temperatures
Minimum Fresh Air
Lighting
Computers
Office Equipment
Miscellaneous

**Figure IV.5** *Activity tab in Design Builder*

Template: Template della costruzione di progetto

External walls: Parete di progetto

Below grade walls: Parete controterra di progetto

Flat roof: Tetto Piano di progetto

Pitched roof (occupied): Tetto Inclinato di progetto

Pitched roof (unoccupied): Tetto Inclinato di progetto

Internal partitions: Partizioni

☑ Model infiltration

Constant rate (ac/h): 0.300

Schedule: On 24/7

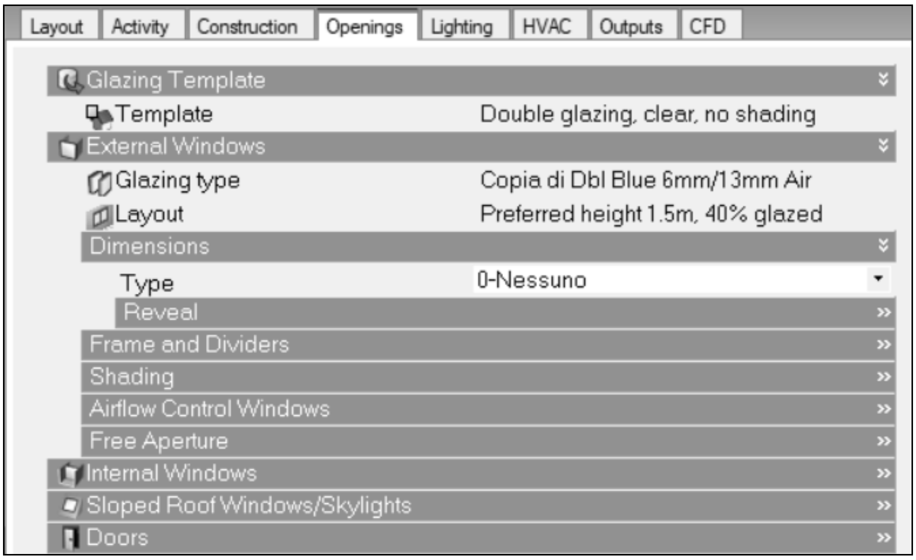
**Figure IV.6** *Construction tab in Design Builder*

The thermo-physical characteristics of the window are defined in the openings tab, in Fig. IV.7, where glazing and relative frames sizes are set; in addition, the solar transmission, visible and thermal transmittance values of these elements are defined (Fig. IV.8). Moreover, eventual shading and doors proprieties are settable.

In the lighting tab, shown in Fig. IV.9, the power density of general lighting is set with the respective schedule and it is possible to define a lighting control according to the daylighting illuminance on the working plane.

The data of the heating, cooling and ventilation systems in the HVAC tab are set, in Fig. IV.10. In this case study, a simple HVAC system is modelled using ideal loads and the corresponding energy consumption is modelled as a post-process according to model options available in the software.

The ventilation operating schedule in this section is set.



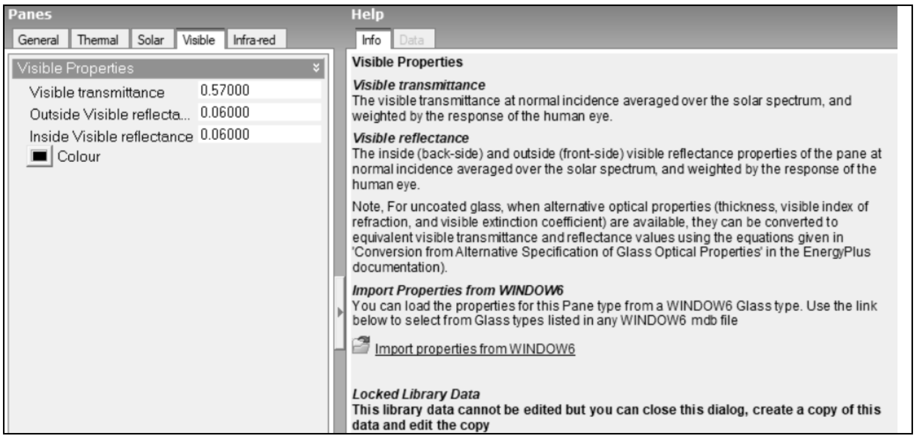
Template: Double glazing, clear, no shading

Glazing type: Copia di Dbl Blue 6mm/13mm Air

Layout: Preferred height 1.5m, 40% glazed

Type: 0-Nessuno

**Figure IV.7** *Openings tab in Design Builder*



Visible transmittance: 0.57000

Outside Visible reflecta...: 0.06000

Inside Visible reflectance: 0.06000

**Visible Properties**

***Visible transmittance***
The visible transmittance at normal incidence averaged over the solar spectrum, and weighted by the response of the human eye.

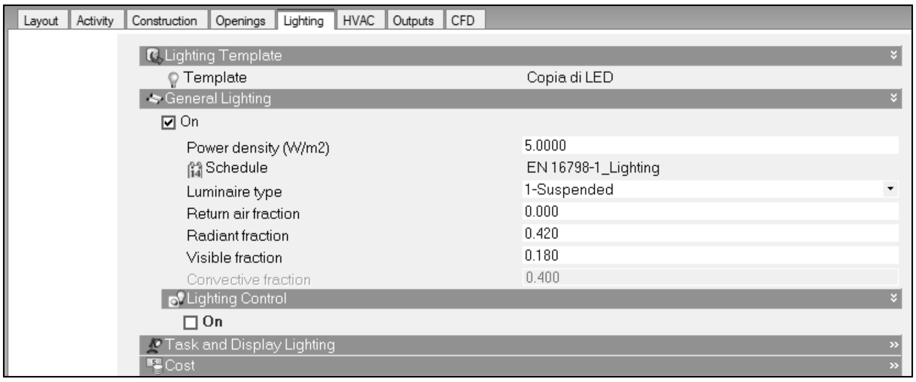
***Visible reflectance***
The inside (back-side) and outside (front-side) visible reflectance properties of the pane at normal incidence averaged over the solar spectrum, and weighted by the response of the human eye.

Note, For uncoated glass, when alternative optical properties (thickness, visible index of refraction, and visible extinction coefficient) are available, they can be converted to equivalent visible transmittance and reflectance values using the equations given in 'Conversion from Alternative Specification of Glass Optical Properties' in the EnergyPlus documentation).

***Import Properties from WINDOW6***
You can load the properties for this Pane type from a WINDOW6 Glass type. Use the link below to select from Glass types listed in any WINDOW6 mdb file

***Locked Library Data***
**This library data cannot be edited but you can close this dialog, create a copy of this data and edit the copy**

**Figure IV.8** *Visible proprieties in Design Builder*



Lighting Template

Template: Copia di LED

General Lighting

☑ On

Power density (W/m2): 5.0000

Schedule: EN 16798-1_Lighting

Luminaire type: 1-Suspended

Return air fraction: 0.000

Radiant fraction: 0.420

Visible fraction: 0.180

Convective fraction: 0.400

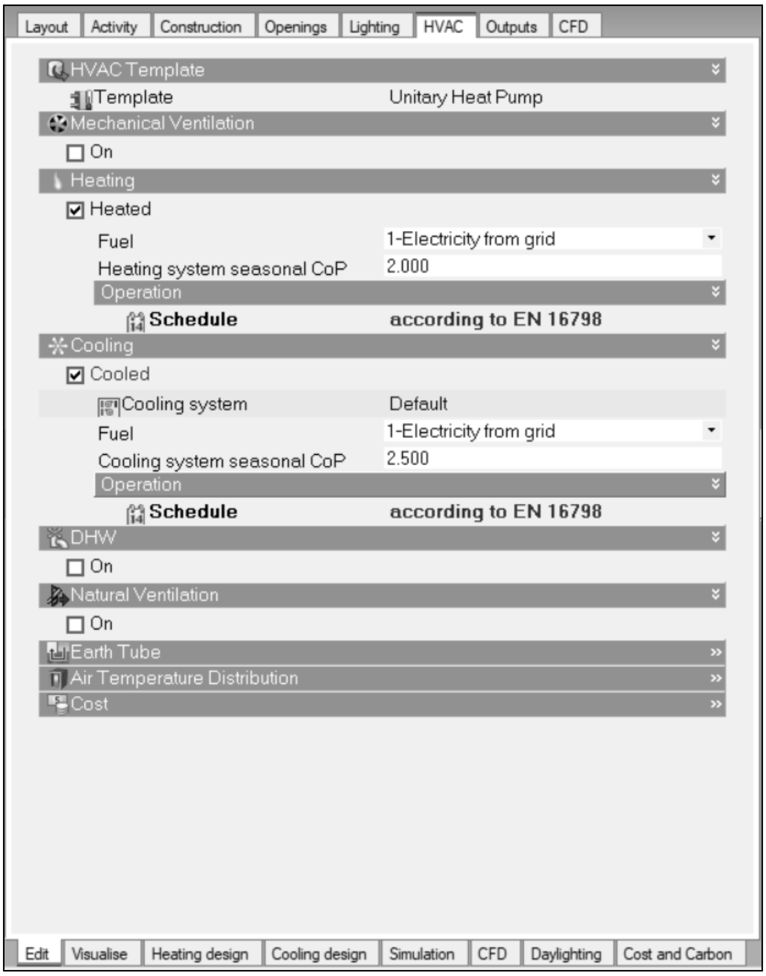
Lighting Control

☐ **On**

Task and Display Lighting

Cost

**Figure IV.9** *Lighting tab in Design Builder*



HVAC Template

Template: Unitary Heat Pump

Mechanical Ventilation

☐ On

Heating

☑ Heated

Fuel: 1-Electricity from grid

Heating system seasonal CoP: 2.000

Operation

**Schedule**: **according to EN 16798**

Cooling

☑ Cooled

Cooling system: Default

Fuel: 1-Electricity from grid

Cooling system seasonal CoP: 2.500

Operation

**Schedule**: **according to EN 16798**

DHW

☐ On

Natural Ventilation

☐ On

Earth Tube

Air Temperature Distribution

Cost

**Figure IV.10** *HVAC tab in Design Builder*

### *IV.3.3 Building model setting*

The building is built with a mixed structure in brick masonry and reinforced concrete. The thermal characteristics of the building components are given in Tab. IV.1. The HVAC system is a heat pump for heating and cooling.

The HVAC have a turn-on-off program based on the occupancy of people and setpoint temperature with control of operative temperature. The setpoint for heating is set at 20.5 °C and for cooling is set at 25.5 °C.

The definition of heating and cooling season is useful to identify the classification of the thermal environment according to EN 16798-2 Standard (CEN, 2019b). The EN 16798-1 Standard contains the reference parameters for the evaluation of thermal comfort during the heating and cooling season without specifying how to identify them. So, for Napoli, the heating season is chosen according to Italian Legislation (President of Italian Republic, 1993), while for Copenhagen a reference period based on the most common period of the switch-on heating system is set, not being specified within the Standards. Tab. IV.2 shows the period of heating and cooling season for each location.

The boundary conditions for occupancy, appliances and lighting are set according to default values suggested by EN 16798-1 for calculations of energy performances in a residential apartment (Tab. IV.3).

The occupant schedules are based on EN 16798-1 Standard, as shown in Tab. IV.4.

The internal loads include the heat production by four occupants with a metabolic rate equal approximately to 1.3 met. Clothing insulation is set to 0.5 clo for summer and 1.0 clo for winter (CEN, 2019a).

A constant value of infiltration of 0.3 $m^3/h$ is considered.

To evaluate impacts on energy uses and on the trend of thermal comfort two simulations are carried out for each city considering the building module: with only the heating system on and with both heating and cooling systems on.

The first 4 simulations, in Tab. IV.5, are repeated assuming the improvements:

- Roof insulation.
- Replacement of windows.
- External thermal insulation on the north façade.

Simulation n. 5 considers the same improvement interventions of simulation n. 4 but assumes for the south façade, a single larger window with a glass area increased by 24%. It is taken into account to observe the influence of greater daylighting.

**Table IV.1** *Thermal characteristics of the building components*

| Building construction | Building components | Thickness [mm] | Density [kg/m$^3$] | Thermal conductivity [W/m·K] | Thermal resistance [m$^2$·K/W] | Specific heat capacity [W·h/kg·K] | U-value [W/m$^2$K] |
|---|---|---|---|---|---|---|---|
| Roof slab | - Zinc metal panel | 5 | 7000 | 113 | 0 | 0.11 | 0.19 |
| | - Expanded Polystyrene | 50 | 10 | 0.05 | 1.0 | 0.39 | |
| | - Wood slats | 100 | 510 | 0.12 | 0.8 | 0.38 | |
| | - Expanded polystyrene | 50 | 10 | 0.05 | 1.0 | 0.39 | |
| | - Asphalt | 2 | 2100 | 0.70 | 0 | 0.28 | |
| | - Screed | 100 | 1800 | 1 | 0.1 | 0.28 | |
| | - Concrete block | 500 | 750 | 0.24 | 2.1 | 0.28 | |
| | - Screed (45%) | | | | | | |
| | - Cement Plaster | - | 1800 | 1 | - | 0.28 | |
| | | 20 | 1760 | 0.72 | 0 | 0.23 | |
| Slab/Floor | - Waterproof membrane | 3 | 70 | 0.06 | 0.1 | 0.42 | 0.184 |
| | - Insulation | 150 | 10 | 0.04 | 3.8 | 0.39 | |
| | - Concrete | 100 | 1200 | 0.38 | 0.3 | 0.28 | |
| | - Screed | 70 | 1200 | 0.41 | 0.2 | 0.23 | |
| | - Ceramic Floor | 10 | 1700 | 0.01 | 1.0 | 0.24 | |
| Outside wall | - Cement plaster | 20 | 720 | 0.22 | 0.1 | 0.37 | 0.342 |
| | - Concrete block | | | | | | |
| | - Air gap | 200 | 910 | 0.17 | 1.2 | 0.23 | |
| | - Concrete block | | - | - | | | |
| | - Cement Plaster | 10 | | | | - | |
| | | 200 | 910 | 0.17 | 1.2 | 0.23 | |
| | | 20 | 720 | 0.22 | 0.1 | 0.37 | |
| Windows | Double glass 6 mm – Air 13 mm | | | - | | | 1.31 |

**Table IV.2** *Heating and cooling season for each location*

| | Napoli | Copenhagen |
|---|---|---|
| Heating season | 15 November – 31 March | 1 September – 30 April |
| Cooling season | 1 April – 14 November | 1 May – 30 September |

**Table IV.3** *Internal gains according to EN 16798-1*

| | |
|---|---|
| Occupants | 2.8W/m$^2$ |
| Appliances | 3 W/m$^2$ |
| Lighting | 5 W/m$^2$ |

**Table IV.4** *Usage schedules according to EN 16798-1. Occ.: occupants; App.: appliances; Light.: lighting*

| | Weekdays | | | Weekends | | |
|---|---|---|---|---|---|---|
| hour | App. | Occ. | Ligh. | App. | Occ. | Ligh. |
| 1 | 1 | 0.5 | 0 | 1 | 0.5 | 0 |
| 2 | 1 | 0.5 | 0 | 1 | 0.5 | 0 |
| 3 | 1 | 0.5 | 0 | 1 | 0.5 | 0 |
| 4 | 1 | 0.5 | 0 | 1 | 0.5 | 0 |
| 5 | 1 | 0.5 | 0 | 1 | 0.5 | 0 |
| 6 | 1 | 0.5 | 0 | 1 | 0.5 | 0 |
| 7 | 0.5 | 0.5 | 0.15 | 0.8 | 0.5 | 0.15 |
| 8 | 0.5 | 0.7 | 0.15 | 0.8 | 0.7 | 0.15 |
| 9 | 0.5 | 0.7 | 0.15 | 0.8 | 0.7 | 0.15 |
| 10 | 0.1 | 0.5 | 0.15 | 0.8 | 0.5 | 0.15 |
| 11 | 0.1 | 0.5 | 0.05 | 0.8 | 0.5 | 0.05 |
| 12 | 0.1 | 0.6 | 0.05 | 0.8 | 0.6 | 0.05 |
| 13 | 0.1 | 0.6 | 0.05 | 0.8 | 0.6 | 0.05 |
| 14 | 0.2 | 0.6 | 0.05 | 0.8 | 0.6 | 0.05 |
| 15 | 0.2 | 0.6 | 0.05 | 0.8 | 0.6 | 0.05 |
| 16 | 0.2 | 0.5 | 0.05 | 0.8 | 0.5 | 0.05 |
| 17 | 0.5 | 0.5 | 0.2 | 0.8 | 0.5 | 0.2 |
| 18 | 0.5 | 0.7 | 0.2 | 0.8 | 0.7 | 0.2 |
| 19 | 0.5 | 0.8 | 0.2 | 0.8 | 0.7 | 0.2 |
| 20 | 0.8 | 0.8 | 0.2 | 0.8 | 0.8 | 0.2 |
| 21 | 0.8 | 0.8 | 0.2 | 0.8 | 0.8 | 0.2 |
| 22 | 0.8 | 0.8 | 0.2 | 0.8 | 0.8 | 0.2 |
| 23 | 1 | 0.6 | 0.15 | 1 | 0.6 | 0.15 |
| 24 | 1 | 0.6 | 0.15 | 1 | 0.6 | 0.15 |

**Table IV.5** *Simulations*

| n. | Location | System |
|---|---|---|
| 1 | Napoli | Heating |
| 2 | Napoli | Heating and Cooling |
| 3 | Copenhagen | Heating |
| 4 | Copenhagen | Heating and Cooling (with small window) |
| 5 | Copenhagen | Heating and Cooling (with larger window) |

### *IV.3.4 Calculations*

The energy use of electricity for appliances, lighting and heating/cooling systems together with the estimated operative temperature is carried out using hourly dynamic simulation.

The internal operative temperature is calculated as the arithmetic mean of the internal air and the mean radiant temperature. As illustrated in chapter 3 this is a simplified method used by Design Builder and so by Energy Plus but it is considered appropriate for this comparison study because it will be important to observe the differences in temperature values.

This calculation method of operative temperature represents a limit in the use of this simulation tool that it does not consent to obtain reliable values of operative temperatures and consequently of PMV for thermal comfort assessment.

The percentage of time when the operative temperature is outside and inside the range of the four categories of thermal comfort is calculated to evaluate thermal comfort.

The range of operative temperature for the analysis of results refers to the defined interval into EN 16798-1 Standard for residential buildings, as shown in Tab. IV.6.

The amount of energy used for conditioning the indoor environment in the building module is determined and compared for the two simulated cities. The annual heating/cooling energy use per square meter of the space ($kWh/m^2 \cdot yr$) is calculated.

**Table IV.6** *Temperature ranges for hourly calculation of cooling and heating energy in four categories*

| Type of building or space | Categories | Temperature range for heating seasons [°C] Clothing 1.0 clo | Temperature range for cooling seasons [°C] Clothing 0.5 clo |
|---|---|---|---|
| Residential buildings, living spaces (bed room's, kitchens, living rooms etc.) | I | 21.0 −25.0 | 23.5 - 25.5 |
| | II | 20.0–25.0 | 23.0 - 26.0 |
| | III | 18.0- 25.0 | 22.0 - 27.0 |
| | IV | 17.0–25.0 | 21.0 – 28.0 |

## IV.4 Results and discussion

The annual energy use for electricity room, lighting and heating/cooling system without improvements is summarized in Tab. IV.7.

To better clarify the comparison of energy use for simulations with and without improvements, the data are shown in Figs. IV.11, 12, 13, 14, 15, 16, and 17 referred to annual and monthly energy uses. Because there are no differences in the energy results for heating between simulations 1-2 and 3-4, only the results of simulations 2, 4 and 5 are shown.

About the operative temperature, the percentage of time when it is outside and inside the range of the four categories of thermal comfort is calculated to evaluate the thermal comfort conditions. The range refers to the defined interval in EN 16798-1 Standard for residential buildings.

Regarding the total energy use, when the cooling system is on it is higher and the thermal comfort improves, in particular for Napoli, where the percentage of the operative temperature outside the range of the four comfort categories decreases from 59% to 16% and the percentage in category I increase (Fig. IV.18).

In the simulation with a larger window (simulation 5) the comfort improves during the cooling season because of the increased solar radiation through the window which improves thermal sensation in a climate such as that of Copenhagen. In fact, the percentage in category I increase, and the percentage of time outside the categories range is reduced from 32% to 18% (Fig. IV.19).

**Table IV.7** *Annual energy use for electricity, appliances and lighting, and heating/cooling system without improvements*

| Location | Electricity appliances [kw·h/m²·yr] | Lighting [kw·h/m²·yr] | Heating [kw·h/m²·yr] | Cooling [kw·h/m²·yr] | Total heating and cooling [kw·h/m²·yr] |
|---|---|---|---|---|---|
| Napoli | 15.7 | 3.5 | 14.3 | 11.6 | 25.9 |
| Copenhagen | 15.7 | 3.5 | 47.7 | 0.2 | 47.9 |

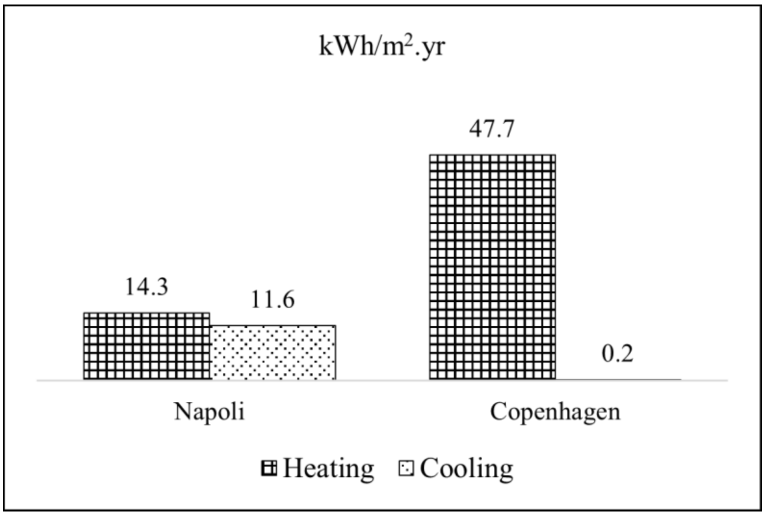


**Figure IV.11** *Annual energy use, Simulations 2-4 without improvements*

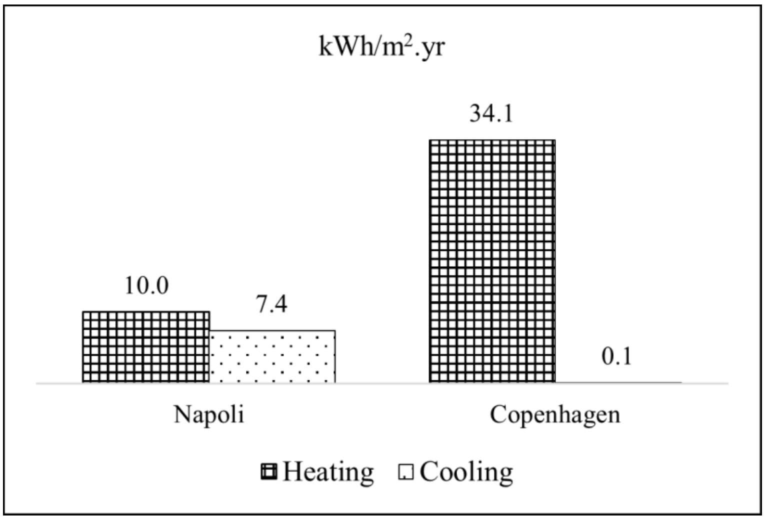


**Figure IV.12** *Annual energy use, Simulations 2-4 with improvements*

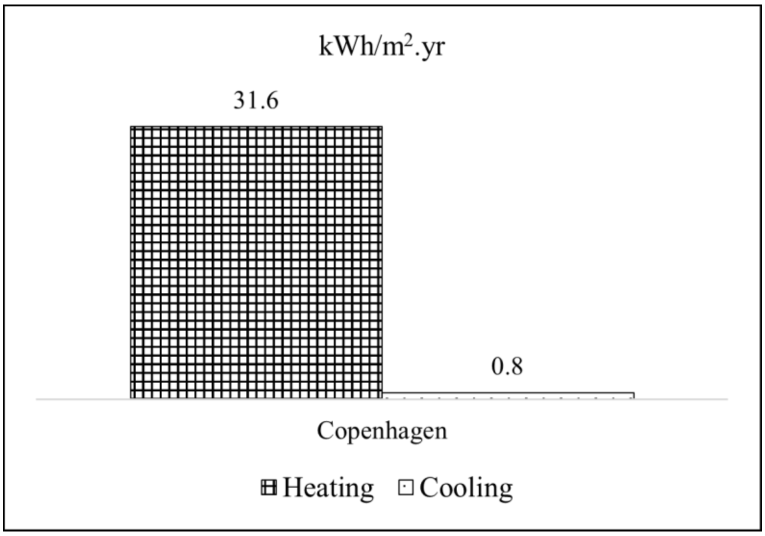


**Figure IV.13** *Annual energy use, Simulations 5*

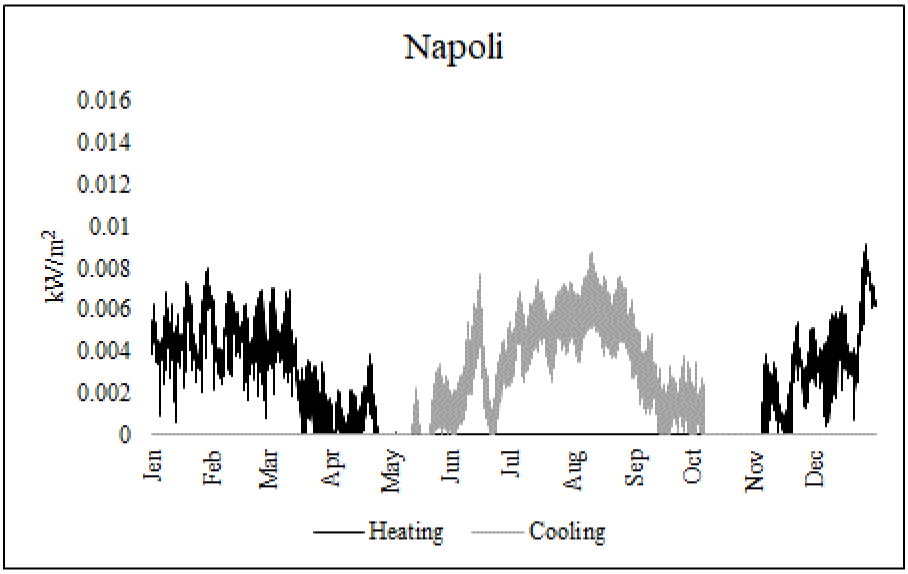


**Figure IV.14** *Hourly energy use for heating and cooling system, Simulation 2 without improvements*

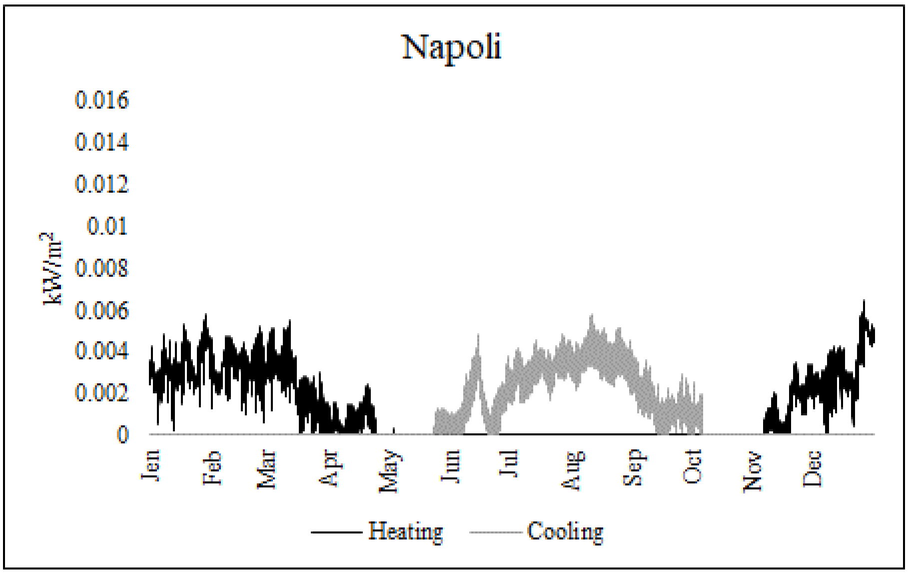


**Figure IV.15** *Hourly energy use for heating and cooling system, Simulation 2 with improvements*

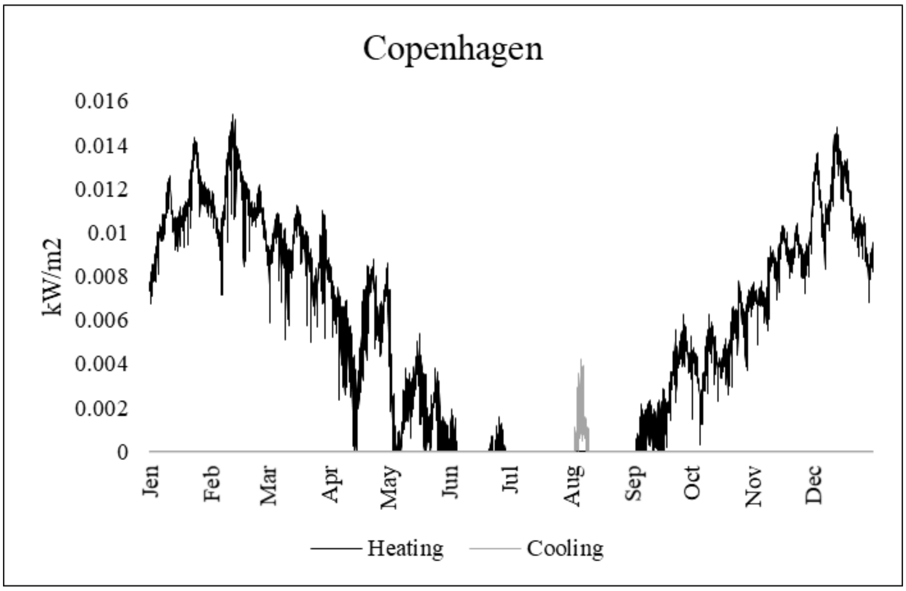


**Figure IV.16** *Hourly energy use for heating and cooling system, Simulation 4 without improvements*

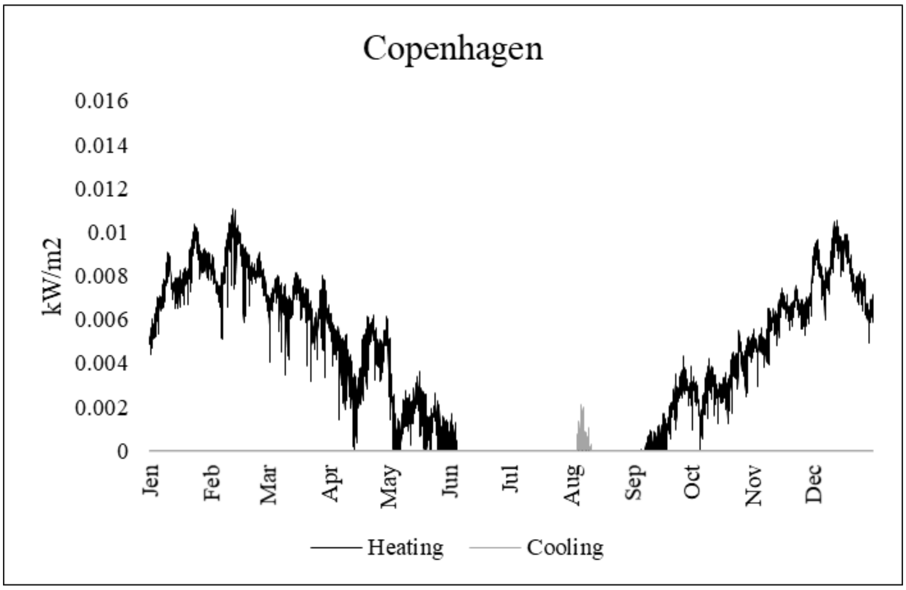


**Figure IV.17** *Hourly energy use for heating and cooling system, Simulation 4 with improvements*

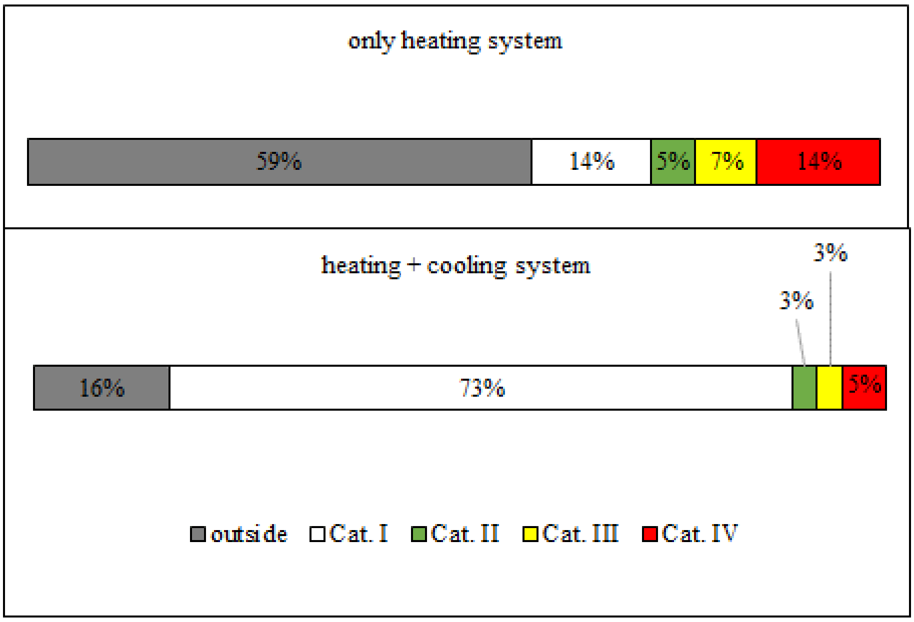


**Figure IV.18** *Classification of thermal environment, cooling season, Napoli*

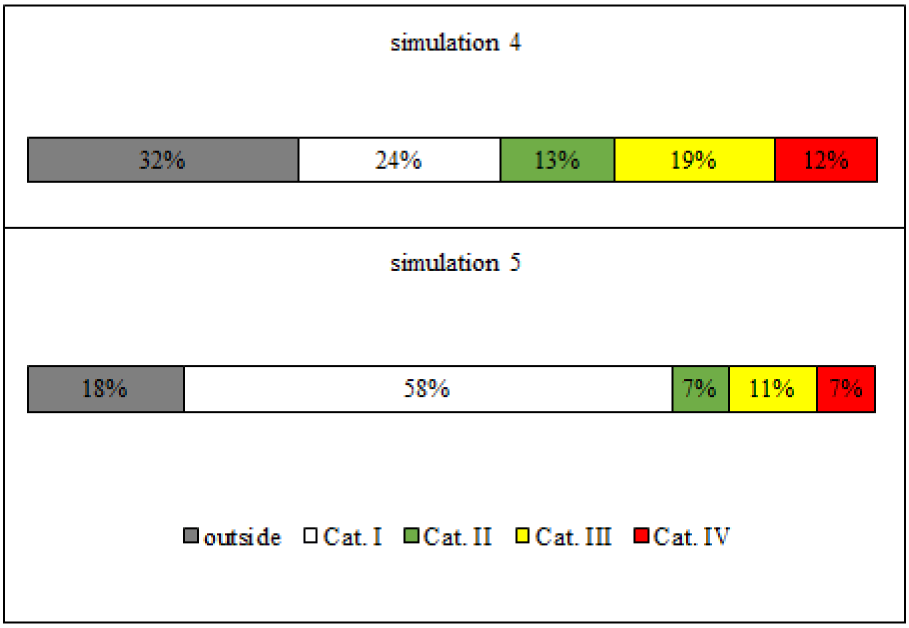


**Figure IV.19** *Classification of thermal environment, cooling season, Copenhagen*

Fig. IV.20 shows the trend of operative temperature in Copenhagen for simulations 4 and 5. In general, the operative temperature profile is higher in simulations n.5 (with a larger window).

Fig. IV.21 illustrates the profile of energy use during the year, which depends on setpoint temperature, and where is marked the start and end of the heating season for Napoli. It is possible to notice that there is a period of energy use outside the period of the heating season (15 November until 31 march). This means that to guarantee thermal comfort conditions the heating should take place for a longer period than the one currently defined in Italian law. If we set in the model the switched-on period of a system according to degree days defined by law rather than based only on setpoint temperature, the operative temperature goes down until it reaches 18 °C (Fig. IV.22). So, the heating season for Napoli so as defined by the standard does not always guarantee comfort conditions.

This is a very important aspect, because in Italy, as mentioned, the heating season is established based on degree days by Presidential Decree 412 of 1993 (President of Italian Republic, 1993).

In the last 30 years, climate changes caused a deep change in the seasons and last but not least, the technology provides effective systems that guarantee the switching on/off systems not on fixed days but according to the external air temperature. Unfortunately, in Italy is in force the old decree which does not respect the need for energy saving that never as in these days of war and risk for energy supplies, are decisive for the Nation.

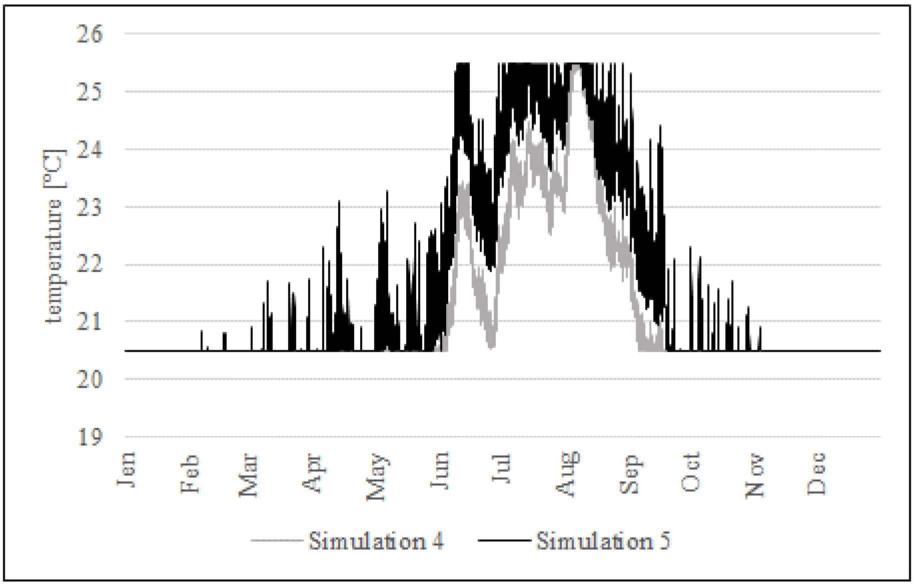


**Figure IV.20** *Hourly operative temperature, Simulations 4 and 5*

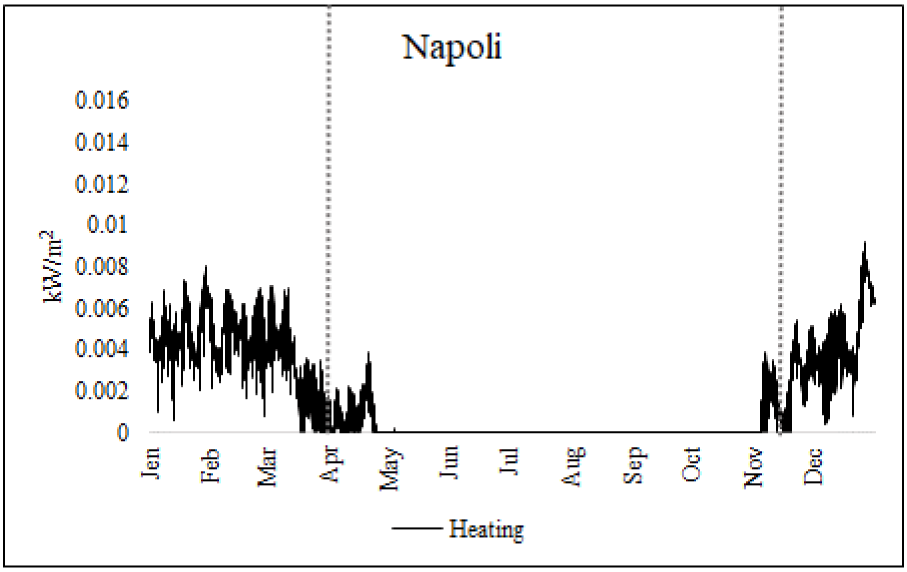


**Figure IV.21** *Hourly energy use for heating system, Simulation 1 with improvements*

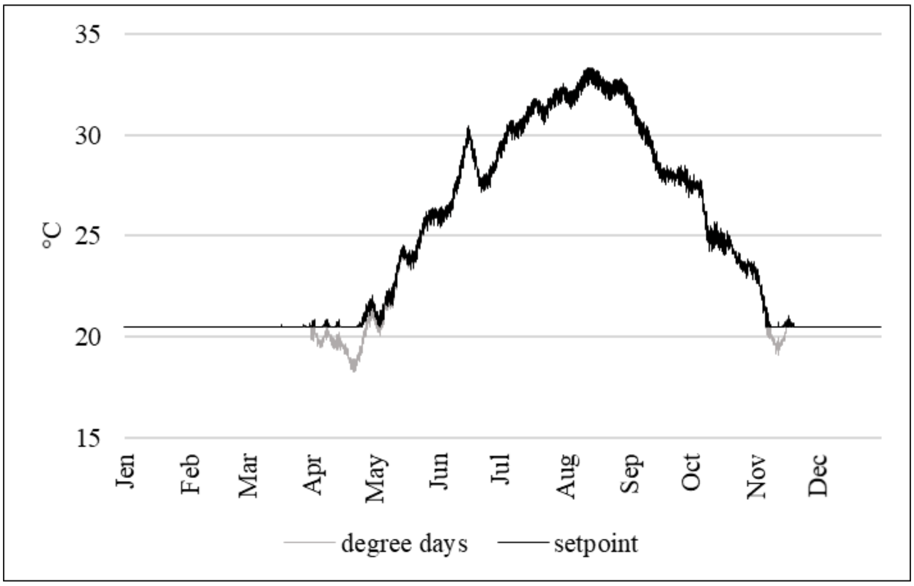


**Figure IV.22** *Hourly operative temperature, Simulation 1 with improvements*

Summarizing the results obtained, overall energy saving with and without improvements is similar in percentage terms for the two cities, but it is distributed differently because in Napoli the energy uses for heating and cooling are quite equivalent (Mediterranean climate), while in Copenhagen the energy use during cooling season is lower than energy use for the heating season. In particular, the energy used for cooling is much lower in Copenhagen than in Napoli, while the energy used for heating is higher in Copenhagen. In terms of energy use during the heating season, there are no particular differences between the results of simulations with or without a cooling system.

In general, as expected both Napoli and Copenhagen energy use are lower in the simulations with improvements. This is due to the better isolation expected from the interventions.

Finally, the cooling system improves the thermal comfort in Napoli while it has no relevant effect on Copenhagen, and this is due to the hotter climate in Napoli compared to Copenhagen.

## IV.5 Conclusions

The simulations carried out permit us to evaluate the performance of the building in terms of energy use and thermal comfort by applying the EN 16798-1 Standard.

Calculated whole-year energy use and the operative temperature distribution percentages within and outside the four categories can be used as the basis for further studies of thermal comfort concerning the energy use of the building. A reference for the evaluation of thermal comfort is the EN 16798-1 Standard with the determination of the quality class of the thermal environment.

From the analysis of the results emerge important aspects:

- The strong correlation between energy use and thermal comfort in a building and the consequent need to study it together to improve the conditions of the indoor environment and optimize energy use.
- The necessity to define the heating and cooling season to study the operative temperature profile and better evaluate the thermal comfort.

About this last aspect, the standard is not clear in the requirements for evaluation of thermal comfort because it writes about the range of temperature for the heating and cooling season for the thermal classification without specifying how to define the heating and cooling season. Moreover, for a complete representation of temperature distribution should be added also the percentage of the temperature outside categories (greater or lesser than the limited temperature of the range) to have more elements to understand the conditions of the indoor environment.

The considerations resulting from this study can provide to improve the standard that is under review, which will be divided into 4 parts of which a specific part will be dedicated exclusively to thermal comfort.

About Italy, it is evident the necessity to modify the definition of the switched-on period of the heating system which currently does not guarantee thermal comfort conditions.

# Chapter V

# Comparison of two building simulation tools for predicting energy use and indoor temperatures

## V.1 Introduction

A dynamic building simulation tool is an instrument to predict building thermo-energy behaviour or to compare different design solutions.

There are many tools validated separately under different boundaries and operating conditions. Whichever tool is used, to obtain correct results from a dynamic simulation it is important to correctly define the required input data and critically evaluate the results obtained.

## V.2 Objective

This Chapter is devoted to a comparison between two commercial tools for dynamic building performance simulation: IDA ICE and Design Builder (with Energy Plus calculation engine) for verifying the differences in evaluation of thermal comfort (in terms of operative temperature) and energy use for heating, cooling and ventilation. The comparison is aimed at highlighting the absolute (Design Builder vs IDA ICE) and relative differences (between two different configurations of the model: with small and large windows).

The investigation is carried out in cooperation with the research group of Professor Bjarne W. Olesen, Head of the International Centre for Indoor Environment and Energy at the Technical University of Denmark, Department of Environmental and Resource Engineering.

## V.3 Method

A reference-building model is built in the two software and the same boundary and operating conditions are established.

As the input interface of the two software is different, a very challenging job is to define the input data to create a single model that is the same (or as much as possible the same) in IDA ICE and Design Builder. For some boundary conditions is not possible directly insert the identical input data because of the different settings of the tool, as discussed below. So, in this case, a solution to better define the model in the two software is identified.

As default input data for thermal comfort and ventilation, the values in Annex B of EN 16798- 1 Standard are used (CEN, 2019a). They are informative values, but valid for the whole of Europe as a reference. It is not possible to use the values regulatory of Annex A, because the values in the Italian Annex are different from those in the Danish one.

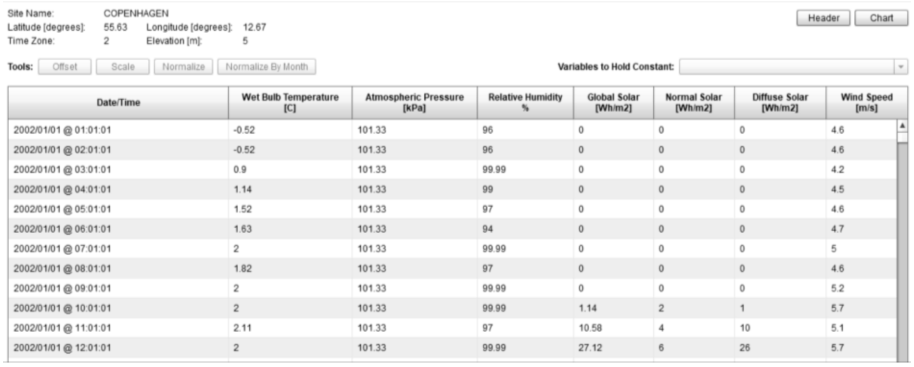
### *V.3.1 Locations and meteorological data definition*

As the outdoor environment may generate differences between results from software, two geographical locations are chosen for the simulation: Copenhagen (Denmark) and Palermo (Italy). In this analysis, Palermo is chosen rather than Napoli, as in the previous study, because of its hotter climate. Therefore, a specific weather file with hourly values of the local climate for each location is entered.

The weather file has a different format in the two software: IDA ICE uses the *.prn* format, while Design Builder uses the *.epw* format and direct conversion is not possible. For this reason, starting from the *.prn* file, the values of each weather parameter are taken to create the *.epw* file using "Element" software: a free, open-source software tool for creating and editing custom weather files for building energy modelling.

In Fig. V.1 the screenshot of the Element software used for creating the *.epw* file with the required input data is shown.

A critical issue encountered using the Design Builder during the creation and testing of the model concerns the reading of the inserted (*.epw*) weather file. In fact, by a check, the hourly output values are the same as those entered initially only for the "Site" level while they do not correspond to initial data if the user is at the "Building" level. This means that the meteorologic data could not correspond to the input data defined for each city, thus affecting results. It should be understood if this leads to a problem in the interpretation of the results.



Site Name: COPENHAGEN
Latitude [degrees]: 55.63 Longitude [degrees]: 12.67
Time Zone: 2 Elevation [m]: 5

Variables to Hold Constant:

| Date/Time | Wet Bulb Temperature [C] | Atmospheric Pressure [kPa] | Relative Humidity % | Global Solar [Wh/m2] | Normal Solar [Wh/m2] | Diffuse Solar [Wh/m2] | Wind Speed [m/s] |
|---|---|---|---|---|---|---|---|
| 2002/01/01 @ 01:01:01 | -0.52 | 101.33 | 96 | 0 | 0 | 0 | 4.6 |
| 2002/01/01 @ 02:01:01 | -0.52 | 101.33 | 96 | 0 | 0 | 0 | 4.6 |
| 2002/01/01 @ 03:01:01 | 0.9 | 101.33 | 99.99 | 0 | 0 | 0 | 4.2 |
| 2002/01/01 @ 04:01:01 | 1.14 | 101.33 | 99 | 0 | 0 | 0 | 4.5 |
| 2002/01/01 @ 05:01:01 | 1.52 | 101.33 | 97 | 0 | 0 | 0 | 4.6 |
| 2002/01/01 @ 06:01:01 | 1.63 | 101.33 | 94 | 0 | 0 | 0 | 4.7 |
| 2002/01/01 @ 07:01:01 | 2 | 101.33 | 99.99 | 0 | 0 | 0 | 5 |
| 2002/01/01 @ 08:01:01 | 1.82 | 101.33 | 97 | 0 | 0 | 0 | 4.6 |
| 2002/01/01 @ 09:01:01 | 2 | 101.33 | 99.99 | 0 | 0 | 0 | 5.2 |
| 2002/01/01 @ 10:01:01 | 2 | 101.33 | 99.99 | 1.14 | 2 | 1 | 5.7 |
| 2002/01/01 @ 11:01:01 | 2.11 | 101.33 | 97 | 10.58 | 4 | 10 | 5.1 |
| 2002/01/01 @ 12:01:01 | 2 | 101.33 | 99.99 | 27.12 | 6 | 26 | 5.7 |

**Figure V.1** *Input data in Element Software for creating the .epw file*

### *V.3.1.1 Wind pressure values*

The airflow through openings depends mainly on the difference between internal and external pressure. It influences aeration, heating and cooling loads, energy use, indoor environmental quality and thermal comfort.

Design Builder permits to insert of the wind pressure values in an *ad hoc* file for editing weather files, while IDA ICE calculates this parameter using pressure coefficients on each surface with Eq. (V.1):

$$P_{\mathrm{W}} = C_{\mathrm{W}} \cdot \frac{\rho v^2}{2} \qquad \text{(V.1)}$$

where:
$P_w$ = wind pressure, Pa;
$C_w$ = pressure coefficient, 1;
$\rho$ = air density, kg/m$^3$;
$v$ = wind speed, at roof height of building, m/s.

Pressure coefficients depend on the façade and wind direction (linear interpolation between given directions). The wind contribution to pressure is assumed to be constant over the whole surface.

The atmospheric pressure value in Copenhagen and Palermo is downloaded from a weather file retrievable from the Energy Plus website in *.epw* format [21]: the source is IWEC[1] for Copenhagen and IGDG[2] for Palermo.

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[1] The IWEC (International Weather for Energy Calculations) are the result of ASHRAE Research Project 1015 by Numerical Logics and Bodycote Materials Testing Canada for ASHRAE Technical Committee 4.2 Weather Information. The IWEC data files are 'typical' weather files suitable for use with building energy simulation programs for 227 locations outside the USA and Canada. All 227 locations in the IWEC data set are available for download in Energy Plus weather format.

The hourly wind data in IDA ICE (*.prn*) are the components (catheters) of the wind vector (hypotenuse), on the x-axis (East-West) and y-axis (North-South). The wind data in the *.epw* file is the wind speed (*w*), calculated with Eq. (V.2):

$$w = \sqrt{x^2 + y^2} \qquad \text{(V.2)}$$

### V.3.2 Building model description

The used model, originally developed by Olesen and Dossi (2004), represents the central module of an office building consisting of two offices separated by a corridor (Figs. V.2 and V.3).

Offices and the corridor are treated as separate zone. The offices have a floor area of 19.8 m$^2$ (5.5 m x 3.6 m) and the corridor has a floor area of 8.6 m$^2$. The external walls, facing north (office north) and south (office south) have a window with a frame whose area is 4.95 m$^2$ (1.65 m x 3 m). All the internal walls of the building model are assumed adiabatic, except for the walls between the corridor and the offices.

The value used for infiltration is 0.3 vol/h in offices north and office south, while for the corridor the infiltration is zero. In Tab. V.1 the thermal-physical characteristics of the building components are shown.

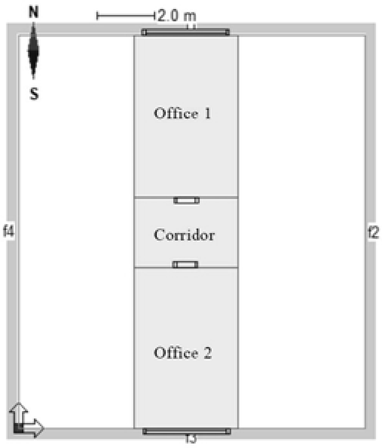

**Figure V.2** *Plan of the model*

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[2] The IGDG (Italian Climatic data collection "Gianni De Giorgio" is a weather data source developed for use in simulating renewable energy technologies, this set of 66 weather files is based on a 1951-1970 period of record.

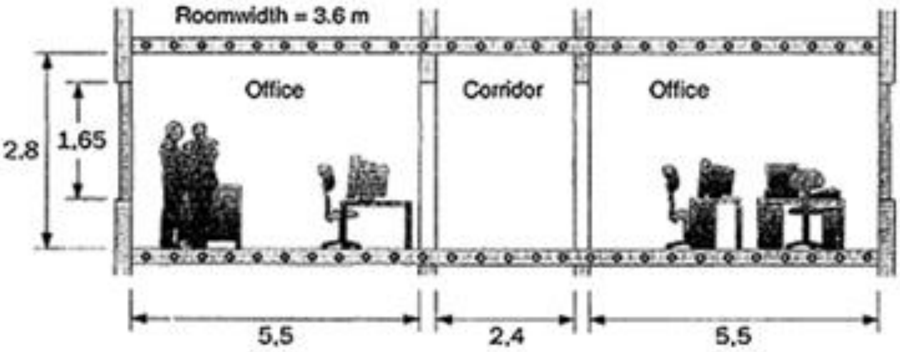


**Figure V.3** *Longitudinal section of the model (Olesen and Dossi, 2004)*

**Table V.1** *Thermal characteristics of the building components. s: thickness; $\rho$: density, $\lambda$: thermal conductivity, c: specific heat, $\varepsilon$: emissivity (Kolarik et al., 2011)*

| Typology | Component | $s$ [mm] | $\rho$ [kg/m$^3$] | $\lambda$ [W/m·K] | $c$ [W·h/kg·K] | $\varepsilon$ [-] |
|---|---|---|---|---|---|---|
| Floor/ceiling | Floor coating | 5 | 1100 | 0.18 | 0.26 | 0.95 |
| | Concrete | 150 | 2300 | 1.7 | 0.24 | |
| | Air gap | 500 | 1.2 | 2.8 | 0.28 | |
| | Ceiling panels | 20 | 970 | 0.22 | 0.30 | |
| Outside wall | Plaster | 8 | 1000 | 0.7 | 0.28 | 0.82 |
| | Insulation | 80 | 40 | 0.04 | 0.42 | |
| | Sand lime Brick | 240 | 1200 | 0.56 | 0.28 | |
| | Plaster | 15 | 1200 | 0.35 | 0.28 | |
| Internal wall | Plaster | 15 | 1200 | 0.35 | 0.28 | 0.82 |
| | Sand lime brick | 115 | 1800 | 0.99 | 0.28 | 0.93 |
| Windows | Wooden frame | Heat transfer coefficient for the frame, W/m$^2$·K | | | | 2.1 |
| | 2 plane glazing, 4-12-5 | Heat transfer coefficient for the glazing, W/m$^2$·K | | | | 1.1 |
| | | Overall heat transfer coefficient, W/m$^2$·K | | | | 1.4 |
| | | Solar heat gain coefficient, 1 | | | | 0.58 |

### V.3.3 Building model setting

The model setting criteria are described below.

#### V.3.3.1 Heat pumps

Each office is equipped with a heating and cooling system connected to a heat pump; the characteristics are in Tab.V.2. The setpoint is defined on the base of EN 16798-1 Standard (CEN, 2019a).

In Tab.V.3 and Tab.V.4, the daily and yearly operation time of the HVAC system is reported. The yearly operation time indicates when the heating is on during winter and the cooling during summer. The heating season in Palermo is consistent with Italian law (President of Italian Republic, 1993), while in Copenhagen it is arbitrary based on the most common period of switch-on heating system, not being specified within the standards.

**Table V.2** *Characteristics of heating and cooling system*

| | Heating (Offices) | Cooling (Offices) | Heating/cooling (Corridor) |
|---|---|---|---|
| Capacity [kW] | 2 | 2 | - |
| Efficiency | 0.9 | 3 | - |
| Setpoint [°C] | 20.5 | 25.5 | - |

**Table V.3** *Operation time for heating, cooling and ventilation*

| Location | Room | Heating | Cooling | Ventilation |
|---|---|---|---|---|
| Copenhagen | Offices | 8:30-16:00 | 8:30-16:00 | 8:30-16:00 |
| Palermo | Corridor | - | - | 8:30-16:00 |

**Table V.4** *Operation period for heating, cooling and ventilation*

| Location | Room | Heating | Cooling | Ventilation |
|---|---|---|---|---|
| Copenhagen | Offices | 01/10-30/04 | 01/05-30/09 | 1/1-31/12 |
| | Corridor | - | - | 1/1-31/12 |
| Palermo | Offices | 01/12-31/03 | 01/04-30/11 | 1/1-31/12 |
| | Corridor | - | - | 1/1-31/12 |

### *V.3.3.2 Ventilation system*

The characteristics of the ventilation system operating both in offices and in the corridor are shown in Tab. V.5 and the ventilation rate values are defined by EN 16798-1 Standard for category II of indoor environmental quality level.

The supplied air is at outdoor temperature and, the system provides heating/cooling when the operative temperature is below/above the desired temperature setpoint.

Tab. V.6 shows the ventilation rate values defined by EN 16798-1 Standard for Category II. Eq. (V.3) shows the total ventilation rate for the breathing zone by combining the ventilation required for people emissions and building emissions (CEN, 2019a):

**Table V.5** *Characteristics of the ventilation system*

| Room | pressure [Pa] | Efficiency [%] |
|---|---|---|
| Offices | 150 | 150 |
| Corridor | 70 | 70 |

**Table V.6** *Ventilation rate value*

| Room | For occupancy per person [l/s-person] | For emissions from building [$l/s\cdot m^2$] |
|---|---|---|
| Offices | 7 | 0.7 |
| Corridor | - | 0.7 |

$$q_{\text{tot}} = n \cdot q_{\text{p}} + A_{\text{R}} \cdot q_{\text{B}} \tag{V.3}$$

where:

$q_{\text{tot}}$ = total ventilation rate for the breathing zone, l/s;

$n$ = design value for the number of persons in the room, 1;

$q_{\text{p}}$ = ventilation rate for occupancy per person, l/(s·person);

$A_{\text{R}}$ = floor area, $m^2$;

$q_{\text{B}}$ = ventilation rate for emissions from building, l/(s·$m^2$).

### *V.3.3.3 Auxiliary devices*

Another relevant difference between the two software is the calculation of energy needed for auxiliary devices: IDA ICE permits to choose of the characteristics of the fans in the AHU in terms of pressure rise, efficiency and specific fan power, *SFP* (in the case study respectively 150 Pa, 70% and

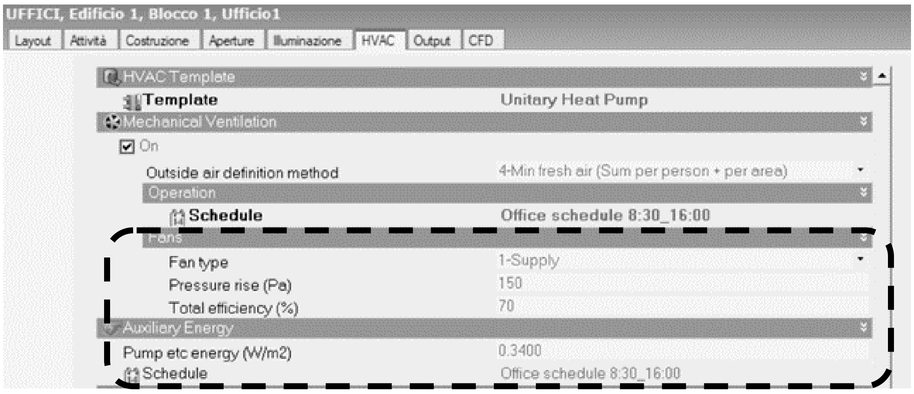
0.21 kW·s /$m^3$) and the characteristics of the pumps used for heating and cooling in terms of nominal pressure heat and efficiency (in case study respectively 30 kPa and 50%).

Design Builder does not consent to insert these data, but it is possible to choose the way to calculate energy used from auxiliary devices, separately for pumps and fans. Particularly, in the section “HVAC” it is possible to establish the values of pressure rise, $\Delta p$ (Pa), and efficiency (%) of the fans, and the power density of pumps, in W/$m^2$ (Fig. V.4). The values of energy consumption of pumps and fans are shown in "Design Builder Result Viewer", a separate application which can be used to view some specific Energy Plus results stored [22].

In Design Builder the total energy needed for pumps is expressed as density power (W/$m^2$). The total energy consumption for each zone is displayed in the Simulation results in the “Electric Equipment” section for each room (office north, corridor, office south).

Design Builder considers the energy of the fans based on fan pressure rise and efficiency values as defined in mechanical ventilation theory. The values of energy use for fans are displayed in simulation results as “Fan Electric Energy” for each room (office north, corridor, office south) and they depend on the actual mechanical ventilation flow rates applied in the simulation [23].

So, to compare the contribution of auxiliary devices' energy, the characteristics of fans and values of the power density for the pump (W/$m^2$) calculated from IDA ICE are used as input values in Design Builder.



Template Unitary Heat Pump
☑ On
Outside air definition method 4-Min fresh air (Sum per person + per area)
Schedule Office schedule 8:30_16:00
Fan type 1-Supply
Pressure rise (Pa) 150
Total efficiency (%) 70
Pump etc energy (W/m2) 0.3400
Schedule Office schedule 8:30_16:00

**Figure V.4** *Energy of auxiliary - Input data in Design Builder*

### *V.3.3.4 Internal heat gains*

The internal loads are due to people, appliances, and lighting. The occupancy hours, the lighting and the appliances are based on the schedules defined in Annex C of EN 16798-1 for a single office: occupants are present only during weekdays from 09:00 to 12.00 and from 13.00 to 16.00 (CEN, 2019a).

#### V.3.3.4.1 Occupants

Each office has 2 occupants with a metabolic rate of 1.2 met which corresponds to 70 W/m$^2$ as specified by the 8996 Standard (CEN, 2021).

Considering a body surface of an adult person equal to 1.8 m$^2$ the metabolic rate value is 126 W/person (Du Bois, 1916).

According to EN 16798-1 Standard, the thermal insulation of clothing values is chosen for the seasons: 1 clo for the heating season and 0.5 clo for the cooling season.

#### V.3.3.4.2 Appliance

According to EN 16798-1 Standard, the thermal load due to appliances for each office is assumed to equal 12 W/m$^2$, corresponding to 237.6 W (CEN, 2019a).

#### V.3.3.4.3 Lighting

The Eq. (V.4) gives the convection fraction of the heat exchanged ($q_c$) between lamps and the air in the considered zone:

$$q_{\mathrm{c}} = 1.0 - \left(q_{\mathrm{e}} + q_{\mathrm{r,l}} + q_{\mathrm{r,s}}\right) \tag{V.4}$$

where:

$q_e$ = fraction of the heat from light that is transported out of the room and into the zone return air (normally into a return plenum), 1;

$q_{r,l}$ = fraction of heat from light that goes into the zone as long-wave radiation, 1;

$q_{r,s}$ = fraction of heat from light that goes into the zone as visible (short-wave) radiation, 1 [24].

For example, using a fraction of long-wave radiation equal to 0.5 and a fraction of visible radiation equal to 0.2 and assuming 50 W installed in offices and 100 W suspended lights in the corridor, the convected fraction is expressed with Eq. (V.5):

$$q_c = 1.0 - \left[0.0 + 0.5 + 0.2\right] = 0.3 \tag{V.5}$$

### *V.3.3.5 Air velocity*

The overall thermal comfort assessment depends on the mean air velocity. The default value in Design Builder is $v_a$= 0.137 m·s$^{-1}$ [25]. A value of $v_a$= 0.1 m·s$^{-1}$ is fixed for both software, which is a value generally used in the simulation of indoor environments when air is stagnant.

## V.4 Results and discussion

This section illustrates the results of simulations performed for each location, considering the same model with two different window area surface values. The synthesis of model configurations and simulations is reported in Tab. V.7.

Tab. V.8 shows a synthesis of results obtained from each comparison.

**Table V.7** *Synthesis of simulations for each software (Design Builder and IDA ICE)*

| Scenario | Location | Simulation | Window size [$m^2$] | Window area [$m^2$] | Increase of window [%] |
|---|---|---|---|---|---|
| 1 | Copenhagen | CPH1 | 4.9 $m^2$ | 49.1 | - |
| | Palermo | PA1 | (1.6 m x 3 m) | | |
| 2 | Copenhagen | CPH2 | 7.4 $m^2$ | 73.7 | 50% |
| | Palermo | PA2 | (2.5 m x 3 m) | | |

**Table V.8** *Synthesis of the simulations: scenarios 1 (small window) vs 2 (large window) and Design Builder vs IDA ICE*

| Comparison | Temperature | Energy flows | Delivered energy |
|---|---|---|---|
| *Relative differences* (Scenario 1 *vs* 2) | trend of $t_o$ | energy flows for each component in kWh | annual heating/cooling energy use per square meter |
| | percentage of time of $t_o$ within the limits of setpoint for winter and summer | percentage of differences of the annual energy flows for each component | percentage of difference of the annual heating/cooling energy use per square meter |
| *Absolute differences* (Scenario 1 or 2 Design Builder *vs* scenario 1 or 2 IDA ICE) | trend of $t_o$ and $t_r$ | energy flows for each component in kWh | percentage of difference of the annual heating/cooling energy use per square meter |
| | percentage of occurrences of differences in $t_o$, $t_a$, $t_r$ for specific ranges | percentage of difference of annual energy flows for each component | |

### *V.4.1 U-value of building components*

The U-value of the building influences both thermal comfort (because operative temperature depends on it) and delivered energy.

Both software initially assumes a fixed U-value which changes during simulation because of external parameters.

As well known, the U-value depends on internal and external surface resistances, which values are prescribed by Standards. IDA ICE and Design Builder use different approaches, so they give different U-values.

IDA ICE sets the surface resistance equal to 0.13 $m^2 \cdot K/W$ and 0.04 $m^2 \cdot K/W$ for plane surfaces respectively internal and external (CEN, 2017). These values vary during simulation according to surface temperatures and ventilation rate for the inside film coefficient and according to wind direction and speed for the outside one [26].

Design Builder uses different heat transfer coefficients depending on the type of building component (floor, ceiling, wall,) according to ASHRAE 90.1 Standard (ASHRAE, 2019).

In Tab. V.9 parameters used in software for calculation of thermal conductance are summarized; in Tab. V.10 the internal and external surface resistances with the resulting U-value calculated from each software are compared. The higher difference, equal to 12%, is related to the floor, followed by the ceiling (6%) and finally to internal walls (with a reduction of 5% from Design Builder to IDA ICE). The reason for lower U-values in Design Builder in the case of the floor is related to the increase of the internal resistance $R_{si}$ (which ranges from 0.11 $m^2K/W$ to 0.16 $m^2K/W$ in Design Builder while does not change in IDA ICE).

The U-value of the windows depends on the thermo-physical properties of the materials in the fenestration product assembly and the weather conditions, such as the difference between indoor and outdoor temperatures and wind speed.

The windows are modelled in *ad hoc* “Window” program to determine the thermal and solar optical properties of glazing and window systems and after the modelling, the windows with their characteristics in Design Builder are imported.

The characteristic of the frame and glasses are in Tab. V.1. The default value in “Window” for estimating the overall U-factor of a fenestration unit is based on NFRC[3] methodology which calculates external U-value using the conditions [27]:

- Wind speed = 5.5 $m \cdot s^{-1}$.
- Indoor air temperature = 21 °C.
- Outdoor temperature = -18°C.

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[3] NFRC-National Fenestration Rating Council is the organization that administers a window certification program in the United States.

**Table V.9** *Thermal property values used for calculation of the thermal conductance in Design Builder and IDA ICE, in the considered model*

| Building Construction | Building component | Thickness [m] | Thermal conductivity [W/m·K] | Thermal conductance [W/m$^2$·K] |
|---|---|---|---|---|
| Ceiling/Roof | Floor coating | 0.005 | 0.18 | |
| | Concrete | 0.15 | 1.7 | |
| | Air gap | 0.5 | 2.8 | |
| | Ceiling panels | 0.02 | 0.22 | |
| | | | | 2.6 |
| Floor | Floor coating | 0.005 | 0.18 | |
| | Concrete | 0.15 | 1.7 | |
| | Air gap | 0.5 | 2.8 | |
| | Ceiling panels | 0.02 | 0.22 | |
| | | | | 2.6 |
| Outside wall | Heavy plaster | 0.008 | 0.7 | |
| | Insulation | 0.08 | 0.04 | |
| | Sand lime brick | 0.24 | 0.56 | |
| | Plaster | 0.015 | 0.35 | |
| | | | | 0.4 |
| Internal wall | Plaster | 0.015 | 0.35 | |
| | Sand lime brick | 0.115 | 0.99 | |
| | Sand lime brick | 0.115 | 0.99 | |
| | Plaster | 0.015 | 0.35 | |
| | | | | 3.1 |

**Table V.10** *Comparison between U-value calculated from Design Builder and IDA ICE in the considered model.* $R_{si}$*: internal resistance;* $R_{se}$*: external resistance,* $\Delta$*: difference*

| | Design Builder | | | IDA ICE | | | |
|---|---|---|---|---|---|---|---|
| | $R_{si}$ [m$^2$·K/W] | $R_{se}$ [m$^2$·K/W] | *U-value* [W/ m$^2$·K] | $R_{si}$ [m$^2$·K/W] | $R_{se}$ [m$^2$·K/W] | *U-value* [W/m$^2$·K] | $\Delta$ [%] |
| Ceiling roof | 0.11 | 0.08 | 1.7 | 0.13 | 0.04 | 1.8 | 6 |
| Floor | 0.16 | 0.08 | 1.6 | 0.13 | 0.04 | 1.8 | 12 |
| Outside wall | 0.12 | 0.03 | 0.4 | 0.13 | 0.04 | 0.4 | 0 |
| Internal wall | 0.12 | 0.03 | 2.1 | 0.13 | 0.04 | 2.0 | -5 |

### *V.4.2 Influence of surface area of the window*

The following section illustrates differences related to each software between scenario 1 (small window) and 2 (large window) in terms of the trend of temperatures and energy use.

#### *V.4.2.1 Operative temperature*

The graphics in Figs.V.5, V.6, V.7, and V.8 show the trend of annual operative temperature. Dashed black lines are the limit of seasons (winter/summer) and red lines limit the limits of the thermal comfort zone according to EN 16798-1 Standard for the heating and cooling season. The graphics are referred to the occupied rooms: office north and office south.

From the trends, the operative temperatures values predicted for scenario 2 (large window) are always higher than those exhibited by scenario 1 (small window).

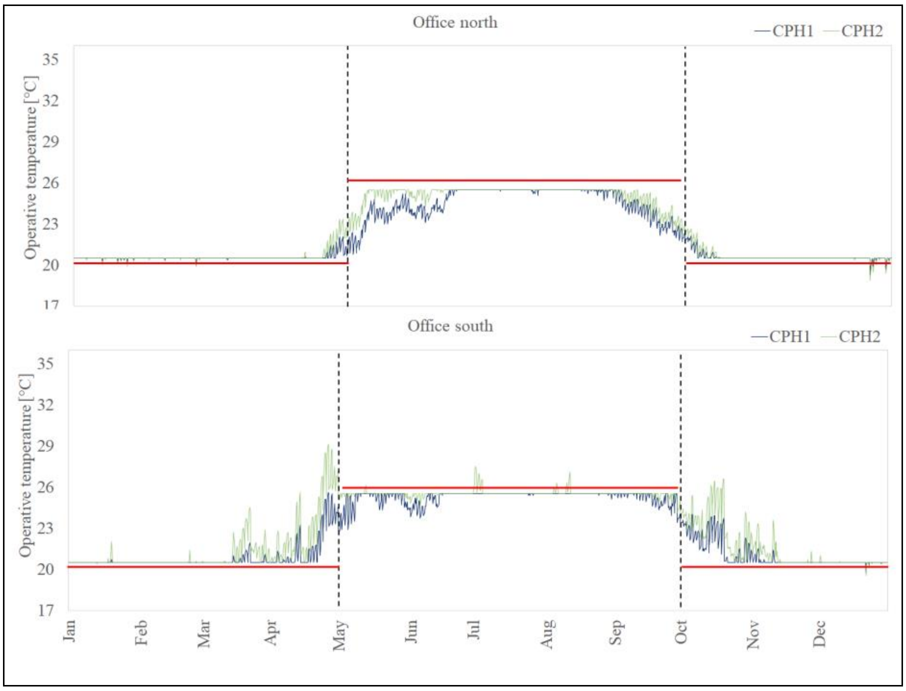

**Figure V.5** *Operative temperature, Copenhagen, Design Builder*

**Figure V.6** *Operative temperature, Copenhagen, IDA ICE*

**Figure V.7** *Operative temperature, Palermo, Design Builder*

**Figure V.8** *Operative temperature, Palermo, IDA ICE*

Tab. V.11 shows the percentage of the hour in which the operative temperature value is equal/higher than the minimum value (20 °C) imposed by EN 16798-1 Standard (CEN, 2019b) for winter and equal/lower than the maximum for summer (26 °C). The percentages of time of operative temperature in the limits of Standard from Eqs. (V.6) and (V.7) are shown for winter and summer.

The equations are valid for Palermo also. The total amount of hours is referred to office opening time:

$$Time_{t_o \geq 20°C,north} = \frac{CPH1_{winter} \cdot 100}{912} \tag{V.6}$$

$$Time_{t_o \leq 26°C,north} = \frac{CPH1_{summer} \cdot 100}{654} \tag{V.7}$$

where:

$CPH1_{winter}$ = hours of temperature values equal/higher than 20°C (setpoint for winter);

$CPH1_{summer}$ = hours of temperature values equal/lower 26°C (setpoint for summer);

$Time_{t_o \geq 20°C,north}$ = percentage of the hour in which the operative temperature value is equal/higher than the minimum value (20°C) for winter in the office north, %;

$Time_{t_o \leq 26°C,north}$ = percentage of the hour in which the operative temperature value is equal/lower than the maximum value (26°C) for summer in the office north, %.

The window surface influences the operative temperature trend mainly in Palermo in the south office, due to the greater solar radiation coming from the larger window.

Although the high percentages in Tab. V.11, this does not correspond to thermal comfort conditions. In fact, as is the case of Palermo with increased window area, during winter, the temperatures also reach 35 ° C.

This is due to a free-running condition whereby the thermal loads in the model are so elevated that the internal environment reaches high-temperature values with a not active heating system.

This condition denotes a limit in the use of Design Builder because the software with a Simple HVAC model, does not allow the simulation of thermal comfort conditions, making available to the user only the possibility of defining the temperature setpoint for winter and summer and not fixing a comfort range so as indicated in the EN 16798-1 Standard.

During the summer, the presence of large windows worsens comfort conditions, especially for Palermo. IDA ICE reports a more noticeable temperature variation in the north office (20%) if compared to Design Builder (6%). In the case of the south office, Palermo reaches higher percentages than those observed in the northern (e.g., 25% of reduction of thermal comfort for IDA ICE and 24% for Design Builder).

Observing the graphs of Figures V.5 to V.8, the differences between scenario 1 and scenario 2 generally occur in the same period of the year for each city in both software.

Furthermore, in the case of Copenhagen, the differences are not very high, and they are mainly recorded during the intermediate seasons, while for Palermo they are greater and concern almost the whole year.

Passing by scenario 1 to scenario 2, the percentages differences during winter and summer for each office, are equal in terms of directions (decrease or increase) in both software. The differences in the trend of operative temperature between scenarios 1 and 2 are higher in IDA ICE compared to Design Builder above all for Palermo during summer. This should make to reflect on the consequences of using different software in the calculation of thermal comfort.

From the Tab. V.11, it is clear that in general between scenarios 1 and 2 there are no major differences in winter, while in summer the percentage of operative temperature hours within the thermal comfort limit is reduced especially for Palermo, for both software. In particular, IDA ICE reports a notable temperature variation also in the north office compared to Design Builder, apparently not justifiable.

**Table V.11** *Percentage of time of operative temperature within the limit of setpoint during winter (W) and summer (S), and the percentage of the difference between scenarios 1 and 2 in winter (ΔW) and in summer (ΔS)*

| Software | Simulation | Office | *W* [%] | *S* [%] | *ΔW* [%] | *ΔS* [%] |
|---|---|---|---|---|---|---|
| Design Builder | CPH1 | North | 100 | 100 | | |
| | | South | 100 | 100 | | |
| | CPH2 | North | 100 | 100 | 0 | 0 |
| | | South | 100 | 97 | 0 | -3 |
| | PA1 | North | 100 | 99 | | |
| | | South | 100 | 85 | | |
| | PA2 | North | 100 | 93 | 0 | -6 |
| | | South | 100 | 61 | 0 | -24 |
| IDA ICE | CPH1 | North | 100 | 100 | | |
| | | South | 99 | 98 | | |
| | CPH2 | North | 97 | 100 | 0 | 0 |
| | | South | 99 | 90 | 0 | -8 |
| | PA1 | North | 100 | 96 | | |
| | | South | 100 | 74 | | |
| | PA2 | North | 100 | 76 | 0 | -20 |
| | | South | 100 | 49 | 0 | -25 |

Moreover, it should be considered that the operative temperature values in Palermo in winter exceed the upper limit of the thermal comfort range, and also when the heating system is off, like in this simulation. This implies switching on the cooling system also during some periods in winter to have thermal comfort conditions.

#### *V.4.2.2 Energy*

The hourly values of the energy represent the sum of latent and sensible heat for each simulated hour of the year.

The Figs. V.9, V.10, V.11, and V.12 show the annual thermal energy flows in kW·h transferred from each building component. Negative values represent heat losses whereas positive are heat gains.

The percentage of differences in energy flows for each component compared to total energy delivered with Eq. (V.8) are calculated:

$$\Delta_{EF} = \frac{(CPH2\text{-}CPH1)_{\text{ENVELOPE}}}{(CPH2+CPH1)_{\text{Tot.}}\cdot 0.5}\cdot 100 \qquad \text{(V.8)}$$

where:

| | |
|---|---|
| $\Delta_{\text{EF}}$ | differences of energy flows for each component, %; |
| $CPH1$ | energy flows for Copenhagen in scenario 1 (small window); |
| $CPH2$ | energy flow for Copenhagen in scenario 2 (large window). |

A similar equation is used for Palermo.

For both simulation tools, the higher differences occur in Palermo for the office south where the energy flow increases by 74% (72%) for “window and solar” and decreases by 49% (34%) for “cooling” in Design Builder (IDA ICE).

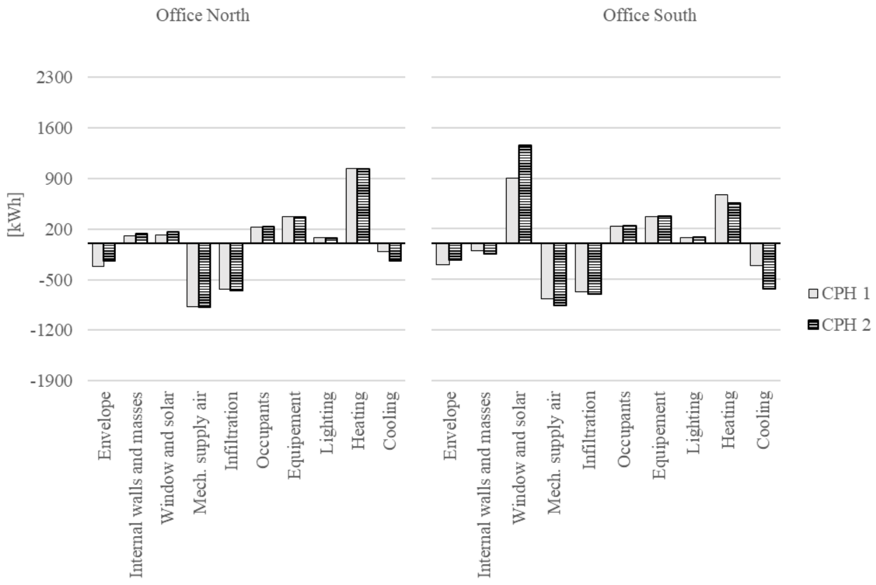

**Figure V.9** *Energy flows, Copenhagen, Design Builder*

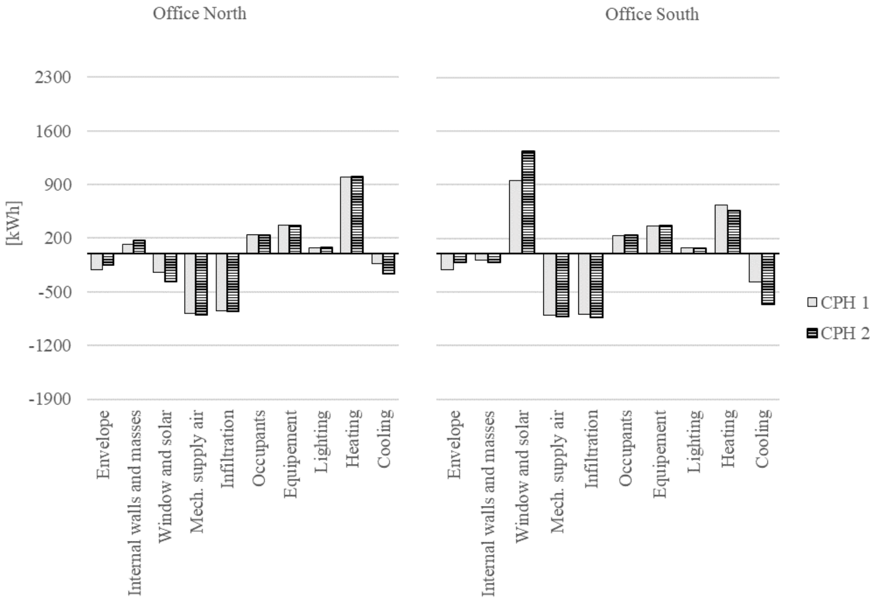

**Figure V.10** *Energy flows, Copenhagen, IDA ICE*

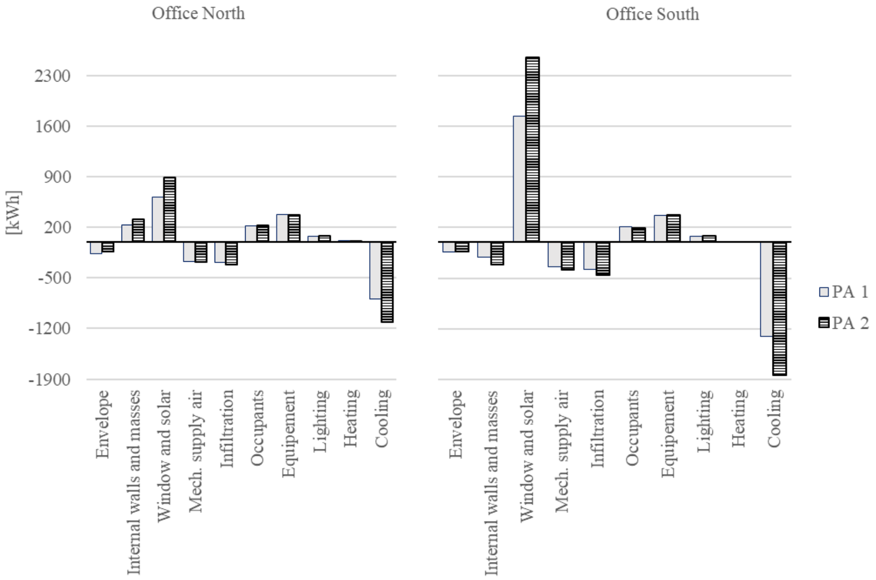

**Figure V.11** *Energy flows, Palermo, Design Builder*

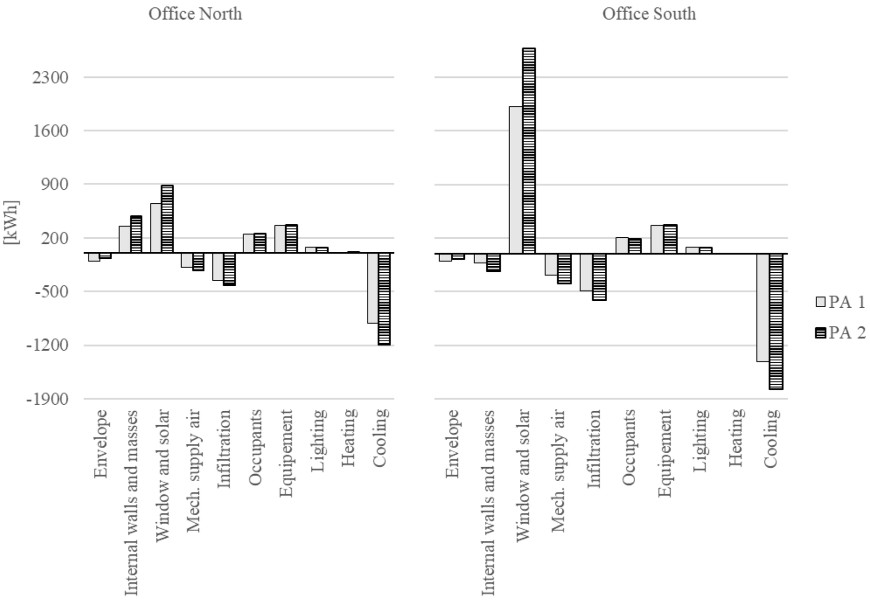

**Figure V.12** *Energy flows, Palermo, IDA ICE*

Regarding solar gains, Energy Plus distinguishes between the positive contributions due to solar gains and the heat losses through windows, while IDA ICE considers a generic external window and solar energy flow which can be negative or positive. So, to compare results, in Design Builder the values related to solar gains and the losses through windows are added.

Design Builder and IDA ICE differ also in the evaluation of solar radiation through windows. In IDA ICE the calculation is based on a simplified model which considers the overall solar radiation absorbed by the window system (Mazzeo et al., 2020). Then, this absorbed solar radiation is split equally on the two boundary faces and the surface heat balance equations are solved. Energy Plus calculates the temperature of each glass pane of the window with a layer-by-layer approach using a specific program WINDOW[4], to define accurately the features of windows [27]. This difference probably affects the results in the higher temperatures trends of IDA ICE compared to Design Builder as previously shown and it could also affect energy flows.

### V.4.2.3 Delivered energy

Fig. V.13 show the annual values of delivered energy for heating and cooling per square meter for each simulation.

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[4] WINDOW is a state-of-the-art, Microsoft Windows TM-based computer program developed at Lawrence Berkeley National Laboratory (LBNL) for use by manufacturers, engineers, educators, students, architects, and others to determine the thermal and solar optical properties of glazing and window systems.

Tab. V.12 shows the percentage of difference in the annual heating/cooling energy use per square meter for cooling and heating. The percentages are calculated by Eqs. (V.9) and (V.10) respectively for cooling and heating which are valid also for Palermo.

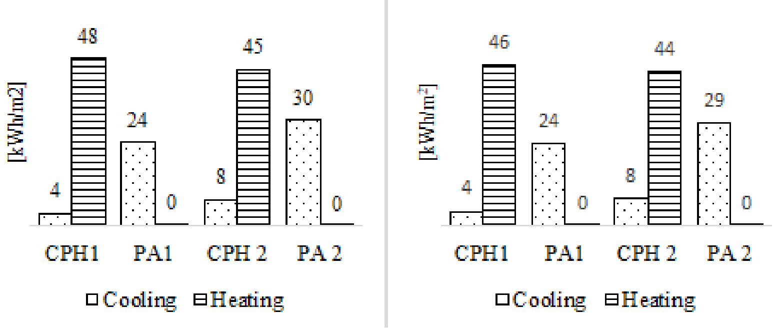


**Figure V.13** *The annual heating/cooling energy use in kW·h/m$^2$ in Design Builder (left), and IDA ICE (right)*

$$\Delta C = \frac{(CPH2\text{-}CPH1)_{\mathrm{C}}}{(CPH2+CPH1)_{\mathrm{Tot.}}\cdot 0.5}\cdot 100 \qquad \text{(V.9)}$$

$$\Delta H = \frac{(CPH2\text{-}CPH1)_{\mathrm{H}}}{(CPH2+CPH1)_{\mathrm{Tot.}}\cdot 0.5}\cdot 100 \qquad \text{(V.10)}$$

where:

| | |
|---|---|
| $\Delta C$ | difference in energy use for cooling, %; |
| $\Delta H$ | difference in energy use for heating, %; |
| $CPH1$ | energy use for Copenhagen in scenario 1 (small window); |
| $CPH2$ | energy use for Copenhagen in scenario 2 (large window). |

**Table V.12** *Difference percentage of the annual delivered energy between scenario 1 (small window) and 2 (large window). ΔC: cooling difference; ΔH: heating difference*

| Software | Simulation | Cooling [kW·h/m$^2$] | Heating [kW·h/m$^2$] | Total [kW·h/m$^2$] | *ΔC* [%] | *ΔH* [%] |
|---|---|---|---|---|---|---|
| Design Builder | CPH1 | 4 | 48 | 52 | | |
| | CPH2 | 8 | 45 | 52 | 8 | **-6** |
| | PA1 | 24 | 0 | 24 | | |
| | PA2 | 30 | 0 | 31 | 22 | 0 |
| IDA ICE | CPH1 | 4 | 46 | 50 | | |
| | CPH2 | 8 | 44 | 52 | 8 | **-4** |
| | PA1 | 24 | 0 | 24 | | |
| | PA2 | 29 | 0 | 29 | 19 | 0 |

The values of annual energy use per square meter are similar in Design Builder and IDA ICE. As expected, there is an increase in energy for cooling and a decrease in energy for heating from scenario 1 to scenario 2. The difference percentage is similar between the two software except for heating in Copenhagen (highlighted in bold in Tab. V.12): in Design Builder the percentage of differences (6%) between the two scenarios is almost double that of IDA ICE (4%). However, the values are low.

In cooling mode, the differences remain small for Copenhagen but increase for Palermo, due to the high radiant load.

Comparing the trend of operative temperature and delivered energy it can be said that a minimum decrease of the energy for heating in scenario 2 does not result in variations in the percentage of operative temperature values higher than 20 °C. The increase of cooling during summer, due to the increased solar radiation, does not result in more time of operative temperatures below 26 °C. This is probably related to the heating and cooling system, which is not sufficient in terms of capacity and/or control, to achieve acceptable thermal comfort conditions.

## *V.4.3 First scenario (small window). Design Builder vs IDA ICE*

### *V.4.3.1 Temperatures*

Figs. V.14, V.15, V.16, V.17, and V.19 show the trend of air temperature, mean radiant temperature, and operative temperature.

**Figure V.14** *Air temperature, Copenhagen, scenario 1*

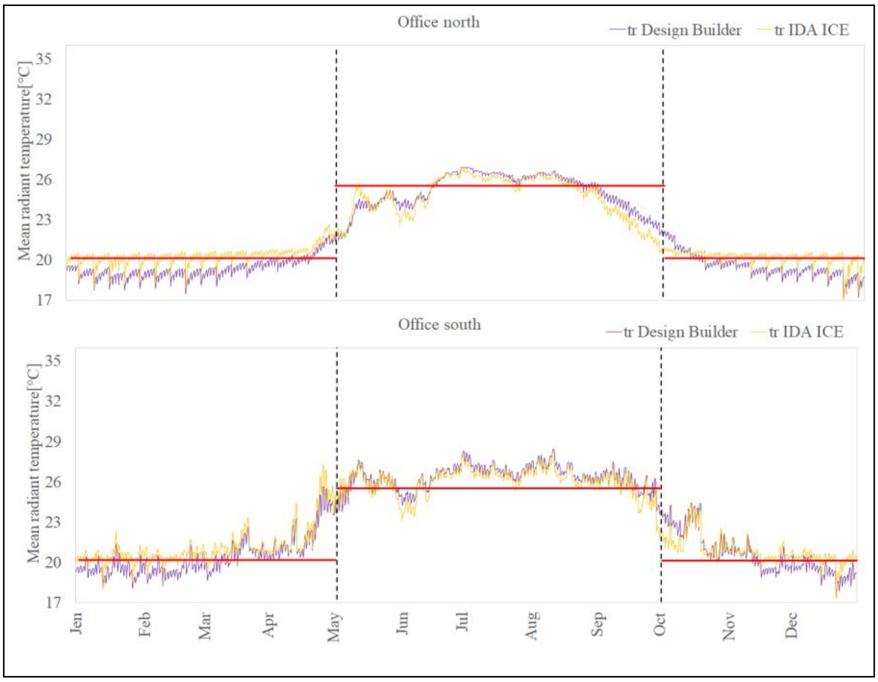


**Figure V.15** *Mean radiant temperature, Copenhagen, scenario 1*

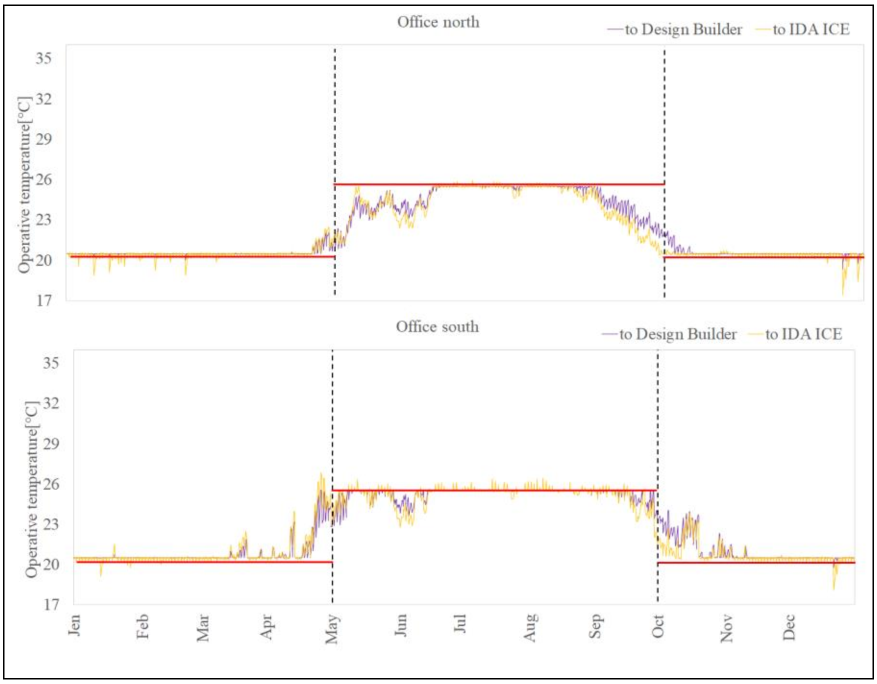


**Figure V.16** *Operative temperature, Copenhagen, scenario 1*

**Figure V.17** *Air temperature, Palermo, scenario 1*

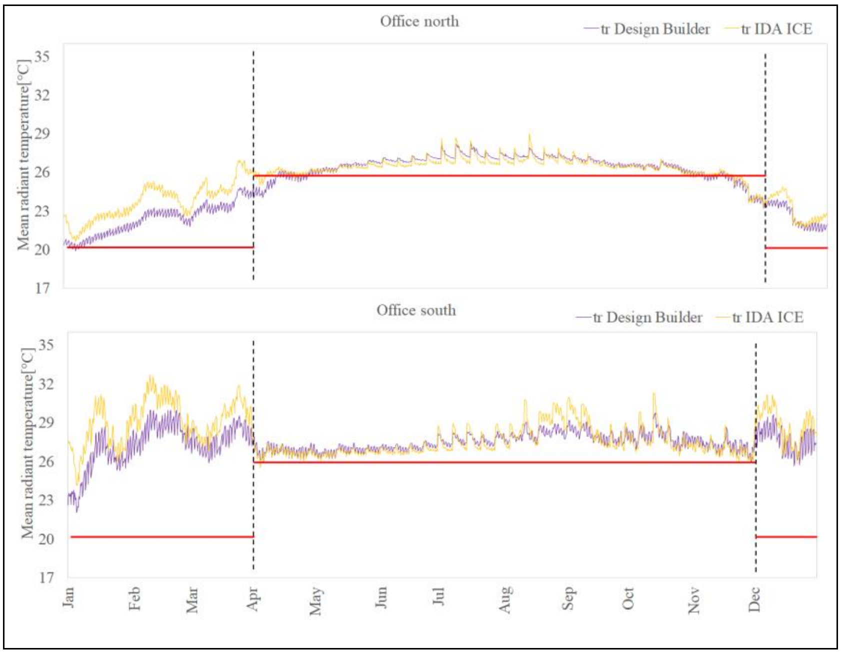


**Figure V.18** *Mean radiant temperature, Palermo, scenario 1*

**Figure V.19** *Operative temperature, Palermo, scenario 1*

Looking at the graphics in general, there are some differences between the results obtained from the two software for both offices.

In Tab. V.13 occurrences of differences in operative temperature, mean radiant temperature, and air temperature (in Copenhagen and Palermo) calculated using the two software are shown. The temperature differences are calculated hour by hour. The range of the difference between the two temperatures, the one determined with Design Builder and the one with IDA ICE, is then defined ($n \leq 0.5$°C; 0.5°C<$n$<1°C; 1°C<$n$<2°C; $n \geq 2$°C). Finally using Eq. (V.11), which is valid for each $n$ and each office, and considering only occupied hours (1566), the percentage of occurrences in each range is calculated:

$$\Delta\theta_{\%} = \frac{n}{1566} \cdot 100 \qquad \text{(V.11)}$$

where:

$\Delta\theta_{\%}$ is the fraction of the time that the temperature difference values fall into a specific range, %;

$n$ is the number of hours that the temperature difference values fall into a specific range, n.d.

The behaviour of the two simulation tools seems to be affected by outdoor climatic conditions. Most specifically, the operative temperature difference in Copenhagen is less than 1 °C for more than 90% of the time and it is more than 2°C for less than 3% of the time. The agreement for the mean radiant temperature is slightly worse for both offices' configurations (the time percentage with $\Delta t \leq 1$°C varies from 70 to 82%).

Due to the higher solar load, the temperature values predicted for Palermo by the two-energy software are less close. Particularly, $\Delta t$ values less than 0.5 °C occur in less than 67% (53%) of the time for the North (South) office in the case of scenario 1. In addition, time percentages with $\Delta t$ values higher than 2 °C occur in the 16% (20%) for the operative temperature (air temperature) in the worst case (south office).

Tabs. V.14 and V.15 show the statistical parameters of operative, air and mean radiant temperature in the first scenario for both software during hours of occupation.

**Table V.13** *Temperatures values: differences between values calculated using Design Builder and IDA ICE*

| | $n$ | Office North [%] | Office South [%] | | $n$ | Office North [%] | Office South [%] |
|---|---|---|---|---|---|---|---|
| | | operative temperature | | | | | |
| *CPH*1 | $n \le 0.5$ | 82 | 83 | *PA*1 | $n \le 0.5$ | 67 | 53 |
| | $0.5<n \le 1$ | 11 | 11 | | $0.5<n \le 1$ | 12 | 10 |
| | $1<n \le 2$ | 7 | 5 | | $1<n \le 2$ | 20 | 21 |
| | $n>2$ | 0 | 0 | | $n> 2$ | 2 | 16 |
| | | mean radiant temperature | | | | | |
| | $n \le 0.5$ | 34 | 50 | | $n<=0.5$ | 66 | 46 |
| | $0.5<n \le 1$ | 36 | 32 | | $0.5<n \le 1$ | 10 | 22 |
| | $1<n \le 2$ | 30 | 18 | | $1<n \le 2$ | 21 | 20 |
| | $n>2$ | 0 | 0 | | $n> 2$ | 3 | 12 |
| | | air temperature | | | | | |
| | $n \le 0.5$ | 32 | 47 | | $n<=0.5$ | 59 | 38 |
| | $0.5<n \le 1$ | 28 | 29 | | $0.5<n \le 1$ | 20 | 18 |
| | $1<n \le 2$ | 38 | 23 | | $1<n \le 2$ | 19 | 24 |
| | $n>2$ | 2 | 1 | | $n> 2$ | 2 | 20 |

**Table V.14** *Statistical parameters of temperatures in scenario 1, Copenhagen. Max: maximum temperature; Min: minimum temperature; Q1, Q2, Q3: first, second and third quartile; STD: standard deviation.*

| Statistical parameter | Design Builder<br>Office North | Design Builder<br>Office South | IDA ICE<br>Office North | IDA ICE<br>Office South |
|---|---|---|---|---|
| | operative temperature [°C] | | | |
| *Max* | 25.5 | 25.6 | 25.9 | 26.9 |
| *Q1* | 20.5 | 20.5 | 20.5 | 20.5 |
| *Q2* | 20.5 | 21.6 | 20.5 | 21.4 |
| *Q3* | 24.4 | 25.5 | 24.1 | 25.4 |
| *Min* | 19.3 | 19.7 | 17.4 | 18.1 |
| *STD* | 2.1 | 2.3 | 2.1 | 2.3 |
| | mean radiant temperature [°C] | | | |
| *Max* | 26.9 | 28.5 | 26.9 | 28.1 |
| *Q1* | 19.2 | 19.9 | 20.3 | 20.6 |
| *Q2* | 20.1 | 22.1 | 20.6 | 22.0 |
| *Q3* | 24.6 | 26.3 | 24.5 | 26.1 |
| *Min* | 16.9 | 17.3 | 16.5 | 17.3 |
| *STD* | 3.0 | 3.1 | 2.4 | 2.73 |
| | air temperature [°C] | | | |
| *Max* | 25.5 | 25.5 | 25.5 | 26.4 |
| *Q1* | 21.6 | 21.1 | 20.5 | 20.3 |
| *Q2* | 22.2 | 22.2 | 21.0 | 21.2 |
| *Q3* | 24.1 | 24.1 | 23.7 | 24.3 |
| *Min* | 20.1 | 19.6 | 18.3 | 19.0 |
| *STD* | 1.4 | 1.6 | 1.8 | 2.0 |

**Table V.15** *Statistical parameters of temperatures in scenario 1, Palermo. Max: maximum temperature; Min: minimum temperature; Q1, Q2, Q3: first, second and third quartile; STD: standard deviation.*

| Statistical parameter | Design Builder Office North | Design Builder Office South | IDA ICE Office North | IDA ICE Office South |
|---|---|---|---|---|
| | operative temperature [°C] | | | |
| *Max* | 26.4 | 29.7 | 27.2 | 32.1 |
| *Q1* | 23.1 | 25.5 | 24.2 | 25.5 |
| *Q2* | 25.5 | 25.5 | 25.5 | 25.9 |
| *Q3* | 25.5 | 26.4 | 25.5 | 28.0 |
| *Min* | 20.5 | 21.3 | 20.4 | 23.5 |
| *STD* | 1.6 | 1.0 | 1.3 | 1.6 |
| | mean radiant temperature [°C] | | | |
| *Max* | 28.2 | 30.0 | 29.0 | 32.7 |
| *Q1* | 23.2 | 26.9 | 24.5 | 26.8 |
| *Q2* | 26.0 | 27.5 | 26.1 | 27.5 |
| *Q3* | 26.9 | 28.1 | 26.7 | 29.0 |
| *Min* | 19.9 | 22.0 | 20.6 | 24.1 |
| *STD* | 2.1 | 1.04 | 1.6 | 1.5 |
| | air temperature [°C] | | | |
| *Max* | 25.7 | 29.3 | 26.4 | 31.5 |
| *Q1* | 22.9 | 23.6 | 23.8 | 24.1 |
| *Q2* | 23.9 | 24.1 | 24.3 | 24.7 |
| *Q3* | 24.4 | 25.1 | 24.7 | 27.0 |
| *Min* | 20.2 | 20.5 | 19.9 | 22.8 |
| *STD* | 1.29 | 1.42 | 1.08 | 1.96 |

### *V.4.3.2 Energy*

The Figs. V.20 and V.21 show the energy flows for each component in Design Builder and IDA ICE.

Eq. (V.12) shows the way to calculate the differences in energy flows for each component compared to the total energy delivered.

$$\Delta_{EF} = \frac{(CPH1_{\mathrm{IDA}} \text{-} CPH1_{\mathrm{DB}})_{\mathrm{ENVELOPE}}}{(CPH1_{\mathrm{IDA}} + CPH1_{\mathrm{DB}})_{\mathrm{Tot.}} \cdot 0.5} \cdot 100 \qquad \text{(V.12)}$$

where:

$\Delta_{\mathrm{EF}}$ differences of energy flows for each component, %;
$CPH1_{\mathrm{IDA}}$ Copenhagen in scenario 1 for IDA ICE;
$CPH1_{\mathrm{DB}}$ Copenhagen in scenario 1 for Design Builder.

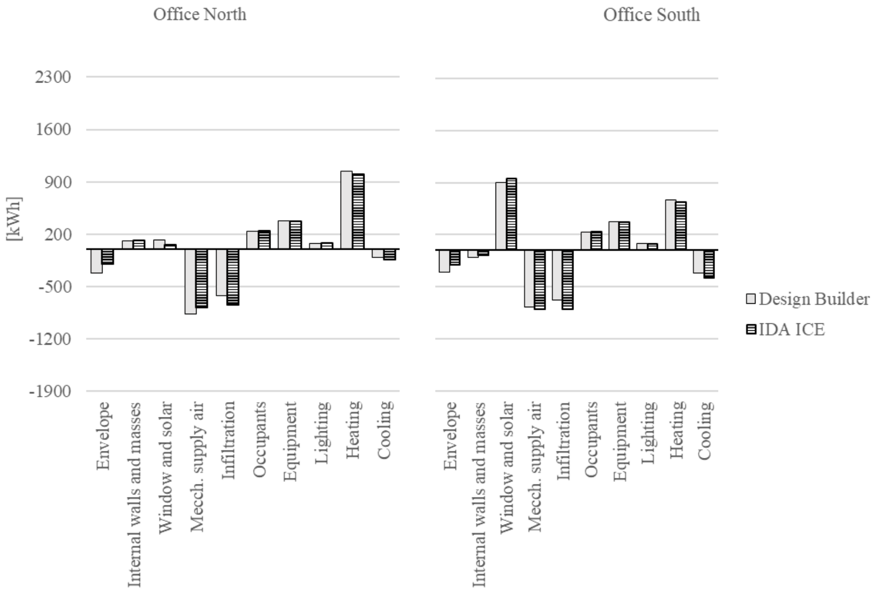


**Figure V.20** *Energy flows, Copenhagen, scenario 1*

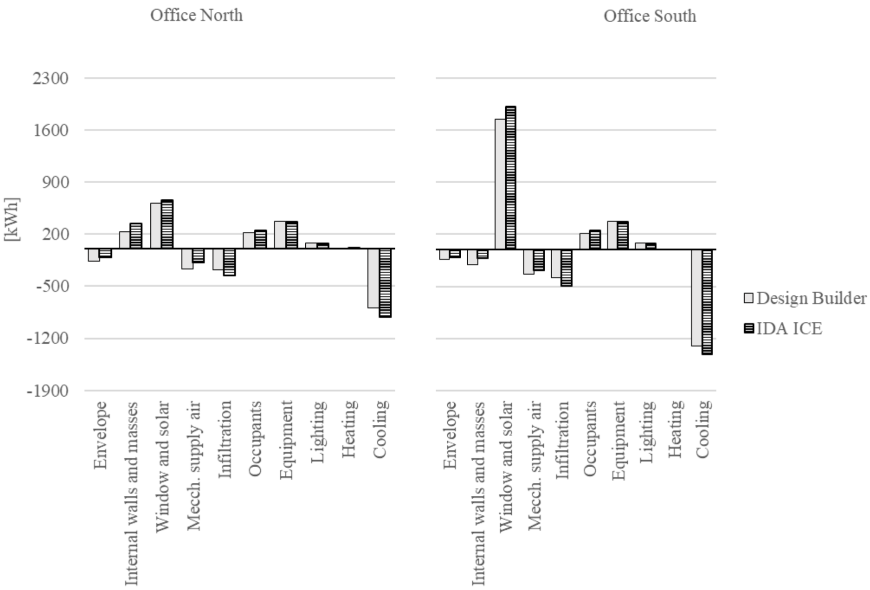


**Figure V.21** *Energy flows, Palermo, scenario 1*

The differences in energy flows predicted by the two simulation tools are generally negligible except for some components where the differences are around 10% (e.g., internal walls and masses, infiltration, windows and solar and cooling). More specifically the “window and solar” component reaches a difference of 19% in the case of office south in Palermo and it could be because of a different way to consider the solar radiation absorbed by the window system in the two software as mentioned above.

### *V.4.3.3 Delivered energy*

In Tab. V.16 the percentages of difference of the annual heating/cooling energy use per square meter compared to the total energy uses are reported. The values are calculated with Eqs. (V.13) and (V.14):

$$\Delta C = \frac{(CPH1_{\mathrm{IDA}}\text{-}CPH1_{\mathrm{DB}})_{\mathrm{C}}}{(CPH1_{\mathrm{IDA}}+CPH1_{\mathrm{DB}})_{\mathrm{Tot.}}\cdot 0.5}\cdot 100 \qquad \text{(V.13)}$$

$$\Delta H = \frac{(CPH1_{\mathrm{IDA}}\text{-}CPH1_{\mathrm{DB}})_{\mathrm{H}}}{(CPH1_{\mathrm{IDA}}+CPH1_{\mathrm{DB}})_{\mathrm{Tot.}}\cdot 0.5}\cdot 100 \qquad \text{(V.14)}$$

where:

| | |
|---|---|
| $\Delta C$ | difference in energy use for cooling, %; |
| $\Delta H$ | difference in energy use for heating, %; |
| $CPH1_{\mathrm{IDA}}$ | energy use for Copenhagen in scenario 1 for IDA ICE; |
| $CPH1_{\mathrm{DB}}$ | energy use for Copenhagen in scenario 1 for Design Builder. |

Data summarized in Tab.16 reveal a good agreement between the two simulation tools in terms of the overall energy use for heating and for cooling with negligible differences (less than 4%) and agree with other literature studies (Vadiee et al., 2018) where differences less than 14-16% have been found.

**Table V.16** *Difference percentage between Design Build and IDA ICE. ΔC: cooling difference, ΔH: heating difference*

| | Design Builder | | IDA ICE | | | |
|---|---|---|---|---|---|---|
| Simulation | Cooling [kW·h/m$^2$] | Heating [kW·h/m$^2$] | Cooling [kW·h/m$^2$] | Heating [kW·h/m$^2$] | *ΔC* [%] | *ΔH* [%] |
| *CPH*1 | 4 | 48 | 4 | 46 | 0 | -4 |
| *PA*1 | 24 | 0 | 24 | 0 | 0 | 0 |

## *V.4.4 Second scenario (larger window). Design Builder vs IDA ICE*

### *V.4.4.1 Temperatures*

The Figs. V.22, V.23, V.24, V.25, V.26, and V.27 show the trend of air temperature, mean radiant temperature and operative temperature.

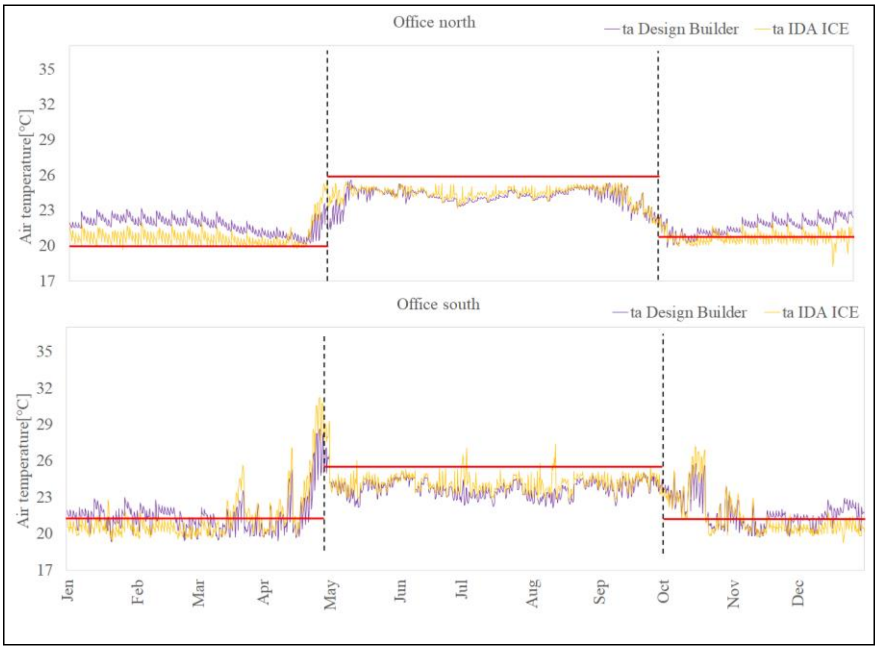


**Figure V.22** *Air temperature, Copenhagen, scenario 2*

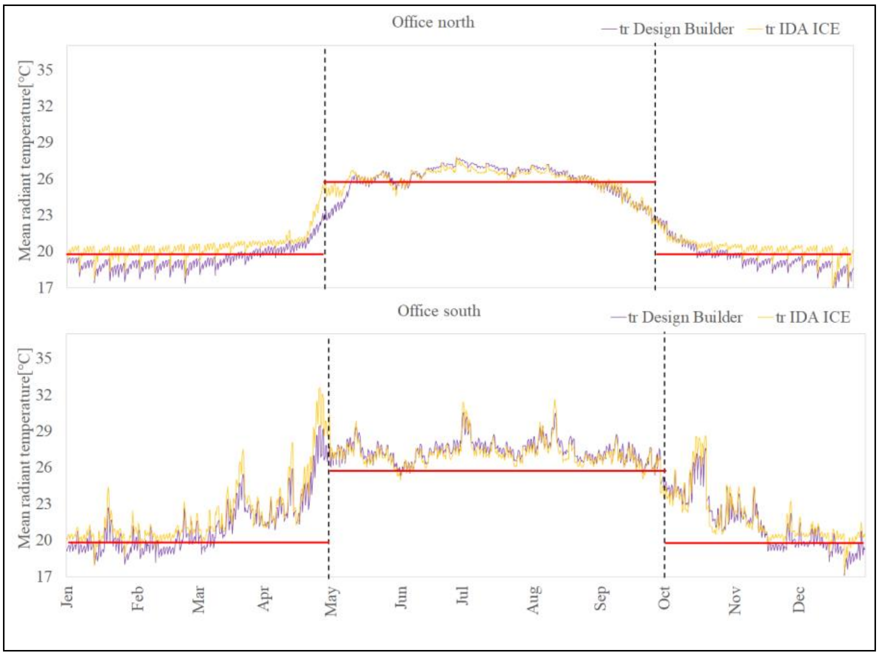


**Figure V.23** *Mean radiant temperature, Copenhagen, scenario 2*

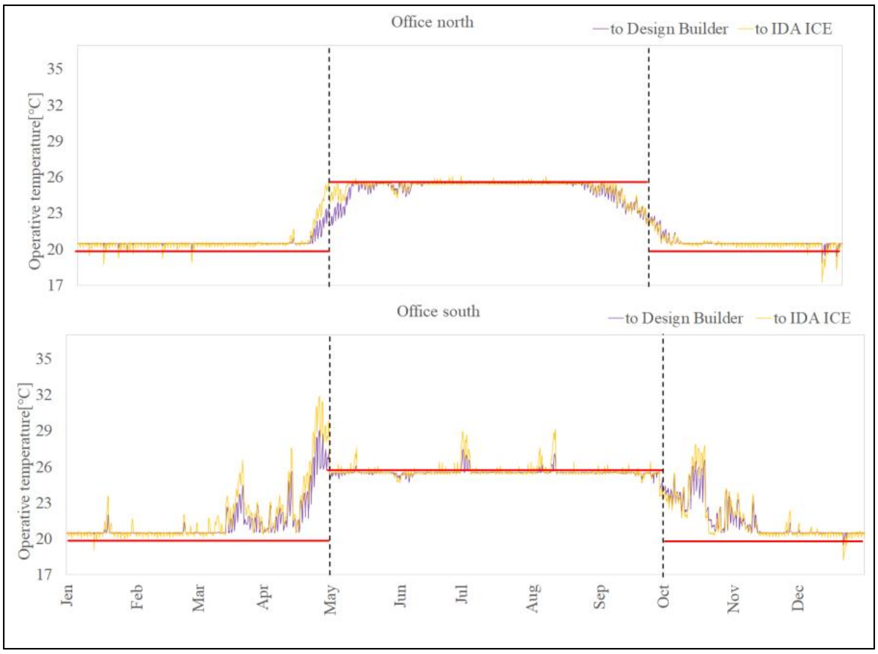


**Figure V.24** *Operative temperature, Copenhagen, scenario 2*

**Figure V.25** *Air temperature, Palermo, scenario 2*

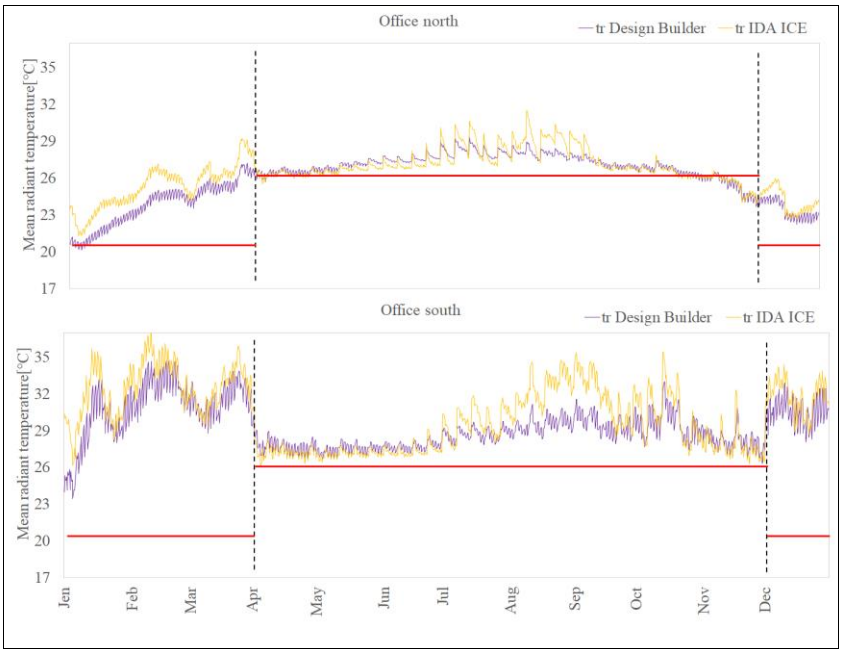


**Figure V.26** *Mean radiant temperature, Palermo, scenario 2*

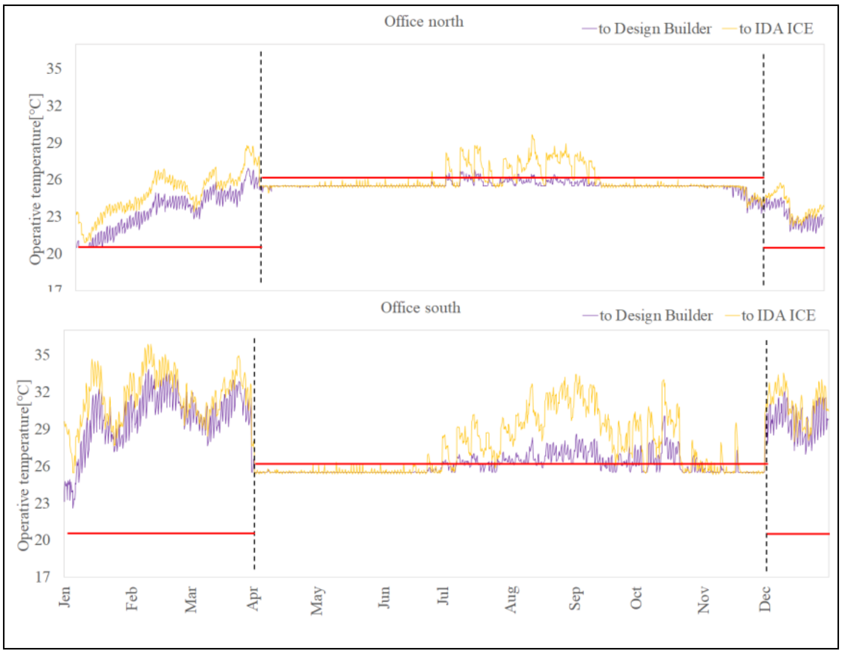


**Figure V.27** *Operative temperature, Palermo, scenario 2*

Looking at the graphics in general, there are some differences between the results obtained from the two software for both offices.

Tab. V.17 shows the occurrences of differences in operative temperature, mean radiant temperature, and air temperature (in Copenhagen and Palermo) calculated as in paragraph V.4.3.1.

For Copenhagen, there are few differences greater than 2°C. Most of the differences are included in the range $0.5^\circ\text{C}<n\leq 2^\circ\text{C}$ and the higher percentages of difference are included in the range from values less than 0.5°C.

In the case of Palermo, the differences bigger than 2 are more frequent than for Copenhagen above all for office south.

The south office with a large window in Palermo is the worst situation, confirming that the estimation of thermal comfort using building dynamic simulation strongly depends on the used software.

Obtained results prove that the agreement between the two simulation engines worsens for high radiative loads. Particularly, while for Copenhagen no significant variations for the first scenario are observed, in the case of Palermo the percentage of occurrences with $\Delta t \leq 0.5$ °C significantly decreases. Most specifically, as far as the operative temperature is concerned, the percentage of time with $\Delta t \leq 0.5$ °C decreases from 67% to 53% (from 53 to 38%) for the North (South) office. In addition, the percentage of time with $\Delta t > 2$ °C increases from 2% to 7% (from 16 to

34%) for the North (South) office. Similar behaviour is for the air temperature (from 20% to 41%) and the mean radiant temperature (from 12% to 25%) in the office south. This implies meaningful differences in the evaluation of thermal comfort conditions using the PMV when different simulation tools are used. In fact, it has been widely demonstrated the high sensitivity of PMV (up to 2 decimal points) to input values (Dell'Isola et al. 2012; d'Ambrosio et al. 2011) even in case of measurements error consistent with the required accuracy recommended by ISO 7726 (e.g., ±0.5 °C and ±2 °C for air temperature and mean radiant temperature, respectively) (CEN, 2001).

Tabs. V.18 and V.19 show the statistical parameters of operative, air and mean radiant temperature in scenario 2 in both software during hours of occupation.

**Table V.17** *Temperatures values: differences between values calculated using Design Builder and IDA ICE*

| | $n$ | Office North [%] | Office South [%] | | $n$ | Office North [%] | Office South [%] |
|---|---|---|---|---|---|---|---|
| | | | operative temperature | | | | |
| *CPH*2 | $n\le0.5$ | 91 | 78 | *PA*2 | $n\le0.5$ | 53 | 38 |
| | $0.5<n\le1$ | 4 | 10 | | $0.5<n\le1$ | 11 | 10 |
| | $1<n\le2$ | 4 | 9 | | $1<n\le2$ | 28 | 18 |
| | $n>2$ | 1 | 3 | | $n>2$ | 7 | 34 |
| | | | mean radiant temperature | | | | |
| | $n\le0.5$ | 47 | 47 | | $n<=0.5$ | 51 | 31 |
| | $0.5<n\le1$ | 22 | 33 | | $0.5<n\le1$ | 18 | 21 |
| | $1<n\le2$ | 30 | 18 | | $1<n\le2$ | 26 | 22 |
| | $n>2$ | 1 | 3 | | $n>2$ | 5 | 25 |
| | | | air temperature | | | | |
| | $n\le0.5$ | 43 | 42 | | $n<=0.5$ | 45 | 22 |
| | $0.5<n\le1$ | 19 | 28 | | $0.5<n\le1$ | 17 | 16 |
| | $1<n\le2$ | 36 | 24 | | $1<n\le2$ | 26 | 22 |
| | $n>2$ | 3 | 5 | | $n>2$ | 12 | 41 |

**Table V.18** *Statistical parameters of temperatures in scenario 2, Copenhagen. Max: maximum temperature; Min: minimum temperature; Q1, Q2, Q3: first, second and third quartile; STD: standard deviation.*

| Statistical parameter | Design Builder | | IDA ICE | |
|---|---|---|---|---|
| | Office North | Office South | Office North | Office South |
| | operative temperature [°C] | | | |
| *Max* | 25.5 | 29.0 | 26.1 | 31.9 |
| *Q1* | 20.5 | 20.5 | 20.5 | 20.5 |
| *Q2* | 20.5 | 23.2 | 20.6 | 23.6 |
| *Q3* | 25.5 | 25.5 | 25.4 | 25.5 |
| *Min* | 18.9 | 19.5 | 17.2 | 18.3 |
| *STD* | 2.2 | 2.3 | 2.4 | 2.6 |
| | mean radiant temperature [°C] | | | |
| *Max* | 27.8 | 30.5 | 27.8 | 32.6 |
| *Q1* | 19.2 | 20.2 | 20.3 | 20.8 |
| *Q2* | 20.5 | 23.9 | 20.9 | 24.2 |
| *Q3* | 26.0 | 27.2 | 26.0 | 27.0 |
| *Min* | 16.4 | 17.1 | 16.2 | 17.3 |
| *STD* | 3.4 | 3.5 | 2.9 | 3.2 |
| | air temperature [°C] | | | |
| *Max* | 25.6 | 28.6 | 25.4 | 31.2 |
| *Q1* | 21.7 | 21.3 | 20.5 | 20.6 |
| *Q2* | 22.4 | 22.5 | 21.3 | 23.0 |
| *Q3* | 24.1 | 23.7 | 24.4 | 24.2 |
| *Min* | 19.8 | 19.3 | 18.3 | 19.2 |
| *STD* | 1.4 | 1.6 | 1.9 | 2.1 |

**Table V.19** *Statistical parameters of temperatures in scenario 2, Palermo. Max: maximum temperature; Min: minimum temperature; Q1, Q2, Q3: first, second and third quartile; STD: standard deviation.*

| Statistical parameter | Design Builder | | IDA ICE | |
|---|---|---|---|---|
| | Office North | Office South | Office North | Office South |
| | operative temperature [°C] | | | |
| *Max* | 27.0 | 33.8 | 29.6 | 35.9 |
| *Q1* | 24.3 | 25.5 | 25.4 | 25.5 |
| *Q2* | 25.5 | 26.3 | 25.5 | 28.7 |
| *Q3* | 25.5 | 28.7 | 25.9 | 31.1 |
| *Min* | 20.5 | 22.6 | 20.9 | 25.3 |
| *STD* | 1.4 | 2.2 | 1.4 | 2.9 |
| | mean radiant temperature [°C] | | | |
| *Max* | 29.4 | 34.8 | 31.5 | 37.0 |
| *Q1* | 24.7 | 27.9 | 25.8 | 27.5 |
| *Q2* | 26.6 | 29.0 | 26.6 | 30.2 |
| *Q3* | 27.5 | 30.4 | 27.2 | 32.5 |
| *Min* | 20.1 | 23.5 | 21.3 | 26.0 |
| *STD* | 2.0 | 1.8 | 1.7 | 2.7 |
| | air temperature [°C] | | | |
| *Max* | 27.1 | 33.1 | 28.4 | 35.0 |
| *Q1* | 23.3 | 23.3 | 24.0 | 24.0 |
| *Q2* | 23.8 | 23.8 | 24.5 | 27.0 |
| *Q3* | 24.3 | 27.7 | 25.2 | 30.0 |
| *Min* | 20.0 | 21.6 | 20.3 | 22.6 |
| *STD* | 1.0 | 2.8 | 1.2 | 3.2 |

### *V.4.4.2 Energy*

Figs V.28 and V.29 show the percentage of differences in energy flows between Design Builder and IDA ICE.

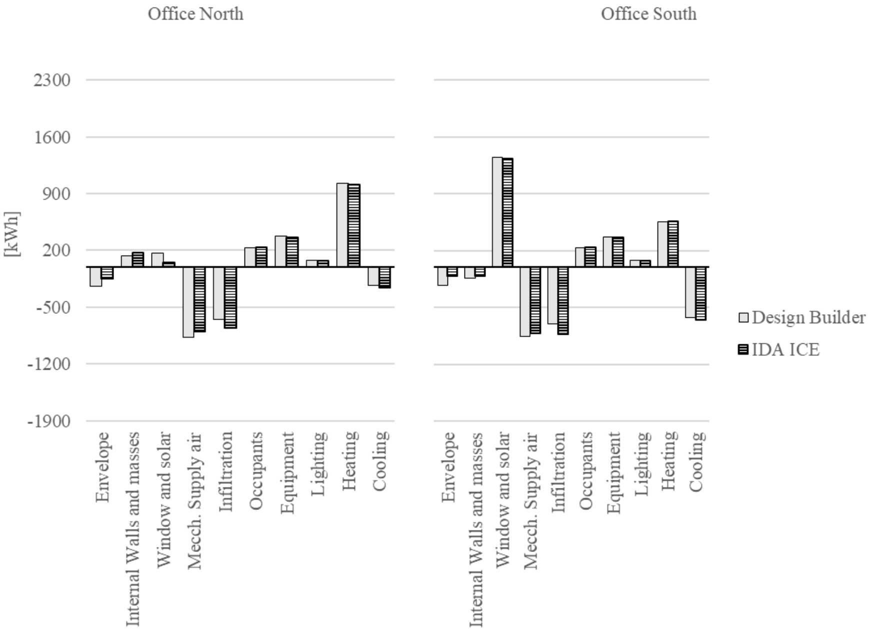


**Figure V.28** *Energy flows, Copenhagen, scenario 2*

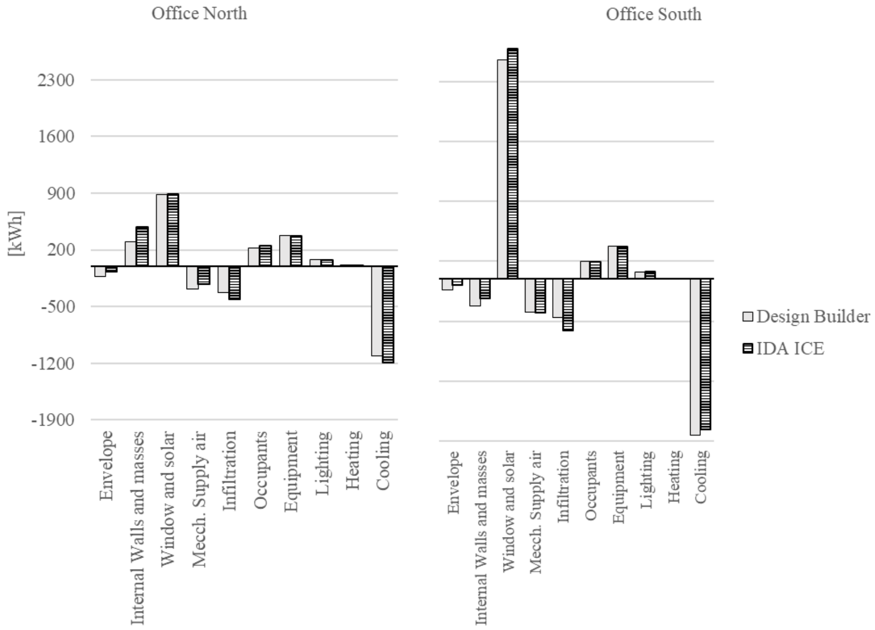


**Figure V.29** *Energy flows, Palermo, scenario 2*

In general, as for scenario 1, there are no significant differences in energy flows between the two tools calculated with Eq. (V.12), except for internal walls and masses, window and solar, infiltration, and cooling where the differences can reach 10%. Among the highest percentages, there is a value of 11% in the office south of Palermo for the “window and solar” component. As the above observed, the reason could be the different way in which the two simulation tools treat the solar radiation by the window system.

### V.4.4.3 Delivered energy

Tab. V.20 shows the percentage of difference of the annual heating/cooling energy use per square meter compared to the total energy uses reported, calculated as in scenario 1.

As above observed, obtained results are in reveal a good agreement between Design Builder and IDA ICE, with overall energy use for heating and cooling very close to each other and with a maximum difference percentage equal to 3%.

**Table V.20** *Difference percentage between Design Build and IDA ICE. $\Delta C$: cooling differences; $\Delta H$: heating differences*

| | Design Builder | | IDA ICE | | | |
|---|---|---|---|---|---|---|
| Simulation | Cooling [kW·h/m$^2$] | Heating [kW·h/m$^2$] | Cooling [kW·h/m$^2$] | Heating [kW·h/m$^2$] | $\Delta C$ [%] | $\Delta H$ [%] |
| *CPH*2 | 8 | 44 | 8 | 44 | 0 | 0 |
| *PA*2 | 30 | 0 | 29 | 0 | -3 | 0 |

## V.5 Conclusions

The purpose of this Chapter is to understand if there are differences in the results of the evaluation of thermal comfort and energy use when using two different dynamic simulation software.

Building simulation tools such as Design Builder and IDA ICE are extensively used for building energy analysis and, thanks to their modular structure, they also permit the evaluation of thermal comfort conditions. Anyway, a reliable prediction of the building behaviour requires an in-depth analysis focused on the modelling procedure with the identification of input data which is a necessary precondition for reliable simulations. The present investigation aimed at identifying the different input data for the modelling which often requires a different approach depending on the used tool and, only in a second phase, comparing the energy use and thermal comfort predictions by the two used tools. The main results can be summarized as follows:

1. The creation of the same building model when using different tools requires great efforts to define input data. Most particularly, it is not always possible to use the same input data set. This means that it is impossible to evaluate how any small variation of the input data can affect the output for the same building model. This is evident from the comparison of the U-values obtained by the two tools which can differ up to 12% for the same building typology (e.g., used materials, thicknesses and so on).
2. According to previous investigations focused on the energy use predicted by different simulation tools, Design Builder and IDA ICE are in good agreement in terms of the overall energy use for heating and for cooling with negligible differences (not exceeding 4%). Some differences exist for the energy flows predicted by the two software for the internal walls and masses, window and solar, air infiltration, and cooling loads where the percentages reach around 10%. In the cases of the last components, a plausible explanation could be the

different ways to consider the solar radiation absorbed by the glazing walls.

3. The most significant differences when using the two tools are related to the operative temperatures rather than the energy delivered for the identical building model. The effects are most important for a hotter climate as in the case of Palermo and the buildings characterized by wide glazing walls. In this case, the temperature differences between the two tools exceed 2 °C up to 40% of occupied hours. This could be related to the different ways the two software calculates the heat transfer coefficients and the solar radiation through a window. However, the differences in the evaluation of thermal comfort conditions using the PMV when different simulation tools are used required further investigations.
4. Design Builder with a simple HVAC system does not allow the user to define a range of thermal comfort, but it gives only the option to define the setpoint temperature for the heating and cooling system. So, the HVAC system provides heating/cooling when the operative temperature is below/above the desired temperature setpoint and, when this does not happen, the reason could be an insufficient capacity (and or/control) of the system plant or a free-running condition, as happened in the study for Palermo.
5. The differences in the results from several dynamic simulation tools could be relevant in terms of design choices or a tender offer.

All the considerations show how important the knowledge of these tools that have so many potentialities but also many limits. The dynamic simulation tools are in fact on the one hand powerful tools capable to perform an energy design and a study of the indoor climate conditions at a detailed time step, on the other hand, they can deviate from the real behaviour of the building users do not know the boundary conditions and the different algorithms at the base of calculations. Both designers and researchers should know the specific tool used, to better manage the multiple input data required and to have a critical approach to the analyses of results, not relying exclusively on the software outputs.

# Chapter VI
# Classification of the thermal environment

## VI.1 Introduction

The EN 16798-2 Standard (CEN, 2019b) prescribes a classification of the indoor environment which includes thermal criteria for winter and summer, air quality and ventilation criteria, lighting criteria, and acoustic criteria. Classification of the indoor environment can be based on design criteria for each parameter, weekly, monthly, or yearly calculations or measurements of relevant parameters like operative temperature, ventilation rates, humidity and $CO_2$ concentrations. In particular, the Standard suggests that an overall classification of the indoor environment should be based on thermal conditions and indoor air quality. Moreover, the Standards recommend including the information of indoor environment in the energy certificate according to what is prescribed in article 7 of EPBD 844/2018 [12].

ALDREN represents a crucial contribution that makes possible a comparable assessment of Energy performance, an improvement of health and well-being, the attainments of IEQ conditions, and a targeted achievement of nearly Zero Energy Building (nZEB) objectives [28]. The goal of ALDREN is to propose a transparent and common European assessment framework to increase the rate and quality of building energy renovations and to trigger more ambitious renovation projects as part of the Green Deal through the adoption of sustainability metrics in certifications and the use of protocols and tools (Bendžalová, 2020).

The project targets and supports investments in deep renovation, encouraging key Building stakeholders to contribute to the Renovation wave announced in the European Green Deal [29]. One of the tools provided by ALDREN is the European Common Voluntary certificate (EVC), which provides a synthesis of a building’s energy performance and a summary of the main renovation actions to be undertaken. The EVC is the core of a

European Voluntary Certification Scheme (EVCS) introduced in Article 11(9) of the EPBD and provides a synthesis of a building's energy performance and a summary of the main renovation actions to be undertaken. ALDREN proposed also EVC+, the EVC with the addition of several sections to describe the actual (measured) energy performance, IEQ (TAIL-index about health & well-being) and to analyse the impacts of proposed energy renovation actions on financial value [30].

## VI.2 Objective

In this Chapter, a comparison between the thermal classification in Design Builder and IDA ICE on the base of EN 16798-1 and -2 Standards and EVC is proposed and discussed.

### *VI.2.1 The classification according to Standards 16798-1 and -2*

The EN 16798-1 Standard and the Technical Report EN 16798-2 define a methodology to assess the thermal comfort level by looking at the distribution of room temperatures in the different categories of the indoor environment, based on the results from building dynamic simulations (CEN 2019a, 2019b). The default indoor temperature ranges for hourly calculation of heating and cooling energy are shown in Tab. VI.1.

**Table VI.1** *Temperature range for offices and similar activity (CEN, 2019a)*

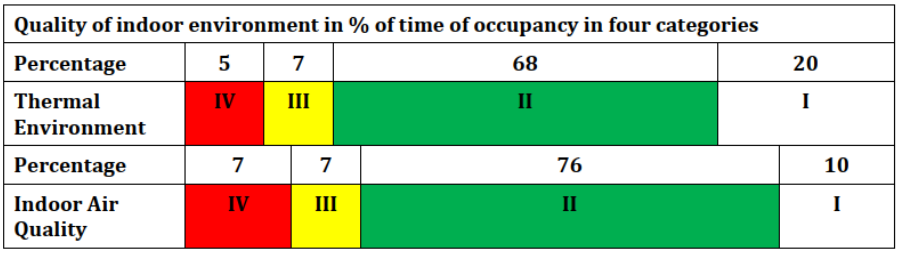
| Category | Temperature range for heating seasons 1.0 *clo* [°C] | Temperature range for cooling seasons 0.5 *clo* [°C] |
|---|---|---|
| I | 21.0 – 23.0 | 23.5 - 25.5 |
| II | 20.0 – 24.0 | 23.0 - 26.0 |
| III | 19.0 – 25.0 | 22.0 - 27.0 |
| IV | 17.0–25.0 | 21.0 – 28.0 |

The EN 16798-2 Standard suggests four different methods to classify the indoor environment:

1) Criteria used for energy calculations in the case of new buildings.
2) Whole year computer simulations of the indoor environment and energy performance, for new and existing buildings.
3) Long-term measurement of selected parameters for the indoor environment in existing buildings.

4) Subjective responses from occupants, for existing buildings.

Using method 2) it is possible to calculate how the parameters are distributed between the four categories, defining the percentage of time of occupancy for each class. Fig. VI.1 shows an example of the classification of the thermal environment and indoor air quality/ventilation, consistent with the EN 16798-2 Standard (CEN, 2019b). The distribution in different categories is weighted through the floor area of the different spaces in the building.



| **Quality of indoor environment in % of time of occupancy in four categories** | | | | |
|---|---|---|---|---|
| **Percentage** | **5** | **7** | **68** | **20** |
| **Thermal Environment** | 🟥 **IV** | 🟨 **III** | 🟩 **II** | **I** |
| **Percentage** | **7** | **7** | **76** | **10** |
| **Indoor Air Quality** | 🟥 **IV** | 🟨 **III** | 🟩 **II** | **I** |

**Figure VI.1** *Example of classification of quality of indoor environment (CEN, 2019b)*

### *VI.2.2 The classification according to Aldren*

The indicator for classifying thermal comfort in the ALDREN European Common Voluntary certificate (EVC) is the thermal comfort score (TCS) which expresses the level of comfort with a single value making immediate the link between the calculated energy use and the respective thermal comfort [28].

The thermal comfort score is based on the percentage of hours of the operative temperature inside the categories of indoor environmental quality, as defined in the EN 16798-1 Standard. Using the thermal comfort score consent for an easier overview of the thermal comfort level from each simulation, compared to the categorization of thermal comfort (Olesen et al., 2020).

TCS is calculated from the Eq. (VI.1), assigning a weight to the percentage of time of operative temperature spent in each category, passing from a value of 1 (Best) to 5 (Worst). It represents an overall assessment of a zone or a building.

$$TCS = \%\mathrm{CatI} \cdot 1 + \%\mathrm{CatII} \cdot 2 + \%\mathrm{CatIII} \cdot 3 + \%\mathrm{CatIV} \cdot 4 + \%\mathrm{outside} \cdot 5 \qquad \text{(VI.1)}$$

## VI.3 Method

The used method consists in determining the quality class of the indoor environment as indicated in EN 16798-2 Standard and using TCS.

The operative temperature values used to determine comfort classes are derived from hourly whole-year simulations obtained for the model presented in paragraph V.5. The range of temperature for classification in the heating and cooling season is referred to as category II of building offices according to EN 16798-1 Standard.

## VI.4 Results and discussion

As follows the two classifications according to EN 16798-1 and ALDREN are discussed.

### *VI.4.1 Classification according to EN 16798-2 Standard*

The Figs. VI.2 and VI.3 show the percentage of temperature time in the four categories according to EN 16798-2 Standard for each room in the considered building models for both software Design Builder and IDA ICE. The graphs also show the percentage of time outside the limits defined by the categories.

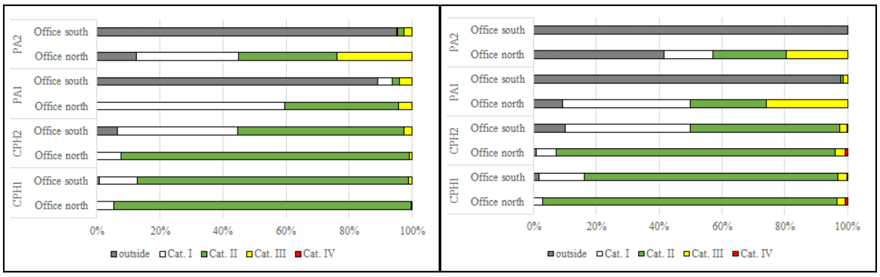


**Figure VI.2** *Classification of thermal environment, heating season, Design Builder (left) and IDA ICE (right)*

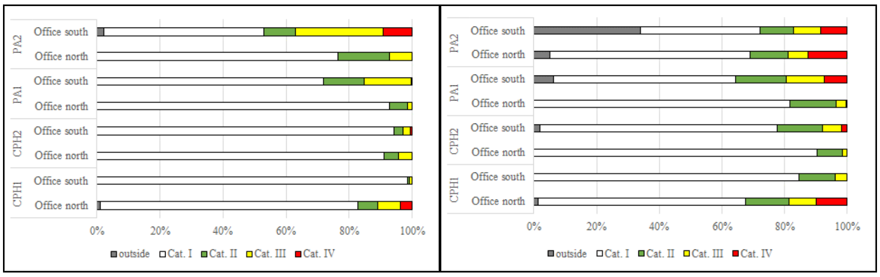


**Figure VI.3** *Classification of thermal environment, cooling season, Design Builder (left) and IDA ICE (right)*

In general, the percentages in the different comfort categories are different comparing the same scenarios of each software, with particular reference to categories II and IV.

The worst scenario occurs during the heating season in the case of Palermo with a larger window on the south wall (PA2) for both software. This situation is a consequence of reaching high-temperature values and at the same time, of the non-operation of the cooling system, as seen in chapter V.

### *VI.4.2 Classification according to thermal comfort score (TCS)*

Tab. VI.2 shows the results of the classification applying the Eq. (VI.1) to calculate the overall thermal comfort score (TCS).

The highest TCS is obtained in the case of PA2. Considering a higher score denotes lower comfort, this result is consistent with the classification in Figs. VI.2 and VI.3.

Looking at Tab. VI.2, it is clear that the results from Design Builder and IDA ICE are very different except for Copenhagen, office north with large windows in cooling mode and office south with a small window in heating mode (no differences). The larger difference is in Palermo, in the office south with large windows in cooling mode (50% of differences). That means that is it not possible to compare results from the two different software.

**Table VI.2** *TCS values. H: heating mode; C: cooling mode*

| | | Office north | | | | Office south | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *CPH*1 | *PA*1 | *CPH*2 | *PA*2 | *CPH*1 | *PA*1 | *CPH*2 | *PA*2 |
| Design Builder | *H* | 1.9 | 1.4 | 1.9 | 2.3 | 1.9 | 4.7 | 1.8 | 4.9 |
| | *C* | 1.4 | 1.1 | 1.1 | 1.3 | 1.0 | 1.4 | 1.1 | 2.0 |
| IDA ICE | *H* | 2.0 | 2.1 | 2.0 | 3.3 | 1.9 | 4.9 | 1.9 | 5.0 |
| | *C* | 1.7 | 1.2 | 1.1 | 1.8 | 1.2 | 1.9 | 1.4 | 2.9 |

## VI.5 Conclusions

The approaches recommended in EN 167987-1 and -2 and ALDREN project are used for the assessment of thermal comfort level looking at the distribution of room temperature in different categories, derived by results from building dynamic simulations.

The assessment of thermal comfort according to EN 16798-2 Standards can be a less direct method when comparing the results for many different scenarios compared to ALDREN method which summarises in only one number the classification.

Furthermore, the classification according to the European standard does not require specifying the percentage of time outside the limits of the comfort categories as envisaged by the TCS formulation.

Finally, the results show once again that the use of two different dynamic simulation software leads to different results.

In particular, the classification carried out with IDA ICE shows higher percentages of time in which the environment is in category 4. In this sense, it is more precautionary, even if the differences relating to category 2 do not always respect the same trend.

The results relating to the Thermal Comfort Score confirm this general trend. In fact, the TCS obtained with IDA ICE are always higher, except for some cases, and it reaches 50% of the difference.

All this demonstrates that it is not possible to directly compare the results of two or more dynamic simulation software to evaluate thermal comfort. This is very important, especially when the comparison is the basis for an important choice, for example in a tender offer.

# Chapter VII
# Calculation methods of mean radiant temperature in Energy Plus

## VII.1 Introduction

One of the most critical parameters in the heat balance of the human body is the mean radiant temperature ($t_r$), defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform enclosure. It is a very significant factor, especially in buildings whose envelope is exposed to strong solar radiation (ASHRAE, 2020). The mean radiant temperature represents the heat transfer between the person and the surrounding environment, and it is one of the six variables on which thermal comfort depends together on air temperature, air velocity and relative humidity (physical variables) and with clothing insulation and metabolic rate (subjective variables). So, its evaluation affects the predicted mean vote (PMV) index (Fanger, 1970).

The mean radiant temperature can be measured using a black globe thermometer or a two-sphere radiometer or calculated from the temperature of the surrounding surfaces or the plane radiant temperatures (CEN, 2001).

## VII.2 Objective

Despite the numerous studies on the evaluation of $t_r$ there are no comparative surveys so specific finalized to verify the validity of the calculation methods proposed by a simulation tool commonly used in the field of thermal comfort research such as Energy Plus and Design Builder.

This Chapter presents a comparison between the methods used for calculating the mean radiant temperature in Energy Plus and Design Builder and those prescribed by the EN ISO 7726 Standard. The influence of the results of the calculation methods considered on the PMV value is also analysed to highlight the main differences and criticism found.

### *VII.2.1 Evaluation of $t_r$*

The methods for measuring the mean radiant temperature are illustrated below.

#### *VII.2.1.1 Methods prescribed from EN ISO 7726*

The measurement methodologies devoted to the assessment of the mean radiant temperature require observing accuracy requirements reported in the EN ISO 7726 Standard.

The Standard defines two methodologies for the assessment of mean radiant temperature based on angle factors between the person and the surrounding surfaces and the plane radiant temperatures ($t_{pr}$) (d'Ambrosio et al., 2013).

When applying the method of angle factors, the Eq. (VII.1) is used; the Eqs. (VII.2) and (VII.3) are used in the method on plane radiant temperatures respectively for seated and standing persons (CEN, 2001).

$$\overline{T}_{\mathrm{r}}^{\,4} = T_1^4 \cdot F_{\mathrm{p-1}} + T_2^{\,4} \cdot F_{\mathrm{p-2}} + \ldots + T_{\mathrm{N}}^{\,4} \cdot F_{\mathrm{p\text{-}N}} \qquad \text{(VII.1)}$$

$$\overline{t}_r = \frac{0{,}18(t_{pr}[\mathrm{up}] + t_{pr}[\mathrm{down}]) + 0{,}22(t_{pr}[\mathrm{right}] + t_{pr}[\mathrm{left}]) + 0{,}30(t_{pr}[\mathrm{front}] + t_{pr}[\mathrm{back}])}{2(0{,}18 + 0{,}22 + 0{,}30)} \qquad \text{(VII.2)}$$

$$\overline{t}_r = \frac{0{,}08(t_{pr}[\mathrm{up}] + t_{pr}[\mathrm{down}]) + 0{,}23(t_{pr}[\mathrm{right}] + t_{pr}[\mathrm{left}]) + 0{,}35(t_{pr}[\mathrm{front}] + t_{pr}[\mathrm{back}])}{2(0{,}08 + 0{,}23 + 0{,}35)} \qquad \text{(VII.3)}$$

where:
$\overline{T}_{\mathrm{r}}$ = mean radiant temperature, K;
$T_{\mathrm{N}}$ = temperature of "N" surface ;
$F_{\mathrm{p\text{-}N}}$ = angle factor between a person and "N" surface;
$t_{\mathrm{r}}$= mean radiant temperature, °C;
$t_{\mathrm{pr}}$ = plane radiant temperature, °C.

#### *VII.2.1.2 Methods used from Energy Plus and Design Builder*

Energy Plus proposes three methods to calculate the mean radiant temperature of a room:

- "Zone average", Eq. (VII.4): the mean radiant temperature is a weighted average of the surface temperatures, using the surface area as the weight coefficient. The method considers the person in the centre of the zone.

This method evaluates $t_r$ with a simple approach suggested by literature considering a relationship between the area surfaces (Yoo, 2018; Wang et al., 2019).

- "Surface weighted", Eq. (VII.5): the mean radiant temperature is the arithmetic average between the modified mean radiant temperature calculated using the "zone averaged" method and the surface temperature that a person is closest to. This method considers that when a person is close to a surface, this surface will have a much greater effect on the thermal comfort of the person.
- "Angle factor", Eq. (VII.6): the mean radiant temperature is the weighted average of the sum of the radiant heat exchange between the person and the surrounding surfaces, using as a weight coefficient the sum of the products of the emissivity of the surfaces per angle factor between the person and the surface. In this method, emissivity can be ignored if all surfaces have equal emissivity, and the emissivity is close to unity [31].

$$T_\mathrm{r} = T_\mathrm{r\text{-}avg} = \frac{\sum \varepsilon_\mathrm{i} A_\mathrm{i} T_\mathrm{i}}{\sum \varepsilon_\mathrm{i} A_\mathrm{i}} \tag{VII.4}$$

$$T_\mathrm{r} = \frac{(T_\mathrm{r\text{-}avg} + T_\mathrm{surf})}{2} \tag{VII.5}$$

$$T_\mathrm{r} = \sqrt[4]{\frac{\sum \varepsilon_\mathrm{i} F_\mathrm{i} (T_\mathrm{i})^4}{\sum \varepsilon_\mathrm{i} F_\mathrm{i}}} \tag{VII.6}$$

where:
$T_\mathrm{r}$ = mean radiant temperature, K;
$T_\mathrm{r\text{-}avg}$ = "zone averaged" radiant temperature, K;
$\varepsilon_\mathrm{i}$ = surface emissivity;
$A_\mathrm{i}$ = surface area, m$^2$;
$T_\mathrm{i}$ = surface temperature, K;
$T_\mathrm{surf}$ = surface temperature to which person is closer, K;
$F_\mathrm{i}$ = angle factor between person and surface, 1.

Design Builder uses only the “zone average” method option for the calculation of $t_r$ without giving the choice possibility of the other two methods proposed by Energy Plus [32].

In any case, the various simulation tools do not generally take into account the real position occupied by the subject.

The position of a person within a space for the calculation of “angle factors” and the temperatures of all surfaces surrounding people are very difficult to define. This is one of the biggest problems associated with the use of simulation programs.

The mean radiant temperature calculated using the “zone averaged” method and “weighted method” can conduce to different results. A study demonstrates that the differences between the “zone averaged” and “weighted method” are greater in winter than in summer because of the greater differences between $t_r$ values calculated with “zone averaged” and the temperatures of the window surfaces during winter. In addition, the mean radiant temperature has a lower trend with the “zone averaged” method than with the “weighted method” during summer. This happens because the influence of solar absorption on thermal sensation becomes lesser in winter since the window surface is still significantly colder than the other surfaces (Lee and Strand, 2001).

Several studies on the evaluation of the mean radiant temperature demonstrate as the complexity of this parameter affects thermal comfort. The segment-wise thermal interactions between the human body and its surrounding (Atmaca et al., 2007), the knowledge of the position of a person and room geometry (Kalmár, F. and Kalmár, T., 2012), the accuracy of measurements (d’Ambrosio et al., 2011; d’Ambrosio et al., 2013; d’Ambrosio et al., 2021), the hypotheses and the simplifications on which calculation procedures and any assumptions are based, are all very important research topics which analysis incorrect may lead to the obfuscation of the true meaning of $t_r$, contributing to the lack of proper evaluation, both numerically and experimentally (Huan et al., 2021).

Researchers must consider the errors in the calculation methods and the assumptions utilized in their applications taking into account the accuracies and the reliability in the estimation of mean radiant temperature (Özbey and Turhan, 2022).

## VII.3 Method

Different methods for the calculation of mean radiant temperature are compared and the effects of the results in terms of PMV index are analysed.

A model is built, considering three different configurations that differ in the glazed surface (facing south), as illustrated in Fig. VII.1.

The phases of the study are:

- Definition of the three models with their thermophysical characteristics (Tab. VII.1) and boundary conditions (Tab. VII.2) in Design Builder.
- Simulations ran for two weather conditions and for different periods to obtain surface temperatures and mean radiant temperatures.
- Exportation of *.idf* file from Design Builder to EP-Launch to calculate mean radiant temperature with methods of Energy Plus.
- Definition of view factors for different models and different person positions.
- Calculation of $t_r$ in Energy Plus and Software 1 (SW1) and 2 (SW2).
- Comparison of $t_r$ values obtained with different methods of Energy Plus, Design Builder and with the equation of Standard.
- Calculation of PMV for each simulation and check of changing class switching from one $t_r$ method to another.

Fig. VII.2 summarizes the main steps of the investigation.

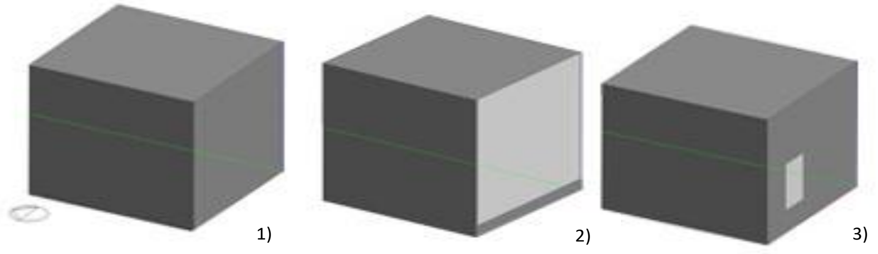


**Figure VII.1** *Model configurations*

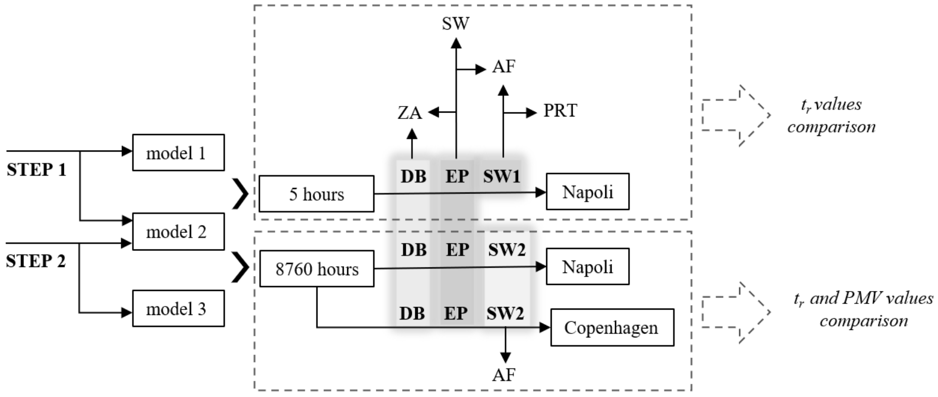


**Figure VII.2** *Workflow of the investigation. DB: Design Builder; EP: Energy Plus; SW1: Software 1; SW2: Software 2; AF: Angle Factors method; ZA: Zone Average method; SW: Surface Weighted method; PRT: Plane Radiant Temperature method*

### *VII.3.1 Building model*

The model is a room 5 m · 5 m · 5 m equipped with a heating and cooling system connected to a heat pump. The supplied air is at outdoor temperature and, the system provides heating/cooling when the operative temperature is below/above the desired temperature setpoint.

Regarding the ventilation system, the ventilation rate is defined according to EN 16798-1 Standard for the breathing zone by combining the ventilation required for people and building emissions (CEN, 2019a). Because $t_r$ is a significant parameter, especially in the case of building envelopes exposed to strong solar radiation, three configurations are considered to take into account the impact of the presence of a glazing surface and the influence of two different window sizes.

The values of air temperature, relative humidity and surface temperatures are output generated by the software.

The stratigraphy of the external walls is shown in Fig. VII.3.

To analyse whether the method of calculating $t_r$ in Design Builder involves switching PMV from one category to another compared to other methods, an increase of U-value of the exterior wall is considered. This is for the whole-year simulations, with models 2 and 3 to examine the error in the calculation method “zone averaged” in Design Builder which is the software with the most simplified model calculation of $t_r$.

**Table VII.1** *Thermophysical characteristics of wall components*

| Model | Component | Thickness [mm] | Emissivity [-] | U-value [W/m$^2$·K] |
|---|---|---|---|---|
| 1, 2, 3 | Internal plaster | 30 | 0.99 | 1.1 |
| | Brick | 120 | | 2.1 |
| | Air gap | 110 | | |
| | External plaster | 200 | | |
| 1, 2 | Glass | SHGC = 0.54 | | 1.2 |
| 2,3* | Glass | SHGC = 0.48 | | 3.8 |

* only for the whole year's simulations

**Table VII.2** *Boundary conditions. H: heating, C: cooling*

| Condition | Model 1 | Model 2 | Model 3 |
|---|---|---|---|
| Opening | Without window | Window area coincident with the south wall | Window area equal to 8% of the south wall surface |
| City | Napoli | Napoli<br>Copenhagen | Napoli<br>Copenhagen |
| Setpoint | *H*: 20°C<br>*C*: 26°C | *H*: 20°C<br>*C*: 26°C | *H*: 20°C<br>*C:* 26°C |
| *COP* | *H* system: 0.9<br>*C* system: 3 | *H* system: 0.9<br>*C* system: 3 | *H* system: 0.9<br>*C* system: 3 |
| Time operation | *H* system: Oct-Mar<br>*C* system: Apr-Sept | *H* system: Oct-Mar<br>*C* system: Apr-Sept | *H* system: Oct-Mar<br>*C* system: Apr-Sept |
| N. people | 1 | 1 | 1 |
| Metabolic rate, *M* | 1.2 met | 1.2 met | 1.2 met |
| Clothing insulation, $I_{\mathrm{cl}}$ | 1 *clo* (winter)<br>0.5 *clo* (summer) | 1 *clo* (winter)<br>0.5 *clo* (summer) | 1 *clo* (winter)<br>0.5 *clo* (summer) |
| Air velocity | $0.137\ \mathrm{m{\cdot}s^{-1}}$ | $0.137\ \mathrm{m{\cdot}s^{-1}}$ | $0.137\ \mathrm{m{\cdot}s^{-1}}$ |
| Simulation time | 5 hours (during hottest day) | 8760 hours | 8760 hours |

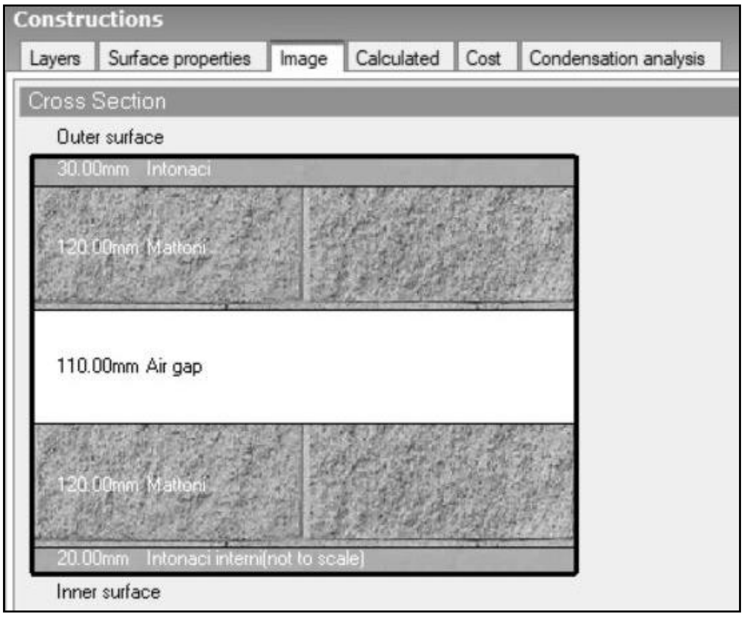


**Figure VII.3** *Stratigraphy of the external wall*

### *VII.3.2 Calculation methods*

To verify the reliability and the differences between the equations used by Energy Plus and Design Builder and those suggested by ISO EN 7726 Standard, two other original simulation tools are created that use the equations according to Standards for the determination of $t_r$ (CEN, 2001) and PMV (CEN, 2005), SW1 and SW2. In particular, SW2 is created to perform a whole-year simulation using the “angle factor” method, especially for model 3 with a small window and to calculate the PMV index. The SW2 is set to determine the PMV for each hour and the relative class of thermal comfort according to the ISO EN 7730 Standard (CEN, 2005).

Tab.VII.3 describes the calculation methods for each used software with relative limits and reference sources.

**Table VII.3** *Calculation of* $t_r$*: tools, methods, limits and reference source*

| Tool | Method | Limits | Reference source |
|---|---|---|---|
| Design Builder | Zone averaged | Person position: only in the centre of the room | Design Builder website [32] |
| Energy Plus | Zone averaged | Person position: only in the centre of the room | Engineering Reference Documentation<br>Energy Plus website [31] |
| | Surface weighted | Approximation in the definition of the person position: the method consent the identification of the surface to which the subject is closest without quantifying the exact distance. | |
| | Angle factors | | |
| SW1 | Angle factors | | ISO EN 7726 (CEN, 2001) |
| | Plan radiant temperature | | ISO EN 7726 (CEN, 2001) |
| SW2 | Angle factors | | ISO EN 7726 (CEN, 2001) |

The procedure followed for the study is illustrated in Tab. VII.4. Starting by considering model 1 in the most critical hours of the hottest day of the year (hours 11 a.m./4 p.m.; 10th August), the trend of $t_r$ is validated using different method calculations of Design Builder, Energy Plus and SW1. In the second step, the mean radiant temperature is calculated using different methods proposed by Energy Plus considering simulations for a whole year in models 2 and 3. Then the calculated $t_r$ values are used to calculate the PMV with SW2.

In addition, four different positions are considered in the "angle factor" method:

- Person in the centre of the room, standing.
- Person in the centre of the room, seated.
- Person near the south wall, standing.
- Person near the south wall, seated.

For each position are calculated angle factors with equations defined in the EN ISO 7726 Standard for standing and seated person and based on model configuration.

**Table VII.4** *Comparison of simulations in Napoli*

| Step | Parameter | Tools | Time | Model 1 | Model 2 | Model 3 |
|---|---|---|---|---|---|---|
| 1 | $t_r$ | Design Builder<br>Energy Plus<br>SW1 | 11.00-16.00<br>(5 hours of the hottest day) | X | X | |
| 2 | $t_r$ | Design Builder<br>Energy Plus<br>SW2 | 00:00-24:00<br>(whole year) | | X | X |
| 3 | PMV | Design Builder<br>Energy Plus<br>SW2 | 00:00-24:00<br>(whole year) | | X | X |

## VII.4 Results and discussion

The following sections describe the results obtained in terms of $t_r$ values and the corresponding PMVs.

### *VII.4.1 Mean radiant temperature evaluation*

Figs. VII.4, VII.5, VII.6, and VII.7 show the trend of mean radiant temperature obtained in Step 1 with model 1. The results show that different methods give very similar results in the case of a person in the centre of the room. There are little differences (around 0.2 °C, highlighted in green in Figs. VII.6 and VII.7) between "zone average" and the other methods when the person is near the south wall, because "zone averaged" method considers only the person at the centre of the room.

In model 2 (Figs. VII.8, VII.9, VII.10, VII.11) the differences between the “zone averaged” method and the other ones are bigger than in model 1: they are around 0.5 °C in the case of a person in the centre of the room and they reach 2 °C of differences in the case of a person near the south wall. This demonstrates that the glazing surface of model 2 affects the calculation of $t_r$.

The comparison of the “zone averaged” method with other methods (highlighted in green in the Figures) aims to underline the limit of Design Builder that does not consent correctly evaluate $t_r$ using only the “zone averaged” method, and therefore it does not guarantee an appropriate evaluation of comfort conditions when the person is not at the centre of the room.

The trend of the mean radiant temperature follows the same progress in all simulations of step 1. In all cases, the change of position from a standing person to a seated person does not involve significant differences.

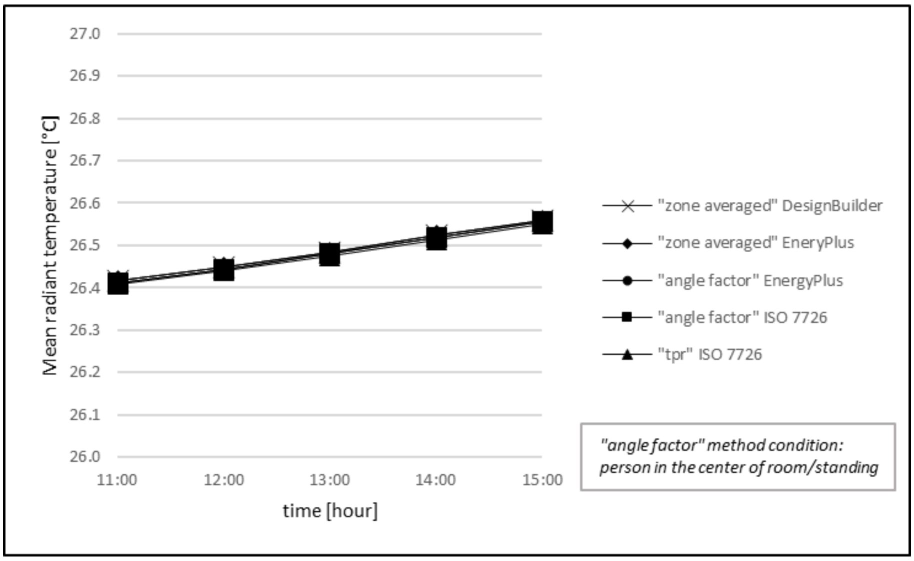


**Figure VII.4** *Trend of* $t_r$*, model 1, the centre of the room, standing person*

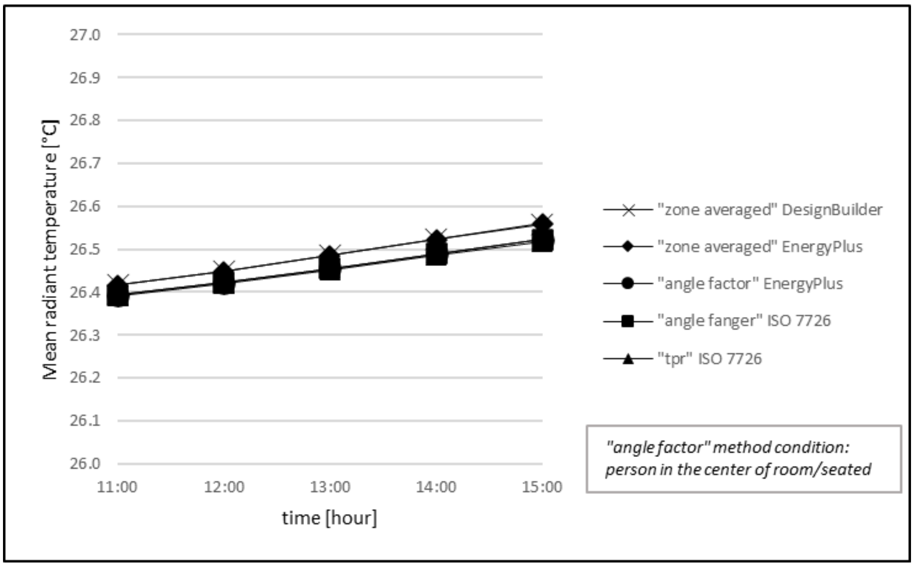


**Figure VII.5** *Trend of* $t_r$*, model 1, the centre of the room, seated person*

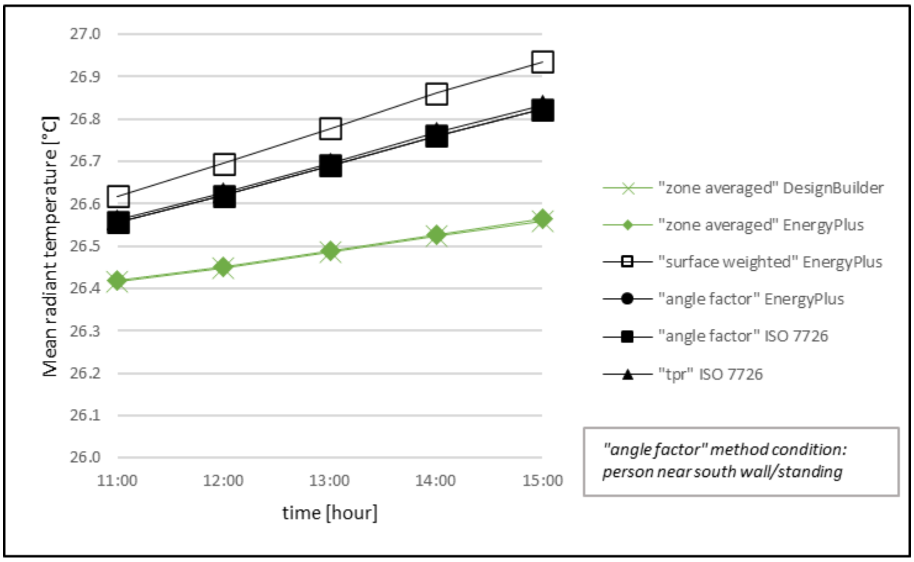


**Figure VII.6** *Trend of $t_r$, model 1, near the south wall, standing person*

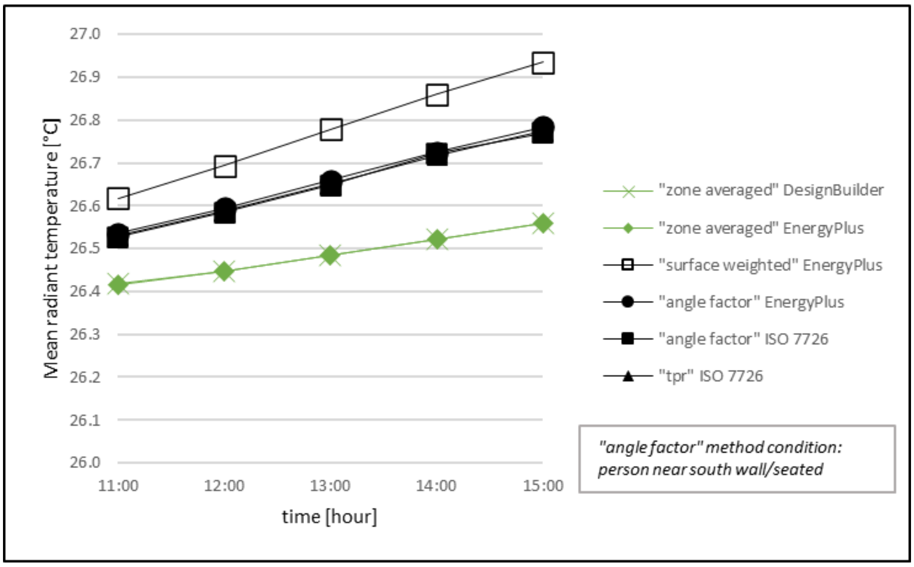


**Figure VII.7** *Trend of $t_r$, model 1, near the south wall, the seated person*

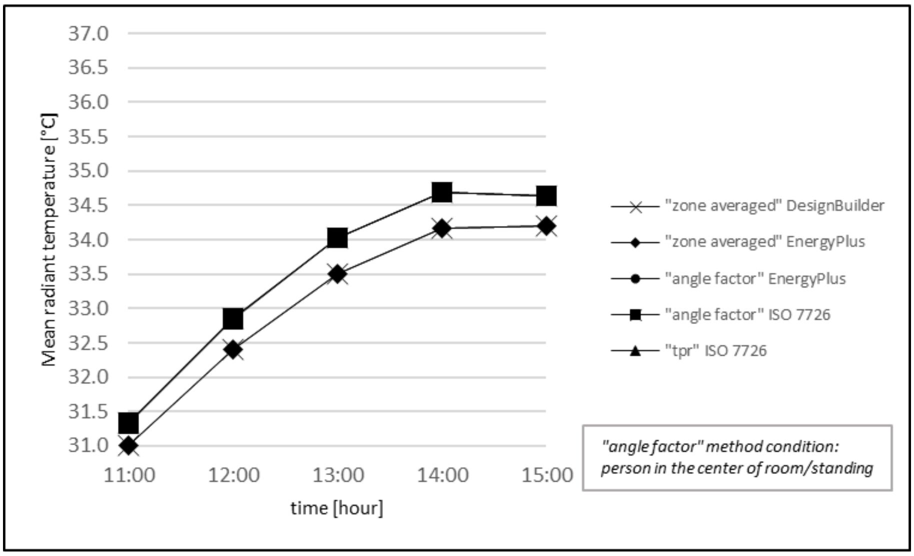


**Figure VII.8** *Trend of* $t_r$*, model 2, the centre of the room, standing person*

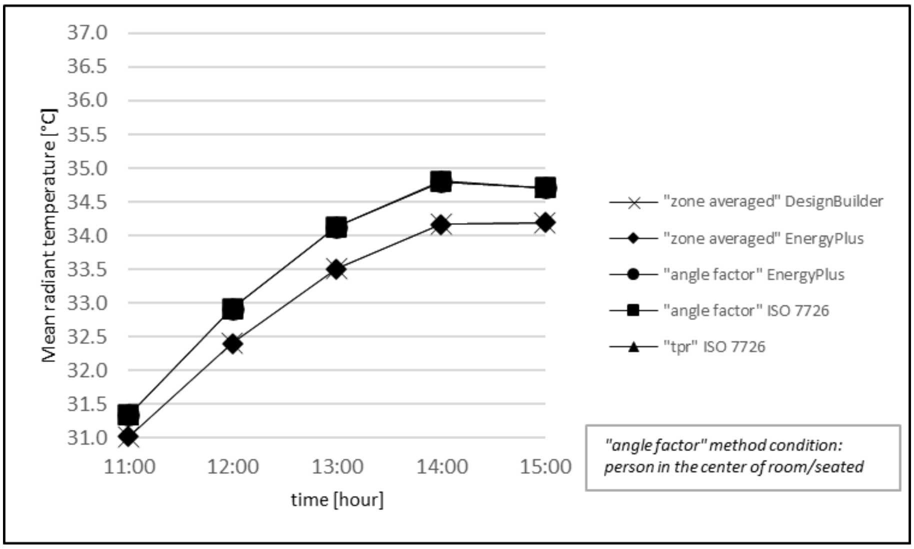


**Figure VII.9** *Trend of* $t_r$*, model 2, the centre of the room, seated person*

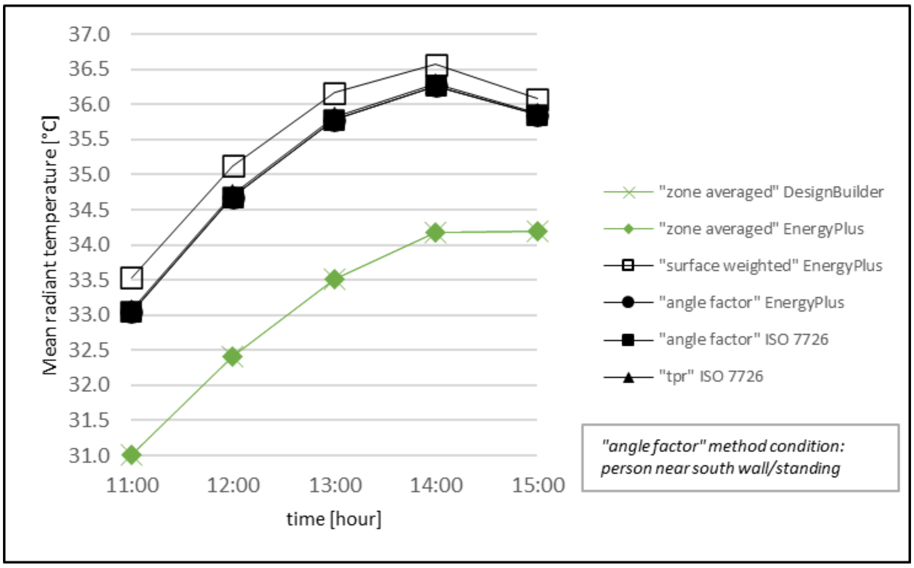


**Figure VII.10** *Trend of* $t_r$*, model 2, near the south wall, standing person*

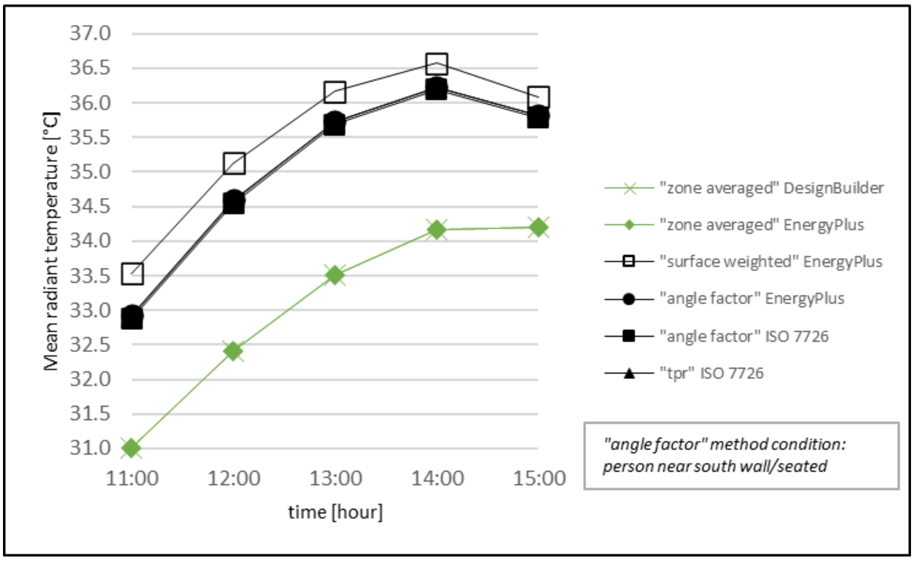


**Figure VII.11** *Trend of* $t_r$*, model 2, near the south wall, the seated person*

In Step 2, the simulation of yearly values of $t_r$ using model 2, reveals a link between the $t_r$ and the surface temperature of glazing. In particular, the lower the surface temperature of the glazing wall, the greater the difference in $t_r$ calculated with the different methods especially in model 2, with a larger glazed surface. This happens comparing methods where the person's position is not the same (in the centre of the room/near the south wall). In Figs. VII.12 to VII. 17 some graphs are shown.

About locations, NA indicates Napoli while CPH indicates Copenhagen, and the close number refers to the kind of model configuration so as defined in Fig. VII.1.

Furthermore, as emerged also by graphics in all cases the methods: “angle factor” of Energy Plus, “angle factor” and “$t_{pr}$” of the EN ISO 7726 Standard are always coincident as well as the “zone averaged” method of Design Builder and “zone averaged” of Energy Plus. Therefore, it is possible to confirm that the “zone averaged” method is exactly reproduced in the graphical interface Design Builder and that the "angle factor" method of Energy Plus always coincides with those defined by Standard, despite the different formulations. So, in this last case, Energy Plus agrees with the Standard.

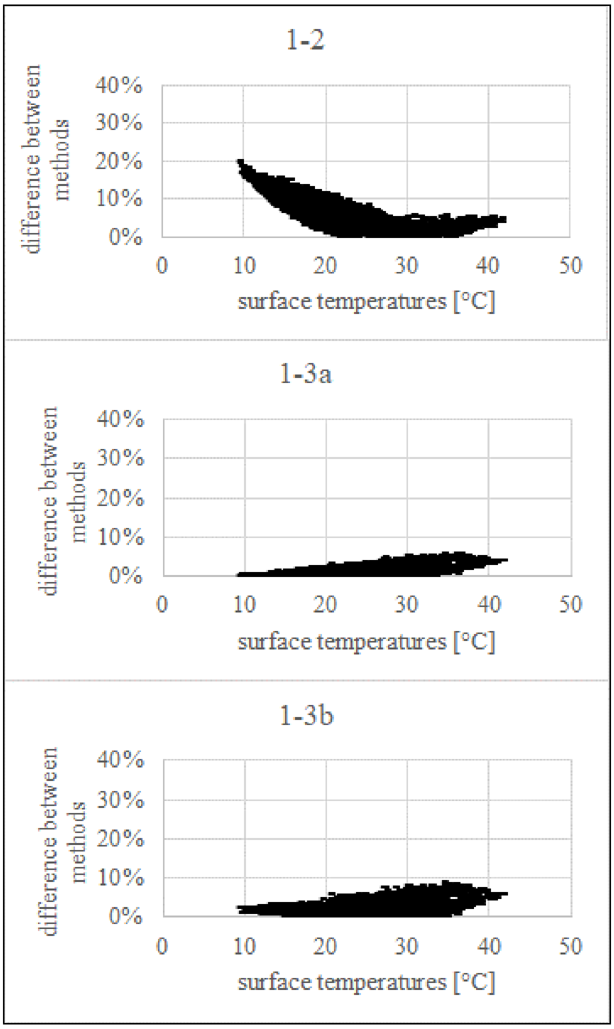


**Figure VII.12** *Differences between models, in percentage vs surface temperatures south wall, NA2. 1: "Zone averaged", 2: "Surface weighted", 3a: "Angle factor – in the centre of room/standing", 3b: "Angle factor - in the centre of room/seated"*

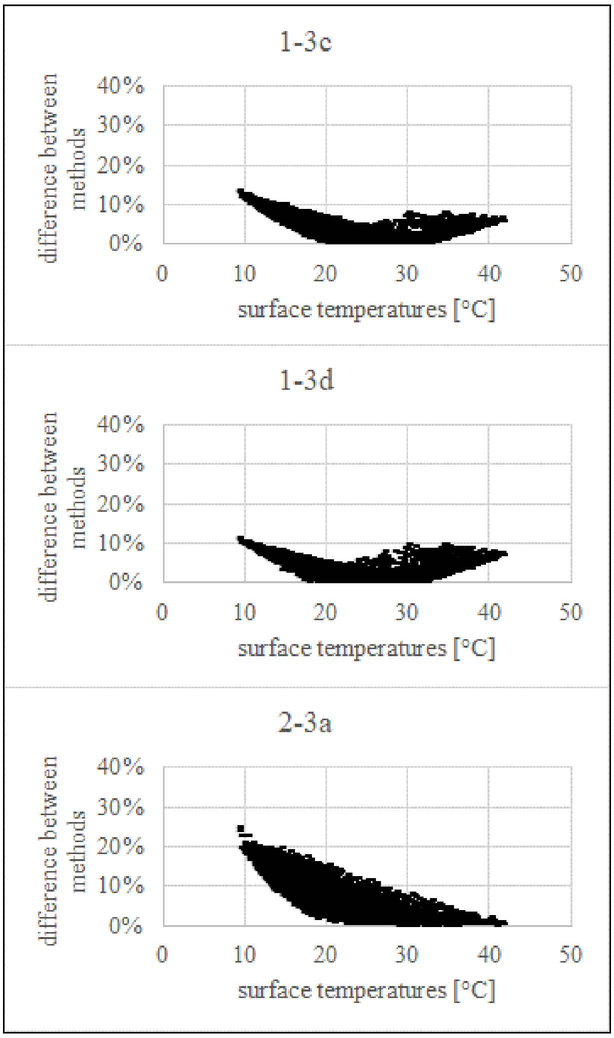


**Figure VII.13** *Difference between models, in percentage, vs surface temperatures south wall, NA2. 1: "Zone averaged", 2: "Surface weighted", 3a: "Angle factor - in the centre of room/standing", 3c: "Angle factor - near south wall/standing", 3d: "Angle factor - near south wall/seated"*

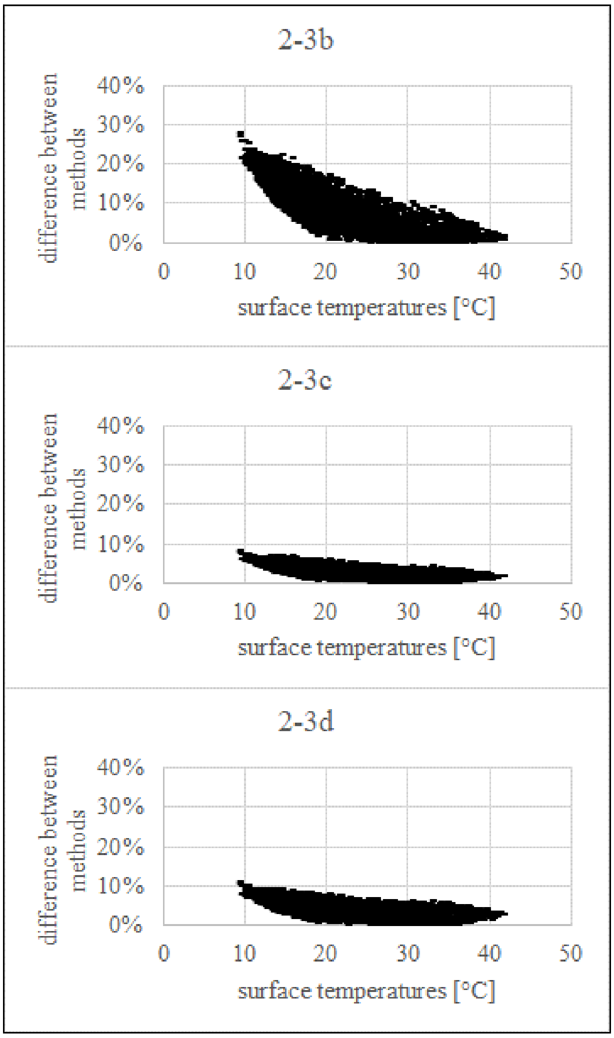


**Figure VII.14** *Difference between models, in percentage, vs surface temperatures south wall, NA2. 2: "Surface weighted", 3b: "Angle factor - in the centre of room/seated", 3c: "Angle factor - near south wall/standing", 3d: "Angle factor - near south wall/seated"*

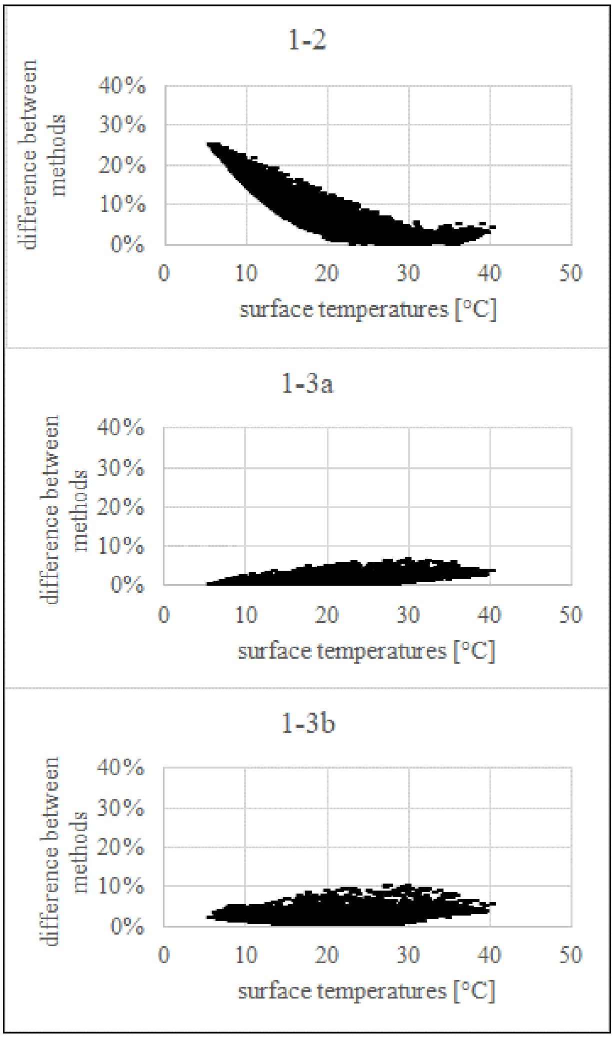


**Figure VII.15** *Difference between models, in percentage, vs surface temperatures south wall, CPH2. 1: "Zone averaged", 2: "Surface weighted", 3a: "Angle factor - in the centre of room/standing", 3b: "Angle factor - in the centre of room/seated"*

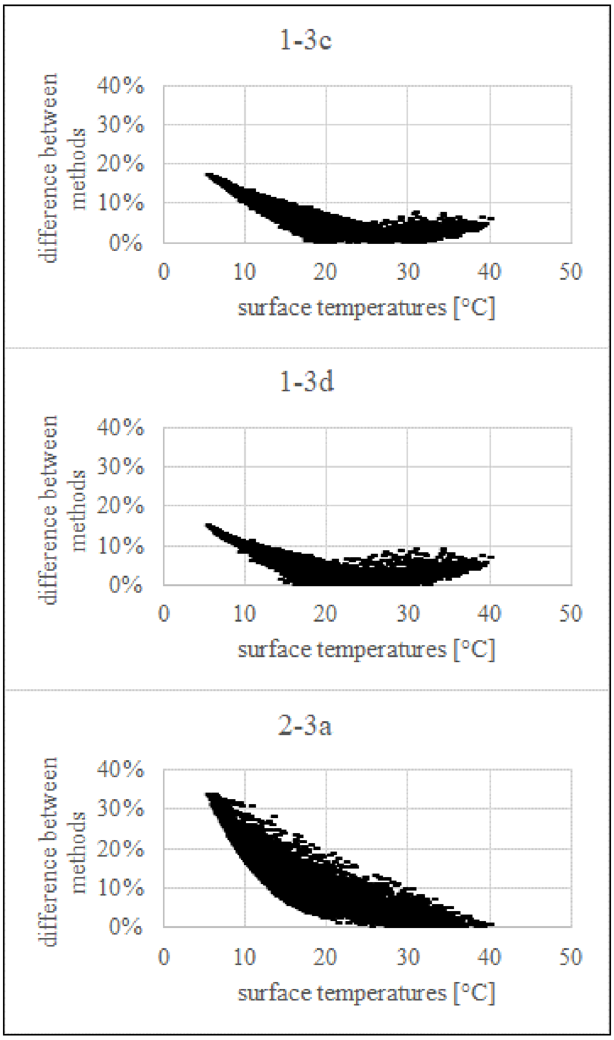


**Figure VII.16** *Difference between models, in percentage, vs surface temperatures, south wall, CPH2. 1: "Zone averaged", 2: "Surface weighted", 3a: "Angle factor – in the centre of room/standing", 3c: "Angle factor - near south wall/standing", 3d: "Angle factor - near south wall/seated"*

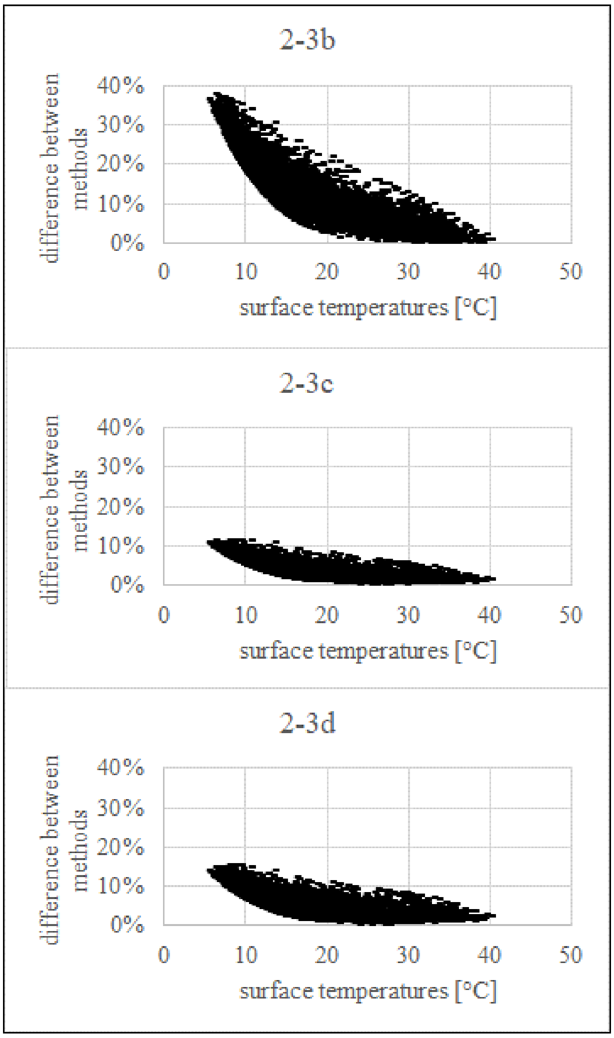


**Figure VII.17** *Difference between models, in percentage, vs surface temperatures south wall, CPH2.* 2*: "Surface weighted", 3b: "Angle factor - in the centre of room/seated",3c: "Angle factor - near south wall/standing",3d: "Angle factor - near south wall/seated"*

### *VII.4.2 Thermal comfort evaluation and classification*

Figs. VII.18 and VII.19 show the results in terms of comfort conditions. Regarding discomfort hours on the whole year with different methods, Copenhagen has a long time of discomfort than Napoli and in the simulations, there is always discomfort because of cold, except for the simulation NA2.

Finally, the influence of different calculation methods of $t_r$ on the thermal environment classification is considered. For each simulation, the PMV for each value of mean radiant temperature is calculated according to ISO EN 7730 Standard (CEN, 2005). Using obtained PMV values, it is possible to define the thermal comfort class and check whether a PMV class change occurs by changing the method. This occurred in a few hours of the year.

More frequent class changes occur with model 2 (larger glazing surface) for both locations (Fig. VII.20). The lower percentages are related to the difference between method 1 “zone averaged” and method 3a “angle factor - in the centre of room/standing”. So, in the condition with the person in the centre of the room/standing the two methods do not give significant differences in the calculation of the PMV.

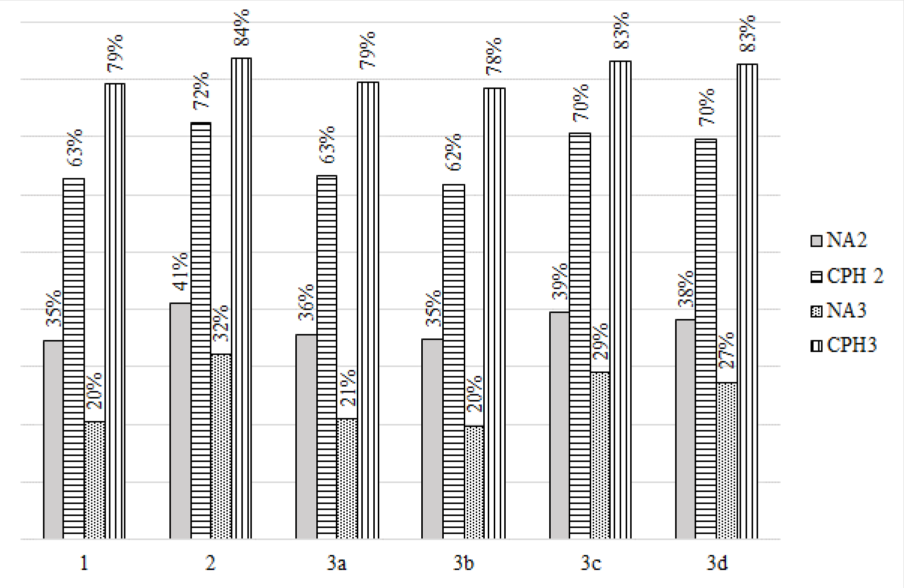


**Figure VII.18** *Time percentage of discomfort during the whole year. 1: "Zone averaged", 2: "Surface weighted", 3a: "Angle factor - in the centre of room/standing", 3b: "Angle factor – in the centre of room/seated" ", 3c: "Angle factor - near south wall/standing", 3d: "Angle factor - near south wall/seated”*

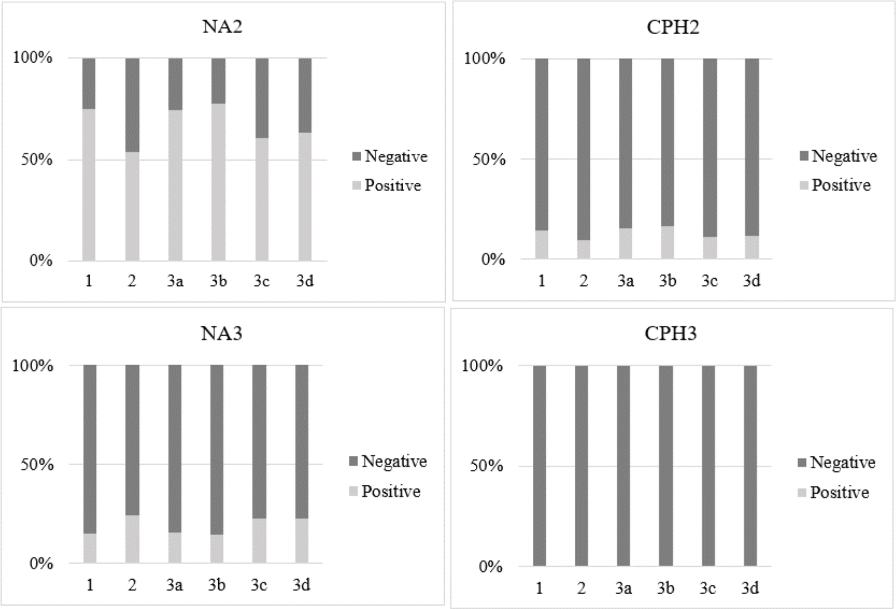


**Figure VII.19** *Time percentage of negative discomfort (cold) and positive discomfort (hot). 1: "Zone averaged", 2: "Surface weighted", 3a: "Angle factor – in the centre of room/standing", 3b: "Angle factor - in the centre of room/seated" ", 3c: "Angle factor - near south wall/standing", 3d: "Angle factor - near south wall/seated"*

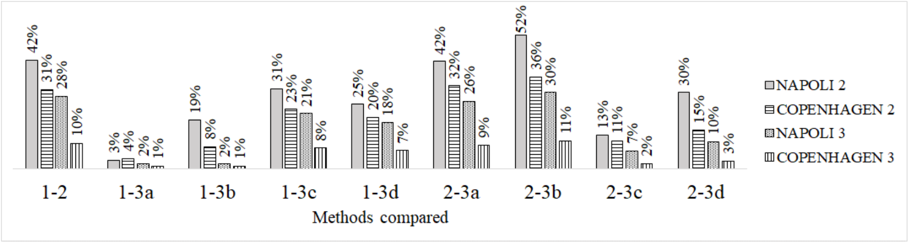


**Figure VII.20** *Time percentage with the class change between different methods. 1: "Zone averaged", 2: "Surface weighted", 3a: "Angle factor – in the centre of room/standing", 3b: "Angle factor – in the centre of room/seated" ", 3c: "Angle factor - near south wall/standing", 3d: "Angle factor - near south wall/seated"*

## VII.5 Conclusions

The results obtained show that the main differences and criticism between the calculation methods of the software and the calculation methods of Standard have an impact on the determination of the PMV.

The different methods used by Energy Plus to calculate $t_r$ do not always allow for carrying out coincident values of mean radiant temperature affecting the thermal comfort evaluation. In particular, the simulations reveal a link between a lower surface temperature of the glazed surface which corresponds to a greater difference in $t_r$ calculated with the different comparison methods.

Furthermore, the values of PMV calculated using $t_r$ obtained from different methods, return a different classification of the thermal environment above all in model 2, with a larger south glazing surface.

Finally, Design Builder, using only the “zone averaged” method, is the tool with the greatest limits because it does not consider the position of a person other than the centre of the room.

Regarding Energy Plus, the “surface weighted” is an incomplete method because it considers the influence of the surface closest to the subject, but it does not specify the exact position of the subject. The method in Energy Plus most in line with the standard is the "angle factors" one.

As said several times in the previous chapters, the simulation tools consider several assumptions that the user should know to better manage the analysis of results. This is also true for the calculation of $t_{r.}$

# Chapter VIII
# Calculation of heat transfer coefficients in Energy Plus

## VIII.1 Introduction

The investigation carried out on the comparison between two simulation tools in Chapter V, highlighted the need to deeply investigate the method for calculating the U-value, whose value influences thermal comfort.

The U-value depends on the thermophysical properties of the layer to which it refers and on the surface heat transfer coefficients. These last parameters are calculated differently depending on the hypotheses on which the calculation of convective ($h_c$) and radiative heat exchange ($h_r$) is based.

The research has so far focused on the thermal balance equations on the external and internal surfaces of the wall (Mazzeo et al., 2020) and on the models to obtain the external convective heat transfer coefficient ($h_{c,e}$) in dynamic energy simulation tools (Mirsadeghi et.al., 2013). Unfortunately, there are no studies concerning the comparison between the value of the heat transfer coefficient obtained with different calculation methods under the same boundary conditions, in particular for the calculation of the heat transfer radiative coefficient.

The investigation to trace the methods used for the calculation of the radiative conductance, mainly due to a lack of systematic studies both in scientific literature and in technical handbooks, is not easy.

Dynamic energy simulation tools consider different operating conditions. So direct comparison is not always straightforward because the data required for modelling are not identical. Another aspect to take into account is the complexity of the mathematical models coupled with the ability to access BPS source code which is relevant in the research field.

As described in Chapter V, Design Builder and IDA ICE use as input data of the heat transfer coefficients the values prescribed respectively by the ASHRAE 2019 and by the ISO EN 6946 Standard. These values change during the simulation according to some parameters and consequently, also the U-value varies.

Comparing the two software Energy Plus (and so Design Builder) and IDA ICE, the first difference is the model used for the convective heat transfer between the surface of the envelope and the surrounding environment. In Energy Plus the calculation of the constant or variable convective heat transfer coefficient is done using algorithms that consider natural, mixed and forced convective models as a function of the wind speed, the inclination of the wall and the temperature difference between air and wall surface. IDA ICE uses a dynamic model as a function of wind speed.

The second difference between the two examined tools is the algorithm used for modelling the heat exchange phenomena and the thermal behaviour of the building envelope. Indeed, Energy Plus considers the wall as a black box and the calculation is performed with the method of the heat exchange function. Instead, IDA ICE applies the finite difference method with a discretization of the wall and a more detailed study of the thermal behaviour of the wall (Johari et al., 2019).

Finally, Energy Plus provides extensive documentation as a reference for the use of the program and describes in detail the algorithms and calculation methods of the software, while IDA ICE provides only a manual and guidance document on the use of the program.

## VIII.2 Objective

In this Chapter, an initial study concerns the analysis of the calculation models of heat transfer convective coefficients on the internal surface ($h_{c,i}$) in Energy Plus.

The aim is to verify the effects in terms of energy consumption and thermal comfort evaluation, using the six main algorithms proposed by Design Builder.

## VIII.3 Method

Model 1 in Fig.VII.1, located in Napoli, is used to calculate $h_{c,i}$ using different methods. The resulting values of energy consumption and PMV index obtained for each simulation are then compared.

For this purpose, initially, the study focus on the heat balance on the internal surfaces of the walls and then the research aims at the identification of the main inside convection algorithm available in Design Builder [31].

Finally, the results of energy consumption and PMVs values obtained with different methods of $h_{c,i}$ in model 1, are compared.

### *VIII.3.1 Heat balance on the internal surface*

Energy Plus considers four heat transfer mechanisms:

1. Conduction through the building elements.
2. Convection between the surface of the wall and zone air.
3. Short wave radiation flux.
4. Longwave radiation.

Short-wave radiation represents the solar radiation entering the zone through windows and the emission from internal sources such as lights. Longwave radiation includes the emission of low-temperature radiation sources, such as all other zone surfaces, equipment, and people.

The heat balance on the internal surface of the wall can be written with Eq. (VIII.1). Fig. VIII.1 shows the components of the heat balance.

$$q''_{\mathrm{ki}}+q''_{\mathrm{conv}}+q''_{\mathrm{SW}}+q''_{\mathrm{LWX}}+q''_{\mathrm{LWS}}+q''_{\mathrm{sol}}=0 \qquad \text{(VIII.1)}$$

where:

$q''_{\mathrm{ki}}$ = conduction flux through the wall, W/m$^2$;
$q''_{\mathrm{conv}}$ = convective heat flux to zone air, W/m$^2$;
$q''_{\mathrm{SW}}$ = net short wave radiation flux to surface from lights, W/m$^2$;
$q''_{\mathrm{LWX}}$ = net longwave radiation exchange flux between zone surfaces, W/m$^2$;
$q''_{\mathrm{LWS}}$ = longwave radiation flux from equipment, other surfaces and people in the zone, W/m$^2$;
$q''_{\mathrm{sol}}$ = transmitted solar radiation flux absorbed at the surface, W/m$^2$.

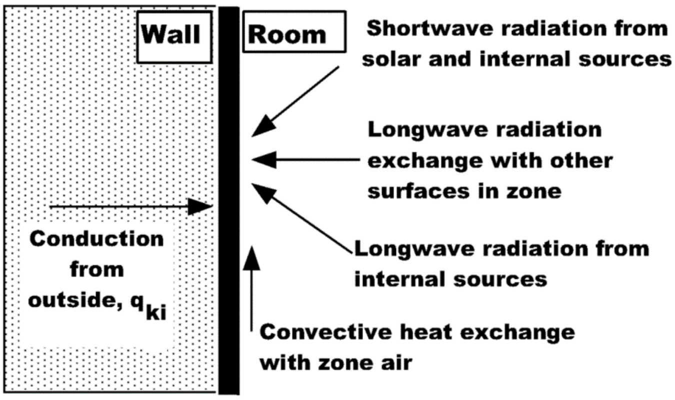


**Figure VIII.1** *Components of inside heat balance [31]*

## VIII.3.2 Inside convection algorithm

Design Builder provides six main algorithms of Energy Plus for calculating the convective heat transfer between internal zone surfaces and the air in the zone: *adaptive convection algorithm, simple natural convection algorithm, CIBSE, ceiling diffuser algorithm, Trombe wall algorithm (or cavity)* and *TARP algorithm* [33]. Table VIII.1 summarizes the six algorithms specifying influencing factors for each model calculation.

As follows the six calculation models are described.

**Table VIII.1** *Influencing factors in the algorithms for calculating* $h_{c,i}$

| Model | Surface orientation | Surface Slope Angle | $\Delta T$ (surface/air) | *ACH* | $Nu$ = Nusselt number | Flow direction (upward/downward) | Conductivity of air | Air gap thickness |
|---|---|---|---|---|---|---|---|---|
| Adaptive convection algorithm | | | as a function of $h_c$ equation selected | | | | | |
| Simple natural convection algorithm | ▨ | | | | | | | |
| CIBSE | | | constant values | | | | | |
| Ceiling diffuser algorithm | | | | ▨ | | | | |
| Trombe wall algorithm | | | | | ▨ | | ▨ | ▨ |
| TARP algorithm | | ▨ | ▨ | | | ▨ | | |

### VIII.3.2.1 Adaptive convection algorithm

Developed by Beausoleil-Morrison (2000), this advanced option provides dynamic management of convection models based on the selection among the available $h_{c,i}$ equations for the one that is most appropriate for a given surface at a given time. As Beausoleil-Morrison notes, the adaptive convection algorithm is intended to be expanded and altered to reflect different classification schemes and/or new $h_c$ equations.

The adaptive convection algorithm is based on classifying surfaces by flow regime and orientation so that the correct equation can be chosen at a particular point in time during the simulation. The classification depends on user input with some aspects processed only once at the beginning and others during each timestep.

The adaptive convection algorithm implemented in Energy Plus for the inside face has a total of 45 different categories for surfaces and 29 different options for $h_c$ equation selections. The guide of Energy Plus summarises in a table the categories and the default assignments for $h_c$ equations.

### *VIII.3.2.2 Simple natural convection algorithm*

The simple convection model uses constant coefficients for different heat transfer configurations. The coefficients are taken directly from Walton (1983) who derived his coefficients from the surface conductance for $\varepsilon$ = 0.90.

Table VIII.2 shows the coefficients used by the model based on the specific condition of the surface.

**Table VIII.2** *Coefficients of the Simple model according to specific conditions*

| Surface condition | $h_{c,i}$ [W/m$^2$·K] |
|---|---|
| Vertical surface | 3.076 |
| Horizontal surface with reduced convection | 0.948 |
| Horizontal surface with enhanced convection | 4.040 |
| Tilted surface with reduced convection | 2.281 |
| Tilted surface with enhanced convection | 3.870 |

### *VIII.3.2.3 CIBSE model*

The algorithm applies a constant heat transfer coefficient derived from traditional CIBSE (Chartered Institution of Building Services Engineers) values.

### *VIII.3.2.4 Ceiling diffuser algorithm*

A mixed and forced convection model for ceiling diffuser configurations. The model correlates the heat transfer coefficient to the air change rate for ceilings, walls and floors. The ceiling diffuser algorithm is based on empirical correlations developed by Fisher and Pedersen (1997). The correlation was reformulated to use the room outlet temperature as the reference temperature. The Eqs. (VIII.2, VIII.3, VIII.4) show the $h_{c,i}$ formulation for different components of the building.

For floors:

$$h_{c,i} = 3.873 + 0.082 \cdot ACH^{0.98} \tag{VIII.2}$$

For ceilings:

$$h_{c,i} = 2.234 + 4.099 \cdot ACH^{0.503} \tag{VIII.3}$$

For walls:

$$h_{c,i} = 1.208 + 1.012 \cdot ACH^{0.604} \tag{VIII.4}$$

### *VIII.3.2.5 Trombe wall algorithm (or Cavity)*

The algorithm was developed to model convection in a “Trombe wall zone”, defined as the air space between a storage wall's external surface and the exterior glazing. The algorithm is identical to the convection model based on ISO 15099 and used in Window5 for convection between glazing layers in multi-pane window systems described in the Energy Plus guide.

The use of the algorithm for modelling an unvented Trombe wall has been validated against experimental data by Ellis (2003). This algorithm gives the convection coefficients for air in a narrow vertical cavity that is sealed and not ventilated. This applies both to the air gap in between the panes of a window or to the air gap between the Trombe wall glazing and the external surface of the envelope.

In this study Trombe wall algorithm is not applicable.

### *VIII.3.2.6 TARP algorithm*

The default algorithm in Design Builder, TARP is based on variable natural convection, and it depends on the surface orientation and the difference between the surface and zone air temperatures.

The algorithm is taken from the one derived by Walton (1983) starting from ASHRAE literature (2001) which gives equations for natural convection heat transfer coefficients in the turbulent range for large, vertical plates and large, horizontal plates facing upward when heated (or downward when cooled) as reported in the Eqs. (VIII.5, VIII.6, VIII.7).

For vertical surface:

$$h_{\mathrm{c,i}} = 1.31|\Delta T|^{\frac{1}{3}} \tag{VIII.5}$$

For ($\Delta T$ < 0.0 and an upward-facing surface) or ($\Delta T$ > 0.0 and a downward facing surface) an enhanced convection correlation is used:

$$h_{\mathrm{c,i}} = \frac{9.482|\Delta T|^{\frac{1}{3}}}{7.283 - |\cos \Sigma|} \tag{VIII.6}$$

For ($\Delta T$ > 0.0 and an upward-facing surface) or ($\Delta T$ < 0.0 and a downward facing surface) a reduced convection correlation is used:

$$h_{\mathrm{c,i}} = \frac{1.810|\Delta T|^{\frac{1}{3}}}{1.382 + |\cos \Sigma|} \tag{VIII.7}$$

where $\Sigma$ is the surface tilt angle.

## VIII.4 Results and discussion

The results of the model simulations are referred to a whole year, considering 8760 occupied hours. Starting from the calculated values of $h_{c,i}$ obtained using the five models described in paragraph VIII.3, the percentage difference of PMVs and the energy consumption values are calculated whit Eqs. (VIII.8) and (VIII.9) respectively.

Figs. VIII.2 and VIII.3 show the results. In Fig. VIII.2 the higher percentage for PMV values is around 5%. This means that using different methods, different thermal comfort conditions for 400 hours occur. Regarding energy consumption comparing the several models, the total annual consumption varies by a maximum of 6%.

$$\% \text{ difference} = \frac{\sum_{i=0}^{n}\left(PMV_a \neq PMV_b\right)}{8760} \qquad \text{(VIII.8)}$$

*where:*

$i$ = hour in which the PMV between two compared methods is different;

$n$ = number of hours in which the PMV value is different;

$a$ = model a;

$b$ = model b.

$$\% \text{ difference} = \frac{\left(EC_a - EC_b\right)}{EC_a} \qquad \text{(VIII.9)}$$

where:

$EC$ = energy consumption, kWh

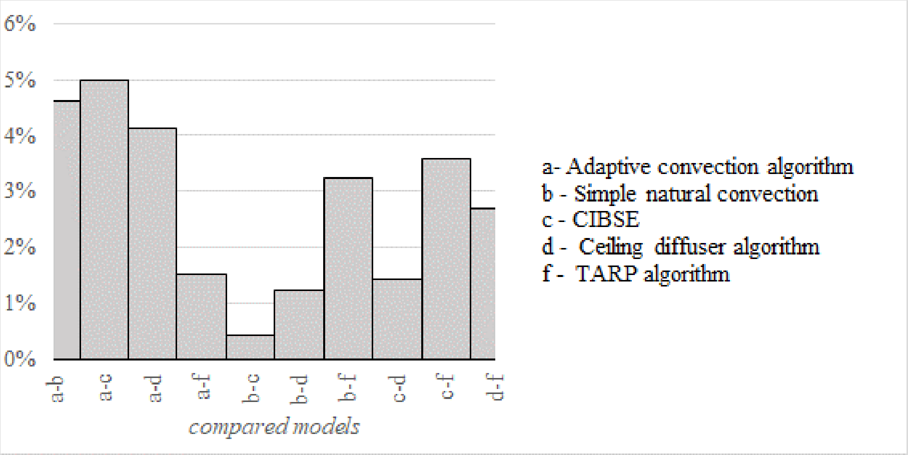


**Figure VIII.2** *Percentage of difference in PMV values obtained for different* $h_{c,i}$ *models calculation*

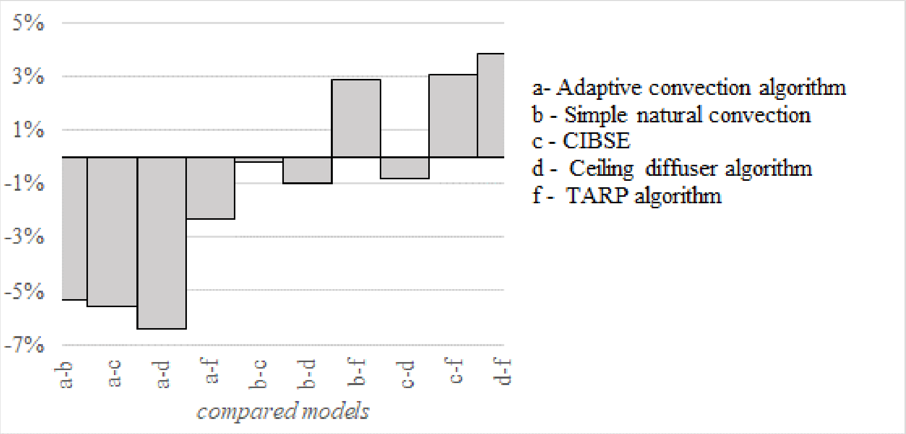


**Figure VIII.3** *Percentage of difference in energy consumption of building models using different* $h_{c,i}$ *model calculation*

## VIII.5 Conclusions

This study compares the influence of different convective heat transfer models proposed by Energy Plus on the energy consumption and PMV index for evaluation of thermal comfort in a building simulation performed with Design Builder.

The results do not show significant differences. The study should be better investigated also considering the calculation models of $h_r$ and comparing results with other simulation tools, such as IDA ICE which does not have exhaustive documentation on the calculation methods for $h_c$ and $h_r$.

# Conclusions

The main objective of this thesis is to identify the role of dynamic energy simulation in the control and optimization of thermal comfort, which is one of the IEQ aspects strongly correlated with the energy efficiency of the buildings, taking into account a critical approach in the use of dynamic simulation tools.

The thesis aims to evaluate the use of dynamic instruments, considering the importance of the knowledge of used tools to predict buildings' thermal energy behaviour.

For this aim, several topics are studied by running simulations.

After an overview of the theoretical aspects of energy efficiency, dynamic simulation, and thermal comfort evaluation, the thesis deals with some issues for building performance evaluation using dynamic simulation tools.

The thesis initially includes a study to understand how to approach at evaluation of energy use and thermal comfort in a building according to indications of the European standard EN16798-1 and -2 using one of the most know simulation tools in the research and professional field: Design Builder with calculation engine Energy Plus.

From the analysis of the results, significant aspects emerged as the strong correlation between energy use and thermal comfort in a building, and the consequent need to study it together to improve the conditions of the indoor environment and optimize energy use. Furthermore, the study highlights the necessity to review the Standard in defining heating and cooling season, for better thermal comfort analyses.

A second topic concerns a comparison between two energy simulation software: Energy Plus, an international standard, and IDA ICE, a common European software. The purpose is to verify the consistency of results, which can affect technical consequences on design choices. The comparison consists of modelling for different building models and weather conditions. The results demonstrate that the frequent differences between the two software are related to the temperatures rather than the energy delivered for the identical model created in the two simulation tools.

The cause of the differences may be due to the way to define input data, the U-value calculation procedure, which influences $t_r$, and the different methods of calculating the radiant energy running through the windows.

For this, the user should be careful when comparing the solutions deriving from different software, especially in a competition.

Further analyses could concern the comparison of software considering different building typologies (e.g. stratigraphy and U-values) and different architectural layouts starting with a simplified geometry.

Another further study could concern the comparative analysis of dynamic simulation tools by analysing which of the software considered can reproduce a building behaviour closest to reality.

Although several studies have been carried out aiming to compare the different simulation tools, up to now there is no deep study describing the modelling procedure, inputs, outputs, and validity of these tools compared to each other. To investigate these differences, initial theoretical work on the determination of the U-value in Energy Plus is studied. In particular, the study focuses on the heat transfer coefficients methods calculation: fundamental parameters which influence U-value in the heat transfer between the building envelope and indoor and external environment.

The study concerns the influence of calculation methods of convective heat transfer coefficient ($h_{c,i}$) in Energy Plus on the thermal comfort assessment.

The results have not shown significant differences. The study on the heat transfer coefficients to be continued forward is only at the beginning of the research.

About thermal comfort evaluation with dynamic simulation tools, a study on mean radiant temperature ($t_r$) is carried out. This temperature cannot be directly measured; it is consistently calculated with ISO 7726, and its value strongly influences the PMV value, thermal comfort index. The aim is to investigate methods for calculation of mean radiant temperature in Energy Plus, to identify differences and criticalities between calculation methods in the software and with the equations of standard, and finally detect the impact of the methods calculation of $t_r$ on the thermal comfort analysis. This topic has not been investigated in the available literature. The obtained results show how small differences in the $t_r$ value induce various classifications of the thermal environment in terms of PMV.

From simulations performed in the thesis, several issues emerge about the role of dynamic simulation tools.

The topics covered highlight how is important critically use dynamic tools and correctly interpret the obtained results. The simulations in the thesis demonstrate how the estimation of thermal comfort strongly depends on the specific simulation tool used.

Furthermore, prior knowledge of the assumptions and simplifications at the base of the simulation tool is required, without unconditionally accepting the output results: different simulation tools can return different results, influencing the analyses of the building performance over time and the designing choices.

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# Webgraphy

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# Symbology

$A$ = parameter function of relative velocity, 1;
$A_b$ = body surface area, $m^2$;
$A_i$ = surface area, $m^2$;
$A_r$ = floor area, $m^2$;
$ACH$ = air change per hour, $h^{-1}$
$C$ = convective heat flow, $W/m^2$;
$c$ = specific heat, W·h/kg·K;
$C_{res}$ = respiratory convective heat flow, $W/m^2$;
$C_w$ = pressure coefficient, 1;
$CPH1$ = output of the simulation performed for Copenhagen in scenario 1
$CPH2$ = output of the simulation performed for Copenhagen in scenario 2
$CPH1_{winter}$ = hours of temperature values equal/higher than 20°C (setpoint for winter);
$CPH1_{summer}$ = hours of temperature values equal/lower 26°C (setpoint for summer);
$DB$ =Design Builder;
$DR$ = draft risk, %;
$E$ = evaporative heat flow at the skin, $W/m^2$;
$E_{res}$ = respiratory evaporative heat flow, $W/m^2$;
$EC$ = energy consumption, kW·h;
$EP$ =Energy Plus;
$f_{cl}$ = clothing surface area factor, 1;
$F_i$ = angle factor between person and surface, 1;
$F_{p\text{-}N}$ = angle factor between a person and “N” surface;
$H_b$ = body height, m;
$h_c$ = convective heat transfer coefficient, $W/m^2 \cdot K$;
$h_{c,i}$ = convective heat transfer coefficient on the internal surface, $W/m^2 \cdot K$;
$h_r$ = radiative heat transfer coefficient, $W/m^2 \cdot K$;
$HVAC$ = Heating, Ventilation & Air Conditioning;

$I_{cl}$ = clothing thermal insulation, clo;
*IGDG* = Italian Climatic data collection "Gianni De Giorgio";
*IWEC* = International Weather for Energy Calculations;
$K$ = conductive heat flow, W/m$^2$;
$M$ = metabolic rate, W/m$^2$;
*NFRC* = National Fenestration Rating Council;

$p_a$ = water vapour partial pressure, Pa;
$P_w$ = wind pressure, Pa;
*PA*1 = output of the simulation performed for Palermo in scenario 1
*PA*2 = output of the simulation performed for Palermo in scenario 2
*PMV* = predicted mean vote, 1;
*PPD* = predicted percentage of dissatisfied, %;
$q''_{conv}$ = convective heat flux to zone air, W/m$^2$;
$q''_{ki}$ = conduction flux through the wall, W/m$^2$;
$q''_{LWS}$ = longwave radiation flux from equipment, other surface and people in zone, W/m$^2$;
$q''_{LWX}$ = net longwave radiation exchange flux between zone surfaces, W/m$^2$;
$q''_{sol}$ = transmitted solar radiation flux absorbed at the surface, W/m$^2$;
$q''_{SW}$ = net short wave radiation flux to surface from lights, W/m$^2$;
$q_c$ = convection fraction of the heat exchanged between lamps and the air, 1;
$q_B$ = ventilation rate for emissions from building, l/(s·m$^2$);
$q_e$ = fraction of the heat from light that is transported out of the room and into the zone return air, 1;
$q_p$ = ventilation rate for occupancy per person, l/(s person);
$q_{r,l}$ = fraction of heat from light that goes into the zone as long-wave radiation, 1;
$q_{r,s}$ = fraction of heat from light that goes into the zone as visible (short-wave) radiation, 1;
$q_{tot}$ = total ventilation rate for breathing zone, l/s;
$R$ = radiative heat flow, W/m$^2$;
$R_{se}$ = external resistance, m$^2$·K/W;
$R_{si}$ = internal resistance, m$^2$·K/W;
*RH* = Relative Humidity, %;
$S$ = body heat storage rate, W/m$^2$;
$s$ = thickness, mm;

$SFP$ = specific fan power, kW·s /m³;
$SW1$ = Software 1;
$SW2$ = Software 2;
$t_\mathrm{a}$ = air temperature, °C;
$t_\mathrm{cl}$ = clothing surface temperature, °C;
$t_\mathrm{ed\text{-}1}$ = daily mean outdoor air temperature for the previous day, °C;
$t_\mathrm{ed\text{-}i}$ = daily mean outdoor air temperature for the *i-th* previous day, °C.
$T_\mathrm{i}$ = surface temperature, K;
$T_\mathrm{N}$ = temperature of “N” surface, K;
$t_\mathrm{o}$ = operative temperature, °C;
$t_\mathrm{pr}$ = plane radiant temperature, °C;
$t_\mathrm{r}$ = mean radiant temperature, °C;
$T_\mathrm{r}$ = mean radiant temperature, K;
$T_\mathrm{r\text{-}avg}$ = “zone averaged” radiant temperature, K;
$t_\mathrm{rm}$ = outdoor running temperature, °C;
$T_\mathrm{surf}$ = surface temperature to which person is closer, K;
$T\mathrm{u}$ = turbulence intensity, %;
$Time_{t_\mathrm{o} \geq 20^\circ\mathrm{C},\mathrm{north}}$ = percentage of the hour in which the operative temperature value is equal/higher than the minimum value (20°C) for winter in the office north, %;
$Time_{t_\mathrm{o} \leq 26^\circ\mathrm{C},\mathrm{north}}$ = percentage of the hour in which the operative temperature value is equal/lower than the maximum value (26°C) for summer in the office north, %;
$TCS$ = thermal comfort score, 1;
$U\text{-}value$ = transmittance, W/m$^2$·K;
$v$ = wind speed, at roof height of building, m/s;
$v_\mathrm{a}$ = air velocity, m/s;
$v_\mathrm{ar}$ = relative velocity, m/s;
$W$ = effective mechanical power, W/m$^2$;
$W_\mathrm{b}$ = body mass, kg;
$w$ = wind vector, m/s;
$x$ = $x$-axis wind vector component, m/s;
$y$ = $y$-axis wind vector component, m/s.

### *Greek letters*

$\alpha$ = constant for outdoor running temperature;
$\Sigma$ = surface tilt angle, °C;
$\lambda$ = thermal conductivity, W/m·K;
$\varepsilon$ = emissivity, 1;
$\rho$ = density, kg/m$^3$;

$\Delta\theta_{\%}$ = fraction of the time that the temperature difference values fall into a specific range, %;
$\Delta_{EF}$ = difference of energy flows for each component, %;
$\Delta C$ = difference in energy use for cooling, %;
$\Delta H$ = difference in energy use for heating, %;
$\Delta S$ = summer difference;
$\Delta T$ = difference of temperature, °C;
$\Delta W$ = winter difference.