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BACS: energy performance and technical-economic analysis of HVAC technologies

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Abstract

In Europe, buildings operation causes 40% of energy consumption and 36% of greenhouse gas emissions. For this reason, the European Union's *Energy Performance of Building Directives* (EPBD) provides policies aimed at optimizing the energy efficiency in buildings. To achieve the goal of optimizing the energy performance of buildings, the directive identifies several technological solutions that can be used.

One of these technological solutions and the topic of this thesis are the *Building Automation and Control Systems* (BACS), whose purpose is to adapt the operation of technical building systems on the real behavior of users according to the external environmental conditions. To develop this work the EN ISO 52120 standard has a relevant importance, since it provides the list of BACS functions, the method to define the BACS efficiency classes, and the detailed and simplified methods to assess the effect of BACS on the building energy performance.

This work is the result of a collaboration with *C2R Energy Consulting*, a consulting company in the energy sector. The goals are twofold.

The first goal is to evaluate the ability to simulate the BACS functions with two different energy modeling tools; *Edilclima EC700*, which uses a simplified dynamic calculation model, and *EnergyPlus/DesignBuilder*, which uses a detailed dynamic calculation model. First, the work illustrates which functions can be simulated and at what relative implementable level. A short guide to the actual simulation of the functions is also provided. A group of classrooms of the *Politecnico di Torino* are modeled with the two software tools to simulate the presence of some of BACS functions used for HVAC and blind control and to evaluate their effects on the energy performances and the energy savings of the building. The thesis provides a comparison of the results of sensible energy needs for heating, sensible energy needs for cooling and ventilation electric energy, obtained from the simulations made with the two software tools. The benefits of having high-energy performance BACS functions are highlighted. As well, the strengths and weaknesses of the two software tools are analyzed. The results show that a high BACS efficiency class allows to reduce the energy consumption both in terms of sensible energy needs for heating and cooling and in terms of ventilation electric energy.

The second goal is to analyze the economic feasibility of installation of BACS devices in the case study and to provide a more realistic evaluation of the cost of these systems. The estimate is done by calculating the payback period based on the real costs of the devices available on the market and on the current cost. The result of the analysis shows that the payback period is lower than the lifespan of BACS devices, which is about 10 years. Therefore, BACS implementation is not only energy effective but also cost effective.

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Chapter 1

Introduction

Buildings are the main consumers of energy in Europe, indeed approximately 40% of all energy consumption and 36% of all greenhouse gas emissions in Europe are due to buildings operations. Moreover, approximately 35% of the building stock is over 50 years old and about 75% of all buildings are not energy efficient [26].

For this reason, the European Union focused on some policies aimed at optimizing the energy efficiency of the existing building stock. These policies are listed in two different directives, *Energy Performance of Buildings Directive* (EPBD) and *Energy Efficiency Directive* (EED), which are part of the wider *Clean energy for all Europeans* package that aims to decarbonize the European energy system in accordance with the European Green Deal objectives.

The main policies recommended to member states in the EPBD and in the EED are [26]:

- to determine a long-term renovation strategy in order to decarbonize their building stock by 2050,
- to set a minimum energy performance requirement for new buildings, for buildings undergoing major renovation and for replacement of building systems; in the case of new buildings the directive requires that they must be nearly zero-energy buildings (NZEB),
- to renovate in an energy efficient way at least 3% of the floor area of buildings owned and occupied by central governments,
- to follow the directives requirements for installation of building automation and control systems.

This last point is the main focus of this work. The EN ISO 52120-1 standard defines *Building Automation and Controls System* (BACS) as a

> system, comprising all products, software and engineering services for automatic controls (including interlocks), monitoring, optimization, for operation, human intervention, and management to achieve energy-efficient, economical, and safe operation of building services [19].

In other words, it is the set of systems that allows to control, monitor and automate a building, increasing the energy efficiency and at the same time maintaining thermal comfort. They comprise heating, cooling, domestic hot water production, ventilation and air-conditioning, lighting appliances, blind control and technical building management. All these systems, if correctly designed and automated, allow to increase the energy performance, decrease energy demand for operation and consequently reduce greenhouse gas emissions.

This work is the result of a collaboration with *C2R Energy Consulting*, which is a company providing technical and scientific consulting services and support for energy-efficiency interventions and energy management.

The goals of this thesis are twofold. The first goal is to evaluate the ability to simulate BACS functions with two different energy modeling tools: *Edilclima EC700*, which uses a simplified dynamic calculation model, and *EnergyPlus/DesignBuilder*, which uses a detailed dynamic calculation model.

The second goal is to provide an economic feasibility assessment for the installation of BACS devices in a case study via a realistic cost-benefits analysis based on an estimate of the payback period.

The work is divided into six main parts. Chapter 2 summarizes the European [23][24][25][27] and Italian [35][36][34][33] legislative frameworks, with a particular focus on BACS efficiency class requirements.

Chapter 3 describes the EN ISO 52120-1:2022 standard [19] providing the list of BACS functions, the method to define the BACS efficiency classes, the detailed methods and the factor-based method to assess the effects of BACS in the building.

Chapter 4 explains which functions can be simulated with the two software tools, *Edilclima EC700* and *EnergyPlus/DesignBuilder*, describing also their relative implementable levels. A short guide to the actual simulation of the functions is provided as well.

Chapter 5 describes the current status of the case study (classroom P of the *Politecnico di Torino*) and its modeling using the two software tools. Some BACS functions used for HVAC and blind control are simulated according to the technical building systems present in the building and the simulation capacities of the software tools. This chapter also provides an analysis of the results obtained from the simulations, highlighting the benefits of having high-energy performance BACS functions.

Chapter 6 provides a market analysis on the availability of the BACS devices considered in the case study. It also provides a cost-benefit evaluation of these systems. The cost estimation is done by calculating the payback period based on the real costs of the devices available on the market and on the current electricity costs.

The conclusions (Chapter 7) highlight the issues of using *Edilclima EC700* and *EnergyPlus/DesignBuilder*, and summarize the average annual energy savings in terms of sensible energy needs for heating, sensible energy needs for cooling and ventilation electric energy. It also summarizes the results of the calculation of the payback period, highlighting the total costs saving after the analyzed period obtained from the use of BACS functions. Finally, some possible future developments of this work are descried.

Chapter 2

Legislative framework

This chapter analyses the European legislative framework and the Italian legislative framework that give some prescriptions about the installation of BACS functions in order to highlight their requirements.

2.1 European legislative framework

The *Energy Performance of Buildings Directive* (EPBD) is part of the legislative framework determined by the European Union in order to increase the energy performance of buildings. The EPBD includes requirements for BACS.

The first version of this directive dates back to 16 December 2002 with the directive 2002/91/EC [23]. In this first version, the topic of BACS was not yet developed.

The directive was revised for the first time on 19 May 2010 and was replaced by the directive 2010/31/EU [24]. This version of the EPBD invites all the European Countries to install automation, control and management systems in order to increase energy savings.

The EPBD is revised again in 2018 (Directive (EU) 2018/844)[25], this new version has been implemented according to the new technologies available. Therefore, there are more specifications about BACS.

BACS are defined by the Directive (EU) 2018/844 [25] as a

> system, comprising all products, software and engineering services for automatic controls (including interlocks), monitoring, optimization, for operation, human intervention, and management to achieve energy-efficient, economical, and safe operation of building services,

as it is also defined in the standard EN ISO 52120-1 [19].

Article 8 of EPBD [25] defines a series of directives about technical building systems. Those directives are:

- all systems and functions must be sized and installed appropriately manner for both new and renovated buildings,
- depending on whether the building is a new construction or a renovation, the systems to install must meet several requirements, which must be economically and technically feasible,
- new buildings must be equipped with devices that auto-regulate the temperature of a room or of a heated zone. In case of renovations, the building must be equipped with automation devices only when the heat generator is replaced,

- all the changes made to the technical building systems shall be recorded since they change the assessment of the energy performance.

In addition to Article 8, Article 14 *Inspection of heating systems* and Article 15 *Inspection of air-conditioning systems* [25] provide further requirements for the use of BACS.

These articles require that in non-residential buildings, equipped with heating and/or air-conditioning systems of more than 290 kW, BACS must be installed by 2025. In this case, the installed BACS must:

- continuously control and monitor the data from the installed systems in order to adjust the energy use,
- assess the energy efficiency, control the losses of the technical building systems, and inform the operator in order to improve energy performance as much as possible,
- allow interoperability between systems and devices connected to the BACS even if they belong to different manufacturers.

On the other hand, in the case of residential buildings, the EPBD requires that they must be equipped with:

- a monitoring system that informs building owners or managers if action is needed,
- control features that ensure optimal energy generation, distribution, and utilization.

The European Commission has put forward a proposal for a new EPBD recast on 15 December 2021 [27]. From the point of view of the BACS, the new proposals of the European Commission of the EPBD recast want to lower the power limit of the heating and air-conditioning systems for non-residential buildings for which the installation of BACS is required. The current limit of 290 kW will be reduced to 70 kW by 31 December 2029.

2.2 Italian legislative framework

The directives present in the EPBD of 2018 are introduced in the Italian legislation by the D.lgs 10 June 2020 number 48. D.lgs 48/2020 introduces both the definition of BACS as described in EPBD and all the directives related to BACS [37].

The Italian legislation does not mention the BACS only in the D.lgs 48/2020. Indeed, there are also references to BACS in the following decrees:

- Decree 26 June 2015 *Requisiti Minimi* [35],
- Decree 8 August 2020 *Requisiti tecnici Ecobonus* [36],
- Decree 16 February 2016 *Conto Termico 2.0* [34],
- Decree 23 June 2022 *Criteri ambientali minimi (CAM)* [33].

These decrees still refer to the old standard EN 15232-1 [4], which was replaced in November 2022 by EN ISO 52120-1. Therefore, the decrees will be subject to revision.

2.2.1 D.M 26 June 2015 *Requisiti minimi*

D.M 26 June 2015 *Requisiti minimi* [35] defines the application methods for calculating the energy performance and the minimum requirements that a building must have in terms of energy efficiency.

Regarding BACS, the decree establishes that in order to optimize the energy use, a minimum level of automation, control and management of the technologies and systems present in the building is required in non-residential buildings. This level must be equal to class B[1] of the old EN 15232 standard [4].

2.2.2 D.M. 8 August 2020 *Requisiti tecnici Ecobonus*

D.M. 26 June 2015 *Requisiti tecnici Ecobonus* [36] identifies the energy efficiency interventions that allow a deduction on the costs. Among the interventions described by the decree, there are those for installation and implementation of BACS devices.

To obtain incentives for BACS, at least class B of the old EN 15232 standard [4] must be installed. Moreover, the automation and control system should guarantee the automatic management of heating, air-conditioning or domestic hot water production, in such a way to:

- monitor and provide energy consumption by periodically updating data,
- display the operating condition and the control temperature of the systems,
- allow the remote management of the systems.

The decree requires that asseveration must be done for systems of more than 100 kW. Otherwise, asseveration can be replaced by an installation declaration.

D.M 8 August 2020 establishes that the applicable deduction is 65% with a maximum expense of €15.000, and the deduction may be divided in a maximum of 10 years. Moreover, if the installation of BACS systems is a trailed intervention[2], the applicable deduction will be 110% of the expenses of the intervention. However, this decree refers to Italian Law 208/2015 art.1 c.88 [30] which states that the incentives are valid only for installations in residential units.

In the end, the decree provides a maximum value of expense for each type of intervention. In the case of BACS, this value is 50€$/m^2$.

2.2.3 D.M. 16 February 2016 *Conto Termico 2.0*

D.M. 16 February 2016 *Conto Termico 2.0* [34] identifies the interventions to increase energy efficiency and production of thermal energy from renewable sources in the buildings of the public administration. The decree includes the interventions related to the BACS.

Furthermore, the application rules defined by the *Gestore Servizi Energetici* (GSE) [29] require at least a class B of BACS. In this case, the applicable deduction is 40% with a maximum expense of €50.000 and a maximum allowable parametric cost of 25€$/m^2$.

2.2.4 D.M. 23 June 2022 *Criteri ambientali minimi (CAM)*

D.M. 23 June 2022 *Criteri ambientali minimi (CAM)* [33] explains the minimum environmental criteria that must be met for new constructions, renovations and maintenance of public buildings.

[1] The class B of standard EN 15232 corresponds to an "advanced" level of automation of the building, the buildings in this class are equipped with advanced functions of control and automation and also specific functions that help the building management. Particularly, room controllers shall be able to communicate with a building automation system.

[2] A trailed intervention is an intervention made with an intervention of thermal insulation of the envelope or an intervention of replacement and redevelopment of condominium thermal systems.

The decree includes BACS among the rewarding criteria. Indeed, in the evaluation of the projects, a score is assigned to the projects that involve the installation of BACS. Those systems should be able to control, automate and manage the energy consumption of the thermal systems of the buildings.

In order to obtain the score, the installed systems must meet the requirements of class A[3] of the old EN 15232 standard [4]. Especially, BACS must:

- provide a continuous feedback from the data collected by the installed sensors to provide the end user and the energy manager with data on energy consumption,
- monitor the principal energy use of the building,
- be able to differentiate the energy consumption by thermal zone if the building requires a different management of heating and cooling systems according to the zone,
- allow control and analysis of building energy consumption,
- be accompanied by a measurement and control plan that illustrates the calculation method with the aim of optimizing the energy management of the building.

Moreover, the decree requires a demonstration that the performance achieved by the presence of automatic systems management is as high as possible.

[3]Class A "high-energy performance" level, comprising all buildings with a high level of control, automation and management functions. To be in class A, the building must further implement the level of automation and control functions compared to Class B and also the technical building management functions.

Chapter 3

Standard EN ISO 52120-1:2022, *Energy performance of buildings - Contribution of building automation, controls and building management*

This chapter describes the EN ISO 52120-1 international standard [19], regarding the contribution of automation, control and management systems for energy performance and comfort of buildings. This standard was published in March 2022 and replaced the previous 2017 standard EN 15232-1: *Impact of Building Automation, Controls and Building Management* [4].

The EN ISO 52120 standard defines *Building Automation and Control Systems* (BACS) as a

> system, comprising all products, software and engineering services for automatic controls (including interlocks), monitoring, optimization, for operation, human intervention, and management to achieve energy-efficient, economical, and safe operation of building services.

Therefore, BACS are all the building control systems, building management systems, and building energy management systems that observe the requirements of ISO 16484 standard [17], which explains how these systems must be designed and implemented in a building.

EN ISO 52120 is subdivided into four main parts:

- a list of building automation and control functions, and technical building management functions involved in the energy performance of buildings, categorized according to building disciplines,
- a classification of BACS efficiency classes, identifying the minimum requirements that a building must have to achieve different levels of automation and control,
- a factor-based method for a first assessment of the impact of BACS functions on a building,
- five detailed calculation methods to evaluate the effect of BACS functions on a building.

3.1 Impacting functions of BACS on the energy performance of buildings

The EN ISO 52120 standard describes the functions of *Building Automation and Control* (BAC) and *Technical Building Management* (TBM) that contribute to the energy performance of a building.

BAC are described as

> products, software, and engineering services for automatic controls, monitoring and optimization, human intervention and management to achieve energy-efficient, economical, and safe operation of building services equipment.

They enable the control of functions related to energy efficiency, such as heating, cooling, ventilation and air-conditioning, domestic hot water, lighting appliances and blind systems. Moreover, they can be set on the real habits of building users to reduce energy consumption and unnecessary CO_2 emissions, while also ensuring thermal comfort in the indoor environment.

TBM are described as

> processes and services related to operation and management of buildings and technical building system through the interrelationships between the different disciplines and trades.

TBM give information about maintenance, operation, service and management of the building, especially on the energy management that supports the building to improve its energy performance.

According to building requirements, BAC and TBM are combined to achieve an optimum level of automation and control of the technical building systems installed. Depending on the BACS functions implemented, the system created can be simple or complex.

EN ISO 52120 specifies 45 different functions, of which 38 are BAC functions and 7 are TBM functions. Each function has at least two levels of implementation. According to the implementation level of each function, the building will have a different level of automation and control. Table A.1 in Appendix A summarizes the list of BAC and TBM functions.

3.2 BACS efficiency classification

The standard defines four different BACS efficiency classes according to the level of functions implemented. The level to be achieved depends on whether the building is residential or not. The BACS efficiency classes are:

- *class D*: "non efficient" level, the lowest level. All buildings equipped with traditional systems that do not have control and automation capabilities are classified in this class,
- *class C*: "standard" level. It is the minimum level of control and automation that a building must have according to EN ISO 52120 standard. Table A.2 in Appendix A describes the minimum level of each function in order to be categorized as a class C building.
- *class B*: "advanced" level. It includes all buildings equipped with advanced functions of control and automation and with specific functions that help the building management. In particular, buildings in this class must be equipped with room controllers capable of communicating with a building automation system. For example, the control of supply air flow in rooms must depend on the occupancy of rooms sensed through the use of sensors,

- *class A*: "high-energy performance" level. It comprises all buildings with a high level of control, automation and management functions. In class A, room controllers contribute to HVAC system regulation according to the information received and facilitate the communication between the HVAC and different building services through additional integrated functions of the room controllers. Indeed, most of the functions implemented for class A work according to a demand-based control that self-regulates the technical building systems. For example, blind control is combined with light and HVAC control to reduce the risk of glare and overheating and to reduce the energy needed for cooling.

To increase the energy efficiency of the building stock, the standard requires that the minimum BACS efficiency class should be at least class C for new buildings and for buildings undergoing major renovations, unless additional requirements are demanded by public authorities (see Chapter 2).

The BACS efficiency class is determined by looking at the functions that contribute significantly to energy efficiency. Therefore, in the assessment of the BACS classification, one considers only the functions that have an impact on energy consumption of more than 5% of the total energy used by the building.

In Italy the BACS efficiency class assessment is defined using the procedure described in the UNI/TS 11651:2023 standard [41]. In order to be classified in a given class, all the functions that are installed in the building must be implemented at a level of automation that is equal or higher than the one required by the class. Table 6 of EN ISO 52120 standard provides the level of implementation that each function must have to achieve the different BACS efficiency classes.

3.3 Factor-based method for evaluating BACS contribution to energy performance of buildings

The *factor-based method* simplifies the calculation of the impact that BACS functions have on the energy efficiency of the buildings. It is used in the preliminary stage of the design when detailed knowledge of control, automation and management functions is still not available.

The impact of each function is calculated over one year. The thermal and electrical energy of class C are taken as reference points of the calculation with factor-based method. These values will be multiplied by a correction factor according to the real BACS class of the building to calculate the thermal and electric energy required.

The correction factors determined by EN ISO 52120 are summarized in Tables A.3, A.4 and A.5 in Appendix A. The tables provide different values depending on the building use destination and BACS efficiency class. These values are 1 for reference class C, between 1 and 1.5 for class D, and between 1 and 0.3 for classes B and A. Moreover, factors used for class B are always greater than those used for class A, as can be seen from Tables A.3, A.4 and A.5.

Since the factors used for class D are higher than one, the values of thermal and electric energy of class D will be higher than the ones of the reference class. On the other hand, since the factors used for class B and A are lower than one, the values of thermal and electric energy of these classes will be lower than of the reference class.

The reference thermal and electric energy values can be calculated with any dedicated algorithm, such as EPB standards, ISO standards, national or local legislation. In any case, in the factor-based method the parameters related to the building type, geometry, building use and climatic conditions must be taken into account in the calculation of the reference values of thermal and electric energy, since the BACS correction factors are independent of these parameters. The standard defines five different efficiency factors:

- thermal energy for space heating and cooling factors ($f_{BAC,H}$ and $f_{BAC,C}$),
- thermal energy for domestic hot water generation factor ($f_{BAC,DHW}$),
- electric energy for ventilation, lighting and auxiliary devices factors ($f_{BAC,L}$ and $f_{BAC,aux}$)

Equations (B.1), (B.2), (B.3), (B.4) and (B.5) in Appendix B illustrate how to calculate the thermal and electric energy with the factor-based method.

3.4 Detailed calculation of BACS contribution in energy performance of buildings

EN ISO 52120-1 identifies five different detailed methods to evaluate analytically the contribution of the BAC and TBM in the energy performance of a building.

The computations of these detailed methods can be done yearly, seasonally, monthly or hourly. Moreover, in order to take into account the real operation of the building, one can apply the dynamic calculation method for the assessment of the energy performance of the building.

The five different approaches to assess the impact of BACS functions are:

- *Direct approach*: it directly calculates the impact of the functions present in the building using a detailed simulation method or an hourly simulation method based on the standard EN ISO 52016-1 [18]. This method will be used by the two software tools for the energy performance assessment of the case study.
- *Operation model approach*: it computes the impact on the energy consumption of the automatic control for each operating mode, corresponding to a given state of the control system. Therefore, the total energy consumption is evaluated as the sum of each energy consumption of the different operating modes,
- *Time approach*: it estimates the impact of the automatic control for those systems that have a direct influence on the operating time of a device. The energy consumption is assessed over a given period according to Equation (B.6) in Appendix B,
- *Set-point approach*: it assesses the impact on energy efficiency of a control system that has a direct effect on the control accuracy. For example, it takes into account the impacts due to emission control of heating and cooling, or due to room controllers. Equation (B.7) in Appendix B calculates the impact on energy consumption,
- *Correction coefficient approach*: it can be used in the case of a control system that has a complex impact, for example a systems that has an effect both on time and temperature. The impact is calculated by Equation (B.8) in Appendix B.

Chapter 4

Simulation of BACS functions in *Edilclima EC700* and *EnergyPlus/DesignBuilder*

This chapter illustrates how to simulate the presence of BACS functions and their relative levels with two energy modeling software tools: *Edilclima EC700* (EC700) and *EnergyPlus/DesignBuilder* (E+/DB).

By studying the user manuals, it is identified the best procedures to simulate BACS functions and the level of BACS functions.

The chapter focuses on the functions of heating, domestic hot water, cooling, ventilation, and air-conditioning, light and blind control. Each function is described in a one-page tab. The tabs are structured in a first part consisting of a summary table and a second part describing how to simulate each level of the function considered.

The summary table provides a short description of the BACS function level, a list of reference standards for the function under consideration and an indication of whether each software tool can implement the function or not.

The second part briefly describes how to simulate with the two software tools the presence of the BACS function for each level that can be simulated.

Figure 4.1: *Edilclima EC700* logo (left), *EnergyPlus* logo (center) and *DesignBuilder* logo (right)

4.1 Heating control

4.1.1 Emission control

Table 4.1: Emission control summary

	Level of BAC function [19]	Standard [1][19]	*EC700*	*E+/DB*
0	No automatic control of the room temperature	EN ISO 52016-1[18] EN 15316-1 [5] EN 15316-2 [6]	YES	YES
1	Central automatic control: there is only central automatic control acting either on the distribution or on the generation. Function is to be integrated in a system.		YES	YES
2	Individual room control: by thermostatic valves or electronic controller		YES	YES
3	Individual modulating room control with communication: between controllers and BACS (e.g. scheduler, room temperature set-point)		YES	YES
4	Individual modulating room control with communication and occupancy detection: between controllers and BACS; demand control/occupancy detection		YES	YES

***Edilclima EC700*[22]**

Level 0 Define the heating system in the *Heating systems* data-sheet. Set the system working temperature in the *General data - Default data* data-sheet.

Level 1 Define the heating system in the *Heating systems* data-sheet. Define a unique hourly temperature profile zone in the *Conditioned zone/local - Hourly profile* data-sheet. Set the profile in each thermal zone, in this way the central automatic control is simulated.

Level 2 Define the heating system in the *Heating systems* data-sheet. In the *Heating systems - Circuit - General data - Monthly activation time* data-sheet select the option *From set-point temperature profile* to simulate the presence of thermostatic valves or electronic controllers.

Level 3 Define the heating system in the *Heating systems* data-sheet. For each thermal zone define the hourly temperature profile in the *Conditioned zone/local - Hourly profile* data-sheet. Set the profile according to the needs of the thermal zone. Then, in the *Heating systems - Circuit - General data - Monthly activation time* data-sheet select the option *Hourly needs*, to operate the heating system according to the established profile.

Level 4 Define the heating system in the *Heating systems* data-sheet. For each thermal zone define the hourly temperature profile in the *Conditioned zone/local - Hourly profile* data-sheet. Set the profile according to the real occupancy of the thermal zone. Then, in the *Heating systems - Circuit - General data - Monthly activation time* data-sheet select the option *Hourly needs*, to operate the heating system according to the established profile.

EnergyPlus/DesingBuilder **[42][43][21]**

Level 0 Leave *ZoneControl:Thermostat* and *SetpointManager:Scheduled* undefined.

Level 1 Set the object *SetpointManager:Scheduled* at the generation level. Define the control temperature profile in the field *Schedule Name*.

Level 2 Define the object *ZoneControl:Thermostat*. In the field *Control Type Schedule Name* set the control type on *Uncontrolled* to simulate the presence of thermostatic valves or electronic controllers.

Level 3 Define the object *ZoneControl:Thermostat*. In the field *Control Type Schedule Name* set the control type on *Single Heating Setpoint*. Then, define the object *ThermostatSetpoint:SingleHeating* with the set-point temperature schedule based on the given values. In the field *Control Object* $< x >$ *Type* set the name of the *ThermostatSetpoint:SingleHeating* as previously defined.

Level 4 Define the object *ZoneControl:Thermostat*. In the field *Control Type Schedule Name* set the control type on *Single Heating Setpoint*. Then, define the object *ThermostatSetpoint:SingleHeating* with the set-point temperature schedule based on the real occupancy values. In the field *Control Object* $< x >$ *Type* set the name of the *ThermostatSetpoint:SingleHeating* as previously defined.

4.1.2 Emission control for TABS

Table 4.2: Emission control for TABS summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	No automatic control of the room temperature	EN ISO 52016-1[18] EN 15316-1 [5] EN 15316-2 [6]	YES	YES
1	Central automatic control: the central automatic control for a TABS zone (which comprises all rooms which get the same supply water temperature) typically is a supply water temperature control loop whose set-point is dependent on the filtered outside temperature, e.g. the average of the previous 24 h		NO	YES
2	Advanced central automatic control: this is a central automatic control of the TABS zone that is designed and tuned to achieve an optimal self-regulating of the room temperature within the required comfort range		NO	YES
3	Advanced central automatic control with intermittent operation and/or room temperature feedback control		NO	YES

Edilclima EC700 **[22]**

Level 0 Define the heating system in the *Heating systems* data-sheet. Set the system working temperature in the *General data - Default data* data-sheet.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow* to simulate a TABS system. Leave the *Availability Schedule Name* undefined.

Level 1 Define the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow*. Set the *Availability Schedule Name* with the temperature profile. In the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow:Design* set the field *Temperature Control Type* on *OutdoorDryBulbTemperature* or *OutdoorWetBulbTemperature*.

Level 2 Define the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow*. Set the *Availability Schedule Name* with the temperature profile. In the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow:Design* set the field *Temperature Control Type* on *MeanAirTemperature*.

Level 3 Define the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow*. Set the *Availability Schedule Name* with the temperature profile. In the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow:Design* set the field *Temperature Control Type* on *MeanAirTemperature*. Then, define the heating set-point temperature in the field *Heating Control Temperature Schedule Name*. Define the field *Heating Control Throttling Range*: it allows to determine when the system runs and with which flow rate.

4.1.3 Control of distribution network hot water temperature (supply or return)

Table 4.3: Control of distribution network hot water temperature (supply or return) summary

Level of BAC function [19]		Standard [1][19]	***EC700***	***E+/DB***
0	No automatic control	EN 15316-1 [5]	YES	YES
1	Outside temperature compensated control: actions generally lower the mean flow temperature		YES	YES
2	Demand based control: for example. based on indoor temperature control variable, actions generally lower the mean flow temperature		NO	NO

Edilclima EC700 [22]

Level 0 Define the heating system in the *Heating systems* data-sheet. In the *Heating systems - Circuits - Subsystems - Control* data-sheet set the control type on *Manual*: in order to have manual control through a boiler thermostat.

Level 1 Define the heating system in the *Heating systems* data-sheet. In the *Heating systems - Circuits - Subsystems - Control* data-sheet set the control type on *Climatic only (compensation with external probe)*: in order to regulate the supply water temperature based on the external temperature.

EnergyPlus/DesignBuilder [42][43][21]

Level 0 Leave the object *SetpointManager:ReturnTemperature:HotWater* undefined.

Level 1 Define the object *SetpointManager:ReturnTemperature:HotWater*. Define the object *SetpointManager:FollowOutdoorAirTemperature*, to regulate the distribution temperature according to the outdoor environmental condition. Set the previously defined object in the field *Plant Supply Inlet Node* of the object *SetpointManager:ReturnTemperature:HotWater*.

4.1.4 Control of distribution pumps in network

Table 4.4: Control of distribution pumps in networks summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	No automatic control	EN 15316-1 [5] EN 15316-3 [7]	YES	YES
1	On/off control: switch on and off automatically, pumps run with no control at maximum speed		NO	YES
2	Multi-stage control: speed of pumps is controlled by a multi-step control		NO	YES
3	Variable speed pump control: constant or variable Δp based on pump unit (internal) estimations		NO	YES
4	Variable speed pump control: variable Δp following an external demand signal, e.g. hydraulic requirements.		NO	NO

Edilclima EC700 **[22]**

Level 0 Define the heating system in the *Heating systems* data-sheet. In the *Heating systems - Circuits - Subsystems - Electrical requirements* data-sheet set the pump operation on *Always working.*

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *Pump:ConstantSpeed*. Set the field *Pump Control Type* on *Continuous*, so that the pump continuously operates at a constant speed.

Level 1 Define the object *Pump:ConstantSpeed*. Set the field *Pump Control Type* on *Intermittent*, so that the pump runs when a load is detected, otherwise it is turned off.

Level 2 Define the object *Pump:VariableSpeed*. Set the field *Pump Control Type* on *Intermittent*, so that when there is a load the pump works with a speed between a minimum and a maximum value. The pump is turned off when there is no load.

Level 3 Define the object *Pump:VariableSpeed*. Set the field *Pump Control Type* on *Intermittent.* Set the field *VFD Control Type* on *PressureSetPointControl* to take into account the pressure drop in the definition of the pump speed.

4.1.5 Hydronic balancing heating (including contribution to the balancing to the emission side)

Table 4.5: Hydronic balancing heating (including contribution to the balancing to the emission side) summary

Level of BAC function [19]		Standard [1][19]	***EC700***	***E+/DB***
0	No balancing	EN 15316-3 [7]	NO	NO
1	Balanced statically per emitter, without group balance		NO	NO
2	Balanced statically per emitter, and a static group balance (e.g. with balancing valve)		NO	NO
3	Balanced statically per emitter and dynamic group balance (e.g. with differential pressure control)		NO	NO
4	Balanced dynamically per emitter (e.g. differential pressure controllers)		NO	NO

Edilclima EC700 **[22]**

It is not possible to find a way to simulate the hydronic balancing heating function for any level of implementation with *Edilclima EC700*.

EnergyPlus/DesignBuilder **[42][43][21]**

It is not possible to find a way to simulate the hydronic balancing heating function for any level of implementation with *EnergyPlus/DesignBuilder*.

4.1.6 Intermittent control of emission and/or distribution

Table 4.6: Intermittent control of emission and/or distribution summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	No automatic control	EN ISO 52016-1[18] EN 15316-1 [5] EN 15316-3 [7]	YES	YES
1	Automatic control with fixed time program: to lower the operation time		YES	YES
2	Automatic control with optimum start/stop: to lower the operation time		NO	YES
3	Automatic control with demand evaluation		NO	YES

***Edilclima EC700* [22]**

Level 0 Define the heating system in the *Heating systems* data-sheet. Set the system working temperature in the *General data - Default data* data-sheet.

Level 1 Define the heating system in the *Heating systems* data-sheet. Define an hourly profile with operating temperatures and periods in the *Conditioned zone/local - Hourly profile*. In this way it is possible to define when the system is on, off or in reduced operation.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Leave the object *Availability Manager* undefined.

Level 1 Define the object *AvailabilityManager:Scheduled* with a fixed time schedule according to which the system works.

Level 2 Define the object *AvailabilityManager:OptimumStart*, to set a optimum start operation of the heating systems without compromising the comfort inside the building.

Level 3 Define the object *AvailabilityManager:Scheduled* with a time schedule based on the values of the occupancy schedule.

4.1.7 Heat generator control for combustion and district heating

Table 4.7: Heat generator control for combustion and district heating summary

Level of BAC function [19]		Standard [1][19]	***EC700***	***E+/DB***
0	Constant temperature control	EN 15316-1 [5] EN 15316-4-1 [8] EN 15316-4-5 [9]	NO	YES
1	Variable temperature control depending on outside temperature		NO	YES
2	Variable temperature control depending on the load: e.g. depending on supply water temperature set-point		NO	NO

Edilclima EC700 **[22]**

It is not possible to find a way to simulate the heat generator control for combustion and district heating function for any level of implementation with *Edilclima EC700*.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *Boiler:HotWater*. Define the object *SetpointManager:Scheduled* to set the hourly schedule profile of the fluid temperature. In this case the value is the same for each hour of the day. In the field *Boiler Water Outlet Node Name* set the name of the the object previously defined. In the field *Boiler Flow Mode* select *LeavingSetpointModulated*. This parameter allows to vary the flow rate to meet the temperature set-point defined.

Level 1 Define the object *Boiler:HotWater*. Define the object *SetpointManager:Scheduled* to set the hourly schedule profile of the fluid temperature. In the field *Boiler Water Outlet Node Name* set the name of the the object previously defined. In the field *Boiler Flow Mode* select *LeavingSetpointModulated*. Then, define the object *SetpointManager:FollowOutdoorAirTemperature* to allow the system to work according to external environmental conditions.

4.1.8 Heat generator control (heat pump)

Table 4.8: Heat generator control (heat pump) summary

<table>
<tr><th colspan="2">Level of BAC function [19]</th><th>Standard [1][19]</th><th>EC700</th><th>E+/DB</th></tr>
<tr><td>0</td><td>Constant temperature control</td><td rowspan="3">EN 15316-1 [5]
EN 15316-4-1 [8]
EN 15316-4-5 [9]</td><td>YES</td><td>YES</td></tr>
<tr><td>1</td><td>Variable temperature control depending on outside temperature</td><td>YES</td><td>YES</td></tr>
<tr><td>2</td><td>Variable temperature control depending on the load: e.g. depending on supply water temperature set-point</td><td>NO</td><td>NO</td></tr>
</table>

***Edilclima EC700* [22]**

Level 0 Define the heating system in the *Heating systems* data-sheet. In the *Heating system - Generation - Generator - Circuit in central - Generating temperature* data-sheet set the heat generator on *Fixed discharge temperature heat generator*. In this way the discharge temperature of the heat pump is equal to a fixed value.

Level 1 Define the heating system in the *Heating systems* data-sheet. Set the *Heating systems - Circuit - Average water temperature - Calculation criteria* data-sheet on *Variable delivery temperature*, meaning that the discharge temperature depends on the external climatic conditions. In the *Heating system - Generation - Generator - Circuit in central - Generating temperature* data-sheet set the heat generator on *Heat generator with sliding temperature*. In this way the supply temperature depends on the setting of the *Heating systems - Circuit - Average water temperature - Calculation criteria* data-sheet.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define the object *HeatPump:WaterToWater:EquationFit:Heating*. In the field *Load Side Outlet Node Name* set the name of *SetpointManager:Scheduled*, to control the temperature of the fluid according to a given time schedule. In this case the schedule is set with a constant temperature for each hour of the day.

Level 1 Define the object *HeatPump:WaterToWater:EquationFit:Heating*. In the field *Load Side Outlet Node Name* set the name of *SetpointManager:Scheduled*, that controls the outlet temperature. In the field *Source Side Inlet Node Name* set the name of *SetpointManager:FollowOutdoorAirTemperature* in order to consider also the outside condition in the control of the temperature.

4.1.9 Heat generator control (outdoor unit)

Table 4.9: Heat generator control (outdoor unit) summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	On/off-control of heat generator	EN 15316-1 [5] EN 15316-4-1 [8]	NO	NO
1	Multi-stage control of heat generator capacity depending on the load or demand (e.g. on/off of several compressors)		NO	NO
2	Variable control of heat generator capacity depending on the load or demand (e.g. hot gas bypass, inverter frequency control)		NO	NO

***Edilclima EC700* [22]**

It is not possible to find a way to simulate the heat generator control for outdoor unit function for any level of implementation with *Edilclima EC700*.

***EnergyPlus/DesignBuilder* [42][43][21]**

It is not possible to find a way to simulate the heat generator control for outdoor unit function for any level of implementation with *EnergyPlus/DesignBuilder*.

4.1.10 Sequencing of different heat generators

Table 4.10: Sequencing of different heat generators summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	Priorities are only based on running time	EN 15316-1 [5] EN 15316-4-1 [8] EN 15316-4-5 [9]	YES	YES
1	Control according to fixed priority list: e.g. heat pump prior to hot water boiler		YES	YES
2	Control according to dynamic priority list (based on current efficiency and capacity of generators, e.g. solar, geothermal heat, cogeneration plant, fossil fuels)		NO	NO
3	Control according to prediction based dynamic priority list (based on current efficiency and capacity of generators, e.g. solar, geothermal heat, cogeneration plant, fossil fuels)		NO	NO

Edilclima EC700 **[22]**

Level 0 Define the heating system in the *Heating systems* data-sheet. In the *Heating system - Generation - Thermal power plant - Multiple generator* data-sheet define the different type of generators present in the heating system without a priority list.

Level 1 Define the heating system in the *Heating systems* data-sheet. In the *Heating system - Generation - Thermal power plant - Multiple generator* data-sheet define the different type of generators and define a fixed priority list. In this way the heat generator with the highest priority works first, until the nominal load is reached; the residual thermal energy requirement is requested to the heat generator with next priority and so on.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the different heat generators. Leave the field *Priority* unset.

Level 1 Define the different heat generators. In the field *Priority* of each heat generator set the priority list. The first heat generator that operates is the one with priority 1, the following has priority 2 and so on.

4.1.11 Control of thermal energy storage (TES) charging

Table 4.11: Control of thermal energy storage (TES) charging summary

	Level of BAC function [19]	Standard [1][19]	***EC700***	***E+/DB***
0	Continuous storage operation	EN 15316-1 [5] EN 15316-5 [10]	YES	YES
1	2-sensor charging of storage		NO	NO
2	Load-prediction based storage operation		NO	NO

Edilclima EC700 **[22]**

Level 0 Define the heating system in the *Heating systems* data-sheet. In the *Heating systems - Storage and primary distribution - Storage* select the command *Storage* and define the dimension of the storage tank. The program considers a continuous storage operation.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *WaterHeater:Mixed* that simulates a storage tank that works continuously. The heater is on while heating the tank until to the set-point temperature. When the set-point is reached, the heater is turned off. The heater cycles on and off to maintain the tank temperature within the dead-band.

4.2 Domestic Hot Water control

4.2.1 Control of DHW storage charging with direct electric heating or integrated electric heat pump

Table 4.12: Control of DHW storage charging with direct electric heating or integrated electric heat pump summary

Level of BAC function [19]		Standard [1][19]	***EC700***	***E+/DB***
0	Automatic on/off control	EN 15316-1 [5] EN 15316-5 [10]	NO	YES
1	Automatic on/off control and scheduled charging enable		NO	NO
2	Automatic on/off control and scheduled charging enable and multi-sensor storage management		NO	NO

Edilclima EC700 [22]

It is not possible to find a way to simulate the control of DHW storage charging with direct electric heating or integrated electric heat pump function for any level of implementation with *Edilclima EC700*.

EnergyPlus/DesignBuilder [42][43][21]

Level 0 Define the object *WaterHeater:Mixed* to simulate a storage tank that works continuously. The heater is on while heating the tank until to the set-point temperature. When the set-point is reached, the heater is turned off. The heater cycles on and off to maintain the tank temperature within the dead-band.

4.2.2 Control of DHW storage charging using hot water generation

Table 4.13: Control of DHW storage charging using hot water generation summary

Level of BAC function [19]		Standard [1][19]	***EC700***	***E+/DB***
0	Automatic on/off control	EN 15316-1 [5] EN 15316-5 [10]	NO	YES
1	Automatic on/off control and scheduled charging enable		NO	NO
2	Automatic on/off control, scheduled charging enable and demand-based supply temperature control or multi-sensor storage management		NO	NO

Edilclima EC700 **[22]**

It is not possible to find a way to simulate the control of DHW storage charging using hot water generation function for any level of implementation with *Edilclima EC700*.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *WaterHeater:Mixed* to simulate a storage tank that works continuously. The heater is on while heating the tank until to the set-point temperature. When the set-point is reached, the heater is turned off. The heater cycles on and off to maintain the tank temperature within the dead-band.

4.2.3 Control of DHW storage charging with solar collector and supplementary heat generation

Table 4.14: Control of DHW storage charging with solar collector and supplementary heat generation summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	Manual control	EN 15316-1 [5] EN 15316-5 [10]	NO	YES
1	Automatic control of solar storage charge (Prio. 1) and supplementary storage charge (Prio. 2)		NO	NO
2	Automatic control of solar storage charge (Prio. 1) and supplementary storage charge (Prio. 2) plus demand-based supply temperature control or multi-sensor storage management		NO	NO

***Edilclima EC700*[22]**

It is not possible to find a way to simulate the control of DHW storage charging with solar collector and supplementary heat generation function for any level of implementation with *Edilclima EC700*.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define the object *SolarCollector:IntegralCollectorStorage* to simulate the domestic hot water storage from the solar collector. This object cannot be automatically controlled.

4.2.4 Control of DHW circulation pump

Table 4.15: Control of DHW circulation pump summary

Level of BAC function [19]		Standard [1][19]	***EC700***	***E+/DB***
0	No control, continuous operation	EN 15316-1 [5]	YES	YES
1	With time program		NO	NO

***Edilclima EC700* [22]**

Level 0 Define the DHW system in the *DHW systems* data-sheet. In the *DHW System - Circuits - Subsystems - Electrical requirements* data-sheet set on *Always working*. In this way the pump works continuously.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define the object *Pump:ConstantSpeed*. Set the field *Pump Control Type* on *Continuous*. In this way the pump continuously operates at a constant speed.

4.3 Cooling control

4.3.1 Emission control

Table 4.16: Emission control summary

	Level of BAC function [19]	Standard [1][19]	***EC700***	***E+/DB***
0	No automatic control of the room temperature	EN ISO 52016-1[18] EN 15316-2 [6]	YES	YES
1	Central automatic control: there is only central automatic control acting either on the distribution or on the generation. Function is to be integrated in a system.		YES	YES
2	Individual room control: by thermostatic valves or electronic controller		YES	YES
3	Individual modulating room control with communication: between controllers and BACS (e.g. scheduler, room temperature set-point)		YES	YES
4	Individual modulating room control with communication and occupancy detection: between controllers and BACS; demand control/occupancy detection		YES	YES

Edilclima EC700 **[22]**

Level 0 Define the cooling system in the *Cooling systems* data-sheet. Set the system working temperature in the *General data - Default data* data-sheet.

Level 1 Define the cooling system in the *Cooling systems* data-sheet. Define a unique hourly temperature profile zone in the *Conditioned zone/local - Hourly profile* data-sheet. Set the profile in each thermal zone, in this way the central automatic control is simulated.

Level 2 Define the cooling system in the *Cooling systems* data-sheet. In the *Cooling systems - Circuit - General data - Monthly activation time* data-sheet select the option *From set-point temperature profile* to simulate the presence of thermostatic valves or electronic controllers.

Level 3 Define the cooling system in the *Cooling systems* data-sheet. For each thermal zone define the hourly temperature profile in the *Conditioned zone/local - Hourly profile* data-sheet. Set the profile according to the needs of the thermal zone. Then, in the *Cooling systems - Circuit - General data - Monthly activation time* data-sheet select the option *Hourly needs*, to operate the heating system according to the established profile.

Level 4 Define the cooling system in the *Cooling systems* data-sheet. For each thermal zone define the hourly temperature profile in the *Conditioned zone/local - Hourly profile* data-sheet. Set the profile according to the real occupancy of the thermal zone. Then, in the *Cooling systems - Circuit - General data - Monthly activation time* data-sheet select the option *Hourly needs*, to operate the heating system according to the established profile.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Leave *ZoneControl:Thermostat* and *SetpointManager:Scheduled* undefined.

Level 1 Set the object *SetpointManager:Scheduled* at the generation level. Define the control temperature profile in the field *Schedule Name*.

Level 2 Define the object *ZoneControl:Thermostat*. In the field *Control Type Schedule Name* set the control type on *Uncontrolled* to simulate the presence of thermostatic valves or electronic controllers.

Level 3 Define the object *ZoneControl:Thermostat*. In the field *Control Type Schedule Name* set the control type on *Single Cooling Setpoint*. Then, define the object *ThermostatSetpoint:SingleCooling* with the set-point temperature schedule based on the given values. In the field *Control Object* $< x >$ *Type* set the name of the *ThermostatSetpoint:SingleCooling* as previously defined.

Level 4 Define the object *ZoneControl:Thermostat*. In the field *Control Type Schedule Name* set the control type on *Single Cooling Setpoint*. Then, define the object *ThermostatSetpoint:SingleCooling* with the set-point temperature schedule based on the real occupancy values. In the field *Control Object* $< x >$ *Type* set the name of the *ThermostatSetpoint:SingleCooling* as previously defined.

4.3.2 Emission control for TABS

Table 4.17: Emission control for TABS summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	No automatic control of the room temperature	EN ISO 52016-1[18] EN 15316-2 [6]	YES	YES
1	Central automatic control: the central automatic control for a TABS zone (which comprises all rooms which get the same supply water temperature) typically is a supply water temperature control loop whose set-point is dependent on the filtered outside temperature, e.g. the average of the previous 24 h		NO	YES
2	Advanced central automatic control: this is a central automatic control of the TABS zone that is designed and tuned to achieve an optimal self-regulating of the room temperature within the required comfort range		NO	YES
3	Advanced central automatic control with intermittent operation and/or room temperature feedback control		NO	YES

Edilclima EC700 **[22]**

Level 0 Define the cooling system in the *Cooling systems* data-sheet. Set the system working temperature in the *General data - Default data* data-sheet.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow* to simulate a TABS system. Leave the *Availability Schedule Name* undefined.

Level 1 Define the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow*. Set the *Availability Schedule Name* with the temperature profile. In the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow:Design* set the field *Temperature Control Type* on *OutdoorDryBulbTemperature* or *OutdoorWetBulbTemperature*.

Level 2 Define the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow*. Set the *Availability Schedule Name* with the temperature profile. In the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow:Design* set the field *Temperature Control Type* on *MeanAirTemperature*.

Level 3 Define the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow*. Set the *Availability Schedule Name* with the temperature profile. In the object *ZoneHVAC:LowTemperatureRadiant:VariableFlow:Design* set the field *Temperature Control Type* on *MeanAirTemperature*. Then, define the heating set-point temperature in the field *Cooling Control Temperature Schedule Name*. Define the field *Cooling Control Throttling Range*: it allows to determine when the system runs and with which flow rate.

4.3.3 Control of distribution network chilled water temperature (supply or return)

Table 4.18: Control of distribution network chilled water temperature (supply or return) summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	Constant temperature control	EN 16798-9 [15] EN 15316-2 [6]	NO	YES
1	Outside-temperature compensated control: actions generally raise the mean flow temperature		NO	YES
2	Demand-based control: e.g. based on indoor temperature control variable, actions generally raise the mean flow temperature		NO	NO

***Edilclima EC700*[22]**

It is not possible to find a way to simulate the control of distribution network chilled water temperature function for any level of implementation with *Edilclima EC700*.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define the object *SetpointManager:ReturnTemperature:ChilledWater*. Set the field *Return Temperature Setpoint Input Type* on *Constant*. Set the field *Return Temperature Setpoint Constant Value* to the value of the return temperature set-point.

Level 1 Define the object *SetpointManager:ReturnTemperature:ChilledWater*. In the field *Plant Supply Inlet Node* define the object *SetpointManager:FollowOutdoorAirTemperature*, to regulate the distribution temperature according to the outdoor environmental condition.

4.3.4 Control of distribution pumps in hydraulic network

Table 4.19: Control of distribution pumps in hydraulic network summary

	Level of BAC function [19]	**Standard** [1][19]	***EC700***	***E+/DB***
0	No automatic control	EN 16798-9 [15] EN 15316-3 [7]	YES	YES
1	On off control: to reduce the auxiliary energy demand of the pumps		NO	YES
2	Multi-stage control: to reduce the auxiliary energy demand of the pumps		NO	YES
3	Variable speed pump control: constant or variable Δp based on pump unit (internal) estimations to reduce the auxiliary energy demand of the pumps		NO	YES
4	Variable speed pump control: variable Δp following an external demand signal, e.g. hydraulic requirements, ΔT, energy optimization to reduce the auxiliary energy demand of the pumps		NO	NO

Edilclima EC700 **[22]**

Level 0 Define the cooling system in the *Cooling systems* data-sheet. In the *Cooling systems - Circuits - Subsystems - Refrigerated water distribution networks* data-sheet set the pump operation on *Always working.*

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *Pump:ConstantSpeed.* Set the field *Pump Control Type* on *Continuous*, so that the pump continuously operates at a constant speed.

Level 1 Define the object *Pump:ConstantSpeed.* Set the field *Pump Control Type* on *Intermittent*, so that the pump runs when a load is detected, otherwise it is turned off.

Level 2 Define the object *Pump:VariableSpeed.* Set the field *Pump Control Type* on *Intermittent*, so that when there is a load the pump works with a speed between a minimum and a maximum value. The pump is turned off when there is no load.

Level 3 Define the object *Pump:VariableSpeed.* Set the field *Pump Control Type* on *Intermittent.* Set the field *VFD Control Type* on *PressureSetPointControl* to take into account the pressure drop in the definition of the pump speed.

4.3.5 Hydronic balancing cooling distribution (including the contribution to the balancing on the emission side)

Table 4.20: Hydronic balancing heating (including contribution to the balancing to the emission side) summary

	Level of BAC function [19]	**Standard** [1][19]	***EC700***	***E+/DB***
0	No balancing	EN 15316-3 [7]	NO	NO
1	Balanced statically per emitter, without group balance		NO	NO
2	Balanced statically per emitter, and a static group balance (e.g. with balancing valve)		NO	NO
3	Balanced statically per emitter and dynamic group balance (e.g. with differential pressure control)		NO	NO
4	Balanced dynamically per emitter (e.g. differential pressure controllers)		NO	NO

Edilclima EC700 **[22]**

It is not possible to find a way to simulate the hydronic balancing cooling distribution function for any level of implementation with *Edilclima EC700*.

EnergyPlus/DesignBuilder **[42][43][21]**

It is not possible to find a way to simulate the hydronic balancing cooling distribution function for any level of implementation with *EnergyPlus/DesignBuilder*.

4.3.6 Intermittent control of emission and/or distribution

Table 4.21: Intermittent control of emission and/or distribution summary

Level of BAC function [19]		**Standard [1][19]**	***EC700***	***E+/DB***
0	No automatic control	EN ISO 52016-1[18] EN 15316-3 [7] EN 16798-3 [12]	YES	YES
1	Automatic control with fixed time program: to lower the operation time		YES	YES
2	Automatic control with optimum start/stop: to lower the operation time		NO	YES
3	Automatic control with demand evaluation		NO	YES

***Edilclima EC700* [22]**

Level 0 Define the cooling system in the *Cooling systems* data-sheet. Set the system working temperature in the *General data - Default data* data-sheet.

Level 1 Define the cooling system in the *Cooling systems* data-sheet. Define an hourly profile with operating temperatures and periods in the *Conditioned zone/local - Hourly profile*. In this way it is possible to define when the system is on, off or in reduced operation.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Leave the object *Availability Manager* undefined.

Level 1 Define the object *AvailabilityManager:Scheduled* with a fixed time schedule according to which the system works.

Level 2 Define the object *AvailabilityManager:OptimumStart*, to set a optimum start operation of the heating systems without compromising the comfort inside the building.

Level 3 Define the object *AvailabilityManager:Scheduled* with a time schedule based on the values of the occupancy schedule.

4.3.7 Interlock between heating and cooling control of emission and/or distribution

Table 4.22: Intermittent control of emission and/or distribution summary

Level of BAC function [19]		Standard [1][19]	*EC700*	*E+/DB*
0	No interlock: the two systems are controlled independently and can provide simultaneously heating and cooling	EN 16798-9 [15]	YES	YES
1	Partial interlock (depending on the HVAC system): the control function is set up in order to minimize the possibility of simultaneous heating and cooling. This is generally done by defining a sliding set-point for the supply temperature of the centrally controlled system		NO	NO
2	Total interlock: the control function enables to guarantee that there will be no simultaneous heating and cooling		NO	NO

Edilclima EC700 **[22]**

Level 0 Define the heating system in the *Heating system* data-sheet. Define the cooling system in the *Cooling system* data-sheet. The two systems will work independently.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *ThermostatSetpoint:SingleHeating* with the heating temperature profile. Define the object *ThermostatSetpoint:SingleCooling* with the cooling temperature profile.

4.3.8 Generation control for cooling

Table 4.23: Generation control for cooling summary

	Level of BAC function [19]	Standard [1][19]	*EC700*	*E+/DB*
0	Constant temperature control	EN 16798-9 [15] EN 16798-13 [11]	NO	YES
1	Variable temperature control depending on outside temperature		NO	YES
2	Variable temperature control depending on the load: this includes control according to room temperature		NO	NO

Edilclima EC700 **[22]**

It is not possible to find a way to simulate the generation control for cooling function for any level of implementation with *Edilclima EC700*.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *Chiller*. Define the object *SetpointManager:Scheduled* to set the hourly schedule profile of the fluid temperature. In this case the value is the same for each hour of the day. In the field *Chiller Water Outlet Node Name* set the name of the object previously defined. In the field *Chiller Flow Mode* select *LeavingSetpointModulated*. This parameter allows to vary the flow rate to meet the temperature set-point defined.

Level 1 Define the object *Chiller*. Define the object *SetpointManager:Scheduled* to set the hourly schedule profile of the fluid temperature. In the field *Chiller Water Outlet Node Name* set the name of the object previously defined. In the field *Chiller Flow Mode* select *LeavingSetpointModulated*. Then, define the object *SetpointManager:FollowOutdoorAirTemperature* to allow the system to work according to external environmental conditions.

4.3.9 Sequencing of different chillers

Table 4.24: Sequencing of different chillers summary

Level of BAC function [19]		Standard [1][19]	*EC700*	*E+/DB*
0	Priorities are only based on running time	EN 16798-9 [15] EN 16798-13 [11]	NO	YES
1	Fixed sequencing based on loads only: for example, depending on the generator's characteristics, e.g. absorption chiller vs. centrifugal chiller		NO	YES
2	Priorities based on generator efficiency and characteristics: the generator operational control is set individually to available generators so that they operate with an overall high degree of efficiency (e.g. outside air, river water, geothermic heat, refrigeration machines)		NO	NO
3	Load prediction-based sequencing: the sequence is based on, e.g. COP and available power of a device and the predicted required power		NO	NO

***Edilclima EC700* [22]**

It is not possible to find a way to simulate the sequencing of different chillers function for any level of implementation with *Edilclima EC700*.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define the different chillers. Leave the field *Priority* unset.

Level 1 Define the different chiller. In the field *Priority* of each chiller set the priority list. The first chiller that operates is the one with priority 1, the following has priority 2 and so on.

4.3.10 Control of thermal energy storage (TES) charging

Table 4.25: Control of thermal energy storage (TES) charging summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	Continuous storage operation	EN 15316-1 [5] EN 15316-5 [10]	YES	YES
1	Time-scheduled storage operation		NO	YES
2	Load-prediction based storage operation		NO	NO

***Edilclima EC700* [22]**

Level 0 Define the cooling system in the *Cooling system* data-sheet. In the *Cooling systems - Storage and primary distribution - Storage* select the command *Storage* and define the dimension of the storage tank. The program consider a continuous storage operation.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define either the *ThermalStorage:ChilledWater:Mixed* or the *ThermalStorage:ChilledWater:Stratified* object to simulate a chiller water tank that works continuously.

Level 1 Define the object *Coil:Cooling:DX:SingleSpeed:ThermalStorage* to simulate the thermal storage cooling with the capability of charge and discharge and the Thermal Energy Storage (TES) tank. Set the field *Operating Mode Control Method* on *ScheduledMode*.

4.4 Ventilation and air-conditioning control

4.4.1 Supply air flow control at the room level

Table 4.26: Supply air flow control at the room level summary

Level of BAC function [19]		Standard [1][19]	*EC700*	*E+/DB*
0	No automatic control: the system runs constantly (e.g. manual controlled switch)	EN 16798-7 [14] EN 16798-3 [12]	YES	YES
1	Time control: the system runs according to a given time schedule		YES	YES
2	Occupancy based control: the system runs dependent on the occupancy (presence, light switch, infrared sensors etc.)		NO	YES
3	Demand based control: the system runs dependent on the air quality demand (measurement of CO2, VOC, etc.)		NO	YES

***Edilclima EC700* [22]**

Level 0 Define the ventilation and air-conditioning system in the *Ventilation system* data-sheet. In the *Ventilation system - General data - System operation - Activation time profile of the system* data-sheet set the hourly profile to work continuously.

Level 1 Define the ventilation and air-conditioning system in the *Ventilation system* data-sheet. In the *Ventilation system - General data - System operation - Activation time profile of the system* data-sheet set a fixed *a priori* hourly profile.

Level 2 Define the ventilation and air-conditioning system in the *Ventilation system* data-sheet. In the *Ventilation system - General data - System operation - Activation time profile of the system* data-sheet set a hourly profile based on the real occupancy schedule.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define one of the following objects, in order to simulate an air terminal that runs at constant volume: *AirTerminal:DualDuct:ConstantVolume*, *AirTerminal:SingleDuct:ConstantVolume:Reheat*, *AirTerminal:SingleDuct:ConstantVolume:NoReheat*. Set the flow rate in the field *Maximum Air Flow Rate*. The system runs with the defined constant flow rate.

Level 1 Define one of the following objecs: *AirTerminal:SingleDuct:ConstantVolume*, *AirTerminal:SingleDuct:VAV*, *AirTerminal:DualDuct:ConstantVolume*, *AirTerminal:DualDuct:VAV*. In the field *Avaiability Schedule Name* set a fixed time schedule according to which the air terminal runs.

Level 2 Define one of the following objecs: *AirTerminal:SingleDuct:ConstantVolume*, *AirTerminal:SingleDuct:VAV*, *AirTerminal:DualDuct:ConstantVolume*, *AirTerminal:DualDuct:VAV*. In the field *Avaiability Schedule Name* set a time schedule based on the date of the occupancy schedule according to which the air terminal runs.

Level 3 Define one of the following objecs: *AirTerminal:SingleDuct:ConstantVolume*, *AirTerminal:SingleDuct:VAV*, *AirTerminal:DualDuct:ConstantVolume*, *AirTerminal:DualDuct:VAV*. In the field *Avaiability Schedule Name* set a time schedule based on the date of the occupancy schedule according to which the air terminal runs. Then, define the object *ZoneControl:ContaminantController* to control the air quality and to set a carbon dioxide set-point that is used to calculate the outdoor airflow rate required by HVAC system to reach the air flow set-point.

4.4.2 Room air temperature control by ventilation system (all air system, combination with static system as cooling ceiling, radiators...)

Table 4.27: Room air temperature control by ventilation system (all air system, combination with static system as cooling ceiling, radiators...) summary

<table>
<tr><th colspan="2">Level of BAC function [19]</th><th>Standard [1][19]</th><th>EC700</th><th>E+/DB</th></tr>
<tr><td>0</td><td>On-off control: fixed air flow rate and fixed supply air temperature at the room level, room temperature set-points are set individually</td><td rowspan="3">EN 16798-5-1 [13]</td><td>YES</td><td>YES</td></tr>
<tr><td>1</td><td>Continuous control: either air flow rate or supply air temperature at the room level can be varied continuously; room temperature set-point are set individually</td><td>YES</td><td>YES</td></tr>
<tr><td>2</td><td>Optimized control: minimum energy demand by optimized control. Both air flow rate as well as supply air temperature at the room level are controlled dependent on heating/cooling load</td><td>YES</td><td>YES</td></tr>
</table>

***Edilclima EC700* [22]**

Level 0 Define the ventilation and air-conditioning system in the *Ventilation system* data-sheet. In the case of heating, set the ventilation combined with the heating system. Set the system working temperature in the *General data - Default data* data-sheet.

Level 1 In the case of heating, set the ventilation combined with the heating system. Then, in the *Heating system - General data - Monthly activation time* data-sheet set *Operation by hourly profile.* In the case of cooling, in the *Cooling system - Activation - Monthly activation time* data-sheet set *Operation by hourly profile.* The hourly temperature profiles are fixed *a priori.*

Level 2 In the case of heating, set the ventilation combined with the heating system. Then, in the *Heating system - General data - Monthly activation time* data-sheet set *Operation by hourly profile.* In the case of cooling, in the *Cooling system - Activation - Monthly activation time* data-sheet set *Operation by hourly profile.* The hourly temperature profiles are based on the real occupancy schedule.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define the object *AirTerminal:SingleDuct:ConstantVolume:Reheat* associated with a room thermostat. If the temperature in the room is below the set-point temperature, the terminal is turned on and provide a constant flow rate at a fixed supply air temperature, otherwise the terminal is turned off.

Level 1 Define the object *AirTerminal:DualDuct:VAV* associated with a room thermostat. The air terminal keeps the required temperature by varying the supply air temperature and the air flow rate.

Level 2 Define the object *AirTerminal:DualDuct:VAV* associated with a room thermostat. The air terminal keeps the required temperature by varying the supply air temperature and the air flow rate. In this case the schedule associated to the room thermostat is based on the values of the occupancy schedule.

4.4.3 Coordination of room air temperature control by ventilation and by static system

Table 4.28: Coordination of room air temperature control by ventilation and by static system summary

	Level of BAC function [19]	**Standard** [1][19]	***EC700***	***E+/DB***
0	Interaction is not coordinated, e.g. closed loop controllers are dedicated to each system to maintain the room air temperature independently	EN 16798-5-1 [13]	NO	YES
1	Interaction is coordinated, i.e. only one system is controlled by a closed loop controller for the room air temperature and the other system conditions the room only to the extent that allows the closed loop controller to benefit from internal and external heat gains		NO	NO

Edilclima EC700 **[22]**

It is not possible to find a way to simulate the coordination of room air temperature control by ventilation and by static system function for any level of implementation with *Edilclima EC700*.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Model the air conditioning systems and the static systems independently one from the other.

4.4.4 Outdoor air (OA) flow control

Table 4.29: Outdoor air (OA) flow control summary

	Level of BAC function [19]	Standard [1][19]	*EC700*	*E+/DB*
0	Fixed OA ratio or OA flow: the system runs according to a given OA ratio, e.g. modified manually	EN 16798-5-1 [13] EN 16798-3 [12]	NO	YES
1	Staged (low/high) OA ratio or OA flow: depending on a given time schedule		NO	YES
2	Staged (low/high) OA ratio or OA flow: depending on the occupancy, e.g. light switch, infrared sensors, etc.		NO	YES
3	Variable control: the system is controlled by sensors which detect the number of people or indoor air parameters or adapted criteria (e.g. CO2, mixed gas or VOC sensors). The used parameters shall be adapted to the kind of activity in the space		NO	YES

***Edilclima EC700* [22]**

It is not possible to find a way to simulate the outdoor air flow control function for any level of implementation with *Edilclima EC700*.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define the object *Controller:OutdoorAir*. Set the field *Economizer Control Type* on *NoEconomizer*.

Level 1 Define the object *Controller:OutdoorAir*. Set the field *Economizer Control Type*. Set in the field *Minimum Outdoor Air Schedule Name* a *a priori* time schedule.

Level 2 Define the object *Controller:OutdoorAir*. Set the field *Economizer Control Type*. Set in the field *Minimum Outdoor Air Schedule Name* a time schedule based on the real occupancy schedule.

Level 3 Define the object *Controller:OutdoorAir*. Set the field *Economizer Control Type* and the field *Minimum Outdoor Air Schedule Name*. Define the object *Controller:MechanicalVentilation* to define a minimum air flow based on the occupancy of the zone and to carry out an evaluation of carbon dioxide(CO_2)-based demand controlled ventilation. In the field *Field: Mechanical Ventilation Controller Name* of the object *Controller:OutdoorAir* inserts the name of the previously defined object.

4.4.5 Air flow of pressure control at air handler level

Table 4.30: Air flow of pressure control at air handler level summary

	Level of BAC function [19]	Standard [1][19]	*EC700*	*E+/DB*
0	No automatic control: continuously supplies air flow for a maximum load of all rooms	EN 16798-3 [12] EN 16798-7 [14]	NO	YES
1	On off time control: continuously supplies air flow for a maximum load of all rooms during nominal occupancy time		NO	YES
2	Multi-stage control: to reduce the auxiliary energy demand of the fan		NO	YES
3	Automatic flow or pressure control without pressure reset: load dependent supplies of air flow for the demand of all connected rooms		NO	NO
4	Automatic flow or pressure control with pressure reset: load dependent supplies of air flow for the demand of all connected rooms (for variable air volume systems with VFD)		NO	NO

***Edilclima EC700* [22]**

It is not possible to find a way to simulate the air flow of pressure control at air handler level function for any level of implementation with *Edilclima EC700*.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define the object *Fan:ConstantVolume* to simulate a fan that operates continuously according to a given time schedule. In this case, the time schedule imposes that the system runs each hour of the day.

Level 1 Define the object *Fan:OnOff*. Set in the field *Availability Schedule Name* a time schedule according to which the system runs. In the filed *Maximum Flow Rate* set the air flow rate of the fan.

Level 2 Define the object *Fan:OnOff* and one object between *AirLoopHVAC:Unitary:Furnace:HeatCool* and *ZoneHVAC:PackagedTerminalAirConditioner* to simulate a multiple-speed fan.

4.4.6 Heat recovery control: icing protection

Table 4.31: Heat recovery control: icing protection summary

Level of BAC function [19]		Standard [1][19]	***EC700***	***E+/DB***
0	Without icing protection control: there is no specific action to avoid icing of the heat exchanger	EN 16798-5-1 [13]	YES	YES
1	With icing protection control: a control loop enables to guarantee that the exhaust air temperature leaving the heat exchanger is not too low, to avoid frosting		YES	YES

***Edilclima EC700* [22]**

Level 0 Define the ventilation and air-conditioning system in the *Ventilation system* data-sheet. In the *Ventilation system - General data* data-sheet select *Heat recovery unit* and leave the *Presence of icing protection* unselected.

Level 1 Define the ventilation and air-conditioning system in the *Ventilation system* data-sheet. In the *Ventilation system - General data* data-sheet select *Heat recovery unit*, select *Presence of icing protection* and define the icing protection temperature.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Define the object *HeatExchanger:AirToAir:SensibleAndLatent.* Set the field *Frost Control Type* on *None.*

Level 1 Define the object *HeatExchanger:AirToAir:SensibleAndLatent.* Set the field *Frost Control Type* on one of the following strategies: *ExhaustAirRecirculation*, *ExhaustOnly* or *MinimumExhaustTemperature.*

4.4.7 Heat recovery control: prevention of overheating

Table 4.32: Heat recovery control: prevention of overheating summary

Level of BAC function [19]		Standard [1][19]	*EC700*	*E+/DB*
0	Without overheating control: there is no specific action to avoid overheating	EN 16798-5-1 [13]	YES	YES
1	With overheating control: during periods when the effect of the heat exchanger will no longer be positive, a control loop will switch between the "off", "modulation" or bypass states of the heat exchanger		YES	YES

Edilclima EC700 **[22]**

Level 0 Define the ventilation and air-conditioning system in the *Ventilation system* data-sheet. In the *Ventilation system - General data* data-sheet select *Heat recovery unit* and leave *Presence of by-pass* unselected.

Level 1 Define the ventilation and air-conditioning system in the *Ventilation system* data-sheet. In the *Ventilation system - General data* data-sheet select *Heat recovery unit* and select *Presence of by-pass.*

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *HeatExchanger:AirToAir:SensibleAndLatent.* Set the field *Supply Air Outlet Temperature Control* on *No.*

Level 1 Define the object *HeatExchanger:AirToAir:SensibleAndLatent.* Set the field *Supply Air Outlet Temperature Control* on *Yes.* Define the object *SetpointManager:Scheduled* to set a threshold value to avoid overheating.

4.4.8 Free mechanical cooling

Table 4.33: Free mechanical cooling summary

Level of BAC function [19]		Standard [1][19]	***EC700***	***E+/DB***
0	No automatic control	EN 16798-13 [11]	NO	YES
1	Night cooling: the amount of outside air is set to its maximum during the unoccupied period provided that firstly the room temperature is above the set-point for the comfort period, and secondly the difference between the room temperature and the outside temperature is above a given limit. If free night cooling will be realized by automatically opening windows there is no air flow control		NO	YES
2	Free cooling: both the amount of outside air and recirculation air are modulated during all periods of time to minimize the amount of mechanical cooling. Calculation is performed on the basis of temperatures		NO	YES
3	Enthalpy based control: the amount of outside air and recirculation air are modulated during all periods of time to minimize the amount of mechanical cooling. Calculation is performed on the basis of temperatures and humidity (enthalpy)		NO	YES

Edilclima EC700 **[22]**

It is not possible to find a way to simulate the free mechanical cooling function for any level of implementation with *Edilclima EC700*.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Leave the object *Controller:OutdoorAir* undefined.

Level 1 Define the object *Controller:OutdoorAir*, specify the field *Economizer Control Type* and the field *Time of Day Economizer Control Schedule Name* with the schedule which controls the outdoor air flow rate based on a time-of-day economizer. In this case the schedule represent the unoccupied period.

Level 2 Define the object *Controller:OutdoorAir* and set the field *Economizer Control Type* on one of the following options: *FixedDryBulb*, *DifferentialDryBulb* or *FixedDewPointAndDryBulb*. The control is based on the air temperature.

Level 3 Define the object *Controller:OutdoorAir* and set the field *Economizer Control Type* on one of the following options: *FixedEnthalpy*, *DifferentialEnthalpy* or *ElectronicEnthalpy*. The control is based on the value of the enthalpy.

4.4.9 Supply air temperature control at the air handling unit (AHU) level

Table 4.34: Supply air temperature control at the air handling unit (AHU) level summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	No automatic control: no control loop enables to act on the supply air temperature		NO	YES
1	Constant set-point: a control loop enables to control the supply air temperature, the set-point is constant and can only be modified by a manual action		NO	YES
2	Variable set-point with outside temperature compensation: a control loop enables to control the supply air temperature. The set-point is a simple function of the outside temperature (e.g. linear function)	EN 16798-5-1 [13]	NO	NO
3	Variable set-point with load dependent compensation: a control loop enables to control the supply air temperature. The set-point is defined as a function of the loads in the room. This can normally only be achieved with an integrated control system enabling to collect the temperatures or actuator position in the different rooms		NO	NO

Edilclima EC700 [22]

It is not possible to find a way to simulate the supply air temperature control at the air handling unit level function for any level of implementation with *Edilclima EC700*.

EnergyPlus/DesignBuilder [42][43][21]

Level 0 Leave the object *Controller:WaterCoil* undefined.

Level 1 Define the object *Controller:WaterCoil* and the object *SetpointManager:Scheduled*. The program reads the set-point air temperature and adjusts the water flow rate in order to meet the set-point.

4.4.10 Humidity control

Table 4.35: Humidity control summary

	Level of BAC function [19]	Standard [1][19]	*EC700*	*E+/DB*
0	No automatic control: no control loop enables to act on the air humidity	EN 16798-5-1 [13]	YES	YES
1	Dew point control: supply air or room air humidity is expressed with the dew point temperature and reheat of the supply air to bring the relative humidity to the set-point		YES	YES
2	Direct humidity control: supply air or room air humidity, a control loop enables the supply air or room air humidity at a given set-point. The set-point is either fixed and predefined by the user or a fluctuating optimal value at a minimum energy but within min./max. limits of room air condition		NO	YES

***Edilclima EC700* [22]**

Level 0 In the *Conditioned zone/local - hourly profile* data-sheet leave the *Humidity set-point* off.

Level 1 In the *Conditioned zone/local - hourly profile* data-sheet select the *Humidity set-point*. Then, define the minimum and maximum value of humidification and dehumidification and set the hourly profile for the humidity control.

***EnergyPlus/DesignBuilder* [42][43][21]**

Level 0 Leave the following objects undefined: *Humidifier:Steam:Electric*, *Humidifier:Steam:Gas*, *Dehumidifier:Desiccant:NoFans*, *Dehumidifier:Desiccant:System*.

Level 1 Define a *Humidifier* and a *Dehumidifier*. Connect them the object *SetpointManager:Scheduled*, to control the humidity ratio at the node.

Level 2 Define the object *ZoneControl:Humidistat* to control the relative humidity at room level. Connected it to the objects *SetpointManager:SingleZone:Humidity:Minimum* and *SetpointManager:SingleZone:Humidity:Maximum* to define a dual humidity set-point schedule (humidifying and dehumidifying set-points).

4.5 Lighting control

4.5.1 Occupancy control

Table 4.36: Occupancy control summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	Manual on/off switch: the luminaire is switched on and off with a manual switch in the room	EN 15193-1 [3]	NO	NO
1	Manual on/off switch plus additional sweeping extinction signal: the luminaire is switched on and off with a manual switch in the room. In addition, an automatic signal automatically switches off the luminaire at least once a day, typically in the evening to avoid needless operation during the night		NO	NO
2	Automatic detection Auto on/dimmed off: the control system switches the luminaire(s) automatically on whenever the illuminated area is occupied, and automatically switches them to a state with dimmed status after the last occupancy in the illuminated area. Auto on/auto off: the control system switches the luminaire(s) automatically on whenever the illuminated area is occupied, and automatically switches them entirely off.		NO	NO
3	Automatic detection Manual on/ partial auto on /dimmed off: the luminaire(s) can only be switched on by means of a manual switch or automatically by occupancy detection sensor located in (or very close to) the area illuminated by the luminaire(s), and, if not switched off manually, is/are automatically switched to a state with dimmed status after the last occupancy in the illuminated area. Manual on/ partial auto on /auto off: the luminaire(s) can only be switched on by means of a manual switch or automatically by occupancy detection sensor.		NO	NO

***Edilclima EC700* [22]**

It is not possible to find a way to simulate the occupancy control function for any level of implementation with *Edilclima EC700*.

***EnergyPlus/DesignBuilder* [42][43][21]**

It is not possible to find a way to simulate the occupancy control function for any level of implementation with *EnergyPlus/DesignBuilder*.

4.5.2 Light level/Daylight control (Daylight harvesting)

Table 4.37: Light level/Daylight control (Daylight harvesting) summary

	Level of BAC function [19]	**Standard [1][19]**	***EC700***	***E+/DB***
0	Manual central: luminaires are controlled centrally, there is no manual switch in the room/zone	EN 15193-1 [3]	YES	YES
1	Manual: luminaires can be switched off with a manual switch in the room		YES	YES
2	Automatic switching: the luminaires are automatically switched off when more than enough daylight is present to fully provide minimum illuminance required and switched on when there is not enough daylight		NO	YES
3	Automatic dimming: the luminaires are dimmed down and finally fully switched off, e.g. when daylight is available or when scene based light level control is applied. The luminaires will be switched on again and dimmed up if the amount of daylight is decreasing or when scene based light level control is applied		NO	YES

Edilclima EC700 **[22]**

Level 0 In the *Conditioned zone/local - Hourly profile - Internal gains* data-sheet define a value that takes into account the presence of the illuminance.

Level 1 In the *Conditioned zone/local - Hourly profile - Internal gains* data-sheet define a value that takes into account the presence of the illuminance.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Define the object *Lights*. Set the time schedule according to which the lights are turned on, there is no possibility to manually turn off the lights.

Level 1 Define the object *Lights*. Set the time schedule based on the occupancy of the room according to which the lights are turned on.

Level 2 Define the object *Daylighting:Controls*. Set the field *Lighting Control Type* on *Stepped*. Set the *Number of Steps* and the *Illuminace Setpoint*.

Level 3 Define the object *Daylighting:Controls*. Set the field *Lighting Control Type* on *Continuous*. In this way the lights dim continually and linearly from the maximum to the minimum electric power and light output in function of the daylight illuminance.

4.6 Blind control

4.6.1 Blind control

Table 4.38: Blind control summary

Level of BAC function [19]		Standard [1][19]	***EC700***	***E+/DB***
0	Manual operation: mostly used only for manual shadowing, energy saving depends only on the user behaviour	EN ISO 52016-1[18]	YES	YES
1	Motorized operation with manual control: mostly used only for easiest manual (motor supported) shadowing, energy saving depends only on the user behaviour		YES	YES
2	Motorized operation with automatic control: automatic controlled dimming to reduce cooling energy		YES	YES
3	Combined light/blind/HVAC control: to optimize energy use for HVAC, blind and lighting for occupied and non-occupied rooms		NO	YES

Edilclima EC700 **[22]**

Level 0 Leave the blinds unset.

Level 1 Leave the blinds unset. The electrical gain due to the motorized blind can be considered negligible with respect to other internal gains.

Level 2 In the *Shading* data-sheet set the *Profile of blinds use*. It can be set according to a defined time profile or according to the *Automatic control of solar radiation* by defining the maximum value of solar irradiation according to which the blinds are closed.

EnergyPlus/DesignBuilder **[42][43][21]**

Level 0 Leave the blinds unset.

Level 1 Leave the blinds unset. The electrical gain due to the motorized blind can be considered negligible with respect to other internal gains.

Level 2 Define the object *WindowShadingControl*. Specify in the field *Shading Type* the type of shading device. Set the field *Shading Control Type* on *OnIfHighZoneCooling*. In this way the shading device is on if zone cooling rate in the previous time-step exceeds power set-point.

Level 3 Define the object *WindowShadingControl*. Specify in the field *Shading Type* the type of shading device. Set the field *Shading Control Type* on *OffNightAndOnDayIfCoolingAndHighSolarOnWindow*. In this way the shading devices are off during the night and on during the day if the solar radiation incident on the windows rises above the defined set-point and if the cooling rate in the earlier time-step is higher that zero.

4.7 Summary of the achievable levels

Table 4.39 summarizes the maximum level achievable by each BACS functions with *Edilclima EC700* and *EnergyPlus/DesignBuilder*.

Table 4.39: Level of BACS functions achievable by the two software tools

BACS function		Achievable levels[1]	
		EC700	***EnergyPlus***
Heating control			
1.1	Emission control	4	4
1.2	Emission control for TABS	1	3
1.3	Control of distribution network hot water temperature (supply or return)	1	1
1.4	Control of distribution pumps in networks	0	3
1.4a	Hydronic balancing heating distribution	-	-
1.5	Intermittent control of emission and/or distribution	1	3
1.6	Heat generator control for combustion and district heating	-	1
1.7	Heat generator control (heat pump)	1	1
1.8	Heat generator control (outdoor unit)	-	-
1.9	Sequencing of different heat generators	1	1
1.10	Control of thermal energy storage (TES) charging	0	0
Domestic Hot Water control			
2.1	Control DHW storage charging with direct electric heating or integrated electric heat pump	-	0
2.2	Control DHW storage charging using hot water generation	-	0
2.3	Control DHW storage charging with solar collector and supplementary heat generation	-	0
2.4	Control DHW circulation pump	0	0
Cooling control			
3.1	Emission control	4	4
3.2	Emission control for TABS	1	3
3.3	Control of distribution network chilled water temperature (supply/return)	-	1
3.4	Control of distribution pumps in networks	0	3
3.4a	Hydronic balancing heating	-	-
3.5	Intermittent control of emission and/or distribution	1	3
3.6	Interlock between heating and cooling control of emission/distribution	0	0
3.7	Generation control for cooling	-	1
3.8	Sequencing of different chillers	-	1
3.9	Control of thermal energy storage (TES) charging	0	1

[1] (-) means functions that cannot be simulated for any level of implementation.

Ventilation and air-conditioning control

4.1	Supply air flow control at the room level, related to the occupancy	1	3
4.2	Room air temperature control by ventilation system, acting on the air flow to regulate the air temperature	2	2
4.3	Coordination of room air temperature control by ventilation and by static system	-	0
4.4	Outdoor air (OA) flow control	-	3
4.5	Air flow of pressure control at air handler level	-	2
4.6	Heat recovery control: icing protection	1	1
4.7	Heat recovery control: prevention of overheating	1	1
4.8	Free mechanical cooling	-	3
4.9	Supply air temperature control at the air handling unit (AHU) level	-	1
4.10	Humidity control	1	2

Lighting control

5.1	Occupancy control	-	-
5.2	Light level and daylight control (Daylight harvesting)	1	3

Blind control

6.1	Blind control	2	3

Chapter 5

Case study

This chapter is divided into three parts. The first one analyses the current status of the case study. The second one explains how the two models are implemented with *Edilclima EC700* and *EnergyPlus/DesignBuilder*. The last part shows the results of the simulations of the different BACS efficiency classes.

5.1 Current status of the building

The case study is the building of classrooms P, which is part of the *Cittadella Politecnica* complex of *Politecnico di Torino*. The building is located in the metropolitan city of Turin, more precisely in Corso Peschiera, 84/A. Its geographical coordinates are 45°7' North and 7°43' East and its altitude is 239 m a.s.l. (Figure 5.1).

The building is a single story building made of a prefabricated reinforced concrete structure. The external opaque envelope is made of precast concrete panels with thermal break. The building has a slab directly placed on the ground and a flat roof.

On the ground floor the surface area is subdivided in: four classrooms of about 220 m^2 positioned in the corners of the building, two restrooms one on the North-East side and the other on the South-West side of the construction and a hallway crossing the building and connecting all the spaces (Figure 5.2). The geometrical characteristics of the building are shown in Table 5.1.

Figure 5.1: Spatial context of the building

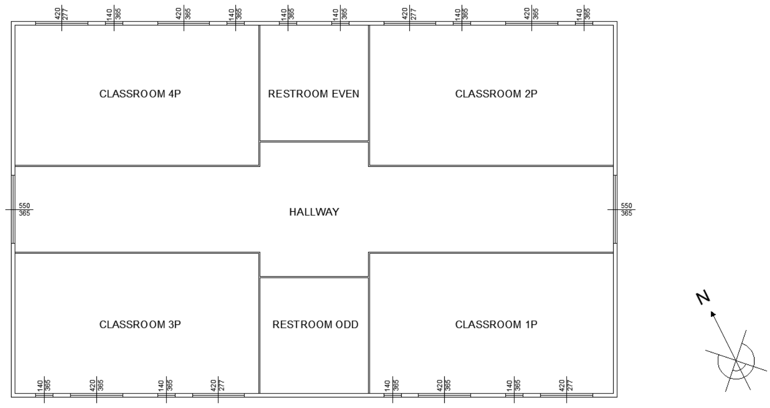

Figure 5.2: Building planimetry (out of scale)

Table 5.1: Geometrical characteristics

Geometrical characteristics	
Net floor area	1394.57 m^2
Gross floor area	1469.81 m^2
Total envelope area	4066.40 m^2
Net volume	7112.31 m^3
Gross volume	9885.96 m^3
S/V ratio	0.41 m^{-1}

5.1.1 Climatic data of the site

Table 5.2, 5.3 and 5.4 show the climatic data of Turin according to the standard UNI 10349-1:2016 [40].

Table 5.2: Climatic data

Climatic data of the building	
Reference Location	Turin-Bauducchi
Climatic zone	E
Degree days	2617 °C d
Wind Characteristics	
Wind region	A
Main wind direction	North-East
Distance from the sea	> 40 km
Average wind speed	1.4 m/s
Maximum wind speed	2.8 m/s
Winter data	
Outdoor design temperature	-8 °C
Conventional heating season	from 15 October to 15 April

Summer design day

Outdoor dry bulb temperature	31.0 °C
Outdoor wet bulb temperature	22.7 °C
Indoor relative humidity	50.0 %
Daily thermal excursion	11.0 °C

Table 5.3: Average monthly solar irradiation

Monthly average daily solar irradiation [MJ/m²]

Orientation	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
N	1.7	2.7	3.6	5.1	7.8	9.7	9.6	6.9	4.5	3.0	1.9	1.4
N-E	1.8	3.3	5.3	7.9	10.5	12.5	13.0	10.3	6.9	4.0	2.1	1.5
E	3.7	5.9	7.9	10.5	12.5	14.7	15.7	13.7	10.4	6.7	3.6	3.2
S-E	6.4	8.5	10.7	11.7	12.0	12.8	13.9	13.6	11.9	9.0	5.6	5.9
S	8.1	10.1	11.2	10.5	9.9	10.2	11.0	11.5	11.6	10.3	6.9	7.6
S-W	6.4	8.5	10.7	11.7	12.0	12.8	13.9	13.6	11.9	9.0	5.6	5.9
W	3.7	5.9	7.9	10.5	12.5	14.7	15.7	13.7	10.4	6.7	3.6	3.2
N-W	1.8	3.3	5.3	7.9	10.5	12.5	13.0	10.3	6.9	4.0	2.1	1.5
Horizontal	4.6	7.7	11.7	16.0	19.7	22.8	24.0	20.2	14.6	9.0	4.8	3.9

Table 5.4: Average monthly outdoor temperatures

Average monthly outdoor temperatures

Temp	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
°C	1.2	3.1	8.3	11.9	18.0	22.1	23.6	22.6	19.1	12.3	6.8	2.6

5.1.2 Activity and thermal zones

The building is used for university activities. For this reason, the use category is E.7 "Buildings used for school activities at all levels and assimilated", in accordance with DPR 412/93 [31]. It is possible to identify seven different thermal zones: the four classes, the two restrooms and the hallway (Figure 5.3). Table 5.5 shows the main data regarding the thermal zones.

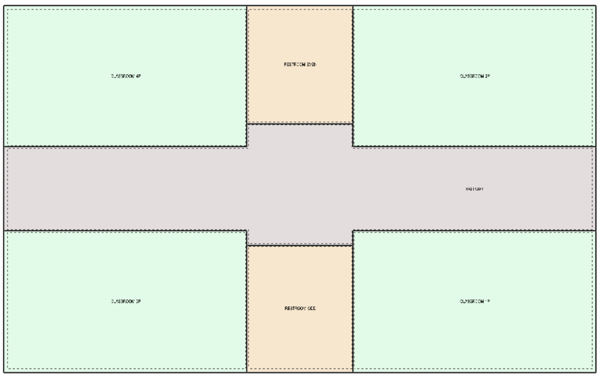

Figure 5.3: Thermal zone subdivision

Table 5.5: Building activity summary

	Classroom[1]	**Restroom**[2]	**Hallway**
Net area [m^2]	220.02	79.24	356.01
Net volume [m^3]	1122.10	404.12	1815.65
Building category	E.7		
Subcategory	University classroom	Restroom	Common space
Ventilation flow rate per person Q_{op} [10^{-3}m^3/s pers]	7.0	Extraction	7.0
Crowding index n_s [pers/m^2]	1.04	-	0.23

Table 5.6 shows the set-point temperature used for the environmental control into the thermal zones according to the data provided in the technical document of the building.

Table 5.6: Building set-points temperature summary

	Classroom	**Restroom**	**Hallway**
Heating set-point temperature [C°]	20.0	20.0	20.0
Cooling set-point temperature [C°]	27.0	27.0	27.0

Table 5.7 shows the values of the internal heat gains due to the presence of people, appliances and lights as reported in standard ISO 18523-1:2016 [32].

Table 5.7: Building internal heat gains summary

	Classroom	**Restroom**	**Hallway**
Internal gains due to people [W/m^2]	59.50	3.60	23.80
Internal gains due to appliance [W/m^2]	2.00	0.00	0.00
Internal gains due to lighting [W/m^2]	20.00	15.00	35.00

The occupancy values are provided by the technical documents of the building and take into account the opening hours of the building. The maximum number of people in each classroom is 225 and the average number of people in the hallway and restrooms is about 120. Table 5.8 shows the occupancy schedule of the building, in terms of occupancy factor, appliances utilization factor, and lighting utilization factor. The factors are shown as a fraction between 0 and 1, where 0 means no occupancy and 1 means the maximum occupancy.

Table 5.8: Building occupancy schedule

h	**Weekdays**			**Weekend-Holidays**		
	f_{occ}	f_{int_A}	$f_{int,L}$	f_{occ}	f_{int_A}	$f_{int,L}$
1	0	0	0	0	0	0

[1] The data in the table refers to only one classroom, because all the classrooms have the same characteristics.
[2] The data in the table refers to only one restroom, because the two restrooms have the same characteristics.

2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0.3	0	1	0	0	0
8	0.7	0.2	1	0	0	0
9	1	0.5	1	0	0	0
10	1	0.5	1	0	0	0
11	1	0.5	1	0	0	0
12	1	0.5	1	0	0	0
13	1	0.5	1	0	0	0
14	1	0.5	1	0	0	0
15	1	0.5	1	0	0	0
16	1	0.5	1	0	0	0
17	1	0.5	1	0	0	0
18	1	0.5	1	0	0	0
19	0.7	0.2	1	0	0	0
20	0.3	0.2	1	0	0	0
21	0	0	1	0	0	0
22	0	0	0	0	0	0
23	0	0	0	0	0	0
24	0	0	0	0	0	0

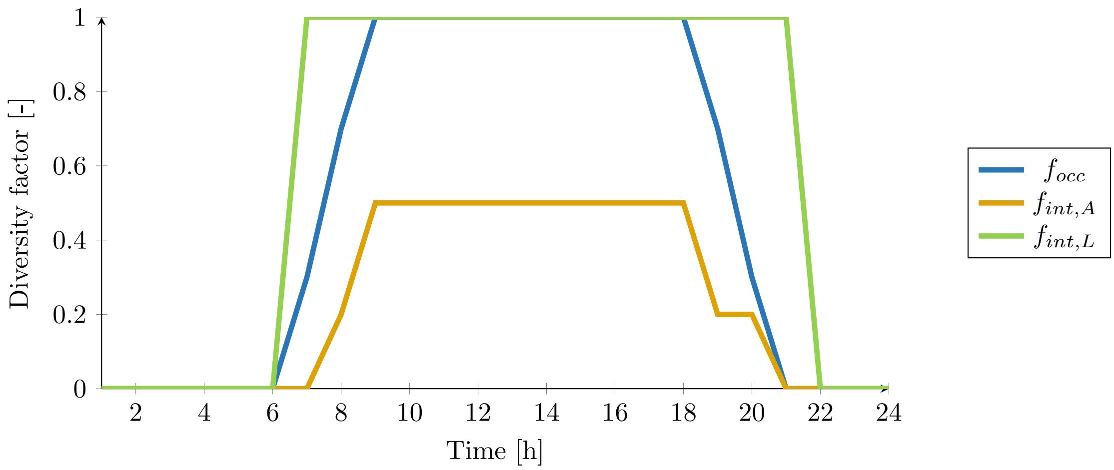

Figure 5.4: Occupancy factor, appliances utilization factor, and lighting utilization factor for the weekdays

5.1.3 Building envelope

Opaque envelope - External wall

The stratigraphy and the thermo-physical characteristics of the external wall are show in Figures 5.5 and 5.6 and Tables 5.9 and 5.10.

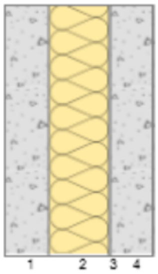

Figure 5.5: External wall stratigraphy

Table 5.9: External wall stratigraphy

N°	**Description**	**d [cm]**	**λ [W/mK]**	R **[m^{2}K/W]**	**ρ [kg/m^3]**	**C [kJ/kgK]**	**μ [-]**
	Internal surface resistance	-	-	0.13	-	-	-
1	Concrete of sand and gravel (internal wall)	9.0	1.910	-	2400	1.00	96
2	Expanded polystyrene synthesized (EPS 100)	11.9	0.035	-	15	1.45	60
3	Weakly ventilated cavity Av=600mm^3/m	0.1	-	-	-	-	-
4	Concrete of sand and gravel (external wall)	9.0	2.150	-	2400	1.00	96
	External surface resistance	-	-	0.04	-	-	-

Table 5.10: External wall thermo-physical characteristic

Thermo-physical charcateristic	
Thermal transmittance	0.271 W/m^{2}K
Thickness	30 cm
Vapor permeability	12.674 10^{-12}kg/sm^{2}Pa
Areal mass	434 kg/m^2
Periodic thermal transmittance	0.067 W/m^{2}K
Decrement factor	0.248
Time lag	-9.1 h

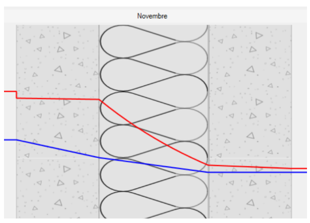

Figure 5.6: External wall interstitial condensation and superficial condensation check in the most critical month (November)

Opaque envelope - Internal wall

The stratigraphy and the thermo-physical characteristic of the internal wall are show in Figures 5.7 and 5.8 and Tables 5.11 and 5.12.

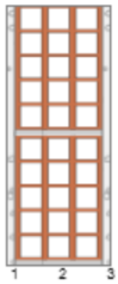

Figure 5.7: Internal wall stratigraphy

Table 5.11: Internal wall stratigraphy

N°	Description	d [cm]	λ [W/mK]	R [m^{2}K/W]	ρ [kg/m^3]	C [kJ/kgK]	μ [-]
	Internal surface resistance	-	-	0.13	-	-	-
1	Lime and gypsum plaster	1.4	0.700	-	1400	1.00	10
2	Brick mansory for internal wall	17.0	0.430	-	1200	1.00	7
3	Lime mortar	1.5	0.900	-	1400	1.00	22
	External surface resistance	-	-	0.13	-	-	-

Table 5.12: Internal wall thermo-physical characteristic

Thermo-physical charcateristic	
Thermal transmittance	1.442 W/m^{2}K
Thickness	20 cm
Vapor permeability	119.760 10^{-12}kg/sm^{2}Pa
Areal mass	252 kg/m^2
Periodic thermal transmittance	0.637 W/m^{2}K
Decrement factor	0.442
Time lag	-7.379 h

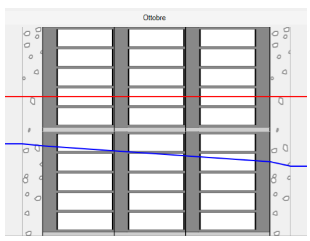

Figure 5.8: Internal wall interstitial condensation and superficial condensation check in the most critical month (October)

Opaque envelope - Slab-on-ground

The stratigraphy and the thermo-physical characteristic of the slab-on-ground are show in Figures 5.9 and 5.10 and Tables 5.13 and 5.14.

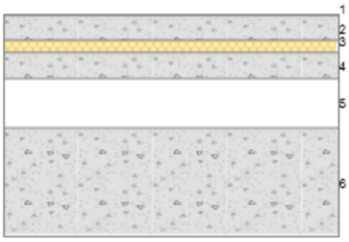

Figure 5.9: Slab-on-ground stratigraphy

Table 5.13: Slab-on-ground stratigraphy

N°	**Description**	**d** [cm]	**λ** [W/mK]	*R* [m²K/W]	**ρ** [kg/m³]	**C** [kJ/kgK]	**μ** [-]
	Internal surface resistance	-	-	0.17	-	-	-
1	Granite tiles	1.0	4.100	-	3000	0.84	10000
2	Lean concrete substrate	10.0	0.700	-	1600	0.88	20
3	Skinless extrude polystyrene foam	5.0	0.034	-	50	1.45	17
4	Concrete of sand and gravel (external wall)	10.0	1.30	-	2000	1.00	96
5	Weakly ventilated cavity Av=900mm^3/m	20.0	-	-	-	-	-
6	General concrete	44.0	0.220	-	500	1.0	96
	External surface resistance	-	-	0.04	-	-	-

Table 5.14: Slab-on-ground thermo-physical characteristic

Thermo-physical charcateristic	
Thermal transmittance	0.142 W/m^{2}K
Thickness	90 cm
Vapor permeability	1.679 10^{-12}kg/sm^{2}Pa
Areal mass	612 kg/m^2
Periodic thermal transmittance	0.001 W/m^{2}K
Decrement factor	0.007
Time lag	-1.200 h

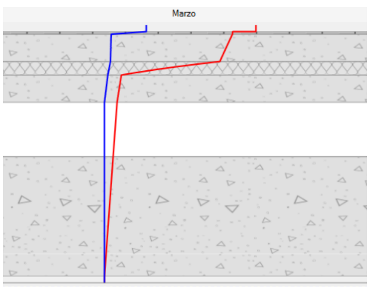

Figure 5.10: Slab-on-ground interstitial condensation and superficial condensation check in the most critical month (March)

Opaque envelope - Flat roof

The stratigraphy and the thermo-physical characteristic of the flat roof are show in Figures 5.11 and 5.12 and Tables 5.15 and 5.16.

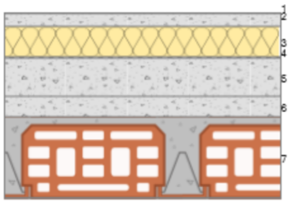

Figure 5.11: Flat roof stratigraphy

Table 5.15: Flat roof stratigraphy

N°	Description	d [cm]	λ [W/mK]	R [m^{2}K/W]	ρ [kg/m^3]	C [kJ/kgK]	μ [-]
	External surface resistance	-	-	0.04	-	-	-
1	Waterproofing in roofing felt	0.5	0.500	-	1600	1.00	188000
2	Concrete distribution screed with mesh	5.0	1.490	-	220	0.88	70
3	Extruded polystyrene foam with leather	12.0	0.034	-	30	1.45	60
4	Vapor barrier made of polyethylene sheets	0.1	0.330	-	920	2.20	100000
5	Expanded clay concrete internal walls in a closed structure	15.0	0.910	-	1700	1.00	96
6	Concrete of sand and gravel (external wall)	8.0	1.260	-	2000	1.00	96
7	Predalles type slab	32.0	0.889	-	1394	0.84	9
	External surface resistance	-	-	0.04	-	-	-

Table 5.16: Flat roof thermo-physical characteristic

Thermo-physical characteristic	
Thermal transmittance	0.231 W/m^{2}K
Thickness	72.6 cm
Vapor permeability	0.186 10^{-12}kg/sm^{2}Pa
Areal mass	984 kg/m^2
Periodic thermal transmittance	0.004 W/m^{2}K
Decrement factor	0.017
Time lag	-20.195 h

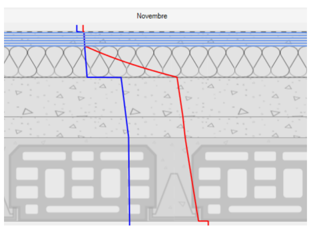

Figure 5.12: Flat roof interstitial condensation and superficial condensation check in the most critical month (November)

Transparent building envelope

The transparent envelope components of the building have all the same type of glass and frame. Therefore, the transparent components are made of a low-e double glazing and a thermal break aluminum frame. The components are characterized by an average thermal transmittance lower than 1.8 W/m^2K and air permeability class 4.

5.1.4 Building systems

Five different direct expansion rooftop systems are installed on the roof of the building to provide the required heating and cooling loads and ventilation requirements in the four classrooms, two restrooms and hallway (Figure 5.13 and Figure 5.14). Four of the rooftop systems have the same performance characteristics, each one providing air conditioning to one classroom. The fifth rooftop system provides air conditioning to the hallway and the restrooms. The domestic hot water is provided by electric boilers installed in the restrooms.

Classroom rooftop system

Table 5.17 illustrates the technical characteristics of the system installed in each classroom. Fifteen helical effect diffusers, installed on the ceiling and with a flow rate of 600 m^3/h each, supply air into each classroom. Air is extracted from each classroom through four intake grilles installed in the ceiling and two intake grilles installed on the wall.

Table 5.17: Classroom rooftop system characteristics

Cooling performance	
Total cooling power	63.0 kW
Cooling recovery power	3.69 kW
Compressor power consumption	15.9 kW
EER	3.96
Supply temperature	14.4 °C
Supply relative humidity	98 %
External temperature	35 °C
External relative humidity	50%
Ambient temperature	27 °C
Ambient relative humidity	47 %
Heating performance	
Total heating power	62.7 kW
Heating recovery power	5.95 kW
Compressor power consumption	12.8 kW
COP	4.89
Supply temperature	36.7 °C
Supply relative humidity	18 %
External temperature	7 °C
External relative humidity	87 %
Ambient temperature	20 °C
Ambient relative humidity	50 %

Ventilation performance	
Supply air flow rate	9000 m^3/h
Total power consumption (supply)	3.09 kW
Return air flow rate	9000 m^3/h
Total power consumption (return)	1.31 kW
Electric resistance for supplementary heating	
Rated power	18.0 kW

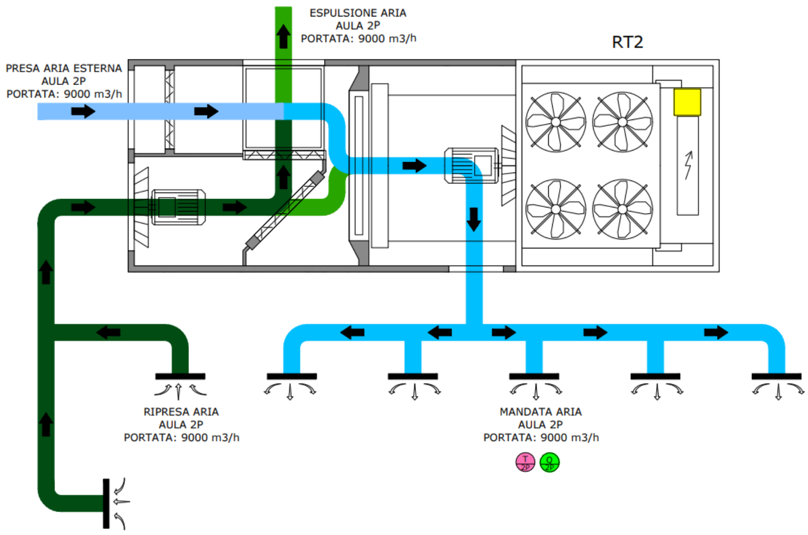

Figure 5.13: Functional diagram of the rooftop system of one class

Hallway and restrooms rooftop system

Table 5.17 illustrates the technical characteristics of the system installed for the hallway and the restrooms. Two linear vents, installed near the entrances, and two helical effect diffusers, installed on the ceiling of the hallway, supply air into the zone. The supply air enter the two restrooms through transit vents. Air is extracted from the zone through intake grilles, installed in the middle of the hallway ceiling and with a total flow rate of 1800 m^3/h, and from twenty-four vents installed in the restrooms that extract the remaining flow rate of 3300 m^3/h.

Table 5.18: Hallway and restroom rooftop system characteristics

Cooling performance	
Total cooling power	32.4 kW
Cooling recovery power	3.69 kW
Compressor power consumption	10.8 kW
EER	2.16
Supply temperature	21 °C

Supply relative humidity	50 %
External temperature	35 °C
External relative humidity	45%
Ambient temperature	26 °C
Ambient relative humidity	50 %
Heating performance	
Total heating power	27.9 kW
Heating recovery power	11.1 kW
Compressor power consumption	2.7 kW
COP	6.19
Supply temperature	22 °C
Supply relative humidity	50 %
External temperature	7 °C
External relative humidity	87 %
Ambient temperature	20 °C
Ambient relative humidity	50 %
Ventilation performance	
Supply air flow rate	5100 m^3/h
Total power consumption (supply)	1.56 kW
Return air flow rate	5100 m^3/h
Total power consumption (return)	1.62 kW
Electric resistance for supplementary heating	
Rated power	18.0 kW

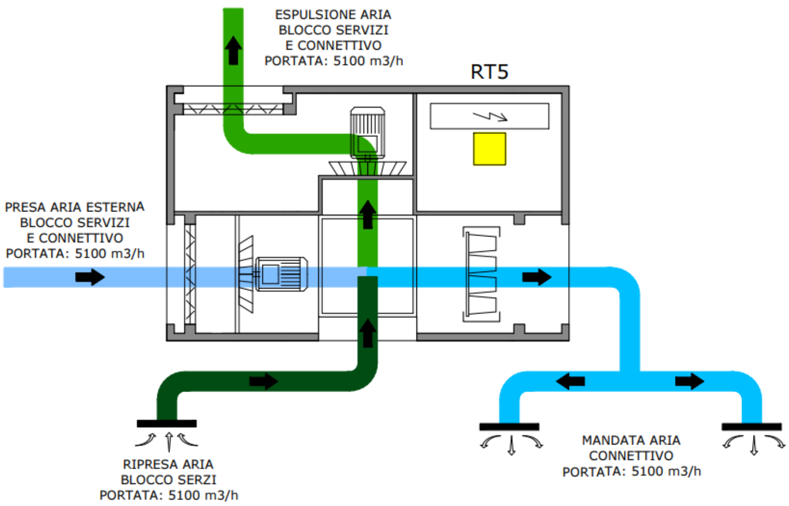

Figure 5.14: Functional diagram of the rooftop system of common spaces

5.2 Model

The building is modeled with two different energy modeling tools: *Edilclima EC700*, that uses a simplified dynamic calculation model, and *EnergyPlus/DesignBuilder*, that uses a detailed dynamic calculation model (Figure 5.15). *Edilclima EC700* allows to model the building graphically and is able to perform the calculation of the energetic performance in accordance with the technical specifications.

EnergyPlus/DesignBuilder are two different software tools with the same computing capabilities and the same calculation model. Indeed, *DesignBuilder* represents the graphical interface of *EnergyPlus*, allows to model the building easily with respect to *EnergyPlus*, which is a console-based program that reads input and writes output to text files, and is connected to *EnergyPlus* to perform the calculations.

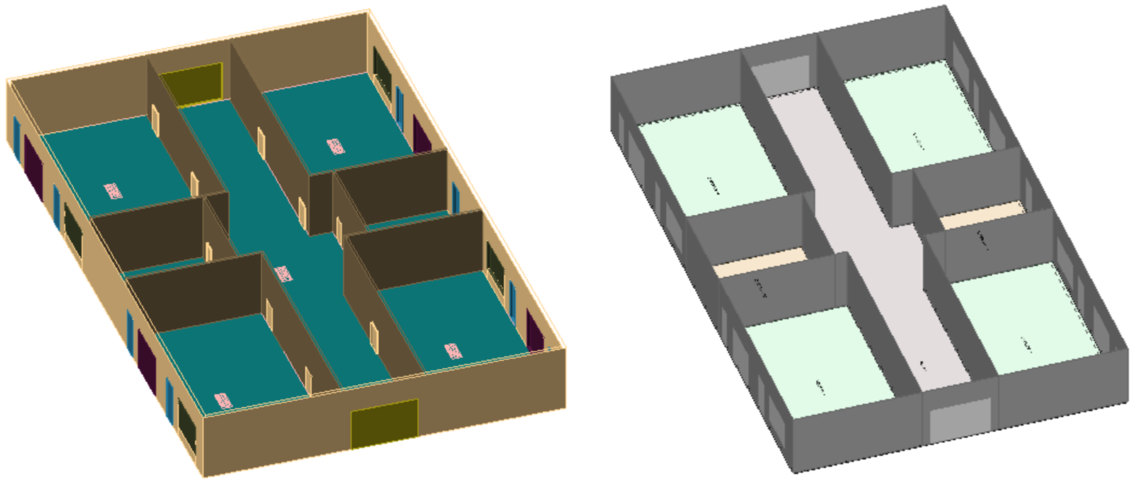

Figure 5.15: *Edilclima EC700* model (left) and *EnergyPlus/DesignBuilder* model (right)

5.2.1 Boundary conditions

The model is set up in the two software tools with the same boundary conditions, i.e., the same climatic conditions and the same type of activity per thermal zone (Figure 5.16 and Figure 5.17). Climatic conditions data are taken from Table 5.2 and from the climatic data provided by *Comitato Termotecnico Italiano* (CTI) which gives the hourly data of a typical climatic year for all the Italian provinces [20]. These data are calculated according to the calculation model of the UNI EN ISO 15927-4:2005 [16]. The activity data are taken from Table 5.5.

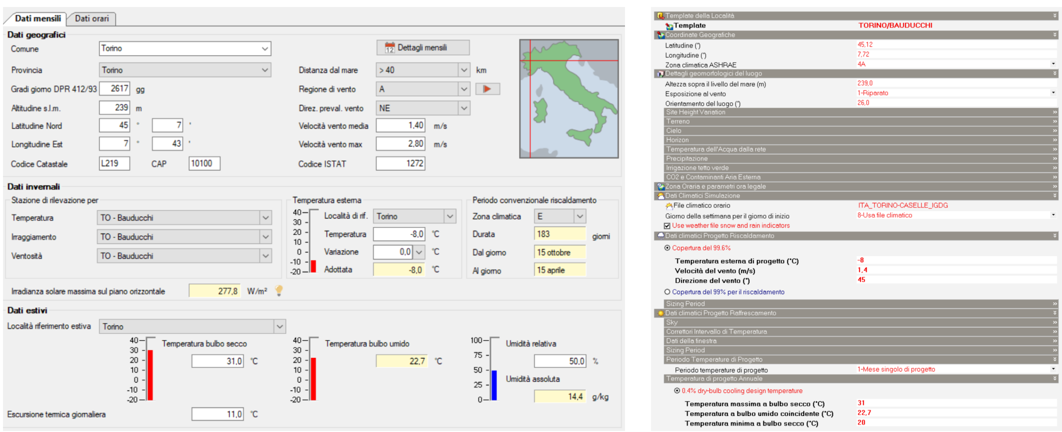

Figure 5.16: Climatic data setting in *Edilclima EC700* (left) and *EnergyPlus/DesignBuilder* (right)

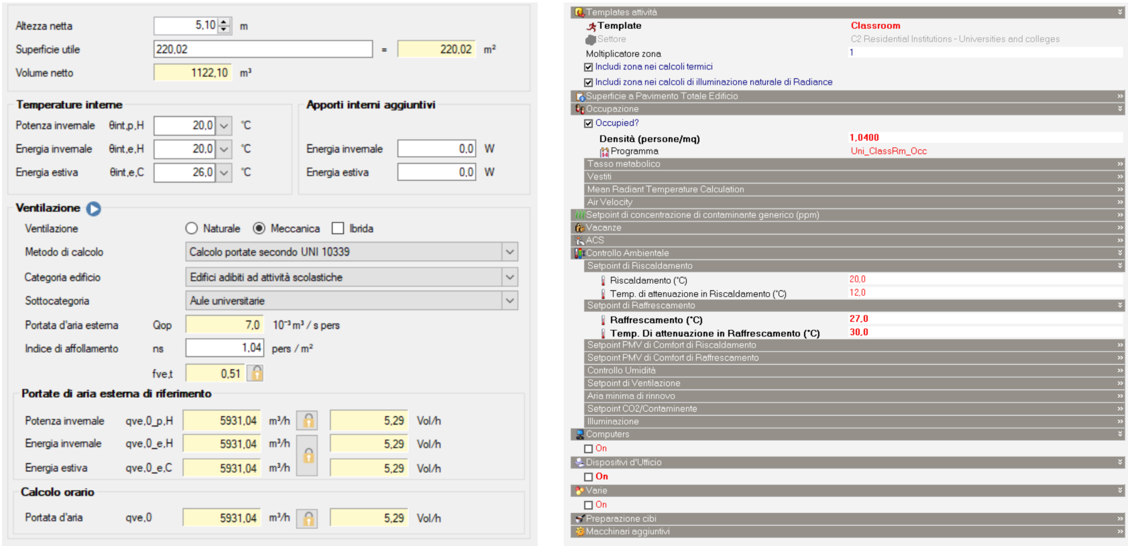

Figure 5.17: Activity data setting in *Edilclima EC700* (left) and *EnergyPlus/DesignBuilder* (right)

5.2.2 Building envelope

The building envelope components of the two models are modeled to have the same thermo-physical characteristics. On one hand, in *Edilclima EC700* the materials are taken from the library, since they had the same thermo-physical characteristic described in the technical document of the building (Figure 5.18 (left)). On the other hand, in *EnergyPlus/DesignBuilder* the materials are created from scratch to set the same thermo-physical characteristics (Figure 5.18 (right)). The information on the thermo-physical data are taken from Subsection 5.1.3.

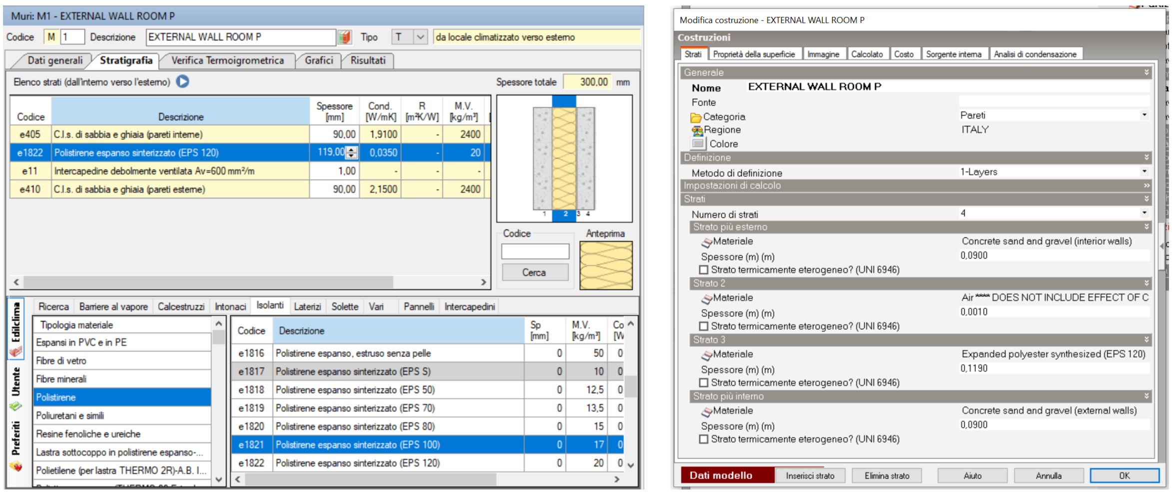

Figure 5.18: Example of stratigraphy settings in *Edilclima EC700* (left) and *EnergyPlus/DesignBuilder* (right)

5.2.3 Building systems

Edilclima EC700 allows to model the technical building systems in a simplified way, while *EnergyPlus/DesignBuilder* allows a more detailed modeling. The following subsection explains how the technical building systems are modeled with the two software tools.

Edilclima EC700

The rooftop systems are created starting from the *General system* data-sheet. Since each classroom has its own rooftop system, the heating and cooling systems are set on *Stand-alone* and the ventilation is set on *Separate production with autonomous system* (Figure 5.19).

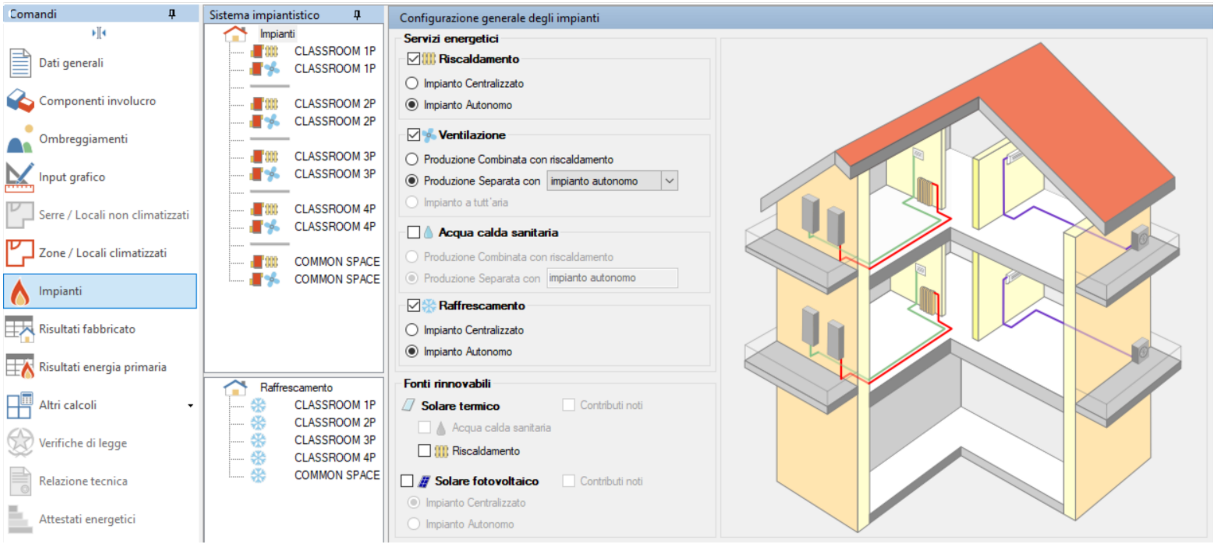

Figure 5.19: Plan tree of the ROOFTOP systems

In the *Heating system - Circuit* data-sheet one sets: air as a heat transfer fluid, *Vents in hot-air systems* in the emission subsystem, *Regulation by thermal zone* in the regulation subsystem and 100% efficiency in the distribution subsystem (Figure 5.20). In the *Heating system - Generation* data-sheet one sets the heat pump generator, and in *Heating system - Generation - Generator* one sets the heat pump data according to the heating performance data of Table 5.17 and Table 5.18 (Figure 5.21).

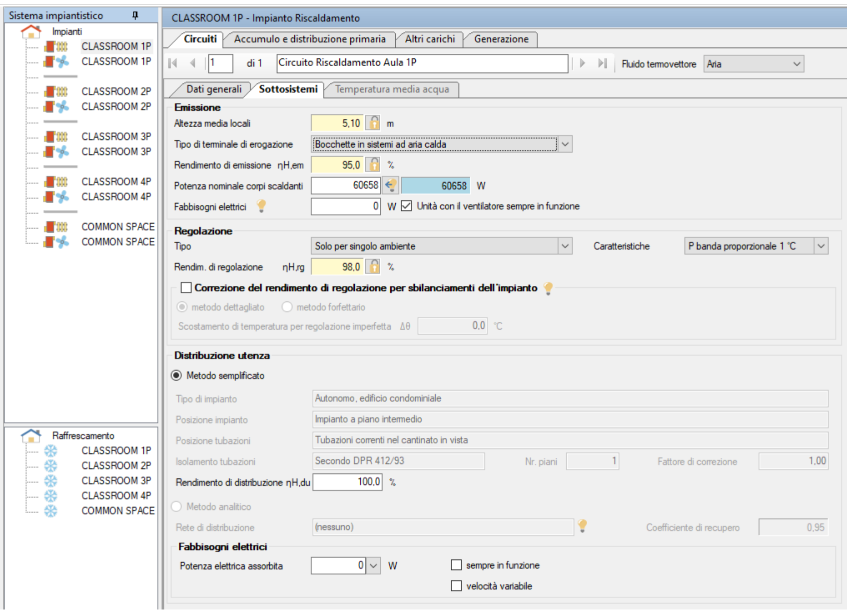

Figure 5.20: *Heating system - Circuit* data-sheet settings

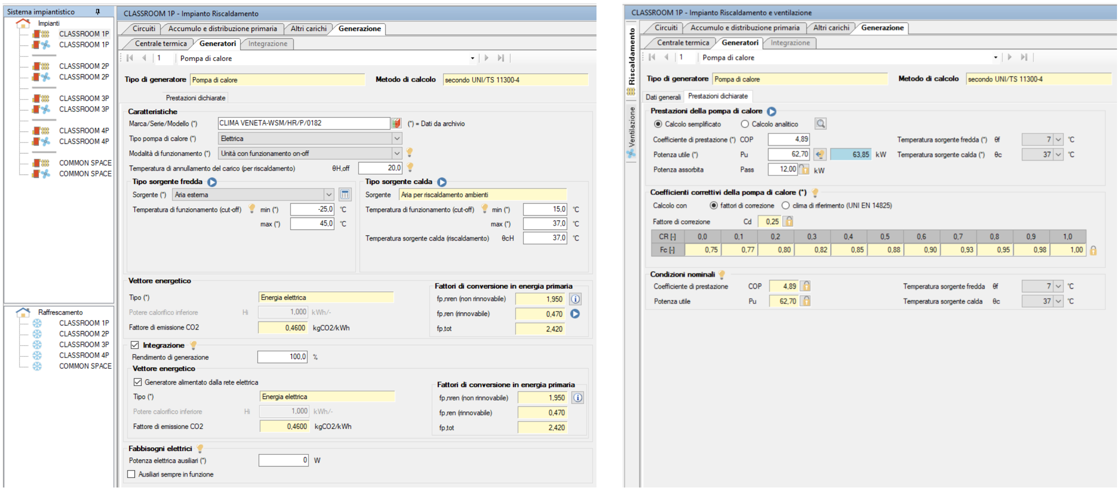

Figure 5.21: *Heating system - Generation - Generator* data-sheet settings

In the *Ventilation system* data-sheet, one sets the *Mechanical ventilation* associated with the *Heat recovery system* according to the data provided in Table 5.17 and Table 5.18 (Figure 5.22). In the *Ventilation system - Flow rate*, one sets the system type on *Return+Supply* and the values of supply and return air flow rate according to Table 5.17 and Table 5.18 (Figure 5.23). In the *Ventilation system - Pipes* data-sheet, one sets the electric power of exhaust fan and supply fan with the values of Table 5.17 and Table 5.18 (Figure 5.24).

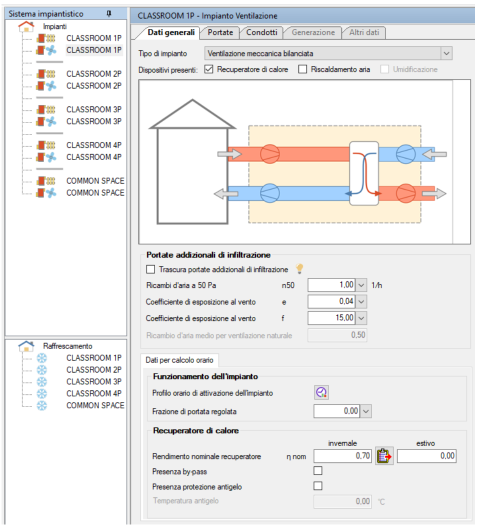

Figure 5.22: *Ventilation system* data-sheet settings

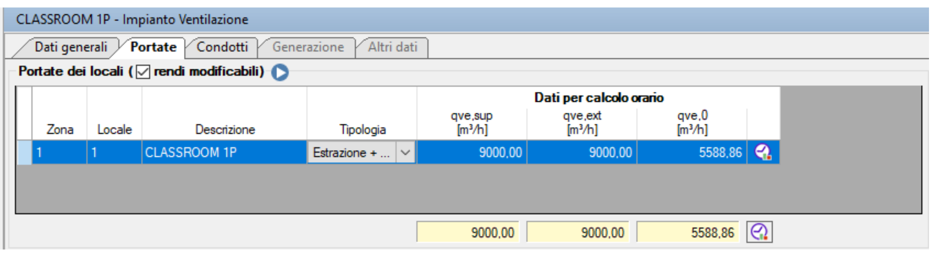

Figure 5.23: *Ventilation system - Flow rate* data-sheet settings

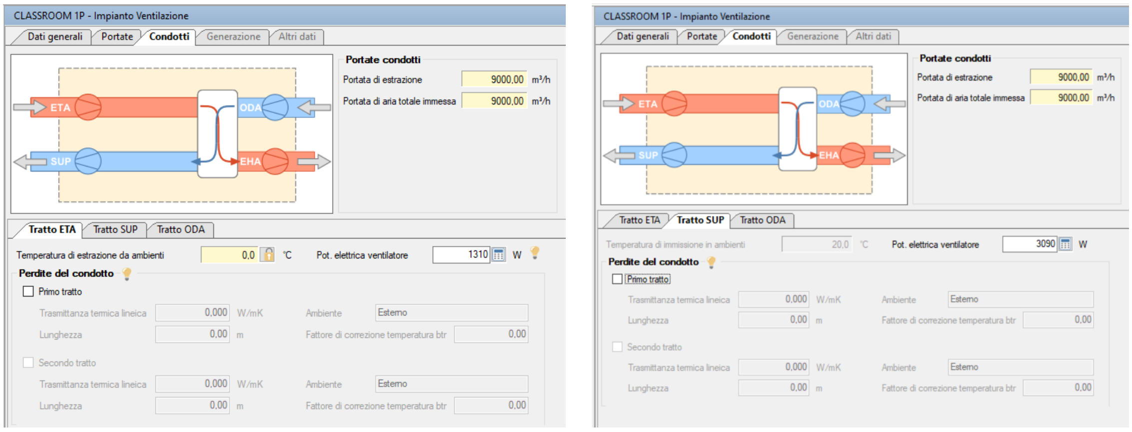

Figure 5.24: *Ventilation system - Pipes* data-sheet settings, exhaust fan (left) and supply fan (right)

In the *Cooling system - Circuit* data-sheet, one sets the *Direct-expansion terminals* in the emission subsystem and the *Regulation by thermal zone* in the regulation subsystem (Figure 5.25). In the *Cooling system - Generation* data-sheet, one sets an electric heat pump generator and the heat pump performance data according to the cooling performances of Table 5.17 and Table 5.18 (Figure 5.26).

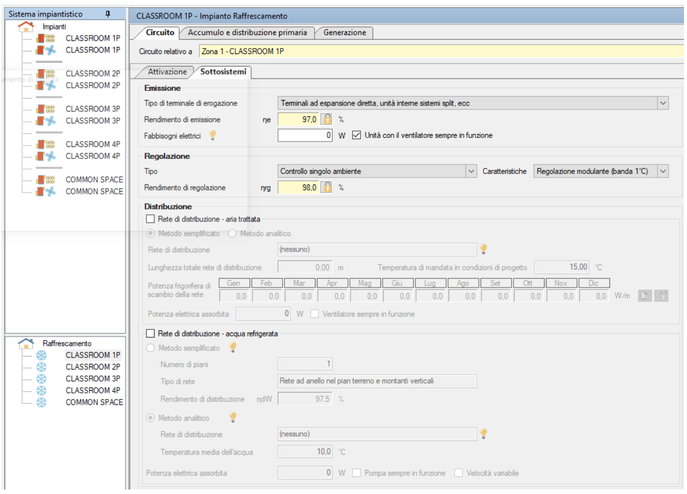

Figure 5.25: *Cooling system - Circuit* data-sheet settings

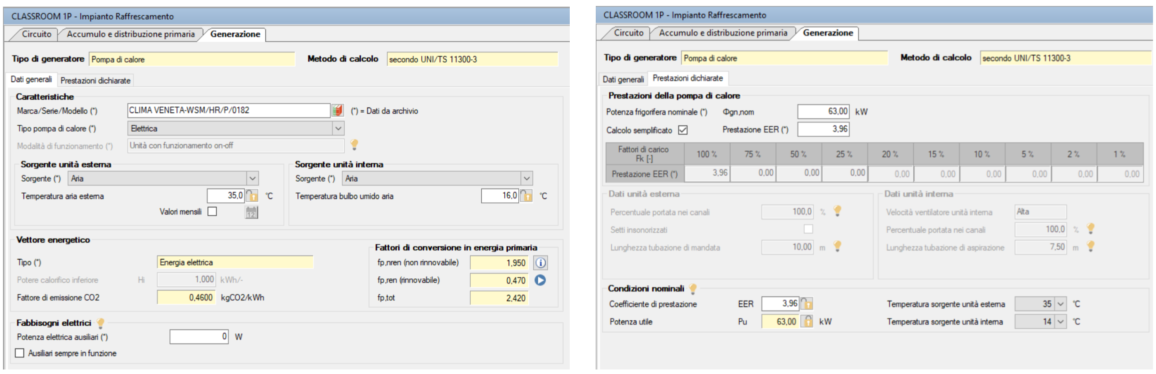

Figure 5.26: *Cooling system - Generation - Generator* data-sheet settings

EnergyPlus/DesignBuilder

The rooftop systems are created using the *Detailed HVAC* setting of *EnergyPlus/DesignBuilder*, allowing to model the HVAC system in a more precise and detailed manner. Figure 5.27 shows the functional scheme of the rooftop systems in the case study. Figure 5.28 and Figure 5.29 show more in detail the two types of rooftop systems installed in the building, the first one for the classrooms and the second one for the hallway and the restrooms.

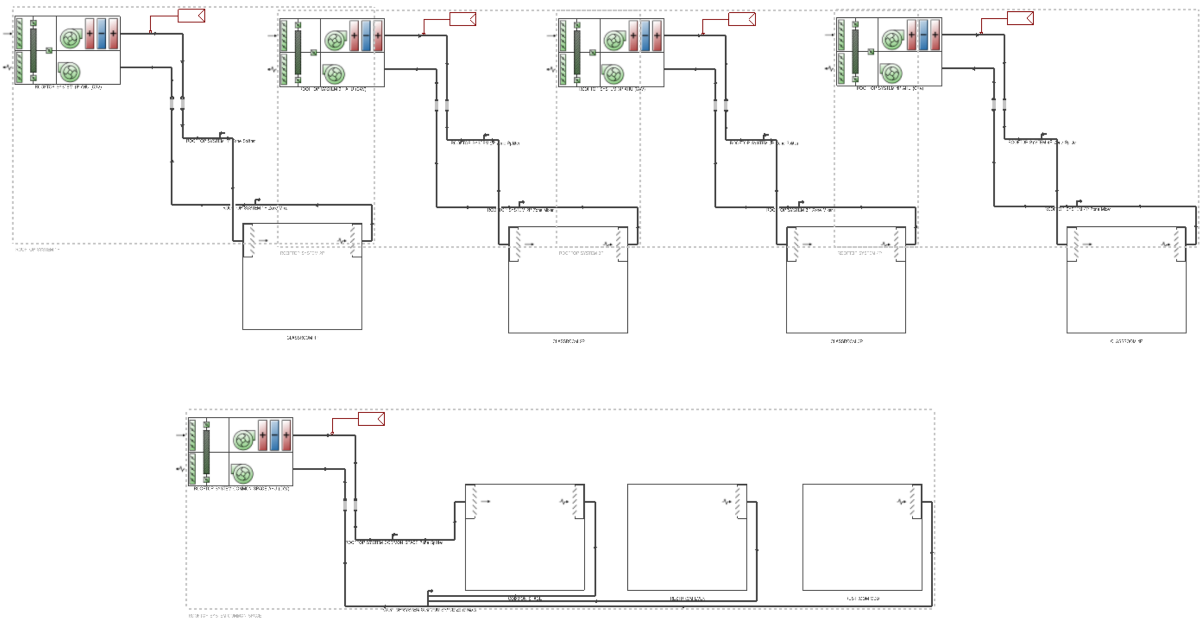

Figure 5.27: Functional scheme of the rooftop systems

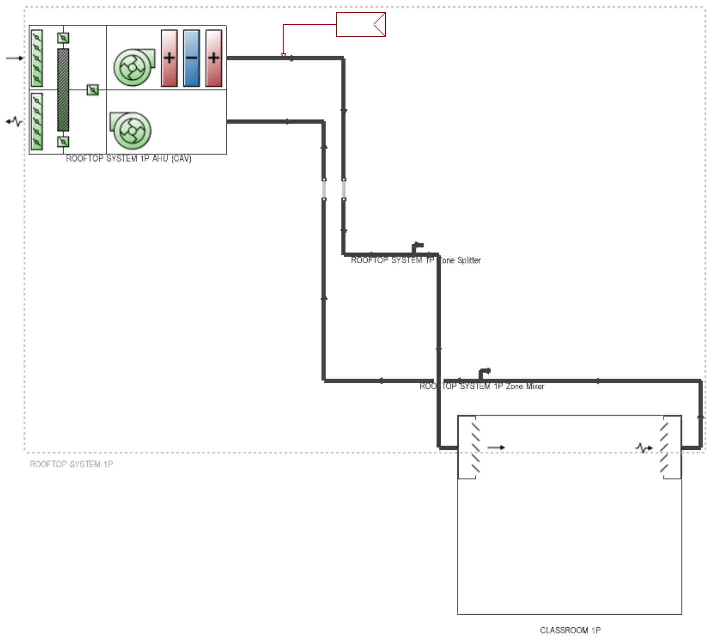

Figure 5.28: Functional scheme of classroom rooftop system

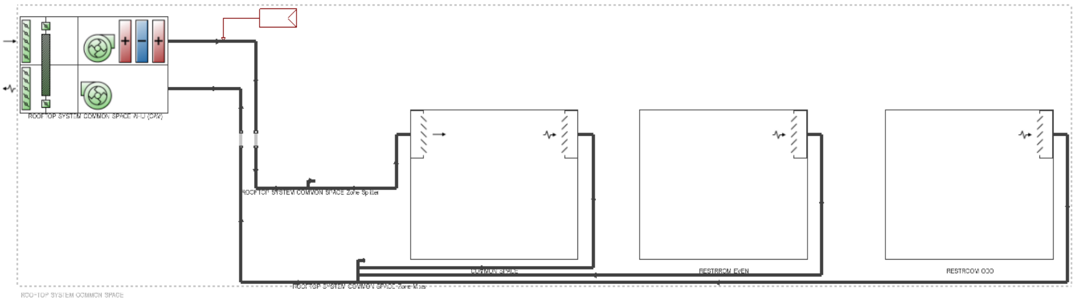

Figure 5.29: Functional scheme of hallway and restrooms rooftop system

To correctly model the rooftop systems, in each thermal zone is added an air distribution terminal and an extraction terminal. The terminals are connected to their respective rooftop air circuits (Figure 5.30 (left)). In the properties of the HVAC of each zone, the supply air temperature and relative humidity in both heating and cooling periods are set according to the information of Tables 5.17 and 5.18 (Figure 5.30 (right)).

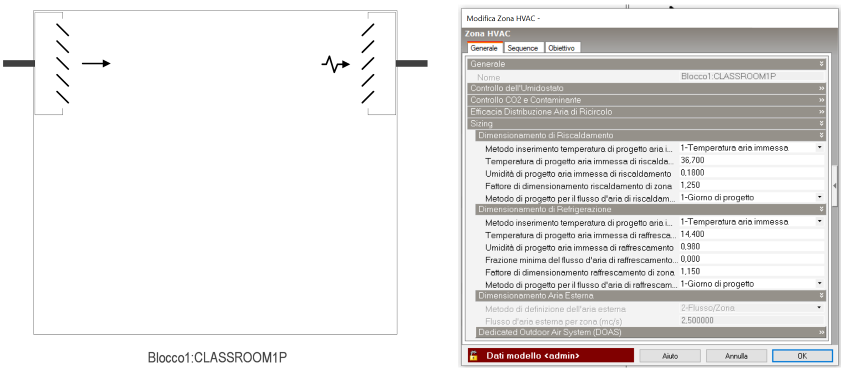

Figure 5.30: HVAC thermal zone graphical representation (left) and settings (right)

The rooftop is modeled starting with a *generic air loop* element comprising a supply and return fan (for air conditioning supply and extraction) and an air-to-air heat exchanger. Then, a direct expansion heating coil, a direct expansion cooling coil, and an electric heating coil for post-heating or heat supplement during winter are added to the *generic air loop* element. The recirculation option is deactivated for the rooftop system of the common space, since the extracted air also arrives from the restrooms (Figure 5.31). The properties of each component, the external air temperature and the relative humidity are set according to the information of Tables 5.17 and 5.18.

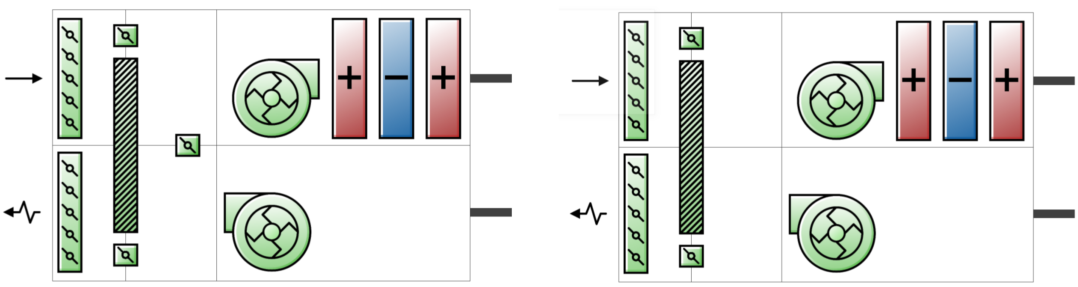

Figure 5.31: Classroom rooftop system diagram (left) and hallway and restrooms rooftop system diagram (right)

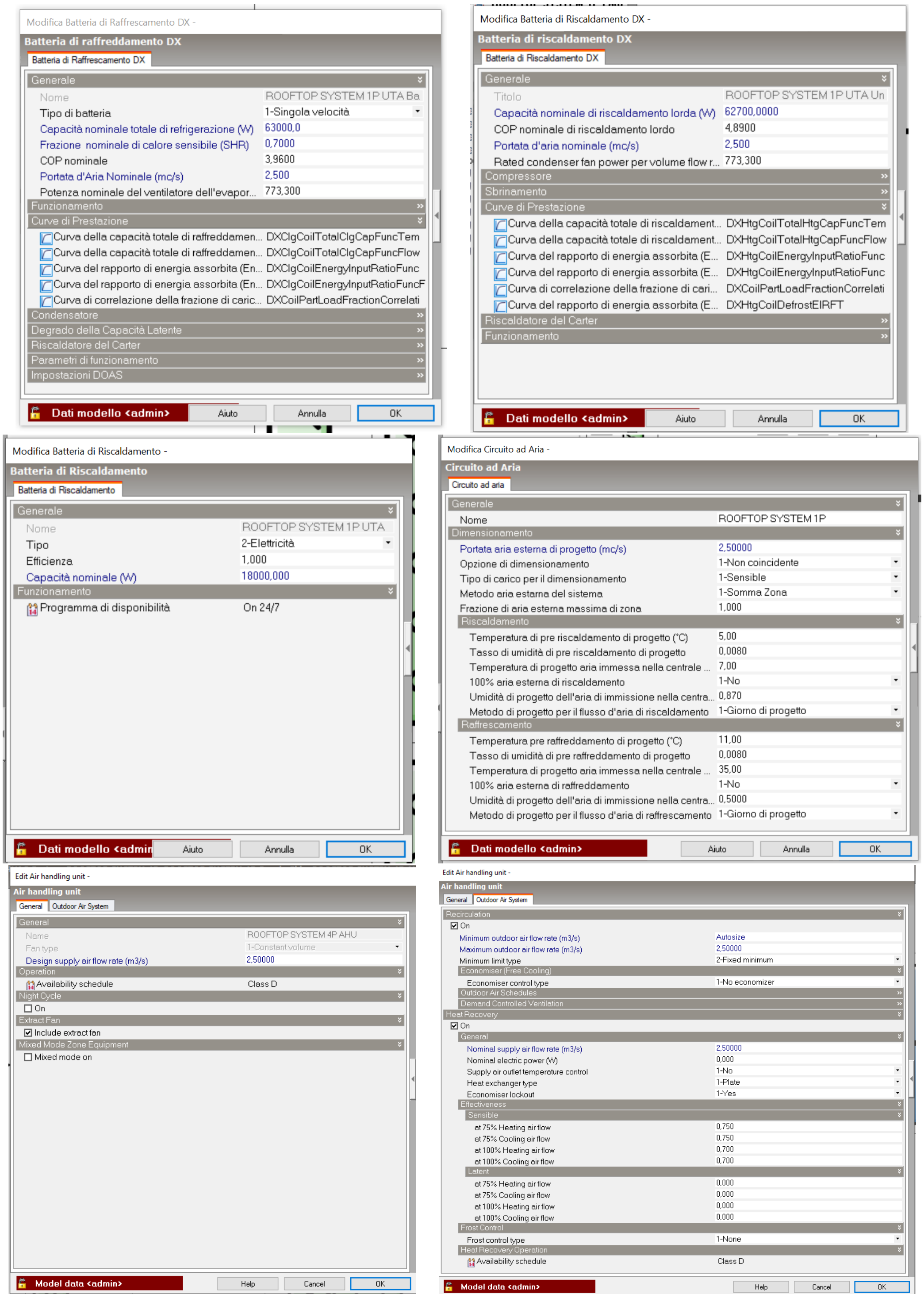

Figure 5.32: rooftop components settings

5.3 Simulation of BACS efficiency class

Given the technical building system present in the building and the functions that can be simulated with the two software tools (Chapter 4), the following BACS functions are implemented in the models:

- Emission control (heating control) (function 1.1 of EN ISO 52120 [19]),
- Intermittent control of emission and/or distribution (heating control) (function 1.5 of EN ISO 52120 [19]),
- Emission control (cooling control) (function 3.1 of EN ISO 52120 [19]),
- Intermittent control of emission and/or distribution (cooling control) (function 3.5 of EN ISO 52120 [19]),
- Supply air flow control at the room level (function 4.1 of EN ISO 52120 [19]),
- Room air temperature control by ventilation system (function 4.2 of EN ISO 52120 [19]),
- Outdoor air (OA) flow control (function 4.4 of EN ISO 52120 [19]),
- Blind control (function 6.1 of EN ISO 52120 [19]).

Table 5.19 summarizes the maximum level of each BACS functions considered for the case study achievable with *Edilclima EC700* and *EnergyPlus/DesignBuilder* (see Chapter 4).

Table 5.19: Selected BACS function level achievable in the two models

BACS function		**BACS function level achievable**	
		EC700	***EnergyPlus/DesignBuilder***
1.1	Emission control (heating control)	4	4
1.5	Intermittent control of emission and/or distribution (heating control)	1	3
3.1	Emission control (cooling control)	4	4
3.5	Intermittent control of emission and/or distribution (cooling control)	1	3
4.1	Supply air flow control at the room level	1	3
4.1	Room air temperature control by ventilation system	2	2
4.4	Outdoor air (OA) flow control	-	3
6.1	Blind control	2	3

Tables 5.20 and 5.21 show which BACS efficiency classes can be obtained by the considered functions with the two software tools according to Table 5.19 and Table 6 of the standard EN ISO 52120 [19].

Edilclima C700

Table 5.20 shows that the maximum BACS efficiency class achievable with *Edilclima EC700* is class C "standard" level.

Table 5.20: Evaluation of BACS class with *Edilclima EC700* software

		Function level	**D**	**C**	**B**	**A**
1.1	0	No automatic control of the room temperature	X			
	1	Central automatic control: there is only central automatic control acting either on the distribution or on the generation. Function is to be integrated in a system.	X			
	2	Individual room control: by thermostatic valves or electronic controller	X	X		
	3	Individual modulating room control with communication: between controllers and BACS (e.g. scheduler, room temperature set-point)	X	X	X	X*
	4	Individual modulating room control with communication and occupancy detection: between controllers and BACS; demand control/occupancy detection	X	X	X	X
1.5	0	No automatic control	X			
	1	Automatic control with fixed time program: to lower the operation time	X	X		
3.1	0	No automatic control of the room temperature	X			
	1	Central automatic control: there is only central automatic control acting either on the distribution or on the generation. Function is to be integrated in a system.	X			
	2	Individual room control: by thermostatic valves or electronic controller	X	X		
	3	Individual modulating room control with communication: between controllers and BACS (e.g. scheduler, room temperature set-point)	X	X	X	X*
	4	Individual modulating room control with communication and occupancy detection: between controllers and BACS; demand control/occupancy detection	X	X	X	X
3.5	0	No automatic control	X			
	1	Automatic control with fixed time program: to lower the operation time	X	X		
4.1	0	No automatic control: the system runs constantly (e.g. manual controlled switch)	X			
	1	Time control: the system runs according to a given time schedule	X	X	X	
4.2	0	On-off control: fixed air flow rate and fixed supply air temperature at the room level, room temperature set-points are set individually	X			
	1	Continuous control: either air flow rate or supply air temperature at the room level can be varied continuously; room temperature set-point are set individually	X	X		
	2	Optimized control: minimum energy demand by optimized control. Both air flow rate as well as supply air temperature at the room level are controlled dependent on heating/cooling load	X	X	X	X
6.1	0	Manual operation: mostly used only for manual shadowing, energy saving depends only on the user behaviour	X			
	1	Motorized operation with manual control: mostly used only for easiest manual (motor supported) shadowing, energy saving depends only on the user behaviour	X			
	2	Motorized operation with automatic control: automatic controlled dimming to reduce cooling energy	X	X		

EnergyPlus/DesignBuilder

Table 5.20 shows that the maximum BACS efficiency class achievable with *EnergyPlus/DesignBuilder* is class A "high-energy performance" level.

Table 5.21: Evaluation of BACS class with *EnergyPlus/DesignBuilder* software

		Function level	**D**	**C**	**B**	**A**
1.1	0	No automatic control of the room temperature	X			
	1	Central automatic control: there is only central automatic control acting either on the distribution or on the generation. Function is to be integrated in a system.	X			
	2	Individual room control: by thermostatic valves or electronic controller	X	X		
	3	Individual modulating room control with communication: between controllers and BACS (e.g. scheduler, room temperature set-point)	X	X	X	X*
	4	Individual modulating room control with communication and occupancy detection: between controllers and BACS; demand control/occupancy detection	X	X	X	X
1.5	0	No automatic control	X			
	1	Automatic control with fixed time program: to lower the operation time	X	X		
	2	Automatic control with optimum start/stop: to lower the operation time	X	X	X	
	3	Automatic control with demand evaluation	X	X	X	X
3.1	0	No automatic control of the room temperature	X			
	1	Central automatic control: there is only central automatic control acting either on the distribution or on the generation. Function is to be integrated in a system.	X			
	2	Individual room control: by thermostatic valves or electronic controller	X	X		
	3	Individual modulating room control with communication: between controllers and BACS (e.g. scheduler, room temperature set-point)	X	X	X	X*
	4	Individual modulating room control with communication and occupancy detection: between controllers and BACS; demand control/occupancy detection	X	X	X	X
3.5	0	No automatic control	X			
	1	Automatic control with fixed time program: to lower the operation time	X	X		
	2	Automatic control with optimum start/stop: to lower the operation time	X	X	X	
	3	Automatic control with demand evaluation	X	X	X	X
4.1	0	No automatic control: the system runs constantly (e.g. manual controlled switch)	X			
	1	Time control: the system runs according to a given time schedule	X	X	X	
	2	Occupancy based control: the system runs dependent on the occupancy (presence, light switch, infrared sensors etc.)	X	X	X	
	3	Demand based control: the system runs dependent on the air quality demand (measurement of CO2, VOC, etc.)	X	X	X	X
4.2	0	On-off control: fixed air flow rate and fixed supply air temperature at the room level, room temperature set-points are set individually	X			
	1	Continuous control: either air flow rate or supply air temperature at the room level can be varied continuously; room temperature set-point are set individually	X	X		
	2	Optimized control: minimum energy demand by optimized control. Both air flow rate as well as supply air temperature at the room level are controlled dependent on heating/cooling load	X	X	X	X

4.4	0	Fixed OA ratio or OA flow: the system runs according to a given OA ratio, e.g. modified manually	X	X		
	1	Staged (low/high) OA ratio or OA flow: depending on a given time schedule	X	X	X	
	2	Staged (low/high) OA ratio or OA flow: depending on the occupancy, e.g. light switch, infrared sensors, etc.	X	X	X	
	3	Variable control: the system is controlled by sensors which detect the number of people or indoor air parameters or adapted criteria (e.g. CO2, mixed gas or VOC sensors). The used parameters shall be adapted to the kind of activity in the space	X	X	X	X
6.1	0	Manual operation: mostly used only for manual shadowing, energy saving depends only on the user behaviour	X			
	1	Motorized operation with manual control: mostly used only for easiest manual (motor supported) shadowing, energy saving depends only on the user behaviour	X			
	2	Motorized operation with automatic control: automatic controlled dimming to reduce cooling energy	X	X		
	3	Combined light/blind/HVAC control: to optimize energy use for HVAC, blind and lighting for occupied and non-occupied rooms	X	X	X	X

The following subsections illustrate the results of simulating the presence of BACS functions within the models described in Section 5.2 and according to the procedures described in Chapter 4.

5.3.1 *Edilclima EC700* simulation results

The results of the simulations are obtained from the hourly dynamic calculation of the energy performance of the building, as required by standard EN ISO 52016 [18]. *Edilclima EC700* does not perform the hourly dynamic calculation by default, so one needs to set the hourly dynamic calculation mode in the *General data - Project data* data-sheet. This software considers year 2022 as reference period for the hourly dynamic calculations.

Figure 5.33 shows the hourly external temperature of the site used for the simulations made with *Edilclima EC700.*

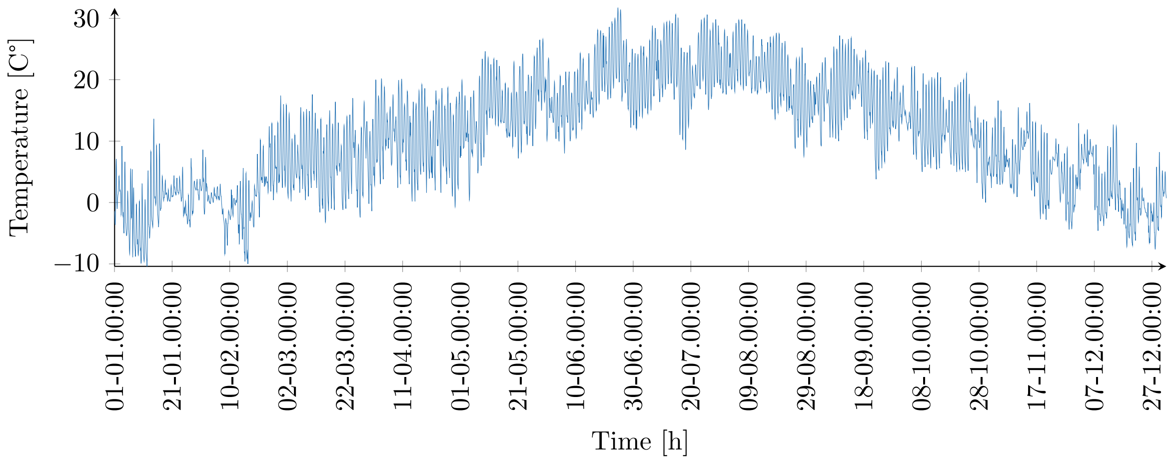

Figure 5.33: Hourly external temperature of the site with *Edilclima EC700*

The results of the simulations show that the values of the internal gains due to occupancy, appliances and lighting are the same for all BACS efficiency classes simulated (Table 5.22 and Figure 5.34). *Edilclima EC700* provides as results the total daily internal gains, which is the sum of the occupancy, appliances and lighting internal gains.

Table 5.22: Daily values of total internal gains with *Edilclima EC700*

	Total daily internal gain [kWh]
Weekdays	1234
Weekend	0
Holidays	0

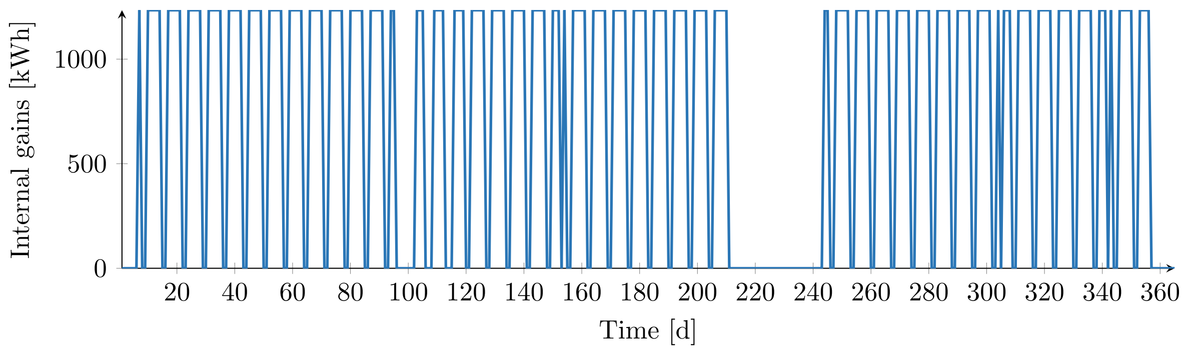

Figure 5.34: Total daily internal gains results with *Edilclima EC700*

BACS efficiency class D

Figure 5.35 shows the hourly values of mean air temperature and set-point temperatures of the whole building in the reference year, obtained from the simulation of class D.

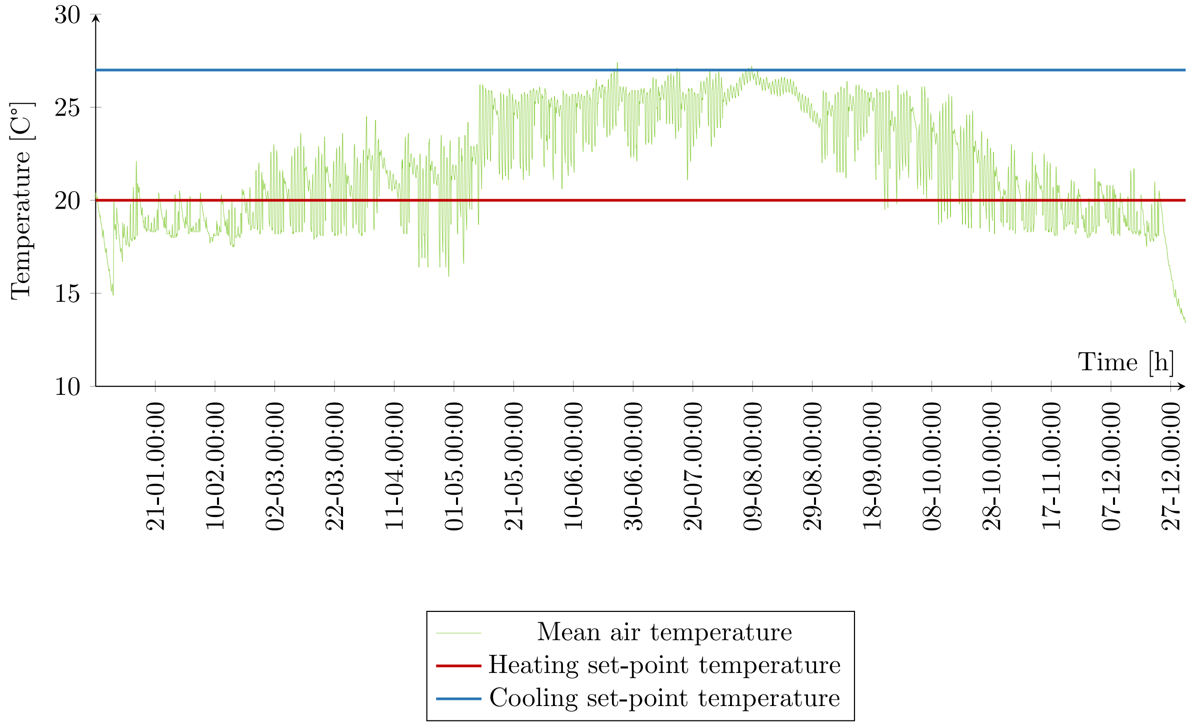

Figure 5.35: Hourly mean air temperature and set-point temperatures of class D with *Edilclima EC700*

Taking into account the presence of blind control function, the solar gains change according to the level of BACS function implemented. For class D, blinds are manually controlled by the users. Figure 5.36 shows the daily values of the solar gains in the building.

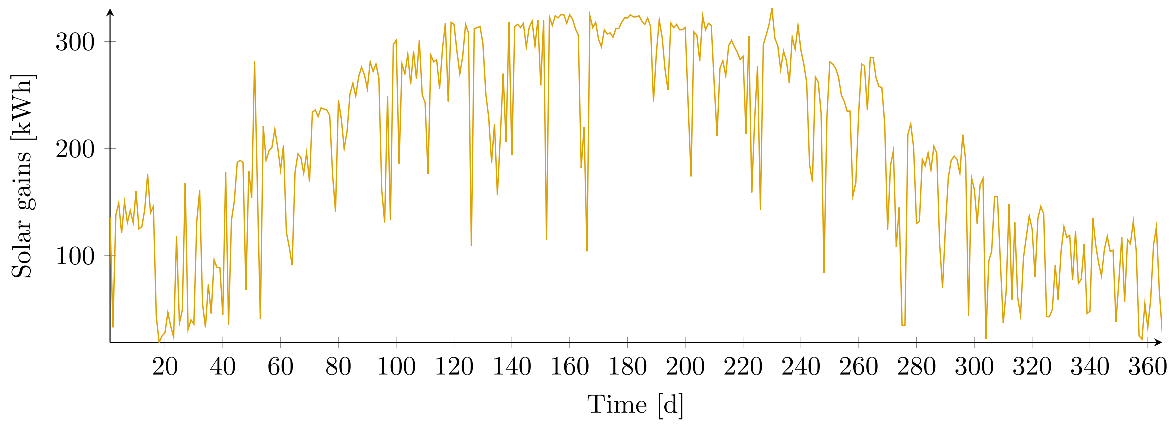

Figure 5.36: Daily solar gains of class D with *Edilclima EC700*

Tables 5.23, 5.24 and 5.25 show the results obtained from the simulation of class D of sensible energy needs for heating, sensible energy needs for cooling and fan electric energy respectively. Figures 5.37 and 5.38 illustrate graphically the monthly values summarized in Tables 5.23, 5.24 and 5.25.

Table 5.23: Monthly sensible energy needs for heating of class D with *Edilclima EC700*

SENSIBLE ENERGY NEEDS FOR HEATING [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	3335	4638	3377	4693	2811	18854
FEB	3222	4145	3294	4204	1915	16780
MAR	902	1752	957	1792	1	5404
APR	6	272	51	284	0	613
MAY	0	0	0	0	0	0
JUN	0	0	0	0	0	0
JUL	0	0	0	0	0	0
AUG	0	0	0	0	0	0
SEP	0	0	0	0	0	0
OCT	0	101	0	137	0	238
NOV	1607	2484	1673	2536	229	8529
DEC	1997	2788	2069	2861	932	10647

Table 5.24: Monthly sensible energy needs for cooling of class D with *Edilclima EC700*

SENSIBLE ENERGY NEEDS FOR COOLING [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	0	0	0	0	0	0
FEB	0	0	0	0	0	0
MAR	0	0	0	0	0	0
APR	958	0	0	0	9	967
MAY	1511	911	1420	882	3043	7767
JUN	3269	2807	3238	2774	5155	17243
JUL	4830	4264	4791	4218	6775	24878
AUG	0	0	0	0	0	0
SEP	2858	1461	2747	1380	3898	12344
OCT	296	29	271	24	673	1293
NOV	0	0	0	0	0	0
DEC	0	0	0	0	0	0

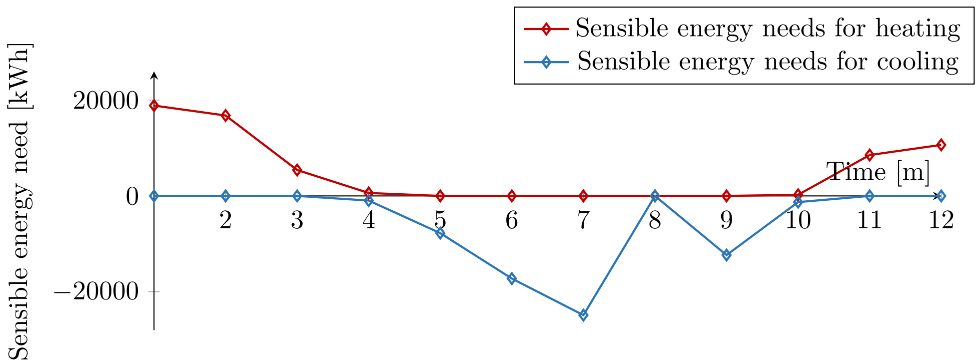

Figure 5.37: Monthly sensible energy needs for heating and cooling of class D with *Edilclima EC700*

Table 5.25: Monthly fan electric energy of class D with *Edilclima EC700*

FAN ELECTRIC ENERGY[kWh]

Month	**1P**	**2P**	**3P**	**4P**	**Common space**	**TOTAL**
JAN	4344	4344	4344	4344	3140	20516
FEB	5111	5111	5111	5111	3694	24138
MAR	5878	5878	5878	5878	4248	27760
APR	3578	3578	3578	3578	2586	16898
MAY	5622	5622	5622	5622	4063	26551
JUN	5367	5367	5367	5367	3879	25347
JUL	5367	5367	5367	5367	3879	25347
AUG	0	0	0	0	0	0
SEP	5622	5622	5622	5622	4063	26551
OCT	5367	5367	5367	5367	3879	25347
NOV	5367	5367	5367	5367	3694	25162
DEC	3833	3833	3833	3833	2770	18102

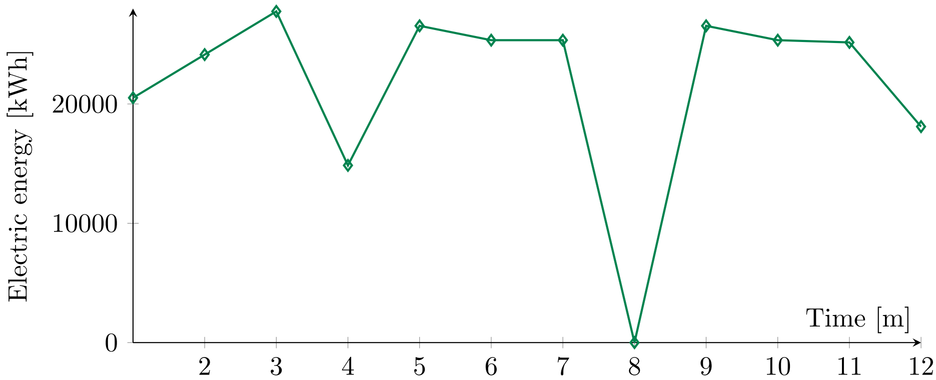

Figure 5.38: Monthly fan electric energy of class D with *Edilclima EC700*

BACS efficiency class C

In the case of BACS efficiency class C, the simulation is made twice; first with the mechanical ventilation system, and then with hybrid ventilation (meaning that, when the mechanical ventilation system is off, outside air enters the thermal zones through shutters to guarantee the minimum air changes per hour required).

Despite the difference between the two ventilation systems, the two simulations give some common results. Indeed, the simulation of class C with mechanical ventilation and with hybrid ventilation provide the same results for solar gains and fan electric energy. The values of the solar gains are the same in the two ventilation modes because the blind control is the set-up in the same way in the two simulations. For class C, blinds are automatically controlled in order to reduce cooling loads required by the building (Figure 5.39).

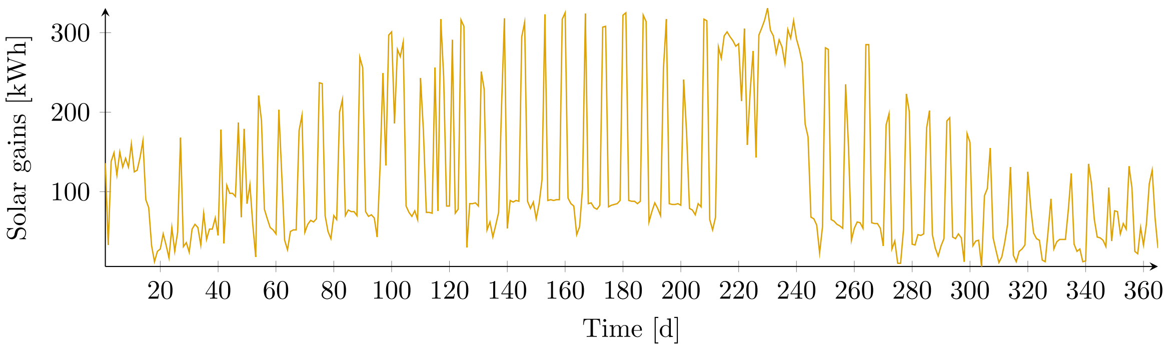

Figure 5.39: Daily solar gains of class C with *Edilclima EC700*

The values of fan electric energy are the same because in both simulations of class C, the mechanical ventilation systems work for the same period. Indeed, both ventilation modes have mechanical ventilation systems that operate according to the same hourly profile. Table 5.26 and Figure 5.40 show the monthly results obtained for the fan electric energy.

Table 5.26: Monthly fan electric energy of class C with *Edilclima EC700*

FAN ELECTRIC ENERGY [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	3439	3439	3439	3439	2486	16242
FEB	4046	4046	4046	4046	2924	19108
MAR	4653	4653	4653	4653	3363	21975
APR	2832	2832	2832	2832	2047	13375
MAY	4451	4451	4451	4451	3217	21021
JUN	4249	4249	4249	4249	3071	20067
JUL	4249	4249	4249	4249	3071	20067
AUG	0	0	0	0	0	0
SEP	4451	4451	4451	4451	3217	21021
OCT	4249	4249	4249	4249	3071	20067
NOV	4249	4249	4249	4249	2924	19920
DEC	3035	3035	3035	3035	2193	14333

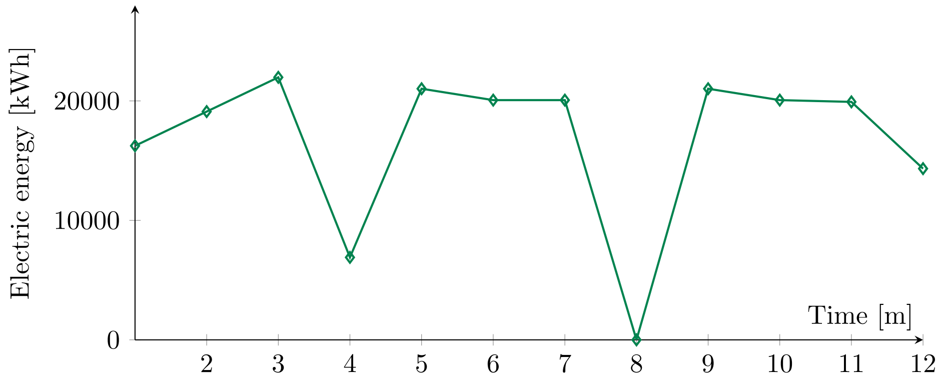

Figure 5.40: Monthly fan electric energy of class C with *Edilclima EC700*

The following subsections illustrate the different results of the two simulations of class C.

Mechanical ventilation

Figure 5.41 shows the hourly values of mean air temperature and set-point temperatures of the whole building in the reference year, obtained from the simulation of class C with mechanical ventilation systems.

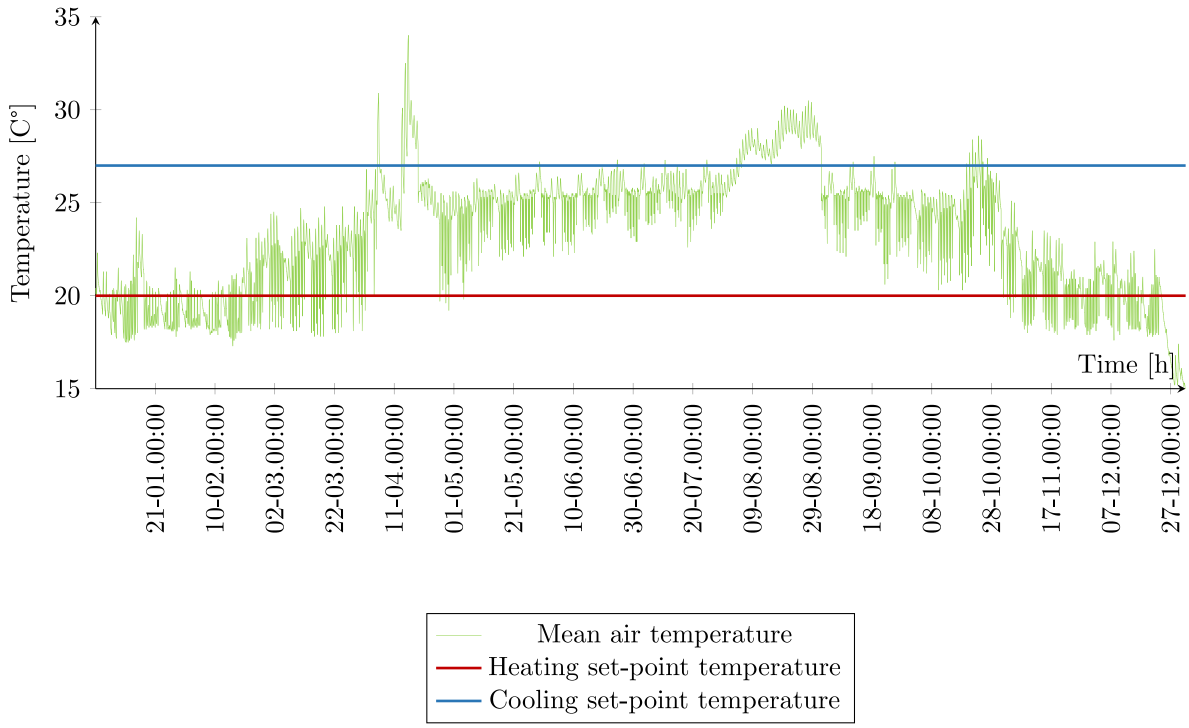

Figure 5.41: Hourly mean air temperature and set-point temperatures of class C with mechanical ventilation systems with *Edilclima EC700*

Tables 5.27 and 5.28 show the results obtained from the simulation of class C with mechanical ventilation systems of sensible energy needs for heating and sensible energy needs for cooling respectively. Figures 5.42 illustrates graphically the monthly values summarized in Tables 5.27 and 5.28.

Table 5.27: Monthly sensible energy needs for heating of class C with mechanical ventilation systems with *Edilclima EC700*

SENSIBLE ENERGY NEEDS FOR HEATING [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	2215	3496	2257	3547	1952	13467
FEB	2101	2937	2163	2991	1210	11402
MAR	120	684	146	716	0	1666
APR	0	77	0	84	0	161
MAY	0	0	0	0	0	0
JUN	0	0	0	0	0	0
JUL	0	0	0	0	0	0
AUG	0	0	0	0	0	0
SEP	0	0	0	0	0	0
OCT	0	10	0	18	0	28
NOV	602	1371	647	1424	10	4054
DEC	1156	1926	1224	1995	408	6709

Table 5.28: Monthly sensible energy needs for cooling of class C with mechanical ventilation systems with *Edilclima EC700*

SENSIBLE ENERGY NEEDS FOR COOLING [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	0	0	0	0	0	0
FEB	0	0	0	0	0	0
MAR	0	0	0	0	0	0
APR	1039	0	57	0	256	1352
MAY	2175	1543	2100	1510	3846	11174
JUN	3794	3387	3764	3354	5727	20026
JUL	5277	4775	5238	4728	7281	27299
AUG	0	0	0	0	0	0
SEP	3390	1991	3278	1905	4491	15055
OCT	558	173	528	152	970	2381
NOV	0	0	0	0	0	0
DEC	0	0	0	0	0	0

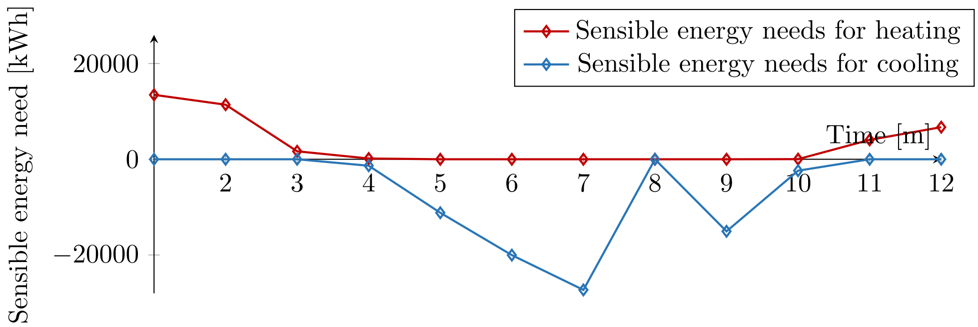

Figure 5.42: Monthly sensible energy needs for heating and cooling of class C with mechanical ventilation systems obtained with *Edilclima EC700*

Hybrid ventilation

Figure 5.43 shows the hourly values of mean air temperature and set-point temperatures of the whole building in the reference year, obtained from the simulation of class C with hybrid ventilation systems.

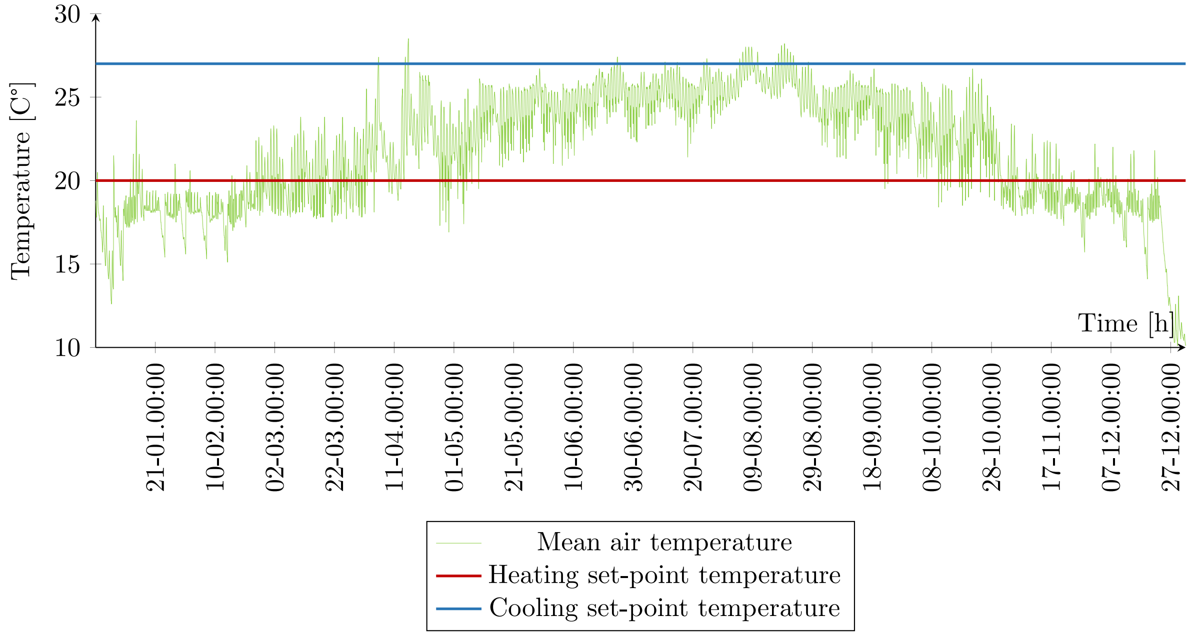

Figure 5.43: Hourly mean air temperature and set-point temperatures of class C with hybrid ventilation systems with *Edilclima EC700*

Tables 5.29 and 5.30 show the results obtained from the simulation of class C with hybrid ventilation systems of sensible energy needs for heating and sensible energy needs for cooling respectively. Figure 5.42 illustrates graphically the monthly values summarized in Tables 5.29 and 5.30.

Table 5.29: Monthly sensible energy needs for heating of class C with hybrid ventilation systems with *Edilclima EC700*

SENSIBLE ENERGY NEEDS FOR HEATING [kWh]

Month	**1P**	**2P**	**3P**	**4P**	**Common space**	**TOTAL**
JAN	4204	5472	4246	5522	6248	25692
FEB	3735	4648	3805	4706	5230	22124
MAR	1162	1932	1213	1967	1728	8002
APR	36	394	195	403	345	1373
MAY	0	0	0	0	0	0
JUN	0	0	0	0	0	0
JUL	0	0	0	0	0	0
AUG	0	0	0	0	0	0
SEP	0	0	0	0	0	0
OCT	37	225	49	269	37	617
NOV	2082	2895	2138	2941	2777	12833
DEC	2443	3239	2514	3310	3489	14995

Table 5.30: Monthly sensible energy needs for cooling of class C with hybrid ventilation systems with *Edilclima EC700*

SENSIBLE ENERGY NEEDS FOR COOLING [kWh]

Month	**1P**	**2P**	**3P**	**4P**	**Common space**	**TOTAL**
JAN	0	0	0	0	0	0
FEB	0	0	0	0	0	0
MAR	0	0	0	0	0	0
APR	274	0	0	0	0	274
MAY	1276	803	1208	777	1098	5162
JUN	3175	2781	3145	2750	3944	15795
JUL	4874	4379	4835	4334	6196	24618
AUG	0	0	0	0	0	0
SEP	2283	1162	2190	1104	1848	8587
OCT	193	5	171	2	4	375
NOV	0	0	0	0	0	0
DEC	0	0	0	0	0	0

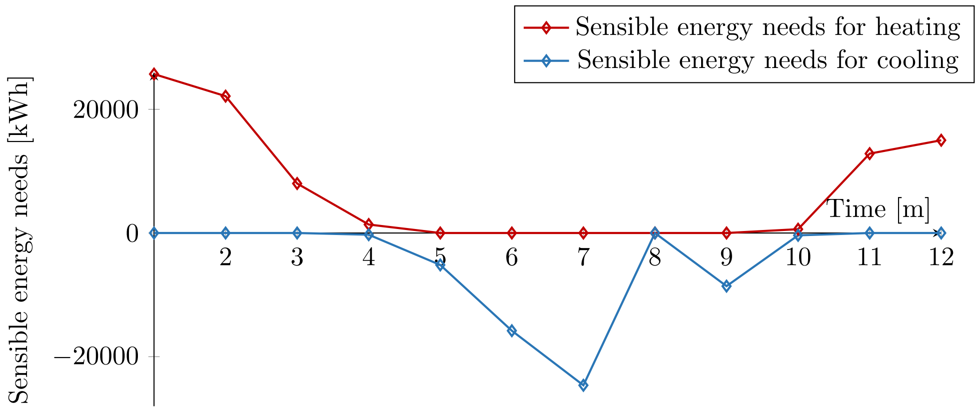

Figure 5.44: Monthly sensible energy needs for heating and cooling of class C with hybrid ventilation systems with *Edilclima EC700*

5.3.2 Comparison of the results of *Edilclima EC700* simulations

Heating

Table 5.31 and Figure 5.45 show the results of sensible energy needs for heating with *Edilclima EC700*. On one hand, it is possible to see that in the case of class C with mechanical ventilation systems, the sensible energy needs for heating required by the building decrease with respect to the values obtained in class D. On the other hand, in the case of class C with hybrid ventilation systems, the sensible energy needs for heating are higher than the results obtained in class D. This is due to the introduction of cold outside air into the thermal zones through the ventilation dampers that are opened when the mechanical ventilation system is turned off. This behavior causes an increment in the sensible energy needs required for heating.

In the end, it is possible to conclude that in the heating season the hybrid ventilation, as implemented by *Edilclima EC700*, does not provide any benefit in the heating sensible energy needs reduction, but it causes an increase of the energy needs required to heat the thermal zones, since the hybrid ventilation is modeled in order to introduce outside air in the environment when the mechanical ventilation systems is turned off.

Table 5.31: BACS efficiency class comparison of monthly sensible energy needs for heating with *Edilclima EC700*

SENSIBLE ENERGY NEEDS FOR HEATING [kWh]

Month	**Class D**	**Class C (mechanical)**	**Class C (hybrid)**
JAN	18854	13467	25692
FEB	16780	11402	22124
MAR	5404	1666	8002
APR	613	161	1373
MAY	0	0	0
JUN	0	0	0
JUL	0	0	0
AUG	0	0	0
SEP	0	0	0
OCT	238	28	617
NOV	8529	4054	12833
DEC	10647	6709	14995
TOTAL	**61065**	**37487**	**85636**

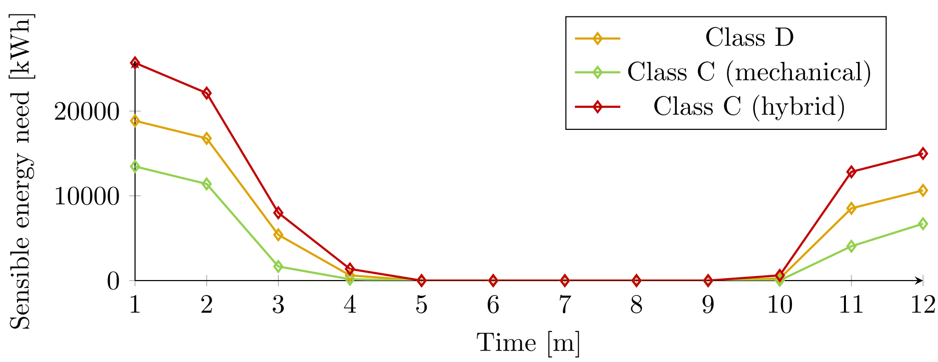

Figure 5.45: BACS efficiency class comparison of monthly sensible energy needs for heating with *Edilclima EC700*

The results obtained from the simulations of class D and class C with mechanical ventilation systems are compared with the one obtained from the application of the factor-based method of EN ISO 52120 [19]. The results obtained from class C are taken as reference values as required by the standard.

In Table 5.32 it is possible to observe that for the case study, the application of BACS systems produces a higher reduction of the sensible energy needs for heating with respect to the results obtained with the factor-based method of the standard. Table 5.55 reports the values of:

- the heating BACS efficiency factor ($f_{BAC,H}$),
- the total heating sensible energy needs of the considered BACS efficiency class with the factor-based method ($Q_{H,tot,BAC}$),
- the factor to be used to obtain the results of the simulations ($f_{EC,H}$)
- the total heating sensible energy needs with *Edilclima EC700* ($Q_{H,tot,EC}$).

Table 5.32: Comparison of heating sensible energy needs results obtained with the factor-based method [19] and the heating sensible energy needs results with *Edilclima EC700*

	Class D	**Class C**
FACTOR-BASED METHOD		
$f_{BAC,H}$ [-]	1,20	1
$Q_{H,tot,BAC}$ [kWh]	44984	37487
SIMULATION RESULTS		
$f_{EC,H}$ [-]	1,63	1
$Q_{H,tot,EC}$ [kWh]	61065	37487

Cooling

Table 5.33 and Figure 5.46 show the results of the sensible energy needs for cooling obtained with *Edilclima EC700*. On one hand, it is possible to see that in the case of class C with the mechanical ventilation systems, the cooling sensible energy needs required by the building increase with respect to the values obtained in class D. Indeed, the mechanical ventilation, as implemented by*Edilclima EC700*, does not take advantages from the introduction of outside air when the systems are turned off. Therefore, when the rooftop systems are turned on, the energy required to reach the comfort temperature is higher. This not happen with class D since the EN ISO 52120 says the systems should run twenty-four hours a day.

On the other hand, in the case of class C with hybrid ventilation system, the sensible energy needs for cooling are lower than the results obtained in class D. This is due to the introduction of outside air into the thermal zones when the mechanical ventilation systems are turned off, i.e. during the night. Since during night hours the external air temperature is usually lower than the ambient temperature, the introduction of external air allows to reduce the cooling sensible energy needs required when the rooftop systems are turned on.

In the end, it is possible to conclude that the hybrid ventilation, as implemented by *Edilclima EC700* in the cooling season provides a benefit in the reduction of the sensible energy needs for cooling.

Table 5.33: BACS efficiency class comparison of monthly sensible energy needs for cooling with *Edilclima EC700*

SENSIBLE ENERGY NEEDS FOR COOLING [kWh]			
Month	**Class D**	**Class C (mechanical)**	**Class C (hybrid)**
JAN	0	0	0
FEB	0	0	0
MAR	0	0	0
APR	967	1352	274
MAY	7767	11174	5162
JUN	17243	20026	15795
JUL	24878	27299	24618
AUG	0	0	0
SEP	12344	15055	8587
OCT	1293	2381	375
NOV	0	0	0
DEC	0	0	0
TOTAL	**64492**	**77287**	**54811**

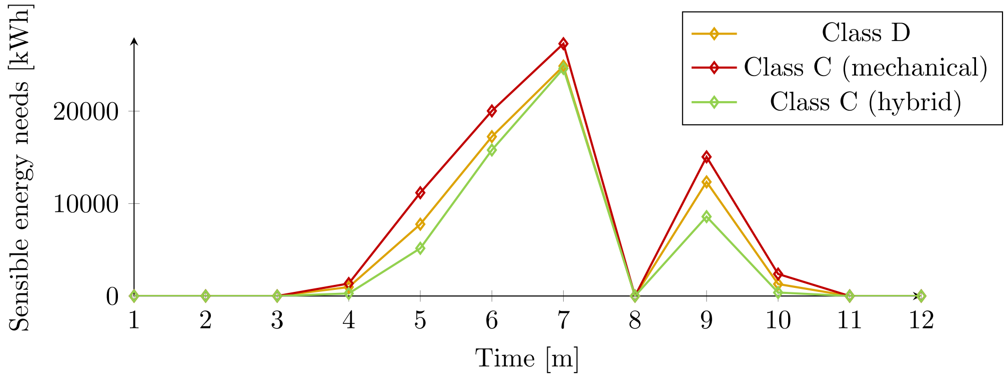

Figure 5.46: BACS efficiency class comparison of monthly sensible energy needs for cooling with *Edilclima EC700*

In the case of cooling, the factor-based method of EN ISO 52120 does not provide any cooling BACS efficiency factor ($f_{BAC,C}$) for educational buildings. Therefore, it is not possible to make the same comparison as for the heating sensible energy needs. Table 5.34 shows $f_{EC,C}$, which is the factor to be used to obtain the results of the simulations, and $Q_{C,tot,EC}$, which is the total cooling sensible energy needs obtained with the software. In this case, the results of class C with hybrid ventilation system is taken into account to perform the calculation.

Table 5.34: Cooling sensible energy needs factors with *Edilclima EC700*

	Class D	**Class C**
SIMULATION RESULTS		
$f_{EC,C}$ [-]	1.18	1
$Q_{C,tot,EC}$ [kWh]	64492	54811

Ventilation

Table 5.35 and Figure 5.47 show that the electric energy required for the mechanical ventilation obtained from the simulation of class C is lower than the one obtained from the simulation of class D. As expected, the electric energy decreases according to BACS efficiency class implemented.

Table 5.35: BACS efficiency class comparison of monthly fan electric energy with *Edilclima EC700*

FAN ELECTRIC ENERGY [kWh]		
Month	**Class D**	**Class C**
JAN	20516	16242
FEB	24138	19108
MAR	27760	21975
APR	16898	13375
MAY	26551	21021
JUN	25347	20067
JUL	25347	20067
AUG	0	0
SEP	26551	21021
OCT	25347	20067
NOV	25162	19920
DEC	18102	14333
TOTAL	**261719**	**207196**

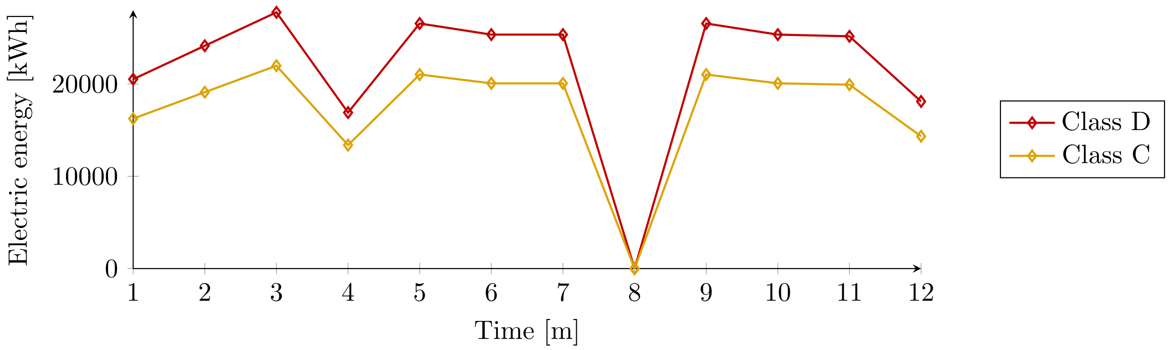

Figure 5.47: BACS efficiency class comparison of monthly fan electric energy with *Edilclima EC700*

Table 5.36 compares the results of factor-based method of EN ISO 52120 [19] for electric energy with the results obtained from the simulations with *Edilclima EC700*. As the standard requires, the results of class C are taken as reference values. It is possible to notice that the values obtained with the simplified method and the values obtained with the software are different. Indeed, the electric energy saving in the case of the simulation with *Edilclima EC700* is higher than the results obtained with the factor-based method of the standard. Table 5.36 shows the following results:

- the electric energy BACS efficiency factor ($f_{BAC,el}$),
- the total supply fan electric energy of the considered BACS efficiency class obtained with the factor-based method ($W_{V,BAC}$),

- the factor to be used to obtain the results of the simulations ($f_{EC,el}$),
- the total fan electric energy with *Edilclima EC700* ($W_{V,EC}$).

Table 5.36: Comparison of fan electric energy results obtained with the factor-based method [19] and the fan electric energy results with *Edilclima EC700*

	Class D	**Class C**
FACTOR-BASED METHOD		
$f_{BAC,el}$ [-]	1.12	1
$W_{V,BAC}$ [kWh]	232060	207196
SIMULATION RESULTS		
$f_{EC,el}$ [-]	1.26	1.00
$W_{V,EC}$ [kWh]	261719	207196

Temperature

Figures 5.48, 5.49 and 5.50 show the mean air temperature of the whole building. It is possible to observe that during the heating season, the temperature is kept around the set-point temperature of 20°C. Instead, in the cooling season during occupied period, the mean air temperature is slightly lower than the set-point temperature of 27 °C.

Figures 5.49 and 5.50 show that the hybrid ventilation systems affect the building temperature more than the mechanical ventilation systems. Indeed, with hybrid ventilation systems, the temperature difference between day and night is higher than with mechanical ventilation systems. This is due to the introduction of outside air into the environment when the mechanical ventilation systems are turned off (during night, weekend and holidays).

It is also possible to notice that the simulations made with *Edilclima EC700* consider the system on the day before of the starting day of the simulation. Therefore, the results of the first week of the considered year do not reflect the real conditions of the building.

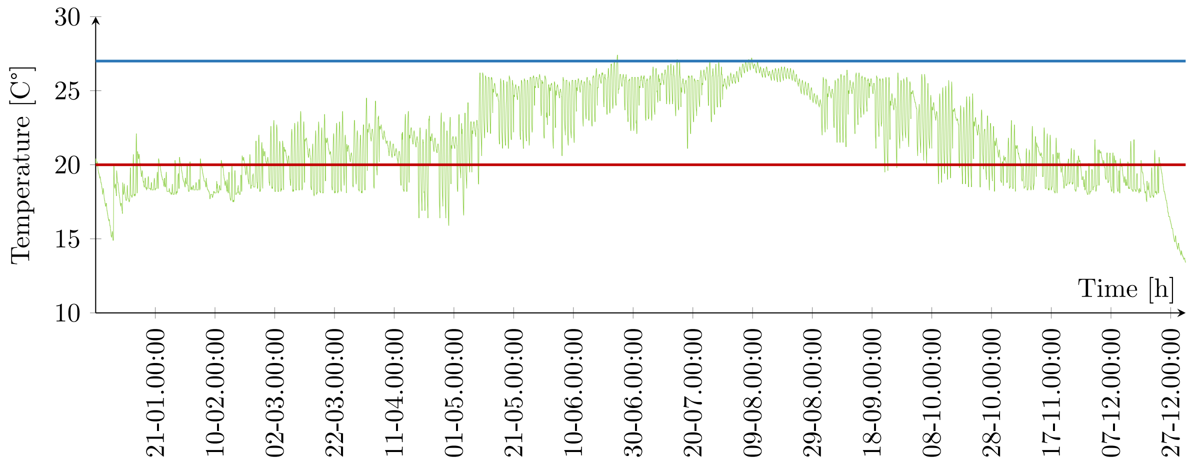

Figure 5.48: Hourly mean air temperature and set-point temperatures of class D with *Edilclima EC700*

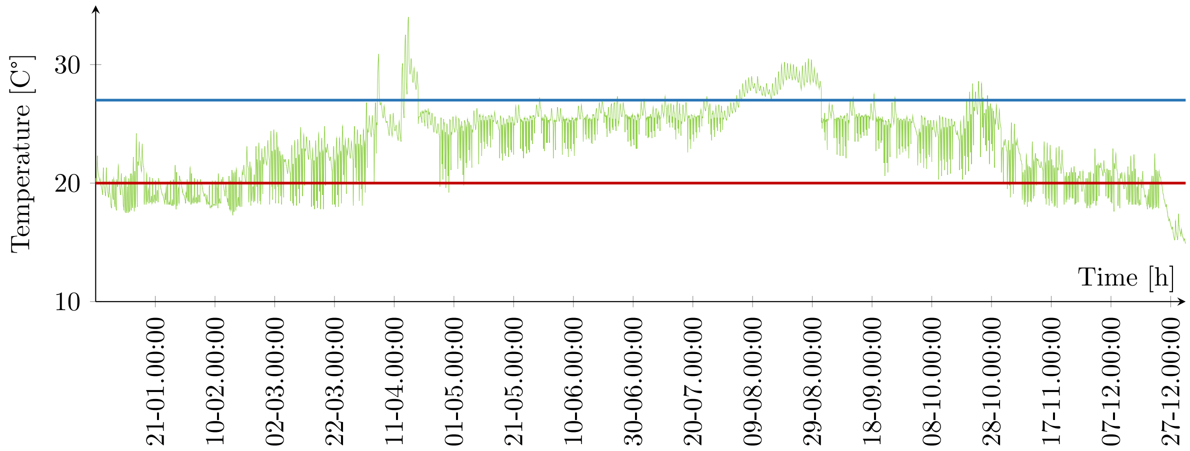

Figure 5.49: Hourly mean air temperature and set-point temperatures of class C with mechanical ventilation systems with *Edilclima EC700*

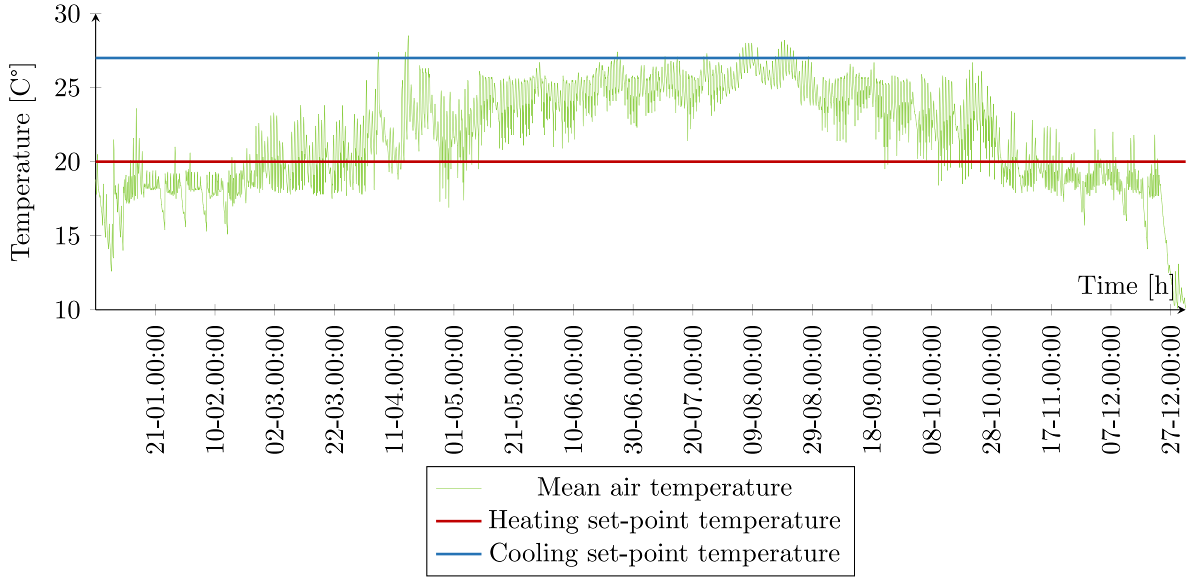

Figure 5.50: Hourly mean air temperature and set-point temperatures of class C with hybrid ventilation systems with *Edilclima EC700*

5.3.3 *EnergyPlus/DesignBuilder* simulation results

The results of the simulations are obtained from the hourly dynamic calculation of the energy performance of the building, as required by EN ISO 52016 standard [18]. *EnergyPlus/DesignBuilder* performs this calculation with the hourly dynamic simulations. This software considers year 2002 as reference period.

Figure 5.51 illustrates the hourly external temperature of the site used for the simulations with *EnergyPlus/DesignBuilder*.

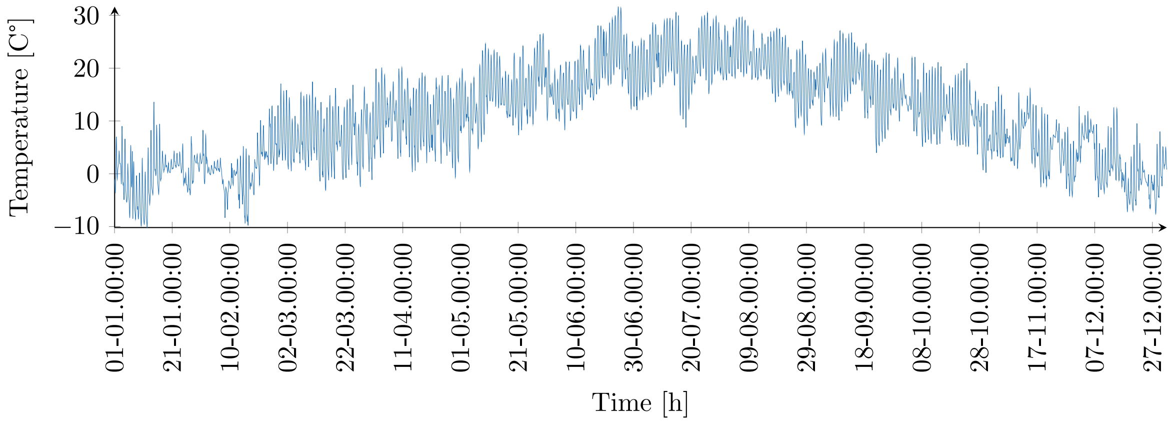

Figure 5.51: Hourly external temperature of the site with *EnergyPlus/DesignBuilder*

The results of the simulations show that the daily internal gains due to occupancy, appliances and lighting are equal in each BACS efficiency classes simulated (Table 5.37 and Figure 5.52).

Table 5.37: Daily internal gains with *EnergyPlus/DesignBuilder*

	Daily occupancy internal gain [kWh]	**Daily appliances internal gain [kWh]**	**Daily lighting internal gains [kWh]**
Weekdays	735	10	485
Weekend	0	0	0
Holidays	0	0	0

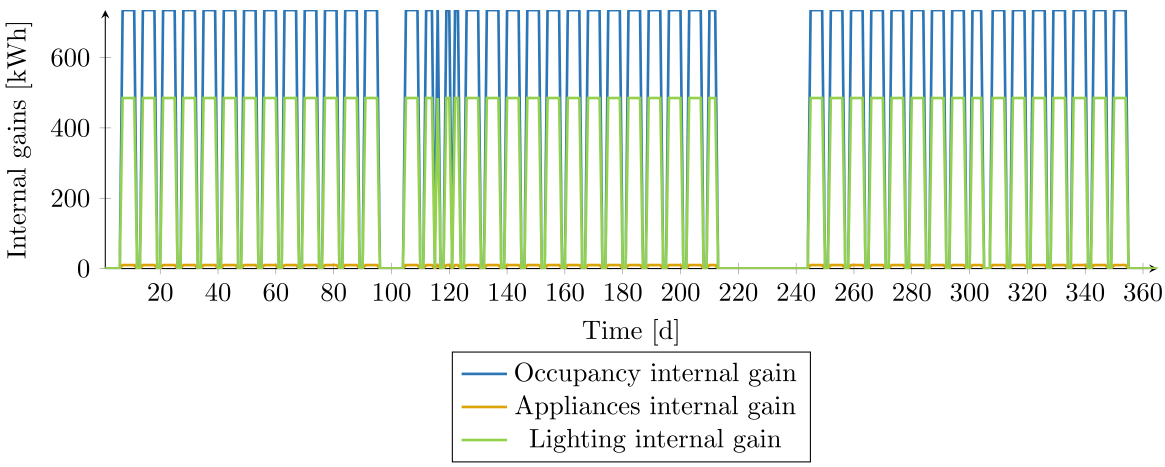

Figure 5.52: Daily internal gains results with *EnergyPlus/DesignBuilder*

BACS efficiency class D

Figure 5.53 shows the hourly values of mean air temperature and set-point temperatures of the whole building in the reference year, obtained from the simulation of class D.

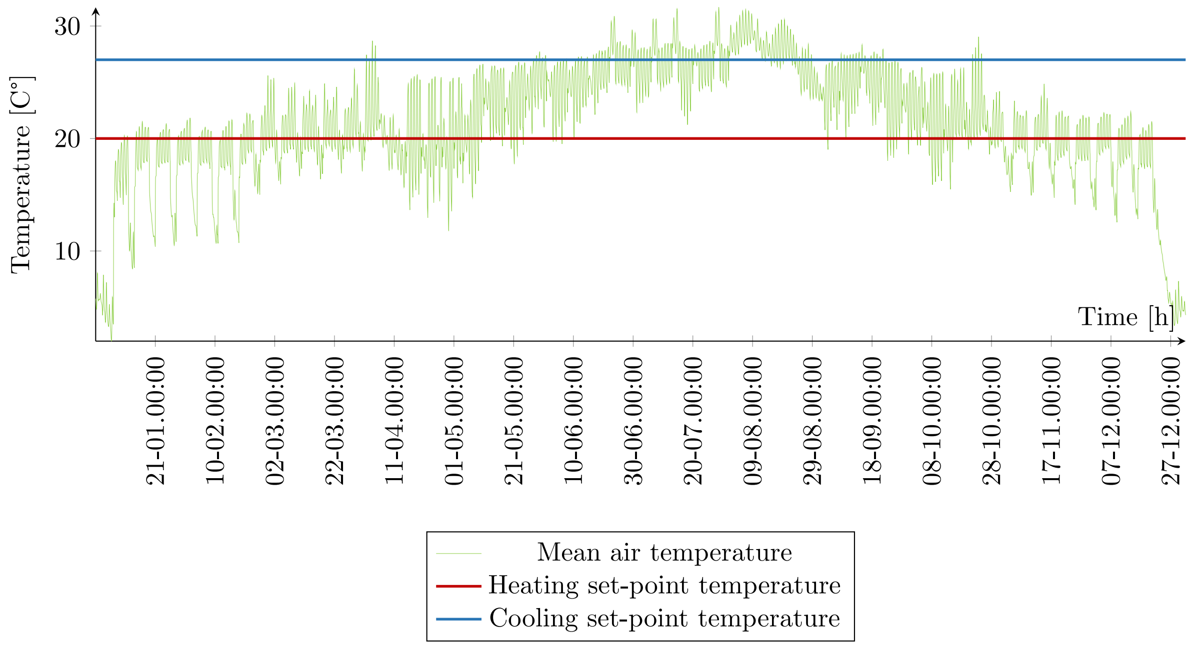

Figure 5.53: Hourly mean air temperature and set-point temperatures of class D with *EnergyPlus/Design Builder*

Taking into account the presence of blind control function, the solar gains change according to the level of BACS function implemented. For class D, blinds are manually controlled by the users. Figure 5.54 shows the daily values of the solar gains in the building.

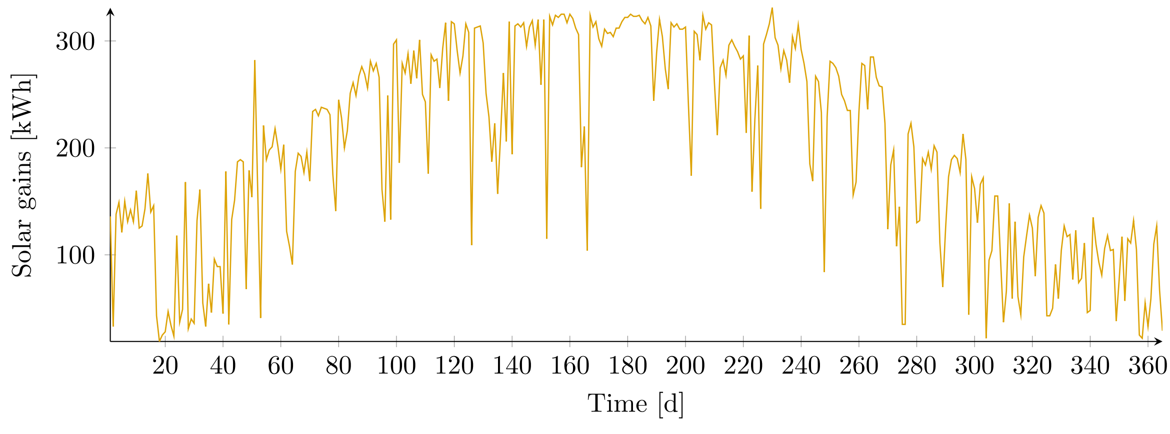

Figure 5.54: Daily solar gains of class D with *EnergyPlus/DesignBuilder*

Tables 5.38, 5.39, 5.40 and 5.41 show the results of the simulation of class D of sensible energy needs for heating, sensible energy needs for cooling, supply fan electric energy and extract fan electric energy respectively. Figures 5.55 and 5.56 illustrate graphically the monthly values summarized in Tables 5.38, 5.39, 5.40 and 5.41.

Table 5.38: Monthly sensible energy needs for heating of class D with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR HEATING [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	1998	2400	2008	2411	3143	11961
FEB	1281	1510	1287	1516	2332	7927
MAR	435	667	441	673	892	3109
APR	52	107	53	108	186	506
MAY	0	0	0	0	18	18
JUN	0	0	0	0	0	0
JUL	0	0	0	0	0	0
AUG	0	0	0	0	0	0
SEP	0	0	0	0	0	0
OCT	47	137	49	140	176	550
NOV	740	882	744	887	1318	4570
DEC	873	989	877	993	1493	5225

Table 5.39: Monthly sensible energy needs for cooling of class D with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR COOLING[3] [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	270	172	267	170	2	880
FEB	710	496	705	491	73	2475
MAR	1784	1496	1777	1490	523	7071
APR	2173	1814	2165	1806	1095	9053
MAY	3856	3502	3847	3494	2203	16903
JUN	4354	4067	4346	4059	2996	19820
JUL	5763	5316	5750	5304	4269	26402
AUG	0	0	0	0	0	0
SEP	4102	3481	4088	3468	2365	17504
OCT	2939	2538	2927	2528	1460	12392
NOV	1223	1057	1219	1052	263	4815
DEC	597	474	593	471	74	2208

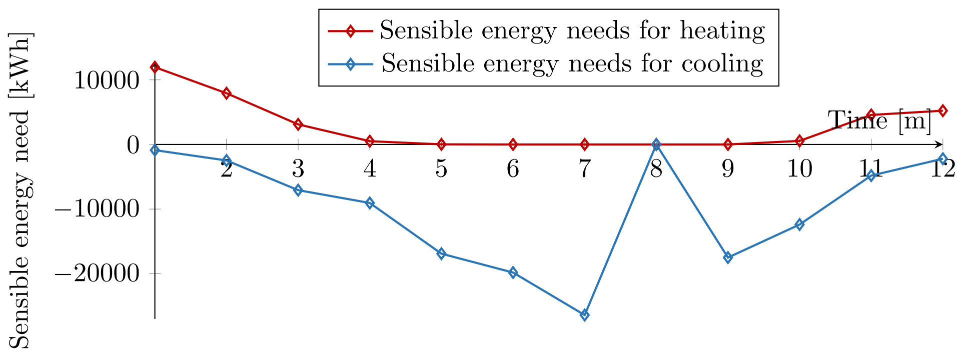

Figure 5.55: Monthly sensible energy needs for heating and cooling of class D with *EnergyPlus/DesignBuilder*

[3]Subsection 5.3.4 explains the presence of sensible energy needs for cooling in the heating months.

Table 5.40: Monthly supply fan electric energy of class D with *EnergyPlus/DesignBuilder*

SUPPLY FAN ELECTRIC ENERGY [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	570	570	570	570	231	2511
FEB	600	600	600	600	243	2643
MAR	630	630	630	630	255	2775
APR	480	480	480	480	194	2114
MAY	660	660	660	660	267	2907
JUN	600	600	600	600	243	2643
JUL	690	690	690	690	279	3039
AUG	0	0	0	0	0	0
SEP	630	630	630	630	255	2775
OCT	690	690	690	690	279	3039
NOV	600	600	600	600	243	2643
DEC	450	450	450	450	182	1982

Table 5.41: Monthly extract fan electric energy of class D with *EnergyPlus/DesignBuilder*

EXTRACT FAN ELECTRIC ENERGY [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	407	407	407	407	185	1813
FEB	429	429	429	429	194	1909
MAR	450	450	450	450	204	2004
APR	343	343	343	343	155	1527
MAY	471	471	471	471	214	2099
JUN	429	429	429	429	194	1909
JUL	493	493	493	493	223	2195
AUG	0	0	0	0	0	0
SEP	450	450	450	450	204	2004
OCT	493	493	493	493	223	2195
NOV	429	429	429	429	194	1909
DEC	321	321	321	321	146	1431

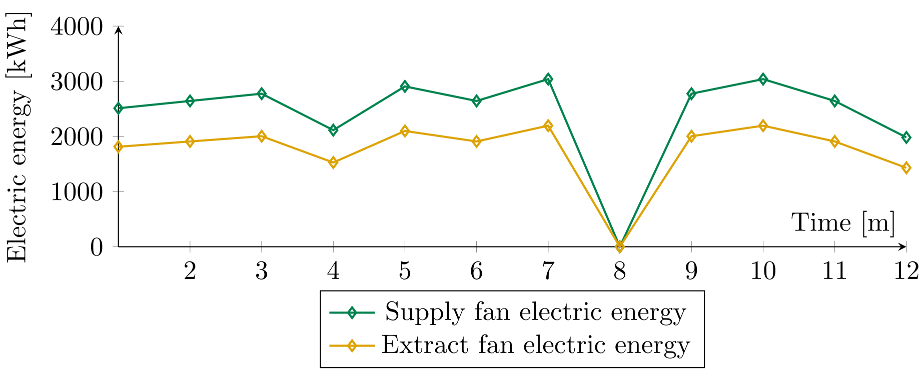

Figure 5.56: Monthly supply and extract fans electric energy of class D with *EnergyPlus/DesignBuilder*

BACS efficiency class C

Figure 5.57 shows the hourly values of mean air temperature and set-point temperatures of the whole building in the reference year, obtained from the simulation of class C.

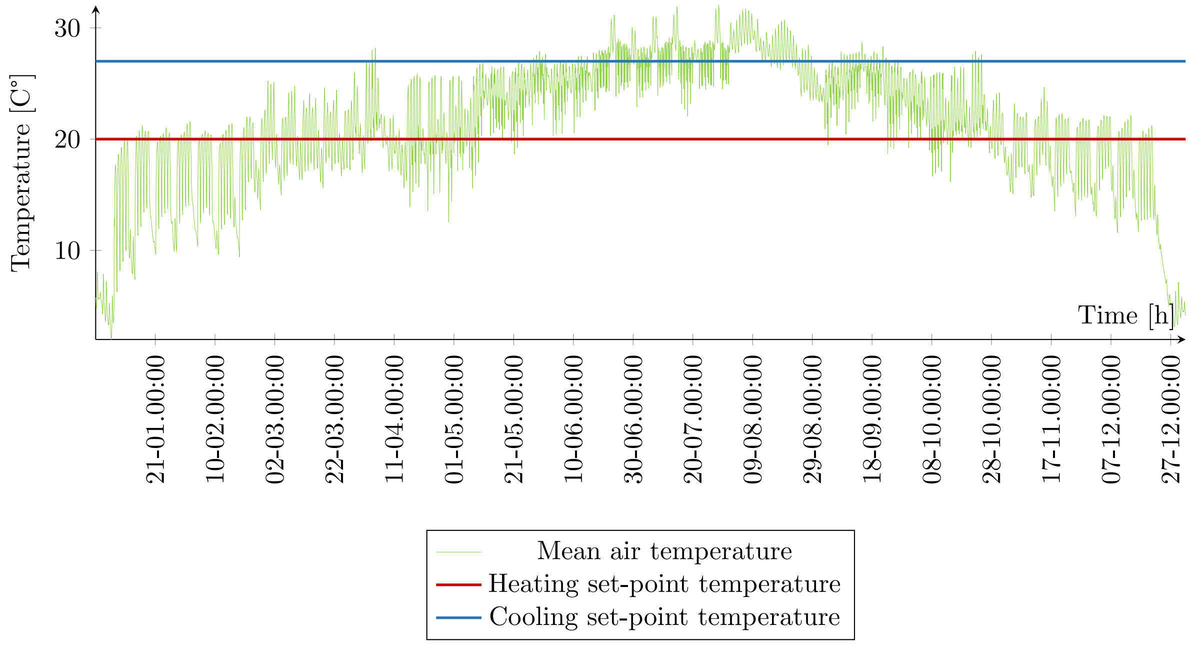

Figure 5.57: Hourly mean air temperature and set-point temperatures of class C with *EnergyPlus/Design Builder*

Taking into account the presence of blind control, the solar gains change according to the level of the blind control function implemented. Figure 5.58 shows the solar gains obtained in class C when blinds are automatically controlled in order to reduce the cooling loads required by the building.

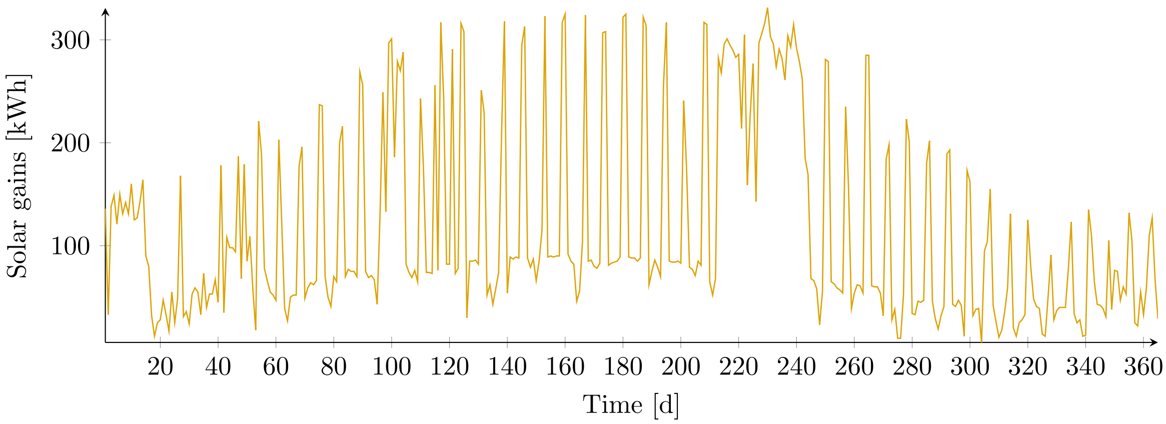

Figure 5.58: Daily solar gains of class C with *EnergyPlus/DesignBuilder*

Tables 5.42, 5.43, 5.44 and 5.45 show the results of the simulation of class C of sensible energy needs for heating, sensible energy needs for cooling, supply fan electric energy and extract fan electric energy respectively. Figures 5.59 and 5.60 illustrate graphically the monthly values summarized in Tables 5.42, 5.43, 5.44 and 5.45.

Table 5.42: Monthly sensible energy needs for heating of class C with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR HEATING [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	1443	1828	1452	1839	2379	8941
FEB	914	1061	919	1067	1705	5667
MAR	334	423	338	427	593	2116
APR	40	64	40	65	151	359
MAY	0	0	0	0	16	16
JUN	0	0	0	0	0	0
JUL	0	0	0	0	0	0
AUG	0	0	0	0	0	0
SEP	0	0	0	0	0	0
OCT	38	74	40	75	101	327
NOV	477	537	480	540	828	2861
DEC	584	660	587	663	1069	3563

Table 5.43: Monthly sensible energy needs for cooling of class C with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR COOLING[4] [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	149	75	147	74	0	445
FEB	512	337	507	332	45	1733
MAR	1545	1327	1538	1320	407	6135
APR	1722	1499	1715	1492	643	7071
MAY	3319	3101	3311	3094	1490	14315
JUN	3823	3661	3816	3654	2308	17263
JUL	5078	4821	5067	4811	3490	23268
AUG	0	0	0	0	0	0
SEP	3570	3168	3557	3157	1699	15150
OCT	2633	2376	2623	2367	1027	11025
NOV	1067	923	1062	918	210	4179
DEC	456	356	453	353	50	1669

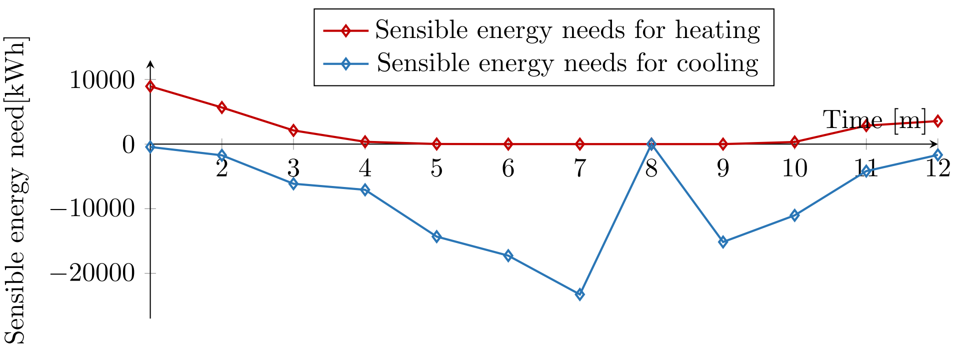

Figure 5.59: Monthly sensible energy needs for heating and cooling of class C with *EnergyPlus/DesignBuilder*

[4]Subsection 5.3.4 explains the presence of sensible energy needs for cooling in the heating months.

Table 5.44: Monthly supply fan electric energy of class C with *EnergyPlus/DesignBuilder*

SUPPLY FAN ELECTRIC ENERGY [kWh]

Month	**1P**	**2P**	**3P**	**4P**	**Common space**	**TOTAL**
JAN	447	447	447	447	122	1909
FEB	470	470	470	470	129	2009
MAR	494	494	494	494	135	2110
APR	376	376	376	376	103	1607
MAY	517	517	517	517	144	2213
JUN	470	470	470	470	155	2035
JUL	541	541	541	541	206	2368
AUG	0	0	0	0	0	0
SEP	494	494	494	494	137	2112
OCT	541	541	541	541	148	2310
NOV	470	470	470	470	129	2009
DEC	353	353	353	353	96	1507

Table 5.45: Monthly extract fan electric energy of class C with *EnergyPlus/DesignBuilder*

EXTRACT FAN ELECTRIC ENERGY [kWh]

Month	**1P**	**2P**	**3P**	**4P**	**Common space**	**TOTAL**
JAN	319	319	319	319	98	1374
FEB	336	336	336	336	103	1446
MAR	353	353	353	353	108	1518
APR	269	269	269	269	82	1157
MAY	369	369	369	369	115	1593
JUN	336	336	336	336	124	1467
JUL	386	386	386	386	165	1709
AUG	0	0	0	0	0	0
SEP	353	353	353	353	110	1520
OCT	386	386	386	386	118	1663
NOV	336	336	336	336	103	1446
DEC	252	252	252	252	77	1085

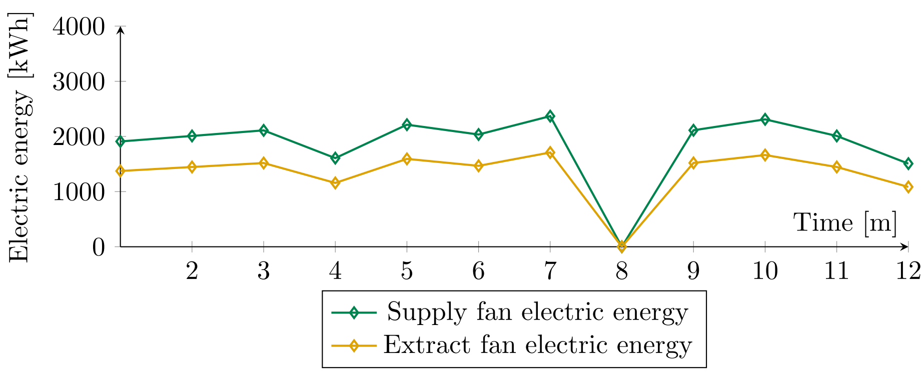

Figure 5.60: Monthly supply and extract fans electric energy of class C with *EnergyPlus/DesignBuilder*

BACS efficiency class B

Figure 5.61 shows the hourly values of mean air temperature and set-point temperatures of the whole building in the reference year, obtained from the simulation of class B.

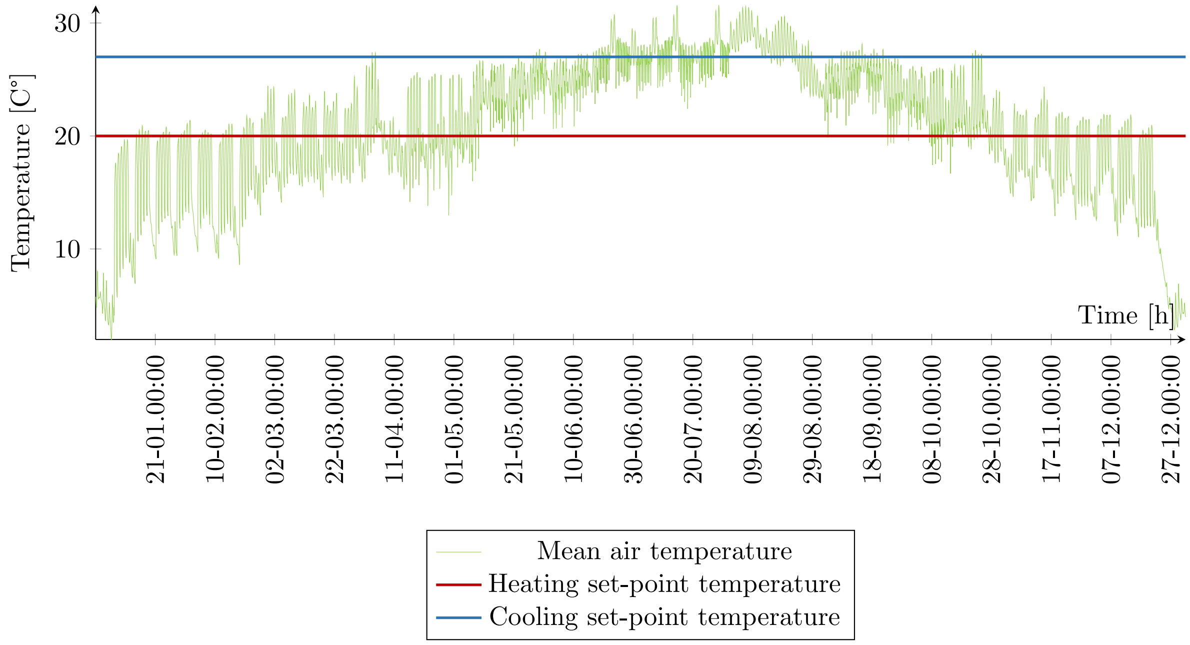

Figure 5.61: Hourly mean air temperature and set-point temperatures of class B with *EnergyPlus/Design Builder*

Taking into account the presence of blind control, the solar gains change according to the level of the blind control function implemented. Figure 5.62 shows the solar gains obtained in class B when blinds are automatically controlled to reduce cooling loads and to avoid glare during the occupied period.

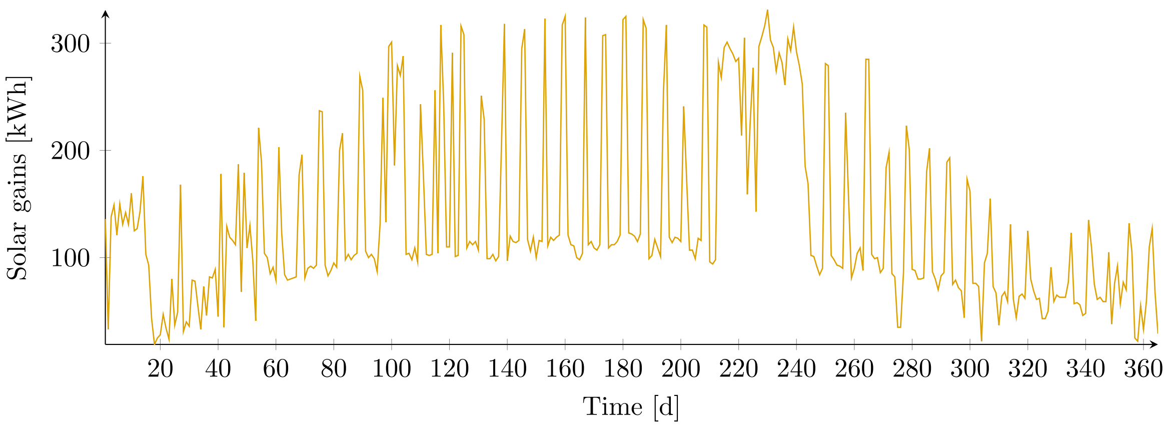

Figure 5.62: Daily solar gains of class B with *EnergyPlus/DesignBuilder*

Tables 5.46, 5.47, 5.48 and 5.49 show the results of the simulation of class B of sensible energy needs for heating, sensible energy needs for cooling, supply fan electric energy and extract fan electric energy respectively. Figures 5.63 and 5.64 illustrate graphically the monthly values summarized in Tables 5.46, 5.47, 5.48 and 5.49.

Table 5.46: Monthly sensible energy needs for heating of Class B with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR HEATING [kWh]

Month	**1P**	**2P**	**3P**	**4P**	**Common space**	**TOTAL**
JAN	1222	1575	1231	1586	1814	7428
FEB	726	843	730	848	1214	4361
MAR	214	267	217	270	368	1336
APR	24	38	24	39	130	256
MAY	0	0	0	0	20	20
JUN	0	0	0	0	0	0
JUL	0	0	0	0	0	0
AUG	0	0	0	0	0	0
SEP	0	0	0	0	0	0
OCT	19	37	20	38	85	201
NOV	320	360	322	362	511	1876
DEC	436	498	438	501	730	2603

Table 5.47: Monthly sensible energy needs for cooling of Class B with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR COOLING[5] [kWh]

Month	**1P**	**2P**	**3P**	**4P**	**Common space**	**TOTAL**
JAN	98	45	96	45	0	284
FEB	439	287	434	282	36	1479
MAR	1494	1292	1487	1285	367	5924
APR	1628	1420	1621	1413	435	6517
MAY	3216	3004	3209	2997	1274	13701
JUN	3740	3571	3733	3565	2157	16766
JUL	4961	4707	4951	4697	3366	22682
AUG	0	0	0	0	0	0
SEP	3450	3073	3438	3062	1468	14492
OCT	2578	2346	2568	2337	804	10633
NOV	1017	882	1012	877	194	3983
DEC	404	316	400	313	43	1477

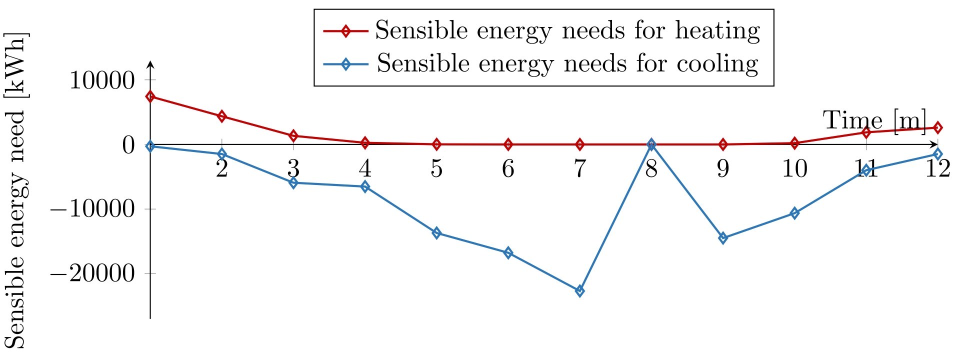

Figure 5.63: Monthly sensible energy needs for heating and cooling of class B with *EnergyPlus/DesignBuilder*

[5]Subsection 5.3.4 explains the presence of sensible energy needs for cooling in the heating months.

Table 5.48: Monthly supply fan electric energy of Class B with *EnergyPlus/DesignBuilder*

SUPPLY FAN ELECTRIC ENERGY [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	400	400	400	400	82	1680
FEB	421	421	421	421	86	1769
MAR	442	442	442	442	90	1857
APR	337	337	336	337	69	1415
MAY	463	463	463	463	111	1962
JUN	421	421	421	421	146	1828
JUL	484	484	484	484	194	2129
AUG	0	0	0	0	0	0
SEP	442	442	442	442	122	1888
OCT	484	484	484	484	99	2034
NOV	421	421	421	421	86	1769
DEC	315	315	315	315	65	1326

Table 5.49: Monthly extract fan electric energy of Class B with *EnergyPlus/DesignBuilder*

EXTRACT FAN ELECTRIC ENERGY [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	285	285	285	285	65	1207
FEB	300	300	300	300	69	1271
MAR	315	315	315	315	72	1334
APR	240	240	240	240	55	1017
MAY	331	331	330	331	89	1411
JUN	300	300	300	300	117	1318
JUL	346	346	346	346	155	1537
AUG	0	0	0	0	0	0
SEP	315	315	315	315	97	1359
OCT	346	346	346	346	79	1461
NOV	300	300	300	300	69	1271
DEC	225	225	225	225	52	953

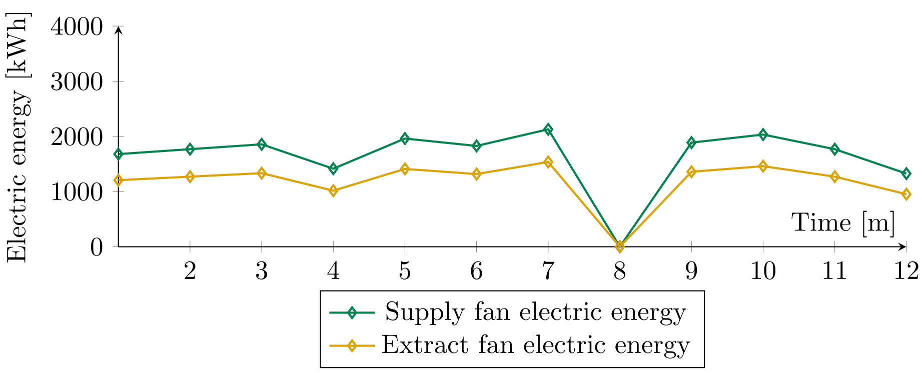

Figure 5.64: Monthly supply and extract fans electric of class B with *EnergyPlus/DesignBuilder*

BACS efficiency class A

Figure 5.65 shows the hourly values of mean air temperature and set-point temperatures of the whole building in the reference year, obtained from the simulation of class A.

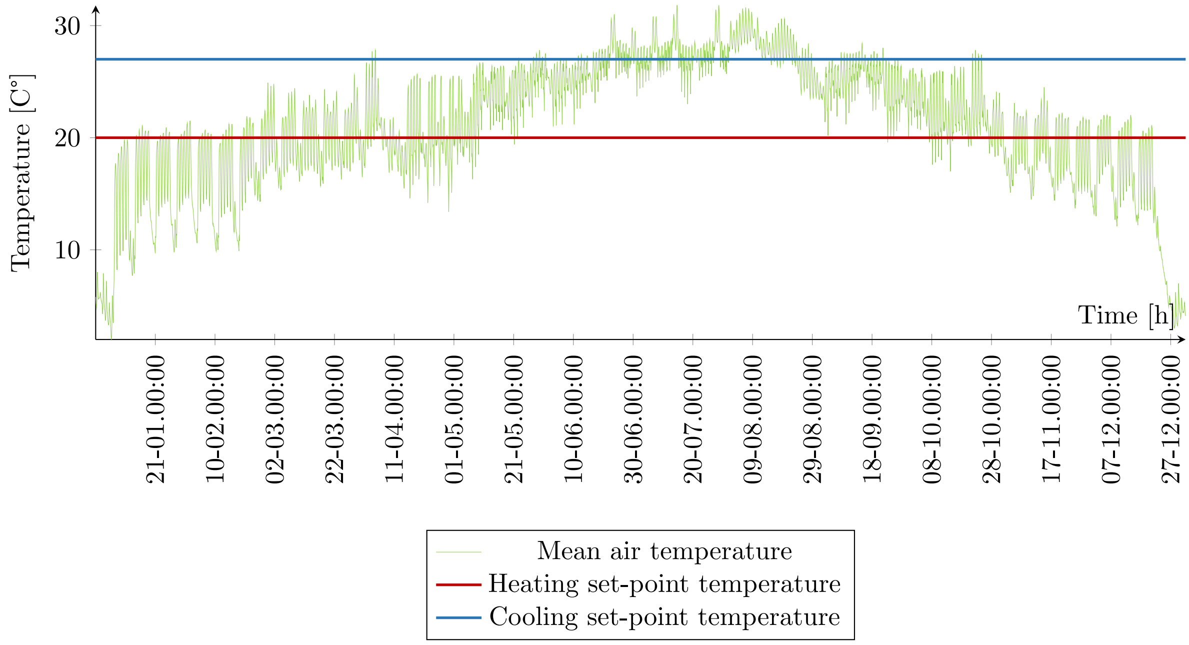

Figure 5.65: Hourly mean air temperature and set-point temperatures of class A with *EnergyPlus/Design Builder*

Taking into account the presence of blind control, the solar gains change according to the level of the blind control function implemented. Figure 5.62 shows the solar gains obtained in class A when blinds are automatically controlled to reduce cooling loads and to avoid glare during the occupied period.

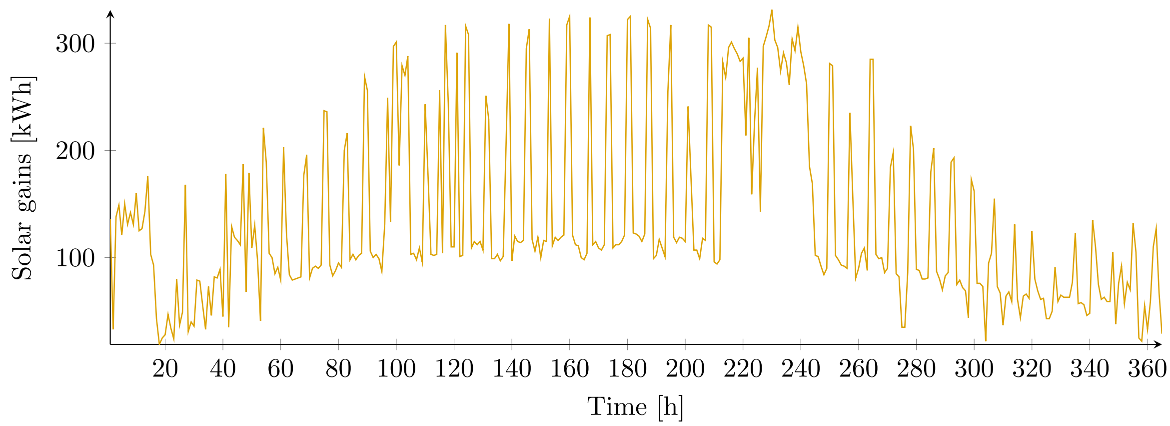

Figure 5.66: Daily solar gains of class A with *EnergyPlus/DesignBuilder*

Tables 5.50, 5.51, 5.52 and 5.53 show the results of the simulation of class A of sensible energy needs for heating, sensible energy needs for cooling, supply fan electric energy and extract fan electric energy respectively. Figures 5.67 and 5.68 illustrate graphically the monthly values summarized in Tables 5.50, 5.51, 5.52 and 5.53.

Table 5.50: Monthly sensible energy needs for heating of class A with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR HEATING [kWh]						
Month	**1P**	**2P**	**3P**	**4P**	**Common space**	**TOTAL**
JAN	790	1148	798	1158	1774	5670
FEB	368	489	371	494	1226	2948
MAR	36	51	36	51	333	507
APR	4	9	4	9	105	131
MAY	0	0	0	0	9	9
JUN	0	0	0	0	0	0
JUL	0	0	0	0	0	0
AUG	0	0	0	0	0	0
SEP	0	0	0	0	0	0
OCT	1	3	1	3	45	52
NOV	76	94	77	95	489	831
DEC	179	241	181	243	727	1571

Table 5.51: Monthly sensible energy needs for cooling of class A with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR COOLING[6] [kWh]						
Month	**1P**	**2P**	**3P**	**4P**	**Common space**	**TOTAL**
JAN	57	19	55	18	0	148
FEB	372	214	367	209	32	1194
MAR	1433	1214	1425	1206	361	5637
APR	1431	1240	1425	1235	482	5814
MAY	2929	2739	2923	2733	1293	12617
JUN	3451	3307	3444	3301	2042	15545
JUL	4590	4367	4581	4358	3089	20984
AUG	0	0	0	0	0	0
SEP	3143	2801	3132	2791	1475	13342
OCT	2389	2183	2381	2176	886	10014
NOV	961	814	956	809	184	3723
DEC	350	259	347	257	35	1248

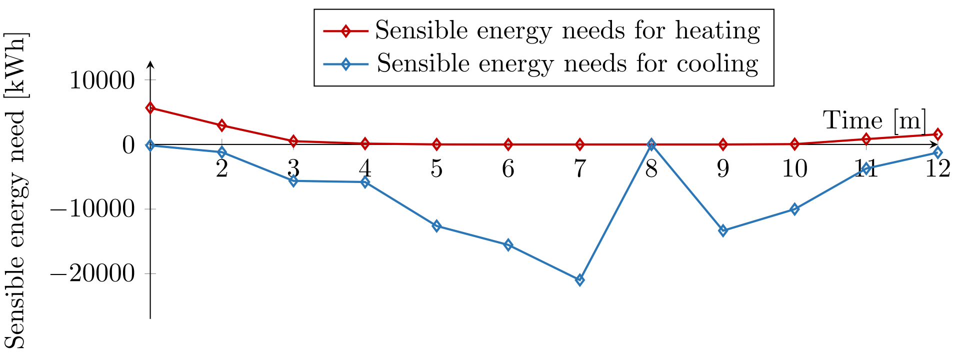

Figure 5.67: Monthly sensible energy needs for heating and cooling of class A with *EnergyPlus/DesignBuilder*

[6]Subsection 5.3.4 explains the presence of sensible energy needs for cooling in the heating months.

Table 5.52: Monthly supply fan electric energy of class A with *EnergyPlus/DesignBuilder*

SUPPLY FAN ELECTRIC ENERGY [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	317	317	317	317	87	1356
FEB	334	334	334	334	91	1428
MAR	351	351	351	351	96	1499
APR	267	267	267	267	73	1142
MAY	367	367	367	367	113	1583
JUN	334	334	334	334	127	1463
JUL	384	384	384	384	156	1692
AUG	0	0	0	0	0	0
SEP	351	351	351	351	116	1519
OCT	384	384	384	384	105	1642
NOV	334	334	334	334	91	1428
DEC	251	251	251	251	69	1071

Table 5.53: Monthly extract fan electric energy of class A with *EnergyPlus/DesignBuilder*

EXTRACT FAN ELECTRIC ENERGY [kWh]

Month	1P	2P	3P	4P	Common space	TOTAL
JAN	227	227	227	227	69	976
FEB	239	239	239	239	73	1028
MAR	251	251	251	251	77	1079
APR	191	191	191	191	59	822
MAY	262	262	262	262	90	1140
JUN	239	239	239	239	101	1056
JUL	274	274	274	274	124	1222
AUG	0	0	0	0	0	0
SEP	251	251	251	251	93	1095
OCT	274	274	274	274	84	1182
NOV	239	239	239	239	73	1028
DEC	179	179	179	179	55	771

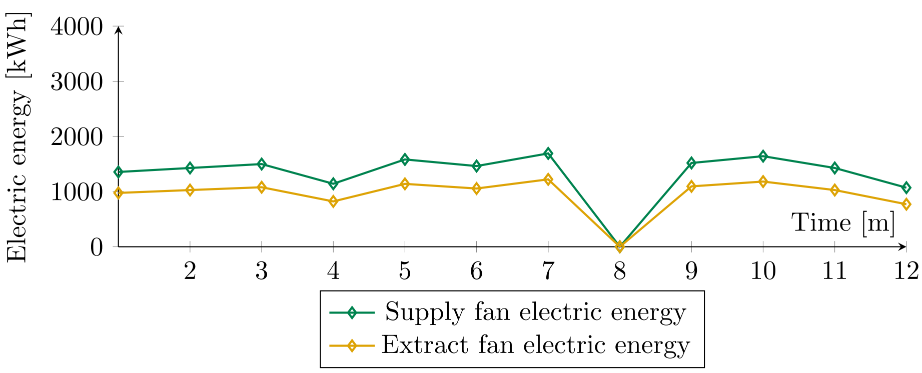

Figure 5.68: Monthly supply and extract fans electric energy of class A with *EnergyPlus/DesignBuilder*

5.3.4 Comparison of the results of *EnergyPlus/DesignBuilder* simulations

Heating

Table 5.54 and Figure 5.69 show that the highest sensible energy needs for heating are obtained with class C and the lowest sensible energy needs for heating are achieved by class A. Therefore, it is possible to say that higher is the BACS class lower are the sensible energy needs required to heat the thermal zones.

Table 5.54: Class comparison of monthly sensible energy needs for heating with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR HEATING [kWh]

Month	Class D	Class C	Class B	Class A
JAN	11961	8941	7428	5670
FEB	7927	5667	4361	2948
MAR	3109	2116	1336	507
APR	506	359	256	131
MAY	18	16	20	9
JUN	0	0	0	0
JUL	0	0	0	0
AUG	0	0	0	0
SEP	0	0	0	0
OCT	550	327	201	52
NOV	4570	2861	1876	831
DEC	5225	3563	2603	1571
TOTAL	**33865**	**23851**	**18080**	**11719**

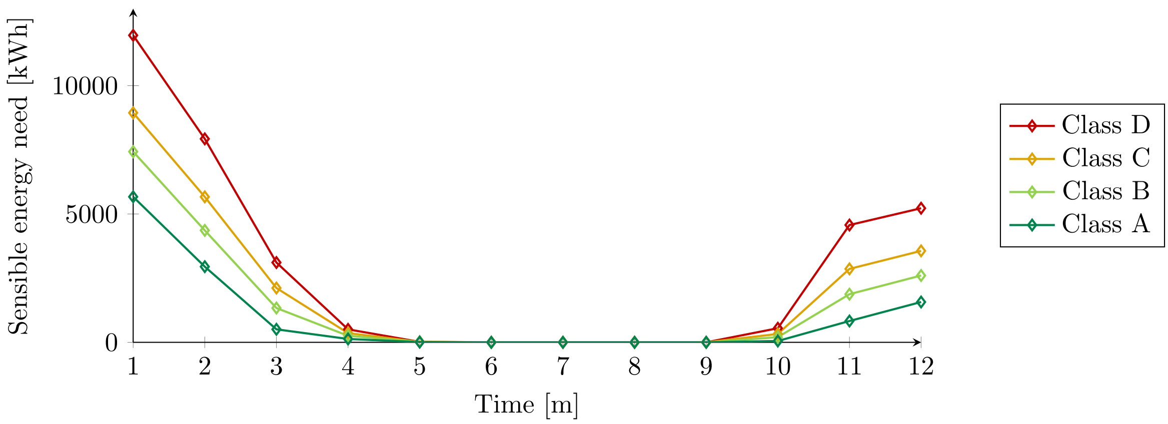

Figure 5.69: Class comparison of monthly sensible energy needs for heating with *EnergyPlus/DesignBuilder*

Taking into account the annual sensible energy needs for heating, it is possible to compare the results of the simulations with *EnergyPlus/DesignBuilder* and the results obtained from the application of the factor-based method of EN ISO 52120 [19]. The results of class C are taken as reference values.

Table 5.55 shows the results of the factor-based method compared with the results with *EnergyPlus/DesignBuilder*. It is possible to observe that performs the calculations with a dynamic calculation software provides a higher reduction of the sensible energy needs for heating with respect to the results with the simplified method of the standard. Table 5.55 shows the values of:

- the heating BACS efficiency factor ($f_{BAC,H}$),
- the total heating sensible energy needs of the considered BACS efficiency class obtained with the factor-based method ($Q_{H,tot,BAC}$),
- the factor to be used to obtain the results of the simulations ($f_{DB,H}$),
- the total heating sensible energy needs with *EnergyPlus/DesignBuilder* ($Q_{H,tot,DB}$).

Table 5.55: Comparison of heating sensible energy needs results with the factor-based method [19] and the heating sensible energy needs with *EnergyPlus/DesignBuilder*

	Class D	**Class C**	**Class B**	**Class A**
FACTOR-BASED METHOD				
$f_{BAC,H}$ [-]	1.20	1	0.88	0.80
$Q_{H,tot,BAC}$ [kWh]	28621	23851	20989	19081
SIMULATION RESULTS				
$f_{DB,H}$ [-]	1.42	1	0.76	0.49
$Q_{H,tot,DB}$ [kWh]	33865	23851	18080	11719

Cooling

Table 5.56 and Figure 5.70 show that the cooling sensible energy needs required by the building decrease according to the BACS efficiency class, as in the case of the sensible energy needs for cooling. Indeed, class D has the highest values of the sensible energy needs for cooling, instead class A has the lowest values.

Table 5.56: Class comparison of monthly sensible energy needs for cooling with *EnergyPlus/DesignBuilder*

SENSIBLE ENERGY NEEDS FOR COOLING[kWh]				
Month	**Class D**	**Class C**	**Class B**	**Class A**
JAN	880	445	284	148
FEB	2475	1733	1479	1194
MAR	7071	6135	5924	5637
APR	9053	7071	6517	5814
MAY	16903	14315	13701	12617
JUN	19820	17263	16766	15545
JUL	26402	23268	22682	20984
AUG	0	0	0	0
SEP	17504	15150	14492	13342
OCT	12392	11025	10633	10014
NOV	4815	4179	3983	3723
DEC	2208	1669	1477	1248
TOTAL	**119522**	**102254**	**97937**	**90267**

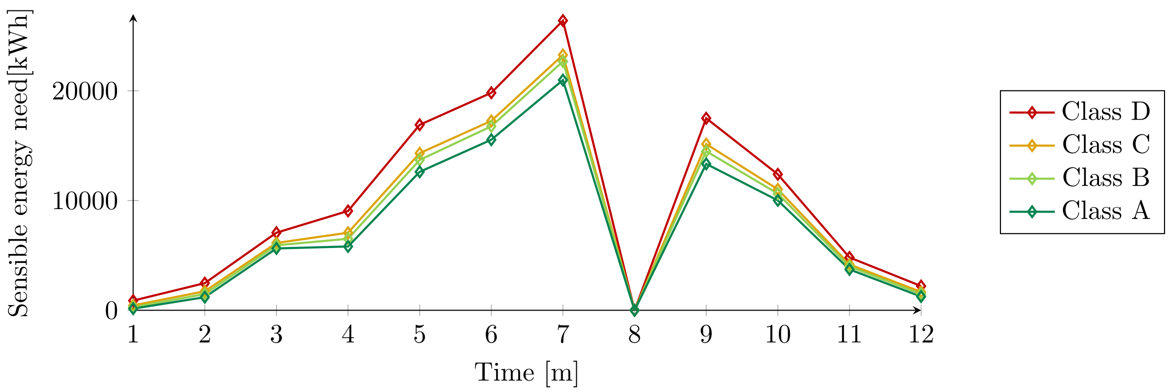

Figure 5.70: Class comparison of monthly sensible energy needs for cooling with *EnergyPlus/DesignBuilder*

It is possible to notice from Figure 5.70 that in the heating season months the sensible energy needs for cooling are greater than zero; this is due to the way cooling sensible energy needs of the zones are calculated by *EnergyPlus/DesignBuilder*. Indeed, the software in the calculation of cooling sensible energy needs takes into account the effect of any air introduced into the zone through the HVAC systems, including the effect of free cooling. Therefore, even if the cooling coil is turned off, the sensible energy needs for cooling are not zero due to the effect of free cooling, which introduces relatively cooler outside air into the thermal zones through mechanical ventilation to guarantee the air changes per hour required [21]. Figure 5.71 reports the values of the sensible energy needs for cooling compared to the cooling coil energy required by the rooftop systems to cool the building.

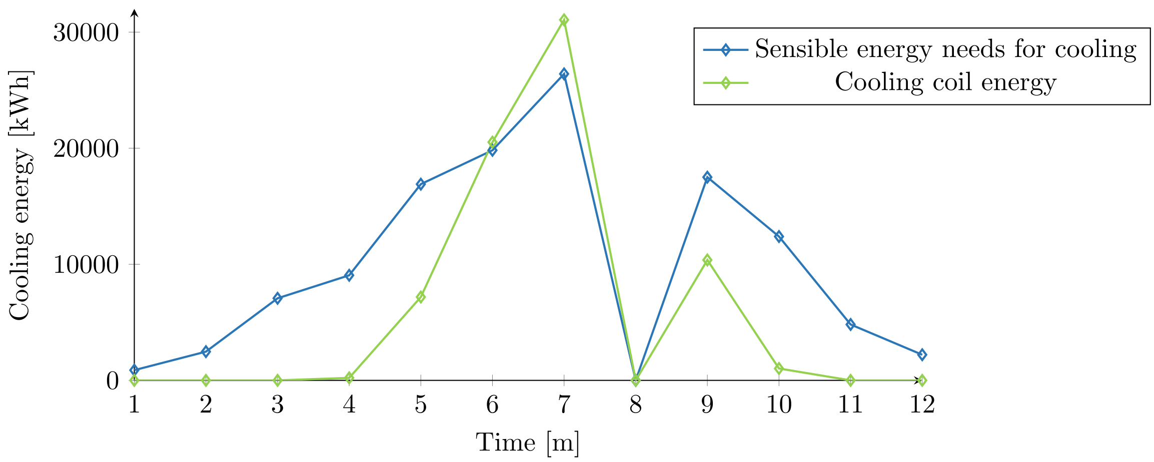

Figure 5.71: Comparison of sensible energy needs for cooling and cooling coil energy with *EnergyPlus/DesignBuilder*

In the case of cooling, the factor-based method of EN ISO 52120 does not provide any cooling BACS efficiency factor ($f_{BAC,C}$) for educational buildings. Therefore, it is not possible to make the same comparison as for the heating sensible energy needs. Table 5.57 shows the factor to be used to obtain the results of the simulations made with *EnergyPlus/DesignBuilder*.

In this case, $f_{DB,C}$ is the factor to be used to obtain the results of the simulations and $Q_{C,tot,DB}$ is the total sensible energy needs for cooling with *EnergyPlus/DesignBuilder*.

Table 5.57: Sensible energy needs for cooling results with *EnergyPlus/DesignBuilder*

	Class D	**Class C**	**Class B**	**Class A**
SIMULATION RESULTS				
$f_{DB,C}$ [-]	1.17	1	0.96	0.88
$Q_{C,tot,DB}$ [kWh]	119522	102254	97937	90267

Ventilation

Tables 5.58 and 5.59 and Figures 5.72 and 5.73 illustrate that also in the case of supply and extract fans, the electric energy required for the mechanical ventilation decreases with the increasing of BACS efficiency class. It is possible to see that the required electric energy achieves the maximum value in class D and the minimum value in class A.

Table 5.58: Class comparison of monthly supply fan electric energy with *EnergyPlus/DesignBuilder*

SUPPLY FAN ELECTRIC ENERGY [kWh]				
Month	**Class D**	**Class C**	**Class B**	**Class A**
JAN	2511	1909	1680	1356
FEB	2643	2009	1769	1428
MAR	2775	2110	1857	1499
APR	2114	1607	1415	1142
MAY	2907	2223	1962	1583
JUN	2643	2054	1828	1463
JUL	3039	2380	2129	1692
AUG	0	0	0	0
SEP	2775	2129	1888	1519
OCT	3039	2310	2034	1642
NOV	2643	2009	1769	1428
DEC	1982	1507	1326	1071
TOTAL	**29072**	**22189**	**19657**	**15822**

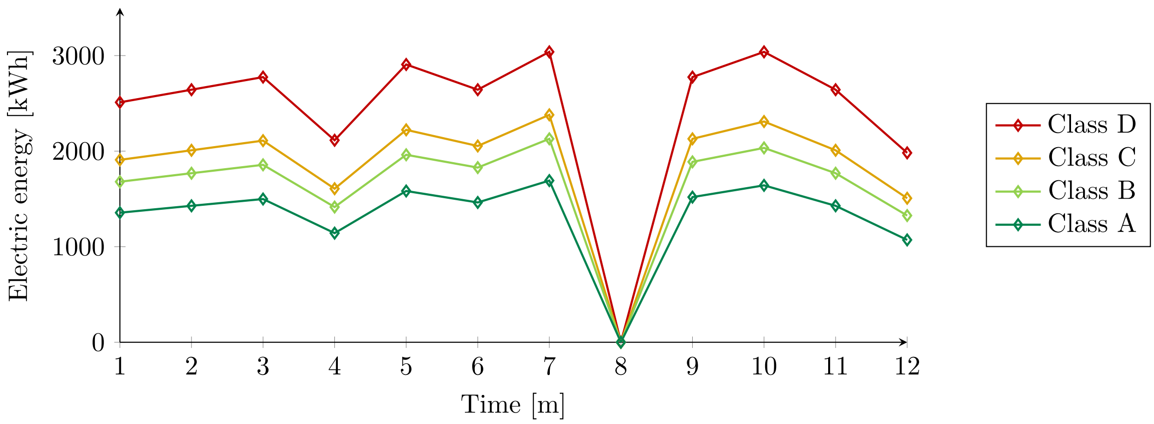

Figure 5.72: Class comparison of monthly supply fan electric energy with *EnergyPlus/DesignBuilder*

Table 5.59: Class comparison of monthly extract fan electric energy with *EnergyPlus/DesignBuilder*

EXTRACT FAN ELECTRIC ENERGY [kWh]				
Month	**Class D**	**Class C**	**Class B**	**Class A**
JAN	1813	1374	1207	976
FEB	1909	1446	1271	1028
MAR	2004	1518	1334	1079
APR	1527	1157	1017	822
MAY	2099	1601	1411	1140
JUN	1909	1482	1318	1056
JUL	2195	1718	1537	1222
AUG	0	0	0	0
SEP	2004	1534	1359	1095
OCT	2195	1663	1461	1182
NOV	1909	1446	1271	1028
DEC	1431	1085	953	771
TOTAL	**20995**	**15978**	**14139**	**11398**

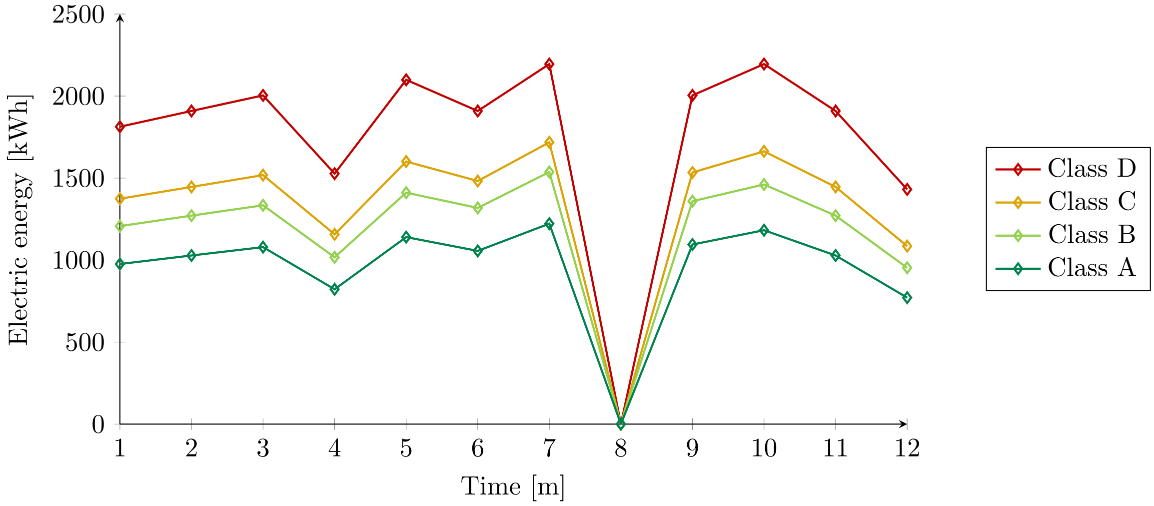

Figure 5.73: Class comparison of monthly extract fan electric energy with *EnergyPlus/DesignBuilder*

Table 5.60 compares the results of factor-based method of EN ISO 52120 for electric energy with the results with *EnergyPlus/DesignBuilder*. As the standard required, the results of class C are taken as reference values. It is possible to notice that the values obtained with the simplified method and the values obtained with the software for class B and class A are similar. Instead, a difference in the results are obtained with class D. The results of factor-based method are lower than the one with *EnergyPlus/DesignBuilder*. Table 5.60 shows the results of:

- the electric energyBACS efficiency factor ($f_{BAC,el}$),
- the total supply fan electric energy of the considered BACS efficiency class obtained with the factor-based method ($W_{V,supply,BAC}$),

- the total extract fan electric energy of the considered BACS efficiency class obtained with the factor-based method ($W_{V,extract,BAC}$),
- the factor to be used to obtain the results of the simulations ($f_{DB,el}$),
- the total supply fan electric energy with *EnergyPlus/DesignBuilder* ($W_{V,supply,DB}$),
- the total extract fan electric energy with *EnergyPlus/DesignBuilder* ($W_{V,extract,DB}$).

Table 5.60: Comparison of fan electric energy results with the factor-based method [19] and the fan electric energy results with *EnergyPlus/DesignBuilder*

	Class D	**Class C**	**Class B**	**Class A**
FACTOR-BASED METHOD				
$f_{BAC,el}$ [-]	1.12	1.00	0.87	0.74
$W_{V,supply,BAC}$ [kWh]	24851	22189	19304	16420
$W_{V,extract,BAC}$ [kWh]	17895	15978	13901	11824
SIMULATION RESULTS				
$f_{DB,el}$ [-]	1.31	1.00	0.88	0.71
$W_{V,supply,DB}$ [kWh]	29072	22189	19657	15822
$W_{V,supply,DB}$ [kWh]	20995	15978	14139	11398

Temperature

Figures 5.74, 5.75, 5.76 and 5.77 show the mean air temperatures of the case study. It is possible to observe that the temperature during occupied periods are maintained around the set-point temperatures (20 °C during winter and 27 °C during summer).

In heating period, it is possible to notice that the temperatures in weekends and holidays decrease more compared to the weekdays. Instead, during the cooling period, it is possible to observe that there are peak values of the temperature during weekends and holidays. This is due to the systems operation.

The results of class C, class B and class A show that during unoccupied periods of weekdays the temperatures decreases more respect to class D. Indeed, the working period of the systems better matches the real behavior of the building users as BACS class changes. Anyway, this trend does not affect the temperatures during the occupied period, that remain around the set-point.

In the end, it is possible to observe that in the first occupied week of the reference year the mean air temperatures do not reach the set-points, likely this is due to the thermal inertia of the building. Indeed, *EnergyPlus/DesignBuilder* consider the rooftop systems off during the period before the simulation year. So, the thermal zones require more time to reach the set-point temperatures.

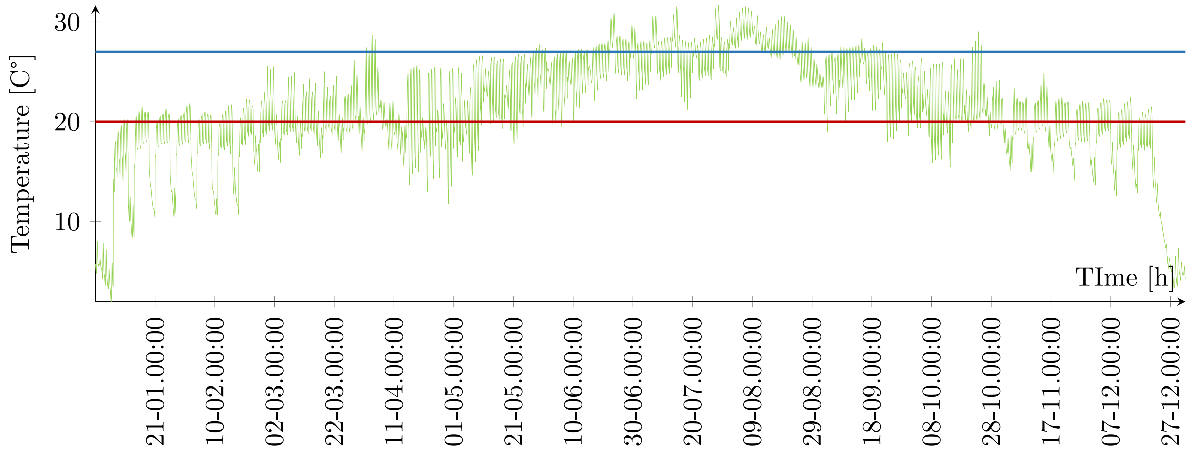

Figure 5.74: Hourly mean air temperature and set-point temperatures of class D with *EnergyPlus/Design Builder*

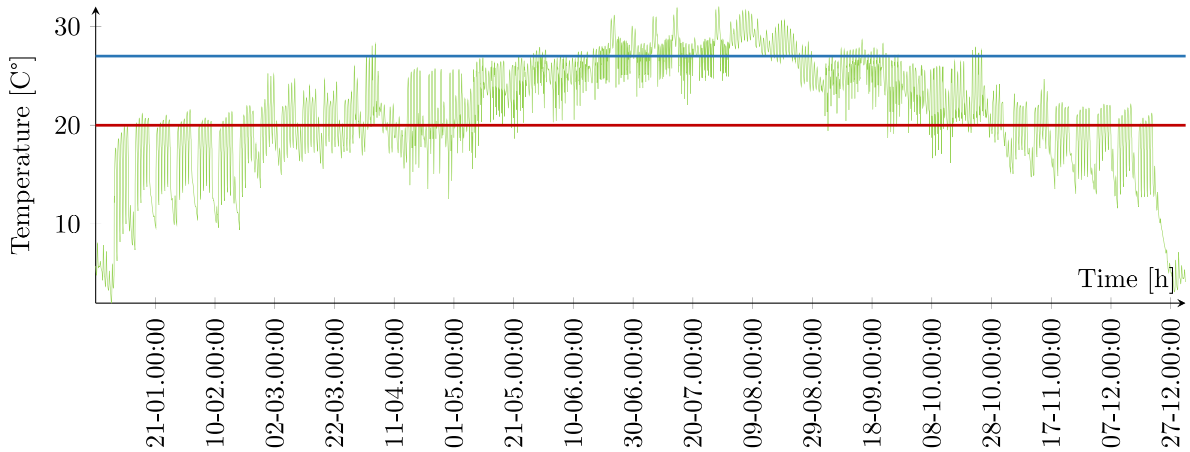

Figure 5.75: Hourly mean air temperature and set-point temperatures of class C with *EnergyPlus/Design Builder*

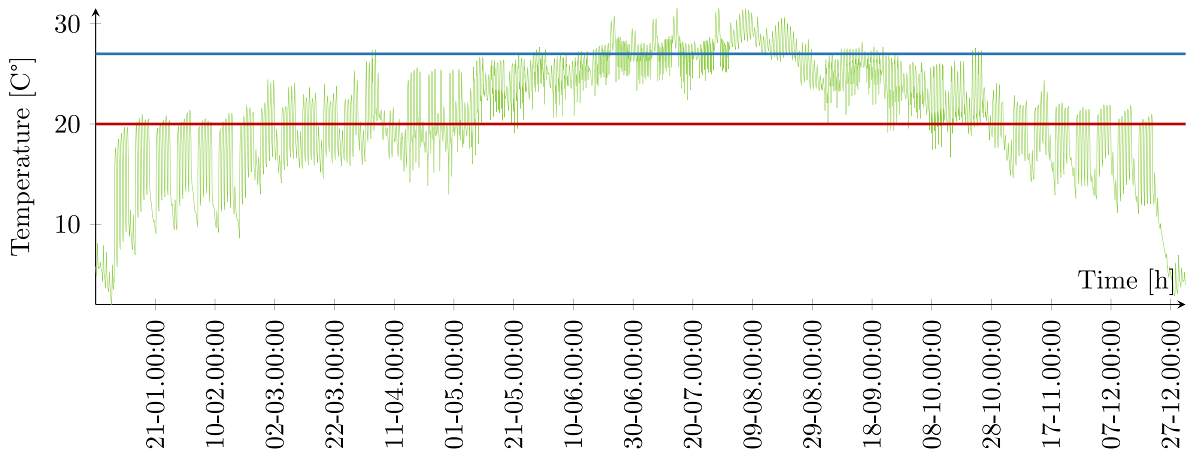

Figure 5.76: Hourly mean air temperature and set-point temperatures of class B with *EnergyPlus/Design Builder*

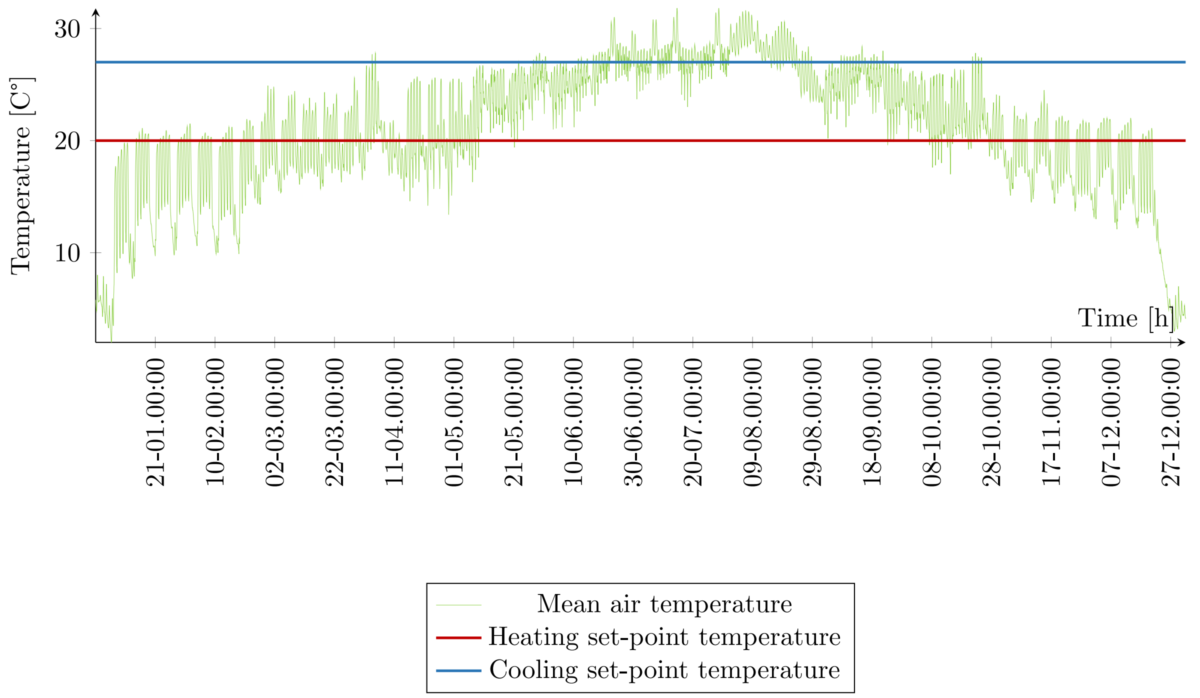

Figure 5.77: Hourly mean air temperature and set-point temperatures of class A with *EnergyPlus/Design Builder*

Chapter 6

Analysis of economic feasibility

This chapter analyzes the economic feasibility of the installation of BACS devices simulated in Chapter 5 and provides a cost-benefits analysis.

6.1 Devices available on the market

Only the devices with the control functions simulated in the models are considered. The reference values are taken to be the economic expenses of class D.

Siemens [39] and Schneider Electric SE [38] are the main manufacturers of building automation and control systems. The catalogs of BACS devices of these two companies provide a wide list of devices that can satisfy the simulated functions in the different BACS efficiency classes. Table 6.1 shows which devices satisfy the BACS functions implemented in each class.

Table 6.1: Devices that satisfy the BACS functions implemented in each BACS efficiency class

BACS class	**BACS devices**
C	HVAC control unit which allows to control heating, cooling and air conditioning and with incorporated temperature and relative humidity sensors
	Solar protection actuator for blind control
B	HVAC control unit which allows to control heating, cooling and air conditioning and with incorporated temperature and relative humidity sensors
	Solar protection actuator for blind control
	Light and presence sensors connectable with the HVAC control unit and solar protection actuator
A	HVAC control unit which allows to control heating, cooling and air conditioning and with incorporated temperature, relative humidity and CO_2 sensors
	Solar protection actuator for blind control
	Light and presence sensors connectable with the HVAC control unit and solar protection actuator

6.2 Economic evaluation of the intervention

First, the electric energy required for the rooftop systems operation is calculated. The estimated annual electric energy are taken from the results of the simulations obtained with *EnergyPlus/DesignBuilder* as this software also allows to get the results for BACS efficiency classes A and B which is not possible with *Edilclima EC700*. Table 6.2 shows the annual electric energy required for each BACS efficiency class by the heating coils, the cooling coils, the supply fans and the extract fans.

Table 6.2: Annual electric energy for each BACS efficiency class

ELECTRIC ENERGY [kWh]

	Class D	**Class C**	**Class B**	**Class A**
Heating coil	42813	30447	25373	18183
Cooling coil	17721	14894	14415	13661
Supply fan	29072	22189	19563	15779
Extract fan	20995	15978	14064	11364
TOTAL	**110601**	**83508**	**73415**	**58987**

The electricity costs are assumed to be the averege electricity costs by the *Gestore Mercati Energetici (GME)*, which is 0.15202 €/kWh for February 2023 [28]. All the calculation made in this chapter are performed with this value of the electricity cost. Table 6.3 provides the total estimated electricity cost for each BACS efficiency class and gives the achievable cost saving for classes C, B and A compared to class D.

Table 6.3: Annual electric costs and annual electric savings compared with class D

BACS efficiency class	**Electricity annual cost [€/year]**	**Electricity annual cost saving [€/year]**	**Electricity costs saving [%]**
D	16814	0	0
C	12695	4119	24
B	11161	5653	34
A	8967	7846	47

Tables 6.4, 6.5 and 6.6 provide the cost of BACS devices and the costs of installation for class C, B and A. The devices costs are divided into four different classes according to the devices available on the market: HVAC control devices, blind control devices, sensors and building management system (BMS).

BMS is not present among the devices simulated in the models, but it still considered in the economic analysis, since the project of the building establishes its presence.

The cost estimate present in the technical documents of the case study project shows that the BMS costs are evaluated equal to € 9751 and installation costs are evaluated equal to € 1004. Moreover, the maintenance plan document of the project illustrates the ordinary and extraordinary maintenance interventions, of which the costs are € 500 for each year. The devices costs are taken from Siemens and Schneider Electric SE catalogs [39][38].

Table 6.4: Devices and installation costs of BACS devices used in class C

	n° of devices	**Cost per devices [€/n°]**	**Total cost [€]**
HVAC control devices	5	280	1400
Blind control devices[1]	4	780	3120.00
BMS	9751		
Installation	1004		
TOTAL	15275		

Table 6.5: Devices and installation costs of BACS devices used in class B

	n° of devices	**Cost per devices [€/n°]**	**Total cost [€]**
HVAC control devices	5	280	1400
Blind control devices	4	780	3120
Light and presence sensors for HVAC and blind control[2]	16	330	5280
BMS	9751		
Installation	1004		
TOTAL	20555		

Table 6.6: Devices and installation costs of BACS devices used in class A

	n° of devices	**Cost per devices [€/n°]**	**Total cost [€]**
HVAC control devices	5	570	2850
Blind control devices	4	780	3120
Light and presence sensors for HVAC and blind control	16	330.00	5280.00
BMS	9751		
Installation	1004		
TOTAL	22005		

Tables 6.7, 6.8 and 6.9 illustrate the calculation of the payback period. The initial investment for each class is assumed to be at the end of year T_0, meaning that the prices of these devices and their installation is paid at time T_0. According to the manufactures, the lifespan of BACS devices is about 10 years if properly maintained [2]. The first row shows the installation and maintenance costs, the second row shows the saving obtained from the BACS operation, and the last row shows the balance between costs and savings. Tables 6.7, 6.8 and 6.9 also estimate the total savings at the end of ten years.

[1] Each classroom is equipped with a solar protection actuator that control all blind devices in the room.
[2] The considered device range is about 60 m^2.

Table 6.7: Payback period analysis for class C

	T_0	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Cost [€]	-15275	-500	-500	-500	-500	-500	-500	-500	-500	-500	-500
Saving [€]	0	4119	4119	4119	4119	4119	4119	4119	4119	4119	4119
Tot [€]	-15275	3619	3619	3619	3619	3619	3619	3619	3619	3619	3619
TOTAL [€]	**20911**										
Payback	**4 years and 3 months**										

Table 6.8: Payback period analysis for class B

	T_0	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Cost [€]	-20555	-500	-500	-500	-500	-500	-500	-500	-500	-500	-500
Saving [€]	0	5653	5653	5653	5653	5653	5653	5653	5653	5653	5653
Tot [€]	-20555	5153	5153	5153	5153	5153	5153	5153	5153	5153	5153
TOTAL [€]	**30974**										
Payback	**4 years**										

Table 6.9: Payback period analysis for class A

	T_0	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Cost [€]	-22005	-500	-500	-500	-500	-500	-500	-500	-500	-500	-500
Saving [€]	0	7846	7846	7846	7846	7846	7846	7846	7846	7846	7846
Tot [€]	-22005	7346	7346	7346	7346	7346	7346	7346	7346	7346	7346
TOTAL [€]	**51458**										
Payback	**3 years**										

It is possible to see from Tables 6.7, 6.8 and 6.9 that in the worst case the required time to recover the initial investment is four years and three months. Even in the worst case, the payback period is sensibly lower than the expected lifespan of properly maintained BACS devices.

Tables 6.7, 6.8 and 6.9 show that even if the initial investment is higher for BACS efficiency class A, the best performing control and automation systems allows to have a higher savings, therefore the payback period for class A decreases and the initial investment is fully recovered in three years.

Chapter 7

Conclusions and future development

The first goal of this thesis was to evaluate the ability of two software tools to simulate BACS functions and to evaluate the effect of some of BACS functions on the energy performances. The case study regarded classrooms P of the *Politecnico di Torino*.

A guide to the simulation of BACS functions and their relative implementable levels was provided. The guide shows that the simulation capabilities of *Edilclima EC700*, which applies a simplified dynamic calculation method based on the energy performance standard, are lower than the ones of *EnergyPlus/DesignBuilder*, which applies a detailed calculation method. This is likely due to the different calculation methods and to how the technical building systems are modeled. Indeed, according to the energy performance standards, *Edilclima EC700* allows a simplified modeling of the technical building systems, which reduces the ability to simulate BACS functions since BACS are strictly connected to technical building systems.

This issue is noticeable in the results of the simulation of class C with *Edilclima EC700*. Indeed, this simulation had to be performed twice, with mechanical and hybrid ventilation respectively, because *Edilclima EC700* is not able to set an hourly profile combining the two ventilation modes. On the other hand, *EnergyPlus/DesignBuilder* uses a detailed dynamic calculation model, allowing to simulate a larger number of BACS functions with a higher level of implementation.

Nonetheless, despite the better simulation capabilities of *EnergyPlus/DesignBuilder*, neither of the two software tools are able to simulate all BACS functions or all implementation levels.

The results of the simulations made on the case study confirm the observations made previously on the ability to simulate BACS functions. Indeed, the BACS efficiency class achievable by the two software tools are different: class C with *Edilclima EC700* and class A with *EnergyPlus/DesignBuilder*.

Because of the reduced simulation capabilities of *Edilclima EC700*, only the results of *EnergyPlus/DesignBuilder* are taken into account for a complete analysis of the energy savings. In any case, even the partial results with *Edilclima EC700* show that reaching efficiency class C increases the energy performances of the case study.

The results with *EnergyPlus/DesignBuilder* show, as expected, that high performance devices allow to reduce the energy consumption. Figure 7.1 shows the percentage savings of sensible energy needs for heating, sensible energy needs for cooling and ventilation electric energy respectively. The reference point is BACS efficiency class D.

As shown in Figure 7.1, the highest savings from class upgrades are obtained by moving from class D to class C. Instead, the energy savings obtained from moving from class C to class B and obtained from moving from class B to class A is about one-third of that between class D and class C.

The greatest energy savings are due to the sensible energy needs for heating, up to 65% with respect to class A. Energy saving from sensible energy needs for cooling is lower, 14% for class C, 18% for class B and 24% for class A, but it still has a sizable impact on the total energy saving. The energy savings due to ventilation electric energy are 24% for class C, 33% for class B and 46% for class A.

From this, it is clear that the use of BACS functions in the building is energy effective. Therefore, the use of these technological solutions provides a huge contribution to the reduction of energy consumption due to building operation.

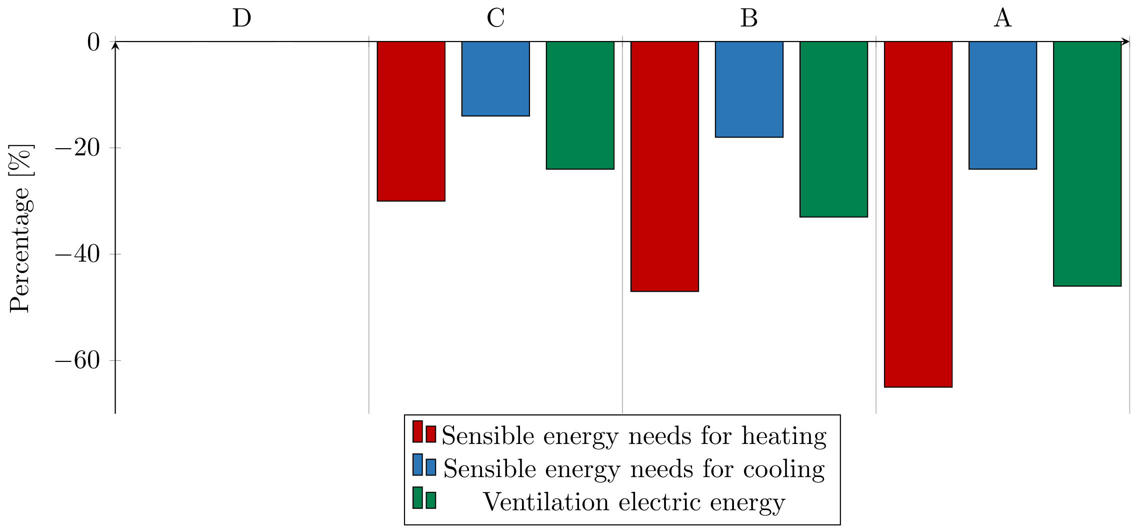

Figure 7.1: Percentage energy savings of classes C,B,A with respect to class D

The second goal was to provide an economical feasibility assessment of the installation of the BACS devices that are simulated in classrooms P of the *Politecnico di Torino*. This evaluation has been done by calculating the payback period of the initial investment.

The results show that the payback period is always significantly lower than the usual lifespan of BACS devices, which is about 10 years if correctly maintained. The payback period is about four years and three months for class C, four years for class B and three years for class A (Figure 7.2).

Figure 7.3 shows the annual electricity cost savings due to the presence of BACS devices in the building. This reduction is about 12% for class C, 18% for class B and 31% for class A. Moreover, the analysis calculates that the average costs savings at the end of the lifespan period is about € 20911 for class C, € 30974 for class B and € 51458 for class A. These cost savings take into account the cost of the devices, the cost of installation and the annual costs for maintenance.

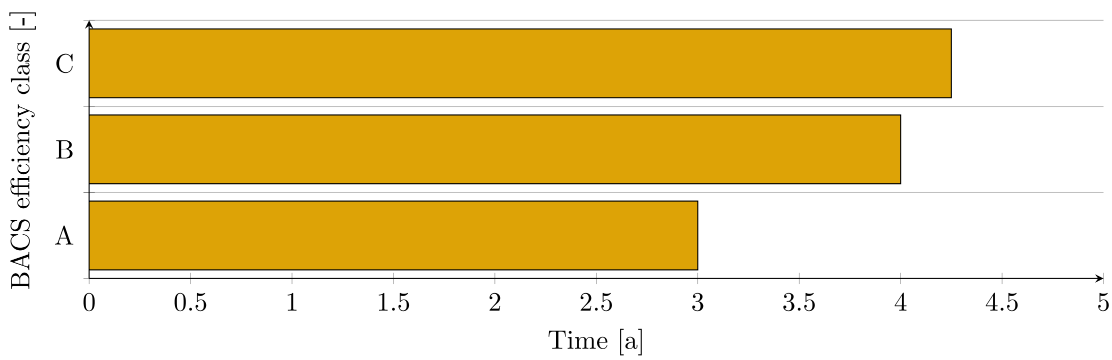

Figure 7.2: Payback period summary

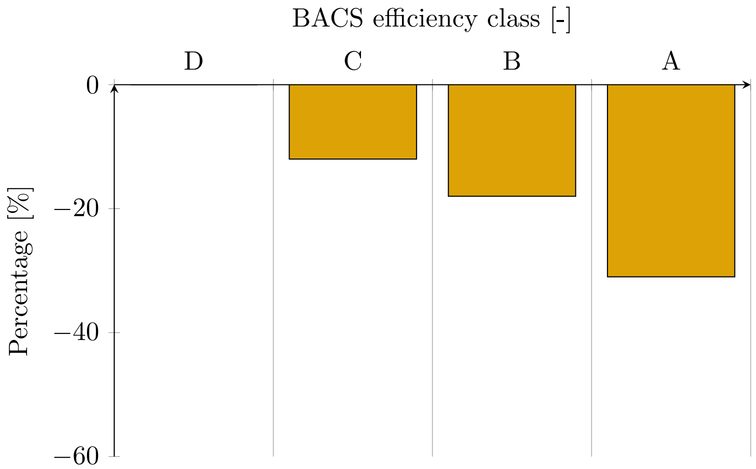

Figure 7.3: Percentage savings of the electricity costs with respect to class D

It is important to highlight that the results obtained are for a specific case study and the simulation of the same devices in a different building or of a different technical building systems could provide different results both in terms of energy saving and cost savings. Moreover, only some BACS functions are simulated in the models and it is important to point out that different BACS functions might have a different impact on the energy performance of the building.

Hence, a possible future development of this work could be the simulation of all BACS functions for different building types and for different technical building systems.

Another possible future development of this thesis is the comparison of the values of sensible energy needs for heating, sensible energy needs for cooling, and ventilation electric energy obtained from the simulation with the actual values measured by sensors installed in the building. This comparison would be useful to evaluate the accuracy of the simulations with respect to the real energy performance of the building.

Appendix A

EN ISO 52120: reference tables

A.1 List of BAC and TBM functions

Table A.1: List of BAC and TBM functions according to standard EN ISO 52120, Table 5 [19]

1	**Heating control**
1.1	Emission control applied to the heat emitter at room level
1.2	Emission control for *Thermal Activated Building Systems* (TABS)
1.3	Control of distribution network hot water temperature (supply or return)
1.4	Control of distribution pumps in networks
1.4a	Hydronic balancing heating distribution (including contribution to the balancing to the emission side)
1.5	Intermittent control of emission and/or distribution
1.6	Heat generator control for combustion and district heating
1.7	Heat generator control for heat pumps
1.8	Heat generator control for out-door unit
1.9	Sequencing of different heat generators (including renewable energy sources)
1.10	Control of *Thermal Energy Storage* (TES) charging

2	**Domestic Hot Water supply control**
2.1	Control of *Domestic Hot Water* (DHW) storage charging with direct electric heating or integrated electric heat pump
2.2	Control of DHW storage charging using hot water generation
2.3	Control of DHW storage charging with solar collector and supplementary heat generation
2.4	Control of DHW circulation pump

3	**Cooling control**
3.1	Emission control applied to the emitter at room level
3.2	Emission control for TABS
3.3	Control of distribution network chilled water temperature (supply or return)
3.4	Control of distribution pumps in hydraulic networks
3.4a	Hydronic balancing cooling distribution (including contribution to the balancing to the emission side)
3.5	Intermittent control of emission and/or distribution

3.6	Interlock between heating and cooling control of emission and/or distribution, to prevent heating and cooling systems from operating simultaneously in the same room
3.7	Generator control for cooling
3.8	Sequencing of different chillers (including renewable energy sources)
3.9	Control of TES charging
4	**Ventilation and air-conditioning control** It refers to all systems that bring air into the building, including additional air required for heating and cooling
4.1	Supply air flow control at room level, related to the occupancy
4.2	Room air temperature control by the ventilation system, acting on the air flow to regulate the air temperature
4.3	Coordination of room air temperature control by ventilation and by static system; in this case, the interaction between different systems must be coordinated
4.4	*Outside air* (OA) flow control
4.5	Air flow or pressure control at the air handler level
4.6	Heat recovery control, to avoid icing in the heat exchanger
4.7	Heat recovery control, to prevent overheating in the heat recovery unit
4.8	Free mechanical cooling control
4.9	Supply air temperature control at the *air handling unit* (AHU)
4.10	Humidity control, including humidification and dehumidification
5	**Lighting control**
5.1	Occupancy control
5.2	Light level and daylight control
6	**Blind control**
6.1	Blind control, to avoid overheating and glare
7	**Technical home and building management** Helping to adapt the systems operation to the needs of the building users. Indeed, through sensors the technical building management checks the operation schedule of heating, cooling, ventilation and lighting to correct and adapt the functioning of the systems to user needs
7.1	Set-point management according to the room/zone operating modes
7.2	Run-time management according to a provided time schedule
7.3	Faults detection of technical building systems and support for the diagnosis of these faults
7.4	Reporting on energy consumption given the indoor conditions
7.5	Management of local energy production and energy from renewable resources
7.6	Use of waste energy and heat shifting
7.7	Manage the interaction between the building and a smart grid

A.2 BAC and TBM minimum function requirements for class C

Table A.2: BAC and TBM minimum function requirements for class C according to standard EN ISO 52120, Table B.1 [19]

	Heating control	Residential	Non-residential
	Emission control		
2	Individual room control	x	x
	Emission control for TABS (heating mode)		
1	Central automatic control	x	x
	Control of distribution network hot water temperature (supply or return)		
1	Outside temperature compensated control	x	x
	Control of distribution pumps in networks		
1	On off control	x	x
	Hydronic balancing heating distribution (including contribution to the balancing to the emission side)		
1	Balanced statically per emitter, without group balance	x	
3	Balanced statically per emitter and dynamic group balance		x
	Intermittent control of emission and/or distribution		
1	Automatic control with fixed time program	x	x
	Heat generator control (combustion and district heating)		
1	Variable temperature control depending on outside temperature	x	x
	Heat generator control (heat pump)		
0	On/off control of heat generator	x	x
	Heat generator control (outdoor unit)		
1	Multi-stage control of heat generator	x	x
	Sequencing of different heat generators		
1	Priorities only based on loads	x	x
	Control of thermal energy storage (TES) charging		
1	2-sensor charging of storage	x	x

	Domestic hot water supply system	Residential	Non-residential
	Control of DHW storage charging with direct electric heating or integrated electric heat pump		
1	Automatic on/off control and scheduled charging enable	x	x
	Control of DHW storage charging using heating water generation		
1	Automatic on/off control and scheduled charging enable	x	x
	Control of DHW storage charging with solar collector and supplementary heat generation		
1	Automatic control of solar storage charge (Prio. 1) and supplementary storage charge (Prio. 2)	x	x
	Control of DHW circulation pump		
1	With time program	x	x

	Cooling control	Residential	Non-residential
	Emission control		
2	Individual room control	x	x
	Emission control for TABS (cooling mode)		

1	Central automatic control	x	x
	Control of distribution network chilled water temperature (supply or return)		
1	Outside temperature compensated control	x	x
	Control of distribution pumps in networks		
1	On off control	x	x
	Hydronic balancing cooling distribution (including contribution to the balancing to the emission side)		
1	Static balancing	x	x
	Intermittent control of emission and/or distribution		
1	Automatic control with fixed time program	x	x
	Interlock between heating and cooling control of emission and/or distribution		
1	Partial interlock (dependent on the HVAC system)	x	x
	Different chiller selection control		
1	Variable temperature control depending on outside temperature	x	x
	Sequencing of different chillers		
1	Priorities only based on loads	x	x
	Control of thermal energy storage (TES) operation		
1	Time-scheduled storage operation	x	x

	Ventilation and air-conditioning control	**Residential**	**Non-residential**
	Supply air flow control at the room level		
1	Time control	x	x
	Room air temperature control (all-air systems)		
1	Continuous control	x	x
	Room air temperature control (air–water systems)		
0	No coordination		x
1	Coordination	x	
	Outside air flow control		
0	Fixed OA ratio/OA flow	x	
1	Staged (low/high) OA ratio/OA flow (time scheduled)		x
	Air flow or pressure control at the air handler level		
1	On off time control	x	x
	Heat recovery control (icing protection)		
1	With icing protection	x	x
	Heat recovery control (prevention of overheating)		
1	With overheating control	x	x
	Free mechanical cooling		
1	Night cooling	x	x
	Supply air temperature control		
1	Constant set-point	x	x
	Humidity control		
1	Dew point control	x	x

	Lighting control	**Residential**	**Non-residential**
	Occupancy control		
0	Manual on/off switch	x	
2	Automatic detention (auto on)		x

	Light level/daylight control		
0	Manual (central)	x	x

	Blind control	**Residential**	**Non-residential**
1	Motorized operation with manual control	x	
2	Motorized operation with automatic control		x

	Technical home and building management	**Residential**	**Non-residential**
	Set-point management		
0	Manual setting room by room individually	x	
1	Adaptation from distributed/decentralized plant rooms only		x
	Run time management		
0	Manual setting (plant enabling)	x	
1	Individual setting following a predefined time schedule including fixed preconditioning phases		x
	Detecting faults of technical building systems and providing support to the diagnosis of these faults		
0	No central indication of detected faults and alarms	x	
1	With central indication of detected faults and alarms		x
	Reporting information regarding energy consumption, indoor conditions		
0	Indication of actual values only (e.g. temperatures, meter values)	x	x
	Local energy production and renewable energies		
0	Uncontrolled generation depending on the fluctuating availability of RES and or run time of CHP; overproduction will be fed into the grid	x	x
	Waste heat recovery		
0	Instantaneous use of waste heat or heat shifting	x	x
	Smart grid interaction		
0	Building is operated independently from the grid load	x	x

A.3 Factor-based method

Table A.3: BACS efficiency factors $f_{BAC,H}$ and $f_{BAC,C}$ (Table A.5 and A.6 of EN ISO 52120-1)

NON-RESIDENTIAL	**D**		**C (reference)**		**B**		**A**	
	$\mathbf{f_{BAC,H}}$	$\mathbf{f_{BAC,C}}$	$\mathbf{f_{BAC,H}}$	$\mathbf{f_{BAC,C}}$	$\mathbf{f_{BAC,H}}$	$\mathbf{f_{BAC,C}}$	$\mathbf{f_{BAC,H}}$	$\mathbf{f_{BAC,C}}$
Offices	1.44	1.57	1	1	0.79	0.80	0.70	0.57
Lecture hall	1.22	1.32	1	1	0.73	0.94	0.30	0.64
Education buildings	1.20	-	1	1	0.88	-	0.80	-
Hospital	1.31	-	1	1	0.91	-	0.86	-
Hotels	1.17	1.76	1	1	0.85	0.79	0.61	0.76
Restaurants	1.21	1.39	1	1	0.76	0.94	0.69	0.60
Wholesale and retail trade service buildings	1.56	1.59	1	1	0.71	0.85	0.46	0.55
Other types	-	-	1	1	-	-	-	-
RESIDENTIAL	1.09	-	1	-	0.88	-	0.81	-

Table A.4: BACS efficiency factor $f_{BAC,DHW}$ (Table A.7 and A.8 of EN ISO 52120-1)

	D	**C (reference)**	**B**	**A**
	$\mathbf{f_{BAC,DHW}}$	$\mathbf{f_{BAC,DHW}}$	$\mathbf{f_{BAC,DHW}}$	$\mathbf{f_{BAC,DHW}}$
NON-RESIDENTIAL	1.11	1	0.9	0.8
RESIDENTIAL	1.11	1	0.9	0.8

Table A.5: BACS efficiency factors $f_{BAC,L}$ and $f_{BAC,aux}$ (Table A.9 of EN ISO 52120-1)

NON-RESIDENTIAL	**D**		**C (reference)**		**B**		**A**	
	$\mathbf{f_{BAC,L}}$	$\mathbf{f_{BAC,aux}}$	$\mathbf{f_{BAC,L}}$	$\mathbf{f_{BAC,aux}}$	$\mathbf{f_{BAC,L}}$	$\mathbf{f_{BAC,aux}}$	$\mathbf{f_{BAC,L}}$	$\mathbf{f_{BAC,aux}}$
Offices	1.10	1.15	1	1	0.85	0.86	0.72	0.72
Lecture hall	1.10	1.11	1	1	0.88	0.86	0.76	0.78
Education buildings	1.10	1.12	1	1	0.88	0.87	0.76	0.74
Hospital	1.20	1.10	1	1	1	0.98	1	0.96
Hotels	1.10	1.12	1	1	0.88	0.89	0.76	0.78
Restaurants	1.10	1.09	1	1	1	0.96	1	0.92
Wholesale and retail trade service buildings	1.10	1.13	1	1	1	0.95	1	0.91
Other types	-	-	1	1	-	-	-	-

Appendix B

EN ISO 52120: calculation method

B.1 Factor-based method

To evaluate the energy delivered with the factor-based method, EN ISO 52120 standard defines the following formulas for each system involved [19].

For heating and cooling systems, the following formulas are used:

$$Q_{H/C,tot,BAC} = (Q_{H/C,nd,B} + Q_{H/C,ls}) \cdot \frac{f_{BAC,H/C}}{f_{BAC,H/C,ref}} \tag{B.1}$$

$$W_{H/C,aux,BAC} = W_{H/C,aux} \cdot \frac{f_{BAC,el}}{f_{BAC,el,ref}} \tag{B.2}$$

where:

- $Q_{H/C,tot,BAC}$ is the total heating (H) or cooling (C) energy of the considered BACS efficiency class,
- $Q_{H/C,nd,B}$ is the heating or cooling energy required by the building,
- $Q_{H/C,ls}$ is the energy loss of the heating or cooling systems,
- $W_{H/C,aux,BAC}$ is the electrical auxiliary energy for heating or cooling related to BACS efficiency class,
- $f_{BAC,H/C}$ is the BACS efficiency factor for thermal energy (heating or cooling),
- $f_{BAC,H/C,ref}$ is the BACS efficiency factor for thermal energy (heating or cooling) of the reference BACS efficiency class C,
- $f_{BAC,el}$ is the BACS efficiency factor for electric energy,
- $f_{BAC,el,ref}$ is the BACS efficiency factor for electric energy of the reference BACS efficiency class.

For the domestic how water production systems, the following formula is used:

$$Q_{DHW,BAC} = Q_{DHW} \cdot \frac{f_{BAC,DHW}}{f_{BAC,DHW,ref}} \tag{B.3}$$

where

- $Q_{DHW,BAC}$ is the energy required for the production of domestic hot water of the considered BACS efficiency class,

- Q_{DHW} is the energy need for domestic hot water production of the building,
- $f_{BAC,DHW}$ is the BACS efficiency factor for thermal energy (domestic hot water production),
- $f_{BAC,DHW,ref}$ is the BACS efficiency factor for thermal energy (domestic hot water production) of the reference BACS efficiency class C.

For the ventilation systems, the following formula is used:

$$W_{V,aux,BAC} = W_{V,aux} \cdot \frac{f_{BAC,el}}{f_{BAC,el,ref}} \tag{B.4}$$

where

- $W_{V,aux,BAC}$ is the electrical auxiliary energy for ventilation system of the considered BACS efficiency class,
- $W_{V,aux}$ is the electrical auxiliary energy for ventilation system of the building,
- $f_{BAC,el}$ is the BACS efficiency factor for electric energy,
- $f_{BAC,el,ref}$ is the BACS efficiency factor for electric energy of the reference BACS efficiency class C.

For the lighting systems, the following formula is used:

$$W_{L,BAC} = W_L \cdot \frac{f_{BAC,el}}{f_{BAC,el,ref}} \tag{B.5}$$

where

- $W_{L,BAC}$ is the electrical energy for the lighting system related to BAC efficiency class,
- W_L is the electrical energy for the lighting system of the building,
- $f_{BAC,el}$ is the BAC efficiency factor for electric energy,
- $f_{BAC,el,ref}$ is the BAC efficiency for electric energy for reference BAC.

B.2 Time approach

The energy consumption assessed for a given period by time approach is calculated by the following formula [19]:

$$E = P \cdot \Delta t \cdot k_{ctr} \tag{B.6}$$

where:

- E is the energy consumption for the given time period,
- P is the input power of the controlled system, provided by the producer,
- Δt is the duration of the given time period,
- k_{ctr} is a characteristic coefficient that represents the impact of the control system. It is computed as the ratio between the starting time of the system and the duration of the time period.

B.3 Set-point approach

The impact on energy consumption calculated with set-point approach is estimated as follows [19]:

$$E = k_{trans} \cdot [(\theta_{set} + \Delta\theta_{ctr}) - \theta_{ref}] \cdot \Delta t \tag{B.7}$$

where:

- E is the energy consumption for the given time period,
- k_{trans} is the transfer coefficient,
- θ_{set} is the temperature set-point of the control system,
- $\Delta\theta_{ctr}$ is the impact of the actual control system. It is equal to 0 if the system is perfectly balanced, it has negative or positive values in the case of cooling or heating respectively,
- θ_{ref} is the reference temperature, according to the external environmental condition,
- Δt is the duration of the given time period.

B.4 Correction coefficient approach

The impact on the energy consumption calculated with the correction coefficient approach is evaluated as follows [19]:

$$E = E_{ref} \cdot k_{ctr} \tag{B.8}$$

where:

- E is the demanded or consumed energy,
- E_{ref} is the consumed energy in the reference situation,
- k_{ctr} is a correction coefficient that represents the increase or decrease of energy consumption with respect to the reference situation. It depends on the boundary conditions, like the climate.

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