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Definition and Assessment of Advanced Control Strategies for a Flexible Double Skin Façade with Building Performance Simulation

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Med vennlig hilsen,

Francesco Vasco

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Abstract of the Thesis work

The increasing energy consumptions and the related environmental impact of the *AEC* sector is one of the most challenging issues that the construction industry is facing in the last decades. For this reason, the engineers and the designers are now called to find new technologies and innovative processes to reach the ambitious target of the complete decarbonization of the building sector by 2050, which is a priority goal for the limitation of the global warming effect in the immediate future.

A possible path to follow in this field is the improvement of the existing envelope technologies, which must ensure a better performance of the building, considering both, the energy efficiency, and the indoor environmental quality for the occupants. Dynamicity and responsivity to different operating and seasonal conditions are the requirements that these new innovative envelope systems must provide, to ensure the best performance under different situations. These types of new envelope solutions are commonly named as *responsive building elements* (*RBEs*). This Thesis in particular deals with a specific typology of this kind of envelopes: the flexible *double skin façade* (*DSF*), an innovative concept of ventilated façade system which offers the possibility to switch between different operating configurations in accordance with specific conditions, to ensure a proper behaviour adaptability and consequently the best building performance.

Dynamic envelope systems such as a flexible *DSF* must be provided with an efficient control logic that must be able to ensure the best adaptability to the different operating and seasonal condition in autonomous ways, without any intervention of the building occupants: the definition and the subsequent implementation of the control logics are consequently crucial steps in the design of this typology of building enclosures. The adoption of wrong or not so effective control solutions can have in fact a negative impact on the system behaviour, generating a worsening of the performance compared to traditional envelope enclosures. In this context, *building performance simulation* (*BPS*) environments such as IDA ICE or EnergyPlus can be an effective tool for the development and the subsequent preliminary testing of several control solutions during the *RBE* design phase.

Connected to these concepts, the Thesis aims to develop different control strategies for a flexible *DSF* with the adoption of a commercial *BPS* tool (IDA ICE), trying to understand the interconnections between the control and the overall performance and behaviour of the building system under a multidomain point of view. The final purpose is in fact to define strengths and weaknesses of the different implemented controls, selecting the optimal solutions that can be applied in different boundary conditions (defined in function of climate, location and façade orientation). Starting from a *temperate* climate (Frankfurt), different *rule-based* control structures have been tested in heating, cooling, and mid-season operating conditions, corresponding to the months of July, January, April and October. The results of the testings have been adopted for the development of a single control structure for the flexible *DSF,* applicable through the whole year, which has been afterwards optimized by means of a parametric routine. The optimized control solution applied to the flexible *DSF* has been at the end compared with the performance of a *single skin* system and a traditional *DSF* (with only *TB* and *OAC* configurations applied), with the purpose to show the advantages offered by this kind of innovative envelope solution.

At the end of the process, the optimization routine for the annual control of the flexible *DSF* has been conducted in a *Mediterranean* and in a *continental* climate, represented by the locations of Madrid and Oslo respectively, characterized by more extreme and critical environmental conditions. This step has investigated the adaptability of the controlled *DSF* system to different boundary conditions, in order to test in which context the proposed solution has generated the best performance improvement compared to traditional transparent envelope enclosures.

List of abbreviations

- *AEC: Architecture, Engineering and Construction*
- *DSF: Double Skin Façade*
- *SSF: Single Skin Façade*
- *RBEs: Responsive Building Elements*
- *BPS: Building Performance Simulation*
- *NMF: Neutral Model Format*
- *ICE: Indoor Climate and Energy*
- *HVAC: Heating, Ventilation and Air Conditioning*
- *AHU: Air Handling Unit*
- *CAV: Constant Air Volume*
- *AS: Air Supply*
- *AE: Air Exhaust*
- *TB: Thermal Buffer*
- *OAC: Outdoor Air Curtain*
- *IAC: Indoor Air Curtain*
- *CF: Climate Façade*
- *U: Thermal Transmittance*
- τ_e: *Total Solar Transmission*
- τ_v: *Visible Transmission*
- *SHGC: Solar Heat Gain Coefficient*
- *TGU: Triple Glazing Unit*
- *DGU: Double Glazing Unit*
- *SGU: Single Glazing Unit*
- *IEA: International Energy Agency*
- *IEQ: Indoor Environmental Quality*
- *IAQ: Indoor Air Quality*
- *ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers*
- *PMV: Predicted Mean Vote*
- *PPD: Predicted Percentage of Dissatisfied*

1. *Introduction of the Thesis work*

1.1. *Energy consumption and carbon emission in the building sector*

According to the 2020 data, *AEC* industry constitutes the *36%* of the global final energy demand and the *37%* of the energy related CO_2 emissions [1]. In 2014, the final energy consumption from the building sector was the *31%* of the overall global value of energy consumption, while the emission share was only *29%* [2]. In 2018 energy-related CO_2 emissions from the building sector reached the highest recorded percentage of *39%* [3] (*Figure 1*).

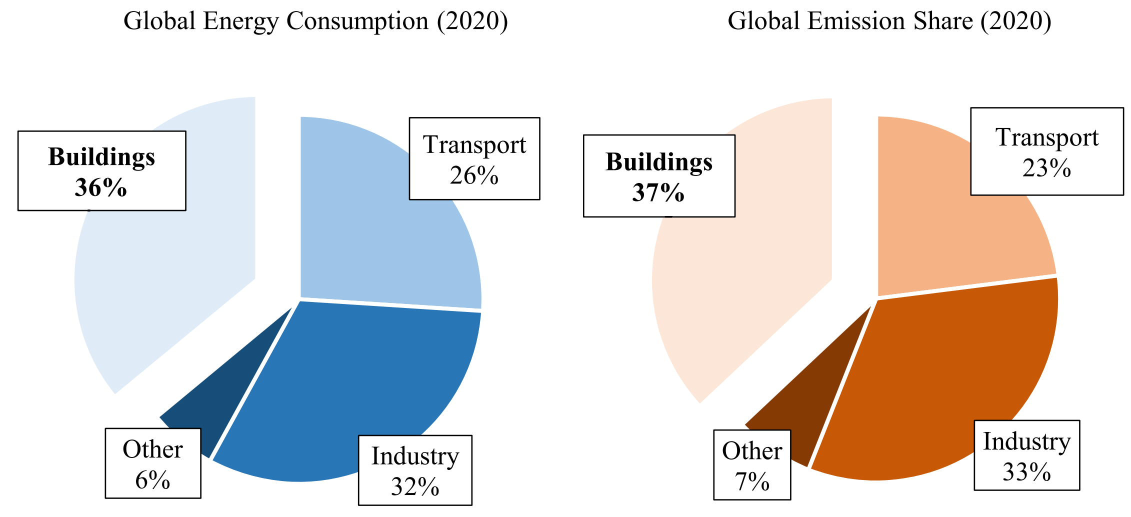


Figure 1: Global share of buildings and construction final energy and emissions (2020) [1].

In this perspective, to achieve the *2015 Paris Agreement* goal of keeping global temperature rise below *2°C*, the global construction sector must be almost entirely decarbonized by *2050*. Crucial strategies for the building industry in the next decades must be consequently devoted to the reduction of the CO_2 outputs. In fact, important performance targets to achieve are the reduction of the overall building energy demand and the increased use of renewable energy sources. Adopting these two solutions, it could be possible to nearly eliminate the carbon emissions from the building operations by *2050* [1]. New constructions and buildings consequently are required to have a very high energy performance, corresponding to a very low energy consumption for all the end uses. New technologies and innovative processes for the building sector are consequently required to reach these ambitious targets in the next years. This Thesis in particular tries to analyse possible innovative solutions that are focused on this objective.

1.2. *Responsive Building Elements: paradigm shifts in the envelope design*

A better performance of the external enclosures of the building (both opaque and transparent) is always linked with a greater energy efficiency of the whole system [4]. In fact, during the last 100 years, the focus in the building envelope design was the reduction of the thermal transmittance value to enhance the insulation level and reduce in this way the transmission heat losses during the heating season. Regarding in detail the transparent portion of the building envelope, significant progresses have been reached in the last decades for the reduction of the overall thermal transmittance, thanks to the adoption of multiple glazing units, high-performance coatings or transparent insulation.
The reduction of the heat losses through the envelope is of course the optimal solution for the lowering of the building space heating demand during the winter season but other important performance targets are required, as for example the energy reduction for space cooling, the optimization of the daylight use and the solar energy exploitation (both passive and active). An efficient building envelope should be consequently able to perform all these different tasks, with the main aim of guarantee the optimal indoor comfort conditions with low energy consumption. Further and innovative research is therefore necessary to improve existing envelope technologies for a better efficiency of the buildings.

This Thesis in fact tries to analyse an innovative kind of envelope technology that can be used for the achievement of these ambitious goals: the *DSF* system. In the specific, an innovative and *flexible* concept of *DSF* has been considered for the Thesis development.

The responsivity to different functional conditions could be a possible feature of such kind of innovative envelope systems. In this field, new functions for the envelope systems can be for example the adaptability to different weather conditions and seasonal operations and the capability to balance opposite performance criteria of the whole system (as, for example, cooling and heating energy needs) [5]. For these reasons, from a static and isolated component, the façade had changed its role into an active and dynamic element, functionally integrated with the other building systems (a *paradigm shift* in the building design process). The dynamicity of the façade stays in fact in its adaptive characteristics and functions that can be adjusted to respond to environmental variations, with the main purpose to keep comfort conditions for the occupants with the lowest possible energy demand [6]. Such kinds of innovative technologies are commonly named as *Responsive Building Elements* (*RBEs*) and systems.

Being characterized by a variation of their features along the year, two crucial requirements for such kinds of elements are the adaptability to different boundary conditions (both internal or external) and the autonomy in the change between a configuration to another one (*Figure* 2). For this reason, dynamic systems as *RBEs* are always managed by a control system, that can change the façade performance requirements in autonomous way if there is a variation in the system boundary conditions [7]. From these first considerations, the impact of the control strategy implementation for an adaptive façade performance is considerably relevant: a wrong control strategy implemented for the dynamic façade can have in fact a negative impact on the whole building energy performance and indoor comfort conditions for the occupants.

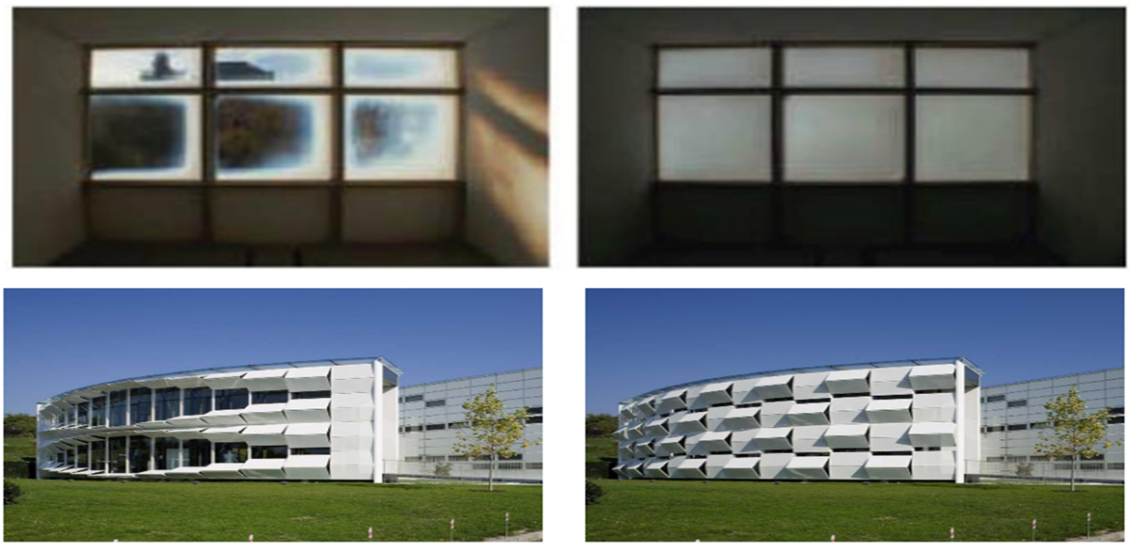


Figure 2: Examples of adaptive and responsive envelope technologies: Thermo-tropic glazing (up) and movable solar shading (down) [8]. The movable solar shading is from Kiefertechnich Building, Ernst Giselbrecht + Partner, Styria, Austria, 2007.

1.3. Scope and research domain of the Thesis work

In function of what it has been stated about the building energy performance and the control implementation of adaptive envelope systems, it is now possible to define the main purpose and the wider objective of the Thesis work. The Thesis scope is the study of optimal control strategies for a responsive building element (in this specific case a flexible *DSF*) and the subsequent evaluation of their effectiveness in the improvement of the overall building performance under a multi domain point of view. For these tasks, a commercial *Building Performance Simulation (BPS)* tool (IDA ICE) has been used.

The research domain of the Thesis can be consequently articulated in the following elements:

- The control strategies implementation for a flexible *DSF*

- The effectiveness evaluation of the implemented control
- The performance assessment of the façade system and its influence on the building performance

1.4. The control of responsive building elements

The control of a building system can be articulated in 3 different levels (*Figure 3*) [9]:

- *Sensor level*
- *Actuator level*
- *Control logic level*

The sensor level is composed by the so-called *sensed variables* or *control variables* that are used by the control logic to monitor the state of the different façade components, the outdoor climate and/or the building environment. The sensed variables can be referred therefore to the external boundary conditions (outdoor air temperature, incident solar radiation, wind velocity, etc.), to the indoor environmental conditions (indoor air temperature, illuminance levels, CO_2 concentrations, etc.) or to the different façade components (cavity air temperature, internal surface temperature, etc.).

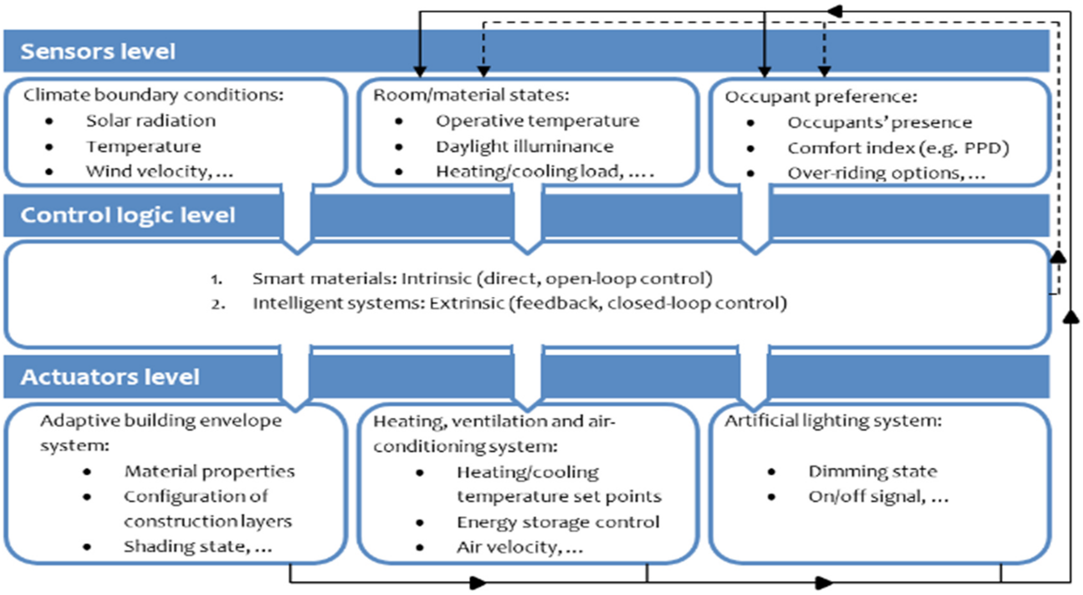


Figure 3: Scheme of the three levels of the control for RBEs [9].

The actuators level comprises all the façade and building components that can be controlled by the implemented control logic. In general, dealing with adaptive façade systems, the main actuators are the operable façade components (blinds, openings, fans, windows, etc.) or the other building technical systems (connection to the *HVAC* system, indoor artificial lighting, etc.) that can change their configurations and operational settings.

At the end, the control logic level provides the link between the sensed variables and the actuator actions, defining the way the different actuators should response to a variation in the boundary conditions.

Another important distinction between different control implementations is the one existing between the two different approaches that can be followed during the control design:

- *Rule-based control*
- *Model-based control*

In the first case, the designer defines a specific set of rules focused on one or more control variables. It is usually defined with the expression *if condition, then action*: this means that if a certain threshold value for a given control variable is reached, a specific actuator state is defined. For this reason, rule-based algorithms usually take the shape of *decision trees* in which to a certain set of predefined conditions correspond the possible configurations of the system. The rule-based approach is the simplest way to follow when the designer must deal with adaptive façade systems, and it is also the most diffused way to control responsive façade elements in buildings.

The rule-based approach has anyway two great disadvantages [10]:

- It is entirely based on the knowledge and experience of the designer about the physical behaviour of the façade and its components: he in fact must understand a priori which will be the operating conditions of the façade and in function of them define the most appropriate set of rules.

- It can offer a response just to a predefined set of boundary conditions, without considering the dynamic and transient behaviour of the system: even if the number of implemented conditions is high (corresponding to a higher number of rules), it is impossible to cover all the possible changes in the operating conditions of the system.

For these reasons, more advanced control strategies have been implemented: it is the case of the *model-based* approach, in which the optimal asset for the actuators is defined for each time step by means of simulations on a virtual model of the system: optimal control actions for the system are therefore defined by means of an embedded simulation, not in function of a pre-defined set of rules [11]. For the actuation of this control strategy, it is necessary to define a priori some performance indicators that will be used by the simulation environment to address the control mechanism of the façade and the optimal asset of the system.

With such a kind of control, the dynamic simulation can define which one of the many possible façade configurations and actuators states produces the best results in terms of overall performance [10]. It is evident that the model-based approach can cover a wider range of configurations and boundary conditions for the dynamic façade but however it is more complex to implement, and it requires a greater computational effort to run all the different dynamic simulations.

During this Thesis work, given the higher complexity of the model-based strategies compared to the rule-based ones, the latter approach has been followed for the implementation of the *DSF* control and the subsequent evaluation of its effectiveness. One of the objectives of the Thesis, however, is the one to show the limitations in the use of less advanced forms of control (as the rule-based) in the performance optimization of a *DSF* system.

As mentioned before, for the implementation of the control for the flexible *DSF* and the subsequent evaluation of the performance of the system, a *BPS* tool (IDA ICE) has been used. Given the high complexity of this kind of simulation environments and the additional difficulties in the modelling of *RBEs* inside them, more details about this topic are inserted inside *Appendix A - The use of BPS tools for the modelling of RBEs and IDA ICE features*, to offer to the reader a wider knowledge about the tools used during the Thesis work.

As written in *1.2* the analysed *RBE* in this Master Thesis is a flexible *DSF*. It is assumed that the reader of the Thesis already knows the main features of this kind of envelope system and its evolution across the last decades. For a better and more detailed description of the *DSF* concept, it is possible to read *Appendix B - The DSF system*. Moreover, the modelling process of this kind of elements inside the IDA ICE simulation environment is illustrated in detail in *Appendix C - DSF modelling in IDA ICE.* In the appendix in fact, it is described the process for the creation of a *flexible DSF* model inside the simulation environment, following the approach and the methodology adopted by Elena Catto Lucchino in her PhD Thesis. This flexible *DSF* model has been used in this Master Thesis for the implementation of the control for this kind of *RBE*.

1.5. Aim and goals of the Thesis in relation to the control of the DSF

The aim of the Thesis is the development of advanced control strategies for a flexible *DSF* by means of the *BPS* tool IDA ICE and the subsequent evaluation of their effects on the overall performance of the system.

The two goals of the Master Thesis, that are specifically interconnected between each other, together aim to reach the wider and more general scope of the work.

1.5.1. Simulation workflow development for the control of the flexible DSF

The first goal is to set a simulation workflow on the *BPS* tool IDA ICE that can be applied to a *DSF* for the study and the effectiveness evaluation of advanced rule-based control strategies on the overall energy and *IEQ* performance of the building. This goal is specifically linked to the definition of a set of methods inside a simulation environment that must be able to assess the effectiveness of different rule-based control strategies under a multi-domain point of view. In synthesis, the result of this goal is to understand how to assess in a quantitative way the effectiveness of a certain control logic by means of a *BPS* tool in different periods of the year (summer, winter, and mid-season conditions) and consequently define an annual control for a flexible *DSF*.

The simulation workflow can be articulated in the following three phases (*Figure 4*):

1) Definition of the initial boundary conditions in which the control logics of the *DSF* can be tested: the initial boundary conditions are defined by a façade orientation (for example, South), a location and the related climate (in this case, Frankfurt, characterised by a *Temperate-Oceanic* climate [12]) and critical cooling season and heating season conditions (corresponding to the months of January and July).

2) Testing of the optimal control logics for summer and winter conditions in the same location and climate and for the same façade orientation but in typical mid-season periods (for example, the months of April for the spring and October for the autumn conditions). In this way, it is possible to test the control effectiveness during the mid-season periods (autumn and spring) characterised by more variable environmental conditions.

3) Combination of the optimal control strategies for the cooling season and heating season conditions and implementation of a single rule-based control for the *DSF* that can be applied to the whole year for the selected location, climate, and façade orientations (in this case, Frankfurt, for a South exposed façade). With this last step, it is possible to define a common control structure for the *DSF* that can be adopted for the whole year during all the different seasons (summer, winter, spring and autumn).

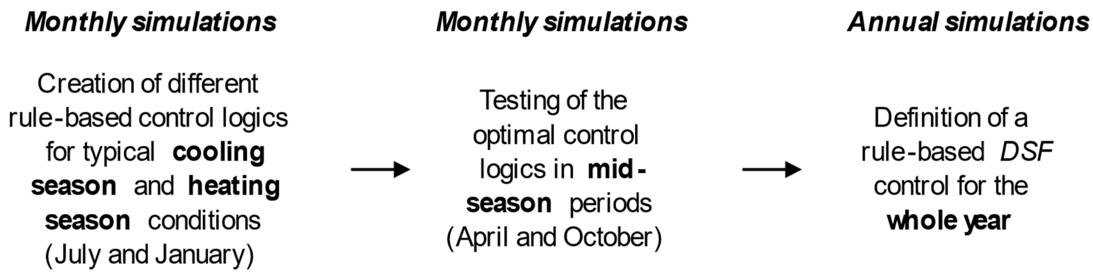


Figure 4: The 3 different phases of the simulation workflow development for the creation of the rule based DSF control for the whole year

1.5.2. Performance optimization for the flexible DSF for other boundary conditions

The second goal is focused on the optimization of the control logic referred to whole year (defined following the first goal) by means of a parametric analysis, in which the threshold values of the different control variables adopted in the rule-based structure are combined in different way with the purpose to find the optimal combination. The second goal consequently is related to the performance optimization of the *DSF*: after the definition of the structure of the control logic for the control of the *DSF* through the whole year by means of the first goal, it is possible in this way to improve the performance of the *DSF* for the selected boundary condition (Frankfurt, South exposed façade) by analysing different combinations of control variables values adopted inside the control logic (this is a so called *parametric* optimization).

The same control structure can be later applied to other boundary conditions (for example other climates, locations and façade orientations) and optimized following the same parametric approach. In this way, given an initial structure for the control referred to whole year, it is possible to change the threshold value adopted in the rule-based control to ensure the adaptation to different boundary conditions.

1.6. Objectives of the Thesis

This section is focused on the definition of the more specific objectives that are linked to the two main goals of the Master Thesis:

- About the first goal, focused on the simulation workflow development for *DSFs* and the definition of a rule-based control logic applicable for the whole year, the main objectives of the Thesis are:

1) Define the performance targets that the *DSF* must guarantee and understand which control strategies can be specifically linked to these performance targets.
2) Define the performance metrics that can be used for a quantitative evaluation of the performance of the *DSF*.
3) Define different combinations of rule-based control strategies and evaluate their effects on the whole performance of the system, during heating, cooling and mid-season conditions and, in accordance with the results of the analysis, develop a single control strategy for the *DSF* that can be used through the whole year.

- About the second goal, focused on the performance optimization for a *DSF,* the main objectives of the Thesis are:

1) Define which control variables of the rule-based decision tree should be selected for the combination creation and the parametric optimization of the control.
2) Define which ranges of values for each control variable can be considered for the performance optimization of the *DSF*.
3) Understand which combinations of values produce the best results for the system performance
4) Understand how the performance of the system is affected by a change in the initial boundary conditions (as for example, climate and location).

1.7. Research hypothesis and simulative methodology of the Master Thesis

Connecting the concepts explained in *1.5* and *1.6,* it is possible to define the methodology of the Master Thesis and the related research hypothesis. The expected research outcomes regarding the control of the *DSF* are the following ones:

- The multi-domain performance of a *RBE* such as a flexible *DSF* is better than a standard *SSF* (for example a traditional openable window) or a traditional *DSF* only if the correct control strategy is implemented for the different façade actuators.
- Different rule-based control strategies have different degrees of effectiveness, affecting consequently in a different way the behaviour and the performance of the *DSF*.
- The adoption of rule-based algorithms for the control of the *DSF* can be ineffective for a *multi-domain* optimization of the system (considering both, *IEQ* and overall energy efficiency), compared to more sophisticated forms of control (as for example the model-based approach).
- If the boundary conditions are changed (for example season, climate or façade orientation) also the effectiveness of a certain control can change.

The main research questions which have been addressed the Thesis work are listed here:

- How can the adaptive envelope system guarantee performance objectives of energy efficiency and comfort for the occupants?
- Which specific control strategies can be connected to these objectives and how they can achieve them?
- Which control variables should be selected for the control?
- Which performance metrics must be then considered for a quantitative evaluation of the *DSF* efficiency in a *multi-domain* perspective?
- Which are the benefits and the disadvantages of the different control structures that can be implemented?
- Which is the optimal control strategy to be applied for a particular boundary condition (in particular, season, façade orientation and climate)?
- How different boundary conditions can change the *DSF* behaviour and consequently the effectiveness of the control?

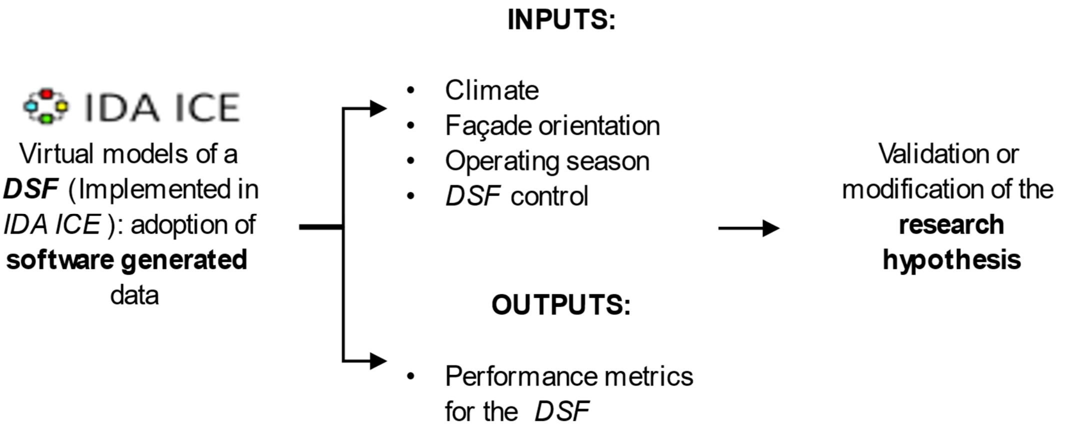


Figure 5: Research methodology and simulative approach scheme followed in the Master Thesis

Being a scientific report, this Master Thesis has followed a quantitative approach for the collection and analysis of the data generated inside the simulation environment of IDA ICE.

According to the research methodology followed during the Thesis work (*Figure 5*), the testing of the different research hypothesis regarding the dynamic behaviour of the *DSF* and the subsequent analysis of the results are carried on a virtual model of a *DSF* model realized on the *BPS* tool IDA ICE.

The simulation environment has been therefore used for the control strategies development and the subsequent evaluation of the system performance. The Thesis has consequently followed a simulative approach, adopting software-generated data instead of experimental ones.

Inside the *BPS* tool a set of inputs and outputs can be defined:

- **Inputs**, corresponding to the boundary conditions of the simulations performed on IDA ICE.

  They are in particular:

  1) The climate and the orientation in which the façade is located.
  2) The operating season of the façade system (heating, cooling or mid-season period as also the whole year).
  3) The implemented control logic for the façade actuators (cavity air flows and shading system).

- **Outputs**, corresponding to the simulated data and the results of the simulations performed on the *BPS* tool.

  They can be referred to the two main performance domains:

  1) Energy efficiency (heating, cooling, and artificial lighting energy needs)

  2) Indoor environmental quality for the occupants (thermal and visual comfort and *IAQ*)

These outputs have been used for the definition of the performance of the *DSF*. According to the outputs, it is possible to verify or modify the previously defined research hypothesis regarding the control of the *DSF* and its effectiveness.

The research method that has been used for the performance assessment and the control effectiveness evaluation during the Thesis work will be discussed more in detail in *3*, after the description of the control implementation for *DSF* systems in *2*.

2. The control of the flexible DSF

Being the Thesis focused on the control implementation for a *DSF* system, in this chapter are described more in detail the concepts regarding the control of this typology of *RBE*.

2.1. Characteristics of the control for a DSF

Ventilated double skin systems, as adaptive envelope systems, require an efficient control to manage the variations of different boundary conditions (seasonal weather variations and changes in the operations of the building).

The two main aims of the control strategies implementation for a *DSF* are therefore the following ones [12]:

- Provide an efficient use of the solar gains during the heating period
- Provide an acceptable environmental comfort during the whole year

In addition to these two major objectives of the control, other two performance targets must be followed:

- During the unoccupied periods (for example the night-time and the weekend), the focus of the control strategy must be the overall energy savings of the building.
- During the occupied periods, the focus of the control strategy must be the comfort conditions for the occupants.

To sum up, the aim of the control strategy is the adaptation of the thermophysical behaviour of the *DSF* according to the different boundary conditions, for a better energy and indoor climate performance.

Considering typical heating and cooling season operations for the façade, the main aims for the *DSF* configurations can be summarized as [4]:

- For cooling season periods, the main aim is the one to reduce the passive solar gains and the related overheating risk. The most feasible ventilation modes of the façade for this aim are the *OAC* and the *AE*. In some cases, also the *AS* configuration can be adopted, to provide the indoor environment with fresh air. For the nights, in colder or temperate climates, it could be necessary also the adoption of *TB* configuration to reduce the heat losses.

- For heating season periods, on the contrary, the main aim of the control strategy is to maximize the passive solar gains to reduce heat losses through the envelope and energy for ventilation heating. The most feasible ventilation modes that can be associated to these aims are *AS*, *TB*, *IAC* and *CF*. Anyway, for some warmer climates, also the use of the *OAC* or *AE* can be required in winter season.

2.2. Control logics and DSF performance

In this section, the focus of the analysis is the evaluation of the possible relations between a certain performance target of the *DSF* and the control strategies that can be used to achieve them.

In fact, this study process can be articulated trough the following 5 steps:

1) *Definition of the performance requirements*
2) *Connection between performance requirements and control strategies*
3) *Selection of the control variables.*
4) *Selection of the façade actuators*
5) *Implementation of the control strategies for the DSF*

2.2.1. Definition of the performance requirements for the DSF

About the first point, there are basically four domains of the performance for a generic façade system [13].

The first three are mainly linked with the indoor environmental quality (*IEQ*) while the fourth one is focused on the energy performance of the whole building.

- Thermal comfort, linked to the indoor temperatures.
- Visual comfort, linked with the illuminance levels inside the indoor environment.
- Indoor air quality, connected with the amount of CO_2 inside the indoor environment.
- Energy need, focused on the energy requirements of the whole building for heating, cooling and artificial lighting.

For these four different aspects of the performance, it is possible to identify standards and regulations (both national and international) that set optimal values for the related physical quantities (temperatures, illuminance levels, energy consumptions etc.), in relation to different performance targets. These values, since they are prescribed by specific requirements and authorities, can be used to address the control definition of the façade system. For the thermal comfort, optimal values of indoor operative temperatures that must be guaranteed inside different typologies of environments are provided in the standards *EN ISO 7730:2005* and *EN 16798-1:2019* [14] [15].

For the visual comfort, minimum values of indoor illuminance levels on the working plane that must be guaranteed are provided in the standard *EN 12464-1:2011* [16]. Additional requirements for daylight are also provided inside the standard *EN 17037:2018*, regarding the glare discomfort risk [17]. About the energy savings, for some countries (Norway for example) maximum values of total net energy demand are expressed for different categories of buildings [18]. It is not anyway possible to have related standards for other countries about the maximum energy consumption for office buildings. For this reason, for the evaluation of the energy performance, a comparison with a traditional transparent façade system can be used (defining a comparative analysis with a baseline system, as done in this Thesis work).

Additional requirements, not specifically linked to the performance of the system, are referred to the ventilation of the indoor environment. The standard *EN 16798-1:2019* defines in this case default predefined ventilation air flow rates for offices, that must be provided to the indoor spaces [19].

A recap of the different performance requirements for the addressing of the control is reported in *Table 1*.

Performance domain	Reference standards
Thermal comfort	• *EN ISO 7730:2005 Table A.5* • *EN 16798-1:2019 Table B.2*
Visual comfort	• *EN 12464-1:2001 Table B.26* • *EN 17037:2018 Table E.1*
Indoor air quality	• *EN 16798-1:2019 Table B.9* • *EN 15251-1:2007 Table B.4* • *ASHRAE* guidelines for ventilation

Table 1: Performance requirements and related reference standards

2.2.2. Connection between performance goals and control strategies for the DSF

For each one of the performance targets, it is then necessary to understand which general control strategies can be defined to reach the predefined goal. In particular, the designer must understand how a specific control can be used to address a specific pre-defined goal.

- For the thermal comfort in the indoor environment, the possible control strategies that can be defined are for example:

1) Control of the solar gains in summer to avoid possible overheating conditions.
2) Control of the solar gains in winter to maximize their benefits on the indoor thermal environment.
3) Control of the cavity ventilation to avoid possible overheating of the cavity air.

4) Control of the air flow paths from the cavity to the indoor environment to avoid possible cold drafts or vice versa hot air streams.

- For the visual comfort, the possible control strategies for the *DSF* actuators are:

1) Guarantee the minimum illuminance levels on the work plane using the daylight.
2) Control of the glare discomfort risk.

- For the overall energy performance:

1) Control and improve the insulation level of the façade system during the winter period to reduce the transmission heat losses towards the external environment and reduce in this way the energy needs for space heating.
2) Control the air flows path in the cavity to guarantee a pre-heating of the ventilation air by means of the incident solar radiation (passive use of solar gains), which can be consequently introduced in the indoor environment or in the ventilation system, with the purpose to reduce the energy need for ventilation heating.
3) Control the air flows paths in the cavity to ensure the extraction of the heated air inside it, reducing the energy need for space cooling during the summer.
4) Control the solar radiation entering in the indoor environment, that can cause possible overheating and therefore an increased energy demand for space cooling.
5) Control the amount of the daylight entering inside the indoor environment, to limit the use of artificial lighting during the occupied hours and therefore the related energy consumption.

2.2.3. Selection of the control variables to be used in the control

After the definition of the possible control strategies, the designer should set a group of control variables that can be used for the addressing of the control strategies for the adaptive façade. The control variables for the *DSF* system can be referred to three main domains:

- Indoor environment, corresponding to the thermal zone linked with the façade system
- Outdoor environment, influenced by climate and weather conditions
- Cavity of the *DSF*

For each one of these domains, it is possible to set a group of possible control variables that can be used for the addressing of the operations of the façade system.

Regarding the indoor environment, the control variables allow to evaluate the indoor climate conditions and in function of them define the proper control strategies for the façade system. These control variables are important especially for the definition and the monitoring of the indoor comfort conditions (both thermal and visual) and the indoor air quality of the zone:

1) *Indoor air temperature* (θ_{indoor})
2) *Indoor illuminance levels on the horizontal plane* (E_H)
3) *Indoor CO_2 concentrations* ($C_{(ppm)}CO_2$)

For the outdoor environment, the control variables can be used to monitor external environmental conditions in which the façade system is working:

1) *Outdoor air temperature* ($\theta_{outdoor}$)
2) *Incident solar radiation on the façade* (I_{sol})

For the DSF cavity, the main one to consider is the cavity air temperature:

1) *Cavity air temperature* (θ_{cavity})

2.2.4. Selection of the DSF actuators and their possible states

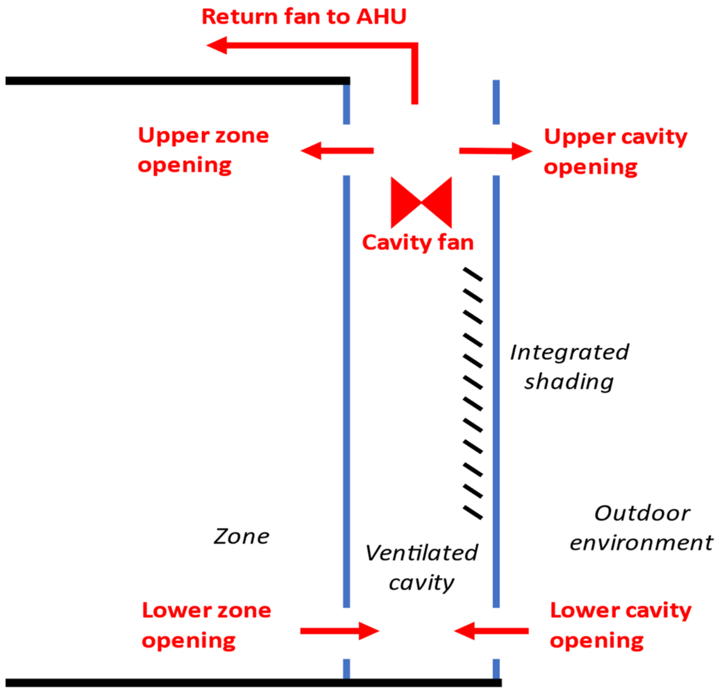


Figure 6: Functional scheme of the flexible DSF model with the different façade actuators

In the next step, it is necessary to understand which actuators of the flexible *DSF* are more suitable for the actuation of the control.

The actuators that can be used for the switching of the *DSF* configurations are the following ones (*Figure 6*), illustrated in the functional scheme of the flexible *DSF* model that has been adopted for the Thesis work.

- Cavity-integrated shading devices (for the selected *DSF* system a venetian blind will be used): for them it is possible to regulate the drawn mechanism (activation of the venetian blind) and the slat angle when the blind is completely drawn.
- Zone openings (upper and lower), located in the inner skin of the *DSF*: they can be open or closed to allow or avoid the air to be transferred between the cavity and the adjacent zone.
- Cavity openings (upper and lower), located at the top and at the bottom of the façade cavity: they can be basically open or closed, as seen for the zone openings. In this case, the openings have the role to allow or stop the air to be transferred between the cavity and the outdoor environment.
- Return fan to the *AHU* (for the implementation of the *CF* configuration): it can be *Off* or *On* (with a certain implemented air flow, corresponding to the one that is provided to the zone).
- Cavity fan for the implementation of the mechanical ventilation in the cavity. It can be *On* or *Off*, with different implemented air flows (minimum and maximum).

Each one of the listed *DSF* actuators, can be suited for the application of a certain control strategy, acting on different aspects of the performance domain.

- **Integrated shading devices**: they are the most suitable actuators that can be used for the performance control of the *DSF* [20]. The main role of the integrated shading devices is to block the direct solar radiation entering inside the indoor environment. This aspect is important both for the indoor thermal comfort conditions and the cooling energy savings during the summer season. Integrated shading devices can be also useful during the heating season: they can absorb the direct solar radiation and then release the heat to the cavity air. They are also important for the daylight availability of the indoor environment and the reduction of energy consumptions for artificial lighting.

- **Zone openings**: they are important for the *IAQ* control of the indoor environment since they can provide fresh air to the zone and reduce in this way the CO_2 concentrations. The use of openings for the air circulation between the air cavity and the zone has also some important consequences on the thermal comfort of the occupants (due to the possibility of too hot or too cold air introduced inside the indoor environment by means of them). Acting on the indoor temperature of the zone, the zone openings control has also effects on the overall energy use for space cooling and heating.

- **Cavity openings**: they can be used for the definition of the façade ventilation modes, as seen for the zone openings. Consequently, the control of the cavity openings (and therefore of the air flows) has multiple effects on the thermal comfort conditions, the energy savings for space cooling, space heating and ventilation pre-heating.

- **Cavity fan**: it can basically act on the air velocity in the cavity when the mechanical ventilation is implemented inside it.

- **Return fan to the AHU**: it can be used to redirect the cavity air to the *AHU* of the thermal zone, exploiting the passive pre-heating of the ventilation air.

2.2.5. Implementation of the control strategies for the DSF

At the end of the process, the control can be implemented for the *DSF*. As mentioned in *1.4* the focus of the control implementation will be the rule-based approach. It is a less advanced control solution compared to the model-based approach, but it is easier to define, and it also requires a lower computational effort from the control system implemented in the façade model.

The most appropriate way to define and assess the efficacy of different rule-based control strategies is to create different combinations of control for the different façade actuators, in the way that will be illustrated in the following section.

The two main objectives of the implemented control strategies are in fact:

- The control of the configuration of the venetian blind (*Up/down* and slat angle values)
- The control of the cavity air flows (by regulating the state of the façade openings and the fans operations)

These two, cavity air flows and shading system, are the so-called *control targets* of the control logic.

As mentioned in *1.5.1*, the initial conditions in which the control effectiveness for the *DSF* is tested correspond to the summer and winter seasons.

It is consequently possible to make a distinction between the different validity periods of the implemented control logics:

- Cooling season
- Heating season

In the first case, the implemented control strategies for the air flows in the cavity are addressed to the typical cooling season configurations of the *DSF* (*OAC*, *AE*, *AS* but also *TB*).

In the second case, on the other hand, the implemented control strategies for the air flows are referred to the typical heating season configurations of the *DSF* (*TB*, *AS*, *IAC*, *CF* but also *AE* and *OAC*).

Given 6 different operating strategies (*TB*, *OAC*, *IAC*, *AS*, *AE* and *CF*), 10 configurations (with both natural and mechanical ventilation) are possible for the summer and winter operations of the *DSF* (*Table 2*).

To each configuration, a number from 1 to 10 can be assigned for an easier recognition (See also, in this case, *Appendix D - Rule-based control implementation in IDA ICE*).

Configuration number	*Cavity air flow configurations*	*Code*
1	Thermal Buffer	*TB*
2	Outdoor Air Curtain (natural ventilation in the cavity)	*OAC_N*
3	Outdoor Air Curtain (mechanical ventilation in the cavity)	*OAC_M VMIN*
4	Outdoor Air Curtain (mechanical ventilation in the cavity and increased air flow)	*OAC_M VMAX*
5	Air Exhaust (natural ventilation in the cavity)	*AE_N*
6	Air Exhaust (mechanical ventilation in the cavity)	*AE_M VMIN*
7	Air Exhaust (mechanical ventilation in the cavity and increased air flow)	*AE_M VMAX*
8	Air Supply	*AS*
9	Climate Façade	*CF*
10	Indoor Air Curtain	*IAC*

Table 2: List of possible air flows configurations that can be implemented inside the cavity, with the related output numbers and codes

For each one of the two periods (cooling season and heating season), specific aims are already defined a priori, as already illustrated at the end of *2.1.*

Inside the two selected periods, it is then possible to define control strategies for the occupied hours and control strategies for the unoccupied periods (mainly lunch hours and night periods), for which different aims must be followed by the façade behaviour: comfort for the occupants in the first case and energy savings in the second one. Inside each one of the two time periods, it is then possible to consider control strategies that are linked to the control of the configurations of the installed dynamic shading devices and on the other hand on the control of the cavity air flows.

The previously listed subdivision is consequently a 3 levels classification based on:

- *Validity period of the control* (Heating or cooling season)
- *Occupancy of the zone* (Occupied or unoccupied hours)
- *Control target* (Shading system or cavity air flows)

According to these three levels it is possible to classify the different typologies of control strategies for the *DSF* in eight different groups (*Table 3*). These groups of controls can be combined in different ways, enabling the definition of different control logics.

Group of controls	*Seasonal operations*	*Occupancy condition in the zone*	*Control target*
Group 1	Cooling season	Occupied	Air flows
Group 2	Cooling season	Unoccupied	Air flows
Group 3	Cooling season	Occupied	Shading
Group 4	Cooling season	Unoccupied	Shading
Group 5	Heating season	Occupied	Air flows
Group 6	Heating season	Unoccupied	Air flows
Group 7	Heating season	Occupied	Shading
Group 8	Heating season	Unoccupied	Shading

Table 3: Definition of the eight different groups of rule-based control types

With this classification, the two *control targets* (shading systems and air flows in the cavity) are basically independent to each other and therefore different combinations of control algorithms can be applied to the façade system (as it will be shown in *2.3*). Different decision blocks referred to the cavity air flows and the shading system can be merged and combined forming wider decision trees, generating in this way different combinations of control that can be implemented for the *DSF*.

According to the existing literature about the control of *DSF* and adaptive envelope systems [5] [6] [21] [22] [23] [24] [25], the possible combinations of control for the cavity air flows and the shading system during the heating and the cooling seasons are numerous. Considering the long process necessary for the implementation of the control in IDA ICE (see *Appendix D - Rule-based control implementation in IDA ICE*) and the subsequent evaluation of the results, a proper number of combinations has been defined. In the next section (*2.3*), the analysis of the different selected combinations will be conducted, analysing the typology of the control, the involved control variables, and the possible benefits regarding their use in the façade operations.

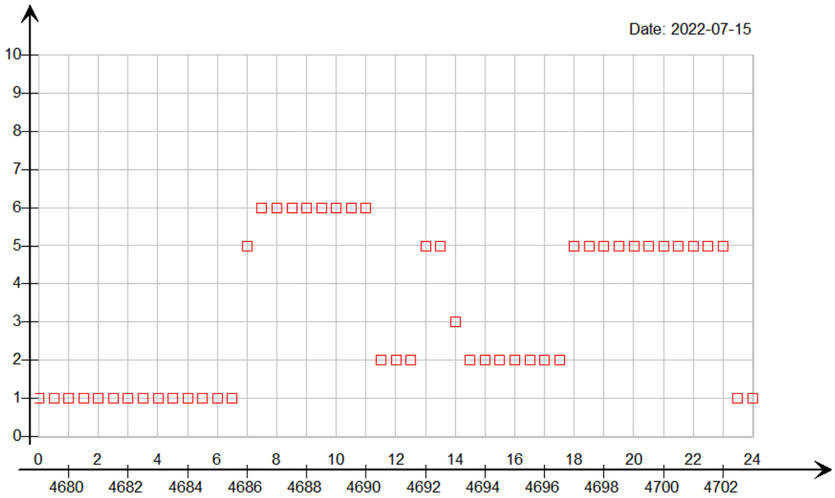


Figure 7: Variation of the flexible DSF configurations with the implementation of the control combination SC#22 in a typical summer day (Output signal from IDA ICE). The configuration numbers are the ones illustrated in Table 2.

In *Figure 7* it is reported an example of variation of the cavity ventilation modes of the flexible *DSF* in a selected summer day in Frankfurt (15th July) with one of the combinations control that will be illustrated in *2.3,* the section focused on the definition of the different control combinations for the façade system. The innovative concept of this kind of flexible *DSF* is in fact the possibility to switch between different operating strategies during the same day, in function of an implemented control logic, to ensure the best adaptability to changing boundary conditions. The implemented control logic in fact must be able to fully exploit the flexibility of the façade system. Traditional examples of *DSF,* on the other hand, are characterized by mainly 2 seasonal configurations, one for the heating and one for the cooling season (typically *TB* for the first one and *OAC* for the last one), allowing in this way a lower degree of freedom of the system.

The same variation can be observed in a typical winter day (4th January), but with the ventilation modes proposed for the heating season in Frankfurt (*Figure 8*). The same concepts valid for the summer season can be of course repeated for the winter: the higher is the number of switchable configurations, the higher is the adaptability capacity of the *DSF*.

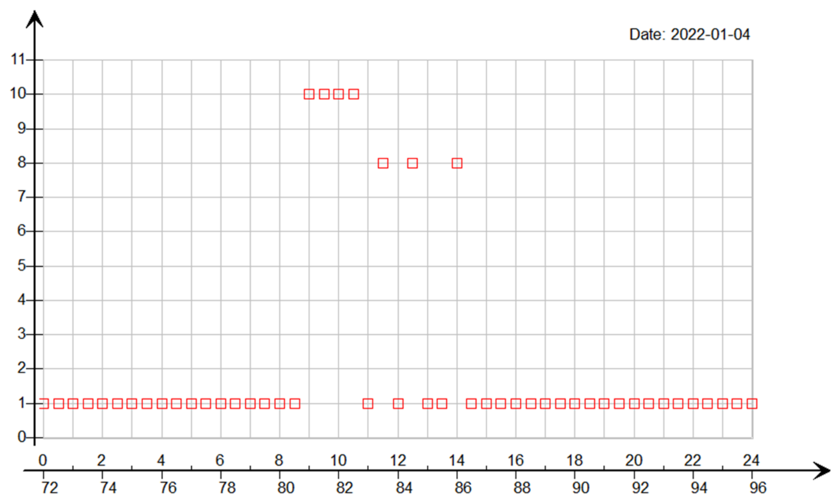


Figure 8: Variation of the flexible DSF configuration with the implementation of the control combination WC#16 in a typical winter day. (Output signal from IDA ICE). The configuration numbers are the ones illustrated in Table 2.

2.3. Combinations of the different control logics

As mentioned before, the different control strategies of the eight groups of control can be combined in different way, creating control decision trees for air flow control and shading control in cooling season and heating season conditions.

The groups of control referred to the occupied and unoccupied hours in the different seasons are always coupled together, to apply different strategies during the working hours and the night or the lunch time. In the next pages, the process used for the definition of different combinations of control strategies for the different actuators will be discussed and analysed.

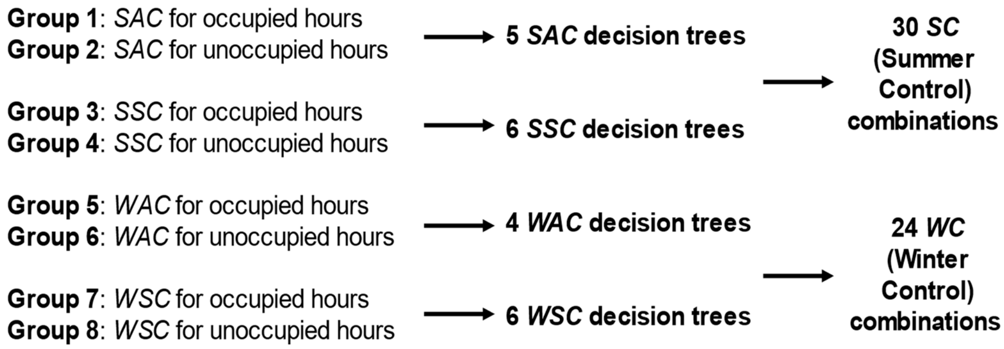


Figure 9: Scheme for the construction of the control combinations in cooling season and heating season

The codes for the definition of the different control decision trees are the following ones:

- *SAC* (*Summer Air Flow Control*), for the control of the cavity air flows in the cooling season
- *SSC* (*Summer Shading Control*), for the control of the shading system in the cooling season
- *WAC* (*Winter Air Flow Control*), for the control of the cavity air flows in the heating season
- *WSC* (*Winter Shading Control*), for the control of the shading system in the cooling season

For sake of simplicity, the *cooling* and the *heating* seasons have been named as *summer* and *winter*. The general scheme used for the defintion of the different control combinations is report in *Figure 9*.

Control for the summer season (*SAC* and *SSC*)

In this section are reported the control structures defined for the cooling season for the shading system and the air flows in the cavity.

Combination of Group 1 and Group 2: Summer Airflow Control (SAC)

Controls of the Group 1 and Group 2 can be used for the air flows control for the cooling season, during the occupied and the unoccupied hours. The code for the identification of these controls is *SAC* (*Summer Air flow Control*). In the case of the summer control of the cavity air flows, 5 different controls will be adopted (from *SAC#1* to *SAC#5*).

In *SAC#1*, the switch between the *OAC* natural and the *AE* natural configuration is performed in function of the indoor CO_2 levels inside the zone. The increasing of the required air flow when the *AE* configuration is implemented is performed in function of the indoor CO_2 levels (the same has been performed also for the 3 other following combinations of summer air flows control): the higher the concentration, the higher the amount of air that is extracted by the cavity of the façade.

The increasing of the required air flow when the *OAC* configuration is implemented on the other hand in function of the indoor air temperature of the zone: the higher the indoor temperature is, the higher is the amount of heat that is extracted from the cavity, for the over-heating prevention inside the thermal zone.

In *SAC#2*, the switch between *OAC* natural and *AE* natural is performed in the same way as *SAC#1*, but the increasing of the ventilation air flow for the *OAC* mechanical configuration is performed in function of the cavity air temperature. Also in this case the over-heating prevention is performed, using another control variable (the cavity air temperature instead of the indoor air temperature).

In *SAC#3* and *SAC#4* respectively, the increasing of the air flows for the *OAC* mechanical configuration are performed in function of the indoor air temperature and the cavity air temperature (as seen in the two previously implemented controls) but the initial switch between the *OAC* natural and the *AE* natural is performed considering the indoor air temperature and the outdoor air temperature. The *OAC* configuration is kept for the worst indoor and outdoor temperature conditions, to ensure the removal of excess heat from the cavity. The *AE* configuration on the other hand is adopted just for milder outdoor conditions (considering a maximum threshold limit of outdoor air temperature).

Finally, for the *SAC#5* control, the use of the *AS* configuration with natural ventilation inside the cavity is implemented, for the introduction of fresh air from the outdoor environment through the cavity of the *DSF*. The *AS* configuration can be implemented if the indoor concentrations of CO_2 are above a certain threshold limit. Anyway, it is necessary to check before the temperature of the cavity, to avoid the introduction of too hot air from the cavity to the room. In this case, if the cavity air temperature is too high, the *AE* configuration is preferred anyway.

For all the control logics, the strategies for the unoccupied hours are the same. During the night, if possible overheating risk is present (indoor air temperature greater than $26°C$) the *AE* natural configuration is applied, to remove the excess of heat. Otherwise, if there is not the necessity to cool down the indoor environment, the *TB* configuration is used, with the purpose to reduce the heat losses through the façade system during the night period. In similar way, during the lunch break, if the indoor air temperature is greater than $26°C$ the *AE* natural configuration is applied. Otherwise, the *OAC* natural configuration is used to avoid possible overheating of the cavity.

The initial threshold limits of the control variables for the switching between the different façade configurations have been initially set in function of the standards regarding the indoor thermal comfort conditions and the *IAQ* for the *Category II* of indoor environmental quality [15] [26] [27] [28].

After the first preliminary simulations preformed on IDA ICE, the values have been modified to ensure a proper flexibility of the façade system between the different configurations implemented for the summer season and at the same time avoid possible numerical instabilities of the simulation (see *Appendix D)*. In this way the control has been optimized for the simulations on the *BPS* tool and the evaluation of the flexibility effectiveness on the performance of the *DSF*. The codes and the related strategies for the occupied and unoccupied hours are reported in *Table 4*.

The decision trees of the different controls are showed from *Figure 10* to *Figure 14* (rotated in vertical orientation to allow a better visualization).

Code for the control	**Occupied hours strategy**	**Unoccupied hours strategy (lunch time and night)**
SAC#1	• *OAC-AE* configurations switch in function of the CO_2 level in the zone • Implementation of *OAC* mechanical configuration in function of indoor air temperature in the office • Increasing of *AE* mechanical air flows in function of the CO_2 levels in the zone	• *AE* natural configuration during the night if overheating is present, otherwise *TB* • *AE* natural configuration during the lunch hour if overheating risk is present, otherwise *OAC* natural
SAC#2	• *OAC-AE* configurations switch in function of the CO_2 level in the zone • Implementation of *OAC* mechanical configuration in function of cavity air temperature • Increasing of *AE* mechanical air flows in function of the CO_2 levels in the zone	• *AE* natural configuration during the night if overheating is present, otherwise *TB* • *AE* configuration during the lunch hour if overheating risk is present, otherwise *OAC* natural

SAC#3	• *OAC-AE* configurations switch in function of the indoor/outdoor air temperatures • Implementation of *OAC* mechanical configuration in function of indoor air temperature in the office • Increasing of *AE* mechanical air flows in function of the CO_2 levels in the zone	• *AE* natural configuration during the night if overheating is present, otherwise *TB* • *AE* natural configuration during the lunch hour if overheating risk is present, otherwise *OAC* natural
SAC#4	• *OAC-AE* configurations switch in function of the indoor/outdoor air temperatures • Implementation of *OAC* mechanical configuration in function of cavity air temperature • Increasing of *AE* mechanical air flows in function of the CO_2 levels in the zone	• *AE* natural configuration during the night if overheating is present, otherwise *TB* • *AE* natural configuration during the lunch hour if overheating risk is present, otherwise *OAC* natural
SAC#5	• *OAC-AS-AE* configurations switch in function of the cavity temperature and the indoor temperature • Increasing of the cavity air flows in function of the indoor temperature (for *OAC*) and CO_2 levels in the zone (for *AE*)	• *AE* natural configuration during the night if overheating is present, otherwise *TB* • *AE* natural configuration during the lunch hour if overheating risk is present, otherwise *OAC* natural

Table 4: Control combinations for the airflows during the summer season

Combination of Group 3 and Group 4: Summer Shading Control (SSC)

Controls of the Group 3 and Group 4 can be used for the shading control for the cooling season, during the occupied and the unoccupied hours. The code for the identification of these controls is *SSC* (*Summer Shading Control*). In the case of the shading, 6 different forms of control will be adopted (from *SSC#1* to *SSC#6*).

2 different types of activation mechanisms of the venetian blind can be used:

- *Incident radiation on the façade*: when the incident solar radiation on the façade is above a certain limit, the venetian blind is drawn.

- *Indoor air temperature*: when the indoor air temperature in the room is above a certain limit, the venetian blind is drawn.

The temperature control of the blind can be influenced with a larger extent by the control of the cavity air flow, which has an influence on the indoor air temperature of the room (both in summer and winter conditions).

On the other hand, the radiation control of the blind is not sensitive on the variation of the indoor environmental conditions since it just considers the incident solar radiation on the façade.

The 2 different types of activation mechanisms for the venetian blind (radiation and temperature), can be coupled with 3 different types of control for the blind slat angle:

- *Fixed*: the blind slat angle is kept constant when the venetian blind is drawn (in this case $45°$, the default one also used inside IDA ICE).
- *Cut*-off: the blind slat angle is regulated to be always orthogonal to the direct incident solar radiation on the façade.
- *Scheduled*: the blind slat angle is regulated to keep a certain illuminance level inside the room.

Consequently, coupling together the 2 different activation mechanisms for the venetian blind with the 3 different types of control for the blind slat angle, the total number of controls for the shading system during the summer season is 6 (the first 3 with the radiation activation while the last 3 with the temperature activation).

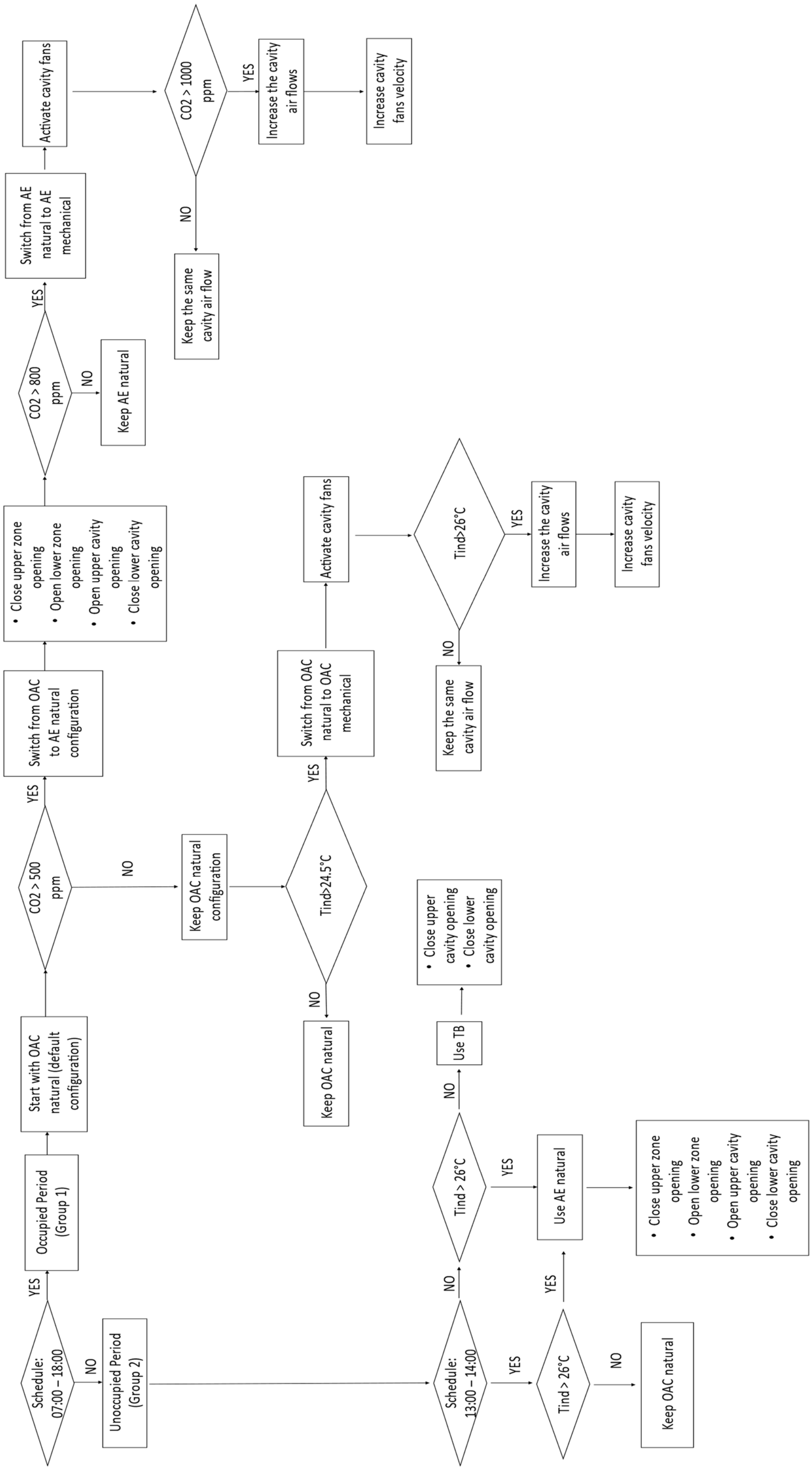


Figure 10: SAC#1 decision tree

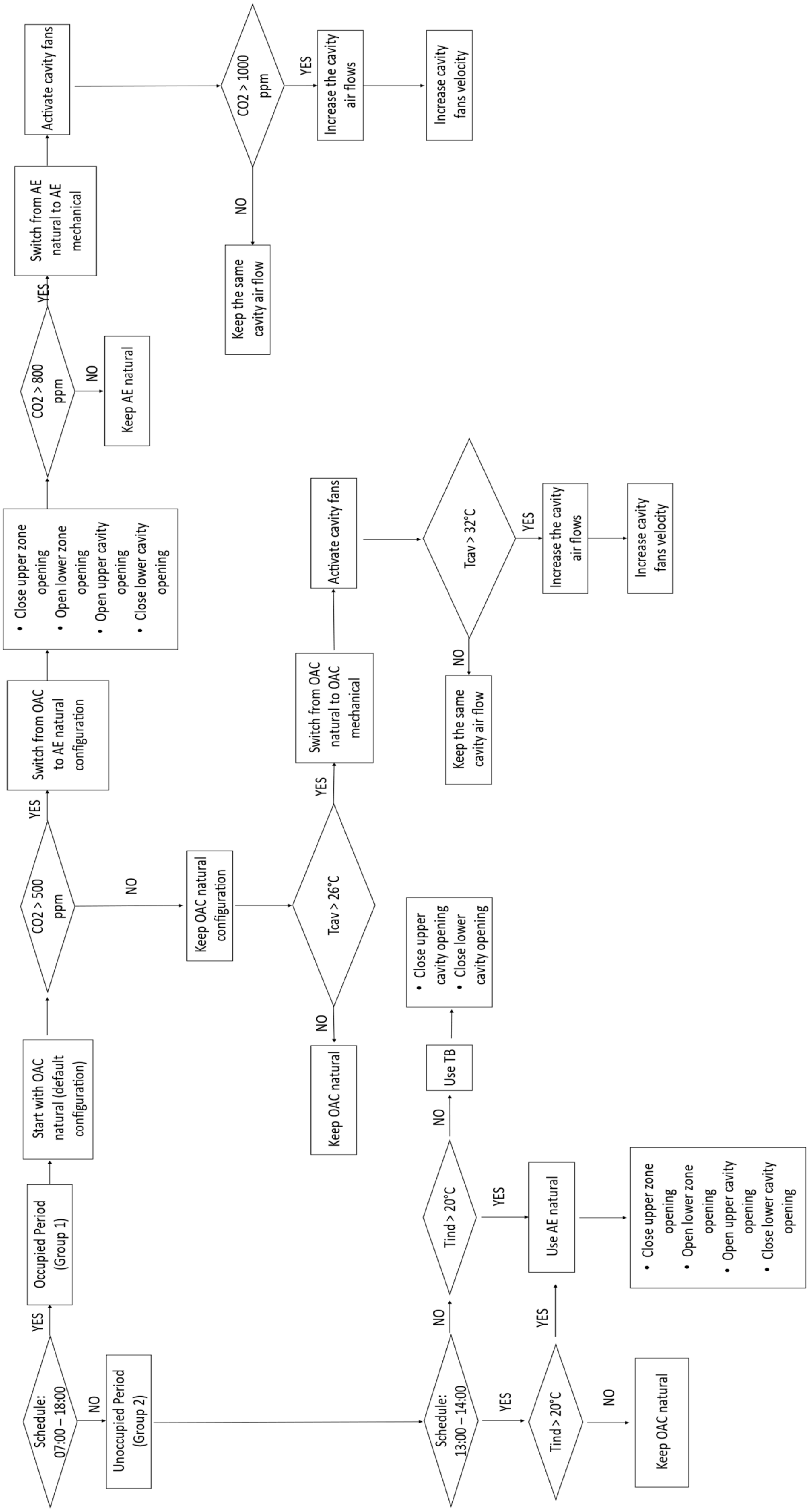


Figure 11: SAC#2 decision tree

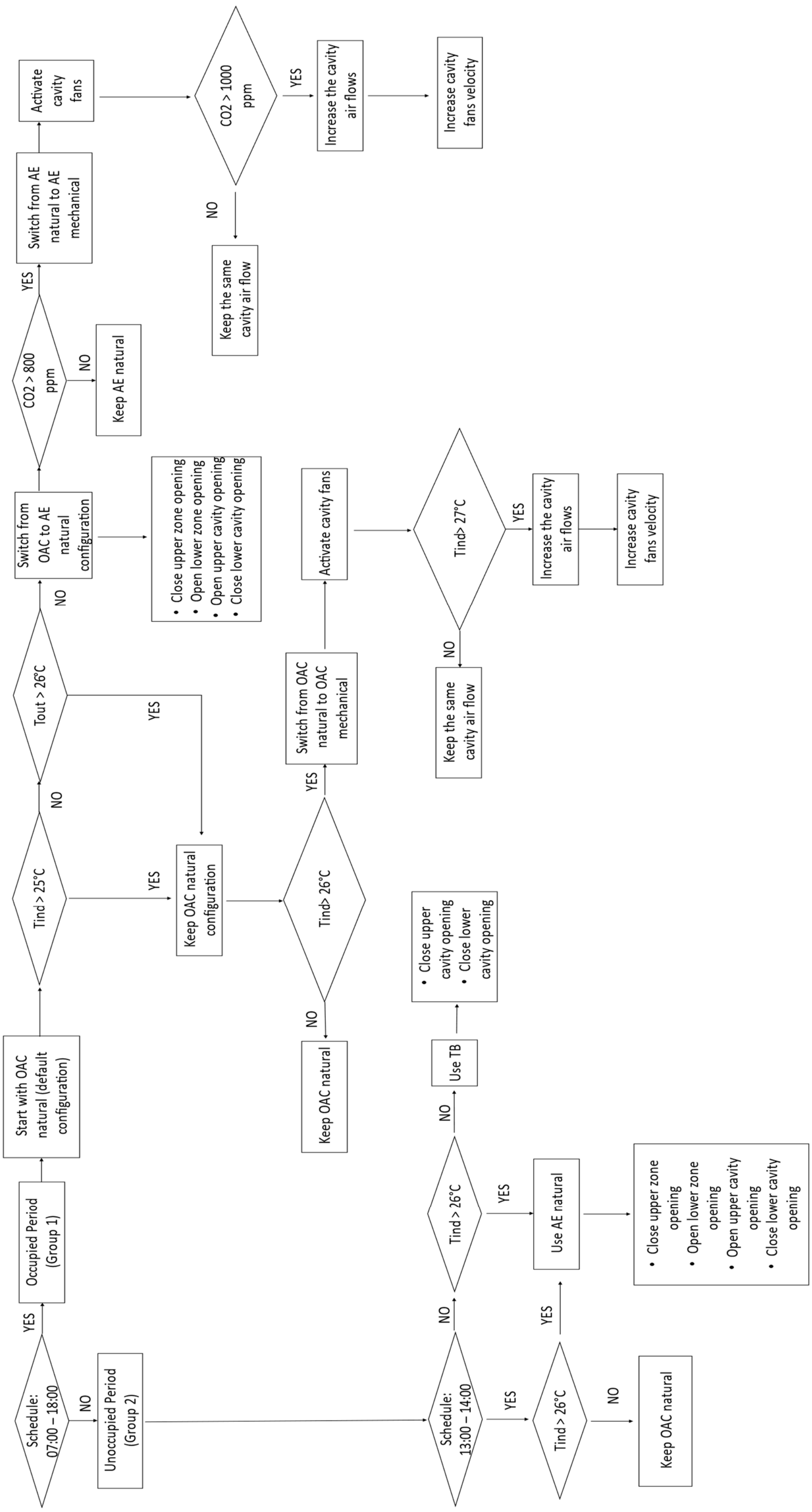


Figure 12: SAC#3 decision tree

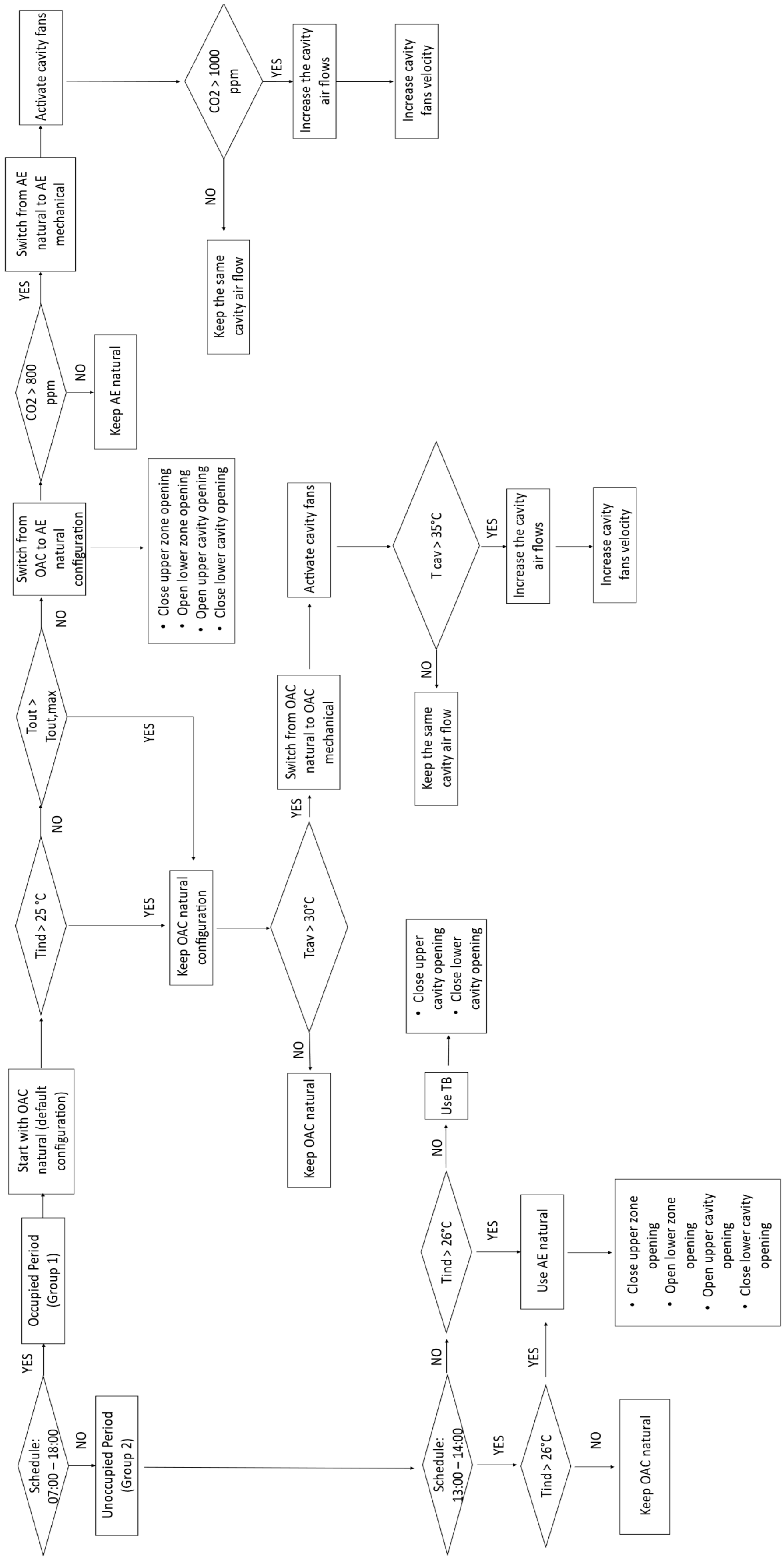


Figure 13: SAC#4 decision tree

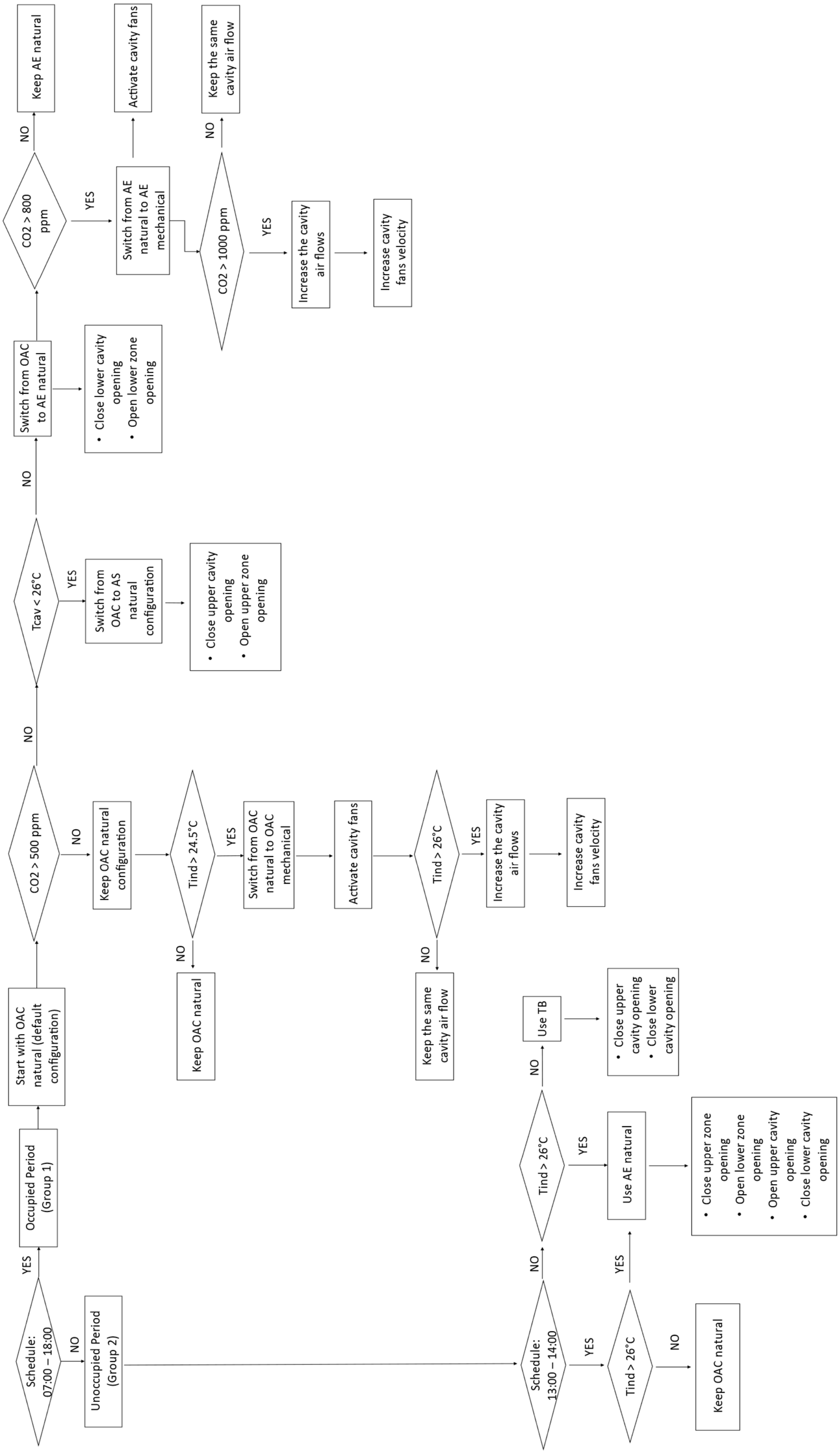


Figure 14: SAC#5 decision tree

The threshold limit for the incident solar radiation on the façade is *350 W/m²*: the value is given by the average between mean and maximum incident solar radiation values on the South façade in Frankfurt (the selected location for the testing of the control), calculated by means of the preliminary simulations on IDA ICE.

In *Table 5* are reported the values used for the calculations, given by the simulation performed on IDA ICE.

Incident solar radiation levels (Frankfurt, Summer)	
Max on South	*583.7 W/m²*
Average on South	*122.5 W/m²*
Mean value	*353 W/m²*
Control value	***350 W/m²***

Table 5: Definition of the threshold value for the blind drawn mechanism during the summer season (month of July)

The threshold value for the activation of the shading, on the other hand, is set equal to *26°C* during the cooling season (equal to the cooling set point defined for the room). In this way the blind is drawn only if the indoor air temperature is above the set point defined for the summer. If the cut-off position for the venetian blind slat is implemented, the angle value for the venetian blind slat (α_{slat}) is calculated for each time step of the simulation in accordance with the following formula:

$$\alpha_{slat} = \theta_{elev} - 90°$$

Where θ_{elev} is the sun elevation angle, defined for each time step of the year using the IDA ICE climate files [30].

If the slat angle is controlled by means of a schedule*,* the indoor illuminance conditions in the zones are considered by varying the slat angle during the day, in the way to have about *500 lux* of illuminance on the working plane [16]. A certain slat angle is kept for the morning period (*5°*), one for the midday period (*45°*) and one for the afternoon (*5°*). These values have been defined considering the average illuminance levels in different periods of the day (morning, midday and afternoon) on the working plane for the occupants, considering different fixed slat angle values (ranging from *5°* to *85°*). In this way it is possible to define in an empirical way the relation between a certain slat angle of the blind and the related illuminance level in the room.

In *Table 6*, are reported the values calculated by means of the simulations performed on IDA ICE.

Fixed slat angle of the blind[°]	***5***	***15***	***25***	***35***	***45***	***55***	***65***	***75***	***85***
Average illuminance in the morning (from 7:00 to 10:30) [lux]	240	236	223	206	185	155	120	80	27
Average illuminance in the midday (from 10:30 to 14:30) [lux]	680	657	615	564	503	419	323	213	73
Average illuminance in the afternoon (from 15:00 to 18:00) [lux]	466	455	429	396	355	296	227	148	51

Table 6:comparison between the fixed slat angle values and the average illuminance levels at the working plane during the morning, the midday, and the afternoon hours (for Frankfurt, in the month of July)

The value of the angle of the slats has been defined performing a preliminary analysis on a thermal zone (with the same geometry and façade system of the one used for the simulation of the control, described in *3.2*) in which the illuminance levels at the occupant desk have been calculated, for different fixed angles of the blind slats (ranging from *5°* to *85°*): for each period, the slat angle that ensured the illuminance levels closer to *500 lux* has been selected. This is a way to consider the visual comfort for the occupants inside the thermal zone.

For all the controls, during the night the blind is not drawn, to ensure a better cavity ventilation during the night with the *AE* configuration. In the lunch hours, since it is not necessary to perform working tasks in the zone, the maximum slat angle (*85°*) is applied, reducing the illuminance levels at the minimum level provided by the related standard (corresponding to *20 lux* according to [16]).

The codes and the related strategies for the occupied and unoccupied hours are reported in *Table 7.* The corresponding decision trees are reported from *Figure 15* to *Figure 20*.

Code for the control	Occupied hours strategy	Unoccupied hours strategy (lunch time and night)
SSC#1	• Radiation control with fixed slat angle (45°)	• Blind not drawn during the night • Slat angle is regulated to keep minimum illuminance levels in the zones during the lunch hour
SSC#2	• Radiation control of the blind drawn mechanism • Regulation of the slat angle in function of the *cut-off* position	• Blind not drawn during the night • Slat angle is regulated to keep minimum illuminance levels in the zones during the lunch hour
SSC#3	• Radiation control of the blind drawn mechanism • Regulation of the slat angle in function of the indoor illuminance levels	• Blind not drawn during the night • Slat angle is regulated to keep minimum illuminance levels in the zones during the lunch hour
SSC#4	• Temperature control of the blind with fixed slat angle (45°)	• Blind not drawn during the night • Slat angle is regulated to keep minimum illuminance levels in the zones during the lunch hour
SSC#5	• Temperature control of the blind drawn mechanism • Regulation of the slat angle in function of the *cut-off* position	• Blind not drawn during the night • Slat angle is regulated to keep minimum illuminance levels in the zones during the lunch hour
SSC#6	• Temperature control of the blind drawn mechanism • Regulation of the slat angle in function of the indoor illuminance levels	• Blind not drawn during the night • Slat angle is regulated to keep minimum illuminance levels in the zones during the lunch hour

Table 7: Control combinations for the shading system during the summer season

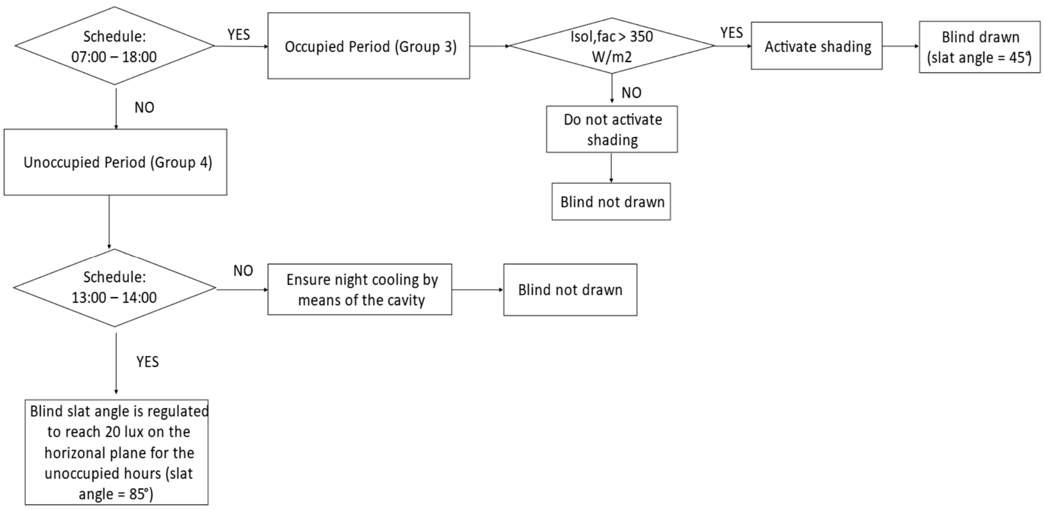


Figure 15: SSC#1 decision tree (Solar radiation activation + fixed slat angle)

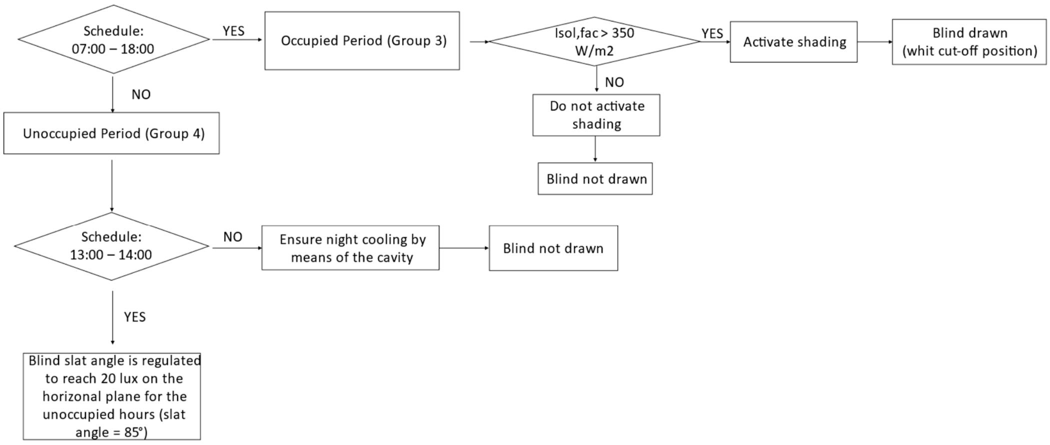


Figure 16: SSC#2 decision tree (Solar radiation activation + cut-off position)

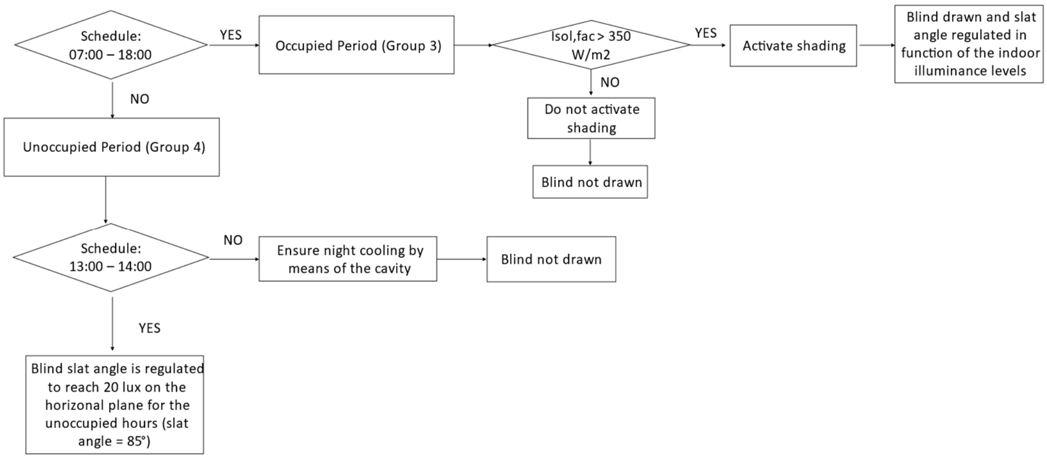


Figure 17: SSC#3 decision tree (Solar radiation activation + scheduled variation)

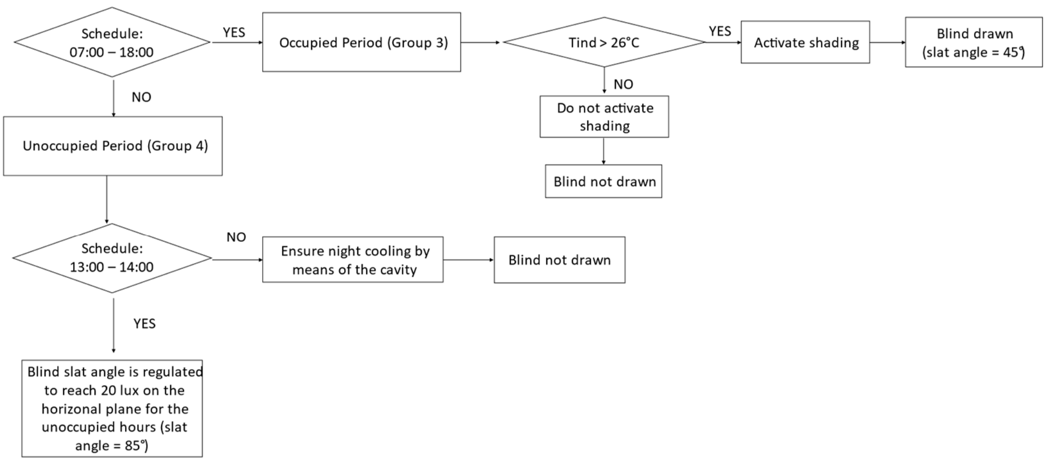


Figure 18: SSC#4 decision tree (Indoor air temperature activation + fixed slat angle)

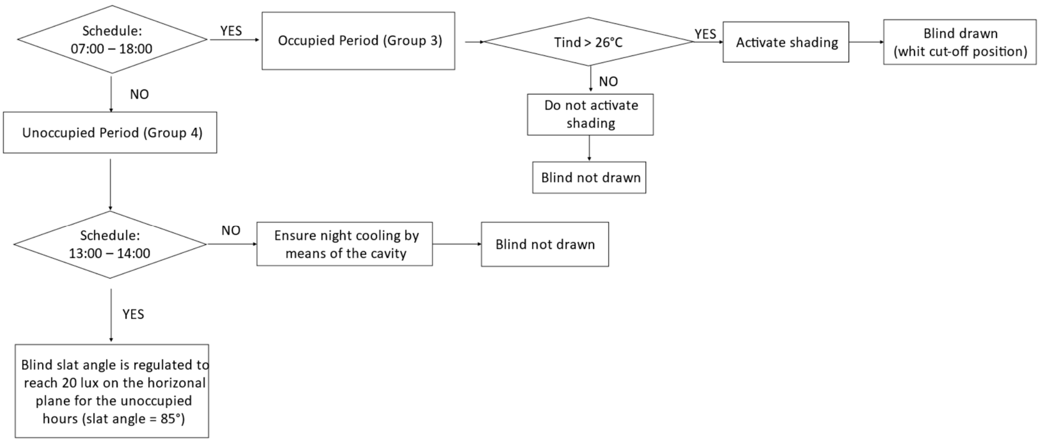


Figure 19: SSC#5 decision tree (Indoor air temperature activation + cut-off position)

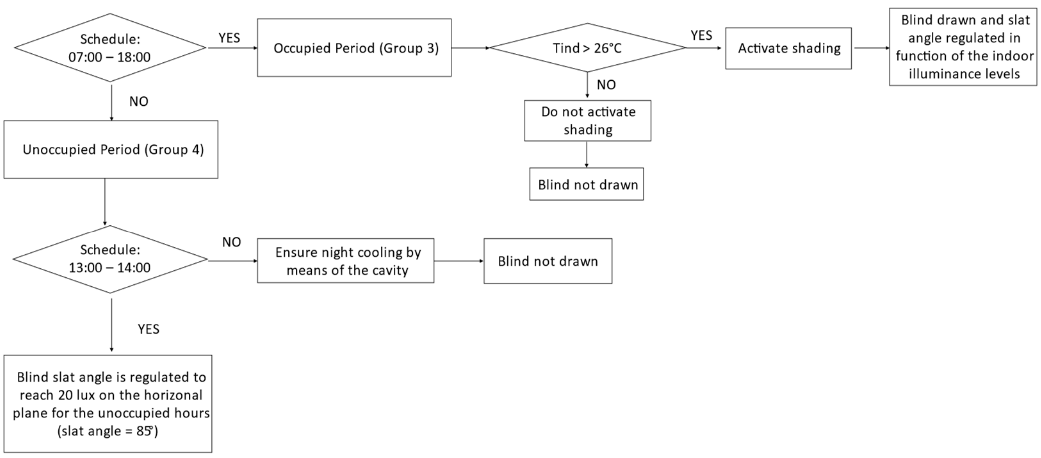


Figure 20: SSC#6 decision tree (Indoor air temperature activation + scheduled variation)

Consequently, these two groups of control (for the airflows and the shading) are combined in summer strategies for the *DSF* control, that can be therefore applied during the cooling season: they are the so-called *SC* (*Summer control*) combinations. In this way, 30 different combinations are possible for summer control of the *DSF* (5 controls for the air flows combined with 6 controls for the shading system).

Control for the winter season (*WAC* and *WSC*)

In this section are reported the control structures defined for the heating season for the shading system and the air flows in the cavity.

<u>Combination of Group 5 and Group 6: Winter Airflow Control (WAC)</u>

Controls of the Group 5 and Group 6 can be used for the air flows control for the heating season. The code for the identification of these controls is *WAC* (*Winter Air flow Control*): 4 different controls have been defined in this case, from *WAC#1* to *WAC#4*.
In *WAC#1*, only the configurations *TB*, *CF*, *AS* and *IAC* are applied. The switch between *TB*, *CF* and *AS* is performed considering the cavity air temperature while for the switch to the *IAC* configuration, also the incident solar radiation on the façade is considered: only if the incident solar radiation on the façade is enough the *IAC* configuration is applied. Otherwise, it is better to keep the *TB* configuration.

In *WAC#2* and *WAC#3* also the *OAC* natural configuration is considered, for possible overheating issues inside the cavity or in the room, which can arise in the high levels of incident solar radiation conditions.

In the first type of control (*WAC#2*), the switch is applied considering the cavity air temperature, while in the second case (*WAC#3*) considering the temperature of the zone: in both cases, a maximum threshold value of air temperature is considered.

In the last decision tree for the cavity air flows (*WAC#4*), is basically the same adopted in *WAC#2* (configuration switching only in function of the façade cavity temperature) but with the additional possibility to use the *AE* configuration if the indoor CO_2 concentrations are too high. Only if the carbon levels inside the room are below the threshold, the adoption of the other configurations (*TB*, *CF*, *AS*, *OAC* and *IAC*) is possible. Otherwise, the *AE* configuration is kept.

For the night period, the *TB* configuration is applied for the heat losses reduction for all the types of control. As done for the control in the summer season, the initial threshold limits of the control variables for the switching between the different façade configurations have been initially set in function of the standard *EN 16798-1* and then modified in function of the results of the first simulation performed on IDA ICE.

The minimum value of incident solar radiation on the façade for the adoption of *IAC* has been defined in function of the preliminary analysis carried on IDA ICE on a South exposed façade in Frankfurt during the month of January (as seen for the definition of the threshold limit for the activation of the shading system, as showed in *Table 9*): the average value is equal to $52\ W/m^2$. Consequently, the incident solar radiation for the activation of the *IAC* configuration should be greater than this amount (as for example, $75\ W/m^2$).

The codes and the related strategies for the occupied and unoccupied hours are reported in *Table 8.* The decision trees are reported from *Figure 21* to *Figure 24*.

Code for the control	Occupied hours strategy	Unoccupied hours strategy (night)
WAC#1	• *TB-CF-AS-IAC* configurations switching in function of the cavity air temperature	• Night thermal buffer
WAC#2	• *TB-CF-AS-IAC* configurations switching • *OAC* switching in function of the cavity air temperature	• Night thermal buffer
WAC#3	• *TB-CF-AS-IAC* configurations switching • *OAC* switching in function of the indoor air temperature	• Night thermal buffer
WAC#4	• Same configurations adopted in the case of WAC#2 • Additional use of AE natural configuration for the control of CO_2 levels in the room	• Night thermal buffer

Table 8: Control combinations for the airflows during the winter season

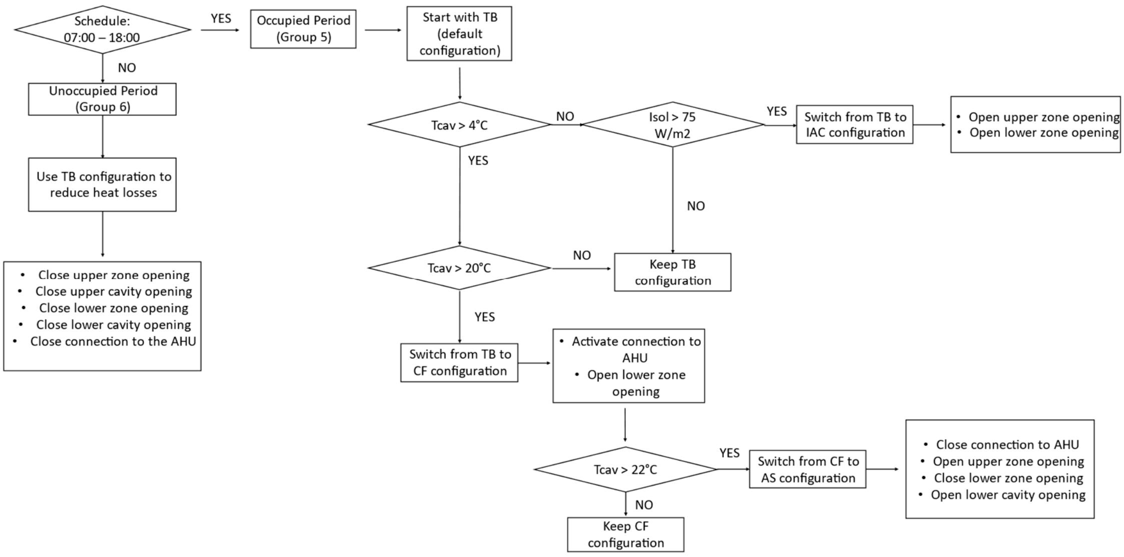


Figure 21: WAC#1 decision tree

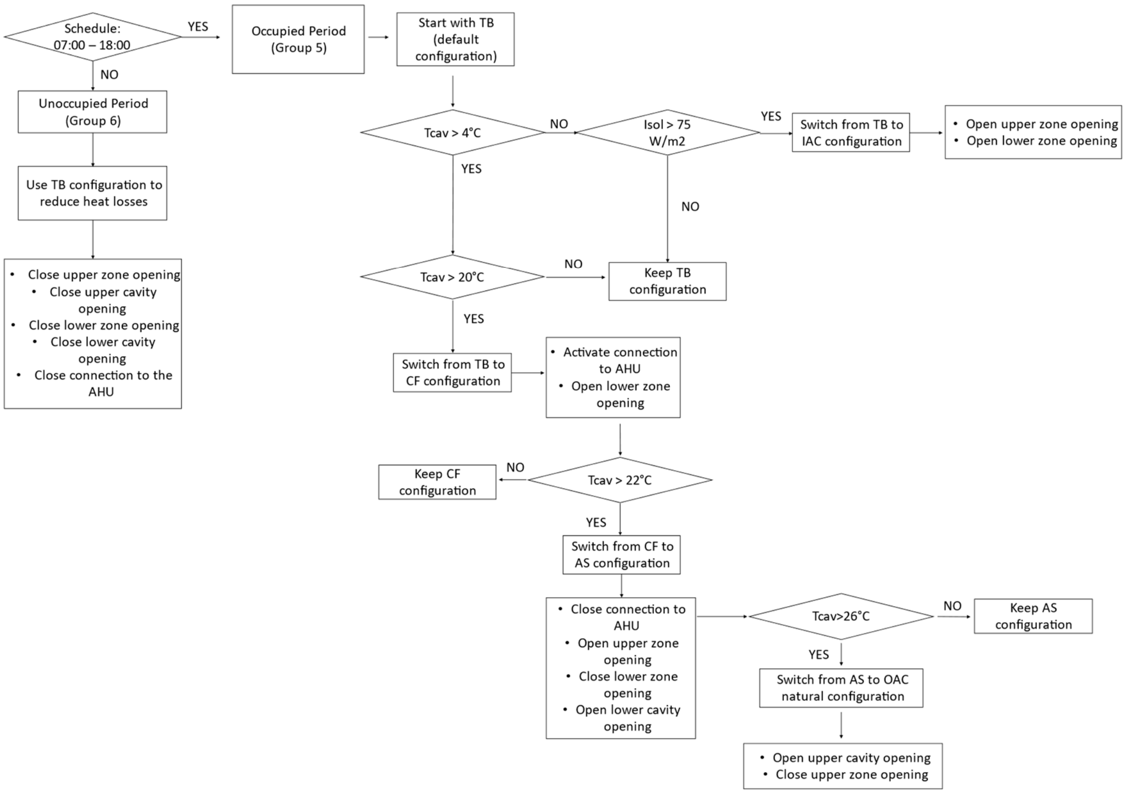


Figure 22: WAC#2 decision tree

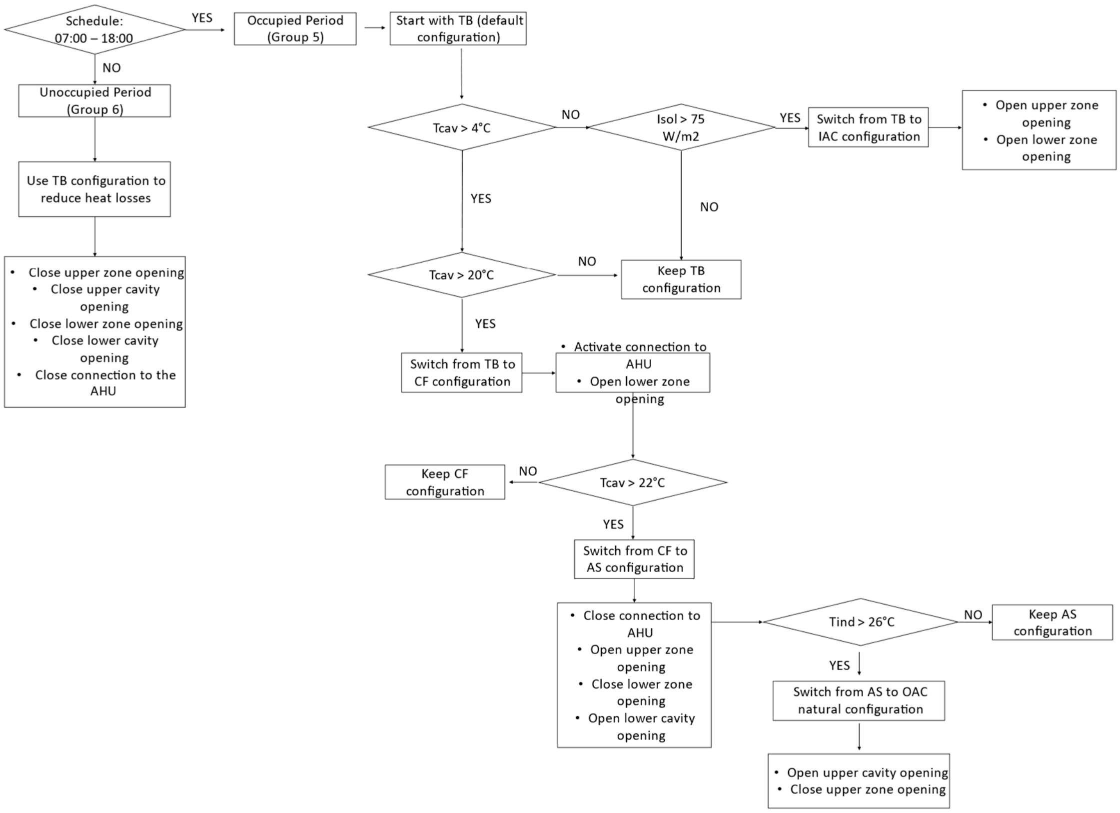


Figure 23: WAC#3 decision tree

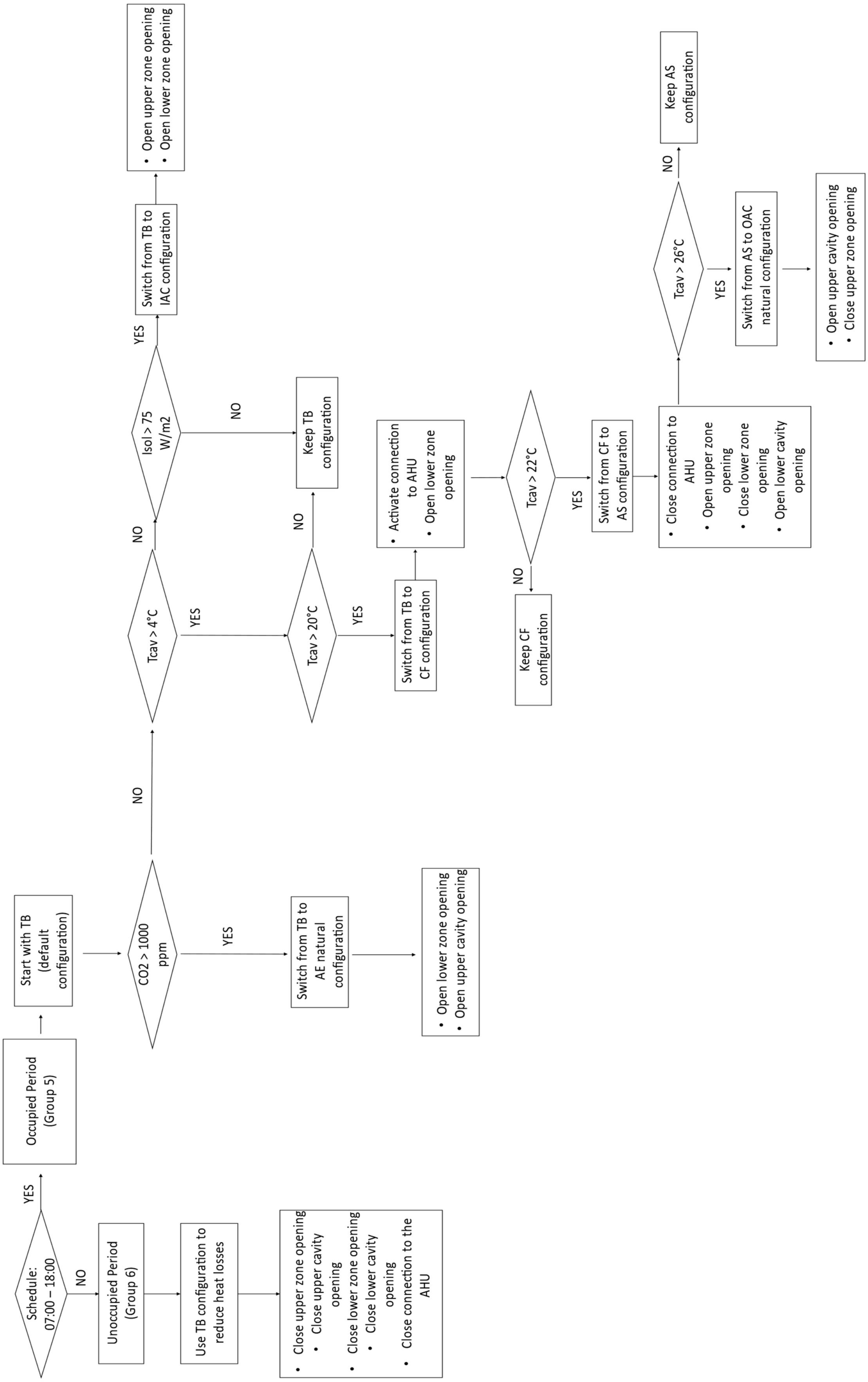


Figure 24: WAC#4 decision tree

Combination of Group 5 and Group 6: Winter Shading Control (WSC)

Controls of the Group 7 and Group 8 can be used for the shading control in the heating season. The code for the identification of these controls is *WSC* (*Winter Shading Control*): the control for the heating season is basically the same implemented in the summer season (with 6 different forms of control from *WSC#1* to *WSC#6*). The radiation control is set at $350\ W/m^2$ for *WSC#1* (the value has been defined in the same way as the summer season case, by means of preliminary simulations on IDA ICE) while the temperature activation in *WSC#2* is reduced to $20°C$ (instead of $26°C$): this corresponds to the heating setpoint for the room.

In *Table 9* are reported the values for the definition of the threshold limits of the incident solar radiation on the South façade, calculated by means of the simulations performed on IDA ICE.

Incident solar radiation levels (Frankfurt, Summer)	
Max on South	$650.4\ W/m^2$
Average on South	$52.2\ W/m^2$
Mean value	$351\ W/m^2$
Control value	$\mathbf{350\ W/m^2}$

Table 9: Definition of the threshold value for the blind drawn mechanism during the winter season (month of January)

The slat angle for the cut off implementation is different since the sun elevation angle is different as well compared to the cooling season [30]. Finally, also the scheduled slat angles are not the same: $5°$ for the morning and the afternoon and $25°$ for the midday period. The values of the slat angle have been defined following the same approach used for the summer season (considering in this case the month of January). The values are reported in *Table 10*.

Fixed slat angle of the blind[°]	5	15	25	35	45	55	65	75	85
Average illuminance in the morning (from 7:00 to 10:30) [lux]	310	260	213	168	125	90	62	40	16
Average illuminance in the midday (from 10:30 to 14:30) [lux]	933	770	616	475	351	249	170	112	41
Average illuminance in the afternoon (from 15:00 to 18:00) [lux]	238	202	167	133	101	73	51	33	14

Table 10: Comparison between the fixed slat angle values and the average illuminance levels at the working plane during the morning, the midday and the afternoon hours (for Frankfurt, in the month of January)

For all the combinations, during the lunch break, if the indoor air temperature is lower than $20°C$, the blind is not drawn to ensure solar gains in the room. Otherwise, the shading is activated with fixed slat angle of $45°$. The codes and the related strategies for the occupied and unoccupied hours are reported in *Table 11*. The decision trees are reported from *Figure 25* to *Figure 28*.

Code for the control	**Occupied hours strategy**	**Unoccupied hours strategy (lunch time and night)**
WSC#1	• Radiation control with fixed slat angle ($45°$)	• Blind drawn with fixed slat angle ($45°$) • Blind not drawn during the lunch time (if no overheating risk is present in the zone)
WSC#2	• Radiation control of the blind drawn mechanism • Regulation of the slat angle in function of the cut-off position	• Blind drawn with fixed slat angle ($45°$) • Blind not drawn during the lunch time (if no overheating risk is present in the zone)
WSC#3	• Radiation control of the blind drawn mechanism • Regulation of the slat angle in function of the indoor illuminance levels	• Blind drawn with fixed slat angle ($45°$) • Blind not drawn during the lunch time (if no overheating risk is present in the zone)
WSC#4	• Temperature control of the blind with fixed slat angle ($45°$)	• Blind drawn with fixed slat angle ($45°$)

		• Blind not drawn during the lunch time (if no overheating risk is present in the zone)
WSC#5	• Temperature control of the blind drawn mechanism • Regulation of the slat angle in function of the cut-off position	• Blind drawn with fixed slat angle (*45°*) • Blind not drawn during the lunch time (if no overheating risk is present in the zone)
WSC#6	• Temperature control of the blind drawn mechanism • Regulation of the slat angle in function of the indoor illuminance levels	• Blind drawn with fixed slat angle (*45°*) • Blind not drawn during the lunch time (if no overheating risk is present in the zone)

Table 11: Control combinations for the shading during the winter season

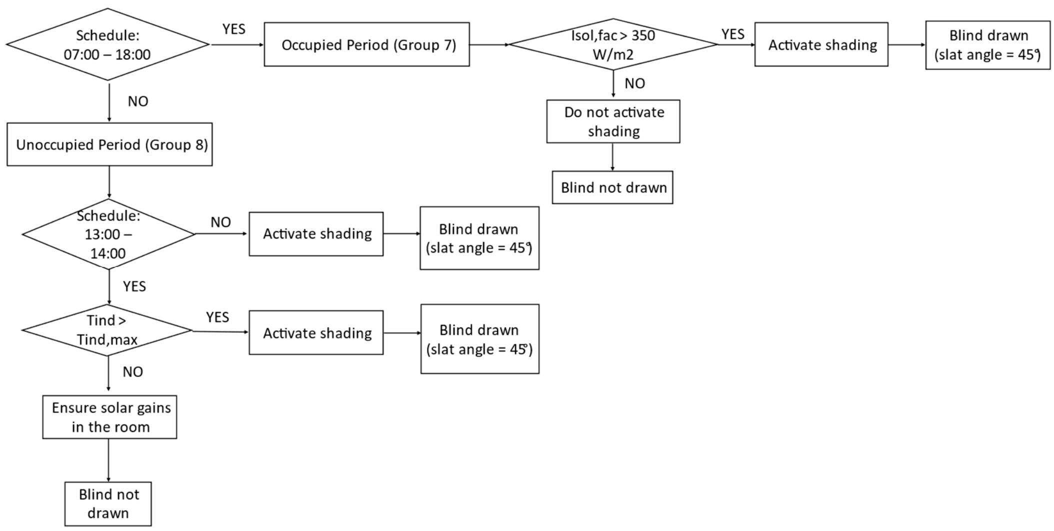


Figure 25: WSC#1 decision tree (Solar radiation activation + fixed slat angle)

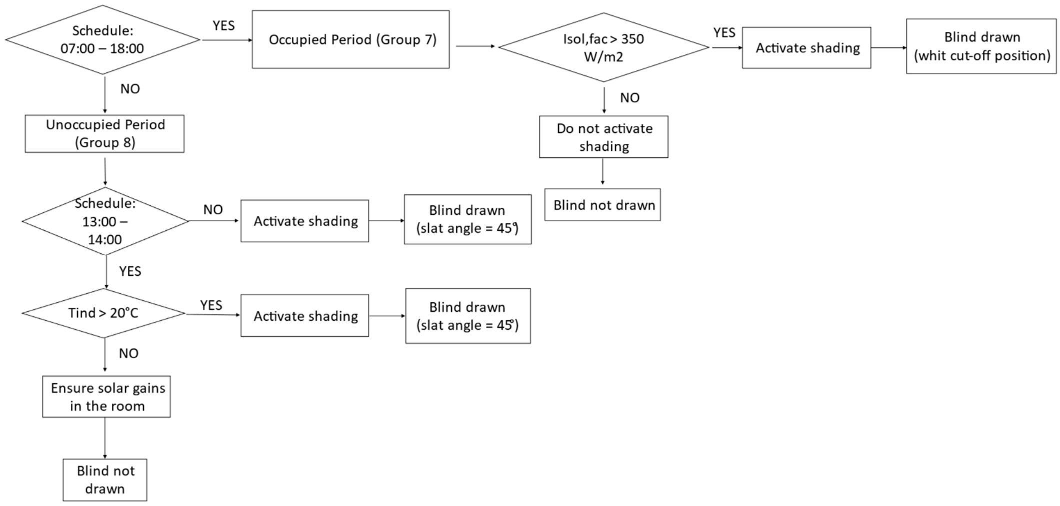


Figure 26: WSC#2 decision tree (Solar radiation activation + cut-off position)

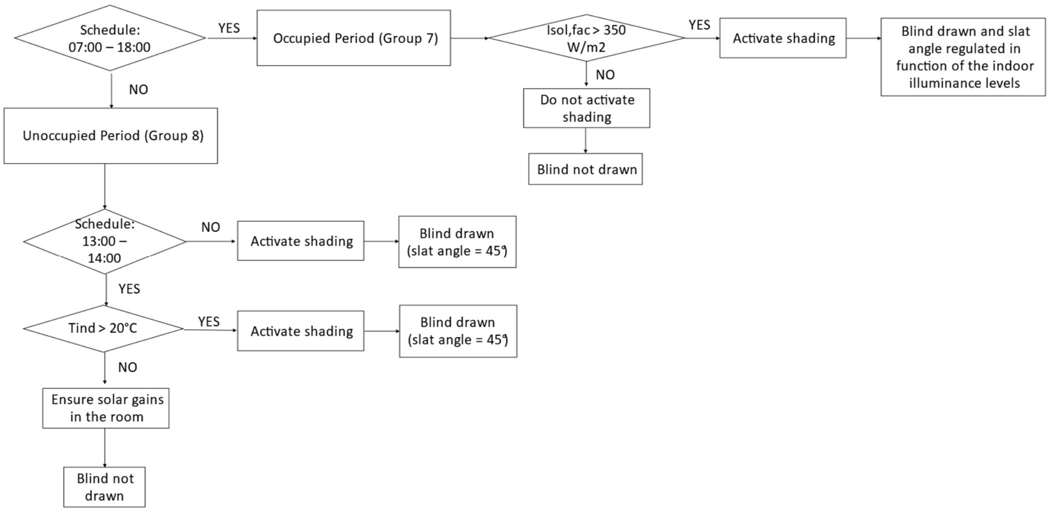


Figure 27: WSC#3 decision tree (Solar radiation activation + schedule)

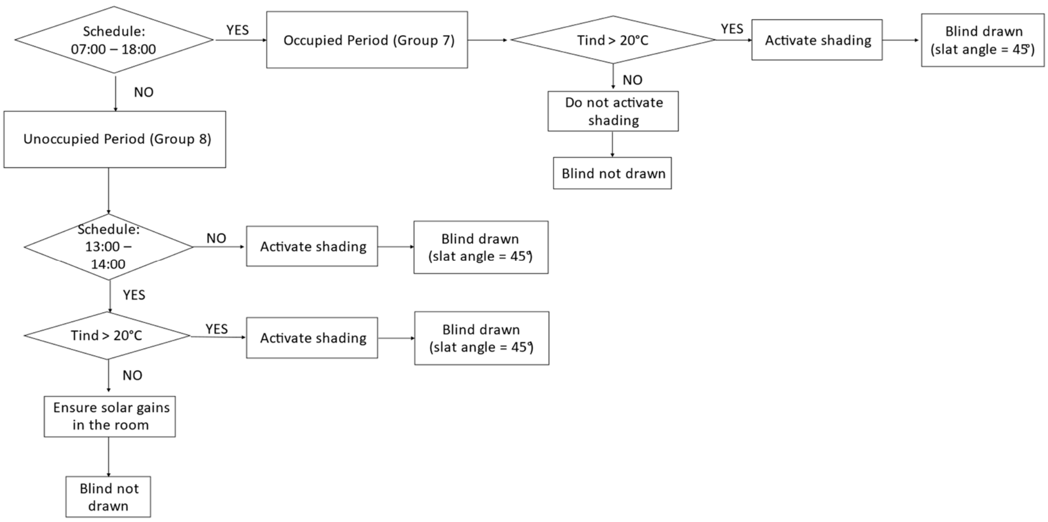


Figure 28: WSC#4 decision tree (Indoor air temperature activation + fixed slat angle)

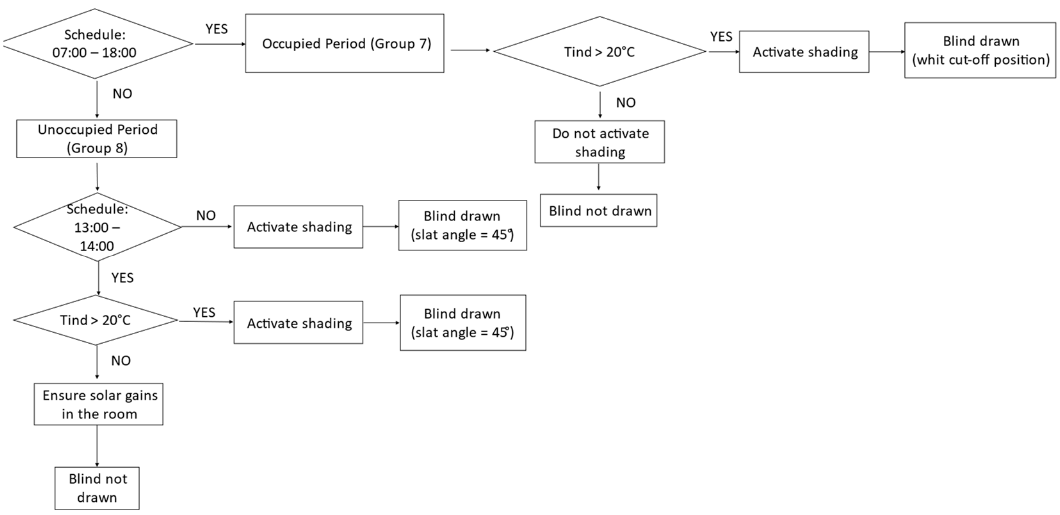


Figure 29: WSC#5 decision tree (Indoor air temperature activation + cut-off position)

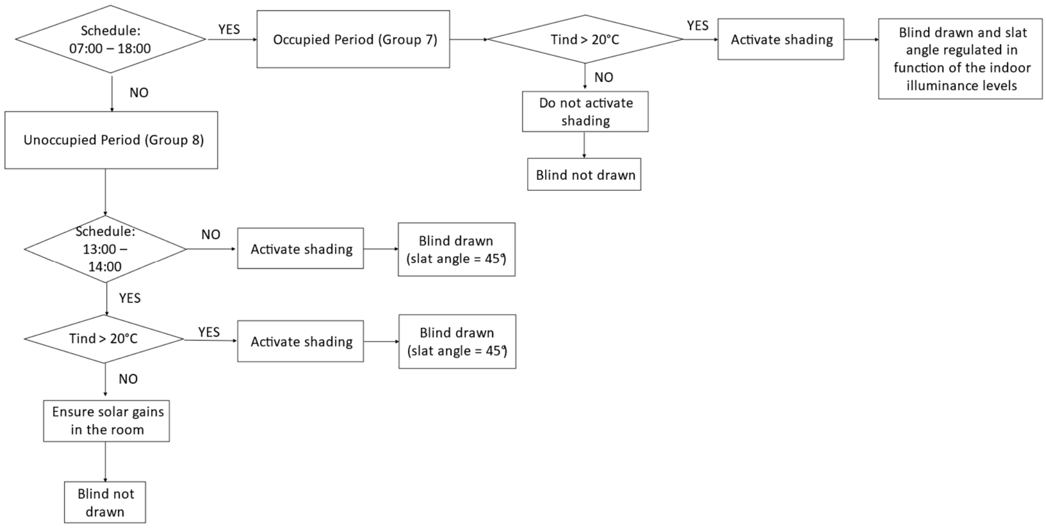


Figure 30: WSC#6 decision tree (Indoor air temperature activation + schedule)

Consequently, these two combinations for the shading and the air flows control are grouped in winter strategies for the *DSF* control, that can be therefore applied during the heating season: they are the so-called *WC* (*Winter control*) combinations.

Each cavity air flow control can be in fact associated to a particular control logic of the shading system, enabling a different result (as seen for the summer season). In this way, 24 different combinations are possible for winter control of the *DSF* (4 different controls for the air flows combined with 6 controls for the shading system).

2.3.1. Combinations of control for the summer season

Control combinations codes
SC#1_SAC#1_SSC#1
SC#2_SAC#1_SSC#2
SC#3_SAC#1_SSC#3
SC#4_SAC#1_SSC#4
SC#5_SAC#1_SSC#5
SC#6_SAC#1_SSC#6
SC#7_SAC#2_SSC#1
SC#8_SAC#2_SSC#2
SC#9_SAC#2_SSC#3
SC#10_SAC#2_SSC#4
SC#11_SAC#2_SSC#5
SC#12_SAC#2_SSC#6
SC#13_SAC#3_SSC#1
SC#14_SAC#3_SSC#2
SC#15_SAC#3_SSC#3
SC#16_SAC#3_SSC#4
SC#17_SAC#3_SSC#5
SC#18_SAC#3_SSC#5
SC#19_SAC#4_SSC#1
SC#20_SAC#4_SSC#2
SC#21_SAC#4_SSC#3
SC#22_SAC#4_SSC#4
SC#23_SAC#4_SSC#5
SC#24_SAC#4_SSC#6
SC#25_SAC#5_SSC#1
SC#26_SAC#5_SSC#2

SC#27_SAC#5_SSC#3
SC#28_SAC#5_SSC#5
SC#29_SAC#5_SSC#5
SC#30_SAC#5_SSC#6

Table 12: The 30 combinations of control for the cooling season, defined combining SAC controls and SSC controls (SC codes)

Here are reported the 30 different combinations of control that can be used during the cooling season period (*Table 12*).

The initial code (*SC*) defines the validity period (in this case the summer), while the second (*SAC*) and the third (*SSC*) define the control adopted for the air flows in the cavity and the shading system.

These control combinations will be tested in summer peak conditions to define their efficacy and effect on the overall system performance.

2.3.2. Combinations of control for the winter season

Control combinations codes
WC#1_WAC#1_WSC#1
WC#2_WAC#1_WSC#2
WC#3_WAC#1_WSC#3
WC#4_WAC#1_WSC#4
WC#5_WAC#1_WSC#5
WC#6_WAC#1_WSC#6
WC#7_WAC#2_WSC#1
WC#8_WAC#2_WSC#2
WC#9_WAC#2_WSC#3
WC#10_WAC#2_WSC#4
WC#11_WAC#2_WSC#5
WC#12_WAC#2_WSC#6
WC#13_WAC#3_WSC#1
WC#14_WAC#3_WSC#2
WC#15_WAC#3_WSC#3
WC#16_WAC#3_WSC#4
WC#17_WAC#3_WSC#5
WC#18_WAC#3_WSC#6
WC#19_WAC#4_WSC#1
WC#20_WAC#4_WSC#2
WC#21_WAC#4_WSC#3
WC#22_WAC#4_WSC#4
WC#23_WAC#4_WSC#5
WC#24_WAC#4_WSC#6

Table 13: The 24 combinations of control for the heating season, defined combining WAC controls and WSC controls (WC codes)

Here are reported the 24 different combinations of control that can be used during the winter period (*Table 13*).

The initial code (*WC*) defines the validity period (in this case the winter), while the second (*WAC*) and the third (*WSC*) define the control adopted for the air flows in the cavity and the shading system. These control combinations will be tested in winter peak conditions to define their efficacy and effect on the overall system performance.

2.3.3.Control for the unoccupied week-end days

Other configurations should be kept in the case of the week-end days, which are unoccupied. The main distinction in this case is the one between the strategies to be applied during the night and the strategies to be applied during the day (for which different outdoor conditions are present).

All these configurations can be activated by means of a schedule, as seen for the other strategies related to the unoccupied hours during the working days. About the shading control, for the summer season, the blind is not drawn during the night (for a better application of the night cooling by means of the façade cavity), while during the day a minimum illuminance level is kept inside the indoor environment, by using a slat angle of *85°*. For the winter season, the venetian blind is kept completely drawn during the week-end period (with a fixed slat angle of *45°*).

Regarding the air flow control, in the summer season the main distinction is applied between operating strategies for the daytime and for the night. During the day, if the indoor air temperature is greater than *26°C*, the *AE* natural configuration can be used. Otherwise, the *OAC* natural can be implemented. In similar way, during the night, if overheating risk is present, the *AE* natural configuration can be used, otherwise the *TB* ventilation mode is applied. In the winter season, on the other hand, it is possible to set the *TB* configuration during the whole period of the weekend, with the aim of reducing the transmission heat losses through the façade.

The implementation of the control combinations inside IDA ICE by means of the *Control Macros* is illustrated in detail inside the *Appendix D*: in the appendix it has been reported the process followed for the definition of specific decision trees, to which a specific *exit code* from 1 to 10 (as showed in *Table 2*) is associated to each configuration of the *DSF*.

In addition, the process followed for the *DSF* modelling and the creations of the different control combinations is illustrated more in detail in *3.1*.

3. Research method definition for the performance evaluation

In this section, the method followed during the Thesis work will be explained and discussed in detail.

The main scope of the implemented research method in particular is the one to create a comparative study between the flexible *DSF* (with a certain implemented control combination, among the ones defined in *2.3.1* and *2.3.2*) and a baseline system to use as reference for the performance comparison.

The research method can be divided into the following seven steps:

1) Modelling of the flexible *DSF* in IDA ICE for the testing of the different control combinations.
2) Modelling of the adjacent thermal zone (for this Master Thesis, an office has been selected).
3) Definition of the initial boundary conditions in which the *DSF* performance will be evaluated (for summer and winter conditions).
4) Multi-domain performance evaluation of the different control combinations using IDA ICE.
5) Comparison with reference façade systems and selection of the optimal control combination for the initial boundary condition.
6) Modification and testing of the optimal control combinations (tested in cooling season and heating season conditions) in the mid-season periods.
7) Creation of the annual rule-based control structure for the flexible *DSF* and simulation with the annual control optimized by means of the IDA API.

The optimal control combination (in heating season and cooling season conditions) selected for the initial boundary condition is the one that produces the best performance improvement compared to the reference façade systems. Following these criteria, for each one of the defined boundary conditions, the optimal control combination for the *DSF* must be selected. To understand how much the changing in the boundary conditions of the system (in particular, climate and façade orientation) can affect the effectiveness of the optimized control it is possible to test the selected control in other locations and for other façade orientations. In this chapter all the steps of the research method have been discussed more in detail.

3.1. Flexible DSF modelling

A flexible *DSF* system has been defined inside the simulation environment of IDA ICE, following the process illustrated in *Appendix C.* About the driving force for the ventilation inside the cavity, the modelled *DSF* should be able to switch between the natural and the mechanical ventilation modes according to the different operating conditions. Therefore, the presence of fans inside the cavity is considered to enable the mechanical ventilation use. The specific typology of *DSF* is a *box-window* (See *Appendix B - The DSF system: history and state of the art*). About the skins, there are many different configurations that can be adopted, according to the existing literature. In general, the inner skin consists of a thermal insulating double or triple pane. The panes are usually made of toughened or unhardened float glass. On the other hand, the outer skin is usually a tempered or laminated single pane [12]. However, this configuration has a particular disadvantage: in the cold winter days, when the exhaust air is introduced in the cavity from the zone, there could be condensation risk, since the exhaust air is often warm and humid while the inner surface of the outer skin surface can be very cold in these conditions. This fact can lead to several problems related to the functioning of the façade components, due to water infiltrations [23].

Therefore, the inner surface of the outer skin should be kept to a warmer temperature while the air from the room is introduced inside the cavity. The best solution is in this case the one to use a double glass unit (*DGU*) for both, inner and outer skins. The properties of the glass (both optical and thermal) and the different panes constructional characteristics are taken from the *WINDOW 7* software data base already implemented inside IDA ICE. In the following table, the characteristics of the glazing systems for the inner and outer skins are reported. The components of the two skins are showed in *Table 14*.

Outer Skin (DGU)	Inner Skin (DGU)
Clear Glass, *4 mm*	Clear Glass, *4 mm*
Argon filled gap, *12 mm*	Argon filled gap, *12 mm*
Low E Glass, *5 mm*	Low E Glass, *5 mm*

Table 14: Layers of the two skins of the DSF.

Visible transmission (τ_v), total solar transmission (τ_e), solar heat gain coefficient (*SHGC*) and thermal transmittance (*U*) of the two skins are automatically calculated by the simulation environment (*Table 15*).

Cavity depth for the *DSF* is set equal to *25 cm*. Both the inner and the outer skins have frame factor equal to 0.1 and the thermal transmittance of the frame equal to $2\ W/m^2K$.

Outer Skin	Inner Skin
$SHGC = 0.715$	$SHGC = 0.649$
$\tau_e = 0.565$	$\tau_e = 0.565$
$\tau_v = 0.75$	$\tau_v = 0.75$
$U = 1.615\ W/m^2K$	$U = 1.627\ W/m^2K$

Table 15: Optical, solar and thermal properties of the outer and the inner skins automatically calculated by IDA ICE.

As shading system, a generic light-dark coloured slat material venetian blind has been selected (with *10 mm* slat width), integrated inside the cavity. The thickness of the slats is set equal to *0.6 mm*, while the thermal conductivity of the material is $160\ W/m\ K$. The properties of the shading system have been defined using the related form inside the *Detailed Window* model. Transmittance and reflectance properties of the aluminium have been defined by default inside the IDA ICE database. The distance between the venetian blind and the outer skin is set equal to *0.125 cm*. In this way the blind is located exactly in the middle of the façade cavity. The flexibility of the façade system is ensured by the 10 different configurations (6 for the heating and 7 for the cooling season) already illustrated in *Table 2*.

As mentioned in *Appendix C*, the standard *DSF* already implemented in IDA ICE has been modified to enable the control from the rule-based logic: the original leaks between the zone and the façade cavity have been substituted by openings while an additional cavity fan has been added for the mechanical ventilation implementation.

The cavity fan can switch between two different values of air flow: a minimum of $41.7\ l/s$ and a maximum of $83.3\ l/s$. These two values correspond to $50\ m^3/h$ and $100\ m^3/h$ per horizontal linear meter of façade (*3 m* for each window of the room). For the return fan to the *AHU* of the thermal zone, the implemented air flow rate is the same already adopted for the ventilation of the zone, corresponding to $1.4\ l/s$ per square meter of floor surface of the room.

For each combination of control, in summer and winter conditions, a different model have been defined (corresponding to a different *.idm* file), with the related *Control Macros* and decision trees (for the cavity air flows and the shading control), for a total number of 54 different flexible *DSF* models (30 for the cooling season and 24 for the heating season).

The general workflow adopted for the *DSF* modelling phase is showed in *Figure 31*.

Figure 31: DSF modelling workflow in IDA ICE for the creation of the different combinations of control for the flexible DSF for the heating and cooling season

3.2. Thermal zone modelling

The next step was focused on the definition of the thermal zone to which the façade system is linked to. The geometrical features of the linked thermal zone are the ones used for the *IEA Building Energy Simulation Test* (*BESTEST*), as showed in *Figure 32*. The room is a rectangular thermal zone, with floor area of $8\ m \times 6\ m = 48\ m^2$. The ceiling height is $2.7\ m$. Therefore, the total heated volume of the zone is set equal to $129.6\ m^3$.

Two different windows with identical features are present in the zone, following the procedures of the *BESTEST*. They have identical dimensions of $3\ m \times 2\ m = 6\ m^2$.

Consequently, the length of $3\ m$ of linear meter of façade has been used for the definition of the cavity air flows. Both the windows are oriented towards the South direction. This orientation is typically better from a solar gains point of view than East and West ones during the summer season but on the contrary the risk of potential overheating is greater during the winter. For this reason, this façade orientation has been preferred during the thermal zone modelling.

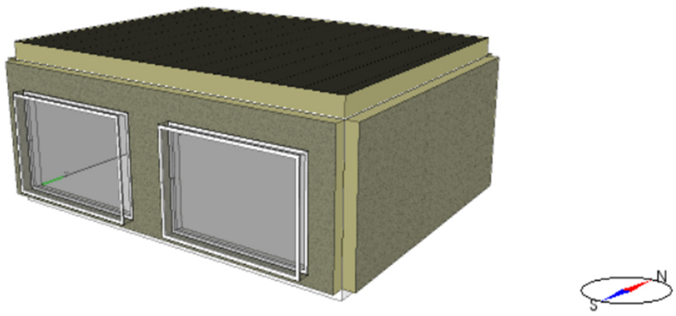


Figure 32: The BESTEST cell used for the thermal zone modelling, with the two identical DSFs applied on the South wall.

Schedules and internal gains inside the thermal zone are defined in function of the European standard *EN 16798-1:2019* [29] and the international standard *ISO 23045:2008* [30]:

- Occupancy period for the zone: 07:00 – 18:00 (Lunch break is set between 13:00 – 14:00). No occupancy in the zone is therefore set during the lunch break. The total number of occupied hours is consequently 10 per day.

- Working days per week: 5 days (from Monday to Friday, no occupancy set during the weekend).

- Internal gains from appliances: a single unit with an emitted heat of $300\ W$ has been considered.

- Internal gains from lighting: 4 different lighting units have been considered inside the room. Each one of them has a rated input of $48\ W$. The luminous efficiency is set equal to $80\ lm/W$, the convective fraction 0.6.

For the internal gains from the occupants, three people inside the room are considered, with metabolic rate equal to $1\ met$. The clothing insulation for the occupants is has been set equal to $0.5\ clo$ for the cooling season and $1\ clo$ for the heatingseason (Typical design criteria followed in the standard *EN ISO 7730*). The ventilation plant is a *Constant Air Volume* (*CAV*), scheduled in function of the occupancy of the zone. The air flow to the zone is set equal to $1.4\ l/s\ m^2$ during the occupied hours and $0.15\ l/s\ m^2$ during the unoccupied hours of the office, in accordance with a *Category II* of *IEQ*. [19].

The *AHU* of the zone has a heat recovery efficiency of 75% and a constant air supply temperature of $16°C$ (this is the standard solution adopted in IDA ICE), both for the summer and the winter seasons. Daylight at the workplace for the electric lighting control is set as $500\ lux$ [16]: below this level, the electric light is turned on. Infiltrations trough the envelope are set equal to $0.5\ ACH$ under a pressure difference of $50\ Pa$, following the criteria used in the *BESTEST* procedure.

Heating and cooling set points for the indoor air temperatures are set equal to *20°C* and *26°C*, in accordance with a *Category II* of IEQ [15]. The indoor temperature is kept by an ideal heating and cooling system, defined in IDA ICE with the use of an ideal heater and an idea cooler systems.

The power for both is set equal to *5000 W*, the efficiency of the heating system is set equal to 1 and the *COP* of the chiller is *3*. In the following table (*Table 16*), it is reported a brief recap about the main data regarding the zone implemented inside IDA ICE.

Destination of Use	*Multiple office room*
Floor Area	*48 m^2*
Ceiling height	*2.7 m*
Total Heated Volume	*129.6 m^3*
Transparent Façade area	*12 m^2 (2 windows with 6m^2 of surface each)*
Occupancy	*3 people (M = 1 met, rest)*
Internal Gains from Lighting	*4 units, 48 W each*
Internal Gains from Appliances	*3 units, 300 W each*
Ventilation (CAV)	*1.4 l/s m^2 (Unoccupied periods: 0.15 l/s m^2)*
Infiltrations	*n_{50} = 0.50 ACH*
Air Temperature Set Points	*20°C – 26°C*
Heating System	*Ideal Heater*
Cooling System	*Ideal Cooler*
Heat Recovery Efficiency (AHU)	*75%*

Table 16: Main data about the zone inserted inside IDA ICE

3.3. Definition of the boundary conditions for the selection of the optimal control combinations

The next step was focused on the definition of the boundary conditions in which the *DSF* behaviour must be tested. The location and the climate for the study of the control efficacy are the ones of Frankfurt. The corresponding climate in function of the Kopper-Geiger classification is *Temperate-Oceanic Climate* (*Cfb*).

In the next figure, it is possible to see the location of the Frankfurt climate in relation with the other Europe (*Figure 33*). The latitude, in accordance with the climate file used inside IDA ICE, is *50.05°N* while the altitude is *112 m*. Frankfurt is in a temperate climate condition; therefore, it is possible to evaluate in a more effective way the influence of façade system as a *DSF* to the overall energy performance of the building.

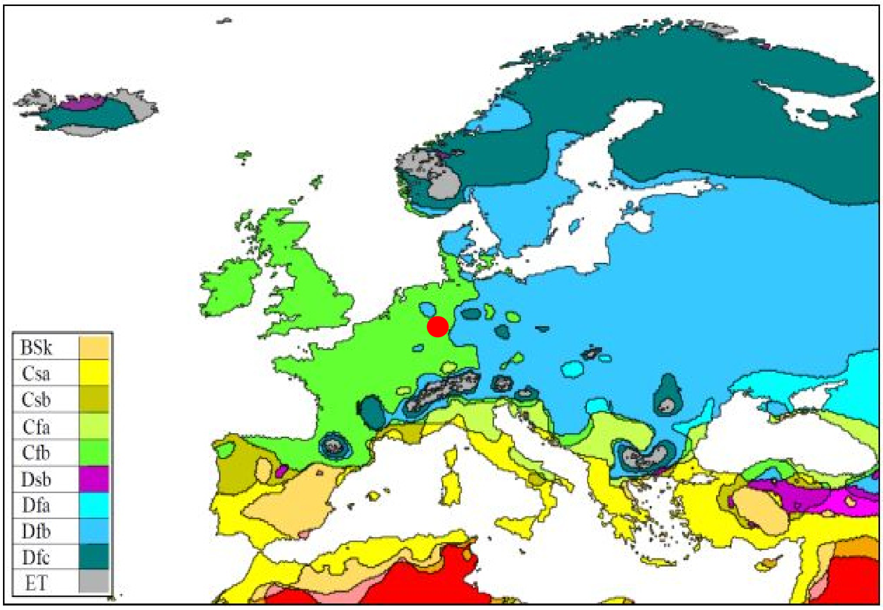


Figure 33: Location of Frankfurt with respect to the other European climates [31].

Location and climate for the building in which the *DSF* is implemented can be defined inside the *General* tab of the *.idm* file of the building. The climatic data are already implemented inside the IDA ICE database. The evaluation of the effectiveness for the heating and cooling season strategies has been performed in the months of January and July respectively.

This methodology aims to evaluate in separate way the façade control strategies during the cooling season (*SC* combinations) from the control strategies for the heating season (*WC* combinations), in which different boundary conditions are of course experienced by the façade itself. At the same time, the duration of the simulation period can allow to have a consistent variation of the outdoor environmental control variables for the façade actuators (in particular, the ones concerning the outdoor air temperatures and the incident solar radiation on the façade).

The selected months are July for the summer conditions and January for the winter conditions evaluation. In July, the average outdoor air temperature is the highest of the year, the same for the solar radiation. In January, on the contrary, the lowest outdoor air temperatures are experienced. This is shown in the following graphs (*Figure 34*, *Figure 36* and *Figure 35*).

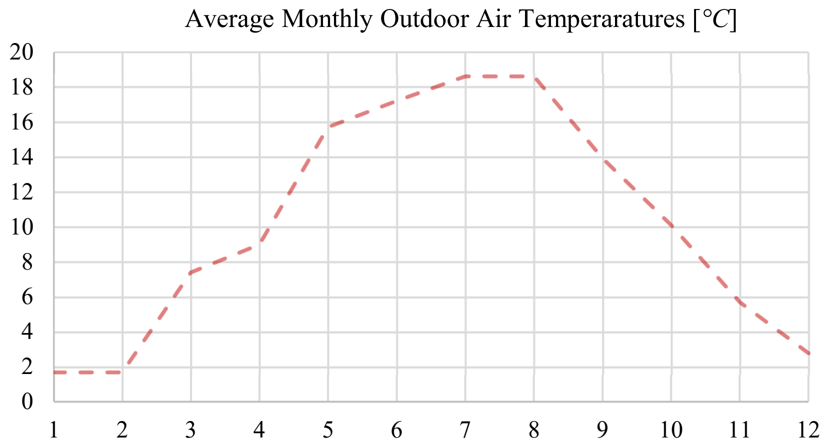


Figure 34: Average monthly values of outdoor air temperature for Frankfurt [32]

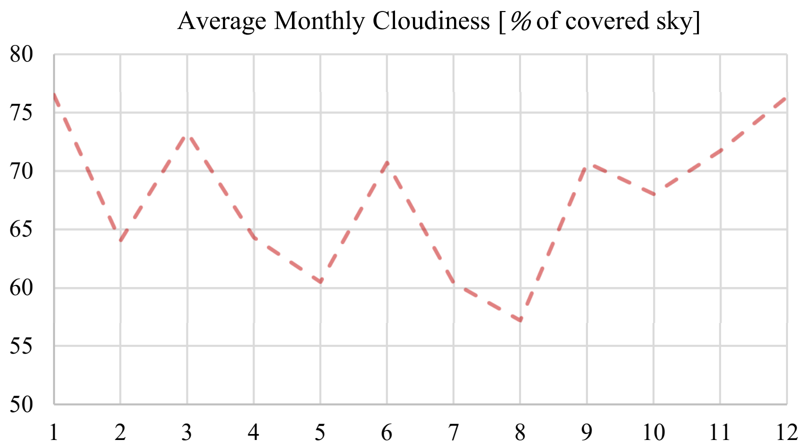


Figure 35: Average monthly values of cloudiness for Frankfurt [32]

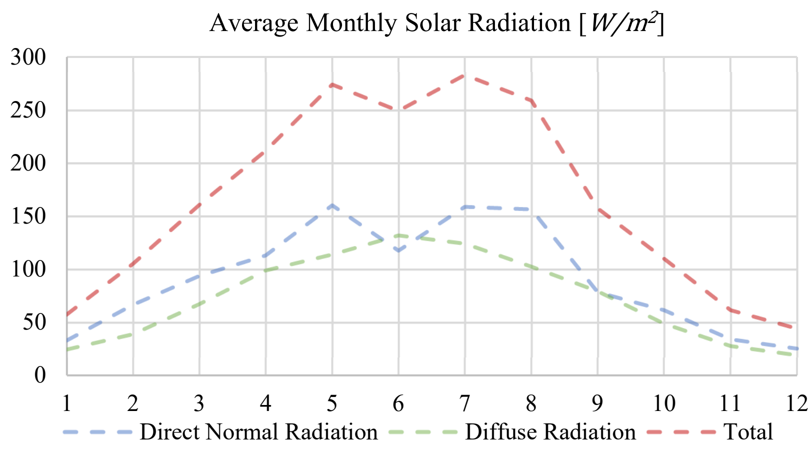


Figure 36: Average monthly values of solar radiation on the horizontal surface for Frankfurt [32]

July (Frankfurt climate)

In the month of July, there is a consistent variation of the outdoor air temperatures, that can range from a maximum of about *5°C* to a maximum of over *30 °C*. Maximum values of total radiation on the horizontal surface are in the order of *1000 W/m²* in some days.
The direct radiation is usually greater compared to the diffuse one. Also the cloudiness of the sky is highly variable, In fact there are fully overcast days, with a cloudiness of *100%*, but also clear days, with a *0%* of cloudiness. Therefore, the environmental conditions during the month of July are highly variable in Frankfurt. The average monthly values are of course lower, as reported in *Table 17*.

Frankfurt (July)
Average Air Temperature [°C]
18.6
Average Total Solar Radiation [W/m²]
283.1
Average Cloudiness [%]
60.4

Table 17: Average monthly values for July in Frankfurt [32]

January (Frankfurt climate)

In the month of January, the lowest temperatures are expected at the beginning of the month (about *-10°C*) while the highest ones at the end of it (about *15 °C*). As seen for the month of July, there is therefore a consistent variation of outdoor temperature conditions. The solar radiation in average is extremely lower compared to the summer, but the peaks are anyway close to *600 W/m²*. In many days, more than the summer, the diffuse component is also greater than the direct normal one. The cloudiness in average is higher than the summer and the number of fully overcast days is larger. Anyway, some clear days are anyway present during the month. Average values of the month are reported in *Table 18*.

Frankfurt (January)
Average Air Temperature [°C]
1.7
Average Total Solar Radiation [W/m²]
57
Average Cloudiness [%]
76.5

Table 18: Average monthly values for July in Frankfurt [32]

To make the performance evaluation of the façade system more robust and comparable to a real case study, the thermal transmittance of the external enclosures of the room (walls, floor and roof) have been defined in function of the energy requirements of the selected location (in this case the Germany). In this way the performance evaluation of the façade system is more coherent with the climate context of the simulated thermal zone. In Germany the requirements for the thermal transmittance of the building envelope components are listed inside the *Energy Savings Ordinance* (*EnVE*) *2013* [33]. The required values are listed in *Table 19*. Ideal materials for the external walls, the floor and the roof have been defined, to reach the minimum requirements for the thermal transmittance of the external enclosures considering an overall thickness of $25\ cm$ (typical for modern office buildings in Europe).

The same thickness is assumed also for the other components of the envelope. The calculation for the definition of the thermal conductivity of the external enclosures of the thermal zone are showed in *Table 19,* in the next page. The physical properties of the ideal material, for all the locations and envelope components, has been set equal to the one the *L/W concrete* (low weight concrete) material already implemented inside IDA ICE: density equal to $500\ kg/m^3$ and specific heat equal to $1050\ J/kg\ K$. These values allow for an external envelope that is nor too heavy nor too light, making the thermal balance of the zone less depending on the overall envelope thermal inertia.

Envelope enclosures					
Walls		**Floors**		**Roofs**	
$U\ [W/m^2K]$	0.28	$U\ [W/m^2K]$	0.35	$U\ [W/m^2K]$	0.2
$R\ [m^2K/W]$	3.571	$R\ [m^2K/W]$	2.857	$R\ [m^2K/W]$	5
$R_{no\ surf}\ [m^2K/W]$	3.401	$R_{no\ surf}\ [m^2K/W]$	2.687	$R_{no\ surf}\ [m^2K/W]$	4.83
$\lambda\ [W/mK]$	0.0735	$\lambda [W/mK]$	0.0930	$\lambda [W/mK]$	0.05176

Table 19: Thermal conductivity calculations for the envelope ideal materials. The thermal transmittance value is expressed in W/m²K, the thermal resistance is expressed in m²K/W while the thermal conductivity is expressed in W/m K.

3.4. Multi-domain performance evaluation using IDA ICE

In IDA ICE, different load and energy simulations can be performed according to the user preferences (in particular, heating and cooling load calculations and energy calculations). For the analysis of the results in this Master Thesis customized energy simulations (ran for a user defined period) has been used for the testing of the research hypothesis related to the control implementation for the *DSF*.

In the *Simulation data* window, it is possible to select between a dynamic and a periodic simulation. A periodic simulation means that a certain period is simulated a certain number of times until the system has stabilized and no longer changes are recorded from a simulation to another one (stabilization process to a periodic state). A dynamic simulation means, on the other hand, that the simulation starts at a particular time and ends at another time. In this case, dynamic simulations have been performed [34] . Tolerance for the resolution of the equations of the mathematical model is set equal to 0.02, while the maximal time-step and the time-step for output are defined as 0.5 hours (*30 minutes*).

Two different kinds of simulations have been performed on the virtual model of the thermal zone, with different purposes and requested outputs for the performance evaluation (*Table 20*): one model with all the active systems turned on and another one with all the actives systems turned off (the so called *free running* configuration).

Using the model with all the active systems turned on (heating, cooling, ventilation plant and artificial lighting) an energy simulation focused on the energy consumption has been performed. The requested outputs were therefore the energy consumption for the zone (space heating and cooling, ventilation heating and cooling and artificial lighting use).

Using the model with all the active systems turned off a simulation focused on the indoor climate conditions has been performed. The requested outputs were consequently the main temperatures in the zones (indoor air and operative temperatures, Fanger's comfort indices (*PMV* and *PPD*), indoor air quality and daylight on the working plane). In this way it was possible to evaluate the indoor comfort conditions without an active system inside the zone.

Performed simulation	*Room model configuration*	*Requested outputs to IDA ICE*
Energy simulation	Active systems turned on (heater, cooler and ventilation)	• Energy for space heating [kWh/m^2] • Energy for space cooling [kWh/m^2] • Energy for ventilation heating [kWh/m^2] • Energy for ventilation cooling [kWh/m^2] • Energy for artificial lighting [kWh/m^2]
Indoor climate simulation	*Free Run*	• Indoor operative temperature [$°C$] • Indoor CO_2 concentrations [ppm] • *PPD* and *PMV* indices [$\%$ and -] • Illuminance levels on the working plane [lux]

Table 20: The two different typologies of simulation performed on IDA ICE and the related simulation outputs

Performing both the simulation typologies (energy and indoor climate) it is possible to make an evaluation of the efficacy of the façade system with a certain implemented control that considers on one side the comfort for the occupants and on the other side the energy consumption. In addition, following this approach, focused on the adoption of building performance indicators (linked to both, energy efficiency and *IEQ*), it is possible to analyse the effects of the adoption of an adaptive façade on the overall performance of the building (in this case, a single thermal zone).

Adopting just the performance indicators of the envelope itself, without considering its complex interconnection with the other building systems cannot be the correct approach to follow: this is caused mainly by the fact that adaptive façades are often characterised by an interconnected performance [9], that influences a wide set of physical phenomena (due to this particularity, the term *multi-domain performance* is often used regarding to advanced envelopes) [7]. The two configurations, with and without active systems, have been defined with two separate versions of the thermal zone model, with the same *DSF* model adopted as façade system. Consequently, given 54 *DSF* models (as illustrated in *3.1*), the total number of generate *.idm* files is 108.

3.5. Comparison with the reference façade systems

Analysing the results of the simulations performed in IDA ICE, it is possible to define which combination of control for the *DSF* (among the proposed ones) is the most appropriate for the selected boundary condition (South façade in Frankfurt, during the heating and the cooling season), in function of the comparison of the performance with a certain reference system. For the cooling season, the best one among the 30 defined combinations should be selected while for the heating season the possible alternatives are 24, as illustrated before.

As reference for the performance comparison (both for the energy evaluation and the indoor climate one), two are the façade systems adopted in this case, characterized with the same geometrical features of the *DSF*:

1) ***First reference system: traditional DSF***

   The first comparison system is the traditional *DSF*, corresponding to a *DSF* for which the ventilation mode in the cavity is kept constant during the whole month. In particular, the two ventilation modes are different for the cooling season and the heating season performance evaluations. A static *TB* configuration has been used for the performance comparison in the winter conditions (in the mont of January) while a static *OAC* configuration has been used as reference system for the summer conditions (in the month of July). These two are the common operational strategies adopted by a traditional *DSF* during the year (*OAC* in the cooling season, while *TB* in the heating season).

   For both the systems, in winter and summer conditions, the shading controls in function of the incident solar radiation on the façade (*SSC#1* and *WSC#1*) has been adopted.
   Also the strategies applied during the week end and the unoccupied hours for the shading system are the same implemented inside the flexible *DSF*.

2) Second reference system: single skin system

The second comparison system is a single skin façade system (*SSF*) (*Figure 37*), with an interior venetian blind of the same typology and material used in the *DSF* system (with fixed slat angle of *45°* and drawn mechanism regulated using the incident solar radiation on the façade). The glazing system is a *TGU* (*triple glazing unit*), the most performant nowadays available for traditional single skin systems as traditional openable windows (*Table 21*).

***TGU* (*SSF*)**
Low E Glass, *5 mm*
Argon filled gap, *12 mm*
Clear Glass, *4 mm*
Argon filled gap, *12 mm*
Low E Glass, *5 mm*

Table 21: Layers of the TGU used in SSF

The optical and thermal properties of the single skin TGU are reported in *Table 22*.

***TGU* (*SSF*)**
$SHGC = 0.547$
$\tau_e = 0.389$
$\tau_v = 0.632$
$U = 0.924\ W/m^2K$

Table 22: Optical and thermal properties of the TGU used in the SSF

Also the frame fraction and the thermal transmittance of the frame are the same inserted as parameters for the *DSF* system. In this way it is possible to define a façade system that has comparable thermal properties respect to the ones of the *DSF*. During the summer, the windows of the *SSF* can be opened by the occupants in the case of which the indoor temperature is above the set point for the cooling season (as traditionally happens with the traditional façade solutions).

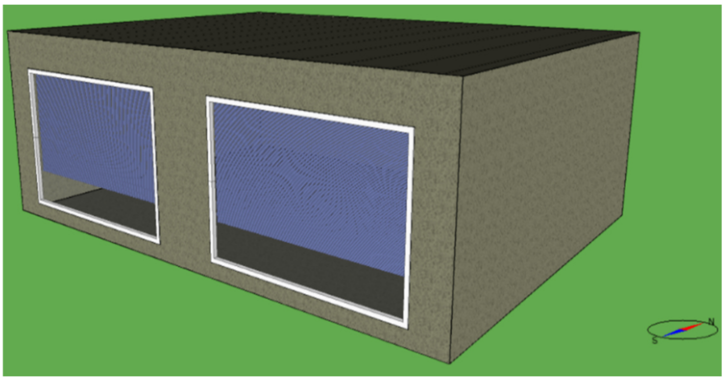


Figure 37: The single skin façade system used as second comparison system for the performance evaluation

As seen for the thermal zone models with the flexible *DSF* used as façade system, also in the case of the reference systems (static *DSF* and *SSF*) two different configurations (with and without active systems) have been defined.

Therefore, other 4 *.idm* files (2 for *SSF* and 2 for the static *DSF*) have been created, for a total number of 116 of thermal zone models used for the performance analysis (108 for the flexible *DSF* configurations and 8 for the reference systems), 58 with the active systems turned on and 58 for the *free running* configuration.

3.6. Testing of the control effectiveness during the mid-season periods

After the testing of the control effectiveness in typical peak summer and winter conditions, the optimal control combinations which have showed a good performance in the months of July and January, have been modified and tested also in mid-season periods, with the durations of 1 month.

The selected months are April (for typical Spring conditions) and October (for typical Autumns conditions): this step had the aim to analyse the control effectiveness in more variable and fluctuating environmental conditions (outdoor air temperature and incident solar radiation in particular), which are typical in mid-season periods. Following this approach, it is possible to test in a more effective and reliable way the flexibility of the façade system, because a greater variability of the outdoor conditions is present (on the other hand, summer and winter conditions are more *extreme* but at the same time less variable and fluctuating).

The environmental conditions in April and October, for the Frankfurt climate, are comparable in terms of average air temperature and cloudiness, but they differ a lot in the case of the average total solar radiation, considerably lower in October than in April. For Frankfurt, the average monthly data for April and October are here reported (*Table 23* and *Table 24*).

Frankfurt (April)
Average Air Temperature [°C]
9
Average Total Solar Radiation [W/m^2]
211.7
Average Cloudiness [%]
64.3

Table 23: Average monthly values for April in Frankfurt [32]

Frankfurt (October)
Average Air Temperature [°C]
10.1
Average Total Solar Radiation [W/m^2]
110
Average Cloudiness [%]
68

Table 24: Average monthly values for October in Frankfurt [32]

The approach followed for the performance evaluation is the same already adopted in analysis for July and January: two different configurations of the *BESTEST* cell model (with the active systems turned on and off) have been used for the control effectiveness evaluation under the point of view of the energy efficiency and the indoor environmental quality for the occupants. The performance parameters for the analysis were the same already used in July and January. The characteristic of the thermal zone are of course unchanged and also the reference systems (*SSF* and static *DSF*) used as baseline.

3.7. Creation of the decision tree for the whole year and parametric optimization

The last step of the method is to merge the optimal control combinations for the heating and the cooling seasons, already modified and tested for typical autumn and spring conditions, in a common decision tree for the *DSF* which can be used for the whole year (not just for a limited period of time, as for example one month): in this way, an single control logic can be applied to the *DSF*, with the aim to manage all the different operating strategies (*TB*, *OAC*, *AE*, *AS*, *CF* and *IAC*) during the whole year.

Before the creation of the definitive *DSF* control logic and the subsequent performance evaluation, it is however necessary a parametric optimization of the control of the *DSF*, by varying the different threshold values of the rule-based decision tree in a in iterative way.

In this way, different combinations of threshold values for the different control variables (incident solar radiation, indoor air temperature, outdoor air temperature, cavity temperature, CO_2 concentrations) can be implemented.

Among these combinations it is necessary to select the ones which produce the best results in terms of overall performance of the system.

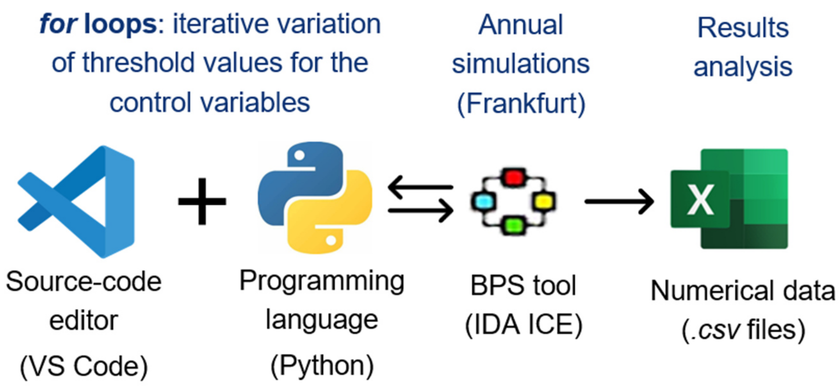


Figure 38: Parametric optimization process applied using the IDA Application Programming Interface

For this purpose, it is necessary to control the IDA ICE simulation environment externally, by means of an *API* (*Application Programming Interface*) written in the programming language Python (*Figure 38*). The API in fact enables the communication between the IDA ICE simulation environment and the user by means of an external interface (in this case *Visual Studio Code*, a source-code editor that can be used with several programming languages, as, for example in this case Python) [35].

Using the IDA API, it is possible to connect the source-code editor with the IDA simulation environment (corresponding to the *idm* file in which the flexible *DSF* is modelled). In particular, by means of the script implemented inside the source-code editor, the user can modify the different parameters of the rule-based decision tree (for example by means of a *for* loop) and then launch the simulation in IDA ICE.

These features make the modelling process considerably easier and faster because it is not necessary to open and modify manually different *.idm* files (as done with the different control combinations in the single months simulations).

After the launch of the simulation, the user can have access to the different outputs of the simulation (for example the different components of the room energy need) using a specific tree structure, which starts from an *ancestor* node (in general the idm file in which the simulation is performed) that is then divided into different *children's* nodes (all the elements that are defined inside the simulation IDA ICE environment).

With the same approach, it is possible to access to all the different parameters and variables of the objects inside the *idm* file (like for example a *DSF* object) using the hierarchical tree structure of the *children's* nodes, modifying them according to a specific control strategy. Consequently, the IDA API can be used for three different main application:

1) Parametric change of the different threshold values for the control variables used in the *DSF* control decision tree
2) Launch of the annual simulations for each implemented combination of values inside the *BPS* environment
3) Analysis of the *DSF* performance for each implemented combination of values

All these features have been used for the optimization of the control for the *DSF* and the subsequent results analysis.

4. DSF behaviour analysis and performance comparisons in July and January

In this section, the results of the analysis performed on IDA ICE on the test cells models (with the different façade systems: flexible *DSF*, static *DSF* and *SSF*) are reported, grouped in the different domains of the performance evaluation (energy efficiency and indoor environmental quality).

During the analysis. the *DSF* performance, with different combinations of control, both in summer and winter conditions, has been compared with the selected reference systems already described in *3.5* (*SSF* and static *DSF* systems).

4.1. Behaviour of the DSF with the different control combinations

In this first part of the results analysis, the behaviour of the *DSF* with the implementation of different control combinations has been analysed and studied.

For this analysis of the *DSF* behaviour, the two configurations of the model (with active systems turned on and *free-running* configuration with the active systems turned off) have been discussed in separate way, since the dynamicity of façade system is influenced by different boundary conditions in these two cases: in particular, without the presence of ideal heating and cooling systems and a ventilation plant, the fluctuation of the different selected control variables is more consistent compared to the configuration with the active systems turned on.

For the control of the cavity air flows, the percentage of hours of the selected months (744 for both January and July) in which the different configurations are applied is considered. The analysis wants mainly to show how the different control combinations can influence the switching between the different operating configurations of the façade system.

4.1.1. Active systems turned on

In this section, the active configuration of the model is considered to evaluate the switch between the different ventilation modes of the *DSF,* both in summer and winter conditions, in the case in which the heating, cooling and ventilation systems are in function.

Cooling season

For the summer season, the configurations assumed by the *DSF* using the *SAC#1* and *#2* combinations are very similar, if the daily trends are considered. From *SC#1* to *SC#12*, the graphs of the output signals analysed in IDA ICE are quite the same, expect for some differences in the output signals during the central hours of the day. If the airflow controls *SAC#3* and *#4* are applied, more variability in the configuration changes is visible. Anyway, the outputs are very similar analysing the configurations from *SC#13* to *SC#24* (as seen in the case of the application of *SAC#1* and *#2*).

In the case of the adoption of *SAC#5* inside the combination, it is visible in some cases the application of the *AS* configuration during the central hours of the day. The percentages of hours for the use of the different configurations are reported from *Figure 39* to *Figure 43*.

The different combinations of control are grouped in function of the different air flow controls that have been used (coupled with the 6 different shading controls). For all the combinations of control, the most adopted configuration is the *TB,* followed by *AE* natural and *OAC* natural. This is because they are the most adopted during the unoccupied hours of the day and in the weekend. For this reason, the percentage of hours with respect to the overall duration of the month is considerably higher compared to other configurations. *AS* configuration is largely adopted in the case of *SAC#5*.

In the case of the adoption of *SAC#1* and *#2*, the percentage of hours for the different configurations are almost the same for all the combinations (from *SC#1* to *SC#12*).

In particular, the adopted configurations are *AE* natural, *AE* mechanical with minimum air flows in the cavity, *OAC* natural and of course *TB*.

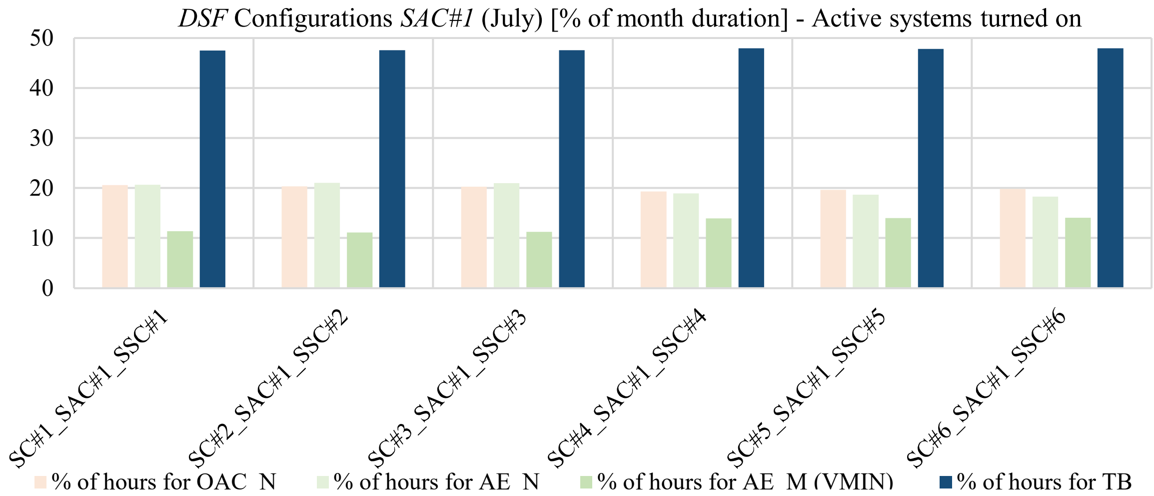


Figure 39: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#1 as airflow control

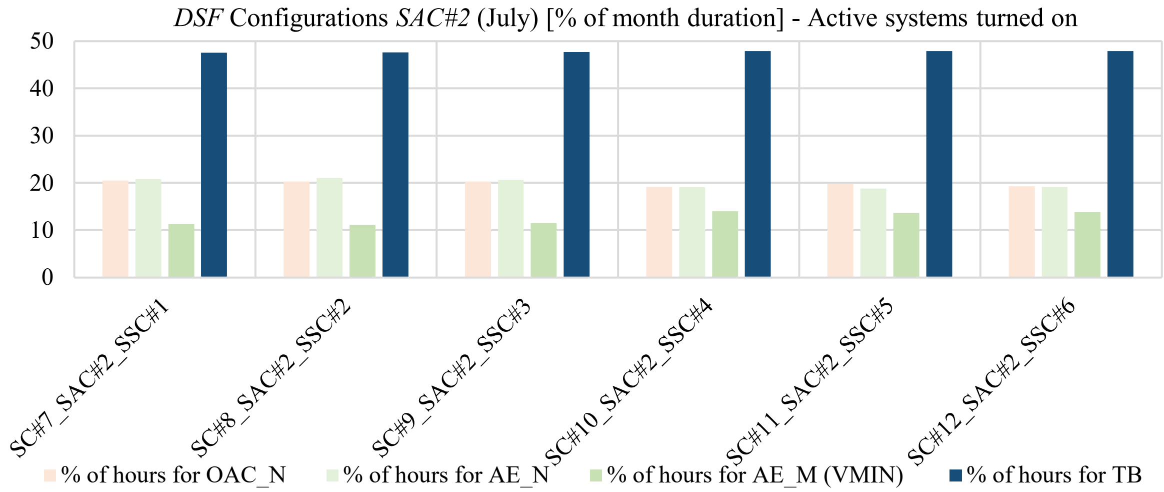


Figure 40: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#2 as airflow control

If the *SAC#3* and *#4* air flows controls are applied in the combination, the additional presence of the *OAC* mechanical configuration (with minimum air flow in the cavity) is visible. This last configuration is applied with equal frequency if the *SAC#3* or *#4* air flow controls are used (the two different used control variables for the switching between natural and mechanical ventilation consequently produce the same results).

Anyway, *AE* natural, *AE* mechanical with minimum air flows in the cavity, *OAC* natural and *TB* remain the most used configurations from *SC#9* to *SC#16*. In the case of the application of *SAC#4* (in which the switch between natural and mechanical ventilation is implemented in function of the cavity air temperature), it is visible also the application of the *OAC* mechanical configuration with maximum fan velocity (only if the radiation control for the shading is activated). Anyway, this configuration is applied for a very limited period.

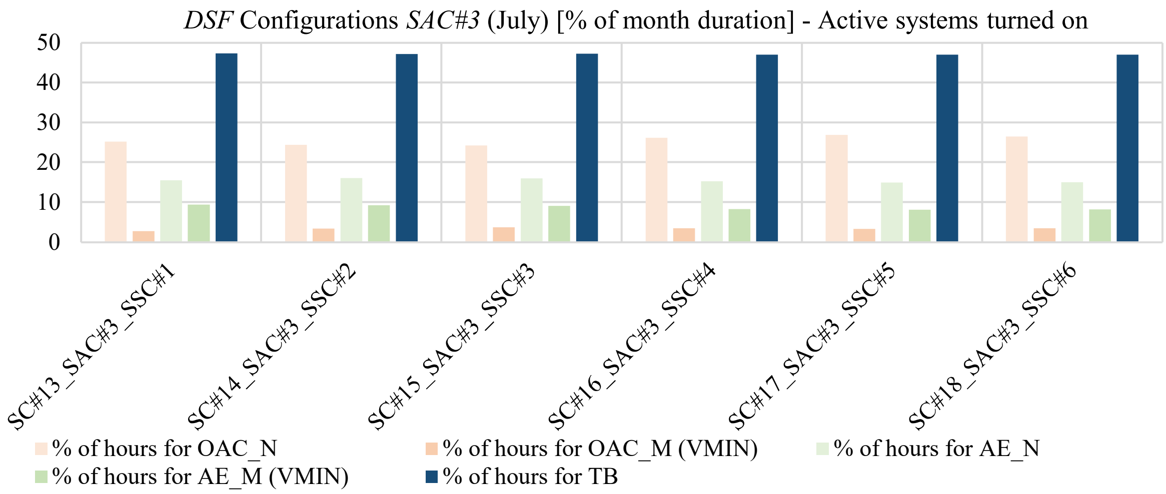


Figure 41: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#3 as airflow control

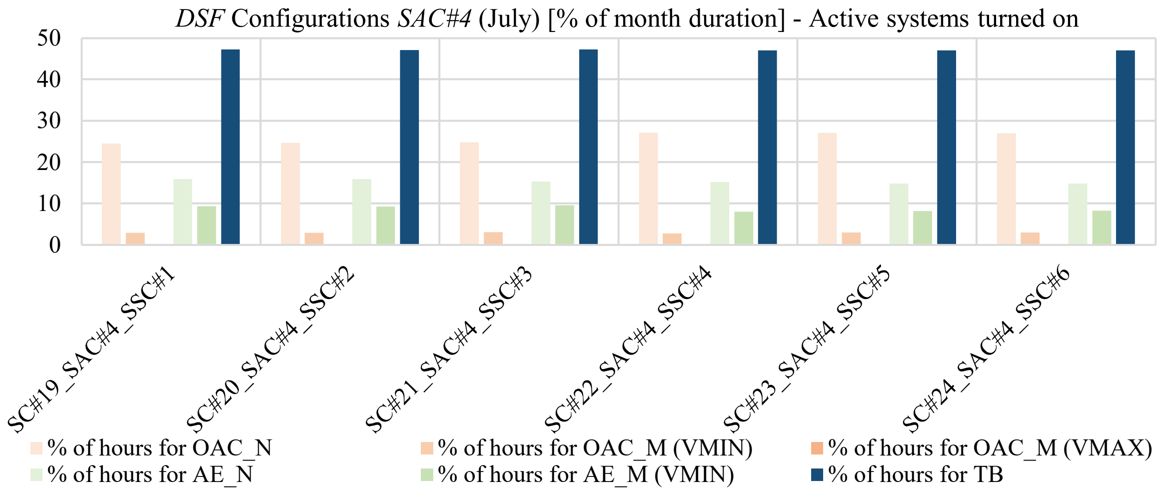


Figure 42: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#4 as airflow control

Using the *SAC#5* air flow control, the additional presence of *AS* configuration is visible, and it is applied with a frequency comparable to *OAC* natural. *AE* natural and mechanical are used in this case with a lower extent. Moreover, with the last air flow control the *OAC* mechanical configuration is never used by the *DSF*.

In general, the different shading controls (from *SSC#1* to *SSC#2*) do not influence in a consistent way the different configurations assumed by the *DSF*.

The most significant differences in percentages of hours are the ones visible between the combinations which adopt the radiation control for the shading (*SSC#1*, *#2* and *#3*) and the temperature control (*SSC#4*, *#5* and *#6*).

This is of course caused by the different activation mechanisms of the blind (radiation and temperature), for which the shading system is down for a different extent of time, influencing in this way the temperature of the cavity and as a consequence the façade behaviour.

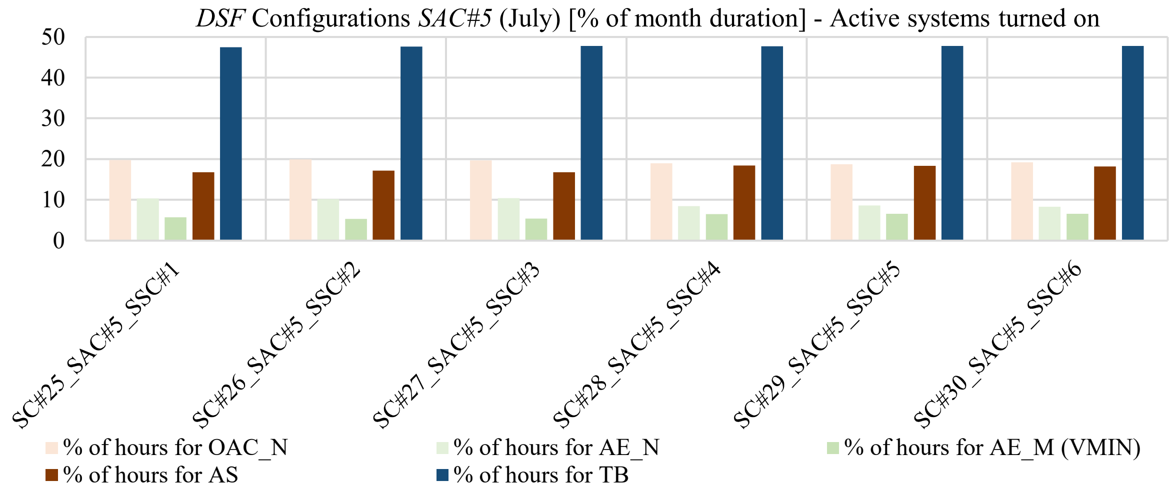


Figure 43: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#5 as airflow control

Focusing the occupied hours only of the room (from *Figure 44* to *Figure 48*), which are 210 in total during the month of July, an higher variability of the results in the configurations changes is visible, since the configurations switching is applied mainly to the occupied hours of the room, while for the unoccupied hours (night, lunch break and week-end) mainly standard and fixed configurations are applied, with less consistent variability in the configuration change.

In fact, the variability in the energy performance among the different control combinations is mainly caused by the adoption of different control strategies during the occupied hours of the room. In the graph the *TB* configuration is used with a considerably lower frequency (in the order of *5%* of the occupied hours during the month).

This is because it is not applied for the occupied hours of the room. Its presence is consequently only caused by the adoption of the *Sliding Average* modules in the *DSF* decision trees (See *Appendix D - Rule-based control implementation in IDA ICE*).

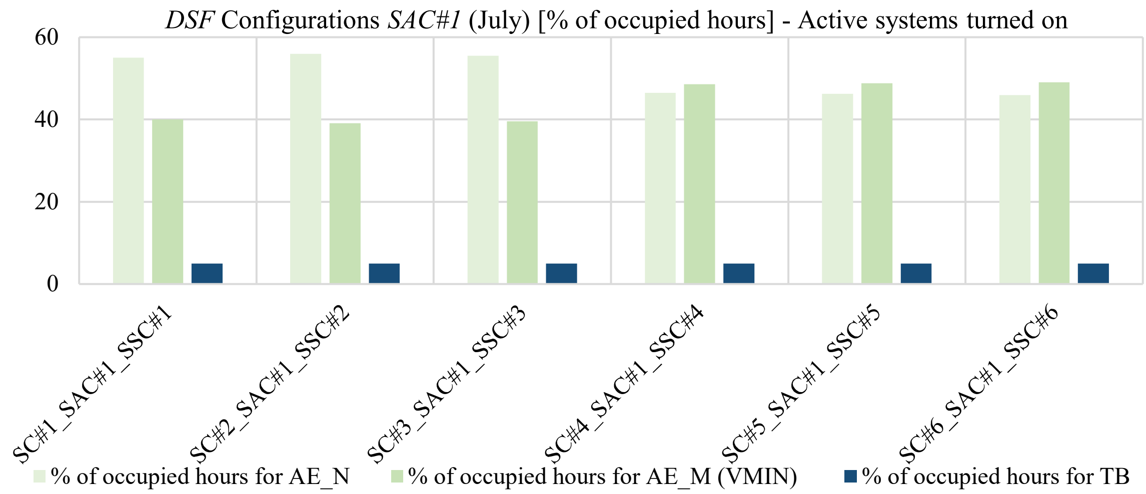


Figure 44: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#1 as airflow control

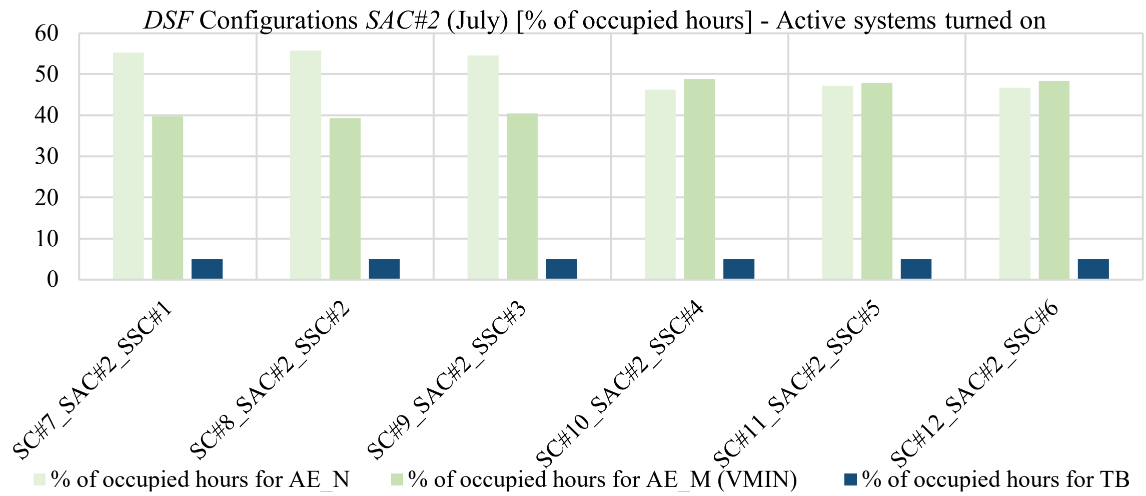


Figure 45: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#2 as airflow control

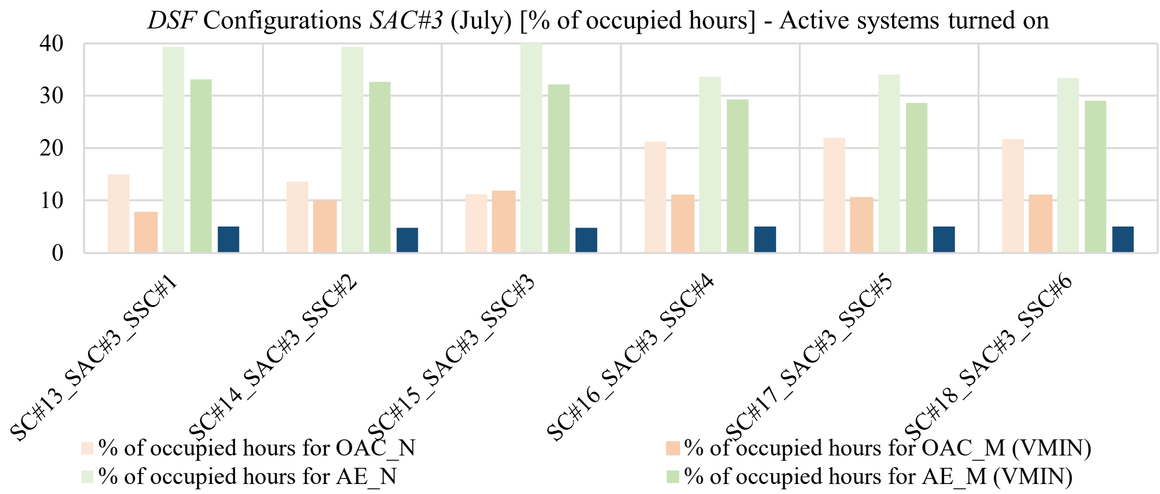


Figure 46: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#3 as airflow control

Using the *SAC#1* and *#2* air flows controls, the configurations adopted by the *DSF* are basically the same from *SC#1* to *SC#12*. For the occupied hours, the main operating strategies of the *DSF* are the *AE* natural and mechanical (with minimum air flow implemented inside the cavity).

Consequently, only 2 configurations are mainly assumed by the *DSF* during the occupied hours of the room if the *SAC#1* and *#2* are applied, *AE* natural and mechanical (the flexibility of the system is not so high in this case).

The only visible difference is in the configurations assumed by the *DSF* with the two control mechanisms (radiation and temperature) for the shading: if the radiation control is used, the *AE* natural configuration is adopted with larger frequency compared to the mechanical one.

The opposite is in the case in which the temperature activation of the blind is used.

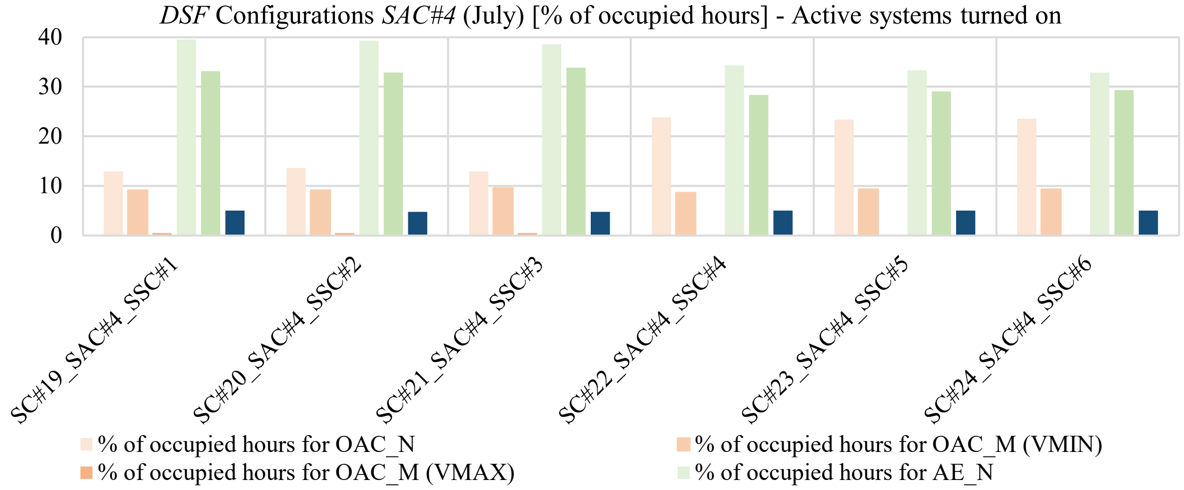


Figure 47: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#4 as airflow control

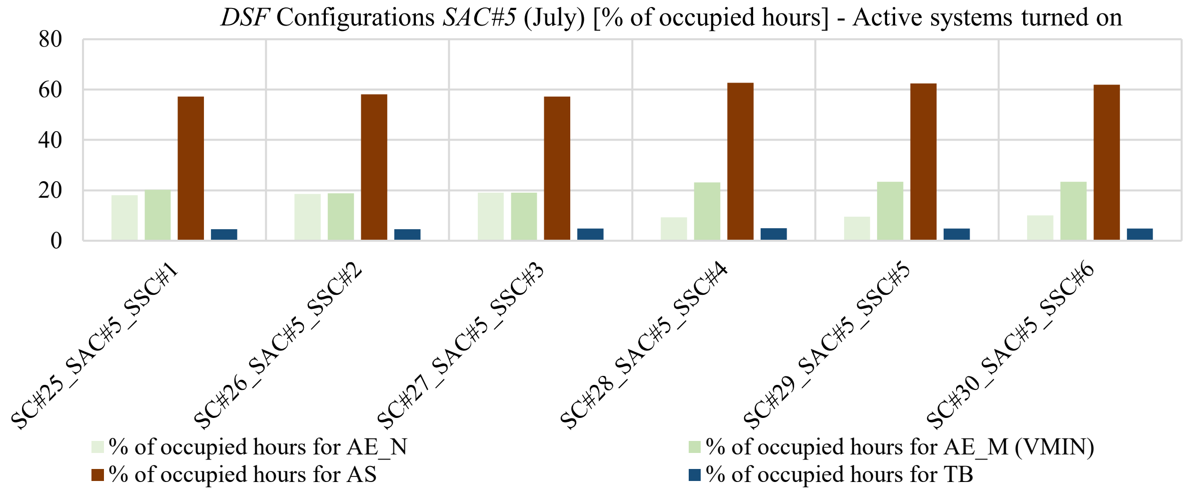


Figure 48: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned on) with SAC#5 as airflow control

Applying the *SAC#3* and *#4* controls, on the other hand, the flexibility of the system during the occupied hours of the room is higher, since the variability of configurations is larger. In these cases, from *SC#13* to *SC#24*, the additional presence of the *OAC* configuration during the occupied hours (natural and mechanical with minimum air flow in the cavity) is visible.

These two airflow controls consequently ensure the larger flexibility in the façade behaviour during the occupied hours of the room. In these cases, it is possible to see that the *OAC* natural configuration is used with larger frequency if the temperature control of the shading is used.

Using the *SAC#5* control, the additional presence of *AS* configuration is visible. This configuration during the occupied hours is used with higher frequency than *AE* configuration (both natural and mechanical). No use of *OAC* configuration in visible, at the same time.

Heating season

In the winter season (from *Figure 49* to *Figure 52*), using the control *WAC#1*, mainly the *TB*, *AS* and *CF* configurations are used, while the *IAC* configuration is never adopted. The possible differences in the configurations adopted by the *DSF* are mainly caused by the application of different control forms for the shading. These differences are anyway not particularly evident.

In the case of the application of *WAC#2* and *#3*, the additional presence of *OAC* configuration is possible, because this configuration is inserted inside the decision tree. However, only in the case of *WAC#2* (in which the cavity temperature is used for the switch between *AS* and *OAC*) the adoption of this configuration is visible. Anyway, the number of hours in which the configuration is used is very limited (for this reason, it is not viewed in the graph). In the case of *WAC#3*, on the other hand, the *OAC* configuration is never used (the control variable used for the *AS*-*OAC* switch is the indoor air temperature in the room).

The *WAC#4* control, if the active systems are turned on, produces very similar configurations compared to *WAC#2*. In particular, the *AE* configuration is never used if the ventilation systems in the room is turned on (because the CO_2 concentrations are kept below the threshold limit of $1000\ ppm$ using the fans). In general, differently from the summer, it is less evident the influence of the two-activation mechanism (temperature and radiation) for the integrated blind on the different configurations assumed by the *DSF*.

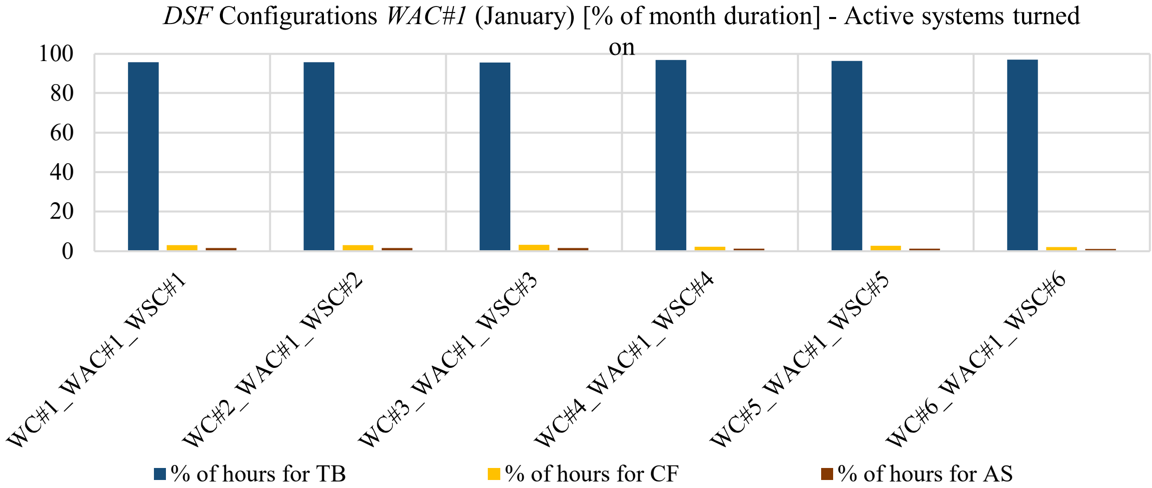


Figure 49: Percentages of hours in the month (January)in which the different DSF configurations have been adopted (active systems turned on) with WAC#1 as airflow control

For the winter season, the largest use is the one for the *TB* configuration, which is used both during the weekend and the night as default configuration. The adoption of this configuration consequently is largely more frequent compared to the other ones. In addition to this, with the active systems turned on, the *IAC* configuration is almost never used with all the combinations of control for the winter season. Consequently, the overall flexibility of the system is lower compared to the one of the summer season.

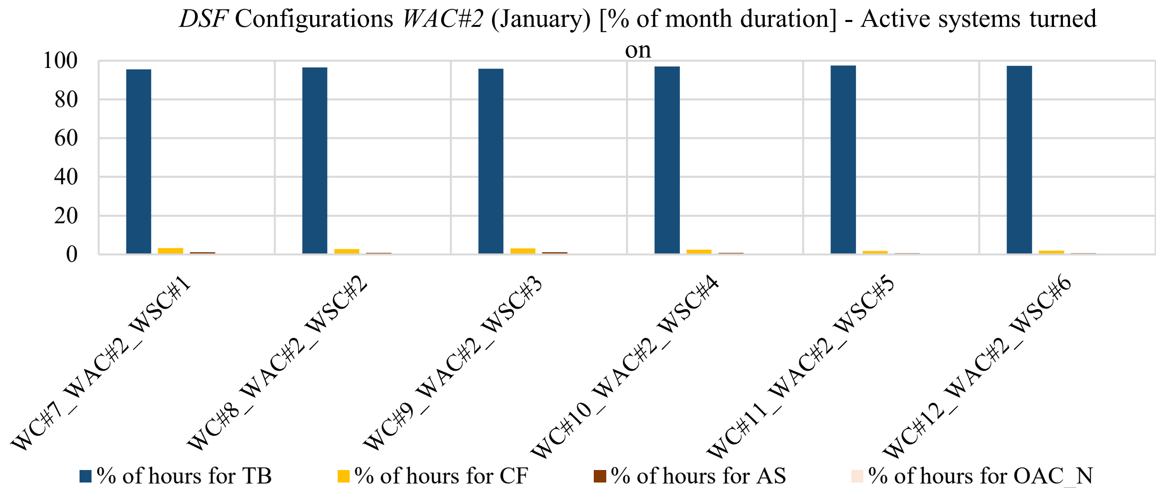


Figure 50: Percentages of hours in the month (January)in which the different DSF configurations have been adopted (active systems turned on) with WAC#2 as airflow control

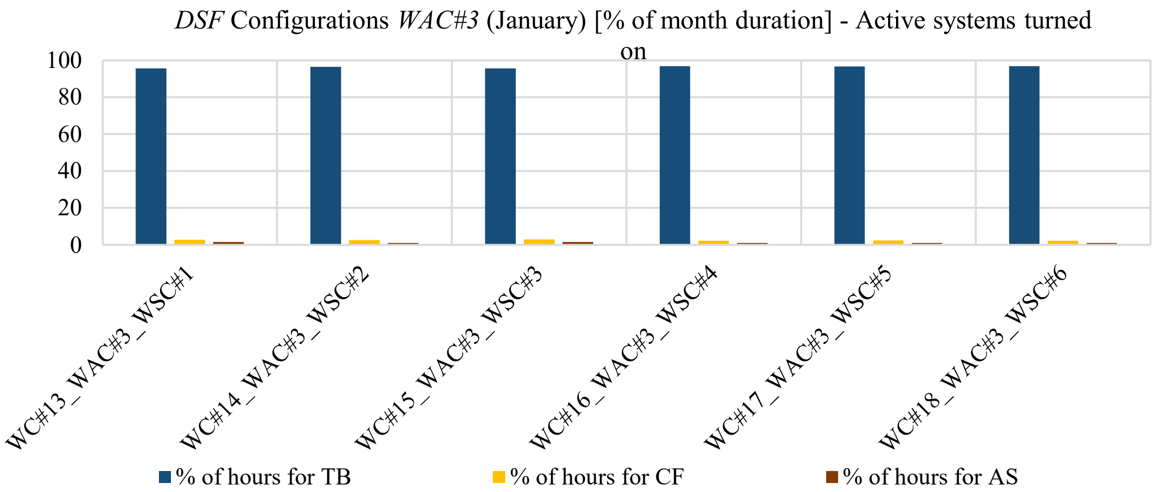


Figure 51: Percentages of hours in the month (January)in which the different DSF configurations have been adopted (active systems turned on) with WAC#3 as airflow control

Focusing on the occupied hours of the room (from *Figure 53* to *Figure 56*), as done for the summer season, the trend in the configuration changes is almost the same observed considering the overall month duration.

The only difference is the lower percentage of use of the *TB* configuration compared to the other ones, since the weekend and the night periods are not considered. This remains anyway the most adopted configuration also during the occupied hours of the room.

In this case it is possible to see that, if *WAC#1*, *#2* and *#3* are coupled with the temperature control of the shading, the *AS* configuration is not adopted during the occupied hours of the room.

In addition, the *CF* configuration is adopted with a slightly higher frequency if the radiation control of the blind is used.

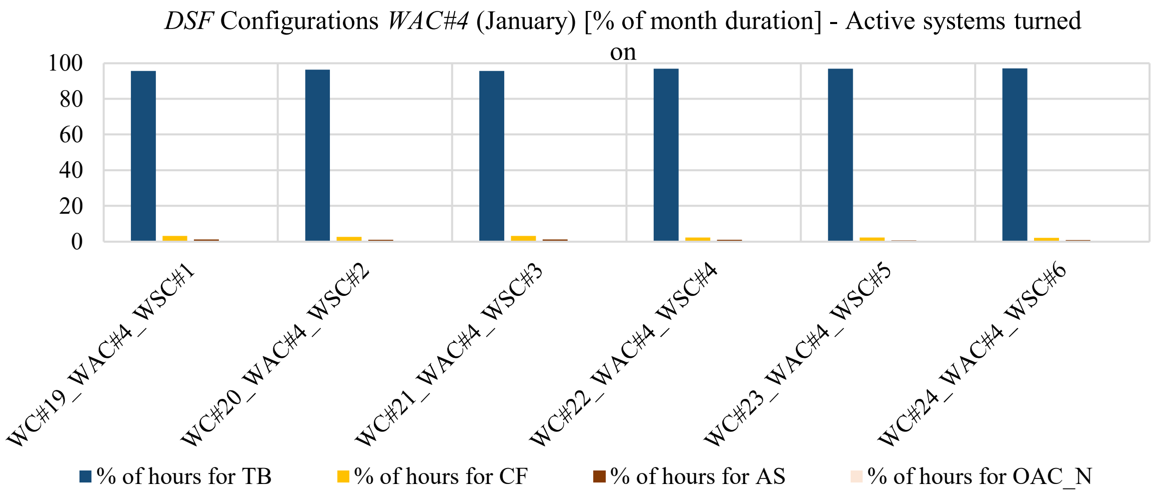


Figure 52: Percentages of hours in the month (January)in which the different DSF configurations have been adopted (active systems turned on) with WAC#4 as airflow control

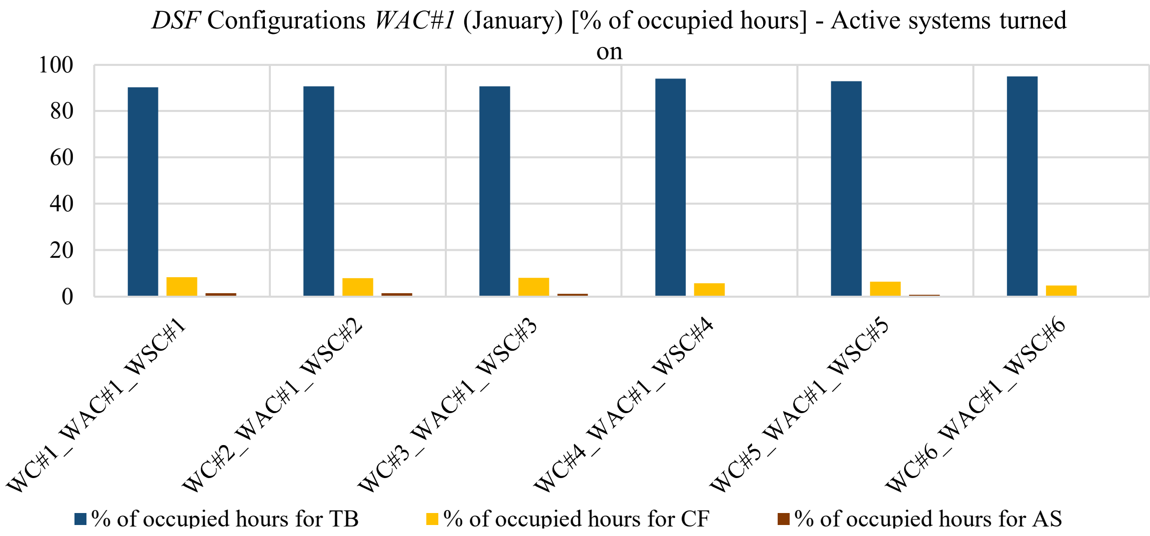


Figure 53: Percentages of occupied hours in the month (January)in which the different DSF configurations have been adopted (active systems turned on) with WAC#1 as airflow control

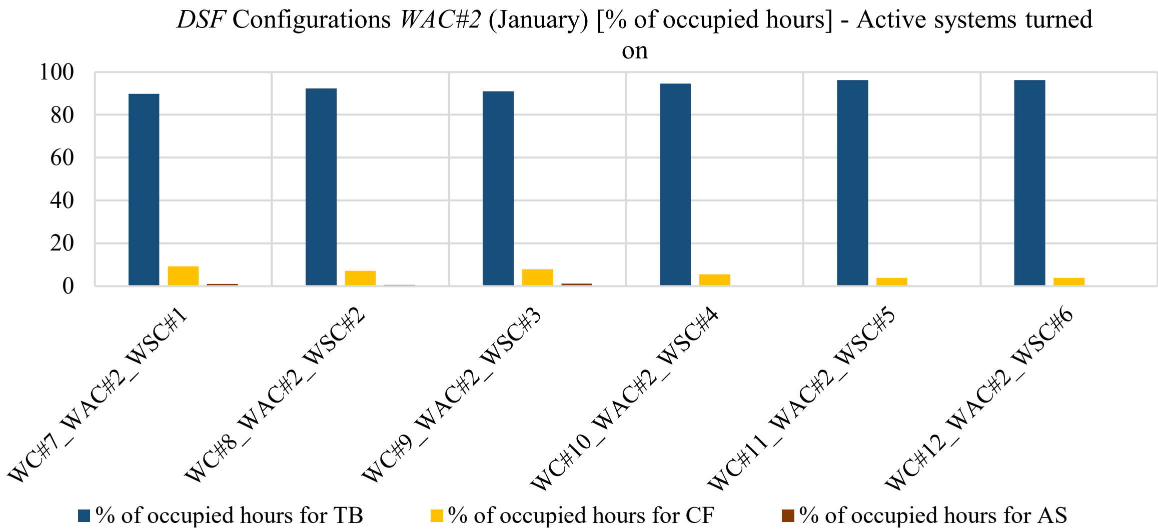


Figure 54: Percentages of occupied hours in the month (January)in which the different DSF configurations have been adopted (active systems turned on) with WAC#2 as airflow control

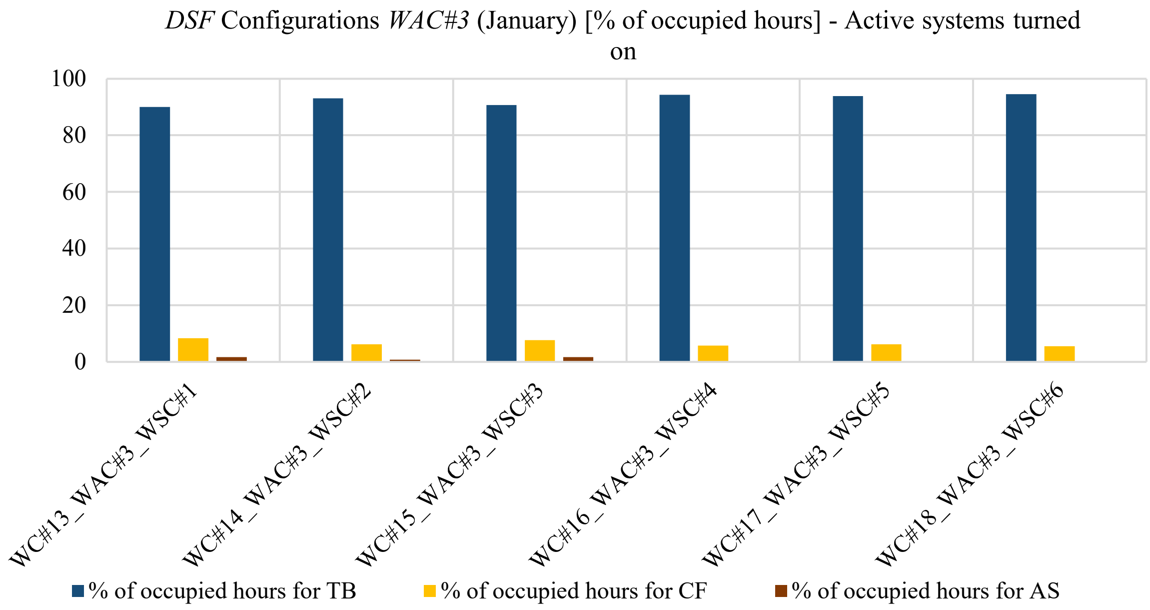


Figure 55: Percentages of occupied hours in the month (January)in which the different DSF configurations have been adopted (active systems turned on) with WAC#3 as airflow control

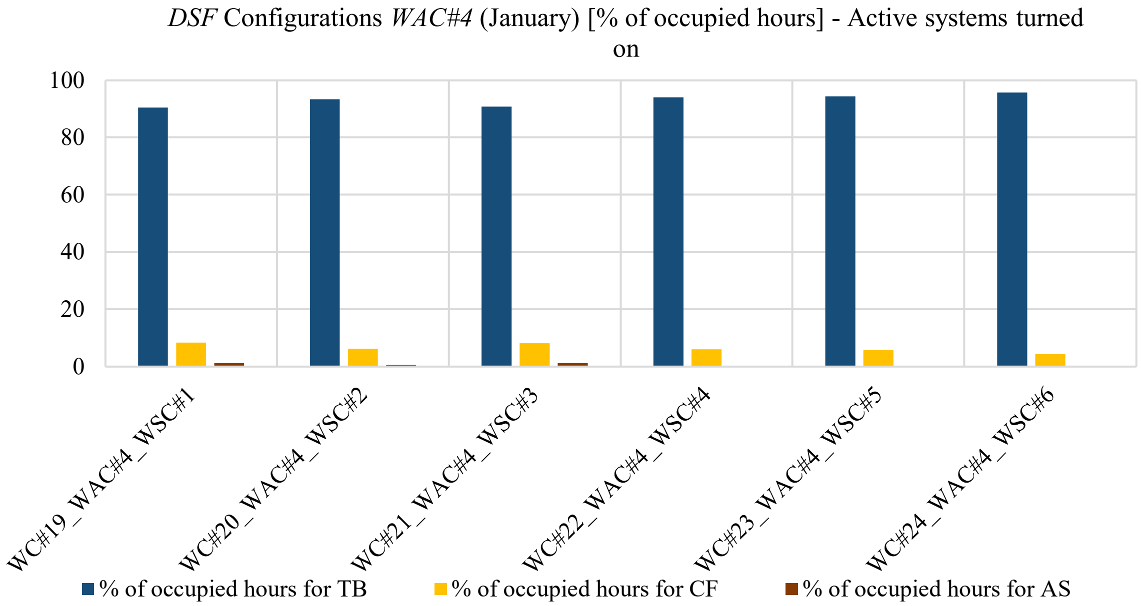


Figure 56: Percentages of occupied hours in the month (January)in which the different DSF configurations have been adopted (active systems turned on) with WAC#4 as airflow control

4.1.2.Active systems turned off

In this section, the free running configuration of the model is considered for the evaluation of the ventilation modes switching for the *DSF*, in the same way performed with the model with the active systems.

Cooling season

In general, a greater variability of the configurations is visible in the free running version of the model and in general the influence of the different form of shading control in the *DSF* configurations change is more evident compared to the active systems model (See from *Figure 57* to *Figure 61*).

As seen for the previous typology of the cell, in the case of the application of *SAC#1* and *#2*, the configurations assumed by the *DSF* are quite the same: some differences are present in the *AE* configurations in the cases of application of temperature and radiation activation of the blind.

On the other hand, the combinations which use the *SAC#3* air flow control produce output configurations which are different from the ones generated by the combinations which adopt *SAC#4*: in general, a greater variability in terms of configurations is visible if the *SAC#3* airflow control is applied, compared to *SAC#4* (this is caused by the different control variables adopted for the switching between *OAC* natural and mechanical).

At the end, as seen for the model with the active systems turned on, in the case of *SAC#5* application the adoption of the *AS* configuration is visible in the central parts of the day. For all the combinations of control, as seen for the model configuration with the active systems turned on, the most adopted ventilation mode during the night is *TB*, while for the weekend day period both *OAC* and *AE* are applied with similar frequency.

With the adoption of *SAC#1* and *#2*, the same percentages of duration for the different configurations are visible for the different control combinations. The most adopted configurations (after *TB*) are the *AE* natural and the *AE* mechanical with both minimum cavity air flows implemented.

The higher CO_2 concentrations in the room, with the ventilation plant turned off, also allow the adoption of the increased mechanical ventilation in the cavity (used anyway for a limited period).

Also *OAC* natural is used with a large frequency. With the adoption of *SAC#3* and *#4*, a higher number of configurations is assumed by the *DSF*, as seen for the active systems version of the room. It is visible the adoption of *OAC* mechanical configurations (with both minimum and maximum cavity air flows).

In the case of *SAC#3* application, the minimum air flow is used with a considerably lower frequency compared to the maximum one.

On the other hand, in the case of the application of *SAC#4*, the maximum air flow rate is used with a lower frequency compared to the minimum one (and the *OAC* natural configuration is adopted with a considerable higher frequency).

This is an effect of the different control variable (indoor air temperature or cavity temperature) that is used for the switching between the different velocities (minimum and maximum) of the cavity fan.

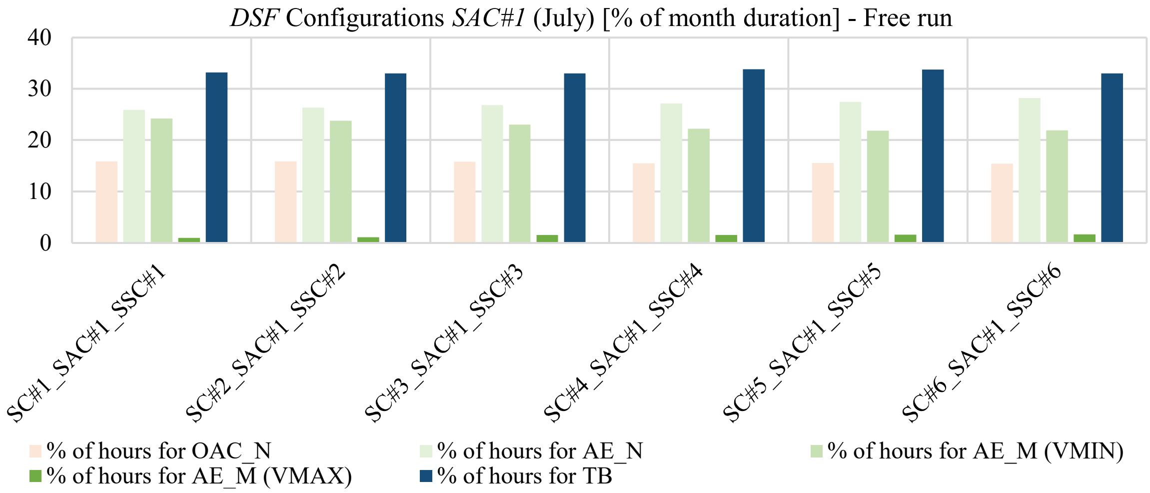


Figure 57: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#1 as airflow control

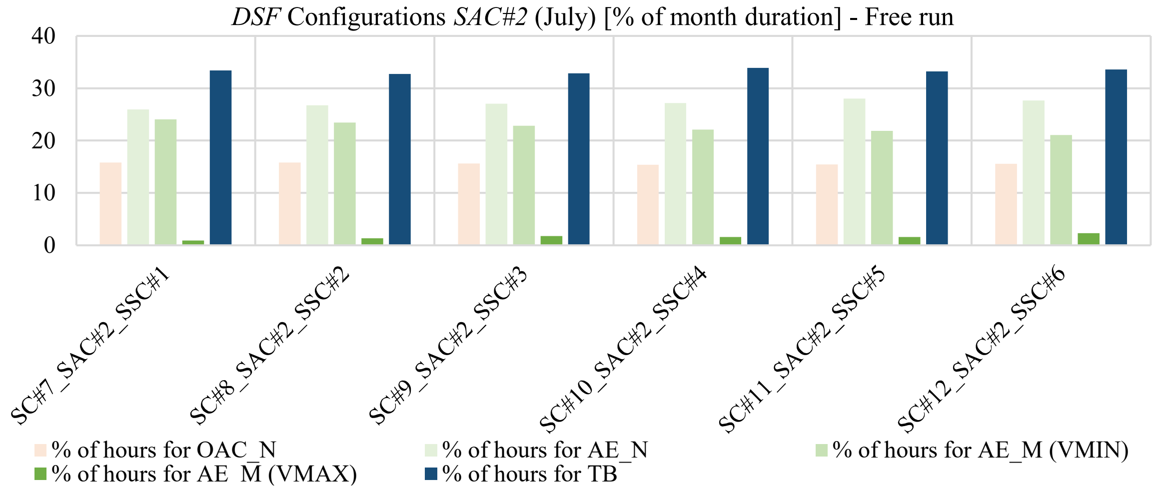


Figure 58: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#2 as airflow control

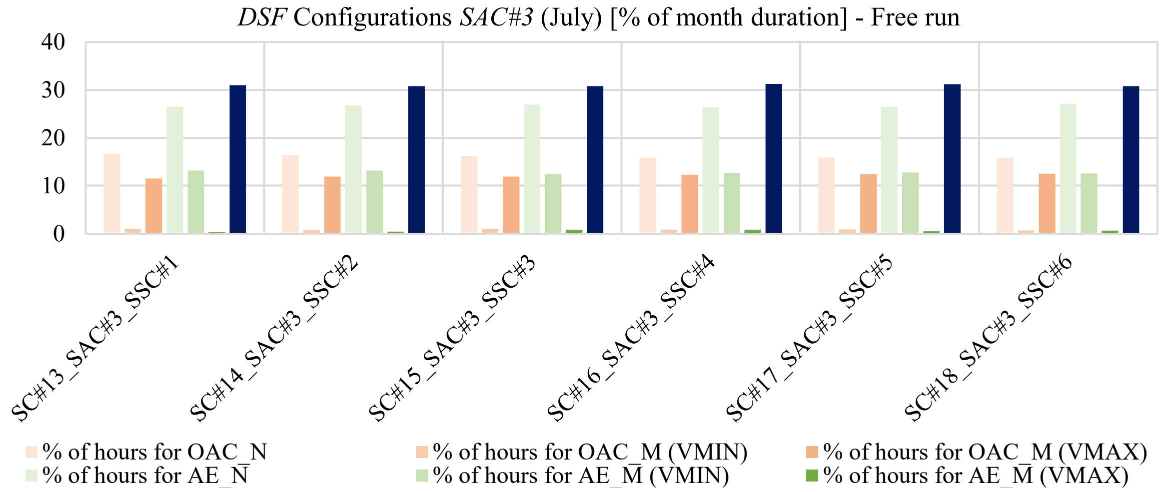


Figure 59: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#3 as airflow control

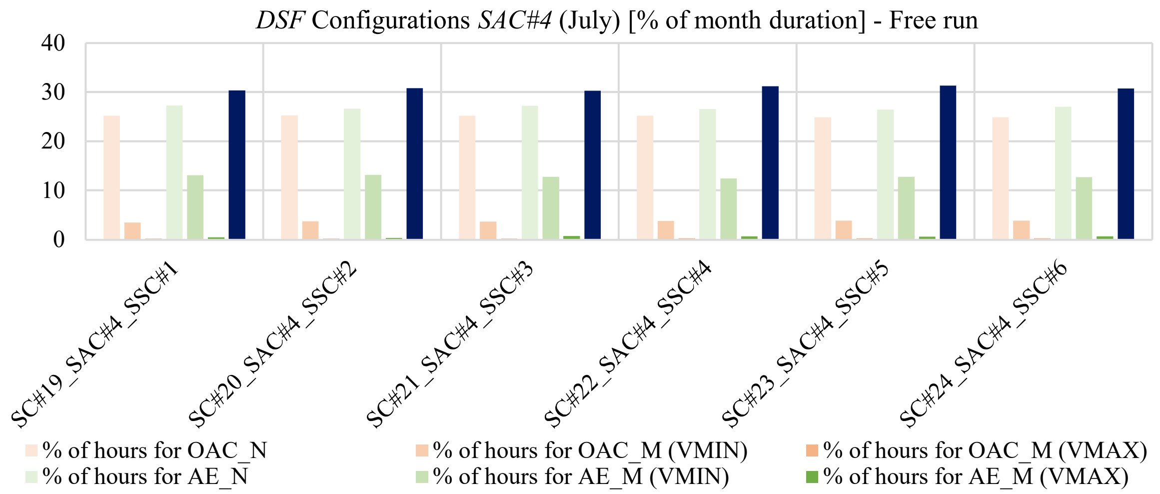


Figure 60: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#4 as airflow control

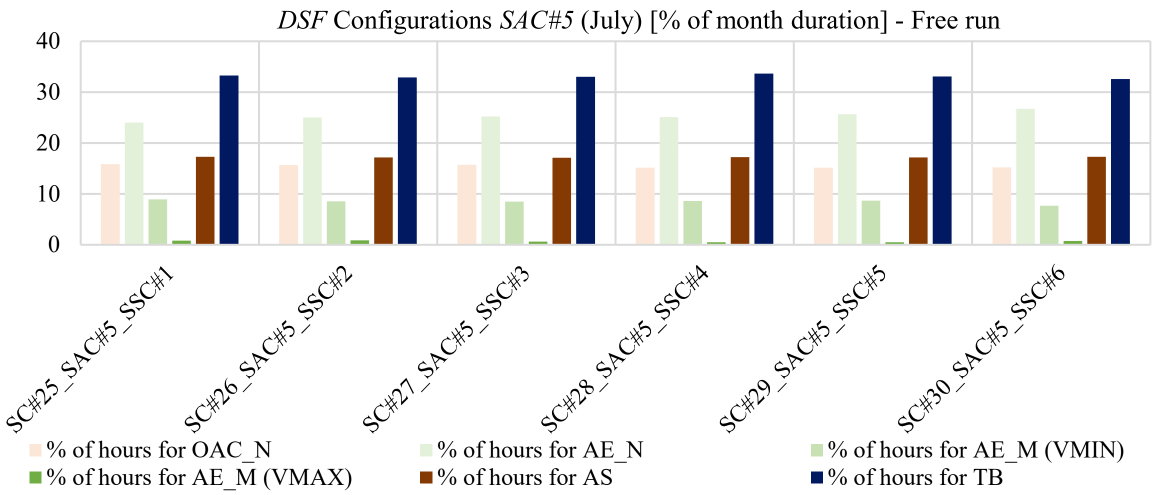


Figure 61: Percentages of hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#5 as airflow control

In the case of *SAC#5* application, the percentages of duration for the different configurations are very similar to the case in which the active systems are turned on.

Anyway, it is also visible the adoption of the *AE* mechanical configuration with the maximum air flow implemented inside the cavity, in all the combinations of control from *SC#25* to *SC#30*: this is of course caused by the increased CO_2concentrations inside the room if the ventilation system is turned off.

As done for the model version with all the active systems turned on, it is possible to consider only the configurations assumed by the *DSF* during the occupied hours of the room (from *Figure 62* to *Figure 66*). In fact, these configurations have the largest impact on the overall comfort conditions for the occupants.

For all the combinations of control, if just the occupied hours are considered, it is possible to see that the *TB* configuration is almost never used. In the case of the use of *SAC#1* and *#2*, there is an exclusive use of *AE* configurations (both natural and mechanical, with minimum and maximum velocity for the cavity fan).

In general, if the radiation control for the shading is used (*SC#1*, *#2* and *#3*), the *AE* natural configuration is adopted with a slightly higher extent.

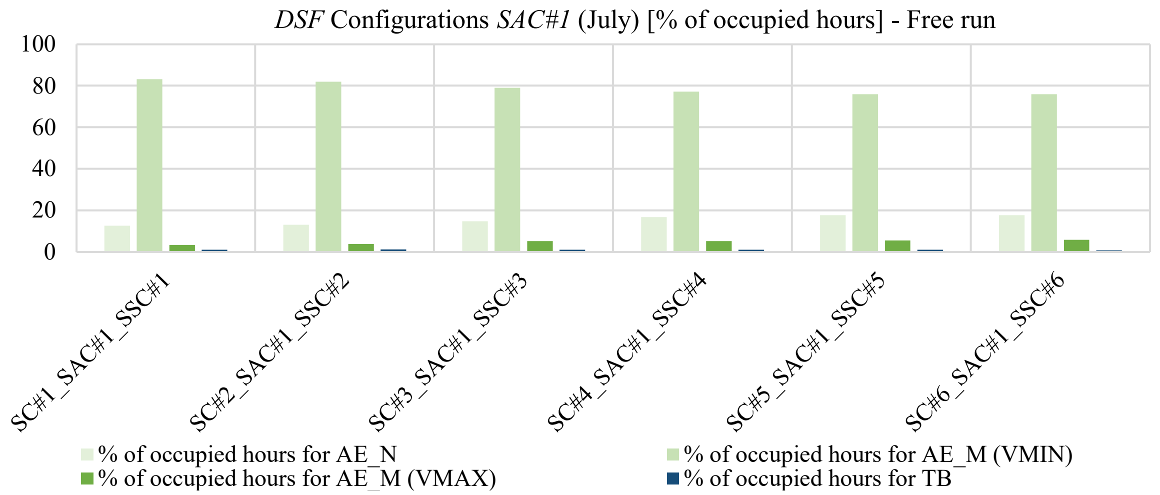


Figure 62: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#1 as airflow control

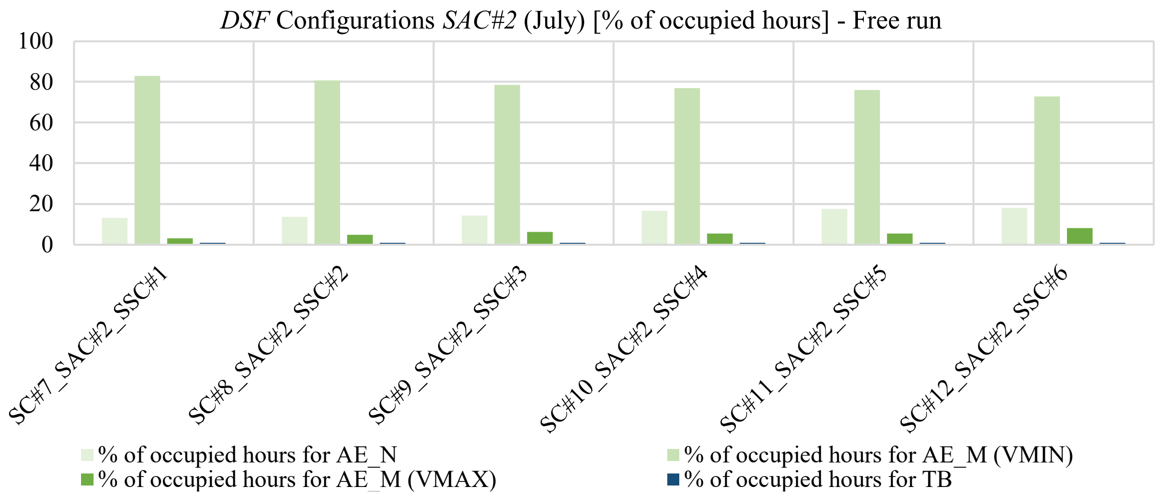


Figure 63: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#2 as airflow control

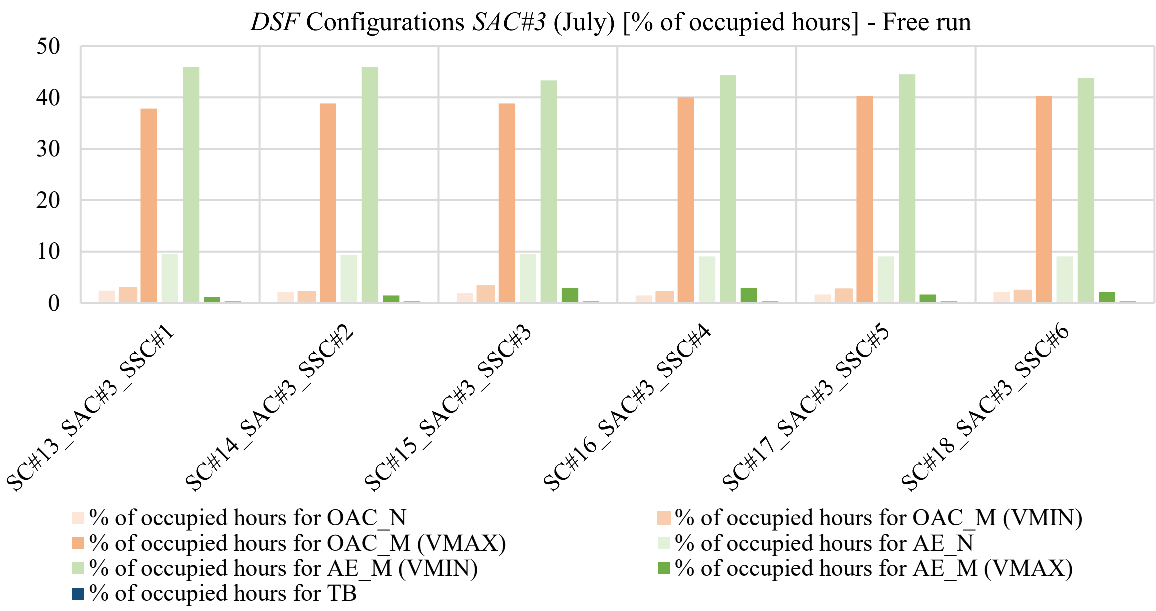


Figure 64: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#3 as airflow control

In the case of the application of *SAC#3* and *#4* air flow controls, the variability of configurations is higher, since all the possible achievable configurations for the *DSF* (during the occupied hours) are adopted.

In the case of the use of *SAC#3* (in which an indoor air temperature control is applied for the *OAC* configuration switching), there is a consistent use of the *OAC* mechanical with maximum implemented air flow configuration.

On the other hand, using the *SAC#4* control (in which a cavity air temperature control is applied for the *OAC* configuration switching), there is a more consistent use of the *OAC* natural configuration.

These are the effects of the use of different control variables for the configurations switching mechanism. For *SAC#1*, *#2*, *#3* and *#4*, anyway, the most used configuration during the occupied hours of the room is *AE* natural.

Finally, using the *SAC#5* air flow control, during the occupied hours there is an extensive use of *AS* configuration, followed by *AE*. No adoption of the *OAC* configuration (neither natural or mechanical), is present.

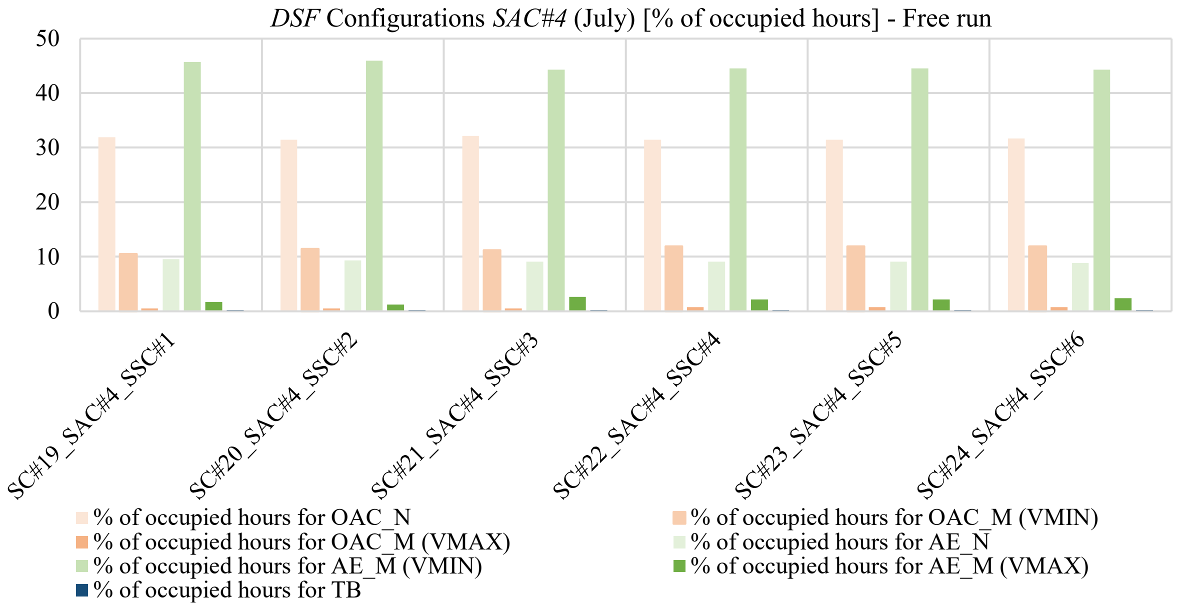


Figure 65: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#4 as airflow control

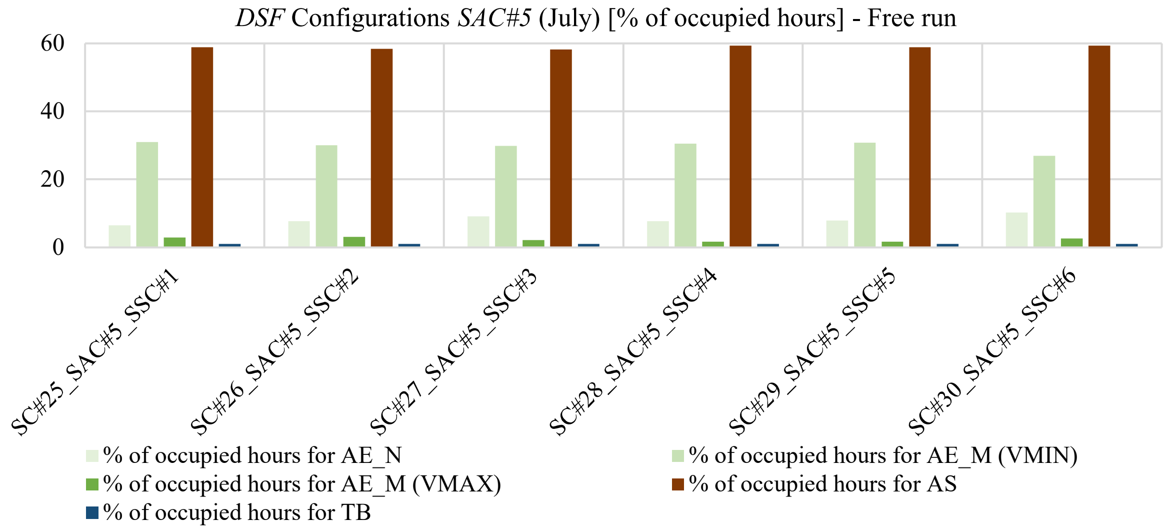


Figure 66: Percentages of occupied hours in the month (July)in which the different DSF configurations have been adopted (active systems turned off) with SAC#5 as airflow control

Heating season

As seen for the summer season, using the free running asset of the model an higher variability of the results is produced by the air flow control. In the free-running version of the test cell, anyway, the use of *CF* configuration is not adopted, because the ventilation plant of the room is turned off (the cavity is used only in a passive way).

For what concerns the application of *WAC#1* air flow control, the adoption of the *IAC* configuration is now visible, and a higher variability of the configuration is present. The same results are present also in the case of the application of *WAC#2* and *#3* air flow controls. At the end, adopting the *WAC#4* air flow control, with the ventilation plant turned off, the *AE* configuration is adopted with higher frequency, since the CO_2 concentrations inside the room are higher.

As done for the summer season, the percentages of hours in which each configuration has been adopted is reported (from *Figure 67* to *Figure 70*). Using the *WAC#1*, *#2* and *#3* controls, basically the same trend is visible in the configuration durations. All the combinations of control in addition show the presence of the *IAC* configuration.

With *WAC#4* control, there is an additional use of the *AE* natural configuration, due to the higher CO_2 concentrations in the room which enable the adoption of this air flow control.

For all the airflow controls, the adoption of *OAC* configuration is not visible (differently from what has been showed in the model with the active systems turned on).

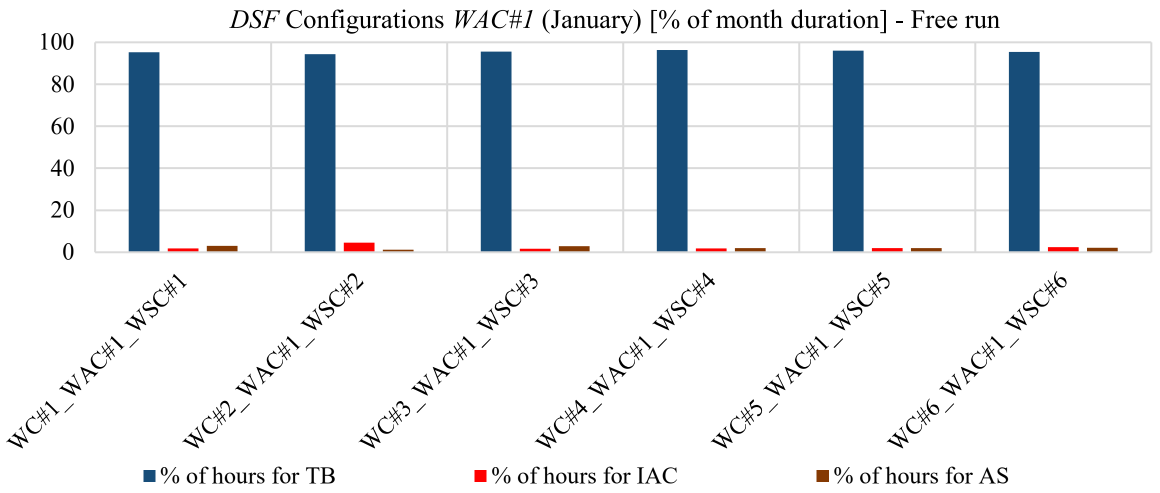


Figure 67: Percentages of hours in the month (January)in which the different DSF configurations have been adopted (active systems turned off) with WAC#1 as airflow control

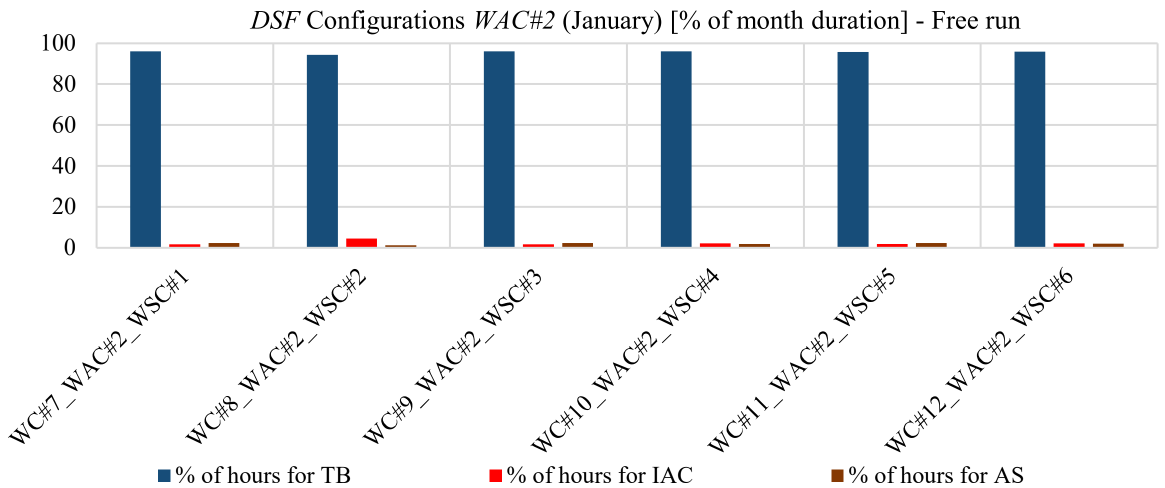


Figure 68: Percentages of hours in the month (January)in which the different DSF configurations have been adopted (active systems turned off) with WAC#2 as airflow control

Focusing on the occupied hours of the room (from *Figure 71* to *Figure 74*), there is an evident difference between the first three typologies of airflow control (*WAC#1, #2, #3)* and *WAC#4*.

In this last case the *AE* natural configuration is the most adopted during the occupied hours of the room, with a higher frequency than the *TB* one.

In comparison with the overall month duration, the percentage of hours in which *IAC* and *AS* are used is higher in the cases of *WAC#1*, *#2* and *#3*. On the other hand, the percentages are analogue in the case of *WAC#4* application.

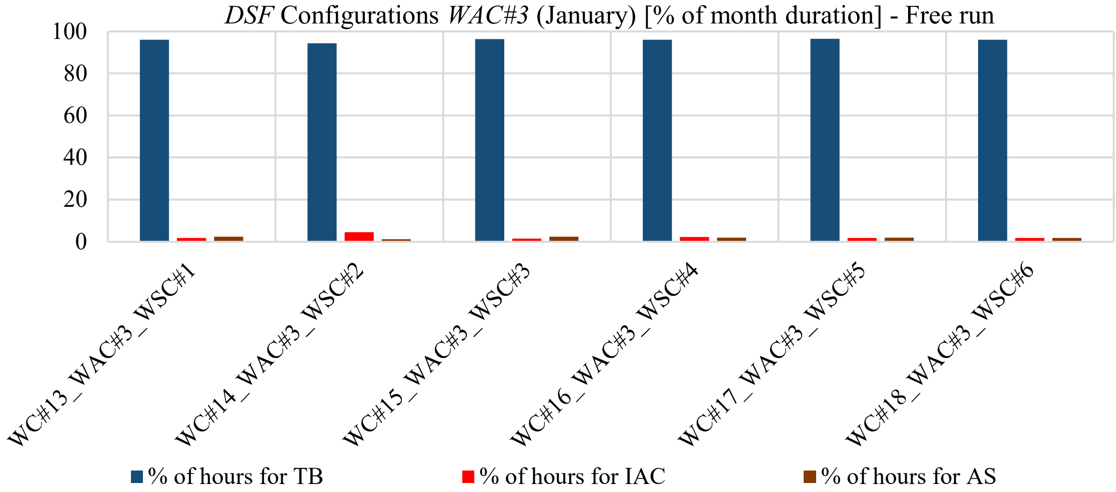


Figure 69: Percentages of hours in the month (January)in which the different DSF configurations have been adopted (active systems turned off) with WAC#3 as airflow control

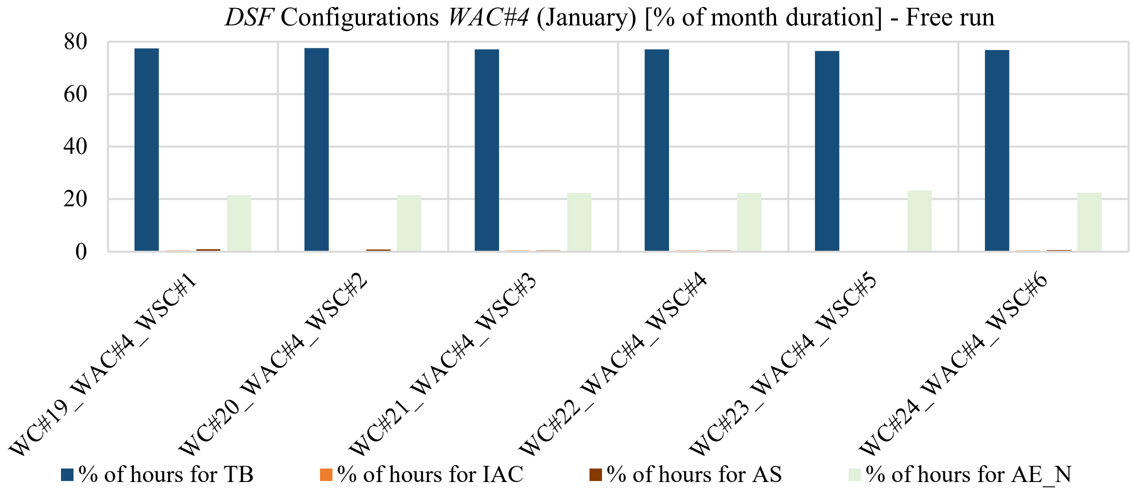


Figure 70: Percentages of hours in the month (January)in which the different DSF configurations have been adopted (active systems turned off) with WAC#4 as airflow control

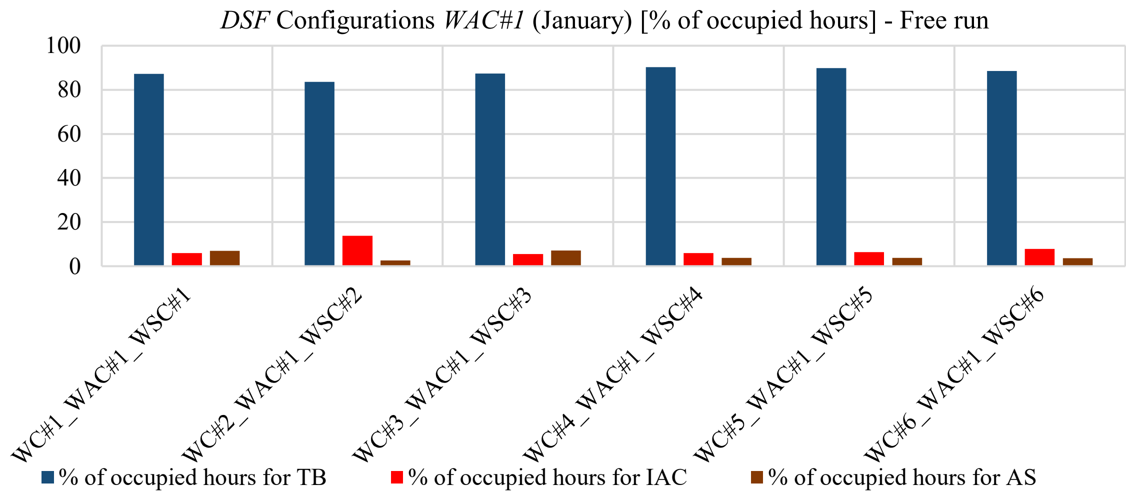


Figure 71: Percentages of occupied hours in the month (January)in which the different DSF configurations have been adopted (active systems turned off) with WAC#1 as airflow control

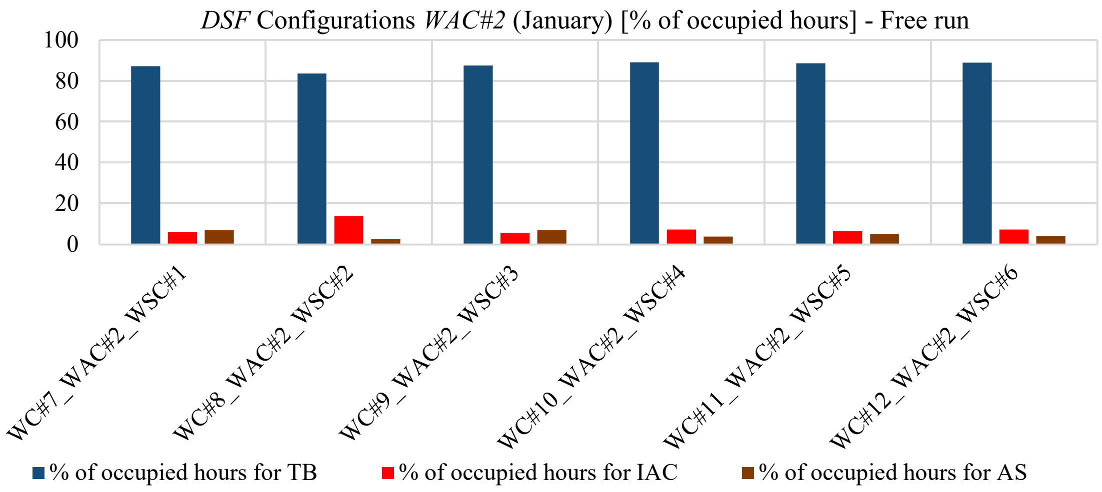


Figure 72: Percentages of occupied hours in the month (January)in which the different DSF configurations have been adopted (active systems turned off) with WAC#2 as airflow control

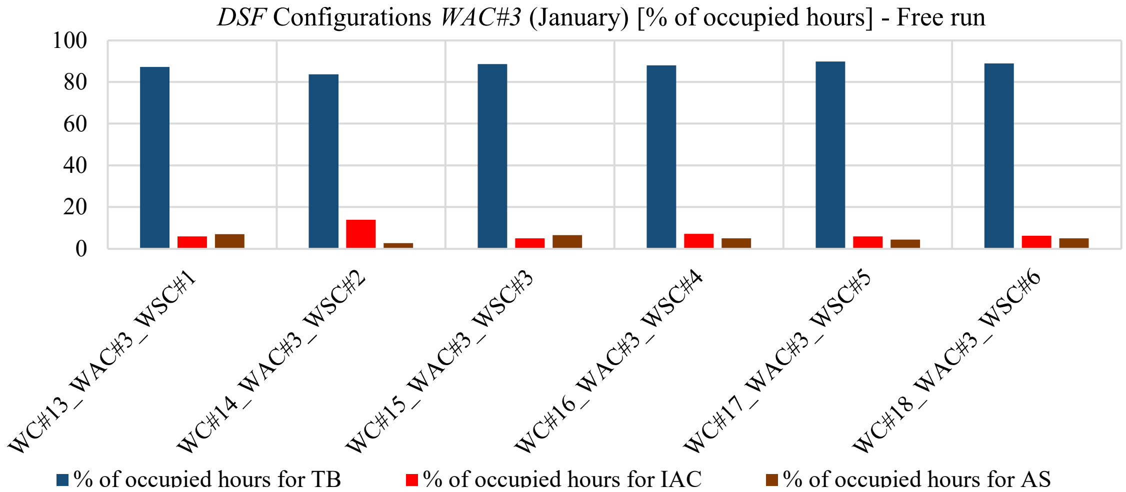


Figure 73: Percentages of occupied hours in the month (January)in which the different DSF configurations have been adopted (active systems turned off) with WAC#3 as airflow control

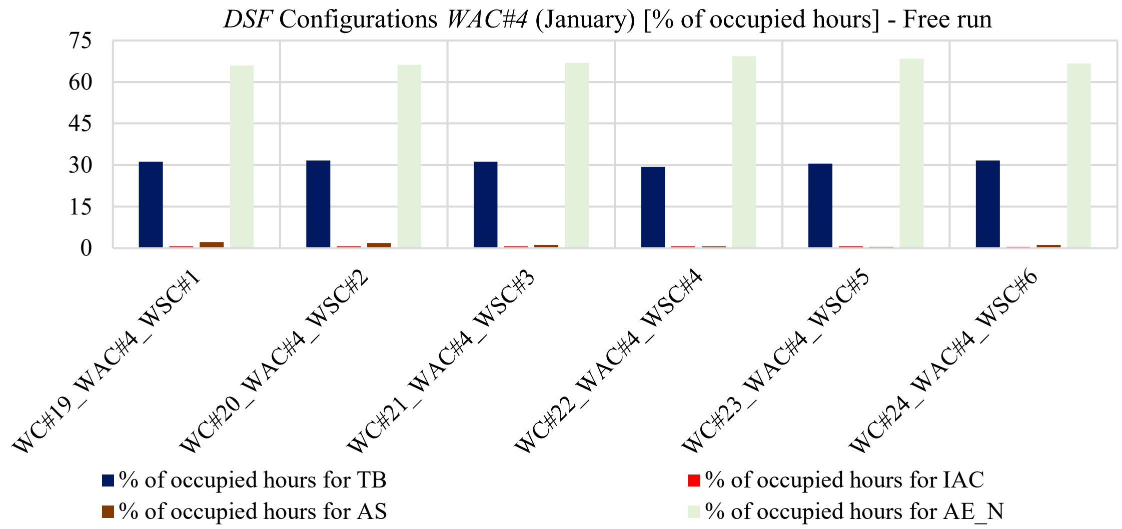


Figure 74: Percentages of occupied hours in the month (January)in which the different DSF configurations have been adopted (active systems turned off) with WAC#4 as airflow control

4.2. Energy performance analysis

In this section the focus of the evaluation is the energy performance of the thermal zone related to the different configurations of control of the *DSF*, performed on the model of the room with all the active systems (ventilation, cooling, heating and artificial lighting) turned on, as in the normal operational time of the building. The values of energy consumption for the thermal zone are referred to the months of July for the summer conditions simulation and to the month of January for the winter conditions simulation.

The following energy consumptions are considered for the multidomain assessment of the energy performance of the different implemented control combinations:

- ***Energy need for space heating***: it corresponds to the overall thermal energy that is required by the ideal heater of the room to keep the indoor temperature set point values for the heating and the cooling season.

- ***Energy need for space cooling***: in similar way to the energy need for the space heating, it corresponds to the energy required by the ideal cooler of the room to keep the indoor temperature set point values for the heating and cooling season.

- ***Energy need for ventilation heating***: it is the energy required by the heating coil of the *AHU* of the room to heat up the ventilation air to the predefined setpoint ($16°C$ for the whole year).

- ***Energy need for the ventilation cooling****:* it is the energy required by the heating coil of the *AHU* of the room to cool down the ventilation air to the predefined setpoint ($16°C$ for the whole year).

- ***Energy need for artificial lighting***: it is the energy required for the functioning of the artificial lighting inside the room.

These are different kinds of energy uses for the considered room. In particular, the energy for space cooling and heating are room loads (for an ideal cooler and an ideal heater), the energy for ventilation heating and cooling is thermal energy that can be given to or extracted from the ventilation air and finally the energy need for artificial lighting is an electrical consumption.

Consequently, it is necessary to consider them in separate way. In fact, the energy for space heating and ventilation heating are grouped together in the heating energy need for the room. In the same way, energy for space cooling and ventilation cooling are grouped together in the cooling energy need for the room. On the other hand, the energy need for artificial lighting is accounted in a separate way.

4.2.1. Cooling season conditions

In this section are report the results regarding the energy analysis performed on the room with the different façade systems during the month of July. The variations, expressed in percentage, are referred to the *SSF* used as reference system of the performance comparison.

4.2.1.1. Heating energy need

In this section, the energy need for heating (both space and ventilation) in the different configurations of control for the *DSF* has been analyzed and compared to the ones of the static *OAC* configuration and the *SSF* system. It is not common to evaluate the energy need for heating during the summer season, but it is anyway necessary to have a wider evaluation of the façade system impact on the overall performance of the building.

The related values of energy consumption (expressed in kWh and kWh/m^2) are reported in *Table 25*.

	TOTAL ENERGY NEED [kWh]			**TOTAL ENERGY NEED [kWh/m²]**			**[%]**
Code	**Space heating**	**Ventilation heating**	**TOT**	**Space heating**	**Ventilation heating**	**TOT**	**Variation (SSF)**
SC#1	27.81	7.14	34.95	0.58	0.15	0.73	**122.9**
SC#2	27.83	7.13	34.96	0.58	0.15	0.73	**123.0**
SC#3	27.75	7.13	34.88	0.58	0.15	0.73	**122.4**

SC#4	27.16	7.14	34.30	0.57	0.15	0.71	**118.7**
SC#5	27.06	7.14	34.20	0.56	0.15	0.71	**118.1**
SC#6	27.21	7.13	34.34	0.57	0.15	0.72	**119.0**
SC#7	27.86	7.14	35.00	0.58	0.15	0.73	**123.2**
SC#8	27.83	7.13	34.96	0.58	0.15	0.73	**123.0**
SC#9	27.72	7.13	34.85	0.58	0.15	0.73	**122.2**
SC#10	27.12	7.14	34.26	0.57	0.15	0.71	**118.5**
SC#11	27.25	7.13	34.38	0.57	0.15	0.72	**119.3**
SC#12	27.17	7.13	34.30	0.57	0.15	0.71	**118.7**
SC#13	27.76	7.14	34.90	0.58	0.15	0.73	**122.6**
SC#14	27.74	7.15	34.89	0.58	0.15	0.73	**122.5**
SC#15	27.67	7.15	34.82	0.58	0.15	0.73	**122.1**
SC#16	26.86	7.17	34.03	0.56	0.15	0.71	**117.0**
SC#17	26.90	7.17	34.07	0.56	0.15	0.71	**117.3**
SC#18	26.84	7.16	34.00	0.56	0.15	0.71	**116.8**
SC#19	27.81	7.14	34.95	0.58	0.15	0.73	**122.9**
SC#20	27.74	7.14	34.88	0.58	0.15	0.73	**122.5**
SC#21	27.22	7.15	34.37	0.57	0.15	0.72	**119.2**
SC#22	26.92	7.17	34.09	0.56	0.15	0.71	**117.4**
SC#23	26.92	7.17	34.09	0.56	0.15	0.71	**117.4**
SC#24	26.82	7.16	33.98	0.56	0.15	0.71	**116.7**
SC#25	18.62	6.03	24.65	0.39	0.13	0.51	**57.2**
SC#26	18.23	6.22	24.45	0.38	0.13	0.51	**55.9**
SC#27	18.25	6.30	24.55	0.38	0.13	0.51	**56.6**
SC#28	18.34	5.91	24.25	0.38	0.12	0.51	**54.7**
SC#29	17.97	6.08	24.05	0.37	0.13	0.50	**53.4**
SC#30	17.97	6.06	24.03	0.37	0.13	0.50	**53.2**
Static OAC	20.18	0.00	20.18	0.42	0.00	0.42	**28.7**
SSF	***15.68***	***0.00***	***15.68***	***0.33***	***0.00***	***0.33***	***REFERENCE***

Table 25: Heating energy requirements for the different façade systems (July)

In the *SSF*, the energy need for space heating in summer is around *0.33 kWh/m²*, while the energy need for ventilation heating is basically null. The adoption of the *DSF* (both static and flexible) increases the amount of the energy that is required for both, ventilation, and space heating: in all the 30 combinations of control it is observable an increasing of the required energy need for heating (around *120%* in all the first 24 control combinations, which use the airflow controls from *SAC#1* to *SAC#5*), with values of energy demand around *0.7 kWh/m².* The average increase for all the 30 different control combinations is *107%.* The exception is for the last form of air flow control (*SAC#5*), which causes an increase of around *50%.* The last air flow control is consequently more effective in the limitation of the heating energy demand increasing, given the fact that the *AE* configuration is used in a lower extent of cases (with a reduced amount of heat that is extracted by the cavity).

The static *OAC* configuration is in this case the most effective in the limitation of the increase of the heating energy demand during the summer season (with an increase equal to *28.7%* compared to *SSF*): this is mainly caused by the fact that the *AE* configuration is not adopted by the static *OAC* façade system. The average variations of the heating energy need for the 5 different air flow controls (coupled with the 6 different types of control for the shading) are reported in *Table 26*. The different typologies of control for the shading produce similar effects in the increase of the energy demand for heating (*Table 27).*

Airflow control	**Increase heating energy demand (compared to *SSF*) [%]**
SAC#1	**120.7**
SAC#2	**120.8**
SAC#3	**119.7**
SAC#4	**119.3**
SAC#5	**55.2**

Table 26: Average variations of the heating energy need produced by the 5 different air flow controls (coupled with the 6 different types of control for the shading) in July

Shading control	Increase heating energy demand (compared to *SSF*) [%]
SSC#1	**109.7**
SSC#2	**109.4**
SSC#3	**108.5**
SSC#4	**105.2**
SSC#5	**105.1**
SSC#6	**104.9**

Table 27: Average variations of the heating energy need produced by the 6 different shading controls (coupled with the 5 different types of control for the air flows) in July

In average the two activation mechanisms for the venetian blind (temperature and radiation) produce the same effects in the increase of the energy need for heating for the room: *109%* in the case of the radiation control while *105%* in the case of the temperature control of the blind. A graphical comparison of the energy needs for heating is reported in *Figure 75*.

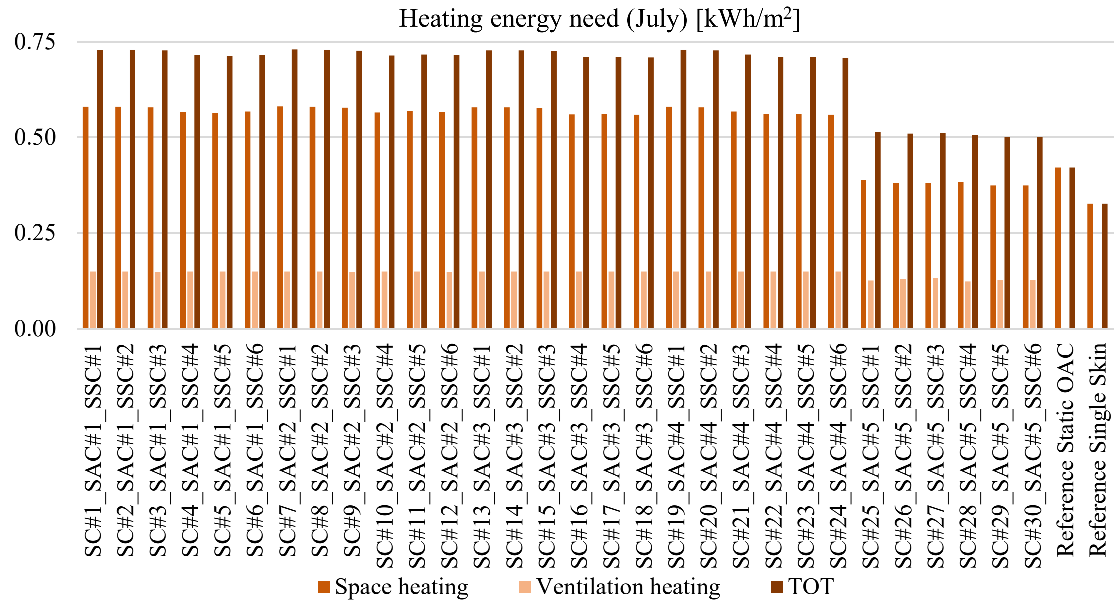


Figure 75: Heating energy requirements for the different façade systems (July)

Analysing the variation of the heating energy need, it is therefore possible to say that the adoption of a *DSF* in a climate as Frankfurt, in which the summer is not particularly hot compared to more southern locations, can be a cause of an increase of the energy required for the heating of a building (for both space and ventilation), compared to a traditional *SSF*. Anyway, the energy demand for heating is lower compared to the one for cooling.

4.2.1.2. Cooling energy need

In this section, the energy need for cooling (both space and ventilation) in the different configurations of control for the *DSF* has been analysed and compared to the ones of the static *OAC* configuration and the *SSF*, as done for the energy need for heating.

The energy need for cooling represents the main component of the overall energy balance of a building which usually the designer wants to minimize during the summer season, for a better energy efficiency of the system. It is consequently the focus of the energy performance evaluation during the cooling season for the different façade systems.

The related values of energy consumption (expressed in *kWh* and *kWh/m²*) are reported in *Table 28*.

	TOTAL ENERGY NEED [kWh]			TOTAL ENERGY NEED [kWh/m^2]			[%]
Code	Space cooling	Ventilation cooling	TOT	Space cooling	Ventilation cooling	TOT	Variation (SSF)
SC#1	44.20	114.60	158.80	0.92	2.39	3.31	**-46.2**
SC#2	44.89	114.7	159.59	0.94	2.39	3.32	**-45.9**
SC#3	45	114.4	159.40	0.94	2.38	3.32	**-46.0**
SC#4	72.80	114.90	187.70	1.52	2.39	3.91	**-36.4**
SC#5	73.13	114.90	188.03	1.52	2.39	3.92	**-36.3**
SC#6	73.39	114.90	188.29	1.53	2.39	3.92	**-36.2**
SC#7	44.25	114.70	158.95	0.92	2.39	3.31	**-46.1**
SC#8	44.95	114.7	159.65	0.94	2.39	3.33	**-45.9**
SC#9	45.01	114.5	159.51	0.94	2.39	3.32	**-45.9**
SC#10	73.06	114.90	187.96	1.52	2.39	3.92	**-36.3**
SC#11	72.77	114.90	187.67	1.52	2.39	3.91	**-36.4**
SC#12	72.81	114.80	187.61	1.52	2.39	3.91	**-36.4**
SC#13	41.42	111.90	153.32	0.86	2.33	3.19	**-48.0**
SC#14	42.13	111.9	154.03	0.88	2.33	3.21	**-47.8**
SC#15	42.23	111.9	154.13	0.88	2.33	3.21	**-47.8**
SC#16	71.31	112.00	183.31	1.49	2.33	3.82	**-37.9**
SC#17	71.38	112.00	183.38	1.49	2.33	3.82	**-37.9**
SC#18	71.39	112.00	183.39	1.49	2.33	3.82	**-37.9**
SC#19	40.36	111.90	152.26	0.84	2.33	3.17	**-48.4**
SC#20	41.14	111.9	153.04	0.86	2.33	3.19	**-48.1**
SC#21	41.72	111.9	153.62	0.87	2.33	3.20	**-47.9**
SC#22	70.48	112.00	182.48	1.47	2.33	3.80	**-38.2**
SC#23	70.47	112.00	182.47	1.47	2.33	3.80	**-38.2**
SC#24	70.85	112.00	182.85	1.48	2.33	3.81	**-38.0**
SC#25	51.94	99.39	151.33	1.08	2.07	3.15	**-48.7**
SC#26	53.84	98.98	152.82	1.12	2.06	3.18	**-48.2**
SC#27	53.29	98.7	151.99	1.11	2.06	3.17	**-48.5**
SC#28	85.07	96.50	181.57	1.77	2.01	3.78	**-38.5**
SC#29	86.49	95.90	182.39	1.80	2.00	3.80	**-38.2**
SC#30	87.23	95.06	182.29	1.82	1.98	3.80	**-38.2**
Static OAC	38.53	111.40	149.93	0.80	2.32	3.12	**-49.2**
SSF	***183.10***	***112.00***	***295.10***	***3.81***	***2.33***	***6.15***	***REFERENCE***

Table 28: Cooling energy requirements for the different façade systems (July)

The application of the different control logics for the cavity air flows in the summer is particularly effective in the influence of the energy need for cooling. In the reference *SSF*, the energy need for cooling (both space and ventilation) is relevant (about *6.15 kWh/m²*).

If the correct strategy is applied for the ventilation of the cavity, a reduction of the energy need for cooling is possible. In particular, the adoption of all the different combinations (with *SAC#1*, *#2*, *#3*, *#4* and *#5*) is particularly effective in the reduction of the energy need for cooling of the room. The average values of variation for the different typologies of airflow controls are reported in *Table 29*.

Airflow control	Reduction cooling energy demand (compared to *SSF*) [%]
SAC#1	**-41.2**
SAC#2	**-41.2**
SAC#3	**-42.9**
SAC#4	**-43.1**
SAC#5	**-43.4**

Table 29: Average variations of the cooling energy need produced by the 5 different air flow controls (coupled with the 6 different types of control for the shading) in July

The highest one is consequently associated with *SAC#5* air flow control, while the remaining ones are slightly less effective in the cooling energy reduction. All the airflow control typologies are anyway effective in the same way in the reduction of the cooling energy need for the room.

The best results in the reduction of the energy need for cooling are achieved with the use of the radiation control for the cavity blind: this shading control produces a higher frequency of activation of the blind compared to the temperature control (if the active systems of the room are turned on), reducing the solar gains entering inside the room. In average, the reduction of the cooling energy need associated to the radiation control of the blind is *-47.3%* while for the temperature control the related reduction is about *-37.4%*. The average reduction of the cooling energy need with the 6 different types of control for the shading are reported in *Table 30*.

Shading control	Reduction cooling energy demand (compared to *SSF*) [%]
SSC#1	**-47.5**
SSC#2	**-47.2**
SSC#3	**-47.2**
SSC#4	**-37.4**
SSC#5	**-37.4**
SSC#6	**-37.3**

Table 30: Average variations of the heating energy need produced by the 6 different shading controls (coupled with the 5 different types of control for the air flows) in July

It is consequently possible to say that the adoption of a ventilated façade system, if the proper control of the cavity air flow is implemented, can be a good solution for the reduction of the overall energy need for cooling also in a temperate climate as Frankfurt.

Anyway, the adoption of the static *OAC* configuration is more effective solution in the reduction of the energy need for cooling *(-49.2 %*) than the combinations of control for the summer season: only the adoption of *SAC#5* air flow control coupled with the radiation control for the blind produces a reduction of the cooling energy need which is comparable to the one generated by the static *OAC* configuration (about *– 48%*).

A graphical comparison of the energy needs for cooling is reported in *Figure 76*.

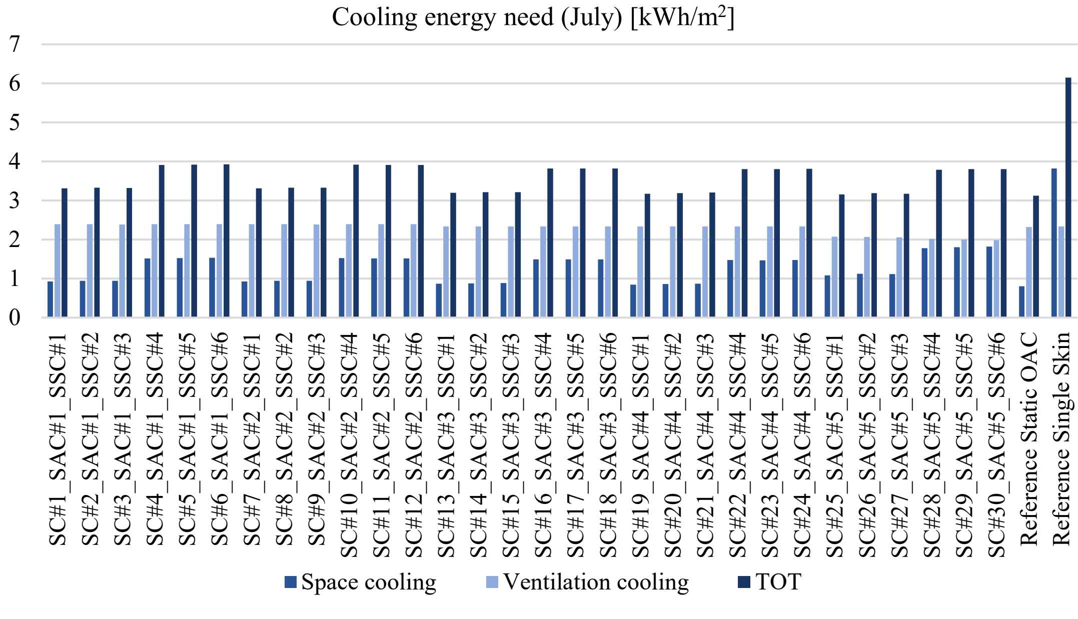


Figure 76: Cooling energy requirements for the different façade systems (July)

Analysing the energy needs for cooling and heating variations with all the 30 different combinations of control which have been adopted, the overall cooling energy need variation is equal to *-42.3%* while in the case of the heating energy need the average increase is *107%*: consequently, the increase of the heating energy need during the summer season is largely greater than the reduction of the cooling energy need (considering the percentual variation with respect to *SSF*).

Anyway, it is necessary to say that during the summer the most consistent share of the energy demand for the room is the one associated to the cooling energy need: in average, for all the 30 combinations of control, the heating energy need is about *19%* of the cooling energy need. For this reason, the variation in absolute terms (kWh/m^2) of the cooling energy need is largely greater than the increase of the heating energy demand.

The total amount of thermal energy for heating and cooling that is necessary for the room units to heat and cool the room in July is consequently reduced with all the different combinations of control.

Of course, it is visible a consistent increase of the ratio between heating and cooling demand for the room compared to the traditional *SSF* reference system, because the cooling demand is reduced, in proportion, of a lower extent.

The overall values are reported in *Table 31*.

Code	Heating demand/cooling demand ratio [%]	Variation heating demand [kWh/m^2]	Variation cooling demand [kWh/m^2]
SC#1	22.0	**0.40**	**-2.8**
SC#2	21.9	**0.40**	**-2.8**
SC#3	21.9	**0.40**	**-2.8**
SC#4	18.3	**0.39**	**-2.2**
SC#5	18.2	**0.39**	**-2.2**
SC#6	18.2	**0.39**	**-2.2**
SC#7	22.0	**0.40**	**-2.8**
SC#8	21.9	**0.40**	**-2.8**
SC#9	21.8	**0.40**	**-2.8**
SC#10	18.2	**0.39**	**-2.2**
SC#11	18.3	**0.39**	**-2.2**
SC#12	18.3	**0.39**	**-2.2**
SC#13	22.8	**0.40**	**-3.0**
SC#14	22.6	**0.40**	**-2.9**
SC#15	22.6	**0.40**	**-2.9**
SC#16	18.6	**0.38**	**-2.3**
SC#17	18.6	**0.38**	**-2.3**
SC#18	18.5	**0.38**	**-2.3**
SC#19	23.0	**0.40**	**-3.0**
SC#20	22.8	**0.40**	**-3.0**
SC#21	22.4	**0.39**	**-2.9**
SC#22	18.7	**0.38**	**-2.3**
SC#23	18.7	**0.38**	**-2.3**
SC#24	18.6	**0.38**	**-2.3**
SC#25	16.3	**0.19**	**-3.0**
SC#26	16.0	**0.18**	**-3.0**
SC#27	16.2	**0.18**	**-3.0**
SC#28	13.4	**0.18**	**-2.4**
SC#29	13.2	**0.17**	**-2.3**
SC#30	13.2	**0.17**	**-2.4**
Static OAC	13.5	**0.09**	**-3.0**
SSF	***5.3***	***REFERENCE***	***REFERENCE***

Table 31: Heating and cooling energy need ratios for the different combinations of control and variations in kWh/m^2 for the heating and cooling energy demands in July

4.2.1.3. Artificial lighting energy need

In this section, the energy need for the artificial lighting in the different configurations of control for the *DSF* has been analysed and compared to the ones of the static *OAC* configuration and the *SSF*, as done for the other energy needs of the room (heating and cooling). While for the energy need for cooling and heating the overall performance of the system is mainly influenced by the control of the cavity air flows, for the artificial lighting the focus is of course on the different shading control that is implemented for the venetian blind. The related values of energy consumption (expressed in kWh and kWh/m^2) are reported in *Table 32*.

	TOTAL ENERGY NEED [kWh]	TOTAL ENERGY NEED [kWh/m²]	[%]
Code	**Artificial lighting**	**Artificial lighting**	**Variation (SSF)**
SC#1	17.12	0.36	**109.4**
SC#2	15.78	0.33	**93.1**
SC#3	13.09	0.27	**60.1**
SC#4	11.15	0.23	**36.4**
SC#5	11.16	0.23	**36.5**
SC#6	11.15	0.23	**36.4**
SC#7	17.12	0.36	**109.4**
SC#8	15.78	0.33	**93.1**
SC#9	13.09	0.27	**60.1**
SC#10	11.14	0.23	**36.3**
SC#11	11.15	0.23	**36.4**
SC#12	11.15	0.23	**36.4**
SC#13	17.11	0.36	**109.3**
SC#14	15.77	0.33	**92.9**
SC#15	13.09	0.27	**60.1**
SC#16	11.15	0.23	**36.4**
SC#17	11.16	0.23	**36.5**
SC#18	11.15	0.23	**36.4**
SC#19	17.11	0.36	**109.3**
SC#20	15.77	0.33	**92.9**
SC#21	13.05	0.27	**59.7**
SC#22	11.15	0.23	**36.4**
SC#23	11.16	0.23	**36.5**
SC#24	11.15	0.23	**36.4**
SC#25	17.10	0.36	**109.2**
SC#26	15.75	0.33	**92.7**
SC#27	13.23	0.28	**61.9**
SC#28	11.14	0.23	**36.3**
SC#29	11.17	0.23	**36.7**
SC#30	11.29	0.24	**38.1**
Static OAC	17.16	0.36	**109.9**
SSF	***8.17***	***0.17***	***REFERENCE***

Table 32: Artificial lighting energy requirements for the different façade systems (July)

The *SSF* has by default an energy need for artificial lighting that is considerably lower compared to the ones of the *DSF*. This is mainly caused by the adoption of two skins of glass instead of one, that can reduce of a certain extent the amount of daylight entering inside the indoor environment, due to a reduced visible transmission of the glazing system (in fact, 4 glass layers are used in total while for a conventional *TGU* only 3).

Analysing the energy consumptions for the different combinations, it is possible to see the difference in the effects generated by the two different control mechanisms of the venetian blind (temperature and incident radiation on the façade). In particular, the radiation control is associated to the largest increase in the artificial lighting energy requirements (in average, *+87.6%*) while a considerably lower increase is associated with the temperature control of the blind (*+36.5%*). A graphical comparison of the energy needs for artificial lighting is reported in *Figure 77.*

It is possible to see, consequently, that the most effective shading control for the reduction of the cooling energy demand (the radiation control) is also the worst under the point of view of the energy required for artificial lighting. It is possible to see that in the case of the temperature control of the blind (*SSC#4*, *#5* and *#6*) it is not visible a significant variation in the increase of the energy need for the artificial lighting.

On the other hand, with the adoption of the radiation control for the blind (*SSC#1*, *#2* and *#3*) the largest increase of the artificial lighting energy demand is associated to the fixed slat angle (*SSC#1*), followed by the cut-off position implementation (*SSC#2*) and the scheduled slat angle (*SSC#3*).

The adoption of the schedule for the slat angle is consequently effective in the limitation of the energy need associated to the artificial lighting of the room. The average increases for the artificial lighting energy requirements associated to the different types of control of the blind slat angle are reported in *Table 33*.

Shading control	Increase artificial lighting energy demand (compared to *SSF*) [%]
SSC#1	**109.3**
SSC#2	**92.9**
SSC#3	**60.4**
SSC#4	**36.4**
SSC#5	**36.5**
SSC#6	**36.8**

Table 33: Average variations of the artificial lighting energy need produced by the 6 different shading controls (coupled with the 5 different types of control for the shading)

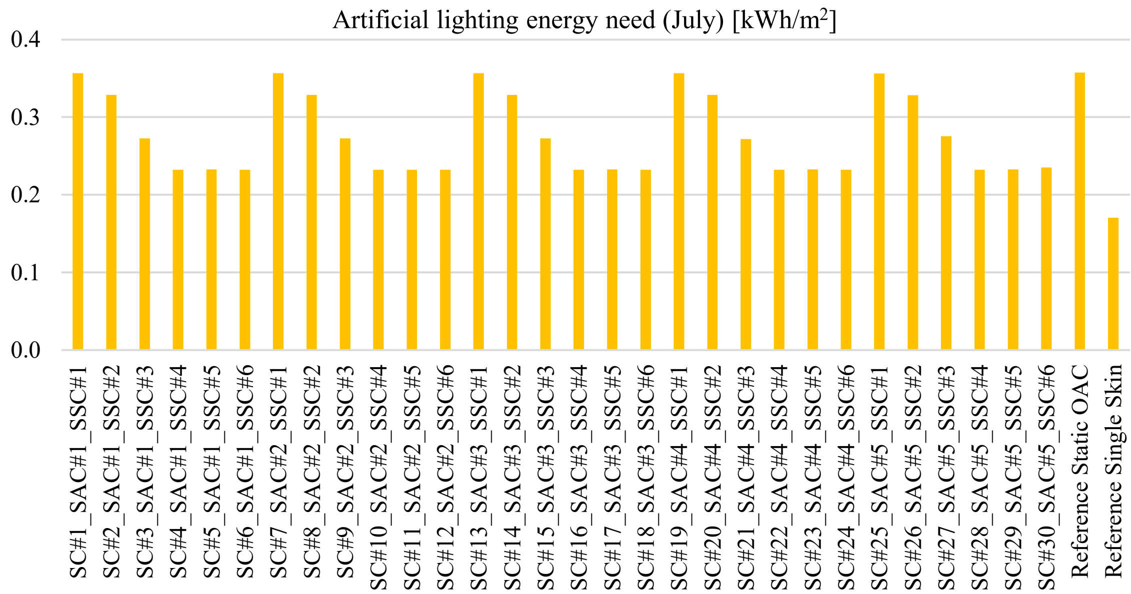


Figure 77: Artificial lighting energy requirements for the different façade systems (July)

The static *OAC* configuration in this case produces the same increase of the combinations of control which use *SSC#1* as shading control. The worsening of the performance under the point of view of the energy need for the artificial lighting can be assumed as critical point in the adoption of the *DSF*, compared to a traditional *SSF* with better visible transmittance properties of the glazing.

4.2.2.Heating season conditions

In this section are report the results regarding the energy analysis performed on the room with the different façade systems during the month of January. The data are reported both, in tabular and graphical way as done for the summer season. The variations, expressed in percentage, are referred to the *SSF*, as done for the summer season.

4.2.2.1. *Heating energy need*

In this section, the energy need for heating (both space and ventilation) in the different configurations of control for the *DSF* has been analysed and compared to the ones of the static *TB* configuration and the *SSF*, as done during the summer season. In similar way to the cooling for the summer season, the energy need for heating represents the main component of the overall energy balance of a building which usually the designer wants to minimize during the heating season, reducing the heat losses through the envelope and exploiting the passive solar gains for the ventilation heating.

The related values of energy consumption (expressed in kWh and kWh/m^2) are reported in *Table 34*.

	TOTAL ENERGY NEED [kWh]			TOTAL ENERGY NEED [kWh/m²]			[%]
Code	**Space heating**	**Ventilation heating**	**TOT**	**Space heating**	**Ventilation heating**	**TOT**	**Variation (SSF)**
WC#1	392.60	17.16	409.76	8.18	0.36	8.54	**-2.7**
WC#2	395.70	17.46	413.16	8.24	0.36	8.61	**-1.9**
WC#3	386.30	16.43	402.73	8.05	0.34	8.39	**-4.3**
WC#4	377.80	15.81	393.61	7.87	0.33	8.20	**-6.5**
WC#5	377.50	15.79	393.29	7.86	0.33	8.19	**-6.6**
WC#6	377.90	15.88	393.78	7.87	0.33	8.20	**-6.5**
WC#7	394.70	17.44	412.14	8.22	0.36	8.59	**-2.1**
WC#8	400.40	17.89	418.29	8.34	0.37	8.71	**-0.7**
WC#9	387.80	16.76	404.56	8.08	0.35	8.43	**-3.9**
WC#10	379.80	15.89	395.69	7.91	0.33	8.24	**-6.0**
WC#11	379.80	15.93	395.73	7.91	0.33	8.24	**-6.0**
WC#12	379.50	15.95	395.45	7.91	0.33	8.24	**-6.1**
WC#13	392.70	17.26	409.96	8.18	0.36	8.54	**-2.6**
WC#14	398.10	17.75	415.85	8.29	0.37	8.66	**-1.2**
WC#15	385.90	16.49	402.39	8.04	0.34	8.38	**-4.4**
WC#16	378.50	15.83	394.33	7.89	0.33	8.22	**-6.3**
WC#17	379.20	15.93	395.13	7.90	0.33	8.23	**-6.2**
WC#18	379.20	15.95	395.15	7.90	0.33	8.23	**-6.1**
WC#19	394.10	18.55	412.65	8.21	0.39	8.60	**-2.0**
WC#20	399.00	18.38	417.38	8.31	0.38	8.70	**-0.9**
WC#21	387.40	17.31	404.71	8.07	0.36	8.43	**-3.9**
WC#22	379.00	16.41	395.41	7.90	0.34	8.24	**-6.1**
WC#23	379.50	16.41	395.91	7.91	0.34	8.25	**-6.0**
WC#24	379.10	17.28	396.38	7.90	0.36	8.26	**-5.9**
Static TB	376.30	16.26	392.56	7.84	0.34	8.18	**-6.8**
SSF	***406.70***	***14.34***	***421.04***	***8.47***	***0.30***	***8.77***	***REFERENCE***

Table 34: Heating energy requirements for the different façade systems (January)

Compared to the summer case and the energy need for cooling, in the winter season there is a more constant trend in the values of energy required for space heating and ventilation heating with the different implemented forms of control for the *DSF*: it is not visible the high variability of performance in the cooling energy need observed for the summer season (as seen for the variability of the *DSF* configurations in *4.1.1.*)

All the 24 combinations of control for the winter season produce a reduction of the energy need for heating (both space and ventilation), compared to the *SSF*. There is consequently a positive effect in the adoption of the flexible *DSF* in the Frankfurt climate. Anyway, the most effective configuration is the static *TB*, with a reduction of the energy for heating equal to *6.8 %*. The flexible *DSF* combinations produce a reduction comprised between *0.7%* and *6.6%*. The percentages of reduction are very similar if the active systems of the room are turned on (due to a low flexibility in the configuration changes for the *DSF*): all the 4 typologies of air flow control generate about the same reduction in the heating energy need of the room (in average *−4.4%* considering the 4 control combinations defined for each control logic for the cavity air flows). As it is possible to see in *Table 35*, the average reductions produced by the different air flow control are all comprised between *4.1%* and *4.7%*. Consequently, just considering the performance gap with the *SSF* the selection of the optimal control combination is consequently more difficult.

Airflow control	Reduction heating energy demand (compared to *SSF*) [%]
WAC#1	**-4.7**
WAC#2	**-4.1**
WAC#3	**-4.5**
WAC#4	**-4.1**

Table 35: Average reductions of the heating energy need produced by the 4 different air flow controls (coupled with the 6 different types of control for the shading) in January

The most effective air flow control after the static *TB* configuration is *WAC#1*, with a reduction of the heating energy need equal to *-4.7%*. This control combination adopts the configurations *TB*, *CF* and *AS*, with no adoption of *OAC* configuration (almost useless in the Frankfurt winter, as observed in *4.1.1*). The influence of the different types of control for the venetian blind (temperature and radiation) is evident, as seen for the summer season in the case of the cooling energy need. The temperature control ensures a higher amount of passive solar gains inside the room, reducing in this way the heating energy need in a more effective way. In average, the reduction of the heating energy need associated with the temperature control of the blind is *-6.2%* while in the case of the radiation control the average reduction is *-2.6%*. The reduction control of the blind is consequently less effective for the reduction of the heating energy need during the winter season. Considering the different control logics for the blind slat angle, if the radiation control is applied, the most effective in the reduction of the heating energy need is the scheduled solution (*WSC#3*) while the worst is the cut-off position implementation (*WSC#2*), because it stops the direct solar radiation against the façade. In fact, *WAC#1* coupled with *WSC#4*, *#5* and *#6* produces a reduction of the heating energy need that is comparable to the one generated by the static *TB* configuration (in the order of *6.5%*). The average reductions produced by the different types of shading control are reported in *Table 36.* A graphical comparison of the energy needs for heating is reported in *Figure 78.*

Shading control	Reduction cooling energy demand (compared to *SSF*) [%]
WSC#1	**-2.4**
WSC#2	**-1.2**
WSC#3	**-4.1**
WSC#4	**-6.2**
WSC#5	**-6.2**
WSC#6	**-6.1**

Table 36: Average variations of the heating energy need produced by the 6 different shading controls (coupled with the 4 different types of control for the air flows) in January

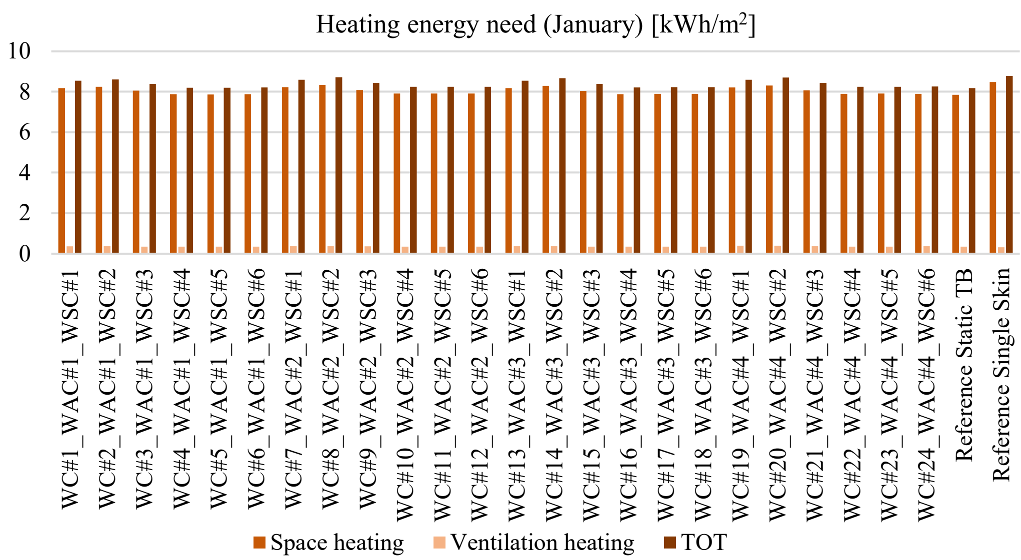


Figure 78: Heating energy requirements for the different façade systems (January)

4.2.2.2. *Cooling energy need*

In this section, the energy need for cooling (both space and ventilation) in the different configurations of control for the *DSF* has been analysed and compared to the ones of the static *TB* configuration and the *SSF*, as done for the energy need for heating. The energy need for cooling (both space and ventilation) is null during the winter season, both for *SSF* and the flexible *DSF* configuration. Only in the case of the application of *WAC#1* coupled with *WSC#4*, *#5* and *#6* (temperature control of the blind) it is visible a certain additional amount of cooling requirements: anyway, this value is almost null and consequently not significant. A little increase of the space heating energy need, but anyway not significant, is visible also with the adoption of the static *TB* configuration.

Consequently, the adoption of the *DSF* system is good for the Frankfurt climate (in a South exposed façade) during the winter season, since a reduction of the energy need for heating is visible and in addition there is not an increase of the energy need for cooling (which could be a possible risk in warmer climates).

4.2.2.3. *Artificial lighting energy need*

In this section, the energy need for the artificial lighting in the different configurations of control for the *DSF* has been analysed and compared to the ones of the static *TB* configuration and the *SSF*. The related values of energy consumption (expressed in kWh and kWh/m^2) are reported in *Table 37*.

	TOTAL ENERGY NEED [kWh]	**TOTAL ENERGY NEED [kWh/m²]**	**[%]**
Code	**Artificial lighting**	**Artificial lighting**	**Variation (SSF)**
WC#1	26.65	0.56	**26.2**
WC#2	32.92	0.69	**55.9**
WC#3	23.68	0.49	**12.2**
WC#4	23.16	0.48	**9.7**
WC#5	23.17	0.48	**9.8**
WC#6	23.14	0.48	**9.6**
WC#7	26.67	0.56	**26.3**
WC#8	32.90	0.69	**55.9**
WC#9	23.68	0.49	**12.2**
WC#10	23.16	0.48	**9.7**
WC#11	23.16	0.48	**9.7**
WC#12	23.14	0.48	**9.6**
WC#13	26.66	0.56	**26.3**
WC#14	32.92	0.69	**55.9**
WC#15	23.69	0.49	**12.2**
WC#16	23.16	0.48	**9.7**
WC#17	23.17	0.48	**9.8**
WC#18	23.14	0.48	**9.6**
WC#19	26.66	0.56	**26.3**
WC#20	32.91	0.69	**55.9**
WC#21	23.65	0.49	**12.0**
WC#22	23.17	0.48	**9.8**
WC#23	23.18	0.48	**9.8**
WC#24	23.14	0.48	**9.6**
Static TB	26.67	0.56	**26.3**
SSF	***21.11***	***0.44***	***REFERENCE***

Table 37: Artificial lighting energy requirements for the different façade systems (January)

The same considerations illustrated in the summer season are of course valid for the winter period. The energy consumption for the artificial lighting is mainly dependent on the typology of shading control, with no significant dependence with the implemented control for the cavity air flows. In addition, an increase of the energy need for artificial lighting is present compared to the *SSF* with all the different combinations of control (as seen also for the summer season). Compared to the summer season, anyway, the increase with respect to the *SSF* is considerably lower (between 9% and 56%). A graphical comparison of the energy needs for artificial lighting is reported in *Figure 79*.

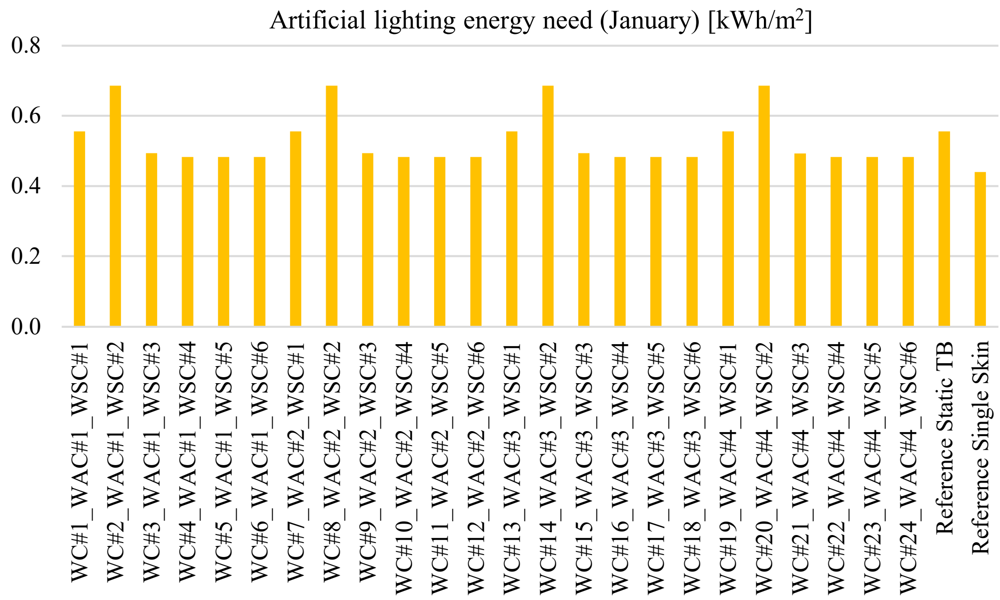


Figure 79: Artificial lighting energy requirements for the different façade systems (January)

As seen for the cooling season, the different types of control for the blind slat angle (temperature and radiation) produce different effects in the variation of the energy need for artificial lighting during the occupied hours of the room. The radiation control produces in average an increase of about *31.5%* if coupled with the different typology of air flows control while in the case of temperature control the average increase is *9.8%*.

If the temperature control is applied, the differences between the types of control for the slat angle are not so evident. On the contrary, if the radiation control is used, the difference in the effects is more evident. In particular, the cut-off position implementation is the worst, with an average increase of the energy need for artificial lighting equal to *60%*. The best solution, on the other hand, is the adoption of the scheduled variation of the blind slat angle (which generates an increase of *12.2%*). Consequently, the adoption of the scheduled variation of the slat angle (that can keep in the indoor environment a level of *500 lux* on the horizontal plane) is effective in the reduction of the required use for artificial lighting, as seen for the summer season. The average increases of the energy need for artificial lighting generated by the different types of slat angle controls are reported in *Table 38.*

Shading control	**Increase artificial lighting energy demand (compared to *SSF*) [%]**
WSC#1	**26.3**
WSC#2	**55.9**
WSC#3	**12.2**
WSC#4	**9.7**
WSC#5	**9.8**
WSC#6	**9.6**

Table 38: Average variations of the artificial lighting energy need produced by the 6 different shading controls (coupled with the 4 different types of control for the air flows) in January

4.3. Indoor climate analysis

Using the IDA ICE model with all the active systems turned off (*free running* configuration) a simulation focused on the indoor climate conditions will be performed, to evaluate the indoor comfort conditions without the presence of active systems for heating, ventilation, and cooling. The requested outputs will be consequently the main temperatures in the zones (indoor air and operative temperatures), Fanger's comfort indices, indoor air quality and daylight on the working plane. It is quite impossible that the façade could operate in such kind of conditions. However, using a *free running* configuration of the thermal zone it is possible to investigate and understand in a wider extent the relation between the façade and the indoor environmental conditions, since the comfort only depends on the façade itself, without the involvement of any active system. It is anyway necessary to implement before the simulation a *warmup* period, for the stabilization of the indoor conditions both in summer and winter season. It corresponds to a customized start up, with the duration of two weeks, defined in the *Simulation* tab in which the indoor air temperature conditions are keep constant ($20°C$ in winter and $26°C$ in summer) inside the thermal zone. The occupancy in the room is also set equal to zero (as a week-end day), to preserve a good indoor air quality condition. After this warmup period, the simulation with the free run configuration of the thermal zone can be performed.

To have a more synthetic and quantitative representation of the results and a more direct comparison of the performances of the different implemented controls, the number of occupied hours (210 in total for both January and July) in which the indoor optimal comfort conditions are not met has been considered. To make the values more understandable, moreover, the number of occupied hours has been converted to a percentage of total number of occupied hours during the months of January and July.

For the summer season, for each configuration of control the following quantities will be reported:

- Percentage of occupied hours above $26°C$.
- Percentage of occupied hours above $30°C$.
- Percentage of occupied hours below $20°C$.
- Percentage of occupied hours above $1000\ ppm$ of CO_2 concentrations.
- Percentage of occupied hours outside the ranges for the Fanger's comfort indices (PPD and PMV).
- Percentage of occupied hours below the minimum limit of $500\ lux$ at the working plane.
- Percentage of occupied hours above the threshold limit for glare discomfort of $3000\ lux$ on the working plane.

On the other hand, for the winter season, in similar way, for each configuration of control the following quantities will be reported:

- Percentage of occupied hours below $20°C$.
- Percentage of occupied hours above $1000\ ppm$ of CO_2 concentrations.
- Percentage of occupied hours outside the ranges for the Fanger's comfort indices (PPD and PMV).
- Percentage of occupied hours below the minimum limit of $500\ lux$ at the working plane.
- Percentage of occupied hours above the threshold limit for glare discomfort of $3000\ lux$ on the working plane.

4.3.1. Cooling season conditions

In this section are reported the results of the analysis for July, in which the summer combinations have been tested. As seen for the energy analysis, the reference systems for the performance comparison will be the static *OAC* configuration and the *SSF*. The variations, expressed in percentage, are referred to the *SSF*, as done for the energy analysis.

4.3.1.1. Indoor operative temperatures

The temperature trends (air and operative ones) in the month of July for all the 30 configurations have been analysed using the simulation outputs from IDA ICE, to understand how much the implemented control can affect the indoor thermal comfort conditions inside the zone. Indoor temperatures in fact are the main physical quantities that can affect the thermal sensation of the occupants. As mentioned before, the percentage of occupied hours in which the threshold limit of $26°C$ is overcame is considered to evaluate how much the implemented control can be effective in the prevention of the overheating risk inside the room [15]. In addition, also a higher temperature limit of $30°C$ has been considered, to consider more extreme indoor environmental conditions. In the same way, it is also possible to evaluate the number of occupied hours in which the indoor operative temperature is below the limit of $20°C$, to evaluate the effects of the cavity air flows on the reduction of the indoor temperature and the possibility to have cold drafts for the occupants [15]. The percentage of occupied hours above the limit of $26°C$ for each configuration of control are reported in *Table 39*.

Code	n° hours Top > 26°C	% of occupied hours Top > 26°C	Variation [%] (SSF)
SC#1	90.9	43.3	**-1.9**
SC#2	93	44.3	**0.3**
SC#3	94.2	44.9	**1.6**
SC#4	97.9	46.6	**5.6**
SC#5	98	46.7	**5.7**
SC#6	97.2	46.3	**4.9**
SC#7	91.8	43.7	**-1.0**
SC#8	93.7	44.6	**1.1**
SC#9	93.7	44.6	**1.1**
SC#10	97.9	46.6	**5.6**
SC#11	96.8	46.1	**4.4**
SC#12	98.7	47.0	**6.5**
SC#13	97.2	46.3	**4.9**
SC#14	99	47.1	**6.8**
SC#15	99.8	47.5	**7.7**
SC#16	103	49.0	**11.1**
SC#17	104	49.5	**12.2**
SC#18	104	49.5	**12.2**
SC#19	98.1	46.7	**5.8**
SC#20	98.9	47.1	**6.7**
SC#21	100	47.6	**7.9**
SC#22	103	49.0	**11.1**
SC#23	103	49.0	**11.1**
SC#24	103	49.0	**11.1**
SC#25	93.2	44.4	**0.5**
SC#26	93.7	44.6	**1.1**
SC#27	94.8	45.1	**2.3**
SC#28	102	48.6	**10.0**
SC#29	102	48.6	**10.0**
SC#30	102	48.6	**10.0**
Static OAC	142	67.6	**53.2**
SSF	***92.7***	***44.1***	***REFERENCE***

Table 39: Percentages of occupied hours above 26°C for the different façade systems (July)

All the combinations of control produce an increase of the number of hours above the limit of *26°C* compared to the *SSF:* in average, considering all the 30 different combinations of control, the increase compared to *SSF* is equal to *5.9%*. Anyway, the flexible *DSF* configurations are largely better than the static *OAC* configuration, which causes a largely bigger increase of the number of hours above the overheating risk limit equal to *53.2%*.

The effects on the indoor operative temperature in the room are widely influenced by the typology of control which is applied to airflow in the cavity. In particular, the most effective air flow controls in the limitation of the increase are *SAC#1* and *#2*, which respectively produce an increase of *2.7%* and *2.9%*. For two control combinations (*SC#1* and *SC#7*), it is also visible a reduction of the number of occupied hours above the limit of *26°C*. The worst solutions, on the other hand, are *SAC#3* and *#4* (increase of about *9%*) while an intermediate solution is *SAC#5* (*+5.7%*). The average increases of the indoor operative temperatures above the limit of *26°C* are reported in *Table 40*.

Airflow control	Increase of the occupied hours above 26°C (compared to *SSF*) [%]
SAC#1	**2.7**
SAC#2	**2.9**
SAC#3	**9.1**
SAC#4	**9.0**
SAC#5	**5.7**

Table 40: Average variations of the occupied hours above 26°C produced by the 5 different airflow controls (coupled with the 6 different types of control for the shading) in July

Shading control	Variation of the occupied hours above 26°C (compared to *SSF*) [%]
SSC#1	**1.7**
SSC#2	**3.2**
SSC#3	**4.1**
SSC#4	**8.7**
SSC#5	**8.7**
SSC#6	**8.9**

Table 41: Average variations of the occupied hours above 26°C produced by the 6 different shading controls (coupled with the 5 different types of control for the air flows) in July

Looking at these data, for the reduction of the overheating risk in the room (function of the number of hours above *26°C*), the adoption of the *AE* configuration (largely used in *SAC#1* and *#2*) is more effective than the use of the *OAC* one (used with higher frequency in the other typologies of air flow controls during the occupied hours). *SAC#3*, *#4* and *#5* show larger increase of the number of hours above the temperature limit: this is caused by a higher percentage of occupied hours in which the *AS* and *OAC* configurations are used by the *DSF*, compared to the *AE* one. The average values of increase of the indoor operative temperatures above the limits of *26°C* are reported in *Table 41*.

In this case, it is also visible the influence of the different typologies of shading control that can be coupled with the air flow controls. In particular, the radiation control, if coupled with the five different types of control for the cavity air flows, produces an increase of the number of hours above the limit equal to *3%*. In the case of the adoption of the temperature control, the average increase is more evident (*+8.8%*). This can be caused by the fact that the temperature activation of the blind is applied with too large frequency in the free running configuration of the model (as it will showed in the analysis of the occupied hours in which the indoor illuminance levels are below *500 lux*): the heat retainment of the drawn blind can be a possible cause of the reduced efficacy in the overall temperature reduction.

If the temperature control of the blind is used, it is not visible a significant variation of the number of occupied hours above the limit of *26°C* in function of the different types of control for the slat angle. On the other hand, if the radiation control is applied, it is possible to see that the fixed slat angle is the most effective (*+1.7%*) in the limitation of the temperature increase above *26°C* while the worst solution in this case is the scheduled variation of the slat angle (*+4.1%*).

A graphical comparison of the number of hours above the limit of *26°C* is reported in *Figure 80*.

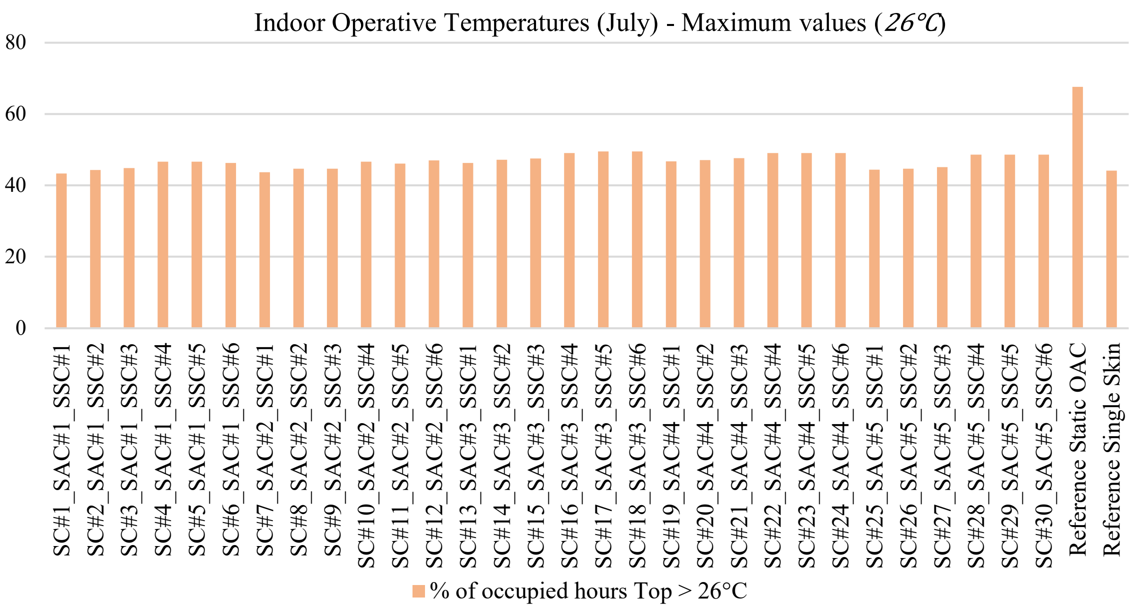


Figure 80: Percentages of occupied hours above 26°C for the different façade systems (July)

It is also possible to analyse the number of occupied hours in which the indoor operative temperature is higher than *30°C*. Given the fact that the system is working in a free running configuration during the month of July it is possible to have very high indoor temperatures inside the room. For this reason, a higher threshold limit for the indoor operative temperature has been selected for the analysis.

In this case, it is evident that the adoption of the *DSF* systems (both flexible and static) can significantly increase the number of occupied hours in which the indoor operative temperature is above *30°C*.

The percentage of occupied hours above the limit of *30°C* for each configuration of control are reported in *Table 42*.

Code	n° hours Top > 30°C	% of occupied hours Top > 30°C	Variation [%] (SSF)
SC#1	40.2	19.1	**311.9**
SC#2	40.6	19.3	**316.0**
SC#3	40.8	19.4	**318.0**
SC#4	41.2	19.6	**322.1**
SC#5	41.6	19.8	**326.2**
SC#6	42.9	20.4	**339.5**
SC#7	40.6	19.3	**316.0**
SC#8	40.6	19.3	**316.0**
SC#9	41.2	19.6	**322.1**
SC#10	40.8	19.4	**318.0**
SC#11	41.2	19.6	**322.1**
SC#12	43.2	20.6	**342.6**
SC#13	58.8	28.0	**502.5**
SC#14	61.5	29.3	**530.1**
SC#15	63.2	30.1	**547.5**
SC#16	56.9	27.1	**483.0**
SC#17	58.2	27.7	**496.3**
SC#18	60.6	28.9	**520.9**
SC#19	59.3	28.2	**507.6**
SC#20	61.5	29.3	**530.1**
SC#21	61.9	29.5	**534.2**
SC#22	57.7	27.5	**491.2**
SC#23	58.6	27.9	**500.4**
SC#24	59.6	28.4	**510.7**
SC#25	39.8	19.0	**307.8**
SC#26	40	19.0	**309.8**
SC#27	41	19.5	**320.1**
SC#28	40.8	19.4	**318.0**
SC#29	42.1	20.0	**331.4**
SC#30	43.7	20.8	**347.7**
Static OAC	86.9	41.4	**790.4**
SSF	***9.76***	***4.6***	***REFERENCE***

Table 42: Percentages of occupied hours above 30°C for the different façade systems (July)

A graphical comparison of the number of hours above the limit of *30°C* is reported in *Figure 81*.

As it is possible to see, the adoption of the *SSF* is associated to few occupied hours of the month (about *5%* of the total) in which the indoor operative temperature is above *30°C*.

The adoption of a flexible *DSF* can significantly increase this number: the percentages for the occupied hours in which the indoor operative temperature is above *30°C* (the percentages are comprised between *19%* and *30%*.

Anyway, the performance of the static *OAC* is largely worse with about *41.4%* of the occupied hours above the limit. Among the different air flow controls, *SAC#3* and *#4* produce the most consistent increase of occupied hours above the limit of *30°C* while *SAC#1*, *#2* and *#5* are in this case more effective in the limitation of the increase.

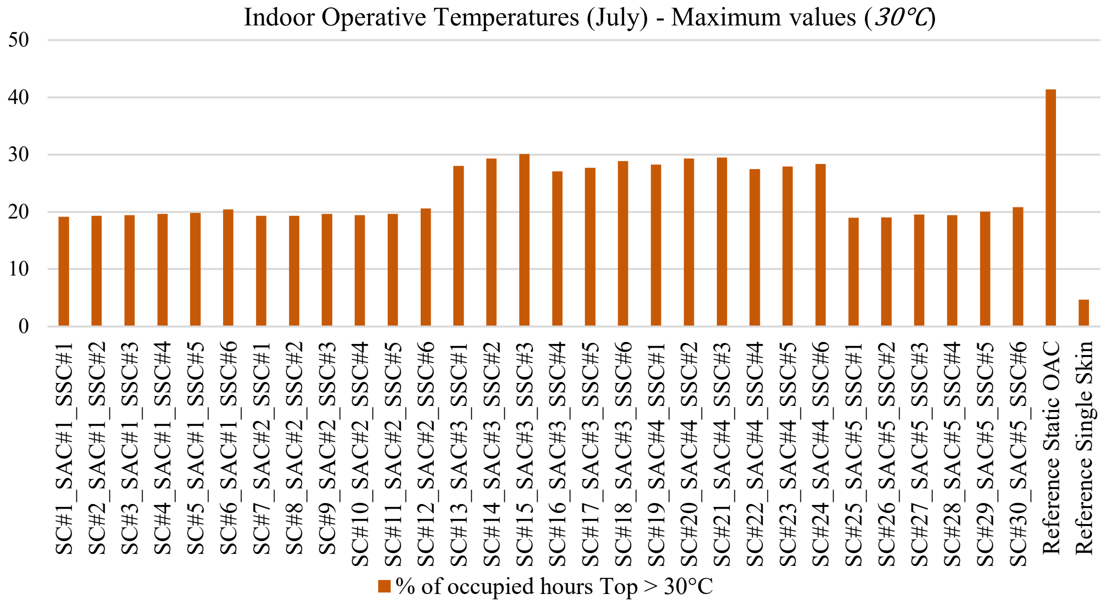


Figure 81: Percentages of occupied hours above 30°C for the different façade systems (July)

The average variations of the number of occupied hours above the limit of *30°C* is reported in *Table 43*.

Airflow control	**Increase of the occupied hours above 30°C (compared to *SSF*) [%]**
SAC#1	**322.3**
SAC#2	**322.8**
SAC#3	**513.4**
SAC#4	**512.4**
SAC#5	**322.5**

Table 43: Average variations of the occupied hours above 30°C produced by the 5 different airflow controls (coupled with the 6 different types of control for the shading) in July

Regarding the shading control, all the six implemented logics produce an increase which has the same order of magnitude. It is not visible, consequently, a great difference in the performance among the different controls for the shading system as observed with the temperature limit of *26°C*. As already mentioned, for the summer season it is also necessary to consider the possibility to have cold drafts in the indoor environment caused by the air flows inside the cavity.

The percentage of occupied hours below the limit of *20°C* for each configuration of control are reported in *Table 44*.

Code	**n° hours Top < 20°C**	**% of occupied hours Top < 20°C**	**Variation [%] (SSF)**
SC#1	31.1	14.8	**207.9**
SC#2	31.8	15.1	**214.9**
SC#3	31	14.8	**206.9**
SC#4	28.8	13.7	**185.1**
SC#5	31.2	14.9	**208.9**
SC#6	31.2	14.9	**208.9**
SC#7	30	14.3	**197.0**
SC#8	31.5	15.0	**211.9**
SC#9	30.8	14.7	**205.0**
SC#10	29.2	13.9	**189.1**
SC#11	31.2	14.9	**208.9**
SC#12	30.6	14.6	**203.0**
SC#13	28.2	13.4	**179.2**

SC#14	27	12.9	**167.3**
SC#15	27.6	13.1	**173.3**
SC#16	27.3	13.0	**170.3**
SC#17	28.2	13.4	**179.2**
SC#18	27.4	13.0	**171.3**
SC#19	27	12.9	**167.3**
SC#20	28.9	13.8	**186.1**
SC#21	29.1	13.9	**188.1**
SC#22	26.7	12.7	**164.4**
SC#23	27.2	13.0	**169.3**
SC#24	27.4	13.0	**171.3**
SC#25	30.7	14.6	**204.0**
SC#26	30.7	14.6	**204.0**
SC#27	31.4	15.0	**210.9**
SC#28	30.7	14.6	**204.0**
SC#29	30.9	14.7	**205.9**
SC#30	31.8	15.1	**214.9**
Static OAC	7.17	3.4	**-29.0**
SSF	***10.1***	***4.8***	***REFERENCE***

Table 44: Percentages of occupied hours below 20°C for the different façade systems (July)

In fact, it is visible that all the configurations of control cause a consistent increase (in average about *+192.6%*) of the number of occupied hours in which the indoor operative temperature is below *20°C*. Only the static *OAC* configuration generates a reduction (about *-6.4%*) of the number of hours below *20°C*.

SAC#1, *#2* and *#5*, the most effective in the limitation of the increase of the number of hours above the limit of *26°C* and *30°C* are also the ones which generate the most consistent increase in the number of occupied hours below *20°C*. On the other hand, *SAC#3* and *#4* are more effective in the limitation of the number of occupied hours below the limit (but they are also associated to a higher overheating risk for the room). The percentages of the increase are anyway very high for all the different types of airflow control. This is of course a critical point under the point of view of the indoor thermal comfort for the occupants, due to the necessity of considering both the discomfort caused by too high and too low indoor operative temperatures. Regarding the different typologies of shading control which can be implemented, radiation and temperature control produce the same increase of the number of occupied hours below the limit (in the order of *190%*). In addition, it is not evident a relation between the different typologies of control for the slat angle and the related increase of the number of occupied hours below the limit of *20°C*.

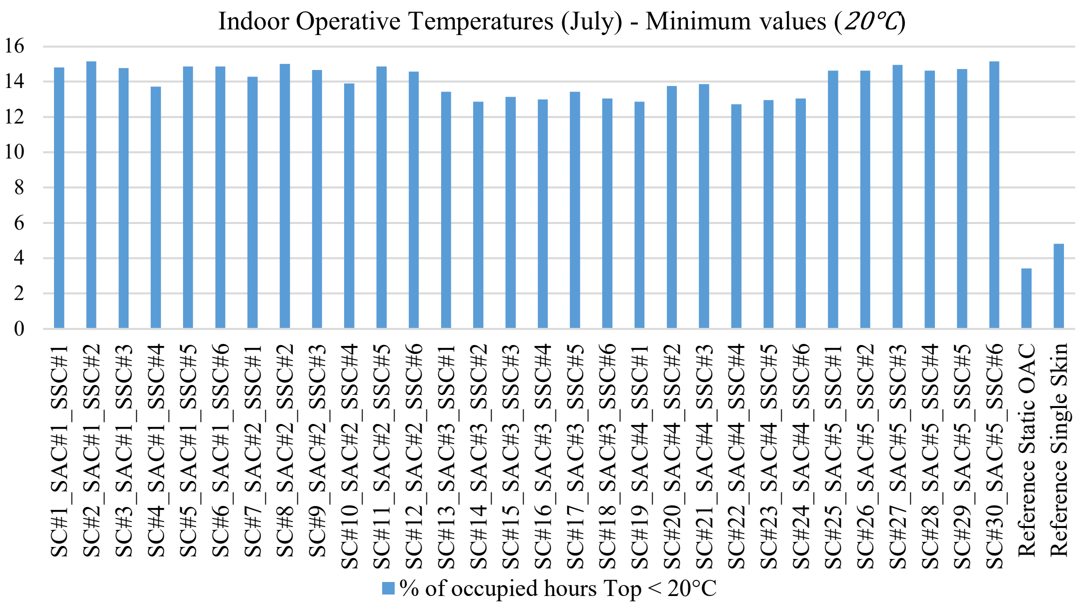


Figure 82: Percentages of occupied hours below 20°C for the different façade systems (July)

4.3.1.2. IAQ

In similar way to the indoor temperatures, also the concentrations of CO_2 in the zone with the different forms of control applied to the *DSF* have been analysed, to evaluate how much the implemented control can affect the *IAQ* of the room. As done for the indoor temperatures in the zone, to have a quantitative evaluation of the impact of each control combination on the performance of the system, here it is reported, for each configuration of control, the percentage of occupied hours above the limit of *1000 ppm.* This is assumed as maximum threshold limit for indoor CO_2 concentrations to provide good health conditions for the occupants, in accordance with the *ASHRAE* standards [27]. The number of hours above the limit for each configuration of control are reported in *Table 45*.

Code	n° hours CO_2 > 1000 ppm	% of occupied hours CO_2 > 1000 ppm	Variation [%] (SSF)
SC#1	0	0.0	**-100.0**
SC#2	0	0.0	**-100.0**
SC#3	0	0.0	**-100.0**
SC#4	0.409	0.2	**-99.3**
SC#5	0	0.0	**-100.0**
SC#6	0.609	0.3	**-99.0**
SC#7	0	0.0	**-100.0**
SC#8	0	0.0	**-100.0**
SC#9	0	0.0	**-100.0**
SC#10	0	0.0	**-100.0**
SC#11	0	0.0	**-100.0**
SC#12	0	0.0	**-100.0**
SC#13	83.5	39.8	**43.2**
SC#14	85.2	40.6	**46.1**
SC#15	86.8	41.3	**48.9**
SC#16	86.3	41.1	**48.0**
SC#17	88.8	42.3	**52.3**
SC#18	87.9	41.9	**50.8**
SC#19	86.1	41.0	**47.7**
SC#20	86.3	41.1	**48.0**
SC#21	87.4	41.6	**49.9**
SC#22	88.8	42.3	**52.3**
SC#23	87.6	41.7	**50.3**
SC#24	87.3	41.6	**49.7**
SC#25	0	0.0	**-100.0**
SC#26	0	0.0	**-100.0**
SC#27	0	0.0	**-100.0**
SC#28	0	0.0	**-100.0**
SC#29	0	0.0	**-100.0**
SC#30	0	0.0	**-100.0**
Static OAC	209	99.5	**258.5**
SSF	***58.3***	***27.8***	***REFERENCE***

Table 45: Percentages of occupied hours above 1100 ppm for the different façade systems (July)

It is visible a consistent variation of the results in function of the typology of the air flow control that is applied to the *DSF*.

A reduction of the number of hours above the limit of *1000 ppm* with respect to the *SSF* is visible in the case of the application of *SAC#1*, *#2* and *#5*. *SAC#1* and *#2* use in a consistent way the *AE* configuration during the occupied hours while *SAC#5* also adopts the *AS* configuration for the introduction of fresh air by means of the cavity (*Table 46*).

Airflow control	Variation of the occupied hours above 1000 ppm (compared to *SSF*) [%]
SAC#1	**-99.7**
SAC#2	**-100.0**
SAC#3	**48.2**

SAC#4	**49.7**
SAC#5	**-100.0**

Table 46: Average variations of the occupied hours above 1000 ppm produced by the 5 different airflow controls (coupled with the 6 different types of control for the shading)

For this reason, the six combinations which use *SAC#5* show the highest percentages of reduction compared to *SSF* with no occupied hours above the limit of *1000 ppm*. Given the fact that the threshold limit for the indoor CO_2 concentrations is never reached, these six combinations of control could be used with no adoption of mechanical ventilation inside the room. Anyway, also *SAC#1* and *#2* are very effective, with almost no hours above the limit of *1000 ppm*.

On the contrary, *SAC#3* and *#4*, which use for a larger extent the *OAC* configuration during the occupied hours, show an evident (from *20%* to *30%*) increase of the number of hours above the limit of *1000 ppm*. This is of course caused by the impossibility to introduce or extract air by means of the cavity if the *OAC* configuration is in use: consequently, the CO_2 concentrations in the zone are higher, with a worsening of the performance compared to *SSF*.

Anyway, the worst performance is the one of the static *OAC* configuration, for which the number of hours above the limit is over 25 times greater than the *SSF*. In the case of the indoor concentrations of CO_2, a dependency with the different types of control for the shading is not present. A graphical comparison of the number of hours above the concentration limit is reported in *Figure 83*.

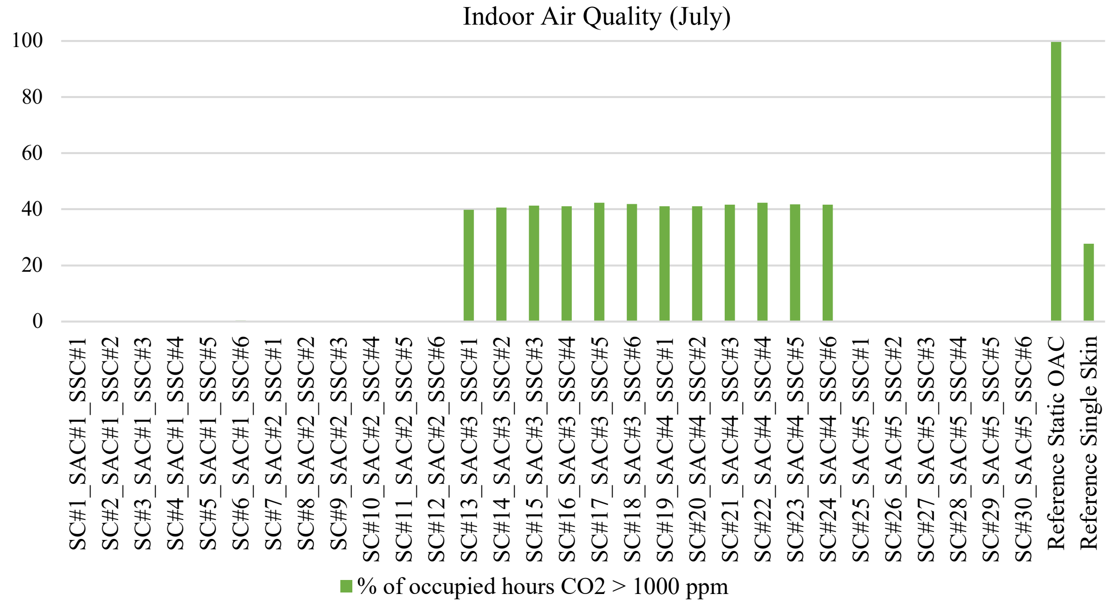


Figure 83: Percentages of occupied hours above 1100 ppm for the different façade systems (July)

4.3.1.3. *Fanger's comfort indices*

For a wider evaluation of the comfort conditions in relation to temperature, radiative discomfort, moisture and draught, the Fanger's comfort indices can be used [34]. It is therefore a better form of evaluation of the indoor environmental quality conditions compared for example to the simpler study of the indoor operative temperatures inside the room. In fact, according to the *Comfort Category B* defined in the standard *EN ISO 7730* [36], *PPD* percentage should be kept below *10%*, while the *PMV* index should be always inside the range [*-0.5; 0.5*], to keep acceptable indoor environmental conditions.

For this reason, for each configuration of control it is reported the number of occupied hours above $PPD = 10\%$, the number of occupied hours above $PMV = 0.5$ and the number of occupied hours below $PMV = -0.5$. The percentage of hours above and below the limits for each configuration of control are reported in *Table 49*.

As it is possible to see, the number of hours in which the PPD index is above 10% is quite different in function of the implemented air flow control inside the cavity. Anyway, the increase of all the considered quantities (PPD and PMV limits), in relation to the *SSF* is evident: the *SSF* with a traditional openable window is absolutely the best solution if the Fanger's comfort indices are considered.

In fact, with the adoption of the *SSF*, the number of occupied hours below the limit of $PMV = -0.5$ is about 30% of the total, while with all the configurations of controlled *DSF* this number is considerably greater (in the order of 45%).

Looking at the opposite case, the number of hours above the limit of 0.5 is of the same order of magnitude of the number of hours below -0.5 (between 30% and 40%), for all the 30 combinations of control that are applied to the *DSF*. This means that the occupants can experience both conditions of thermal discomfort due to too cold or too hot thermal sensations (as seen with the analysis of the indoor operative temperatures).

Anyway, compared to the static *OAC* configuration, all the combinations of control show (in the largest part of the cases) a lower number of hours above the limit for PPD: the percentage of occupied hours above the limit of 10% in the case of static *OAC* configuration is near 85%, while for the greatest part of flexible *DSF* configurations the percentages are quite never above 80%.

Under the point of view of the Fanger's comfort indices, the performance of the static *OAC* configuration is consequently worse than the flexible *DSFs*. In addition, the static *OAC* configuration produces a higher number of hours above the limit of 0.5 for PPM (about 65% of the occupied hours), in comparison to the other combinations of controlled façade systems.

On the other hand, the number of hours below the limit of $PMV = -0.5$ is significantly lower in comparison with the controlled *DSF* configurations (only 19.1% of the occupied hours). The static *OAC* configuration is anyway in the complex largely worse in terms of overheating risk compared to the flexible *DSF* configurations, considering the *PMV* indices (as observed with the trend of the indoor operative temperature).

Airflow control	Variation for PPD > 10% [%]	Variation for PMV > 0.5 [%]	Variation for PMV < -0.5 [%]
SAC#1	**66.7**	**108.9**	**57.7**
SAC#2	**66.5**	**109.6**	**57.1**
SAC#3	**90.9**	**192.3**	**56.0**
SAC#4	**91.3**	**194.2**	**56.1**
SAC#5	**64.4**	**112.7**	**52.4**

Table 47: Average variations of Fanger's comfort indices produced by the 5 different airflow controls (coupled with the 6 different types of control for the shading) in July

Among the different typologies of air flow controls (*Table 47*), the worst results are achieved using *SAC#3* and *#4* (highest number of occupied hours above 10% for *PPD* and above 0.5 for *PMV*). The other forms of control (*SAC#1*, *#2* and *#5*) are on the other hand slightly better (but there is anyway a worsening compared to *SSF*).

At the end, the influence of the different typologies of shading control is not so evident (*Table 48*). Anyway, it is possible to say that the radiation control is associated to a higher number of hours below the limit of -0.5, but also to a lower time above the limit of 0.5.

The radiation control of the blind is consequently more effective in the overheating risk reduction than the temperature control (as seen from the analysis of the indoor operative temperatures).

In the complex, anyway, the radiation control is associated with a slighter higher average increase of the number of occupied hours above *PPD = 10%* (*77.4%* for the radiation control, while *74.5%* for the temperature control).

Shading control	Variation for PPD > 10% [%]	Variation for PMV > 0.5 [%]	Variation for PMV < -0.5 [%]
SSC#1	**77.3**	**137.2**	**60.9**
SSC#2	**76.9**	**141.6**	**58.0**
SSC#3	**77.9**	**146.3**	**57.6**
SSC#4	**73.6**	**142.7**	**52.9**
SSC#5	**74.8**	**145.7**	**52.9**
SSC#6	**75.2**	**147.6**	**52.8**

Table 48: Average variations of Fanger's comfort indices produced by the 6 different shading controls (coupled with the 5 different types of control for the cavity air flows) in July

A graphical comparison of the variation of the comfort indexes is reported in *Figure 84.*

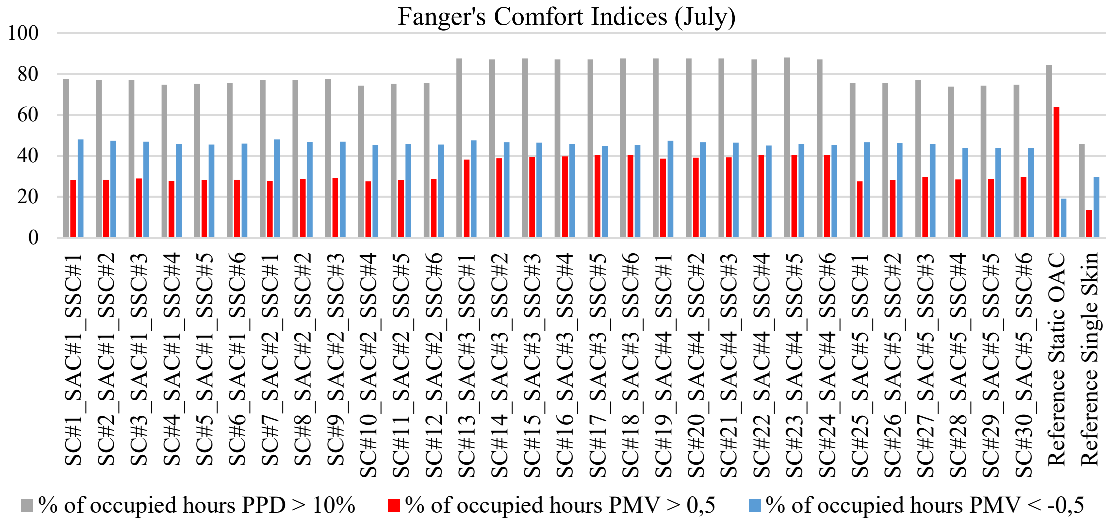


Figure 84: Variation of the comfort indexes in the room for the different façade systems (July)

Code	n° hours PPD > 10%	% of occupied hours PPD > 10%	n° hours PMV > 0,5	% of occupied hours PMV > 0,5	n° hours PMV < -0,5	% of occupied hours PMV < -0,5	Variation PPD >10% (SSF)	Variation PMV > 0,5 (SSF)	Variation PMV < -0,5 (SSF)
SC#1	163	77.6	59.1	28.1	101	48.1	**69.6**	**108.1**	**62.6**
SC#2	162	77.1	59.5	28.3	99.5	47.4	**68.6**	**109.5**	**60.2**
SC#3	162	77.1	60.8	29.0	98.7	47.0	**68.6**	**114.1**	**58.9**
SC#4	157	74.8	58.1	27.7	95.9	45.7	**63.4**	**104.6**	**54.4**
SC#5	158	75.2	59.1	28.1	95.6	45.5	**64.4**	**108.1**	**53.9**
SC#6	159	75.7	59.4	28.3	96.8	46.1	**65.5**	**109.2**	**55.9**
SC#7	162	77.1	58.1	27.7	101	48.1	**68.6**	**104.6**	**62.6**
SC#8	162	77.1	60.6	28.9	98.2	46.8	**68.6**	**113.4**	**58.1**
SC#9	163	77.6	61.1	29.1	98.8	47.0	**69.6**	**115.1**	**59.1**
SC#10	156	74.3	58	27.6	95.5	45.5	**62.3**	**104.2**	**53.8**
SC#11	158	75.2	59.1	28.1	96.2	45.8	**64.4**	**108.1**	**54.9**
SC#12	159	75.7	60.2	28.7	95.6	45.5	**65.5**	**112.0**	**53.9**
SC#13	184	87.6	80.3	38.2	100	47.6	**91.5**	**182.7**	**61.0**
SC#14	183	87.1	81.5	38.8	97.9	46.6	**90.4**	**187.0**	**57.6**
SC#15	184	87.6	82.8	39.4	97.6	46.5	**91.5**	**191.5**	**57.2**
SC#16	183	87.1	83.4	39.7	96.4	45.9	**90.4**	**193.7**	**55.2**
SC#17	183	87.1	85.1	40.5	94.4	45.0	**90.4**	**199.6**	**52.0**
SC#18	184	87.6	84.9	40.4	94.9	45.2	**91.5**	**198.9**	**52.8**
SC#19	184	87.6	81.3	38.7	99.5	47.4	**91.5**	**186.3**	**60.2**
SC#20	184	87.6	82.2	39.1	98.1	46.7	**91.5**	**189.4**	**58.0**
SC#21	184	87.6	82.6	39.3	97.8	46.6	**91.5**	**190.8**	**57.5**
SC#22	183	87.1	85.2	40.6	94.6	45.0	**90.4**	**200.0**	**52.3**
SC#23	185	88.1	85	40.5	96.5	46.0	**92.5**	**199.3**	**55.4**
SC#24	183	87.1	85	40.5	95.2	45.3	**90.4**	**199.3**	**53.3**
SC#25	159	75.7	58	27.6	98	46.7	**65.5**	**104.2**	**57.8**
SC#26	159	75.7	59.3	28.2	97	46.2	**65.5**	**108.8**	**56.2**
SC#27	162	77.1	62.5	29.8	96.5	46.0	**68.6**	**120.1**	**55.4**
SC#28	155	73.8	59.9	28.5	92.2	43.9	**61.3**	**110.9**	**48.5**
SC#29	156	74.3	60.6	28.9	92	43.8	**62.3**	**113.4**	**48.1**
SC#30	157	74.8	62.1	29.6	92	43.8	**63.4**	**118.7**	**48.1**
Static OAC	177	84.3	134	63.8	40.2	19.1	**84.2**	**371.8**	**-35.3**
SSF	***96.1***	***45.8***	***28.4***	***13.5***	***62.1***	***29.6***	***REFERENCE***	***REFERENCE***	***REFERENCE***

Table 49: Variation of the comfort indexes in the room for the different façade systems (July)

4.3.1.4. Daylight and glare

In comparison to the indoor temperatures, the indoor CO_2 concentrations and the comfort indices, the indoor illuminance levels on the working plane shows a greater variability of the results, due to the different control logics used for the definition of the slats angle of the blinds (fixed or in function of the cut-off position or of the indoor illuminance levels in the room). In this case it is possible to analyse the percentage of occupied hours in which the illuminance levels inside the zone are below the limit of *500 lux*, to define which control logic better fits with the minimum requirements established by the regulations [16]. The number of hours below the limit for each configuration of control are reported in *Table 50*.

Code	n° hours E < 500 lux	% of occupied hours E < 500 lux	Variation [%] (SSF)
SC#1	94	44.8	**108.0**
SC#2	85.9	40.9	**90.0**
SC#3	69	32.9	**52.7**
SC#4	119	56.7	**163.3**
SC#5	110	52.4	**143.4**
SC#6	94.2	44.9	**108.4**
SC#7	93.7	44.6	**107.3**
SC#8	85.9	40.9	**90.0**
SC#9	69.1	32.9	**52.9**
SC#10	119	56.7	**163.3**
SC#11	111	52.9	**145.6**
SC#12	95.2	45.3	**110.6**
SC#13	93.6	44.6	**107.1**
SC#14	85.8	40.9	**89.8**
SC#15	68.8	32.8	**52.2**
SC#16	123	58.6	**172.1**
SC#17	115	54.8	**154.4**
SC#18	97.9	46.6	**116.6**
SC#19	93.6	44.6	**107.1**
SC#20	86.5	41.2	**91.4**
SC#21	69	32.9	**52.7**
SC#22	124	59.0	**174.3**
SC#23	113	53.8	**150.0**
SC#24	97.9	46.6	**116.6**
SC#25	93.4	44.5	**106.6**
SC#26	86.3	41.1	**90.9**
SC#27	68.7	32.7	**52.0**
SC#28	117	55.7	**158.8**
SC#29	109	51.9	**141.2**
SC#30	93.7	44.6	**107.3**
Static OAC	93.4	44.5	**106.6**
SSF	***45.2***	***21.5***	***REFERENCE***

Table 50: Percentage of occupied hours below the limit of 500 lux (July)

For all the 30 combinations of control for the summer season, it is visible an increased number of hours below the limit of *500 lux* (as seen for the increasing of the energy for artificial lighting). The radiation control is associated to a lower increase of the number of hours below the limit (in average *83.4%*) while the temperature control produces worse results (the increases are comprised between *111.9%* and *166.4%*): consequently, the situation is the opposite visible in the room configuration in which the active systems are turned on (in which the highest increase of the artificial lighting consumptions is associate with the radiation control of the blind). In fact, in the free running configuration of the room, the higher number of occupied hours above the limit of *26°C* produces a more frequent activation of the venetian blind, reducing in this way the indoor daylight availability.

Shading control	Variation of the occupied hours below 500 lux (compared to *SSF*) [%]
SSC#1	**107.2**
SSC#2	**90.4**
SSC#3	**52.5**
SSC#4	**166.4**

SSC#5	**146.9**
SSC#6	**111.9**

Table 51: Average variations of the occupied hours below 500 lux produced by the 6 different shading controls (coupled with the 5 different types of control for the air flows) in July

In this case, the influence of the different typologies of control for the blind slat angle is visible (*Table 51*): the slat angle control by means of the schedule is the most efficient system for the limitation of the increase of the number of hours below *500 lux* (*SSC#3* and *SSC#6*). The worst solution is on the other hand the adoption of the fixed slat angle for the blind (*SSC#1* and *SSC#4*). A solution with intermediate efficacy is finally the cut-off position implementation. A graphical comparison of the variation of the percentage of occupied hours below the minimum levels of illuminance is reported in *Figure 85*.

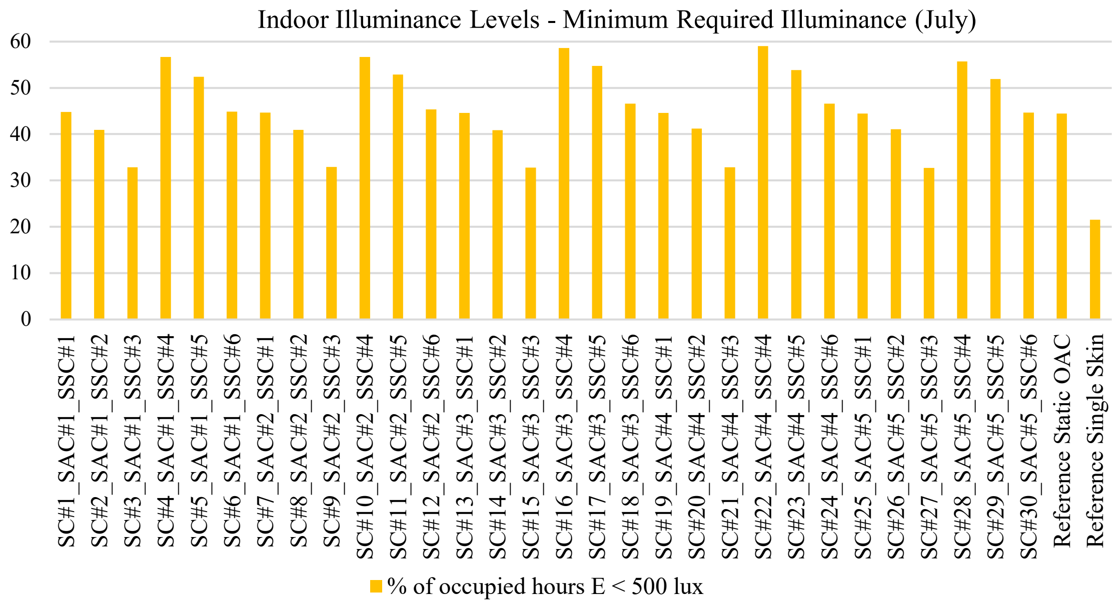


Figure 85: Percentage of occupied hours below the limit of 500 lux (July)

Considering the opposite case, for the evaluation of the glare risk a maximum threshold limit of horizontal illuminance equal to *3000 lux* can be assumed. The glare risk should be evaluated considering vertical illuminance levels at the occupant's eye height (between *1.2 m* and *1.7 m*), in accordance with the standard *EN 17037:2018* [17]. It is anyway impossible to evaluate the variation of the vertical illuminance during the selected simulation periods inside IDA ICE: for this reason, a maximum threshold limit of horizontal illuminance equal to *3000 lux* can be used as reference for the evaluation of the glare risk. Anyway, no one of the selected forms of control reaches a so high value on the working plane considering the occupied hours of the office (both with *SSF* and *DSF* systems). The glare risk during the occupied hours in the office can be therefore assumed as null during the summer season with all the four shading control logics proposed.

4.3.2. Heating season conditions

In this section are reported the results of the analysis for the month of January, used for the evaluation of the winter operating conditions for the *DSF*. The results are presented in the same way used for the analysis of the results during the summer season. As seen for the energy analysis, the reference systems for the performance comparison will be the static *TB* configuration and the *SSF*.

4.3.2.1. Indoor operative temperatures

As done in the case of the summer season, the indoor temperatures trends have been analysed for the different configurations of control for the air flows and the shading system. As mentioned before, the percentage of occupied hours in which the threshold limit of *20°C* is not kept is considered to evaluate how much the implemented control can be effective in the prevention of too low operative temperatures inside the room [15]. Differently from the summer, only the number of occupied hours below the limit of *20°C* has been considered, given the fact that (analysing the temperature trends for the different configurations during the month of January) the limit of *26°C* is never reached by the indoor operative temperatures in the *DSF* systems (only the *0.2%* of the occupied hours are above this limit in the *SSF* system). The percentages of occupied hours below the limit for each configuration of control are reported in *Table 52*.

Code	n° hours Top < 20°C	% of occupied hours Top < 20°C	Variation [%] (SSF)
WC#1	207	98.6	**20.3**
WC#2	208	99.0	**20.9**
WC#3	206	98.1	**19.8**
WC#4	187	89.0	**8.7**
WC#5	190	90.5	**10.5**
WC#6	190	90.5	**10.5**
WC#7	206	98.1	**19.8**
WC#8	208	99.0	**20.9**
WC#9	206	98.1	**19.8**
WC#10	186	88.6	**8.1**
WC#11	183	87.1	**6.4**
WC#12	187	89.0	**8.7**
WC#13	206	98.1	**19.8**
WC#14	208	99.0	**20.9**
WC#15	206	98.1	**19.8**
WC#16	186	88.6	**8.1**
WC#17	188	89.5	**9.3**
WC#18	188	89.5	**9.3**
WC#19	207	98.6	**20.3**
WC#20	208	99.0	**20.9**
WC#21	206	98.1	**19.8**
WC#22	197	93.8	**14.5**
WC#23	204	97.1	**18.6**
WC#24	199	94.8	**15.7**
Static TB	180	85.7	**4.7**
SSF	***172***	***81.9***	***REFERENCE***

Table 52: Percentage of occupied hours below 20°C for the different façade systems (January)

Considering the different typologies of air flows control (*Table 53*), the worst results in terms of indoor operative temperatures are achieved with the use of *WAC#4* (with an average increase of *18.3%* of the occupied hours below the limit). This can be caused by the adoption of the *AE* configuration, which can extract the heat accumulated inside the room during the day causing a sort of overcooling effect of the room. Using *WAC#1*, *#2* and *#3*, the results are better, because the *AE* configuration is not adopted: in average, *WAC#2* is the best option, with an increasing of the number of occupied hours in which the indoor operative temperature is below *20°C* equal to only *14%*.
WAC#1 and *WAC#2* show intermediate results, anyway, better compared to *WAC#4*. Consequently, during the winter season, the impact of the different control combinations on the indoor operative temperature trends is slightly better compared to the summer season, with the average increases which are considerably lower. This is anyway caused by the fact that also in the *SSF* system the number of occupied hours below *20°C* is high.

Airflow control	Increase of the occupied hours below 20°C (compared to *SSF*) [%]
WAC#1	**15.1**
WAC#2	**14.0**
WAC#3	**14.5**
WAC#4	**18.3**

Table 53: Average variations of the occupied hours below 20°C produced by the 4 different airflow controls (coupled with the 6 different types of control for the shading) in January

In the winter season (more than in the summer), the number of hours in which the indoor temperature is below the limit of *20°C* is strongly dependent with the typology of shading control that is implemented (*Table 54*), since this can affect the solar gains entering inside the room, which can be significant also in a temperate climate as Frankfurt.

In fact, in a free running configuration of the room, they are the only form of thermal energy that can increase the indoor temperature. In particular, the radiation control is associated to a higher increase of the number of hours below the limit (in average *20.3%*), since the shading is activated with higher frequency during the occupied hours in the free running configuration.

Consequently, there is a reduction of the passive solar gains in the room, with a subsequent reduction of the indoor operative temperatures. On the other hand, using the temperature activation of the blind, the average increase is reduced to *10.7%*. In both the cases (temperature and radiation activation), the influence of the different typologies of control for the slat angle (fixed, cut-off and scheduled) is not particularly evident.

Shading control	**Increase of the occupied hours below 20°C (compared to *SSF*) [%]**
WSC#1	**20.1**
WSC#2	**20.9**
WSC#3	**19.8**
WSC#4	**9.9**
WSC#5	**11.2**
WSC#6	**11.0**

Table 54: Average variations of the artificial lighting energy need produced by the 6 different shading controls (coupled with the 4 different types of control for the air flows) in January

A graphical representation of the percentage of hours below the limit of *20°C* for the different façade systems is reported in *Figure 86*.

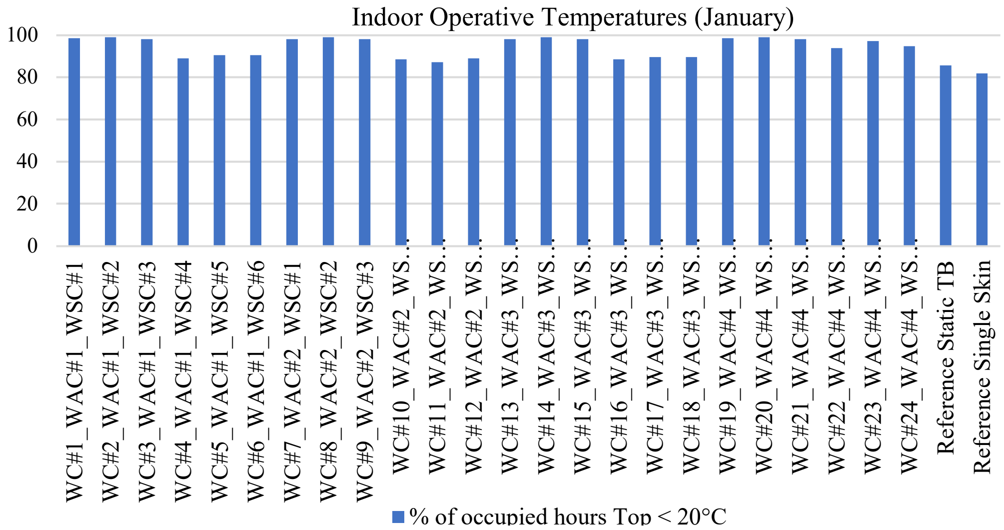


Figure 86: Percentage of occupied hours below 20°C for the different façade systems (January)

4.3.2.2. *IAQ*

The analysis of the indoor concentrations of CO_2 in the zone has been performed in the same way as the summer case, analysing the concentrations trend during the month of January.

As done for the summer season, to have a quantitative evaluation of the impact of each control combination on the performance of the system, here it is reported, for each configuration of control, the percentages of occupied hours above the limit of *1000 ppm.*

Airflow control	Variation of the occupied hours above 1000 ppm (compared to *SSF*) [%]
WAC#1	**-12.1**
WAC#2	**-11.6**
WAC#3	**-10.5**
WAC#4	**-19.3**

Table 55: Average variations of the occupied hours above 1000 ppm produced by the 4 different airflow controls (coupled with the 6 different types of control for the shading) in January

The percentages of occupied hours below the limit for each configuration of control are reported in *Table 56*.

Code	**n° hours CO2 > 1000 ppm**	**% of occupied hours CO2 > 1000 ppm**	**Variation [%] (SSF)**
WC#1	181	86.2	**-12.6**
WC#2	182	86.7	**-12.1**
WC#3	182	86.7	**-12.1**
WC#4	186	88.6	**-10.1**
WC#5	181	86.2	**-12.6**
WC#6	180	85.7	**-13.0**
WC#7	181	86.2	**-12.6**
WC#8	182	86.7	**-12.1**
WC#9	181	86.2	**-12.6**
WC#10	186	88.6	**-10.1**
WC#11	185	88.1	**-10.6**
WC#12	183	87.1	**-11.6**
WC#13	181	86.2	**-12.6**
WC#14	182	86.7	**-12.1**
WC#15	189	90.0	**-8.7**
WC#16	186	88.6	**-10.1**
WC#17	186	88.6	**-10.1**
WC#18	188	89.5	**-9.2**
WC#19	162	77.1	**-21.7**
WC#20	163	77.6	**-21.3**
WC#21	170	81.0	**-17.9**
WC#22	169	80.5	**-18.4**
WC#23	167	79.5	**-19.3**
WC#24	171	81.4	**-17.4**
Static TB	209	99.5	**1.0**
SSF	***207***	***98.6***	***REFERENCE***

Table 56: Percentages of occupied hours above 1100 ppm for the different façade systems (January)

The performance of all the 24 flexible *DSF* configurations is better than the *SSF* and the static *TB* (with a reduction of the number of occupied hours above the limit of *1000 ppm*), but the situation is anyway worse compared to the summer season. It is possible in this case to compare the performance of the different implemented air flow controls (*Table 55*).

Using *WAC#1*, *#2* and *#3*, the percentage of occupied hours above the limit is constantly around *90%* (*86.2%* in the best case, *90%* in the worst). This is caused mainly by the fact that the adoption of the *AS* configuration is not so frequent in the free running asset of the room: consequently, fresh air cannot be introduced inside the indoor environment.

The best results in terms of *IAQ* are reached with the use of *WAC#4* (which adopts the *AE* configuration, the most used during the occupied hours of the office if the ventilation plant is turned off). In this case, the highest percentage of occupied hours above the limit is *74.8%* and the reduction compared to the *SSF* is between *17.4%* and *21.7%*.

A graphical comparison of the number of hours above the concentration limit is reported in *Figure 87*.

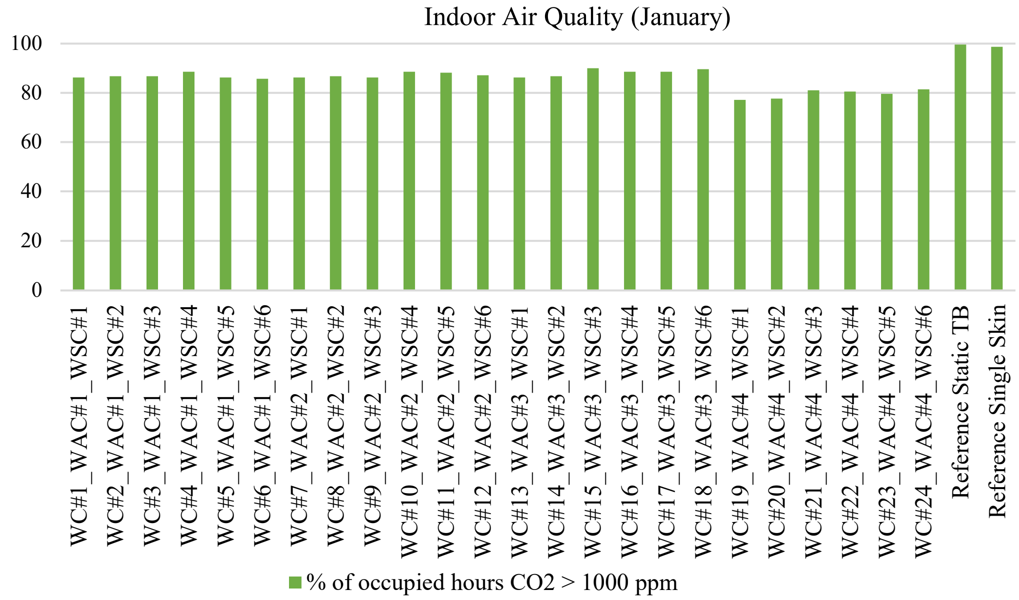


Figure 87: Percentages of occupied hours above 1000 ppm for the different façade systems (January)

4.3.2.3. Fanger's comfort indices

The number of hours above and below the limits for each configuration of control are reported in *Table 59*. During the winter season, as seen for the summer, there is a worsening in terms of Fanger's comfort indices, but the situation is less critical.
The average increase for the occupied hours in which the *PPD* index is above *10%* is around 8% while the average increase for the occupied hours in which the *PMV* index is below -0.5 is *20%*.

Anyway, in the complex the effects of the static *TB* configuration on the indoor comfort indices is slightly better, with a reduction of the number of occupied hours in which the *PPD* index is above *10%*. A graphical comparison of the number of hours above and below the threshold limits is reported in *Figure 88*.

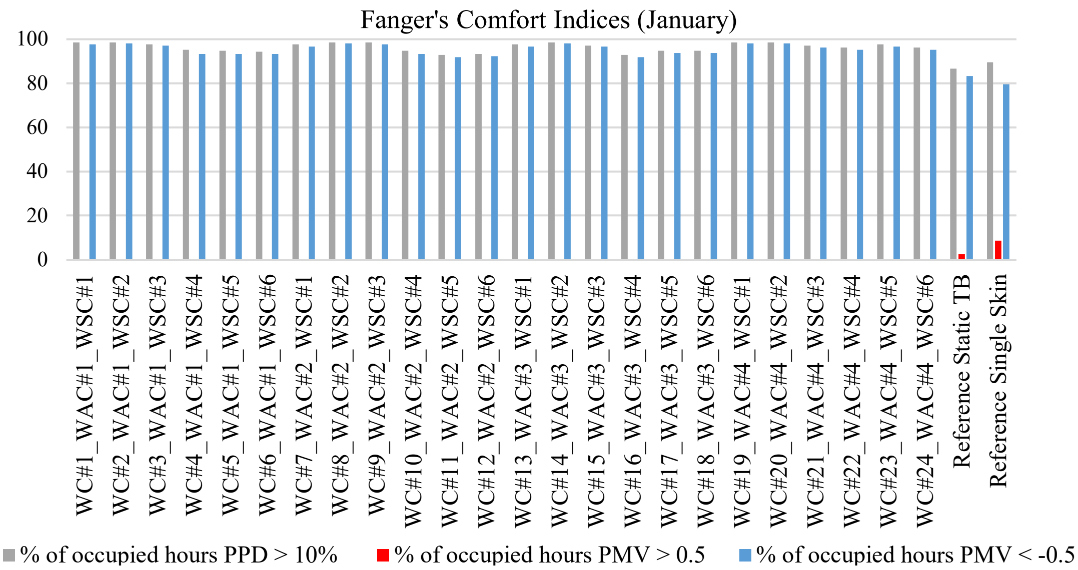


Figure 88: Variation of the comfort indexes in the room for the different façade systems (January)

The most effective air flow controls (*Table 57*) under this point of view are *WAC#2* and *#3*, but also *#1* and *#4* show analogue results. In addition, the adoption of the flexible *DSF* configurations delete the number of occupied hours above the limit of *PMV = 0.5*: in the *SSF* system the number of occupied hours above the limit is *8.6%* of the total, while *2.5%* in static *TB*.

There is consequently a reduction of the overheating risk in winter with the adoption of the flexible *DSF* systems.

Airflow control	Variation for PPD > 10%	Variation for PMV < -0.5
WAC#1	**7.8**	**20.1**
WAC#2	**7.2**	**19.5**
WAC#3	**7.2**	**19.7**
WAC#4	**8.8**	**21.5**

Table 57: Average variations of Fanger's comfort indices produced by the 4 different airflow controls (coupled with the 6 different types of control for the shading) in January

As seen for the analysis of the indoor operative temperatures, the shading control has an influence of the indoor thermal comfort conditions (*Table 58*).

In particular, the radiation control of the blind (*WSC#1, #2* and *#3*) is associated to the largest increase of the number of hours in which the *PPD* index is above *10%* (in average, *9.6%* increase compared to *SSF*): since it is activated with higher frequency than the temperature control, it reduces the solar gains entering in the room and consequently the indoor operative temperatures (to the radiation control it is also associated an higher average increase of the number of occupied hours in which the *PMV* index is below -0.5).

In case of temperature control of the blind (*WSC#4*, *#5* and *#6*) the average increase for *PPD* is lower (*5.9%*), as well as minimum *PMV*. In both the cases (radiation and temperature activation), the different controls for the blind slat angle produce analogue effects on the comfort indices.

Shading control	Variation for PPD > 10%	Variation for PMV < -0.5
WSC#1	**9.6**	**22.3**
WSC#2	**10.1**	**23.4**
WSC#3	**9.0**	**21.9**
WSC#4	**5.9**	**17.5**
WSC#5	**6.1**	**18.1**
WSC#6	**5.7**	**17.8**

Table 58: Average variations of Fanger's comfort indices produced by the 6 different shading controls (coupled with the 4 different types of control for the cavity air flows) in January

Code	n° hours PPD > 10%	% of occupied hours PPD > 10%	n° hours PMV > 0,5	% of occupied hours PMV > 0,5	n° hours PMV < -0,5	% of occupied hours PMV < -0,5	Variation PPD >10% (SSF)	Variation PMV > 0,5 (SSF)	Variation PMV < -0,5 (SSF)
WC#1	207	98.6	0	0.0	205	97.6	10.11	-100.00	22.75
WC#2	207	98.6	0	0.0	206	98.1	10.11	-100.00	23.35
WC#3	205	97.6	0	0.0	204	97.1	9.04	-100.00	22.16
WC#4	200	95.2	0	0.0	196	93.3	6.38	-100.00	17.37
WC#5	199	94.8	0	0.0	196	93.3	5.85	-100.00	17.37
WC#6	198	94.3	0	0.0	196	93.3	5.32	-100.00	17.37
WC#7	205	97.6	0	0.0	203	96.7	9.04	-100.00	21.56
WC#8	207	98.6	0	0.0	206	98.1	10.11	-100.00	23.35
WC#9	207	98.6	0	0.0	205	97.6	10.11	-100.00	22.75
WC#10	199	94.8	0	0.0	196	93.3	5.85	-100.00	17.37
WC#11	195	92.9	0	0.0	193	91.9	3.72	-100.00	15.57
WC#12	196	93.3	0	0.0	194	92.4	4.26	-100.00	16.17
WC#13	205	97.6	0	0.0	203	96.7	9.04	-100.00	21.56
WC#14	207	98.6	0	0.0	206	98.1	10.11	-100.00	23.35
WC#15	204	97.1	0	0.0	203	96.7	8.51	-100.00	21.56
WC#16	195	92.9	0	0.0	193	91.9	3.72	-100.00	15.57
WC#17	199	94.8	0	0.0	197	93.8	5.85	-100.00	17.96
WC#18	199	94.8	0	0.0	197	93.8	5.85	-100.00	17.96
WC#19	207	98.6	0	0.0	206	98.1	10.11	-100.00	23.35
WC#20	207	98.6	0	0.0	206	98.1	10.11	-100.00	23.35
WC#21	204	97.1	0	0.0	202	96.2	8.51	-100.00	20.96
WC#22	202	96.2	0	0.0	200	95.2	7.45	-100.00	19.76
WC#23	205	97.6	0	0.0	203	96.7	9.04	-100.00	21.56
WC#24	202	96.2	0	0.0	200	95.2	7.45	-100.00	19.76
Static TB	182	86.7	5.28	2.5	175	83.3	-3.19	-70.83	4.79
SSF	*188*	*89.5*	*18.1*	*8.6*	*167*	*79.5*	*REFERENCE*	*REFERENCE*	*REFERENCE*

Table 59: Variation of the comfort indexes in the room for the different façade systems (January)

4.3.2.4. Daylight and glare

As done for the summer season, it is possible to analyse the duration curves of the illuminance levels inside the zone for the definition of the number of working hours in which the limit of *500 lux* is not reached, to define which control logic better fits with the minimum requirements established by the regulations.

As seen for the summer season, all the combinations of control produce a worsening of the indoor daylight conditions, but the overall situation is anyway better compared to the summer season: the maximum increasing of the number of hours below the limit of *500 lux* is around *55%.*

The percentage of occupied hours below the limit for each configuration of control are reported in *Table 60*.

Code	n° hours E < 500 lux	% of occupied hours E < 500 lux	Variation [%] (SSF)
WC#1	137	65.2	**25.7**
WC#2	169	80.5	**55.0**
WC#3	123	58.6	**12.8**
WC#4	119	56.7	**9.2**
WC#5	120	57.1	**10.1**
WC#6	119	56.7	**9.2**
WC#7	137	65.2	**25.7**
WC#8	169	80.5	**55.0**
WC#9	122	58.1	**11.9**
WC#10	120	57.1	**10.1**
WC#11	119	56.7	**9.2**
WC#12	120	57.1	**10.1**
WC#13	137	65.2	**25.7**
WC#14	169	80.5	**55.0**
WC#15	123	58.6	**12.8**
WC#16	120	57.1	**10.1**
WC#17	120	57.1	**10.1**
WC#18	120	57.1	**10.1**
WC#19	137	65.2	**25.7**
WC#20	169	80.5	**55.0**
WC#21	122	58.1	**11.9**
WC#22	119	56.7	**9.2**
WC#23	119	56.7	**9.2**
WC#24	119	56.7	**9.2**
Static TB	138	65.7	**26.6**
SSF	***109***	***51.9***	***REFERENCE***

Table 60: Percentage of occupied hours below the limit of 500 lux (January)

The number of hours below the limit of *500 lux,* as seen for the cooling season case, is influenced by the typology of control implemented for the shading (*Table 61*). In this case, anyway, the observed trend is opposite compared to the cooling season: in winter, in fact, the number of hours below the limit of indoor illuminance is greater for radiation control (*+31%* in average), compared to the temperature control (*+9.6%*).

This is caused by the fact that in winter the activation of the blind caused by the temperature is less frequent compared to the one with incident solar radiation on the façade, as said in the previous sections of the analysis. Consequently, the radiation control for the blind in January is not optimal for both, artificial lighting energy demand and indoor daylight (in the summer, on the other hand, the situations are opposite in the 2 model configurations).

Shading control	Variation of the occupied hours below 500 lux (compared to *SSF*) [%]
WSC#1	**25.7**
WSC#2	**55.0**
WSC#3	**12.4**
WSC#4	**9.6**
WSC#5	**9.6**
WSC#6	**9.6**

Table 61: Average variations of the occupied hours below 500 lux produced by the 6 different shading controls (coupled with the 4 different types of control for air flows) in January

If the radiation control for the blind is used, it is clearly visible the influence of the different slat angle variation mechanisms: the cut-off position implementation (*WSC#2*) is the worst solution (*+55%* of occupied hours below the limit of *500 lux*) while the scheduled slat angle variation (*WSC#3*) produces the best results (*+12.4%*, comparable to the one produced by the temperature control of the blind).

A graphical representation of the variation of the number of hours below the limit of 500 lux is showed in *Figure 89*.

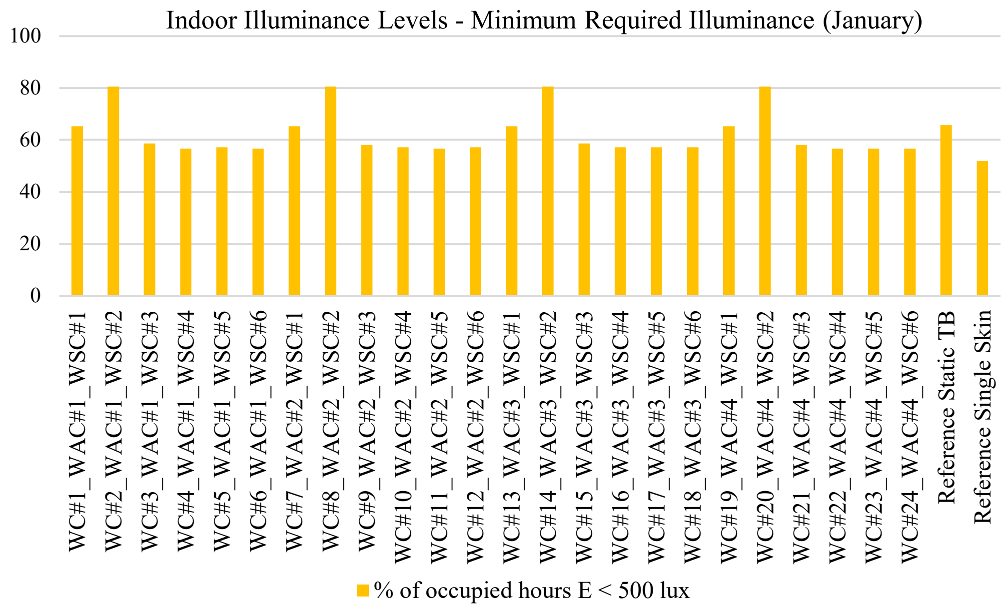


Figure 89: Percentage of occupied hours below the limit of 500 lux (January)

For the evaluation of the glare risk a maximum threshold limit of horizontal illuminance equal to *3000 lux* can be assumed, as seen for the summer season. Differently from the summer season, anyway, peak values of horizontal illuminance levels during the occupied hours are considerably higher and consequently this threshold limit can be overreached in some cases. The number of hours above the limit for each configuration of control are reported in *Table 62*.

Code	n° hours E > 3000 lux	% of occupied hours E > 3000 lux	Variation [%] (SSF)
WC#1	1.45	0.7	**-75.9**
WC#2	1.25	0.6	**-79.2**
WC#3	3.21	1.5	**-46.6**
WC#4	20.8	9.9	**246.1**
WC#5	21.3	10.1	**254.4**
WC#6	21.3	10.1	**254.4**
WC#7	1.45	0.7	**-75.9**
WC#8	1.25	0.6	**-79.2**
WC#9	3.21	1.5	**-46.6**
WC#10	21.3	10.1	**254.4**
WC#11	20.9	10.0	**247.8**
WC#12	21	10.0	**249.4**
WC#13	1.45	0.7	**-75.9**
WC#14	1.25	0.6	**-79.2**
WC#15	3.21	1.5	**-46.6**
WC#16	20.6	9.8	**242.8**
WC#17	20.8	9.9	**246.1**
WC#18	21.3	10.1	**254.4**
WC#19	1.45	0.7	**-75.9**
WC#20	1.25	0.6	**-79.2**
WC#21	3.22	1.5	**-46.4**
WC#22	21.3	10.1	**254.4**
WC#23	21.8	10.4	**262.7**
WC#24	21.5	10.2	**257.7**
Static TB	0.561	0.3	**-90.7**
SSF	***6.01***	***2.9***	***REFERENCE***

Table 62: Percentage of occupied hours above the limit of 3000 lux (January)

The related visual comparison between the number of hours above the glare risk limit for the different façade configurations is reported in *Figure 90*.

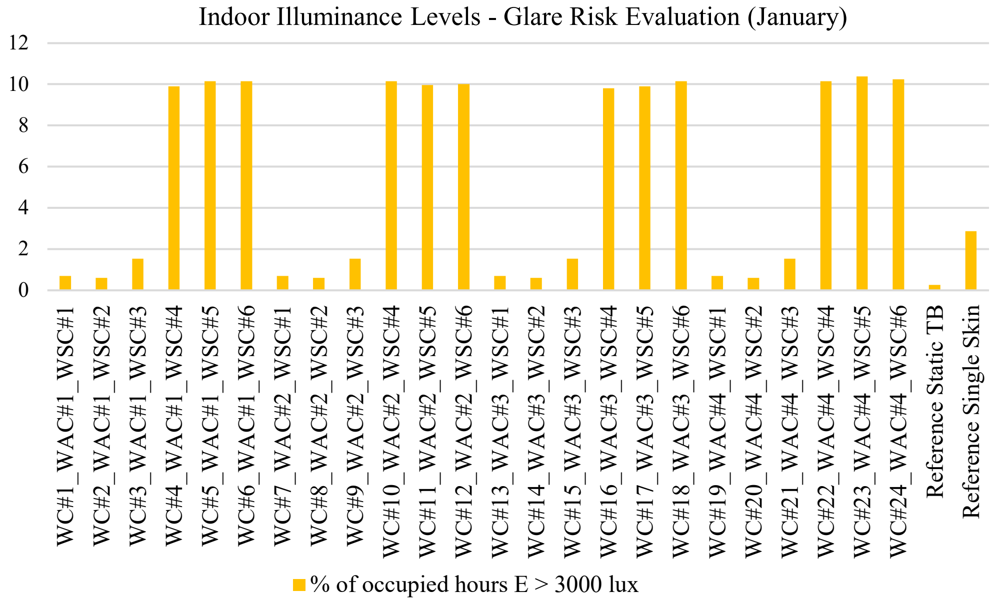


Figure 90: Percentage of occupied hours above the limit of 3000 lux (January)

In all the façade systems (also in the *SSF*), it is possible to observe a certain number of occupied hours in which the limit of *3000 lux* is reached (*2.9%* of the occupied hours in the case of *SSF*). Only the control configurations in function of the incident solar radiation on the façade (*WSC#1, #2* and *#3*) show a percentage of occupied hours above the limit that is approximately zero: *0.6%* in the case of the cut-off slat angle, *1.5%* in the case of the scheduled variation.

The reduction is in the order of *80%* in the best case (cut-off position implementation).

This is a consequence of the higher frequency of activation of the blind compared to the temperature control (*Table 63*): the latter produces a consistent increase of the number of occupied hours above the limit of *3000 lux* (*+250%* in average).

In this case, the different types of control for the blind slat angle produce analogue increases of the number of occupied hours above the limit of *3000 lux*.

Shading control	**Variation of the occupied hours above 3000 lux (compared to *SSF*) [%]**
WSC#1	**-75.9**
WSC#2	**-79.2**
WSC#3	**-46.5**
WSC#4	**249.4**
WSC#5	**252.7**
WSC#6	**254.0**

Table 63: Average variations of the occupied hours below 500 lux produced by the 6 different shading controls (coupled with the 4 different types of control for the air flows) in January

Anyway, it is necessary to say that the number of occupied hours in which there could be a glare risk for the occupants in the room (if the temperature control is used) is not particularly high: the average percentage of occupied hours above *3000 lux* for all the combinations which use temperature control of the blind is about *10%*.

The glare risk is consequently not particularly relevant in the room during the month of January.

5. Results analysis for the summer and the winter conditions

In this section, the optimal control for both, cooling, and heating season conditions, is selected, focusing on the results of the analysis performed in the previous chapter. The selected boundary condition for which the optimal control combination is defined is the one already described in *3.3* (Frankfurt climate, south exposed façade).

For each season, the two aspects of the performance, energy consumption and indoor comfort for the occupants, in comparison with the two reference systems, are considered for the definition of the optimal control for the *DSF*. After this, the conclusions, and the findings regarding the application of the rule-based control approach for the multi-domain performance optimization of the *DSF* will be illustrated and discussed.

5.1. Optimal control selection

The first section is focused on the selection of the optimal control combinations, for cooling season and heating season, considering the two performance domains of the system (energy efficiency and indoor environmental quality) in function of the results of the analysis performed in the previous chapter.

5.1.1. Selection of the optimal control combinations for the cooling season

In this section the evaluation of the results for the selection of the optimal control strategy for the summer season, considering the different domains of the performance, is reported.

5.1.1.1. Energy Efficiency

- Energy need for heating

  For the cooling season, from the point of view of the energy need, the focus is of course the minimization of the energy need for cooling (both space and ventilation). However, as mentioned in the part related to the results analysis, it is important to consider also the impact of the implemented control on the possible increasing of the energy consumption for the heating energy need of the room (which is anyway present also in *SSF*).
  All the implemented control combinations for the cooling season produce a worsening of the energy performance under the point of view of the energy need for heating during the summer season (with percentages comprised between *55%* and *120%*). Under this point view, the lowest increase is associated with *SAC#5* air flow control (in average around *+55%*) since it adopts the *AS* configuration and reduces the use of *AE*. Under this point of view the performance of the static *OAC* compared to the one of *SSF* is anyway considerably better with an average worsening of about *28.7%*. In this case, the impact of the two different types of control for the shading (temperature and radiation) is almost the same.

- Energy need for cooling

  Considering the cooling energy need, all the combinations of control for the summers season produce a similar reduction of the energy need for cooling of the room (in average *42.3%*). In particular, the air flow control *SAC#5* is the most effective in the reduction (*-43.4%*), followed by *SAC#3* and *#4* (about *-43%*) and *SAC#2* and *#1* (about *-41%*). Anyway, only the combinations which adopt the radiation control of the blind (*SSC#1*, *#2* and *#3*) produce a reduction (*-47.3%*) that is comparable with the one generated by static *OAC (-49.2%*). With the adoption of the temperature control, on the other hand, the average reduction is only *37.4%*. Consequently, the radiation control of the blind is more effective in the cooling energy need reduction compared to the temperature control during the summer season.

- Energy need for artificial lighting

  As mentioned in the energy analysis it is anyway necessary to consider also the energy need for artificial lighting, which is mainly influenced by the adoption of a certain control for the shading. All the combinations of control produce a consistent worsening of the required energy need for artificial lighting (given by default by the adoption of 2 glass skins instead of 1). Given the fact that the energy consumption for artificial lighting is influenced mainly by the shading control, all the air flow control logics show the same average increases of this energy need (around *62%*).

The worst combinations are the ones which use the radiation control of the blind (*SSC#1*, *#2* and *#3*) with an average increase of *87.3%*, while the temperature control can limit the increase to *36.5%*. Among the different types of control for the blind slat angle, the scheduled control is the one which provides the best results in the limitation of the increase (*+60.4%* if coupled with the radiation control) while the fixed slat angle and the cut-off position implementation are considerably less effective.

Given these aspects, it is evident that the best control combinations for the summer season are the ones which use *SAC#5* air flow control (for the heating and the cooling energy needs), if the energy consumptions are considered. This one can be consequently assumed as optimal control solution for the cooling season.

A schematic recap of the impact of the 6 combinations which adopts *SAC#5* (from *SC#25* to *SC#30*) on the room energy efficiency considering the different domains of the energy performance is reported in *Table 64* and *Table 65*.

Optimal control combinations	***Cooling energy need***	***Heating energy need***	***Artificial lighting energy need***
SAC#5	Average reduction of *43.4%* of the cooling energy need of the room compared to *SSF,* comparable to the one produced by the static *OAC* configuration (if coupled with the radiation control of the blind)	Limitation of the increase of the heating energy need (*+55.2%*) compared to the other air flow controls (which are in the order of *+100%*)	The average increase of the energy need for artificial lighting is almost the same produced by the other air flow controls (*+62%*)

Table 64: Selection of the optimal control for the summer season in terms of energy efficiency

SAC#5 Performance in the 6 considered combinations (Variations with respect SSF, %)	
Heating energy need	**55.2**
Cooling energy need	**-43.4**
Artificial lighting energy need	**62.5**

Table 65: Average variations of the energy need components with respect to SSF, if SAC#5 is applied (July)

5.1.1.2. Indoor Environmental Quality

Focusing on the indoor environmental quality evaluation, the selection of an optimal control is much more complex, since a greater number of domains and parameters should be considered (Fanger's comfort indices, CO_2 concentrations, daylight levels, indoor operative temperatures).

- <u>Indoor operative temperatures</u>

All the five air flow control logics produce an increase of the number of occupied hours above *26°C* and *30°C*. *SAC#1*, *#2* and *#5* produce similar effects under this point of view, while *SAC#3* and *#4* are considerably worse for the overheating risk in the room (almost the double of the increase compared to *SSF*), if applied to the free run configuration of the model.

Among the different controls for the shading, the average increase produced by the temperature control is higher compared to the one generated by the radiation control (*+3%* in the case of radiation control and *+8.8%* in the case of temperature control if the limit of *26°C* is considered). Consequently, the radiation control of the blind is more effective for the limitation of the overheating risk increase during the summer season, compared to the temperature control of the blind. Regarding the number of occupied hours below the limit of *20°C*, all the controls for the cavity air flows produce similar effects in its increase: *SAC#3* and *#4* are anyway slightly better under this point of view. In this case, the impacts of the different types of control for the shading are almost the same.

- *Indoor Air Quality*

  Looking at the indoor air quality of the room, there is a reduction of the maximum CO_2 concentrations in the room if the *SAC#1*, *#2* and *#5* air flows control are used.
  The best results are achieved with the adoption of *SAC#5* and *#2*, for which no occupied hours in which the limit is overcame are observed. On the other hand, it is present a worsening of the indoor CO_2 concentrations if *SAC#3* and *#4* are applied.

- *Fanger's comfort indices*

  There is a worsening of both *PMV* and *PPD* for all the combinations of control referred to the summer season, for all the control combinations. In the complex, *SAC#5* is the one associated with the lowest increase of *PPD* and *PMV < -0.5* and it is the third most effective in the limitation of the increase of *PMV > 0.5* after *SAC#1* and *#2*. In this case, the influence of the different types of control for the shading is not particular evident.

- *Indoor daylight*

  For the indoor illuminance levels, the lower increase of the number of hours below the limit of *500 lux* is associated to the radiation control of the blind (in average, *+83.4%*), that is in this case more effective compared to the temperature control (in average *+141.7%*): this is the opposite situation compared to the energy consumptions for artificial lighting in the room (with the active systems turned on).
  It is also visible that the lowest increase is associated to the scheduled variation of the blind slat angle, if coupled with both temperature and radiation control.

The optimal control for *IEQ* should be effective enough for all the listed performance domains. Anyway, it is evident a consistent worsening of the performance for the greatest part of the performance domains related to the comfort of the occupants for all the implemented combinations: Fanger's comfort indices, operative temperatures, and minimum illuminance levels. In addition, all the air flow controls produce similar effects on the different performance domains and for this reason the selection of an optimal solution is much more difficult.

In average, *SAC#5* (already selected as optimal control for the energy efficiency of the system) is slightly better compared to the other air flow controls: it is in fact associated with the lowest increase of *PPD* above *10%* and *PMV* below -0.5.

It is also one of the best solutions under the point of view of the indoor air quality for the occupants. For these reasons, it can be considered as optimal control solution also under the point of view of the indoor environmental quality for the occupants. In this way, the optimal control combinations under the point of view of the energy efficiency are also the best ones under the point of view of the indoor environmental quality.

5.1.2. Weaknesses of the summer optimal control

The negative aspects of the selected optimal control for the summer season (*SAC#5*) from the point of view of both the energy efficiency and the indoor environmental quality are summarized in *Table 66*.

As said before, there are some weaknesses of the selected control for several performance domains: the selected optimal control has some positive features under the point of view of the indoor environmental quality and the energy efficiency, but also some consistent limitations in the same performance domains.

Anyway, it is necessary to underline that all the negative aspects which are present in the selected optimal control are present also in the other control solutions.

Therefore, it is impossible to select an optimal control combination which is the best for all the different performance domains of the system, regarding both the overall energy efficiency and the indoor comfort conditions for the occupants during the occupied hours.

Optimal control combinations	*Negative aspects of the summer optimal control*
SAC#5	• It produces a worsening of the energy need for heating (*+55.2%*) that is higher than the reduction of the energy need for cooling (*-43.4%*). • The overall performance in terms of energy need for cooling and heating is comparable to the one of the static *OAC* configuration, with no significant improvement. • It produces a consistent increase of the energy need for artificial lighting (*+62.5%* in average). • It produces a consistent worsening of the indoor thermal comfort condition (Fangers's comfort indices and operative temperatures) • It produces a worsening of the indoor daylight conditions

Table 66: Negative aspects of the performance for the selected optimal control for the summer season

5.1.3. Selection of the optimal control combinations for the heating season

In this section the evaluation of the results for the selection of the optimal control strategy for the winter season, considering the different domains of the performance, is reported, following the same path already defined for the summer season.

5.1.3.1. Energy Efficiency

- Energy need for heating

  As mentioned before, during the winter season the focus for the control implementation, under the point of view of the energy need, is the reduction of the energy need for heating compared to the one in the *SSF*. All the combinations of control produce a reduction of the energy need for heating of the room, but the variability of the effectiveness is not particularly evident. The combinations of control which adopt *WAC#1* (which does not implement the *OAC* configuration in the control) show in average a reduction of the energy need for heating that is slightly higher than the other (*-4.7%*).

  The other typologies of control for the cavity air flow anyway are very similar in terms of effectiveness. Among the different solutions of control for the shading, the temperature control in average produces a reduction (*-6.2%*) which is more consistent than the one generated by the radiation control (*-2.6%*). The latter is consequently less effective for the reduction of the heating energy need during the winter season. The cut-off position implementation is associated with the lowest reduction of the heating energy need of the room if coupled with the radiation control.

- Energy need for cooling

  The energy need for cooling is almost null for all the implemented control combinations, as in the reference *SSF*. The control combinations are consequently effective in the limitation of the increase of the cooling energy need, which can be possible with the adoption of double skin systems.

- Energy need for artificial lighting

  As observed for the summer, there is an increase of the energy need for artificial lighting with all the implemented control combinations (anyway, it is considerably less evident). Considering the energy requirements for artificial lighting, all the implemented controls for the air flows are quite similar in their effectiveness, as seen for the summer (the average increase is *20.6%*).
  The most effective shading control in the limitation of the increase is the temperature control (as observed in the summer season) associated with an average increase of *9.7%* while the radiation control produces an average increase of *31.5%*.

Considering this analysis, the optimal control for the heating season under the point of view of the energy efficiency is more difficult to be selected, given the fact that all the airflow controls produce in average similar effects in terms of heating energy need reduction. *WAC#1* is the one to which it is associated the highest reduction of the heating energy need: if is coupled with the temperature control for the shading, the reduction is comparable to the one generated by the static *TB* configuration. A schematic summary on the selection of *WAC#1* as optimal control for the overall energy efficiency is reported in *Table 67* and *Table 68*.

Optimal control combinations	***Heating energy need***	***Cooling energy need***	***Artificial lighting energy need***
WAC#1	Average reduction of the heating energy need of *4.7%*.	No variation of the cooling energy need (which remains null): there is not an additional overheating risk caused by the presence of the ventilated cavity.	The average increase of the energy need for artificial lighting is the same produced by the other air flow controls (*+20.6%*)

Table 67: Selection of the optimal control for the winter season in terms of energy efficiency

WAC#1 Performance (Variations with respect SSF, %)	
Heating energy need	**-4.7**
Cooling energy need	**No Variation**
Artificial lighting energy need	**20.6**

Table 68: Average variations of the energy need components with respect to SSF, if WAC#1 is applied (January)

5.1.3.2. Indoor Environmental Quality

Considering the indoor environmental quality, the same parameters analysed for the cooling season should be of course considered.

- Indoor operative temperatures

  For the limitations of the number of occupied hours in which the indoor operative temperature is below *20°C* the use of *WAC#4* should be avoided (*WAC#1*, *#2* and *#3* are more effective): anyway, the average increases are for the different air flow controls are very similar (ranging from *14%* to *18%*).

  Among the different control logics for the shading, the radiation control is associated to an average increase which is the double of the one generated by the temperature control (*20.3%* against *10.7%*). The temperature control is consequently the best solution in terms of heating energy need reduction and overcooling risk reduction during the winter season.

- Fanger's comfort indices

  In similar way as seen for the indoor operative temperature, the adoption of *WAC#4* and radiation control should be avoided. The percentages of increase of the *PPD* index for the different control logics for the cavity air flows are anyway very similar (ranging between *7.2%* and *8.8%*).

- Indoor Air Quality

  Under the point of view of the CO_2 concentrations in the room, the *WAC#4* air flow control is the most effective in the limitation of the number of occupied hours above the limit of *1000 ppm,* with an average reduction of *19.3%* compared to *SSF*. This control anyway, as mentioned before, is not the optimal one for the thermal comfort of the occupants (both considering indoor operative temperatures and Fanger's comfort indices).

  For this reason, *WAC#1* and *#2* can be a possible compromise, with an average reduction of about *12%* compared to *SSF*. Anyway, using these controls for the cavity air flows the number of occupied hours above the limit of *1000 ppm* is in the order of *90%*.

- *Indoor daylight and glare discomfort*

  For the evaluation of the daylight levels inside the zone, in the case of the winter season it is necessary to also consider the possibility to have glare discomfort for the occupants. It is possible to see that the temperature control for the blind is the most effective in the limitation of the number of occupied hours in which the indoor illuminance levels on the working plane are below the limit of *500 lux*.

  Vice versa, the radiation control for the blind is the only one which ensure a reduction of the glare discomfort risk for the occupants compared to *SSF* (however, the number of occupied hours above the limit of *3000 lux* is limited to *10%* of the total in the cases in which the temperature control is used).

In average, the impact of the different control combinations on the indoor comfort conditions during the winter season is slightly better compared to the summer season. *WAC#1* (already selected as optimal control under the point of view of the energy efficiency of the system) can be consequently selected as optimal control also under the point of view of the indoor environmental quality of the room. In this way, the optimal control combinations under the point of view of the energy efficiency are also the best ones under the point of view of the indoor environmental quality, as observed during the cooling season.

5.1.4. Weaknesses of the winter optimal control

In *Table 69*, the same analysis performed for the summer season in *Table 66* is applied to the optimal control for the winter season (*WAC#1*), analysing the negative aspects for the different performance domains. As it has been already observed for the summer season, the selected optimal control has some positive features under the point of view of the indoor environmental quality and the energy efficiency, but also some consistent limitations in the same performance domains: for the winter season, consequently, it is impossible to select an optimal control combination which is the best for all the different performance domains of the system (in the case of both, *IEQ* and energy efficiency), as observed for the cooling season.

However, it is necessary to underline that all the negative aspects which are present in the selected optimal control are present also in the other control solutions (as done for July).

Optimal control combinations	***Negative aspects of the selected winter optimal control***
WAC#1	• There is anyway an increase of the energy requirements for artificial lighting compared to the *SSF (+20.3%* in average*)* • The performance of the heating energy need reduction is worse than the one of the static *TB* configuration • It produces a worsening of the indoor daylight conditions (both for minimum illuminance levels inside the rooms and the glare risk for the occupants if the temperature control is used) • The number of occupied hours in which the CO_2 concentrations are above the limit of *1000 ppm* is too high (*87%* of the total occupied hours in average) even if there is a reduction compared to *SSF* system.

Table 69: Positive features and negative aspects of the performance for the selected optimal control for the winter season

5.2. Critical points of the rule-based control effectiveness for the winter and summer conditions

After the selection of the optimal control combinations for cooling season and heating season conditions (*SAC#5* and *WAC#1*) it is now possible to underline some conclusions regarding the selection of the optimal rule-based control for the *DSF* and its effectiveness in the optimization of the overall system performance, starting from the quantitative comparisons performed in *5.1.1* and during the results analysis reported in *4*.
The conclusions can be divided in the two main performance domains of the system, the overall energy efficiency, and the indoor comfort conditions for the occupants.

Energy performance optimization

Considering the analysis performed on the model with the active systems turned on for the performance optimization of the *DSF* under the energy need point of view, the following conclusions, and critical points in the application of the rule-based control can be underlined:

1) The reduction of the energy need for cooling is lower than the increase of the heating energy need during the summer season for all the 30 combinations of control (*Figure 91*). The average reduction of the cooling energy demand is about *42.3%*, around *50%* in the best cases, while the energy need for heating is almost doubled in all the combinations of control for the summer season (average increase of *107.1%*) In addition, the static *OAC* configuration produces a higher reduction of the cooling energy need compared to the largest part of control combinations (*-49.2%*), without compromising in an evident way the energy need for heating (*+28.7%* with respect to *SSF*).

   This is a critical limitation in the application of the flexible *DSF* system in a climate as Frankfurt. Anyway, it is necessary to say that the heating energy need (space and ventilation) is anyway not significant compared to the cooling energy demand of the room during the summer season: it is about *5%* in *SSF* while it is increased to *13%-16%* in the case of the application of *SAC#5*.

2) Both in summer and winter season, there is an increase of the amount of energy required for artificial lighting, compared to *SSF*, with all the different combinations of control, both in the case of the adoption of the radiation control and the temperature control of the blind (the increase is considerably worse in the summer season).

   This is by default caused by the application of a double skin system instead of a conventional single skin one. In addition to this limitation, the most effective shading control for the cooling energy need (the radiation control for the blind) during the summer season is also the worst under the point of view of the artificial lighting requirements, considering all the typologies of air flows control.

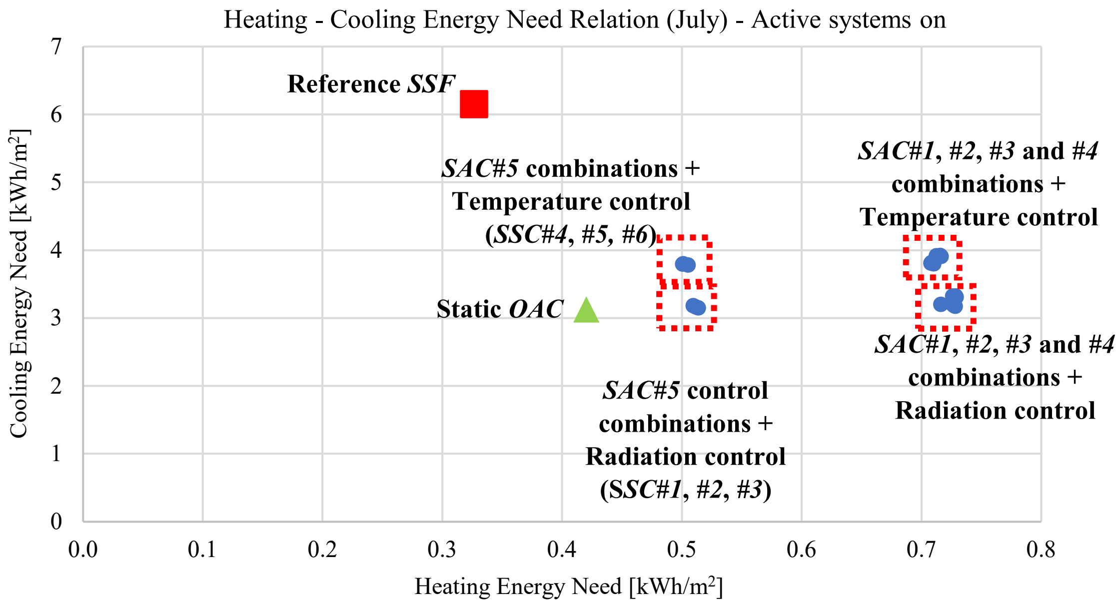


Figure 91: Relation between the heating and cooling energy needs of the room with the adoption of the different façade system (July).

This is of course caused by the increased energy need for artificial lighting caused by a too frequent activation of the blind. The relation between the cooling energy need and the energy requirements for artificial lighting with the different façade systems is reported in *Figure 92*. As it possible to see, the temperature control of the blind causes the highest values of cooling energy need of the room, coupled with lower energy consumption for the artificial lighting (the opposite is of course in the case of the radiation control).

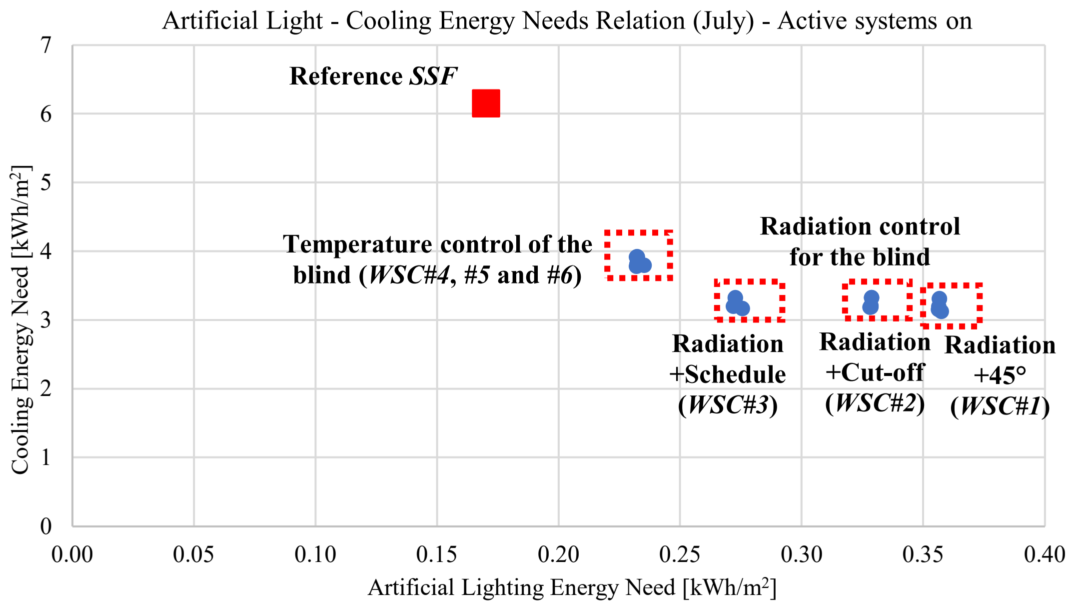


Figure 92: Relation between the artificial lighting and cooling energy needs of the room with the adoption of the different façade system (July).

3) During the winter season it is not visible a significant variability in the results regarding the effectiveness in the reduction of the heating energy need if the 24 combinations of control are considered (all the results are comprised between *1%* and *6.6%*). This is caused by a not significant difference in the configurations changes for the different air flow control logics if the active systems of the room are turned on. In addition, the static *TB* configuration is anyway better in the reduction of the heating energy need for the room in winter (*-6.8%*).

4) With the proposed combinations, it is impossible to reduce at the same time all the components of the overall energy efficiency of the system (heating, cooling and artificial lighting). This situation is particularly evident in summer, in which it is impossible to reduce the energy need for cooling without compromising the energy need for heating of a certain extent (this is valid also for the selected optimal control combination for the summer season). For the winter season on the other hand the situation is considerably better since there is a reduction of the heating energy need without a variation of the cooling, and the artificial lighting requirements increase is less critical.

Indoor environmental quality improvement

On the other hand, considering the indoor environmental quality requirements and the simulations performed on the model in free-running configuration, the following conclusions can be observed:

1) The worsening of the Fanger's comfort indices during the summer season is evident compared to the *SSF*: this is linked with a consistent increase of the number of occupied hours in which the indoor operative temperatures are below *20°C* and above *30°C* if the flexible *DSF* is used.

   Also in winter it is visible a general worsening of the Fanger's comfort indices, but the situation is anyway better, in particular in the case of the application of the temperature control for the cavity blind.

2) During the summer season, the temperature control (which is the optimal solution for the limitation of the increasing of the energy need for artificial lighting) is also the less effective for the minimum illuminance levels inside the room. Anyway, all the typologies of shading control (radiation and temperature activation of the blind) produce a consistent increase in both, the number of occupied hours below *500 lux* and the overall energy need for artificial lighting.

   During the month of January, the situation under this point of view is less critical, as observed also for the energy requirements for the artificial lighting.

3) During the winter season, the *IAQ* in the room with the different flexible *DSF* configurations is better compared to the *SSF*, but the percentage of occupied hours above the limit of *1000 ppm* is anyway too high (*77%* in the best case, over *88%* in the worst).

   This is of course a possible limitation for the adoption of the *DSF* for natural ventilation during the heating season.

4) Regarding the visual comfort for the occupants during the winter season, the best control for the glare risk prevention (radiation control) is also the worst under the point of view of the indoor illuminance levels. Vice versa, the best for indoor illuminance levels (temperature control) is also the less effective in glare risk prevention.

   Anyway, the number of occupied hours in which the glare risk for the occupants is present is always kept below the *10%* of the overall number of hours. The relation between the indoor illuminance levels and the glare risk for the occupants (in function of the illuminance levels at the working plane) is reported in *Figure 93*.

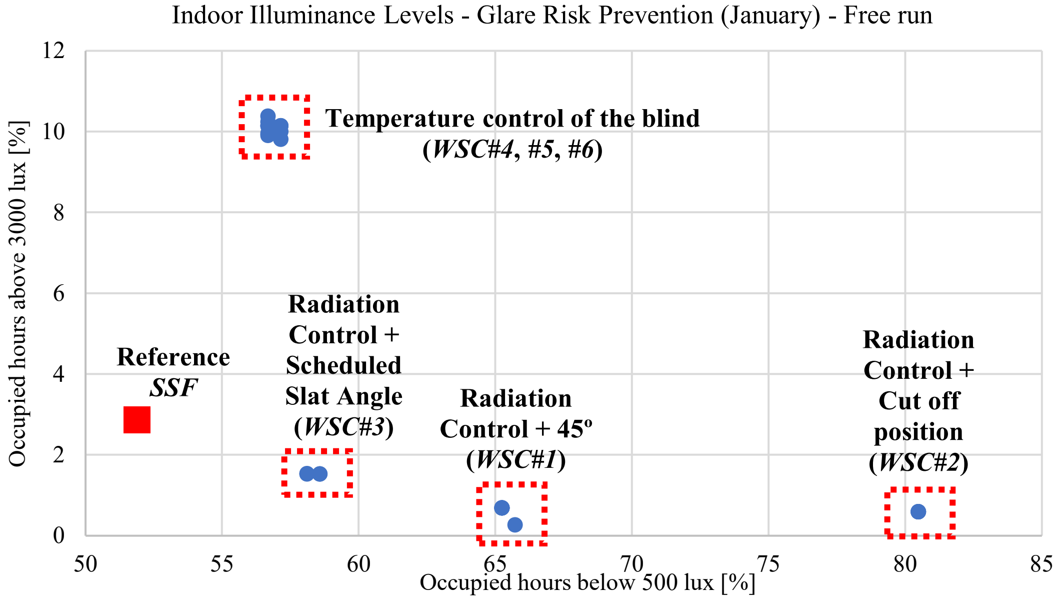


Figure 93: Relation between the percentages of occupied hours in which the horizontal illuminance levels are above and below the limits of 3000 lux and 500 lux (January).

In addition, the optimal control for glare risk prevention (radiation control) is also the worst for indoor thermal comfort since it considerably reduces the passive solar gains in the room during the heating season (*Figure 94*). Anyway, all the different control combinations show high percentages of occupied hours below the limit of *20°C*, regardless the typology of activation mechanism of the blind (temperature or radiation).

Regarding the relation between indoor thermal and visual comfort conditions during the summer season, it is also possible to see that, for the 30 combinations of control defined for the *DSF*, the percentage of occupied hours below *500 lux* (depending on the frequency of activation of the blind and the slat angle regulation) is directly proportional to the percentage of hours above *26°C*.

This means that a higher frequency of activation of the shading inside the *DSF* cavity can increase the overheating risk of the indoor environment, with a higher number of hours above the temperature limit. This is visible in the case of the temperature control coupled with the fixed slat angle or the cut-off position implementation (*SC#5* and *SC#6*): higher percentages of occupied hours below the limit of *500 lux* are associated with slightly higher percentages of occupied hours above *26°C*.

The temperature control is consequently associated to a higher overheating risk in the room during the summer season, compared to the radiation control. The relation between the two percentages is showed in *Figure 95*: the combinations which use the temperature control for the blind in average show higher percentages of occupied hours below *500 lux* and higher percentages of occupied hours above *26°C*.

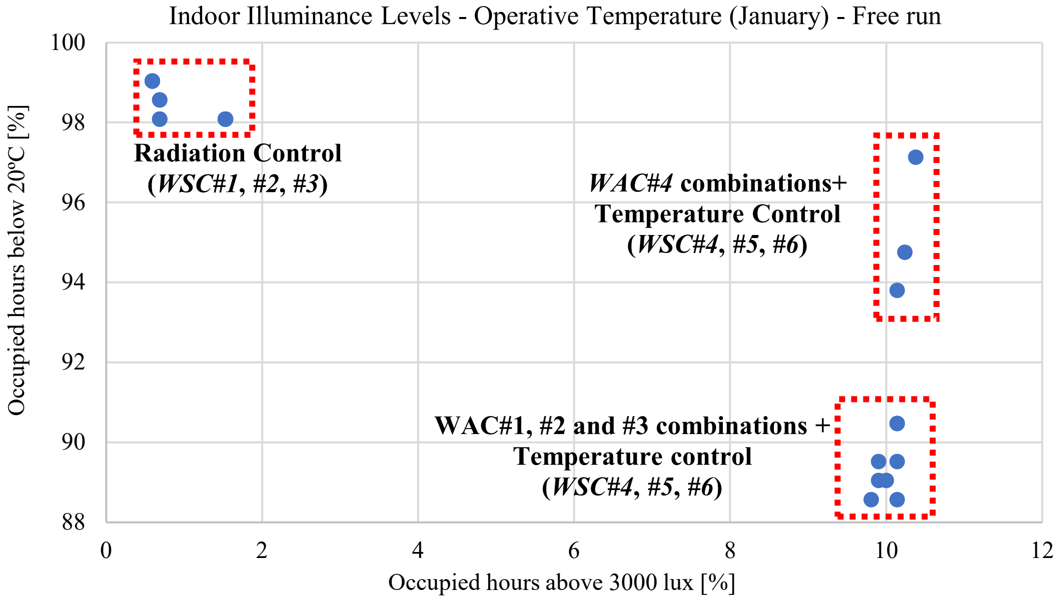


Figure 94: Relation between the percentages of occupied hours in which the horizontal illuminance levels are above 3000 lux and the percentages of occupied hours in which the indoor operative temperature is below 20°C.

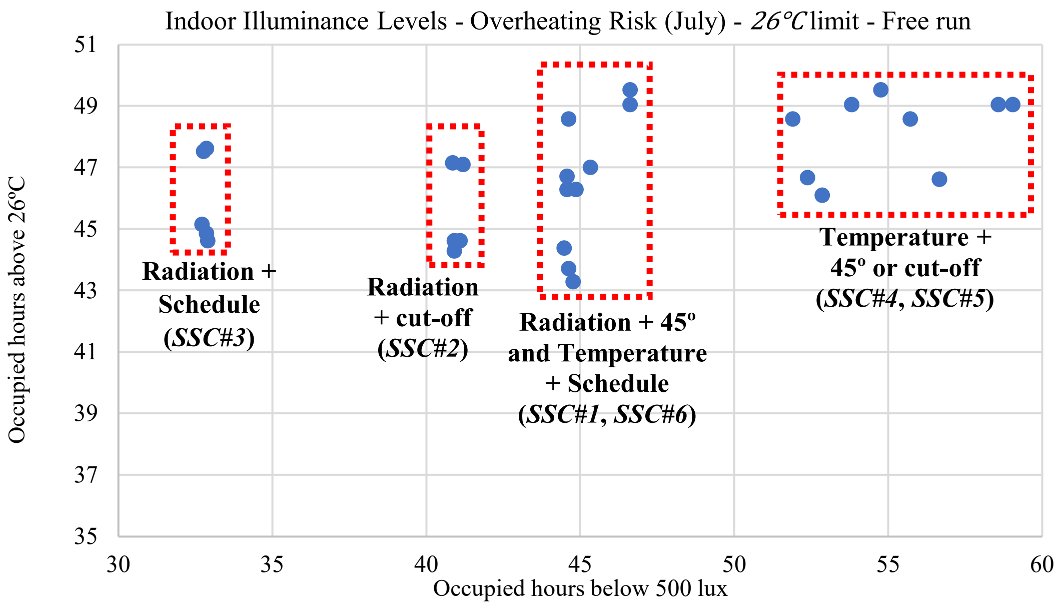


Figure 95: Relation between the percentages of occupied hours above 26°C and below 500 lux (July).

5) As observed in energy efficiency domain, it is difficult to optimize at the same time all the aspects of the system performance linked to the indoor environmental quality (thermal comfort, indoor air quality and illuminance levels).

   For the summer, for example, the selected optimal control combination is effective under the point of view of the *IAQ*, but it is not particularly good for thermal comfort and the visual comfort. During the winter, on other hand, the selected optimal control combination is more effective under the point of view of the thermal comfort (compared to the summer), but it shows consistent limitations in the domains of the *IAQ* and visual comfort for the occupants.

6. Testing of the optimal control combinations during the mid-season periods

After the selection of the optimal control combinations (the ones with *WAC#1* and *SAC#5*, 12 in total) for the initial boundary condition (Frankfurt, South exposed façade) in winter and summer conditions, it is possible to test the *DSF* behaviour and the control effectiveness under the point of view of both (*IEQ* and energy efficiency) if the boundary conditions of the evaluation are changed. It is possible, for example, to consider mid-season periods, characterized by different (and more fluctuating) conditions in terms of indoor air temperature, solar radiation, and cloudiness. For this purpose, the optimal airflow controls for summer (*SAC#5*) and winter (*WAC#1*) conditions have been selected (coupled with the 6 different types of control for the shading), for a total number of 12 combinations to be tested in mid-season conditions.

The considered mid-season months are April and October. In this section, the analysis already performed for all the control combinations have been repeated for the selected optimal air flow control combinations (both for summer and winter conditions), using the two different configurations of the *BESTEST* cell model in IDA ICE (with active systems turned on and free-running configuration). The reference systems used for the comparison are in this case *SSF* (as performed during the summer and the winter seasons tests) and the 2 static *DSF* configurations (*TB* and *OAC* natural) already considered during the previous analysis. Following this approach, it is possible to evaluate the performances of the flexible *DSF* system and the reference ones in more variable and fluctuating environmental conditions (as the ones typically present in April and October).

System settings change for the mid-season periods

Some differences in the system settings in the IDA ICE models (both with active systems and without) have been applied to consider the change in the season: this preliminary step is necessary if a performance comparison between the different façade systems must be performed in different boundary conditions and operating conditions.

Modifications for the air flow control in the cavity:

1) The optimal control for the cavity air flows referred to the winter season is *WAC#1*, as illustrated in the previous section. Anyway, it is necessary to say that this air flow control is optimal for extreme winter conditions (as the ones normally present in January). Considering mid-season periods, it could be necessary to adopt also the *OAC* configuration for the façade operations. For this reason, the *WAC#4* air flow control has been selected for the testing in mid-season conditions: it adopts both the *OAC* configuration and the *AE* configurations, allowing in this way a larger flexibility of the system. In addition, the original control for the unoccupied hours has been modified, allowing the adoption of the *OAC* configuration both during the night and the weekend if the cavity temperature is above *26°C* (cooling setpoint of the room): in the original control, only the *TB* configuration has been adopted for night and weekend periods.

2) Additional modifications have been performed in the case of the radiation level used in *WAC#4* for the switching to the *IAC* configuration of the *DSF*. As already done for Frankfurt in January and July, the radiation level has been selected considering the average incident solar radiation on the South façade in the two selected mid-season periods (April and October). For the month of April, the resulting value is *150 W/m²* while for the month of October the resulting value is *100 W/m²* (both the values are greater than the one used for the month of January, equal to *75 W/m²*).

Modifications for the shading control:

1) For all the façade systems (*SSF*, static *DSF* and flexible *DSF*), the radiation level for the activation of the blind has been varied in function of the selected periods. This level has been defined following the same approach already adopted for Frankfurt for the months of January and July, considering the different average and maximum values of incident solar radiation in the months of April and October in this case. For both the months the adopted value is *450 W/m²*. The indoor air temperature limit for the activation of the blind on the other hand has been set equal to *26°C* (the value used for July) for both the control combinations which adopt *SAC#5* and *WAC#4*. Also the strategies for the control of the shading during the unoccupied hours of the room (lunch break, night and weekend) have uniformized

for the 2 air flow controls, adopting in particular the ones defined with the winter season (with activation of the shading during the lunch break if the indoor air temperature is greater than *26°C* (in January the limit has been originally set equal to *20°C*). In this way, the same shading control is applied to the 2 different air flow control selected for the mid-season test, allowing a more reliable comparison between the heating and cooling season air flow controls.

2) The last modification is the one performed for the schedule of the blind slat angle for keeping the *500 lux* indoor illuminance levels. In this case, the schedules for the winter and summer seasons defined for Frankfurt (considering the minimum illuminance levels on the working plane to be provided during the occupied hours) has been modified to consider the different seasonal periods (and consequently the different sun altitude) of April and October. The final slat angle schedules defined for April and October are the following ones: for April *5°* in the morning and in the afternoon, *35°* in the central part of the day, for October *5°* in the morning and in the afternoon, *25°* in the central part of the day.

Overall list of control combinations to be tested

As mentioned before, the selected optimal control combinations to be tested in the mid-season periods are 12, corresponding to the ones which couple together *SAC#5* and *WAC#4* with the 6 different control logics for the shading control: from *WC#19* to *WC#24* and from *SC#25* to *SC#30*. In *Table 70* there is the complete list:

Combinations of control
WC#19_WAC#4_SC#1
WC#20_WAC#4_SC#2
WC#21_WAC#4_SC#3
WC#22_WAC#4_SC#4
WC#23_WAC#4_SC#5
WC#24_WAC#4_SC#6
SC#25_SAC#5_SC#1
SC#26_SAC#5_SC#2
SC#27_SAC#5_SC#3
SC#28_SAC#5_SC#4
SC#29_SAC#5_SC#5
SC#30_SAC#5_SC#6

Table 70: list of the control combinations tested for the mid-season periods (April and October)

For sake of simplicity, the different typologies of control for the shading, have been renamed as *SC* (shading control): the first three types of control (*SC#1*, *#2* and *#3*) correspond to the radiation control of the blind, coupled with the different control logics for the slat angle.

The last three types of control (*SC#4*, *#5* and *#6*) correspond on the other hand to the temperature control of the blind, coupled with the different control logics for the blind slat angle.

6.1. April test for the optimal control solutions

In this first section the 12 selected optimal control combinations for summer and winter season have been tested for the month of April. The same structure of the analysis already performed for January and July has been followed.

6.1.1. Energy Efficiency

The results of the simulations performed on the model with the active systems turned on are here reported.

6.1.1.1. DSF configurations in April (Active systems turned on)

As first step, it is necessary to analyse the configurations adopted by the *DSF* with the two air flow controls applied (*WAC#4* and *SAC#5*) as already done for the months of July and January.

There are of course several differences compared to the months of July and January, due to different boundary conditions for the façade operations: the flexibility of the façade system in fact ensures a variation of the operating strategies in function of the environmental conditions which are considered. Of course, the variation of the *DSF* configurations affect the overall performance of the system (both considering the energy efficiency and the indoor environmental quality for the occupants).

Considering *SAC#5* and the overall month duration (*Figure 96*), the configurations adopted by the *DSF* are the same observed in July (*OAC* natural, *AS*, *TB*, *AE* natural and *AE* mechanical with the minimum air flow rate implemented in the cavity). The percentages of use for *TB* and *OAC* are almost unchanged, while *AS* is used with larger frequency (due to a lower temperature of the cavity). *AE* configurations, on the other hand, are adopted with a smaller extent compared to the summer, because there is a larger adoption of the *AS* configuration.

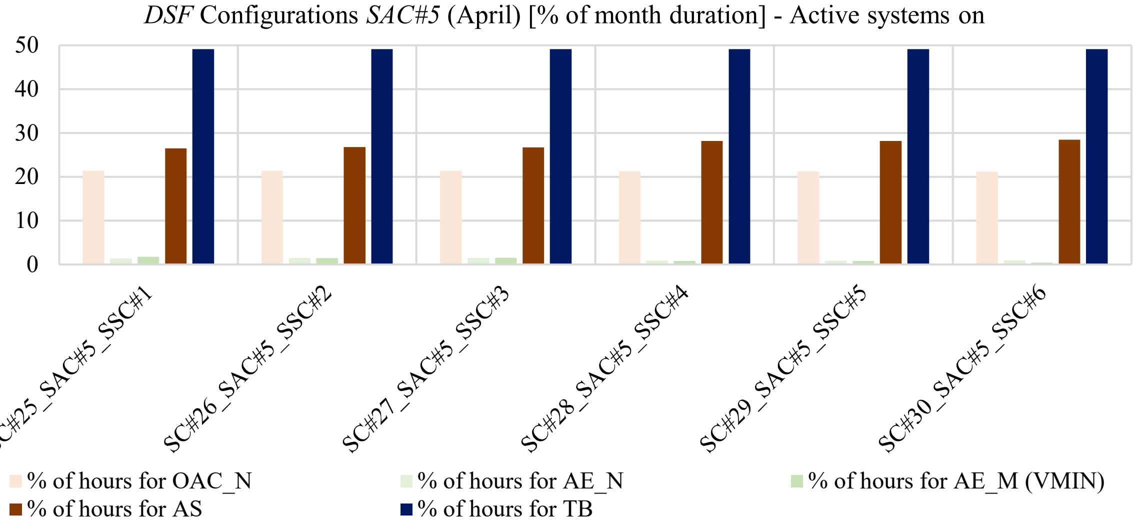


Figure 96: Percentages of hours in the month (April)in which the different DSF configurations have been adopted (active systems turned on) with SAC#5 as airflow control

Looking at the occupied hours (*Figure 97*), the same trend is visible: *AS* is adopted with a larger frequency compared to the summer season while *AE* configurations with a lower frequency.

In both the cases, overall month duration and occupied hours only, it is not visible a consistent difference in the configurations if the different typologies of shading control are coupled with the different controls for the air flows.

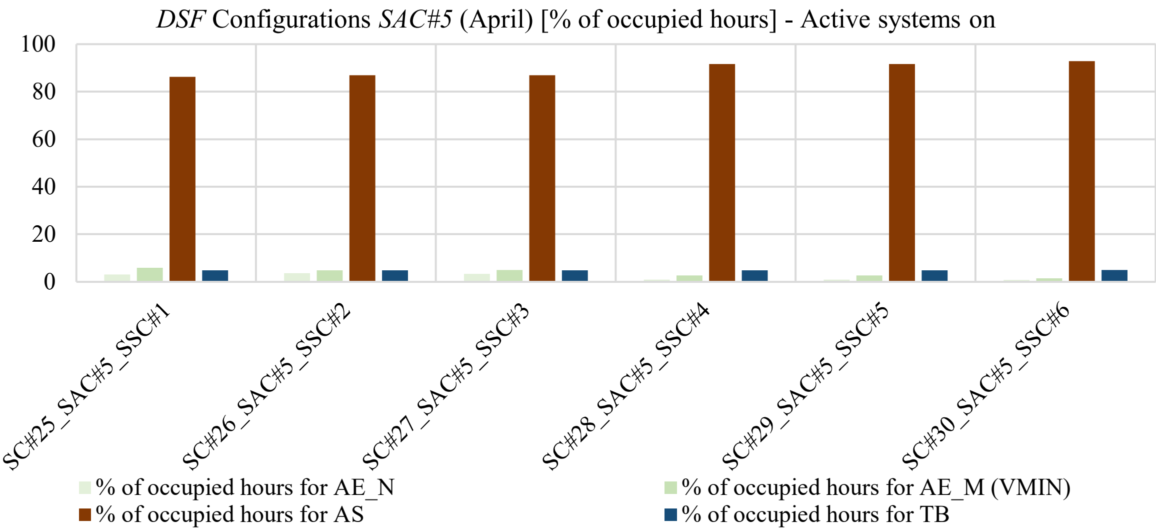


Figure 97: Percentages of occupied hours in the month (April)in which the different DSF configurations have been adopted (active systems turned on) with SAC#5 as airflow control

More consistent differences are visible in the case of the application of the winter air flow control (*WAC#4*): there is a reduction of the use of *TB* and an increase of the adoption of the other configurations (*CF*, *AS* and *OAC* natural).

The latter is the configuration with the most significant increase in comparison with the winter season (due to higher temperatures in the cavity compared to the winter). As observed in January, no use of *IAC* is visible (*Figure 98*).

Considering the occupied hours only (*Figure 99*), the same variation is visible. However, the most used configuration during the occupied hours, after *TB*, is *AS* (if the radiation control of the shading is applied). On the other hand, if the temperature control of the blind is used, the most adopted configuration after *TB* is *CF* (due to a lower temperature of the *DSF* cavity).

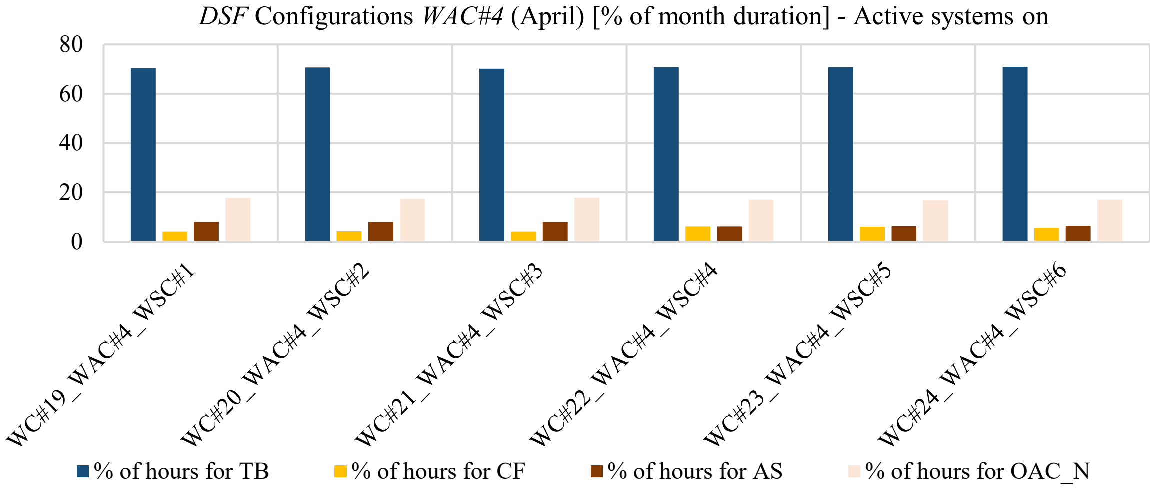


Figure 98: Percentages of hours in the month (April)in which the different DSF configurations have been adopted (active systems turned on) with WAC#4 as airflow control

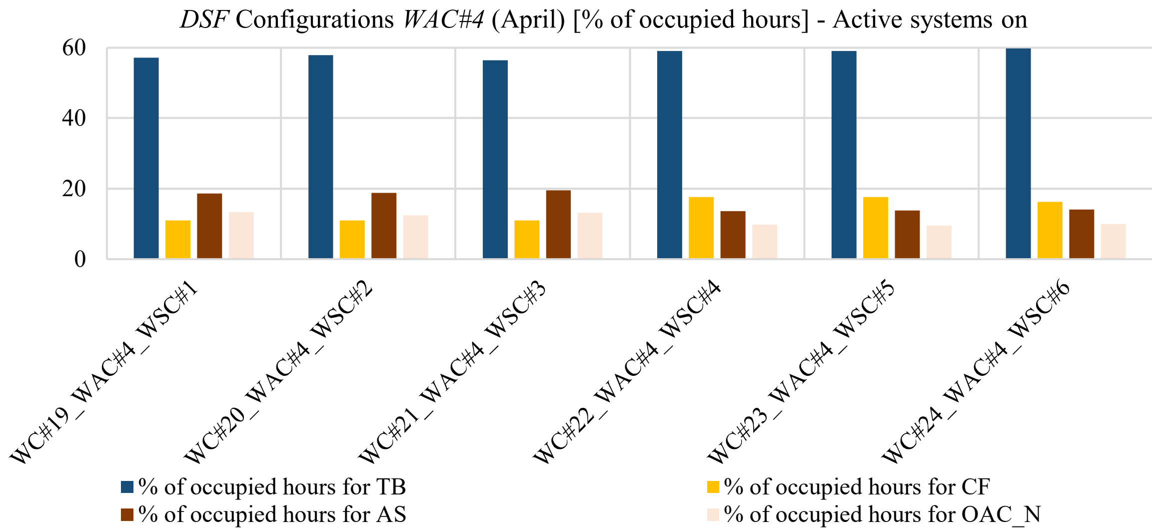


Figure 99: Percentages of occupied hours in the month (April)in which the different DSF configurations have been adopted (active systems turned on) with WAC#4 as airflow control

6.1.1.2. Heating energy need

For all the façade systems (flexible *DSF*, static *DSF* and *SSF*) the heating energy need during the month of April is greater than the cooling energy need. For this reason, during the month of April, the adoption of *WAC#4* is more effective for the reduction of both, heating and cooling energy needs compared to *SAC#5*.

WAC#4 combinations produce an average reduction of the heating energy need equal to *19.8%* while the combinations with *SAC#5* on the other hand produce and increase of the heating energy need equal to *67.9%*.

There is consequently a worsening of the heating energy need increase caused by *SAC#5*, already observed in summer. In this case, the increase is also greater and in addition the heating energy need of the room is larger than the cooling energy need.

Therefore, considering the heating energy need the adoption of *SAC#5* as air flow control is totally ineffective.

The related values of energy consumption (expressed in *kWh* and *kWh/m²*) are reported in *Table 71.*

	TOTAL ENERGY NEED [kWh]			TOTAL [kWh/m²]			[-]
Combinations of control	**Space heating**	**Ventilation heating**	**TOT**	**Space heating**	**Ventilation heating**	**TOT**	**Variation (Single Skin)**
WC#19	128.50	1.07	129.57	2.68	0.02	2.70	**-17.6**
WC#20	129.9	1.07	130.97	2.71	0.02	2.73	**-16.7**
WC#21	128.8	1.07	129.87	2.68	0.02	2.71	**-17.4**
WC#22	121.20	1.05	122.25	2.53	0.02	2.55	**-22.2**
WC#23	121.40	1.05	122.45	2.53	0.02	2.55	**-22.1**
WC#24	120.70	1.05	121.75	2.51	0.02	2.54	**-22.6**
SC#25	187.50	79.40	266.90	3.91	1.65	5.56	**69.8**
SC#26	186.8	79.22	266.02	3.89	1.65	5.54	**69.2**
SC#27	190.8	75.97	266.77	3.98	1.58	5.56	**69.7**
SC#28	179.10	82.22	261.32	3.73	1.71	5.44	**66.2**
SC#29	177.60	83.22	260.82	3.70	1.73	5.43	**65.9**
SC#30	183.80	77.90	261.70	3.83	1.62	5.45	**66.5**
Static OAC	175.20	1.06	176.26	3.65	0.02	3.67	**12.1**
Static TB	116.70	1.00	117.70	2.43	0.02	2.45	**-25.1**
SSF	***156.30***	***0.90***	***157.20***	***3.26***	***0.02***	***3.27***	***REFERENCE***

Table 71:Heating energy need variation for April

Regarding the static *DSF* configurations, the static *OAC* (as visible in July) produces an increase of the heating energy need (lower than the one of *SAC#5*) while the static *TB* (as seen in January) is more effective in the reduction of the heating energy need than *WAC#4*. A graphical comparison of the energy needs for heating is reported in *Figure 100*.

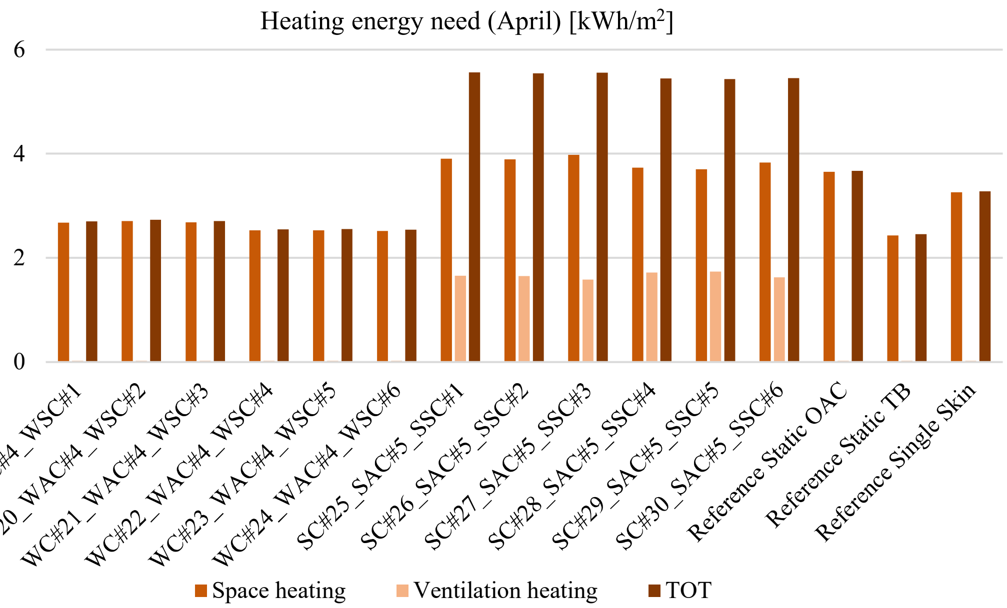


Figure 100: Heating energy requirements for the different façade systems (April)

Looking at the different types of control for the shading, the reduction of the heating energy need (in the case of the application of *WAC#4*) is more evident if the temperature control is applied (*-22.3%*) compared to the one with the radiation control (*-17.2%*): as seen for the winter season, the temperature control is consequently more effective for the reduction of the heating energy need, also in a mid-season month.

On the other hand, considering the application of *SAC#5*, the same average increase of the heating energy need is associated with the radiation and the temperature control for the blind.

6.1.1.3. Cooling energy need

Regarding the cooling energy need, there is a reduction of the requirements with both, *WAC#4* and *SAC#5*. However, the average reduction of the cooling energy need in the case of the application of *SAC#5* (*-82.9%*) is largely better compared to the one produced by *WAC#4* (*-68.5%*).

The two air flows controls are consequently effective in the reduction of the cooling energy need. Also the two static *DSF* configurations produce a reduction of the energy need for cooling (more evident in the case of static *OAC*, which is the most effective in the reduction of the energy need for cooling (*-96.1%*).

About the different types of control for the shading, the radiation control is more effective in the reduction of the cooling energy need compared to the temperature control (as observed in summer): radiation control in average produces a reduction of the energy need for cooling equal to *-87%*, while for the temperature control the average reduction is *-64.4%*.

Consequently, as observed during the summer season, the radiation control is more effective for the lowering of the energy for cooling in the room, since it is activated with larger frequency. The different in efficacy is almost the same in the cases of application with the two air flow controls (about *23%* of difference). The related values of energy consumption (expressed in *kWh* and kWh/m^2) are reported in *Table 72.*

	TOTAL ENERGY NEED [kWh]			**TOTAL [kWh/m²]**			**[-]**
Combinations of control	**Space cooling**	**Ventilation cooling**	**TOT**	**Space cooling**	**Ventilation cooling**	**TOT**	**Variation (Single Skin)**
WC#19	15.22	2.20	17.42	0.32	0.05	0.36	**-79.5**
WC#20	14.38	2.214	16.59	0.30	0.05	0.35	**-80.5**
WC#21	15.57	2.243	17.81	0.32	0.05	0.37	**-79.0**
WC#22	32.44	2.17	34.61	0.68	0.05	0.72	**-59.2**
WC#23	32.25	2.16	34.41	0.67	0.05	0.72	**-59.5**
WC#24	37.69	2.10	39.79	0.79	0.04	0.83	**-53.1**
SC#25	2.25	2.36	4.61	0.05	0.05	0.10	**-94.6**
SC#26	2.344	2.359	4.70	0.05	0.05	0.10	**-94.5**
SC#27	2.822	2.359	5.18	0.06	0.05	0.11	**-93.9**
SC#28	20.40	2.15	22.55	0.43	0.04	0.47	**-73.4**
SC#29	20.02	2.20	22.22	0.42	0.05	0.46	**-73.8**
SC#30	25.59	2.09	27.68	0.53	0.04	0.58	**-67.4**
Static OAC	0.96	2.35	3.31	0.02	0.05	0.07	**-96.1**
Static TB	45.75	2.36	48.11	0.95	0.05	1.00	**-43.3**
SSF	***82.53***	***2.36***	***84.89***	***1.72***	***0.05***	***1.77***	***REFERENCE***

Table 72: Cooling energy need variation for April

A graphical comparison of the energy needs for cooling is reported in *Figure 101.*

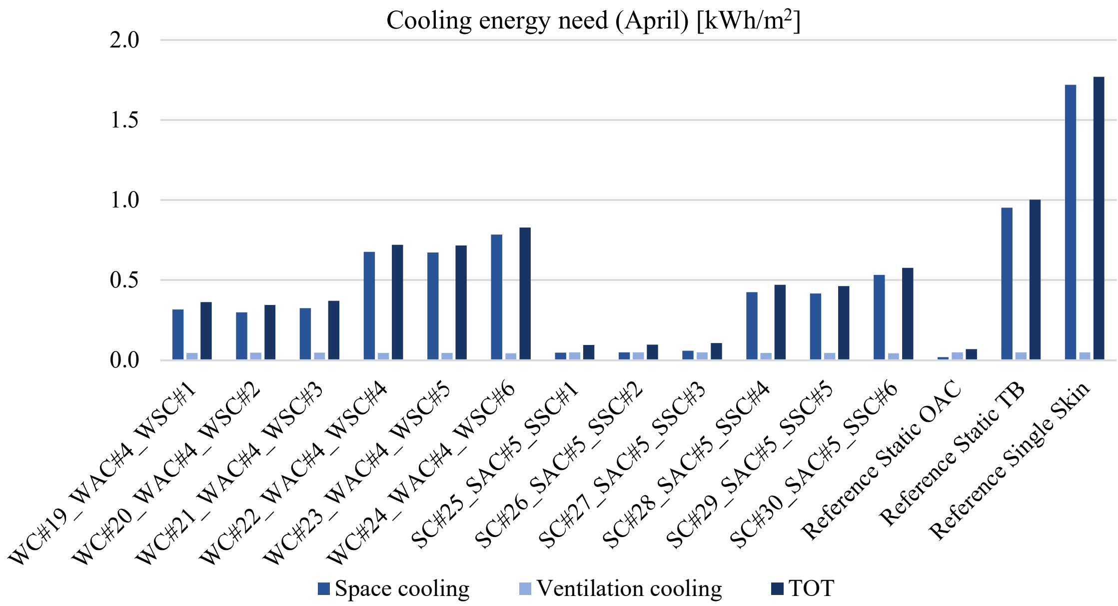


Figure 101: Cooling energy requirements for the different façade systems (April)

The overall performance in terms of cooling and heating requirements variations is reported in *Table* 73.

	Variation cooling energy need (With respect to SSF, %)	Variation heating energy need (With respect to SSF, %)
WAC#4	**-68.5**	**-19.8**
SAC#5	**-82.9**	**67.9**
Static *OAC*	**-96.1**	**12.1**
Static *TB*	**-43.3**	**-25.1**

Table 73: Variation of heating and cooling requirements in the cases of application of SAC#5 and WAC#4 and the two static configurations of DSF (April)

The overall performance is consequently better in the case of application of *WAC#4*, for which a reduction of both (heating and cooling requirements) is visible: therefore, the reduction of total heating and cooling requirements for the room is largely bigger (also better than the one produced by static *TB* and *OAC*). This is of course a very positive aspect for the application of the rule-based control for a flexible *DSF* system.
On the other hand, *SAC#5* produces an increase of the overall heating and cooling energy that is required for the room (as observed for *OAC*).

6.1.1.4. Artificial lighting energy need

As observed during the summer and winter seasons, it is visible an increase of the required energy need for artificial lighting in the room. The average increases are in this case intermediate between the summer (worst case) and the winter.

The related values of energy consumption (expressed in kWh and kWh/m^2) are reported in *Table 74*. A graphical comparison of the energy needs for artificial lighting is reported in *Figure 102*.

	TOTAL [kWh]	***TOTAL [kWh/m2]***	**[%]**
Combinations of control	**Artificial lighting**	**Artificial lighting**	**Variation (Single Skin)**
WC#19	17.54	0.37	**66.3**
WC#20	18.68	0.39	**77.1**
WC#21	14.24	0.30	**35.0**
WC#22	13.88	0.29	**31.6**

WC#23	13.87	0.29	**31.5**
WC#24	13.86	0.29	**31.4**
SC#25	17.12	0.36	**62.3**
SC#26	18.46	0.38	**75.0**
SC#27	14.05	0.29	**33.2**
SC#28	13.87	0.29	**31.5**
SC#29	13.86	0.29	**31.4**
SC#30	13.86	0.29	**31.4**
Static OAC	17.30	0.36	**64.0**
Static TB	17.35	0.36	**64.5**
SSF	***10.55***	***0.22***	***REFERENCE***

Table 74: Artificial lighting energy need variation for April

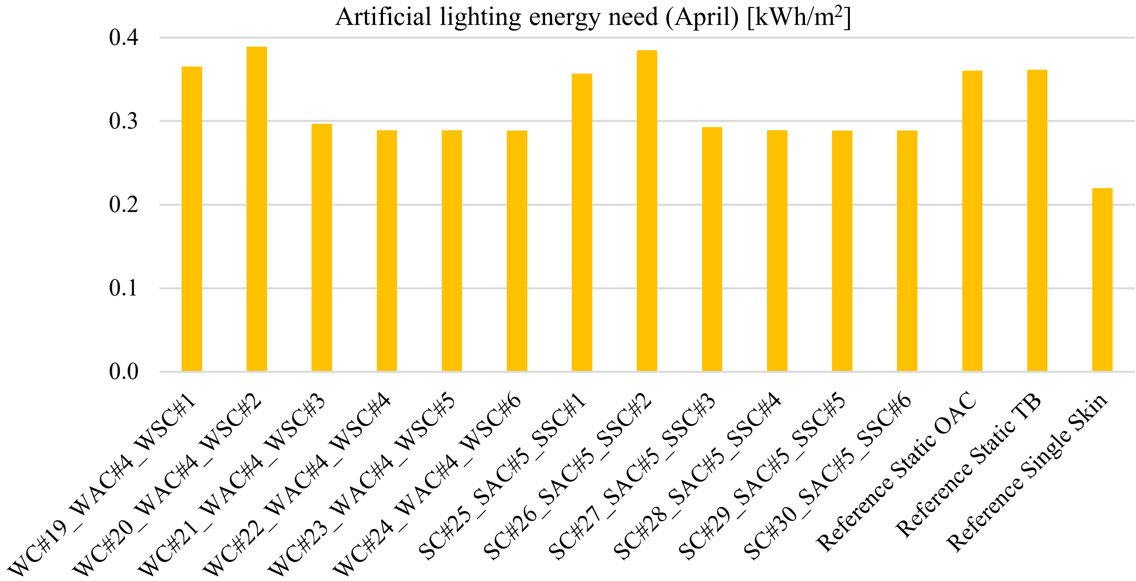


Figure 102: Artificial lighting energy requirements for the different façade systems (April)

As observed in winter and summer conditions, the average increases for the artificial lighting energy needs are function of the different control logics that are implemented for the shading system (in particular, the activation mechanism for the blind).

The average increases for the artificial lighting energy requirements associated to the different types of control of the blind slat angle are reported in *Table 75*.

Shading control	**Increase artificial lighting energy demand (compared to *SSF*) [%]**
SC#1	**64.3**
SC#2	**76.0**
SC#3	**34.1**
SC#4	**31.5**
SC#5	**31.4**
SC#6	**31.4**

Table 75: Average variations of the artificial lighting energy need produced by the 6 different shading controls coupled with WAC#4 and SAC#5 in April

The largest increase is consequently associated with the radiation control for the blind (*+58.1%* in average), while the temperature control is more effective in the limitation of this increase (*+31.4%*): this is the same situation already seen in the summer and winter analysis. If the radiation control is applied it is clearly visible the influence of the different control logics for the blind slat angle: the cut-off position is associated to the largest increase of the energy need for artificial lighting, followed by the fixed slat angle.

On the other hand, the scheduled variation of the blind slat angle produces an increase of *35%*, analogue to the one generated by the temperature control of the blind.

The scheduled variation is consequently quite effective in the limitation of the increase of the energy for artificial lighting. If the temperature control is applied, the different control logics for the blind slat angle produce basically the same results (as observed in summer and winter conditions).

6.1.2. IEQ

The results of the simulations performed on the model with the active systems turned off are here reported. For the analysis during the mid-season periods in the free-running configuration of the model, the clothing insulation for the occupants has been set equal to *0.75 clo* (instead of using *1 clo* and *0.5 clo* as for the months of July and January).

Also in the case of the indoor environmental quality analysis opposite effects on the performance are visible if *SAC#5* and *WAC#4* are applied.

6.1.2.1. DSF configurations in April (Active systems turned off)

As already performed in the case of the model with the active systems turned on, it is possible to analyse the different configurations assumed by the *DSF* in the month of April if the active systems of the room are turned off.

Compared to the summer, it is visible a larger application of *TB* (the most adopted configuration), *OAC* natural and *AS*. On the other hand, the adoption of *AE* (both natural and mechanical) is considerably lower compared to the summer season (*Figure 103*).

Looking at the occupied hours only (*Figure 104*), as observed in July, the most adopted configuration is *AS*.

This configuration is used with a larger frequency compared to the summer (above *80%*) and a consistent reduction of the use of *AE* is visible: due to a larger use of *AS*, the adoption of *AE* is considerably reduced.

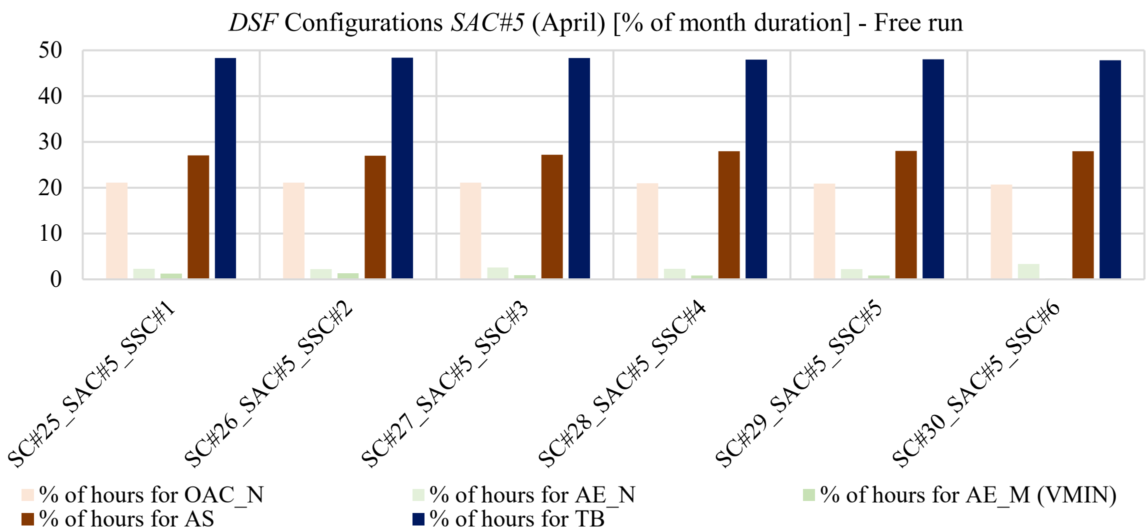


Figure 103: Percentages of hours in the month (April)in which the different DSF configurations have been adopted (active systems turned off) with SAC#5 as airflow control

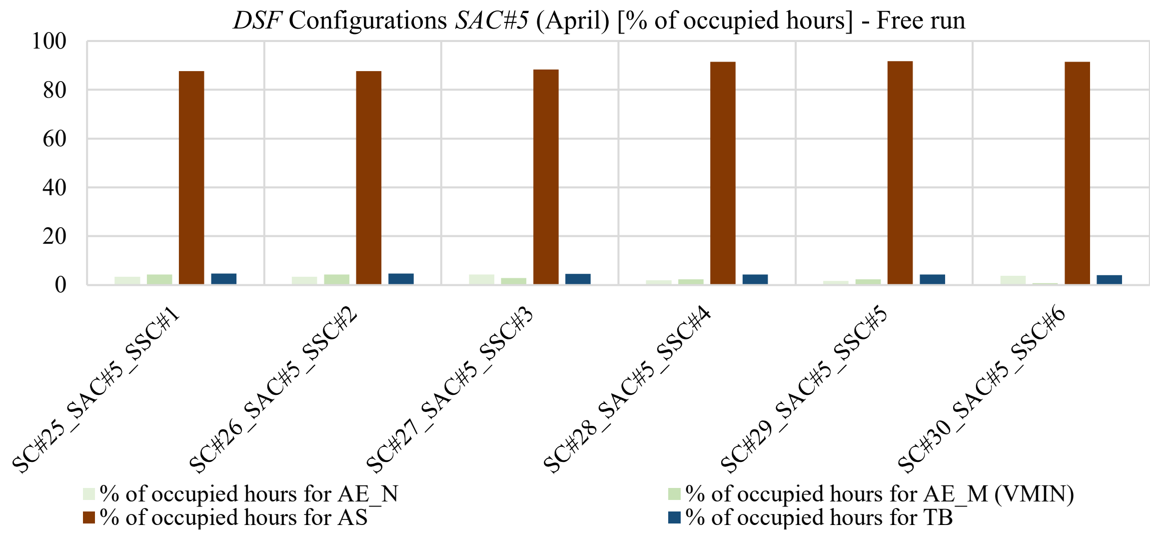


Figure 104: Percentages of occupied hours in the month (April)in which the different DSF configurations have been adopted (active systems turned off) with SAC#5 as airflow control

Considerable differences are also visible in the case of *WAC#4* (*Figure 105*): in particular, the adoption of *TB* is reduced, while the use of *AS* is increased. Compared to the winter, the additional presence of *OAC* natural is visible (due to the higher temperatures inside the cavity) while *IAC* is never used.

On the other hand, the percentage of use of *AE* natural is almost the same (around *20%*). Just considering the occupied hours of the room (*Figure 106*), *AE* remains the most adopted configuration (but with a lower percentage of use) followed by *TB* (also in this adopted with a reduced frequency).

The use of *AS* is considerable higher and the additional presence of *OAC* is visible.

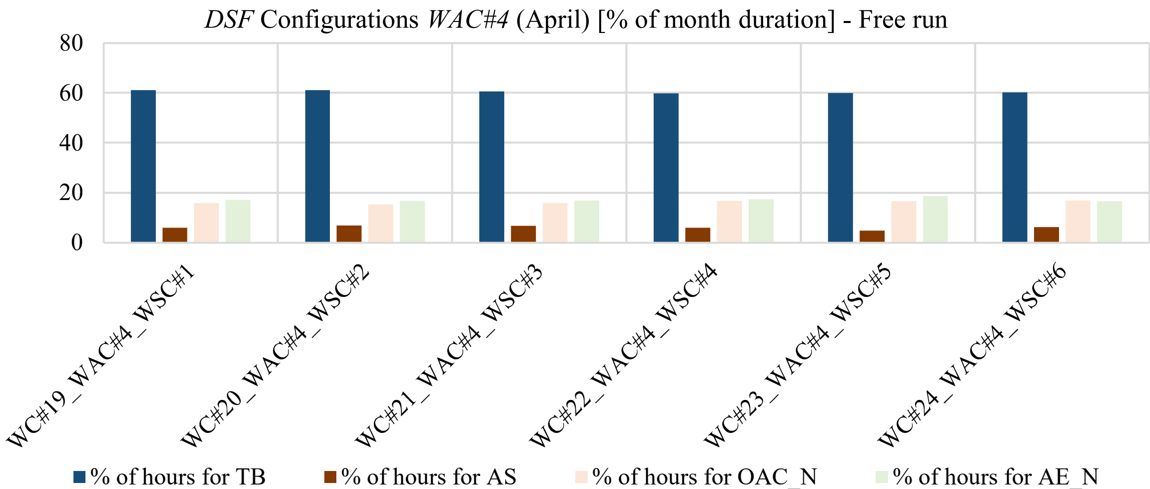


Figure 105: Percentages of hours in the month (April)in which the different DSF configurations have been adopted (active systems turned off) with WAC#4 as airflow control

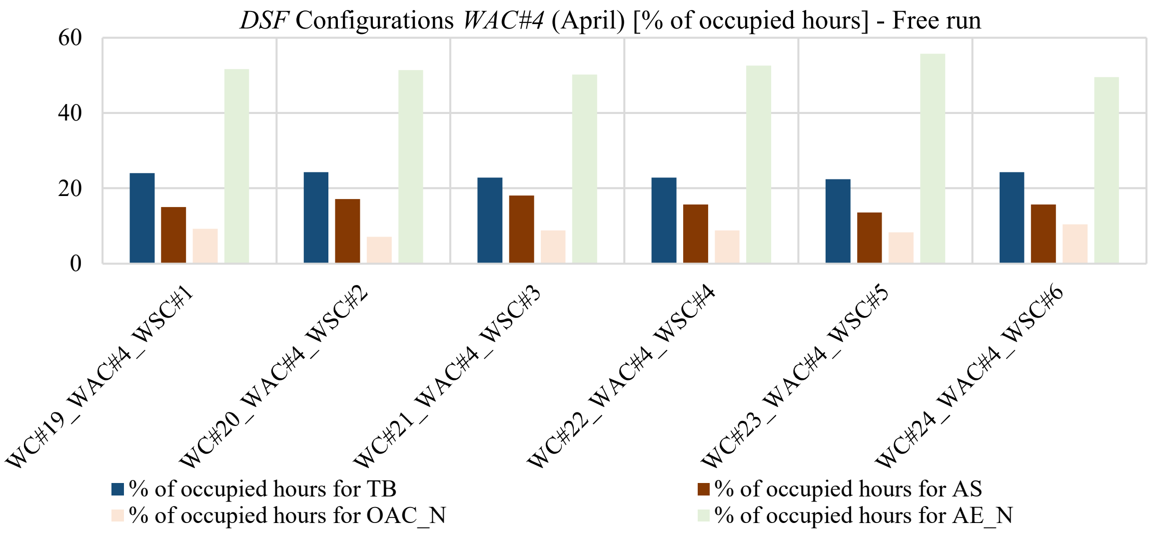


Figure 106: Percentages of occupied hours in the month (April)in which the different DSF configurations have been adopted (active systems turned off) with WAC#4 as airflow control

6.1.2.2. Indoor operative temperatures

As done for the summer season, three different threshold limits for the indoor operative temperature have been considered: *20°C*, *26°C* and *30°C*. The percentage of occupied hours above the limit of *26°C* for each configuration of control are reported in *Table 76*.

Combinations of control	n° hours Top > 26°C	% of occupied hours Top > 26°C	Variation (Single Skin)
WC#19	14.8	7.0	**-45.4**
WC#20	14.1	6.7	**-48.0**
WC#21	17.2	8.2	**-36.5**
WC#22	29.7	14.1	**9.6**
WC#23	27.4	13.0	**1.1**
WC#24	30.3	14.4	**11.8**
SC#25	9.71	4.6	**-64.2**
SC#26	9.54	4.5	**-64.8**
SC#27	10.4	5.0	**-61.6**
SC#28	17.8	8.5	**-34.3**
SC#29	17.4	8.3	**-35.8**
SC#30	18.6	8.9	**-31.4**
Static OAC	37.8	18.0	**39.5**
Static TB	79.8	38.0	**194.5**
SSF	***27.1***	***12.9***	***REFERENCE***

Table 76: Percentages of occupied hours above 26°C for the different façade systems (April)

Regarding the variation of the number of occupied hours above the limit of *26°C* the reduction compared to *SSF* is visible in the cases of the application of *SAC#5* and *WAC#4* coupled with the radiation control of the blind.

On the other hand, there is an increase (but only *+7.5%* in average), in the case of *WAC#4* coupled with the temperature control of the blind. In the complex, anyway, the effect of the 12 different combinations of control is quite positive, with an average reduction of *33%* compared to *SSF*.

The best results are anyway achieved by *SAC#5*, which shows a largely better performance compared to *WAC#4* (*-48.7%* against *-17.9%*). The two static configurations of *DSF* (*OAC* and *TB*) are in this case the worst solution, increasing of a larger extent the number of occupied hours above the limit of *26°C*.

A graphical comparison of the number of hours above the limit of *26°C* is reported in *Figure 107*.

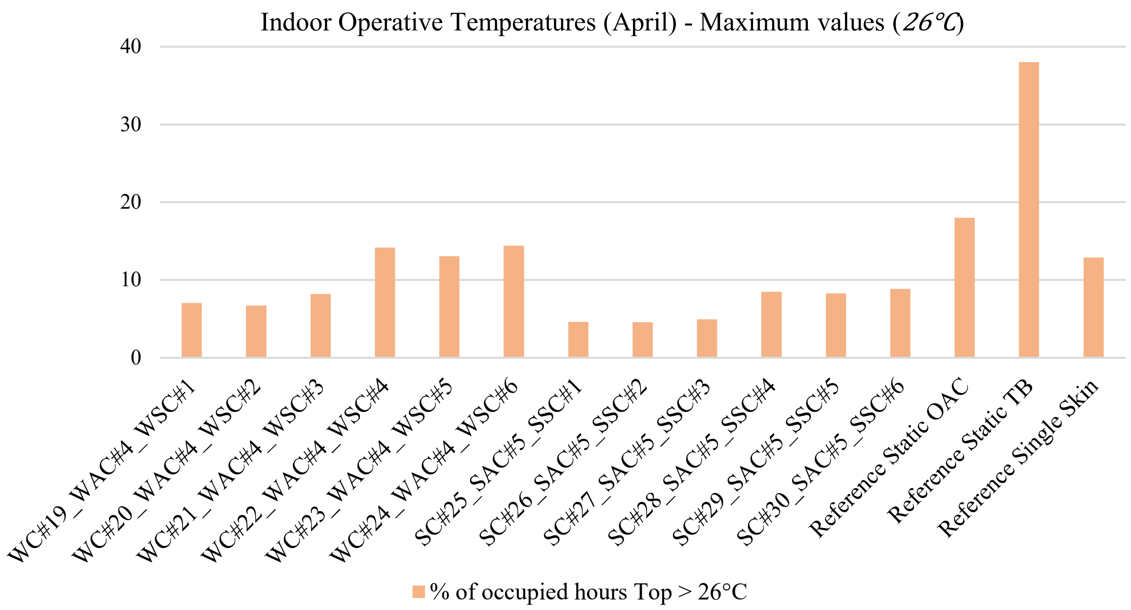


Figure 107: Percentages of occupied hours above 26°C for the different façade systems (April)

About the relation with the different typologies of control for the shading, it is clearly visible the difference between temperature and radiation control. The latter is largely better in terms of reduction of the number of occupied hours above the limit of *26°C*. In average the reduction with the radiation control is largely greater than the one generated by the temperature control (*-53.4%* against *-13.2%*). The percentage is also bigger if *SC#1*, *#2* and *#3* are coupled with *SAC#5* (*-63.5%*). As seen for the cooling energy need, the radiation control is more effective for the limitation of the number of hours above the limit of *26°C* during the month of April.

Among the different controls for the blind slat angle (*Table 77*), the cut-off position implementation is the most effective in the reduction of the number of hours above the limit of *26°C* (both in the case of radiation and temperature control of the blind).

Shading control	**Variation of the occupied hours above 26°C (compared to *SSF*) [%]**
SC#1	**-54.8**
SC#2	**-56.4**
SC#3	**-49.1**
SC#4	**-12.4**
SC#5	**-17.3**
SC#6	**-9.8**

Table 77: Average variations of the occupied hours above 26°C produced by the 6 different shading controls (April)

Almost the same trend is visible analysing the number of occupied hours above the limit of *30°C*: in this case, *SAC#5* avoids the presence of occupied hours above this limit (about zero also in *SSF*) while *WAC#4* shows an increased number of hours in which the limit is overcame (the same for the static *OAC* configuration). However, the percentage of occupied hours in which this situation is present is very low (between *0.8%* and *4.6%* of the entire number of occupied hours during the month).

Under this point of view, the worst solution is the static *TB* configuration (*24%* of occupied hours above the limit of *30°C*). Also in this case, the radiation control is more effective in the reduction of the overheating risk: in the case of the coupling with *WAC#4*, the increasing is almost the half of the one generated by the temperature control. In the case of the use of *SAC#5*, the coupling with *SC#6* (scheduled variation of the blind slat angle) is the only that causes a certain number of hours above the limit.

The percentage of occupied hours above the limit of *30°C* for each configuration of control are reported in *Table 78*.

Combinations of control	n° hours Top > 30°C	% of occupied hours Top > 30°C	Variation (Single Skin)
WC#19	4.14	2.0	**1143.2**
WC#20	1.77	0.8	**431.5**
WC#21	5.36	2.6	**1509.6**
WC#22	4.79	2.3	**1338.4**
WC#23	9.72	4.6	**2818.9**
WC#24	6.54	3.1	**1864.0**
SC#25	0	0.0	**-100.0**
SC#26	0	0.0	**-100.0**
SC#27	0	0.0	**-100.0**
SC#28	0	0.0	**-100.0**
SC#29	0	0.0	**-100.0**
SC#30	1.2	0.6	**260.4**
Static OAC	7.89	3.8	**2269.4**
Static TB	50.4	24.0	**15035.1**
SSF	***4.14***	***2.0***	***1143.2***

Table 78: Percentages of occupied hours above 30°C for the different façade systems (April)

A graphical comparison of the number of hours above the limit of *30°C* is reported in *Figure 108*.

The opposite behaviour is visible considering the number of occupied hours below the limit of *20°C*: *WAC#4* is associated with a lower increase of the number of occupied hours below the limit (*+35.8%*) compared to *SAC#5* (*+65.4%*). Also the static *OAC* configuration produces an increased number of occupied hours above the limit while the only configuration which reduce the number of occupied hours below the limit is the static *TB*.

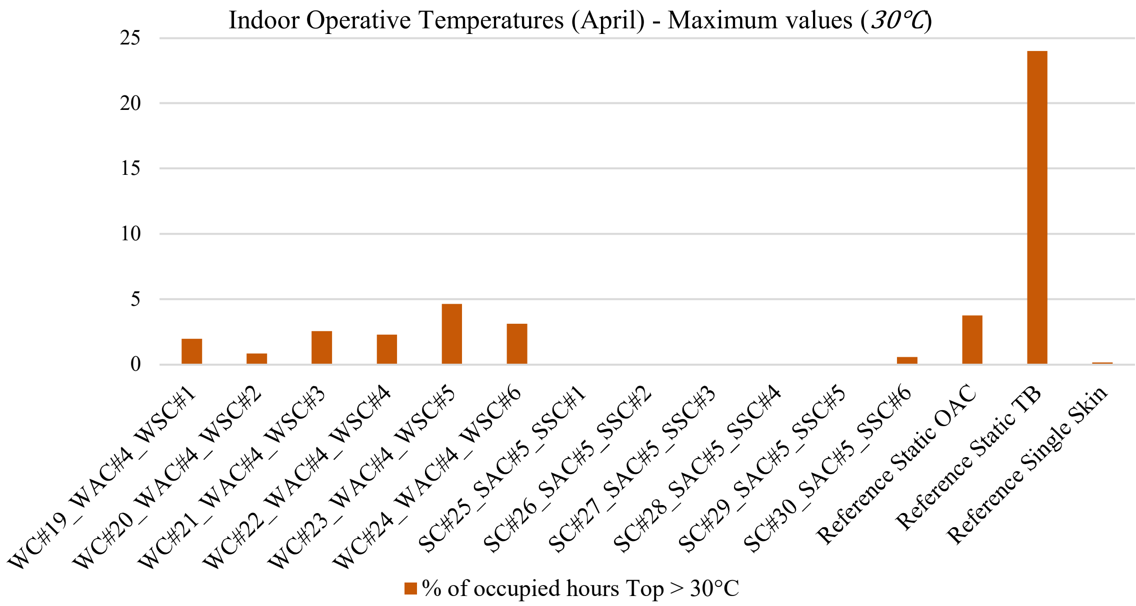


Figure 108: Percentages of occupied hours above 30°C for the different façade systems (April)

The percentage of occupied hours below the limit of *20°C* for each configuration of control are reported in *Table 79*. A graphical comparison of the number of hours below the minimum temperature limit is reported in *Figure 109*.

Combinations of control	n° hours Top < 20°C	% of occupied hours Top < 20°C	Variation (Single Skin)
WC#19	132	62.9	**47.2**
WC#20	137	65.2	**52.7**
WC#21	130	61.9	**44.9**
WC#22	108	51.4	**20.4**

WC#23	109	51.9	**21.5**
WC#24	115	54.8	**28.2**
SC#25	164	78.1	**82.8**
SC#26	164	78.1	**82.8**
SC#27	155	73.8	**72.8**
SC#28	136	64.8	**51.6**
SC#29	138	65.7	**53.8**
SC#30	133	63.3	**48.3**
Static OAC	107	51.0	**19.3**
Static TB	74.4	35.4	**-17.1**
SSF	***89.7***	***42.7***	***REFERENCE***

Table 79: Percentages of occupied hours below 20°C for the different façade systems (July) coupled with WAC#4 and SAC#5 (April)

As seen for the heating energy need, the temperature control for the blind is linked to a more effective reduction of the overcooling risk for the room (both in the case of the coupling with *SAC#5* and *WAC#4*): the average increase in the case of the adoption of temperature control is *37.3%* while for the radiation control it is *63.9%*.

Among the different types of control for the slat angle (*Table 80*), the scheduled variation of the slat angle (*SC#3* and *SC#6*) is associated to the lowest increases of the number of occupied hours below the limit of *20°C* (both in the cases of the application of *WAC#4* and *SAC#5*).

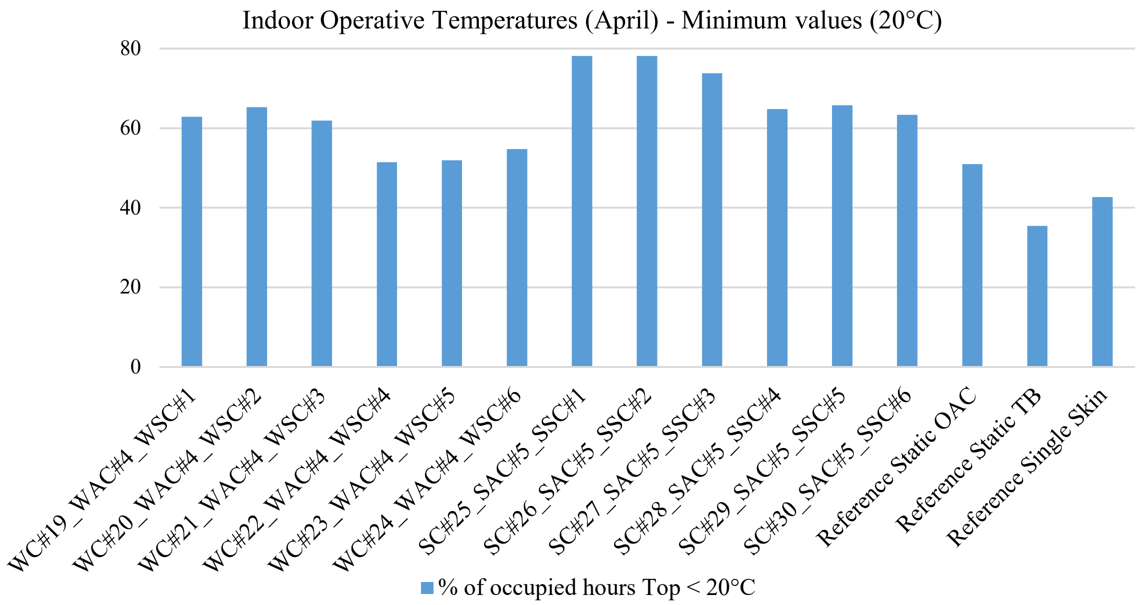


Figure 109: Percentages of occupied hours below 20°C for the different façade systems (April)

Shading control	Increase of the occupied hours below 20°C (compared to *SSF*) [%]
SC#1	**65.0**
SC#2	**67.8**
SC#3	**58.9**
SC#4	**36.0**
SC#5	**37.7**
SC#6	**38.2**

Table 80: Average variations of the artificial lighting energy need produced by the 6 different shading controls in April

6.1.2.3. IAQ

All the 12 control combinations produce a reduction of the number of hours above the limit of *1000 ppm*. Anyway, the most effective under this point of view is *SAC#5*, with an average reduction of *100%* (no hours above the limit are present). On the other hand, the reduction in the case of *WAC#4* is largely lower (*-30.6%*).

The situation is analogue to what has been already observed in summer and winter seasons.

The two static *DSF* configurations (*OAC* and *TB*) are equally ineffective under this point of view, increasing the number of occupied hours above the limit of *1000 ppm* of about *55%*.

The percentages of occupied hours below the limit for each configuration of control are reported in *Table 81*.

Combination of controls	n° hours CO2 > 1000 ppm	% of occupied hours CO2 > 1000 ppm	Variation (Single Skin)
WC#19	92.3	44.0	**-31.6**
WC#20	86.9	41.4	**-35.6**
WC#21	90.1	42.9	**-33.3**
WC#22	94.3	44.9	**-30.1**
WC#23	99.2	47.2	**-26.5**
WC#24	99.6	47.4	**-26.2**
SC#25	0	0.0	**-100.0**
SC#26	0	0.0	**-100.0**
SC#27	0	0.0	**-100.0**
SC#28	0	0.0	**-100.0**
SC#29	0	0.0	**-100.0**
SC#30	0	0.0	**-100.0**
Static OAC	209	99.5	**54.8**
Static TB	209	99.5	**54.8**
SSF	***135***	***64.3***	***REFERENCE***

Table 81: Percentages of occupied hours above 1100 ppm for the different façade systems (April)

A graphical comparison of the number of hours above the concentration limit is reported in *Figure 110*.

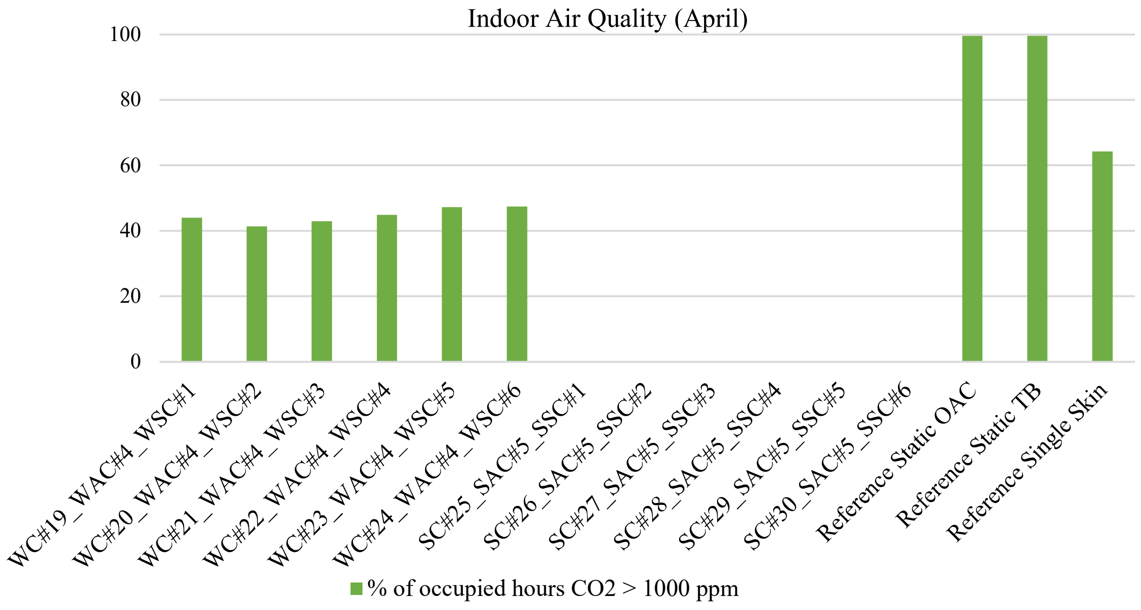


Figure 110: Percentages of occupied hours above 1000 ppm for the different façade systems (April)

6.1.2.4. Fanger's comfort indices

The two air flow controls produce a general increase of the number of hours in which the *PPD* index is above *10%*. The percentages are in this case analogue: *+47.6%* for *WAC#4* and *+54.2%* for *SAC#5*.

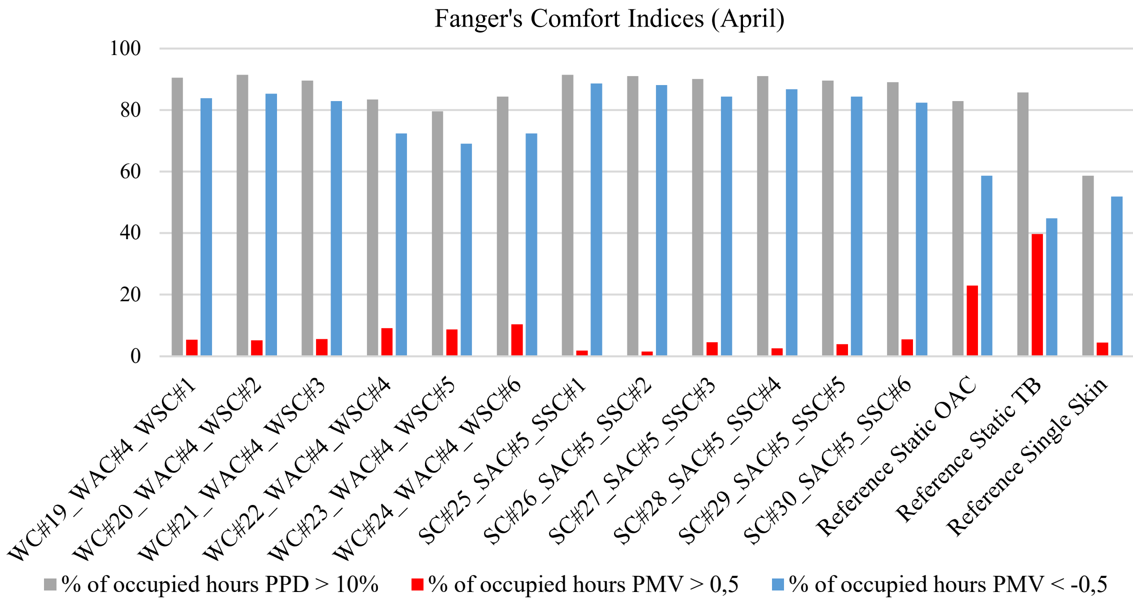


Figure 111: Variation of the comfort indexes in the room for the different façade systems (April)

Anyway, the causes for this increase are different: *SAC#5* produces a more evident increase of the number of occupied hours below *PMV = -0.5* (overcooling risk), while reducing the number of occupied hours above the limit of *PMV = 0.5* (as seen with the analysis of the indoor operative temperatures trend).

On the contrary, the adoption of *WAC#4* is associated to a larger increase of the number of hours above the limit of *PMV = 0.5* (as observed in the analysis of the number of occupied hours above the limit of *30°C*). Consequently, the two airflow controls are associated with opposite causes of potential thermal discomfort for the occupants: overheating in the case of *WAC#4*, overcooling for *SAC#5*.

A graphical comparison of the number of hours above and below the threshold limits is reported in *Figure 111*.

Combinations of control	n° hours PPD > 10%	% of occupied hours PPD > 10%	n° hours PMV > 0,5	% of occupied hours PMV > 0,5	n° hours PMV < -0,5	% of occupied hours PMV < -0,5	Variation PPD (Single Skin)	Variation PMV > 0,5 (Single Skin)	Variation PMV < -0,5 (Single Skin)
WC#19	190	90.5	11.2	5.3	176	83.8	**54.5**	**21.0**	**61.5**
WC#20	192	91.4	10.7	5.1	179	85.2	**56.1**	**15.6**	**64.2**
WC#21	188	89.5	11.6	5.5	174	82.9	**52.8**	**25.3**	**59.6**
WC#22	175	83.3	19	9.0	152	72.4	**42.3**	**105.2**	**39.4**
WC#23	167	79.5	18.3	8.7	145	69.0	**35.8**	**97.6**	**33.0**
WC#24	177	84.3	21.7	10.3	152	72.4	**43.9**	**134.3**	**39.4**
SC#25	192	91.4	3.74	1.8	186	88.6	**56.1**	**-59.6**	**70.6**
SC#26	191	91.0	3.25	1.5	185	88.1	**55.3**	**-64.9**	**69.7**
SC#27	189	90.0	9.4	4.5	177	84.3	**53.7**	**1.5**	**62.4**
SC#28	191	91.0	5.42	2.6	182	86.7	**55.3**	**-41.5**	**67.0**
SC#29	188	89.5	8.13	3.9	177	84.3	**52.8**	**-12.2**	**62.4**
SC#30	187	89.0	11.5	5.5	173	82.4	**52.0**	**24.2**	**58.7**
Static OAC	174	82.9	48.1	22.9	123	58.6	**41.5**	**419.4**	**12.8**
Static TB	180	85.7	83.3	39.7	94	44.8	**46.3**	**799.6**	**-13.8**
SSF	*123*	*58.6*	*9.26*	*4.4*	*109.0*	*51.9*	*REFERENCE*	*REFERENCE*	*REFERENCE*

Table 82: Variation of the comfort indexes in the room for the different façade systems (April)

The two static configurations of *DSF* (*OAC* and *TB*) are more effective in the limitation of the increase of *PPD = 10%*. Static *TB* is also associated with a reduction of the number of occupied hours below the limit of *PMV = -0.5*. The shading control has an influence in the variation of the comfort indices also in April: the radiation control, if coupled with *SAC#5*, is more effective in the reduction of the number of occupied hours above the limit of *PMV = 0.5* than temperature control (*-41%* against *-9.8%*). It is therefore more effective for the overheating risk reduction.

If coupled with *WAC#4*, on the other hand, the radiation control produces a larger increase of the number of occupied hours below the limit of *PMV = -0.5*. It is consequently linked to a larger overcooling risk for the occupants. These conclusions are analogue to the ones defined during the analysis of the indoor operative temperature trends. The number of hours above and below the limits for each configuration of control are reported in *Table 82*.

6.1.2.5. Daylight and glare

As observed in January and July, it is visible a worsening of the indoor daylight conditions also for April. The increase of the number of occupied hours below the limit of *500 lux* is anyway less critical compared to the summer season (as observed for the increasing of the energy consumption for artificial lighting).

The percentage of occupied hours below the limit for each configuration of control are reported in *Table 83*.

Combination of control	n° hours E < 500 lux	% of occupied hours E < 500 lux	Variation (Single Skin)
WC#19	89.7	42.7	**64.3**
WC#20	95.8	45.6	**75.5**
WC#21	73	34.8	**33.7**
WC#22	85.6	40.8	**56.8**
WC#23	83.8	39.9	**53.5**
WC#24	79.6	37.9	**45.8**
SC#25	89.6	42.7	**64.1**
SC#26	95.7	45.6	**75.3**
SC#27	72.9	34.7	**33.5**
SC#28	77.7	37.0	**42.3**
SC#29	78.6	37.4	**44.0**
SC#30	75.8	36.1	**38.8**
Static OAC	89.3	42.5	**63.6**
Static TB	88.9	42.3	**62.8**
SSF	***54.6***	***26.0***	***REFERENCE***

Table 83: Percentage of occupied hours below the limit of 500 lux (April)

Shading control	Variation of the occupied hours below 500 lux (compared to *SSF*) [%]
SC#1	**64.2**
SC#2	**75.4**
SC#3	**33.6**
SC#4	**49.5**
SC#5	**48.7**
SC#6	**42.3**

Table 84: Average variations of the number of occupied hours below the limit of 500 lux produced by the 6 different shading controls in April

The influence of the different typologies of control for the shading system also in this case is evident (*Table 84*). The radiation control in average produces an increase (*+57.7%*) which is considerably larger than the one observed with the application of the temperature control for the blind (*+46.9%*). This is the same situation already observed for the winter season: the temperature control is the better solution for both, indoor illuminance levels and energy consumption of the artificial lighting (even if it is present a worsening of the performance compared to *SSF*).

The temperature control produces a lower average increase if coupled with *SAC#5*, due to a lower indoor air temperature generated by this air flow control. Anyway, the best combinations in terms of limitation of the increase of the number of occupied hours below the limit of *500 lux* are *SC#27* and *WC#21*, which adopt the radiation control coupled with the scheduled variation of the blind slat angle (in average the increase is *+ 34%*, lower than the average increase generated by the adoption of the temperature control for the blind).

A graphical representation of the variation of the number of hours below the limit of 500 lux is showed in *Figure 112*.

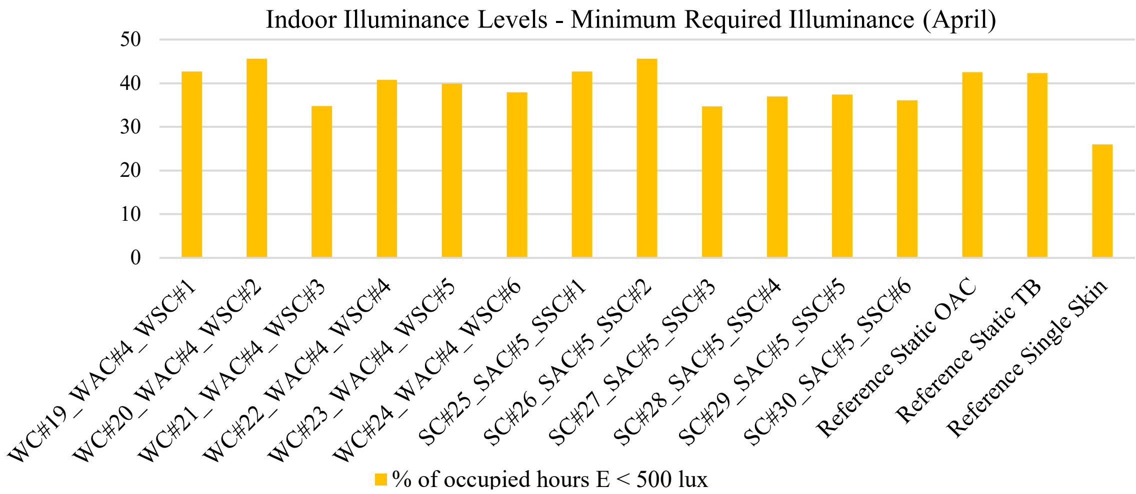


Figure 112: Percentage of occupied hours below the limit of 500 lux (April)

6.2. October test for the optimal control solutions

In this first section the 12 selected optimal control combinations for summer and winter season have been tested for the month of October, as done previously for the month of April.

Being a mid-season month, as April, during this period the overall behaviour of the system under the point of view of both, energy efficiency and indoor environmental quality, is the almost similar.

6.2.1. Energy Efficiency

The results of the simulations performed on the model with the active systems turned on are here reported.

6.2.1.1. DSF configurations in October (Active systems turned on)

As already done for April, also for October it is necessary first to analyse the different configurations assumed by the *DSF*. Considering that the environmental conditions in April and October are quite similar, also the configurations assumed by the *DSF* are analogue.

Starting from *SAC#5*, if the overall month duration is considered (*Figure 113*), the percentages of use for the different configurations (*TB*, *AS*, *AE* and *OAC*) are almost the same already observed in April.

The same is of course visible just looking at the occupied hours only during the month (*Figure 114*).

If the winter control applied (*Figure 115*), it is visible a larger adoption of *TB* compared to April (around *80%*) and a smaller use of *OAC* natural.

On the other hand, the percentages for the adoption of *AS* and *CF* are almost the same. The same is also visible considering only the occupied hours of the room (*Figure 116*), but anyway *TB* configuration remains the most adopted one.

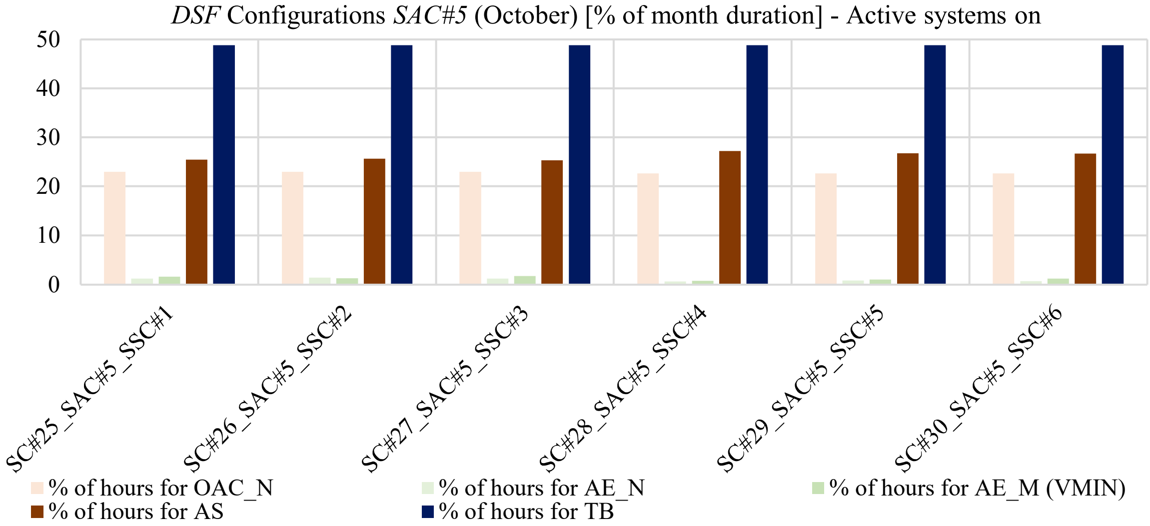


Figure 113: Percentages of hours in the month (October)in which the different DSF configurations have been adopted (active systems turned on) with SAC#5 as airflow control

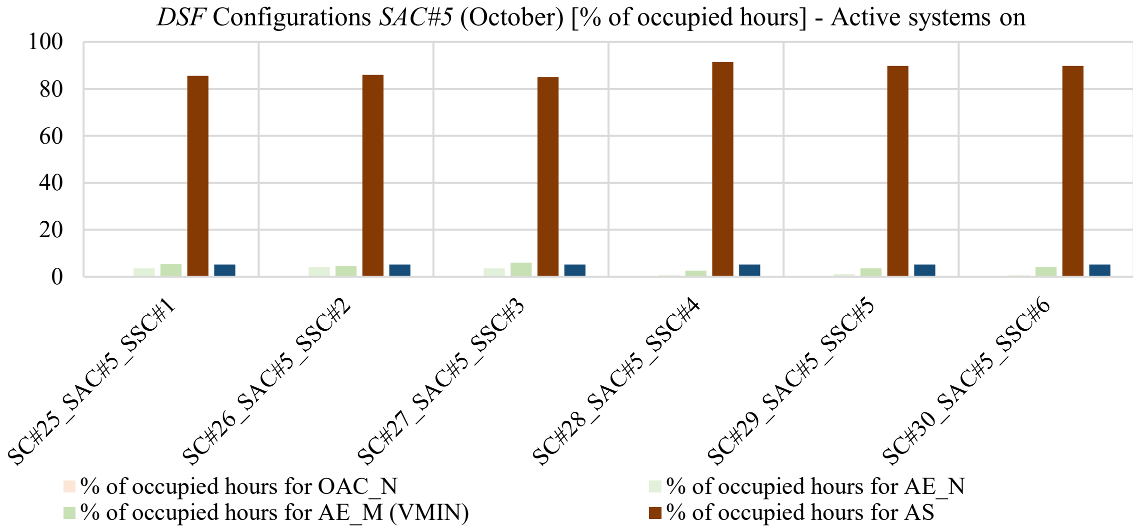


Figure 114: Percentages of occupied hours in the month (October)in which the different DSF configurations have been adopted (active systems turned on) with SAC#5 as airflow control

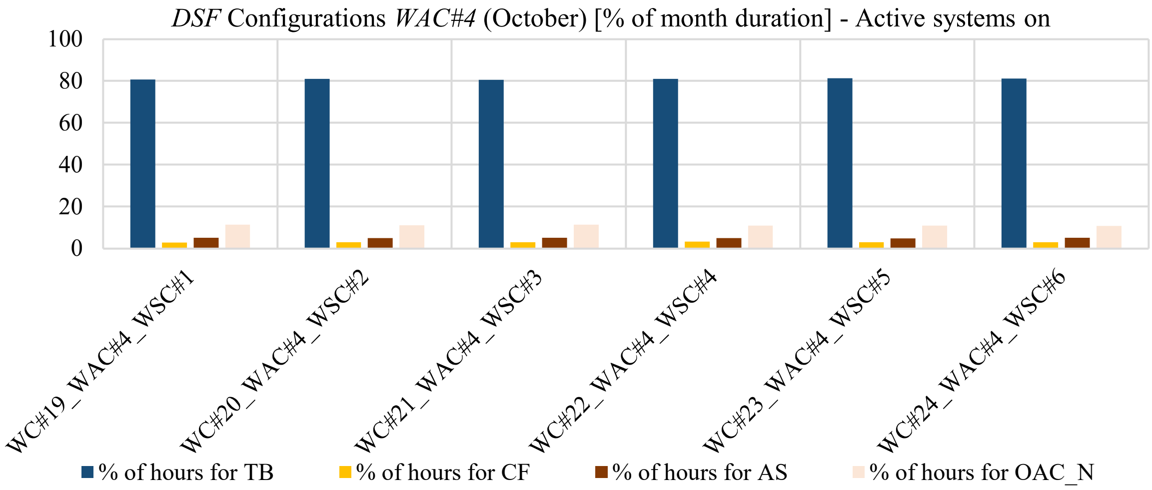


Figure 115: Percentages of hours in the month (October)in which the different DSF configurations have been adopted (active systems turned on) with WAC#4 as airflow control

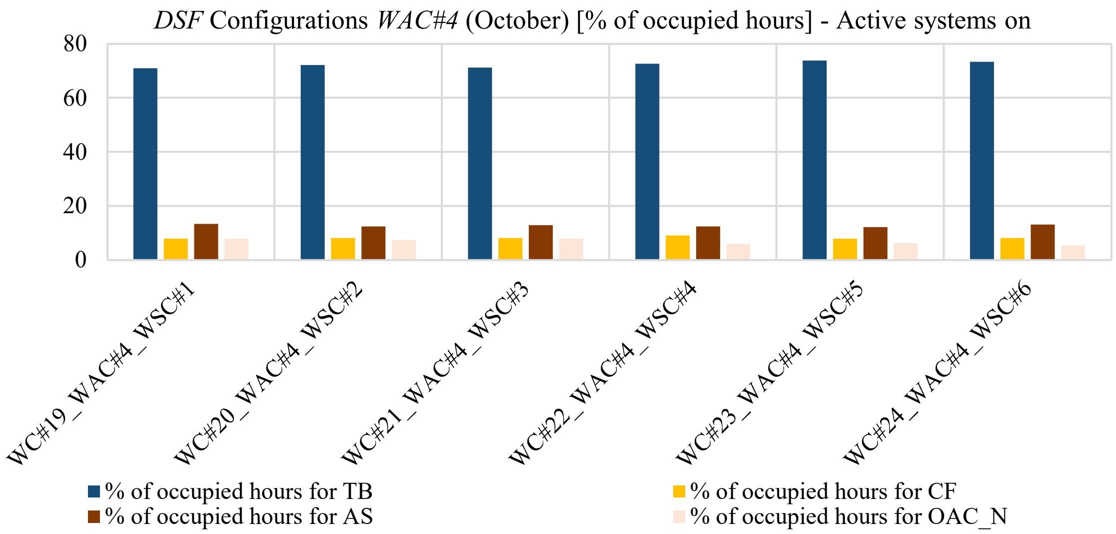


Figure 116: Percentages of occupied hours in the month (October)in which the different DSF configurations have been adopted (active systems turned on) with WAC#4 as airflow control

6.2.1.2. Heating energy need

For all the façade systems (flexible *DSF*, static *DSF* and *SSF*) the heating energy need during the month of October is greater than the cooling energy need: it consequently more effective a reduction of the heating energy need with respect to a lowering of the cooling energy need. This is the same situation already observed for the month of April. In the complex, the application of *WAC#4* is more effective for the reduction of the heating energy need of the room, as observed during the month of April.

Anyway, the situation is more critical: in fact, only *WAC#4* coupled with the temperature control of the blind can reduce the energy need for heating in the room. *WAC#4* coupled with the radiation control produces an average increase of the heating demand equal to *2.8%*. In addition, the average reduction generated by *WAC#4* coupled with the temperature control is not particularly effective (*-1.3%*).

Consequently, there is an overall *+0.8%* variation of the heating energy need of the room compared to *SSF*. *SAC#5* on the other hand produce and increase of the heating energy need (in average *+92.8%*): it consequently ineffective for the reduction of the heating energy need, as observed for the month of April. In this case the average increase is also greater compared to the spring.

As observed for the month of April, *WAC#4* is consequently the optimal solution for the reduction of the heating energy need, compared to *SAC#5*. Among the two static *DSF* configurations (*OAC* and *TB*), only the latter produces a reduction of the heating energy of the room (*-5.1%*) while *OAC* increases the energy requirements for heating as *SAC#5* (*+30.4%*).

The related values of energy consumption (expressed in *kWh* and *kWh/m²*) are reported in *Table 85*.

	TOTAL ENERGY NEED [kWh]			TOTAL [kWh/m²]			[-]
Combinations of control	**Space heating**	**Ventilation heating**	**TOT**	**Space heating**	**Ventilation heating**	**TOT**	**Variation (Single Skin)**
WC#19	148.60	0.15	148.75	3.10	0.00	3.10	**3.3**
WC#20	148.5	0.16	148.66	3.09	0.00	3.10	**3.2**
WC#21	146.6	0.13	146.73	3.05	0.00	3.06	**1.9**
WC#22	142.00	0.10	142.10	2.96	0.00	2.96	**-1.3**
WC#23	141.80	0.11	141.91	2.95	0.00	2.96	**-1.5**
WC#24	142.50	0.10	142.60	2.97	0.00	2.97	**-1.0**
SC#25	210.30	69.02	279.32	4.38	1.44	5.82	**94.0**
SC#26	211	69.97	280.97	4.40	1.46	5.85	**95.1**
SC#27	216.3	65.21	281.51	4.51	1.36	5.86	**95.5**
SC#28	200.80	72.63	273.43	4.18	1.51	5.70	**89.9**
SC#29	199.80	73.43	273.23	4.16	1.53	5.69	**89.7**

SC#30	209.30	67.79	277.09	4.36	1.41	5.77	**92.4**
Static OAC	187.70	0.04	187.74	3.91	0.00	3.91	**30.4**
Static TB	136.70	0.03	136.73	2.85	0.00	2.85	**-5.1**
SSF	***144.00***	***0.02***	***144.02***	***3.00***	***0.00***	***3.00***	***REFERENCE***

Table 85:Heating energy need variation for April

Looking at the different types of control for the shading, the reduction of the heating energy need (in the case of the application of *WAC#4*) is more evident if the temperature control is applied (*-1.3%*) compared to the performance with the radiation control (*+2.8%*): as seen for the winter season and for the month of April, the temperature control is consequently more effective for the heating energy need. The performance is anyway worse compared to the one produced for the month of April.

On the other hand, considering the application of *SAC#5*, almost the same average increase of the heating energy need is associated with the radiation and the temperature control for the blind (both in the order of *90%*). A graphical comparison of the energy needs for heating is reported in *Figure 117*.

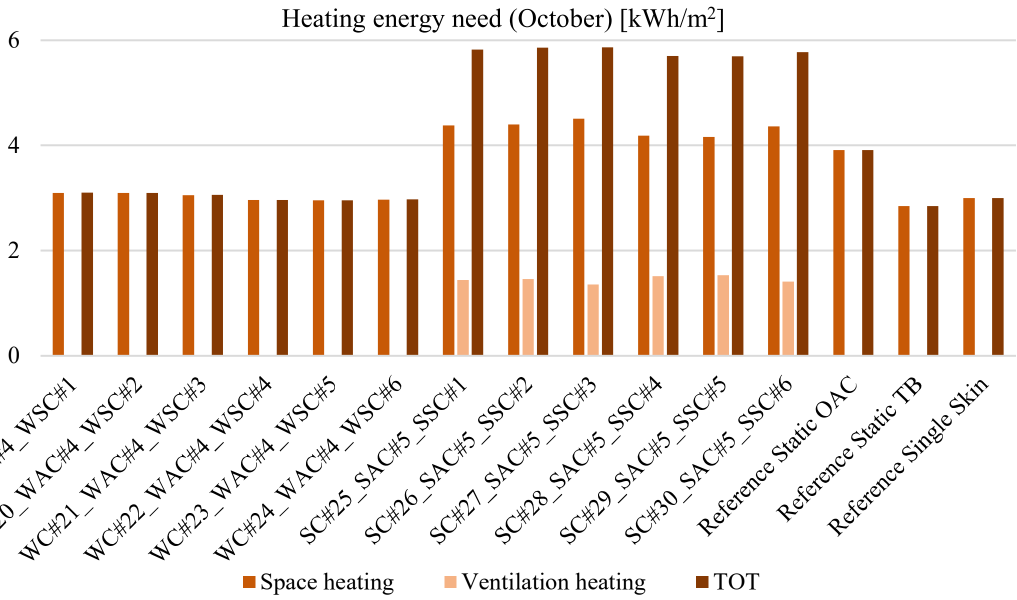


Figure 117: Heating energy requirements for the different façade systems (October)

6.2.1.3. Cooling energy need

Regarding the cooling energy need, there is a reduction of the requirements with both, *WAC#4* and *SAC#5*. However, the average reduction of the cooling energy need in the case of the application of *SAC#5* (*-81.1%*) is better compared to the one produced by *WAC#4* (*-71.9%*). The two air flows controls are consequently effective in the reduction of the cooling energy need, as observed for April. In this case, the difference in performance between the two air flow controls is less evident.

As observed in April, also the two static *DSF* configurations produce a reduction of the energy need for cooling (more evident in the case of static *OAC*, which is the most effective in the reduction of the energy need for cooling (*-93%*). The related values of energy consumption (expressed in *kWh* and *kWh/m²*) are reported in *Table 86.*

	TOTAL ENERGY NEED [kWh]			**TOTAL [kWh/m²]**			**[-]**
Combinations of control	**Space cooling**	**Ventilation cooling**	**TOT**	**Space cooling**	**Ventilation cooling**	**TOT**	**Variation (Single Skin)**
WC#19	10.48	4.78	15.26	0.22	0.10	0.32	**-80.4**
WC#20	10.51	4.767	15.28	0.22	0.10	0.32	**-80.4**
WC#21	11.96	4.771	16.73	0.25	0.10	0.35	**-78.6**
WC#22	24.04	4.71	28.75	0.50	0.10	0.60	**-63.1**

WC#23	24.04	4.71	28.75	0.50	0.10	0.60	**-63.1**
WC#24	21.91	4.71	26.62	0.46	0.10	0.55	**-65.9**
SC#25	1.29	4.62	5.91	0.03	0.10	0.12	**-92.4**
SC#26	1.208	4.536	5.74	0.03	0.09	0.12	**-92.6**
SC#27	2.659	4.663	7.32	0.06	0.10	0.15	**-90.6**
SC#28	19.36	4.08	23.44	0.40	0.09	0.49	**-70.0**
SC#29	18.85	4.08	22.93	0.39	0.08	0.48	**-70.6**
SC#30	19.23	4.10	23.33	0.40	0.09	0.49	**-70.1**
Static OAC	0.63	4.81	5.45	0.01	0.10	0.11	**-93.0**
Static TB	32.07	4.82	36.89	0.67	0.10	0.77	**-52.7**
SSF	***73.22***	***4.80***	***78.02***	***1.53***	***0.10***	***1.63***	***REFERENCE***

Table 86: Cooling energy need variation for October

A graphical comparison of the energy needs for cooling is reported in *Figure 118*.

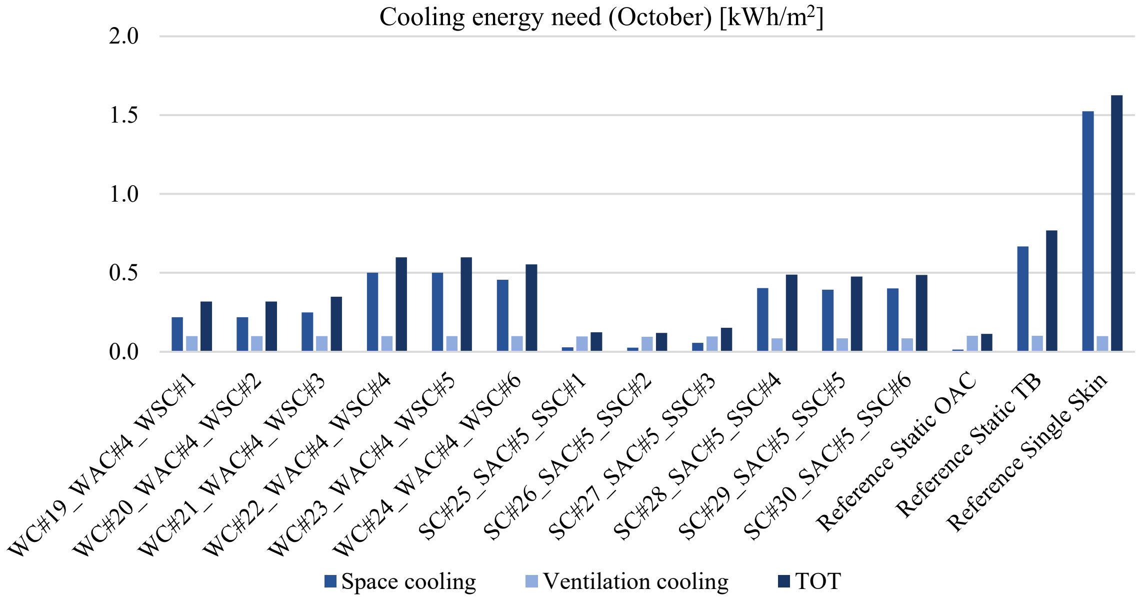


Figure 118: Cooling energy requirements for the different façade systems (October)

About the different types of control for the shading, the radiation control is more effective in the reduction of the cooling energy need compared to the temperature control (as observed for April): radiation control in average (considering both *SAC#5* and *WAC#4*) produces a reduction of the energy need for cooling equal to *-85.8%*, while for the temperature control the average reduction is *-67.1%*.

Consequently, as observed during the summer season and in April, the radiation control is more effective for the lowering of the energy for cooling in the room, since it is activated with larger frequency.

The overall performance is consequently better in the case of application of *WAC#4*, for which a reduction of the total requirements for heating and cooling is visible (there is no variation of the heating energy need of the room, compared on the other hand to the worsening generated by *SAC#5*): the reduction of total heating and cooling requirements for the room is also better than the one produced by static *TB* and *OAC*, as observed for the month of April.

On the other hand, *SAC#5* produces an increase of the overall heating and cooling energy that is required for the room.

The overall performance in terms of cooling and heating requirements variations is reported in *Table 87*.

	Variation cooling energy need (With respect to SSF, %)	Variation heating energy need (With respect to SSF, %)
WAC#4	**-71.9**	**0.8**
SAC#5	**-81.1**	**92.8**
Static *OAC*	**-93**	**30.4**
Static *TB*	**-52.7**	**-5.1**

Table 87: Variation of heating and cooling requirements in the cases of application of SAC#5 and WAC#4 (October)

6.2.1.4. Artificial lighting energy need

As observed during the month of April, it is visible an increase of the required energy need for artificial lighting in the room. The average increases are in this case intermediate lower than the ones in April. The average increases are of course function of the different control logics implemented for the shading (as observed for the other periods of the year). In particular, the difference between radiation and temperature control is evident: radiation control in average produces an increase of *45.8%* of the artificial lighting energy requirements, while the temperature control of the blind only *24.7%*.

If the radiation control is applied it is clearly visible the influence of the different control logics for the blind slat angle: the cut-off position is associated to the largest increase of the energy need for artificial lighting, followed by the fixed slat angle. On the other hand, the scheduled variation of the blind slat angle produces an increase of *25.3%*, analogue to the one generated by the temperature control of the blind (in average, about *25%*). The scheduled variation is consequently quite effective in the limitation of the increase of the energy for artificial lighting (as observed for the month of April).

On the other hand, if the temperature control is applied, the different control logics for the blind slat angle produce basically the same results (as observed in summer and winter conditions and during April).

The related values of energy consumption (expressed in *kWh* and *kWh/m²*) are reported in *Table 88.*

	TOTAL [kWh]	***TOTAL [kWh/m2]***	**[%]**
Combinations of control	**Artificial lighting**	**Artificial lighting**	**Variation (Single Skin)**
WC#19	25.77	0.54	**42.8**
WC#20	30.53	0.64	**69.2**
WC#21	22.6	0.47	**25.3**
WC#22	22.48	0.47	**24.6**
WC#23	22.48	0.47	**24.6**
WC#24	22.60	0.47	**25.3**
SC#25	25.80	0.54	**43.0**
SC#26	30.53	0.64	**69.2**
SC#27	22.54	0.47	**24.9**
SC#28	22.44	0.47	**24.4**
SC#29	22.47	0.47	**24.6**
SC#30	22.46	0.47	**24.5**
Static OAC	25.81	0.54	**43.1**
Static TB	25.97	0.54	**44.0**
SSF	***18.04***	***0.38***	***REFERENCE***

Table 88: Artificial lighting energy need variation for October

The average increases for the artificial lighting energy requirements associated to the different types of control of the blind slat angle are reported in *Table 89*.

Shading control	**Increase artificial lighting energy demand (compared to *SSF*) [%]**
SC#1	**42.9**
SC#2	**69.2**
SC#3	**25.1**

SC#4	**24.5**
SC#5	**24.6**
SC#6	**24.9**

Table 89: Average variations of the artificial lighting energy need produced by the 6 different shading controls coupled with WAC#4 and SAC#5 (October)

A graphical comparison of the energy needs for artificial lighting is reported in *Figure 119.*

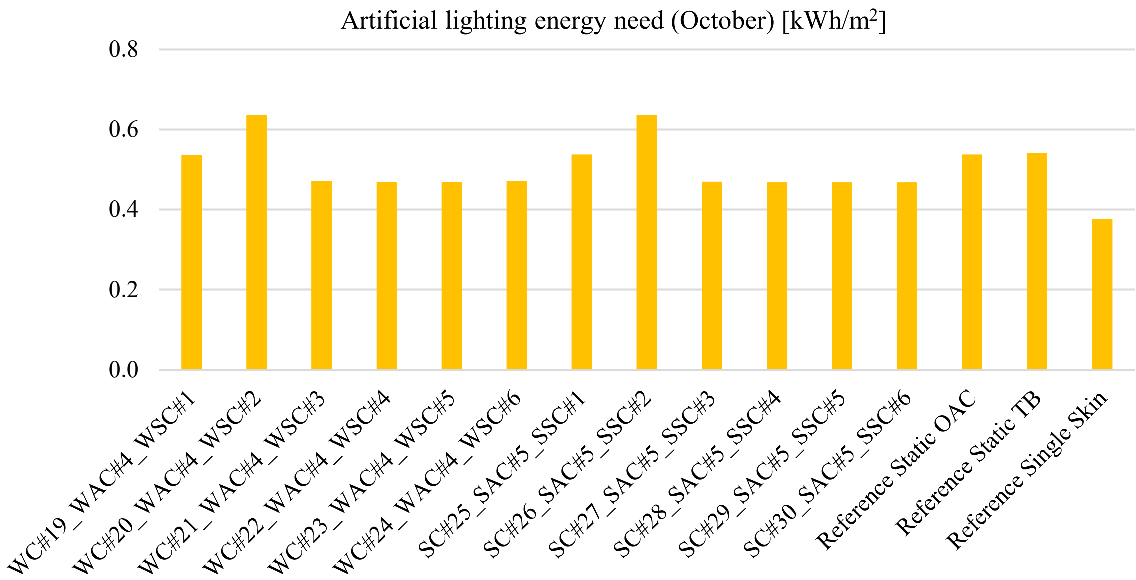


Figure 119: Artificial lighting energy requirements for the different façade systems (October)

6.2.2. IEQ

The results of the simulations performed on the model with the active systems turned off are here reported. For the analysis during the mid-season periods in the free-running configuration of the model, the clothing insulation for the occupants has been set equal to *0.75 clo*, as done for the month of April.

6.2.2.1. DSF configurations in October (Active systems turned off)

As observed for the model with the active systems turned on, if the summer control is applied, the configurations assumed by the *DSF* are almost the same in April and October (*Figure 120* and *Figure 121*).

The only difference is the application of *AE* mechanical with the maximum air flow in the cavity in *SC#27*.

If the winter control is applied, a larger use of *TB* is present compared to April, while *AE*, *OAC* and *AS* are adopted with a smaller extent, if the overall month duration is considered (*Figure 122*).

In the case of the occupied hours only (*Figure 123*), *TB* is adopted for an analogue percentage of hours compared to April while an increased adoption of *AE* configuration is visible (above *60%*).

On the other hand, the use of *OAC* and *AS* is considerably lower.

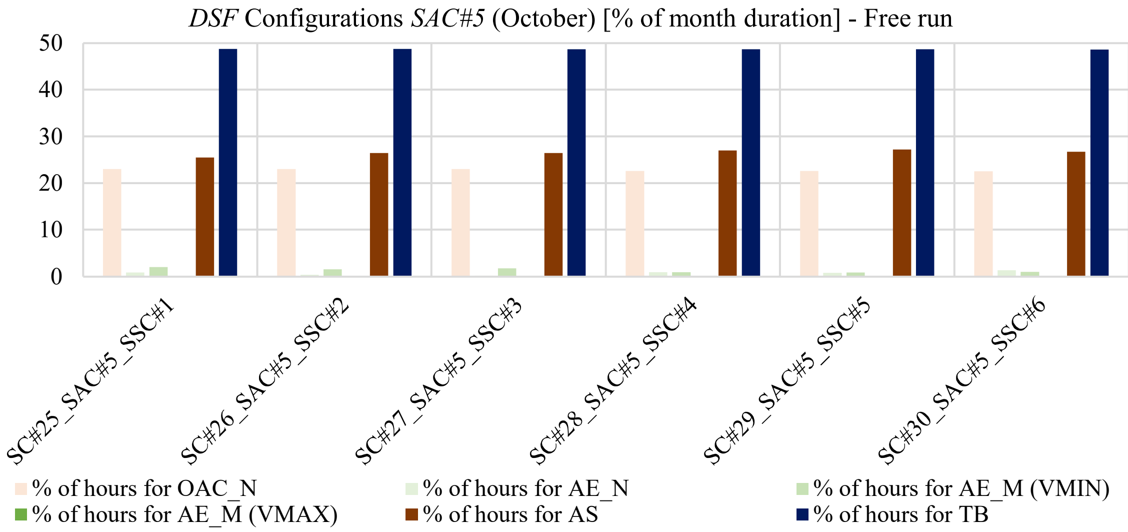


Figure 120: Percentages of hours in the month (October)in which the different DSF configurations have been adopted (active systems turned off) with SAC#5 as airflow control

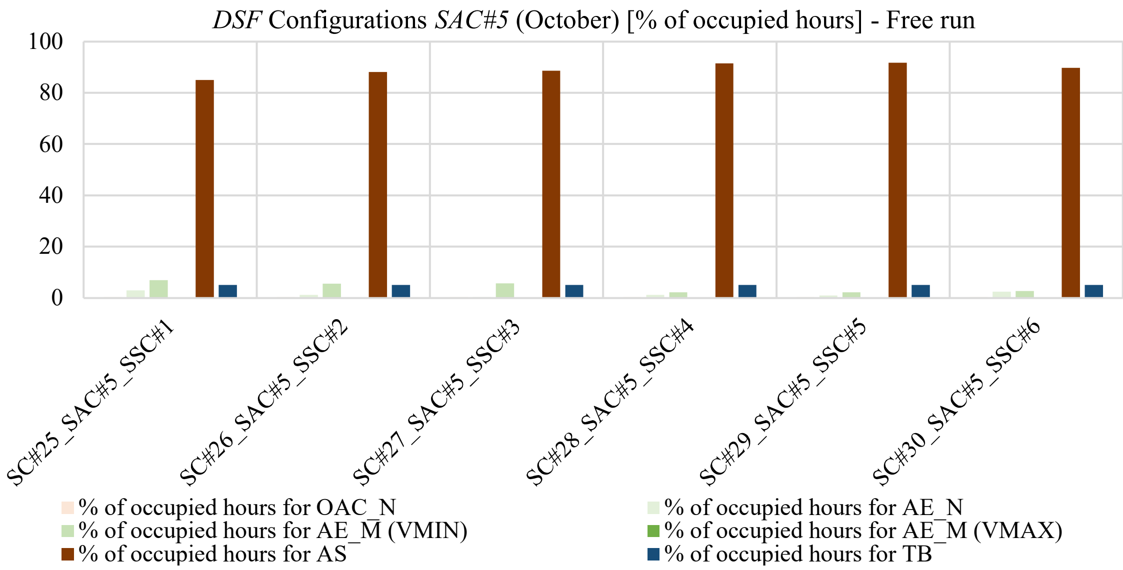


Figure 121: Percentages of occupied hours in the month (October)in which the different DSF configurations have been adopted (active systems turned off) with SAC#5 as airflow control

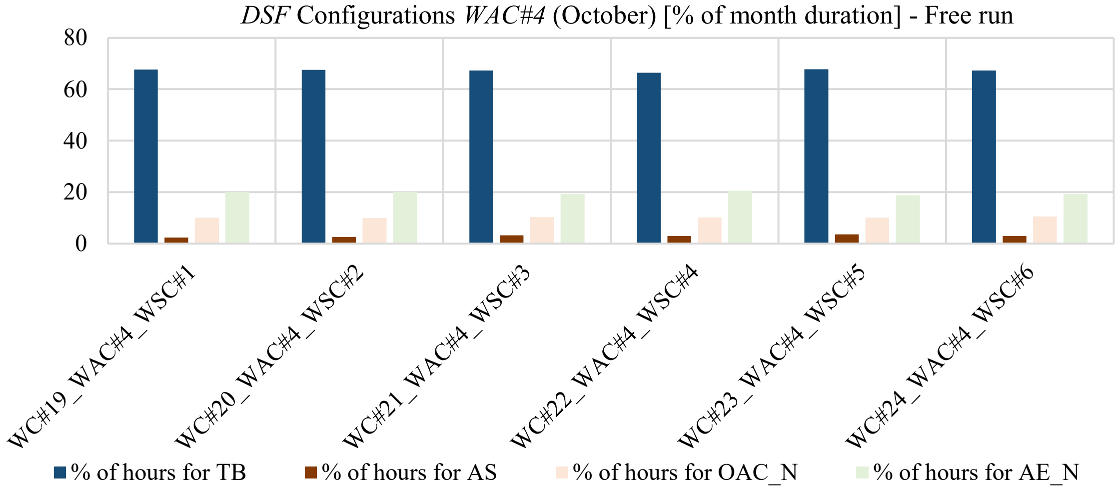


Figure 122: Percentages of hours in the month (October)in which the different DSF configurations have been adopted (active systems turned off) with WAC#4 as airflow control

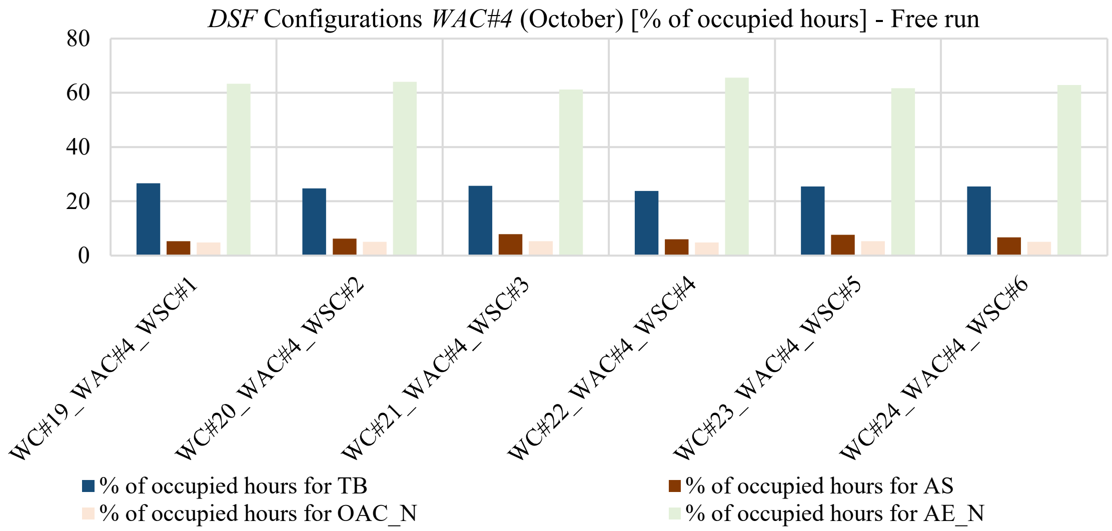


Figure 123: Percentages of occupied hours in the month (October)in which the different DSF configurations have been adopted (active systems turned off) with WAC#4 as airflow control

6.2.2.2. Indoor operative temperatures

As done for the summer season, three different threshold limits for the indoor operative temperature have been considered: *20°C*, *26°C* and *30°C*. Regarding the variation of the number of occupied hours above the limit of *26°C* the reduction compared to *SSF* is visible in the cases of the application of *SAC#5* and *WAC#4* coupled with the radiation control of the blind, as observed in April.

On the other hand, there is an increase (*+21.6%*), in the case of *WAC#4* coupled with the temperature control of the blind: compared to April, the overheating risk if *WAC#4* and temperature control are coupled together is consequently higher.

In the complex, anyway, the effect of the 12 different combinations of control is quite positive, with an average reduction of *-22.4%* compared to *SSF* (lower compared to April). The best results are anyway achieved by *SAC#5*, which shows a largely better performance compared to *WAC#4*: in the case of *SAC#5*, the average reduction is *-48.6%* while for *WAC#4* in the complex there is an increase of *3.8%* of the number of occupied hours above the limit of *26°C*.

The two static configurations of *DSF* (*OAC* and *TB*) are in this case the worst solution, increasing of a larger extent the number of occupied hours above the limit of *26°C*. The percentage of occupied hours above the limit of *26°C* for each configuration of control are reported in *Table 90*.

Combinations of control	n° hours Top > 26°C	% of occupied hours Top > 26°C	Variation (Single Skin)
WC#19	22.3	10.6	**-9.7**
WC#20	20.1	9.6	**-18.6**
WC#21	21.4	10.2	**-13.4**
WC#22	31.4	15.0	**27.1**
WC#23	27.8	13.2	**12.6**
WC#24	30.9	14.7	**25.1**
SC#25	7.42	3.5	**-70.0**
SC#26	4.82	2.3	**-80.5**
SC#27	11.3	5.4	**-54.3**
SC#28	17.4	8.3	**-29.6**
SC#29	15.2	7.2	**-38.5**
SC#30	20.1	9.6	**-18.6**
Static OAC	29.1	13.9	**17.8**
Static TB	51.2	24.4	**107.3**
SSF	***24.7***	***11.8***	***REFERENCE***

Table 90: Percentages of occupied hours above 26°C for the different façade systems (October)

A graphical comparison of the number of hours above the limit of *26°C* is reported in *Figure 124*.

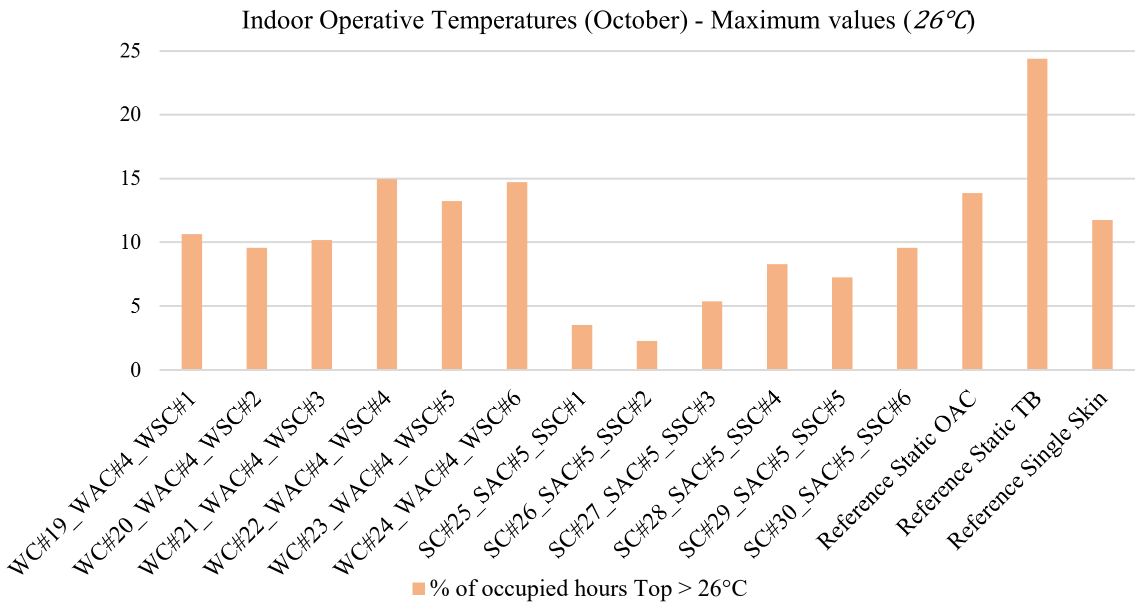


Figure 124: Percentages of occupied hours above 26°C for the different façade systems (October)

Regarding the relation with the different typologies of control for the shading, it is clearly visible the difference between temperature and radiation control (as observed in April). The latter is largely better in terms of reduction of the number of occupied hours above the limit of *26°C*.

In average the reduction with the radiation control is largely greater than the one generated by the temperature control (*-41.1%* against *-3.6%*). The percentage is also bigger if *SC#1*, *#2* and *#3* are coupled with *SAC#5* (*-68.2%*, larger than April).

As seen for the cooling energy need, the radiation control is more effective for the limitation of the number of hours above the limit of *26°C* during the month of October.

Among the different controls for the blind slat angle (*Table 91*), the cut-off position implementation is the most effective in the reduction of the number of hours above the limit of *26°C* (both in the case of radiation and temperature control of the blind), as seen for April.

The only typology of shading control which causes an increase of the number of occupied hours above the limit of *26°C* is *SC#6* (temperature activation of the blind coupled with the scheduled variation of the blind).

Shading control	**Variation of the occupied hours above 26°C (compared to *SSF*) [%]**
SC#1	**-39.8**
SC#2	**-49.6**
SC#3	**-33.8**
SC#4	**-1.2**
SC#5	**-13.0**
SC#6	**3.2**

Table 91: Average variations of the occupied hours above 26°C produced by the 6 different shading controls in October

An analogue trend is visible analysing the number of occupied hours above the limit of *30°C*: in this case, *SAC#5* reduces (*-27.5%* in average) the number of occupied hours above this limit (which are about zero also in *SSF,* as seen in April) while *WAC#4* shows an increased number of hours in which the limit is overcame (the same for the static *OAC* configuration).

However, the percentage of occupied hours in which this situation is present is very low (between *1.7%* and *5.3%* of the entire number of occupied hours during the month, as in April). Under this point of view, the worst solution is the static *TB* configuration (*14.3%* of occupied hours above the limit of *30°C*).

The percentage of occupied hours above the limit of *30°C* for each configuration of control are reported in *Table 92*.

Combinations of control	**n° hours Top > 30°C**	**% of occupied hours Top > 30°C**	**Variation (Single Skin)**
WC#19	4.37	2.1	**438.2**
WC#20	0	0.0	**-100.0**
WC#21	4.85	2.3	**497.3**
WC#22	10	4.8	**1131.5**
WC#23	3.66	1.7	**350.7**
WC#24	11.2	5.3	**1279.3**
SC#25	0	0.0	**-100.0**
SC#26	0	0.0	**-100.0**
SC#27	0	0.0	**-100.0**
SC#28	1.14	0.5	**40.4**
SC#29	0	0.0	**-100.0**
SC#30	2.39	1.1	**194.3**
Static OAC	0.655	0.3	**-19.3**
Static TB	30.1	14.3	**3606.9**
SSF	***0.812***	***0.4***	***REFERENCE***

Table 92: Percentages of occupied hours above 30°C for the different façade systems (October)

A graphical comparison of the number of hours above the limit of *30°C* is reported in *Figure 125*.

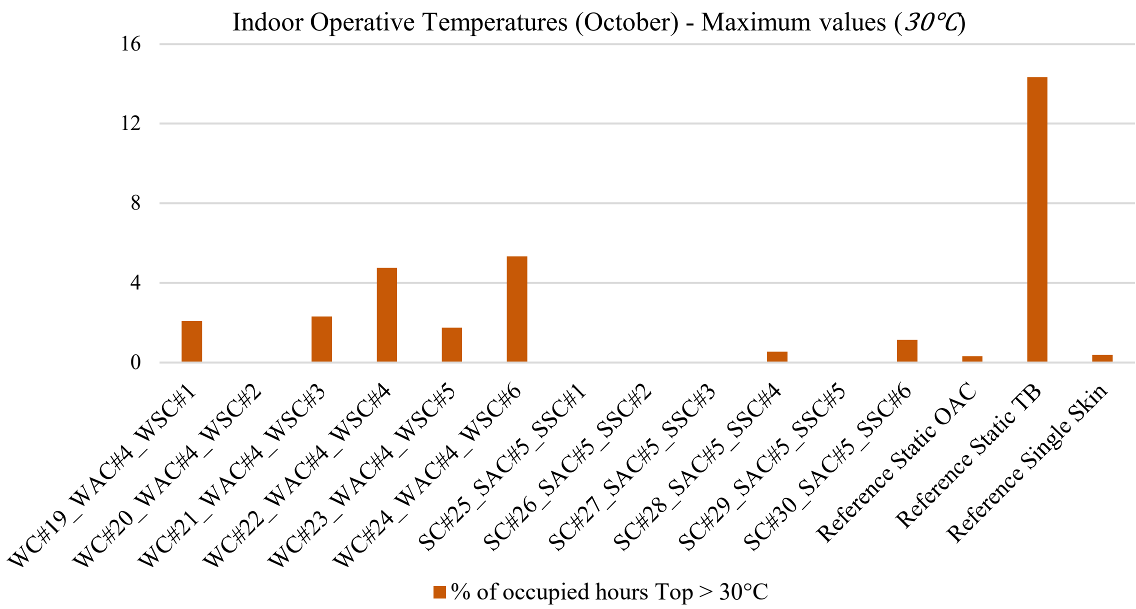


Figure 125: Percentages of occupied hours above 30°C for the different façade systems (October)

As observed for the temperature limit of *26°C*, the radiation control is more effective in the reduction of the overheating risk: in the case of the coupling with *WAC#4*, the increasing is less than one third of the one generated by the temperature control. Moreover, in the case of the use of *SAC#5*, the radiation control always shows zero occupied hours above the limit of *30°C* while the temperature control is associated to an average increase of about *45%*.

Of course, as seen in April, the opposite behaviour is visible considering the number of occupied hours below the limit of *20°C*: *WAC#4* is associated with a lower increase of the number of occupied hours below the limit (*+44.6%*) compared to *SAC#5* (*+72%*). Also the static *OAC* configuration produces an increased number of occupied hours below the limit while the static *TB* is the only one which is able to reduce it (as seen for April).

As seen for the heating energy need, the temperature control for the blind is linked to a more effective reduction of the overcooling risk for the room (both in the case of the coupling with *SAC#5* and *WAC#4*): the average increase in the case of the adoption of temperature control is *50.8%* while for the radiation control it is *65.8%*. The percentage of occupied hours below the limit of *20°C* for each configuration of control are reported in *Table 93*.

Combinations of control	n° hours Top < 20°C	% of occupied hours Top < 20°C	Variation (Single Skin)
WC#19	139	66.2	**48.7**
WC#20	145	69.0	**55.1**
WC#21	142	67.6	**51.9**
WC#22	128	61.0	**36.9**
WC#23	128	61.0	**36.9**
WC#24	129	61.4	**38.0**
SC#25	169	80.5	**80.7**
SC#26	171	81.4	**82.9**
SC#27	164	78.1	**75.4**
SC#28	155	73.8	**65.8**
SC#29	155	73.8	**65.8**
SC#30	151	71.9	**61.5**
Static OAC	130	61.9	**39.0**
Static TB	84.1	40.0	**-10.1**
SSF	***93.5***	***44.5***	***REFERENCE***

Table 93: Percentages of occupied hours below 20°C for the different façade systems (July) coupled with WAC#4 and SAC#5 (October)

Among the different types of control for the slat angle (*Table 94*), the scheduled variation of the slat angle (*SC#3* and *SC#6*) is associated to the lowest increases of the number of occupied hours below the limit of *20°C* (both in the cases of the application of *WAC#4* and *SAC#5*), in analogue way with respect to April. The cut-off position coupled with the radiation control is the only type of control for the slat angle which is able to reduce the number of occupied hours above the limit of *30°C* if combined with *WAC#4*.

Shading control	Increase of the occupied hours below 20°C (compared to *SSF*) [%]
SC#1	**64.7**
SC#2	**69.0**
SC#3	**63.6**
SC#4	**51.3**
SC#5	**51.3**
SC#6	**49.7**

Table 94: Average variations of the artificial lighting energy need produced by the 6 different shading controls in October

A graphical comparison of the number of hours below the minimum temperature limit is reported in *Figure 126*.

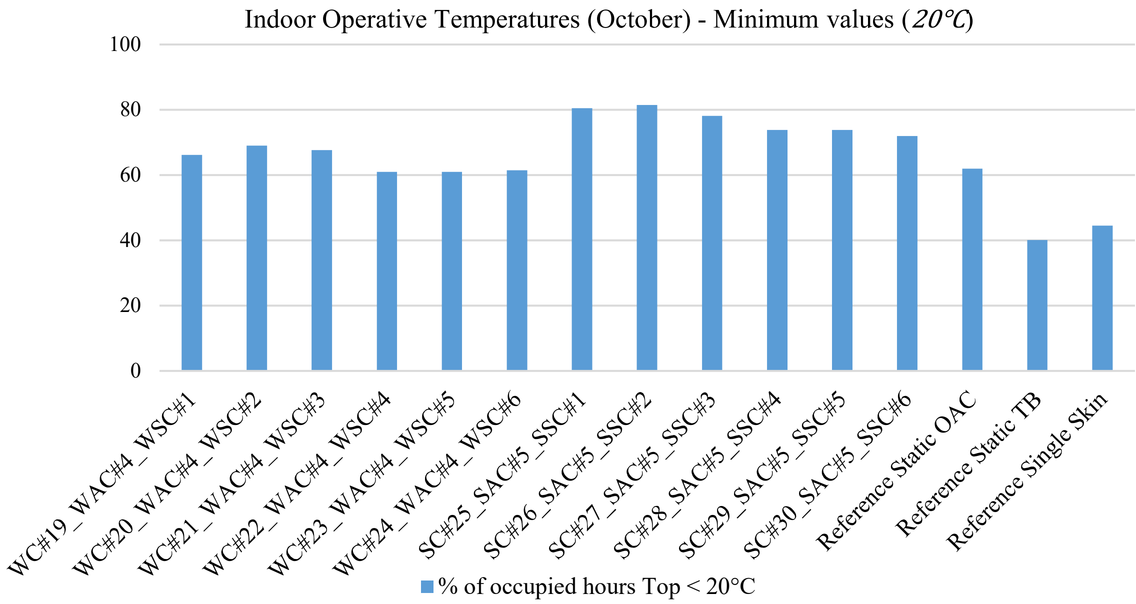


Figure 126: Percentages of occupied hours below 20°C for the different façade systems (October)

6.2.2.3. IAQ

All the 12 control combinations produce a reduction of the number of hours above the limit of *1000 ppm*. Anyway, the most effective under this point of view is *SAC#5*, with an average reduction of *100%* (no hours above the limit are present). On the other hand, the reduction in the case of *WAC#4* is largely lower (*-11.4%*).

The situation is analogue to what has been already observed in April, but the difference in performance between the two airflow controls is more evident. In this case, all the combinations of control with *WAC#4* show percentage of occupied hours above the limit of *1000 ppm* in the order of *60%*. The two static *DSF* configurations (*OAC* and *TB*) are equally ineffective under this point of view, increasing the number of occupied hours above the limit of *1000 ppm* of about *37%*. The percentages of occupied hours below the limit for each configuration of control are reported in *Table 95*.

Combination of controls	n° hours CO2 > 1000 ppm	% of occupied hours CO2 > 1000 ppm	Variation (Single Skin)
WC#19	139	66.2	**-8.6**
WC#20	136	64.8	**-10.5**

WC#21	126	60.0	**-17.1**
WC#22	138	65.7	**-9.2**
WC#23	135	64.3	**-11.2**
WC#24	134	63.8	**-11.8**
SC#25	0	0.0	**-100.0**
SC#26	0	0.0	**-100.0**
SC#27	0	0.0	**-100.0**
SC#28	0	0.0	**-100.0**
SC#29	0	0.0	**-100.0**
SC#30	0	0.0	**-100.0**
Static OAC	208	99.0	**36.8**
Static TB	209	99.5	**37.5**
SSF	***152***	***72.4***	***REFERENCE***

Table 95: Percentages of occupied hours above 1100 ppm for the different façade systems (October)

A graphical comparison of the number of hours above the concentration limit is reported in *Figure 127*.

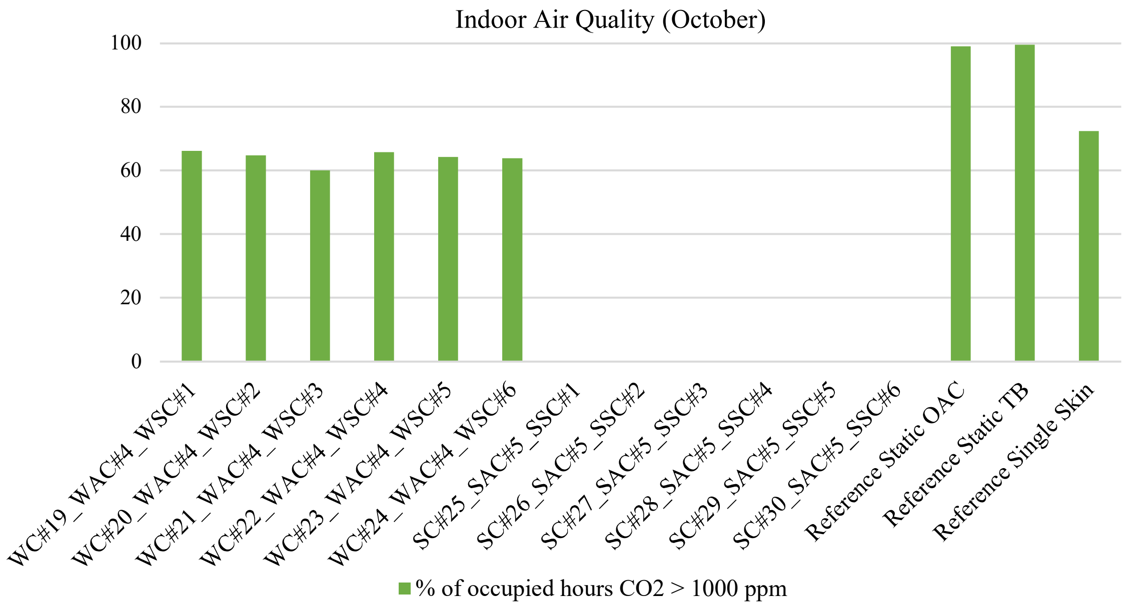


Figure 127: Percentages of occupied hours above 1000 ppm for the different façade systems (October)

6.2.2.4. Fanger's comfort indices

Both the two air flow controls (*SAC#5* and *WAC#4*) produce a general increase of the number of hours in which the *PPD* index is above *10%*.

The percentages are in this case analogue: *+47.6%* for *WAC#4* and *+54.2%* for *SAC#5*, as observed for the month of April.

Anyway, the causes for this increase are different: *SAC#5* produces a more evident increase of the number of occupied hours below $PMV = -0.5$ while reducing the number of occupied hours above the limit of $PMV = 0.5$ On the contrary, the adoption of *WAC#4* is associated to a larger increase of the number of hours above the limit of $PMV = 0.5$.

This is of course an analogue situation to the one observed in April, in which the two air flow controls can be associated to opposite thermal discomfort conditions (overcooling for *SAC#5* and overheating for *WAC#4*).

The number of hours above and below the limits for each configuration of control are reported in *Table 96*.

Combinations of control	n° hours PPD > 10%	% of occupied hours PPD > 10%	n° hours PMV > 0,5	% of occupied hours PMV > 0,5	n° hours PMV < -0,5	% of occupied hours PMV < -0,5	Variation PPD (Single Skin)	Variation PMV > 0,5 (Single Skin)	Variation PMV < -0,5 (Single Skin)
WC#19	193	91.9	18.3	8.7	172	81.9	**38.8**	**40.8**	**42.1**
WC#20	190	90.5	12.9	6.1	174	82.9	**36.7**	**-0.8**	**43.8**
WC#21	191	91.0	17.3	8.2	171	81.4	**37.4**	**33.1**	**41.3**
WC#22	184	87.6	23.7	11.3	157	74.8	**32.4**	**82.3**	**29.8**
WC#23	180	85.7	18.6	8.9	158	75.2	**29.5**	**43.1**	**30.6**
WC#24	184	87.6	23.8	11.3	158	75.2	**32.4**	**83.1**	**30.6**
SC#25	188	89.5	4.79	2.3	181	86.2	**35.3**	**-63.2**	**49.6**
SC#26	186	88.6	1.83	0.9	183	87.1	**33.8**	**-85.9**	**51.2**
SC#27	188	89.5	6.56	3.1	180	85.7	**35.3**	**-49.5**	**48.8**
SC#28	186	88.6	12	5.7	171	81.4	**33.8**	**-7.7**	**41.3**
SC#29	182	86.7	9.01	4.3	171	81.4	**30.9**	**-30.7**	**41.3**
SC#30	187	89.0	15.3	7.3	169	80.5	**34.5**	**17.7**	**39.7**
Static OAC	180	85.7	31	14.8	147	70.0	**29.5**	**138.5**	**21.5**
Static TB	168	80.0	54.3	25.9	111	52.9	**20.9**	**317.7**	**-8.3**
SSF	*139*	*66.2*	*13*	*6.2*	*121.0*	*57.6*	*REFERENCE*	*REFERENCE*	*REFERENCE*

Table 96: Variation of the comfort indexes in the room for the different façade systems (October)

As observed in April, the two static configurations of *DSF* (*OAC* and *TB*) are more effective in the limitation of the increase of *PPD = 10%*. Static *TB* is also associated with a reduction of the number of occupied hours below the limit of *PMV = -0.5*.

The shading control has of course an influence in the variation of the comfort indices also in April: the radiation control, if coupled with *SAC#5*, is more effective in the reduction of the number of occupied hours above the limit of *PMV = 0.5* than temperature control (*-66.2%* against *-6.9%,* with a more consistent difference compared to the one observed in April).

It is therefore more effective for the overheating risk reduction. If coupled with *WAC#4*, on the other hand, the radiation control produces a larger increase of the number of occupied hours below the limit of *PMV = -0.5* (the same is also visible in the coupling with *SAC#5*). It is consequently linked to a larger overcooling risk for the occupants. These conclusions are analogue to the ones defined during the analysis of the indoor operative temperature trends and to which has been observed in April.

A graphical comparison of the number of hours above and below the threshold limits is reported in *Figure 128.*

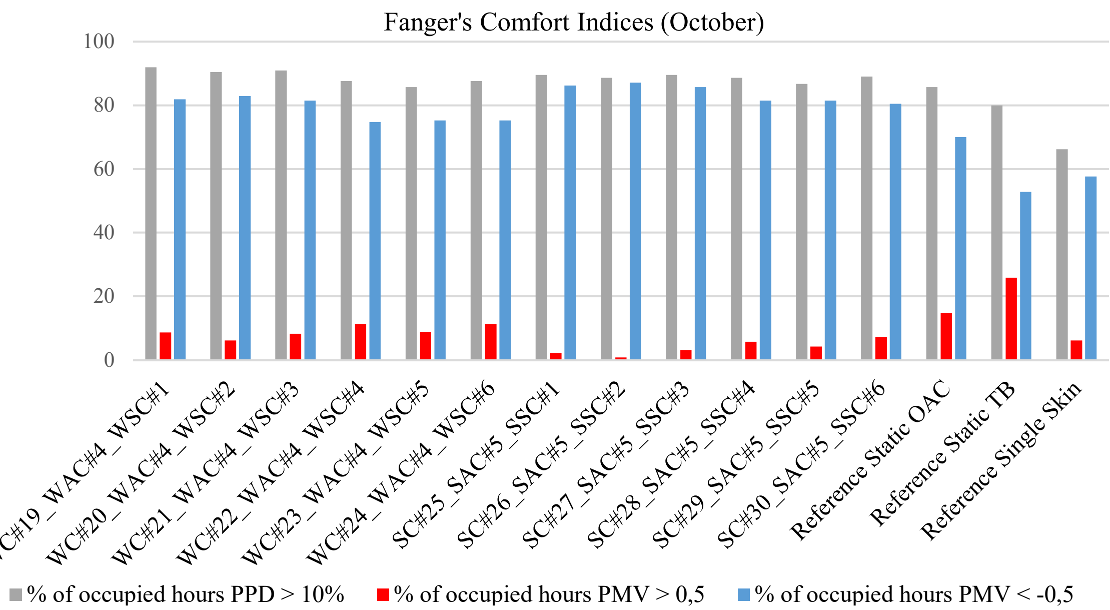


Figure 128: Variation of the comfort indexes in the room for the different façade systems (October)

6.2.2.5. Daylight and glare

As observed in January, July and April, it is visible a worsening of the indoor daylight conditions also for October. The increase of the number of occupied hours below the limit of *500 lux* is anyway less critical compared to the April (as observed for the increasing of the energy consumption for artificial lighting). The percentages of increase are consequently smaller than the ones in the April analysis.

The percentage of occupied hours below the limit for each configuration of control are reported in *Table 97.*

Combination of control	n° hours E < 500 lux	% of occupied hours E < 500 lux	Variation (Single Skin)
WC#19	137	65.2	**45.1**
WC#20	161	76.7	**70.6**
WC#21	121	57.6	**28.2**
WC#22	128	61.0	**35.6**
WC#23	132	62.9	**39.8**
WC#24	123	58.6	**30.3**
SC#25	136	64.8	**44.1**
SC#26	161	76.7	**70.6**
SC#27	120	57.1	**27.1**
SC#28	124	59.0	**31.4**
SC#29	127	60.5	**34.5**
SC#30	123	58.6	**30.3**
Static OAC	137	65.2	**45.1**
Static TB	137	65.2	**45.1**
SSF	***94.4***	***45.0***	***REFERENCE***

Table 97: Percentage of occupied hours below the limit of 500 lux (October)

The influence of the different typologies of control for the shading system also in October is evident (*Table 98*).

The radiation control in average produces an increase (*+47.6%*) which is larger than the one observed with the application of the temperature control for the blind (*+33.7%*). This is the same situation already observed for the winter season and in April: the temperature control is the better solution for both, indoor illuminance levels and energy consumption of the artificial lighting (even if it is present a worsening of the performance compared to *SSF*).

The temperature control produces a lower average increase if coupled with *SAC#5*, due to a lower indoor air temperature generated by this air flow control.

Anyway, the best combinations in terms of limitation of the increase of the number of occupied hours below the limit of *500 lux* are *SC#27* and *WC#21* (as seen in April), which adopt the radiation control coupled with the scheduled variation of the blind slat angle (in average the increase is *+27.6%*, lower than the average increase generated by the adoption of the temperature control for the blind, always above *30%*).

Shading control	Variation of the occupied hours below 500 lux (compared to *SSF*) [%]
SC#1	**44.6**
SC#2	**70.6**
SC#3	**27.6**
SC#4	**33.5**
SC#5	**37.2**
SC#6	**30.3**

Table 98: Average variations of the number of occupied hours below the limit of 500 lux produced by the 6 different shading controls in October

A graphical representation of the variation of the number of hours below the limit of *500 lux* is showed in *Figure 129.*

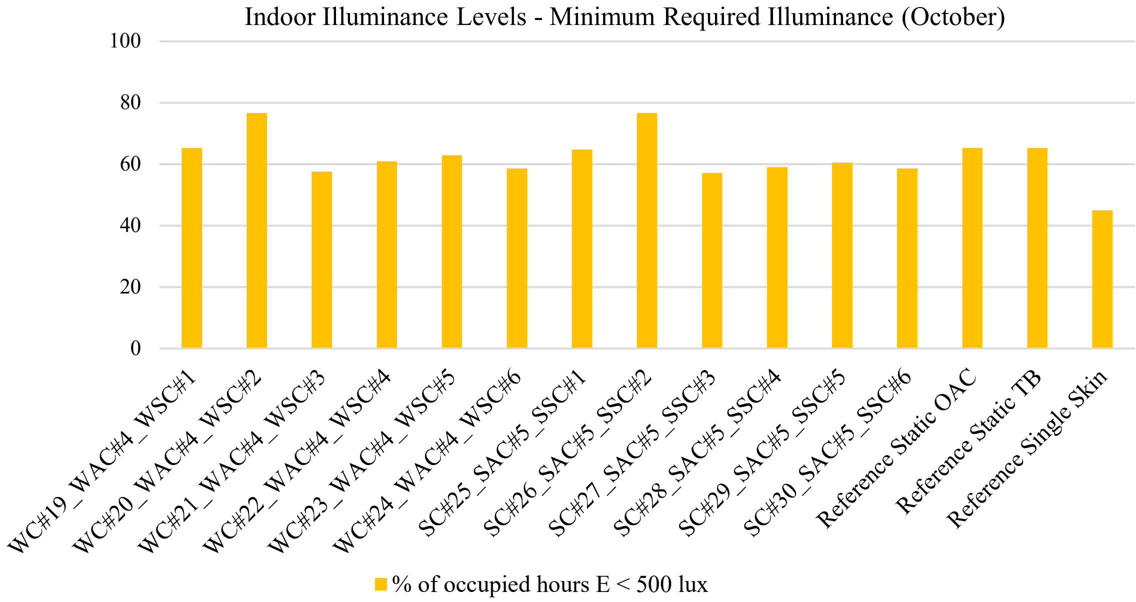


Figure 129: Percentage of occupied hours below the limit of 500 lux (October)

Differently from April, in all the façade systems (*Table 100*), it is possible to observe a certain number of occupied hours in which the limit of *3000 lux* is reached (*4.7%* of the occupied hours in the case of *SSF*).

Only the control configurations in function of the incident solar radiation on the façade (*SC#1, #2* and *#3*) show a percentage of occupied hours above the limit that is approximately zero: in these cases, the reduction is about *100%* compared to *SSF*. On the other hand, the temperature control is associated with an increase of the number of hours above the glare risk limit (*Table 99*).

However, the average increase is very low (about *5.3%*) and the percentage of occupied hours in which the limit of *3000 lux* is reached is never above *5%*. The performance is consequently largely better compared to the winter season (in January the percentage of occupied hours above the limit was higher than *10%*).

Moreover, the optimal control for the keeping of *500 lux* in the room (radiation control coupled with the scheduled variation of the blind slat angle) is also the one which completely avoid the glare risk in the zone (-*100%* compared to *SSF*).

Shading control	**Variation of the occupied hours above 3000 lux (compared to *SSF*) [%]**
SC#1	**-98.4**
SC#2	**-98.5**
SC#3	**-100.0**
SC#4	**6.2**
SC#5	**3.6**
SC#6	**6.2**

Table 99: Average variations of the occupied hours below 500 lux produced by the 6 different shading controls in October

The number of hours above the limit for each configuration of control are reported in *Table 100.*

Combination of control	**n° hours E > 3000 lux**	**% of occupied hours E > 3000 lux**	**Variation (Single Skin)**
WC#19	0.162	0.1	**-98.4**
WC#20	0.147	0.1	**-98.5**
WC#21	0	0.0	**-100.0**
WC#22	10.6	5.0	**7.2**
WC#23	10.1	4.8	**2.1**
WC#24	10.5	5.0	**6.2**
SC#25	0.161	0.1	**-98.4**

SC#26	0.147	0.1	**-98.5**
SC#27	0	0.0	**-100.0**
SC#28	10.4	5.0	**5.2**
SC#29	10.4	5.0	**5.2**
SC#30	10.5	5.0	**6.2**
Static OAC	0	0.0	**-100.0**
Static TB	0	0.0	**-100.0**
SSF	***9.89***	***4.7***	***REFERENCE***

Table 100: Percentage of occupied hours above the limit of 3000 lux (October)

The related visual comparison between the number of hours above the glare risk limit for the different façade configurations is reported in *Figure 130.*

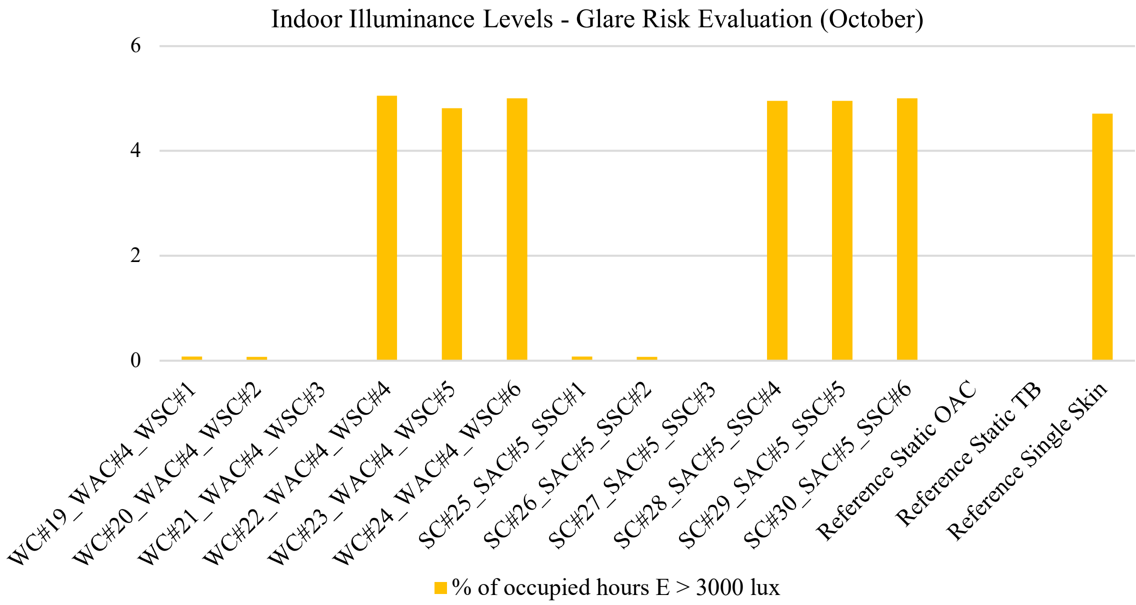


Figure 130: Percentage of occupied hours above the limit of 3000 lux (October)

6.3. Critical points in the application of the control during the mid-season months

After the testing of the optimal control combinations for summer and winter conditions (*SAC#5* and *WAC#4*) in the mid-season months of April and October, it is now possible to underline some conclusions as already done for the analysis in the months of July and January.

In general, it is possible to say that the impact of the two selected air flow control logics and the related 12 control combinations during the mid-season periods is considerably better compared to the one in summer (for *SAC#5*) and winter (for *WAC#4*) peak conditions.

This is of course due to milder and less critical environmental conditions under the point of view of air temperature, solar radiation, and cloudiness.

However, as done for the summer and the winter season, some critical points can be underlined also for the analysis performed in April and October. These critical points can be divided in the two main performance domains of the system, the overall energy efficiency, and the indoor comfort conditions for the occupants and they are reported in the next pages.

Energy performance optimization

Considering the analysis performed on the model with the active systems turned on for the performance optimization of the *DSF* under the energy need point of view, the following conclusions, and critical points in the application of the rule-based control can be underlined:

1) As seen for the summer and the winter conditions, there is an increasing of the energy requirements for artificial lighting for the room (*Figure 131*).

   The worsening in this case is intermediate between the July (worst increase) and the January analysis (less critical increase) since intermediate natural lighting conditions are present in the selected mid-season months. The difference between summer, winter and mid-season conditions is more evident in the case in which only the radiation control is considered. On the other hand, the performance of the temperature control is largely better in all the four considered months.

   This is of course caused by the fact that the radiation control is more dependent on the outdoor solar radiation conditions, compared to the temperature one. For this reason, the performance worsening (if the active systems are turned on) compared to *SSF* is more evident. During the month of January, for example, the increase compared to *SSF*, if the temperature control is applied, is limited to about *10%.*

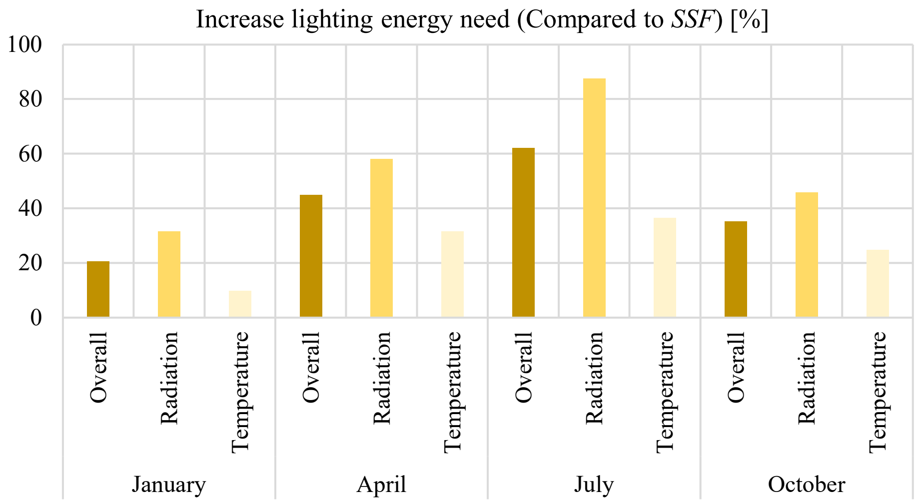


Figure 131: Average lighting energy need increase in four considered months, considering the one produced by the radiation control, the temperature control and both together

2) The optimal shading control for lighting energy need and heating energy need in October (temperature control of the blind) is also the worst under the point of view of the glare discomfort risk for the occupants (as seen for January): with the adoption of the temperature control in October (coupled with *WAC#4*) there is a reduction of *1.3%* of the heating energy need and the increase of the lighting requirements is limited to about *25%.*

   At the same time, anyway, an increase of *5.2%* of the number of occupied hours above *3000 lux* is visible in the free running configuration of the room. However, the percentages of occupied hours above the limit of *3000 lux* are not particularly significant (in the worst case, *5%* of the overall occupied hours): in the complex the situation is less critical compared to the January case, in which the percentage of occupied hours above the limit of *3000 lux* was in the order of *10%.*

3) In the month of October, it is also visible that only *WAC#4* coupled with the temperature control for the blind can reduce the heating energy need for the room. In addition, this reduction is not significant.

   This is the most critical aspect related to the energy performance optimization during the month of October, in which a more critical condition (considering heating and cooling energy requirements) is present, compared to the one visible in April, in which the performance of *WAC#4* was largely better.

Indoor environmental quality improvement

On the other hand, considering the indoor environmental quality requirements and the simulations performed on the model in free-running configuration, the following conclusions can be observed:

1) The most evident critical point in this case is that the air flow control which shows best overall results under the point of view of heating and cooling requirements reduction in October and April (*WAC#4*) is also associated to a higher overheating risk if applied to the free running configuration of the room.

   In October, *WAC#4* coupled with the temperature control for the blind is the only one which can reduce the heating demand of the room but in the free running configuration it is visible an increase of the number of occupied hours in which *PMV* is above 0.5 (*+47%*) and the operative temperature exceeds the limits of *26°C* (*+3.8%*) and *30°C* (*+600%*).

   In April, *WAC#4* is the only control which reduces both, heating, and cooling requirements in the room. It is anyway less effective in the reduction of the occupied hours above *26°C* compared to *SAC#5* and it is associated with an increase of the number of occupied hours in which the limit of *30°C* is reached (in a more evident way compared to October).

   During the mid-season periods, it is consequently more difficult to find a control for the air flow which can optimize both, energy efficiency of the system and thermal comfort for the occupants (considering the overall performance of *WAC#4* and *SAC#5* combinations in April and October).

2) In addition to the problems related to the overheating risk, *WAC#4* is also not effective in the limitation of the number of occupied hours in which the CO_2 concentrations in the room are above *1000 ppm*, compared to *SAC#5* (*Figure 132*).

   Only *SAC#5* can avoid peak concentrations of CO_2 in all the months in which it is applied (April, July and October), as it is possible to see in the graph.

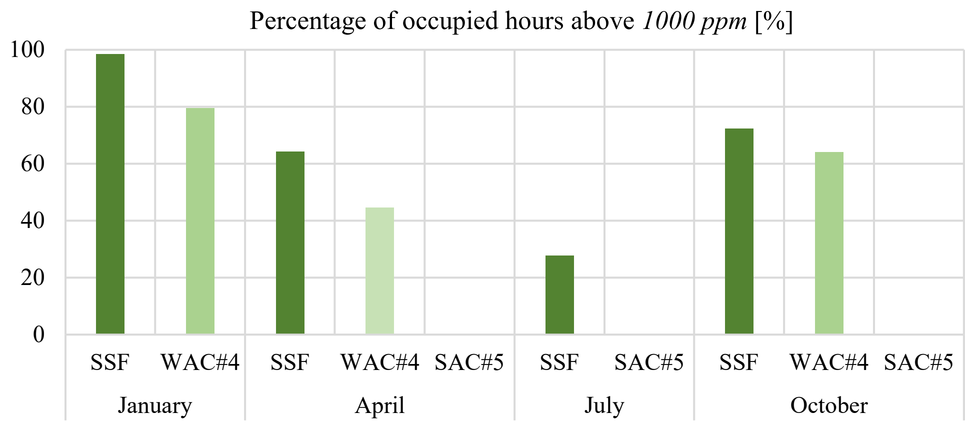


Figure 132: Percentage of occupied hours above the limit of 1000 ppm in the four considered months

In both the mid-season months (April and October), *SAC#5* avoids the presence of occupied hours above the limit of CO_2 concentrations (thanks to the adoption of the *AS* configuration), while *WAC#4* only reduces them of a not significant extent compared to *SSF* (*-11.4%* in the case of October and *-30.6%* in the case of April).

Consequently, the air flow control which is optimal under the energy efficiency point of view cannot be used for natural ventilation purposes, due to a too high percentage of occupied hours in which *1000 ppm* limit is reached (*44.6%* in April and *64.1%* in October). This is the same problem already occurred during the analysis performed in the month January, in which the winter air flow controls have been tested.

7. Definition of the annual control and optimization with the IDA API

The last step of the research method illustrated in *3* is the construction of a common rule based flexible *DSF* control structure which can be adopted for the whole year (not just for a limited period, as for example a single month), starting from the strategies already tested in January, July, April and October.

The optimal control combinations for heating and cooling seasons, tested also for mid-season periods, *SAC#5* and *WAC#4*, have been consequently merged in a common control logic, applicable in the whole year. These two air flow controls in fact have been shown the best performances (both for the energy efficiency and the *IEQ*) during the July and January tests respectively, with good results also in the case of the application in mid-season periods (April and October). In addition, they ensure the switching between the largest number of possible configurations among the ones defined in *2.3*.

The distinction in the use of heating and cooling season strategies through the year is defined in function of the temperature difference between the indoor (θ_{indoor}) and the outdoor environment (θ_{amb}): if the outdoor air temperature is lower of a certain extent (θ_{switch}) than the indoor air temperature, the heating season strategies (*WAC#4*) are applied while on the contrary the cooling seasons strategies (*SAC#5*) are used (*Figure 133*).

In fact, if the model with the active systems turned on is considered, the indoor air temperature is almost always in the range between *20°C* and *26°C* (heating and cooling set points): it is consequently possible to adopt this distinction for the selection of heating and cooling strategies for the *DSF* through the year (*Figure 134*).

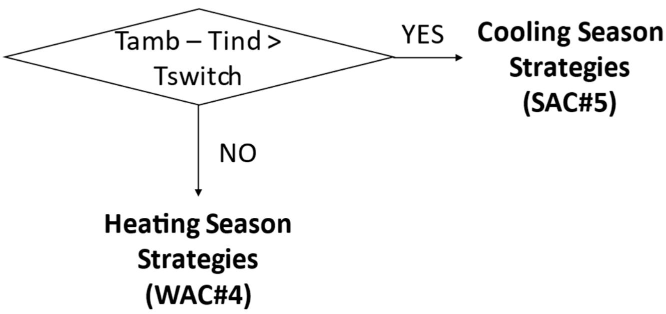


Figure 133: Selection of the cooling and heating season strategies for the DSF operations in function of the temperature difference between indoor and outdoor environment (active systems of the room turned on)

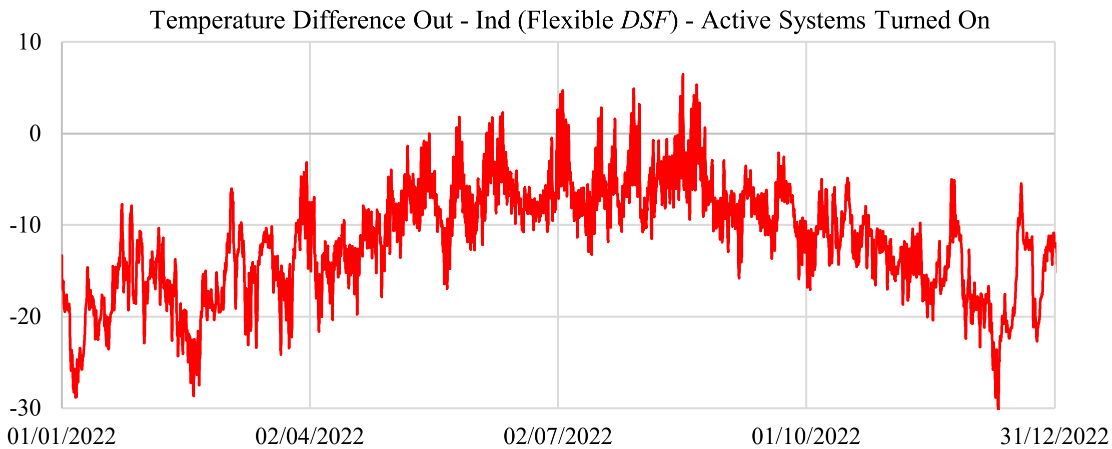


Figure 134: Variation through of the air temperature difference between the outdoor and the indoor environments, if the active systems of the room are on (the flexible DSF system is considered)

The strategies for the unoccupied hours (lunch break, night and weekends) are the ones already used for *SAC#5* in the case of the cooling season and *WAC#4* in the case of the heating season (they have been described in *2.3.3*), already modified in the case of the application in April and October (as illustrated in *6*).

For the shading system, different strategies have been selected among the 6 implemented in the monthly tests.

For the occupied hours, a radiation control with cut-off position implementation for the slat has been selected (*SC#2* in accordance with the shading control classification illustrated at the beginning of *6*). This selection is motivated by the fact that the radiation control has shown a better ability in the reduction of the cooling energy need and the overheating risk for the occupants, compared to the temperature control (which is on the other hand more effective for the heating energy need and the overcooling risk reductions), during the months of July, April and October.

Among the different types of control for the blind slat angle, the cut-off position implementation is the most effective for the limitation of the overheating risk in the room (also in mid-season periods, especially in October): if coupled with *WAC#4* it can reduce the peaks of the indoor air temperature compared to *SSF*. It also allows the greatest flexibility of the shading system because the slat angle is automatically calculated for each time step of the simulation in function of the sun elevation (already implemented in the IDA ICE climate file).

In addition, the definition of a schedule for the slat angle in function of the illuminance levels inside the room can be feasible for a limited period (for example a single month, as performed for April, October, July and January) but it could be more complex process if the whole year duration is considered.

For the unoccupied hours (lunch breaks and weekends), in the other hand, the temperature control of the blind coupled with the cut-off position implementation (*SC#5*) has been used. In this way, the shading is activated only if the indoor air temperature is above a certain limit. On the other hand, if the indoor air temperature is low enough, the blind is not activated, ensuring passive solar gains from the sun (which can reduce the heating energy need of the room in winter and mid-season periods).

A recap of the different strategies adopted in the annual *DSF* control is reported in *Table 101*.

Annual flexible *DSF* control	
Optimal heating season air flow control	*WAC#4* (Modified for April and October tests)
Optimal cooling season air flow control	*SAC#5*
Shading control (Occupied hours)	Radiation control + cut-off (*SC#2*)
Shading Control (Unoccupied hours)	Temperature control + cut-off (*SC#5*)

Table 101: List of the different strategies for the flexible DSF air flow and shading control during the heating and cooling seasons

7.1. Definition of the different combinations of values for the parametric analysis

Different control variables are used in the annual control for the *DSF*.

As illustrated in *3.7*, it is necessary to define different combinations of control variables threshold values and evaluate which ones of them produce the best results in terms of performance.

The selected control variables are the ones already defined in *2.2.3*:

- *Indoor air temperature* (θ_{indoor})
- *Outdoor air temperature* ($\theta_{outdoor}$)
- *Incident solar radiation on the façade* (I_{sol})
- *CO_2 levels in the room* ($C_{(ppm)}CO_2$)
- *Cavity air temperature* (θ_{cavity})

In the specific case of the annual control for the flexible *DSF*, 7 different rule-based algorithm control variables have been considered.

Here the control variables are reported with the names defined inside the optimization script implemented in Python.

- TAir_switch: it is the air temperature difference (θ_{amb} - θ_{indoor}) between indoor and outdoor air for the switching between heating and cooling seasonal strategies.

- Rad_shad: it is the radiation level on the façade for the shading activation during the occupied hours.

- TAir_shad: it is the indoor air temperature for the activation of the shading during the unoccupied hours.

- CO2_Summer: are the indoor CO_2 concentrations in the room for the switching between the different *AE* configurations (natural, mechanical and mechanical with maximum implemented air flow) during the cooling season, if *SAC#5* is in use. 3 different levels for the CO_2 concentrations (corresponding to the 3 configurations of *AE*) are used in the control logic.

- TCav_Summer: it is the maximum cavity air temperature for the adoption of *AS* during the cooling season if *SAC#5* is in use.

- CO2_Winter: it is the maximum CO_2 concentrations in the room for the adoption of *AE* configuration during the heating season if *WAC#4* is in use.

- TCav_Winter: are the cavity air temperature for the adoption of the different configurations for the heating season (*TB*, *IAC*, *CF*, *AS* and *OAC*), if *WAC#4* is in use. 4 different levels for the cavity air temperature are used in the control logic.

The possible values adopted for the different control variables are reported in *Table 102*. The overall number of control variables implemented in the IDA ICE *Control Macros* is consequently 12.

Control variable	**Possible values for the control variable**	**Combinations**
temp_switch	*-10°C, -5°C, 0°C*	3
rad_shad	*200 W/m², 300 W/m², 400 W/m², 500 W/m²*	4
temp_shad	*20°C, 23°C, 26°C*	3
CO2_Summer	*500 ppm, 700 ppm, 900 ppm* or *600 ppm, 900 ppm, 1000 ppm*	2
TCav_Summer	*20°C, 23°C, 26°C*	3
CO2_Winter	*800 ppm, 1000 ppm*	2
TCav_Winter	*2°C, 19°C, 22°C, 25°C* or *4°C, 21°C, 24°C, 27°C*	2
	Total number of combinations	**864**

Table 102: Possible values and related combinations for the different control variables in the annual decision tree fof the DSF operations.

In the case of the temperature difference value for the seasonal switching, three different values can be used: *-10°C*, *-5°C* or *0°C*. The lower is the value of the temperature difference, the more the cooling season strategies can be used with respect to the heating season strategies. Greater values of temperature difference are not appropriate in a climate as Frankfurt, since the outdoor air temperature rarely is above the cooling set point for the room (*26°C*).

For the solar radiation on the façade, 4 different values, ranging from *200 W/m²* to *500 W/m²* have been used (the maximum incident solar radiation on the South façade in Frankfurt is about *850 W/m²*). The indoor air temperature for the activation of the shading can be varied in the range between the heating and cooling set point in the room: for this reason, *20°C*, *26°C* and the intermediate value *23°C* have been selected as possible solutions.

The original values of CO_2 concentrations used in *SAC#5* for the *AE* configurations switching (provided in the standards *EN 15251-1:2007* and *EN 16798-1:2019* and in the *ASHRAE* guidelines) have been modified: 2 different combinations of values are in this case possible *500 ppm*, *700 ppm* and *900 ppm* or in alternative *600 ppm*, *900 ppm* and *1000 ppm*. In the first case, the CO_2 concentrations for the *DSF* configurations switching are lowered compared to *SAC#5* original decision tree while in the second combination the values are slightly higher (keeping anyway the maximum level of *1000 ppm* provided by the *ASHRAE* guidelines).

For the temperature of the air in the cavity for the adoption of *AS* configuration in summer, as performed for the temperature activation of the shading, 3 different temperature levels have been selected: *20°C*, *23°C* and *26°C*. For the adoption of the AE configuration in winter, 2 different values have been proposed: *1000 ppm* (already used in *WAC#4*) and *800 ppm* (both provided by the standard, as illustrated before).

For the cavity temperature during the winter season, the original values used in *WAC#4* were *4°C*, *20°C*, *22°C* and *26°C*. Also in this case, 2 different combinations have been selected: one with the temperature values slightly reduced (*2°C*, *19°C*, *22°C* and *25°C*) one with the temperature values slightly increased (*4°C*, *21°C*, *24°C* and *27°C*).

The values for the different control variables have been modified by using 7 different *for* loops (1 for each control variable) in which each threshold value has been changed. In this way, all the possible combinations of values have been implemented.

The optimization scripting with the related for loops implemented in VS Code is reported in *Appendix E - Optimization scripting in the IDA ICE API.* In the complex, the total number of combinations is 864. The first 10 and the last 10 combinations of values are reported in *Table 103*.

For each one of the reported combinations, an energy simulation for the whole year has been performed, defining the overall consumptions for heating, cooling and artificial lighting (as already performed during the analysis in winter, summer and mid-season conditions).

n° of combination	**Temperature difference [°C]**	**Solar Radiation Shading [W/m^2]**	**Temperature Shading [°C]**	**CO_2 Summer Limit 1 [ppm]**	**CO_2 Summer Limit 2 [ppm]**	**CO_2 Summer Limit 3 [ppm]**	**Cavity Temp Max Summer [°C]**	**CO_2 Winter Limit [ppm]**	**Cavity Temp Winter 1 [°C]**	**Cavity Temp Winter 2 [°C]**	**Cavity Temp Winter 3 [°C]**	**Cavity Temp Winter 4 [°C]**
1	-10	200	20	500	700	900	20	800	2	19	22	25
2	-10	200	20	500	700	900	20	800	4	21	24	27
3	-10	200	20	500	700	900	20	1000	2	19	22	25
4	-10	200	20	500	700	900	20	1000	4	21	24	27
5	-10	200	20	500	700	900	23	800	2	19	22	25
6	-10	200	20	500	700	900	23	800	4	21	24	27
7	-10	200	20	500	700	900	23	1000	2	19	22	25
8	-10	200	20	500	700	900	23	1000	4	21	24	27
9	-10	200	20	500	700	900	26	800	2	19	22	25
10	-10	200	20	500	700	900	26	800	4	21	24	27
[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]
855	0	500	26	600	900	1000	20	1000	2	19	22	25
856	0	500	26	600	900	1000	20	1000	4	21	24	27
857	0	500	26	600	900	1000	23	800	2	19	22	25
858	0	500	26	600	900	1000	23	800	4	21	24	27
859	0	500	26	600	900	1000	23	1000	2	19	22	25
860	0	500	26	600	900	1000	23	1000	4	21	24	27
861	0	500	26	600	900	1000	26	800	2	19	22	25
862	0	500	26	600	900	1000	26	800	4	21	24	27
863	0	500	26	600	900	1000	26	1000	2	19	22	25
864	0	500	26	600	900	1000	26	1000	4	21	24	27

Table 103: List of the first 10 and last 10 control variable values implemented for the annual control of the DSF

Given an average duration of the year simulation equal to 11-12 minutes, the required time for the running of all the combinations is about 1 week. As done for single month simulations (July, January, April and October).

2 reference systems have been selected for the performance comparison:

1) A *SSF* system, analogue to the one adopted in the previous simulations

2) A traditional *DSF* system, in which only 2 configurations (*TB* and *OAC*) are possible. The application of the two configurations is defined considering the temperature difference between indoor and outdoor environment, as done for the flexible *DSF* system.

   In this case, *TB* is adopted as heating season configuration while *OAC* as cooling season configuration: consequently, the adaptability to the different seasonal conditions is ensured by just two different operating strategies.

In this way, it is possible to evaluate the effectiveness of the implemented annual control for a flexible *DSF* system in comparison with both, a traditional *DSF* system and a *SSF*.

7.2. Results from the different combinations of values

The results of the 864 different simulations performed on the flexible *DSF* system are here reported.

The results obtained by the yearly simulations, as done for the monthly simulations, are the total energy need for heating (space and ventilation), the total energy need for cooling (space and ventilation) and artificial lighting. A total annual value of primary energy need for the room has been also considered for the annual simulations.

The total primary energy is calculated assuming the adoption of an invertible heat pump which can be used for both, heating, and cooling, during the whole year duration. The heat pump is powered by the local electricity grid. In this way, it is possible to consider in a common performance indicator all the different energy uses of the room which can be affected by the control of the flexible *DSF* through the year. The primary energy is calculated as:

$$E_{primary} = \left(\frac{Q_{heat}}{COP} + \frac{Q_{cool}}{SEER} + Q_{ill}\right) f_p = E_{delivered} f_p$$

Where:

- Q_{heat}, Q_{cool} and Q_{ill} are the annual energy need of the room for heating, cooling and artificial lighting respectively, calculated by the annual simulations in IDA ICE.
- COP is the coefficient of performance for the heat pump when it is used for heating purposes. It is set as 2.5.
- $SEER$ is the seasonal energy efficiency ratio of the heat pump when it is used for cooling purposes. It is set as 3.5.
- $E_{delivered}$ is the annual delivered energy to the room, given by the sum of the different energy uses divided by COP and $SEER$.
- f_p is the primary energy conversion factor, defined in accordance with the national context. For sake of simplicity, the average value of primary energy factor for *EU* countries in accordance with the European Energy Directive has been adopted: this is equal to 2.29 [37].

The variation of the annual heating demand for the different combinations of values is reported in *Figure 135* on the left. All the combinations produce an annual heating demand which varies from a minimum of *39.81 kWh/m²* to a maximum of *48.86 kWh/m²*. The variation of the annual cooling demand for the different combinations of values is reported in *Figure 135* on the right. All the combinations produce an annual cooling demand which varies from a minimum of *13.43 kWh/m²* to a maximum of *18.87 kWh/m²*. For Frankfurt, the heating demand is consequently largely bigger compared to the cooling demand, if the flexible *DSF* system is applied. The lowest values are reached in the last implemented combinations.

The variation of the annual artificial lighting demand for the different combinations of values is reported in *Figure 136* on the right. All the combinations produce an annual artificial lighting energy demand which varies from a minimum of *5.7 kWh/m²* to a maximum of *7.5 kWh/m²*. The lowest values are reached with the first implemented combinations (opposite with respect to the heating).

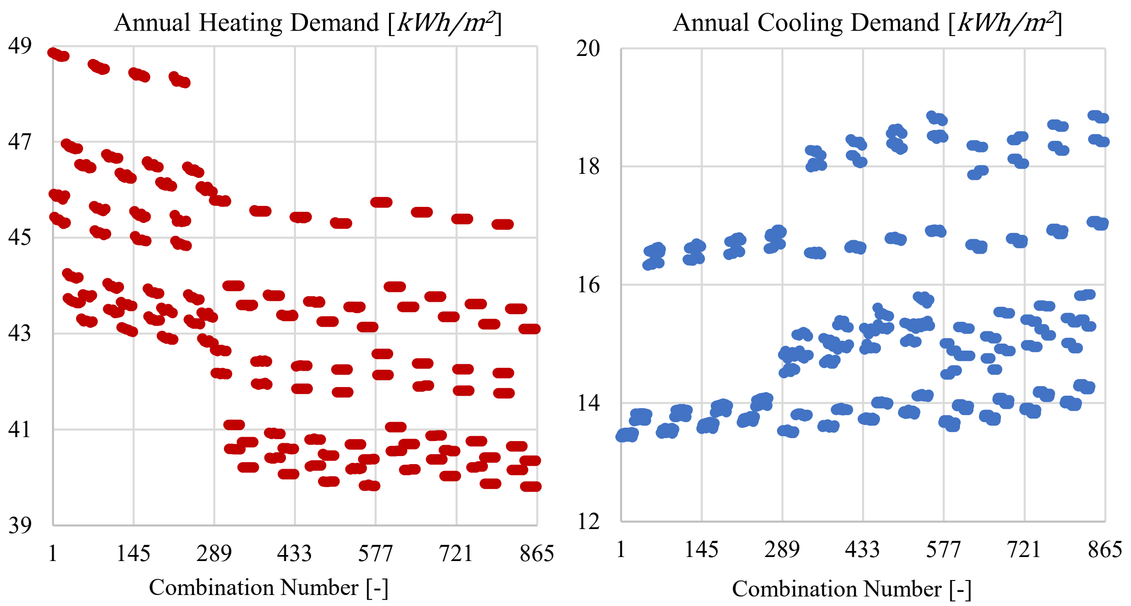


Figure 135: Heating (left) and cooling (right) energy need variation for the 864 different combinations

The variation of the heating and cooling demands for the different combinations of values is reported in *Figure 136* on the left. As it is possible to see, minimum cooling demands are associated with maximum heating demands (the opposite in the case of the minimum heating demands).

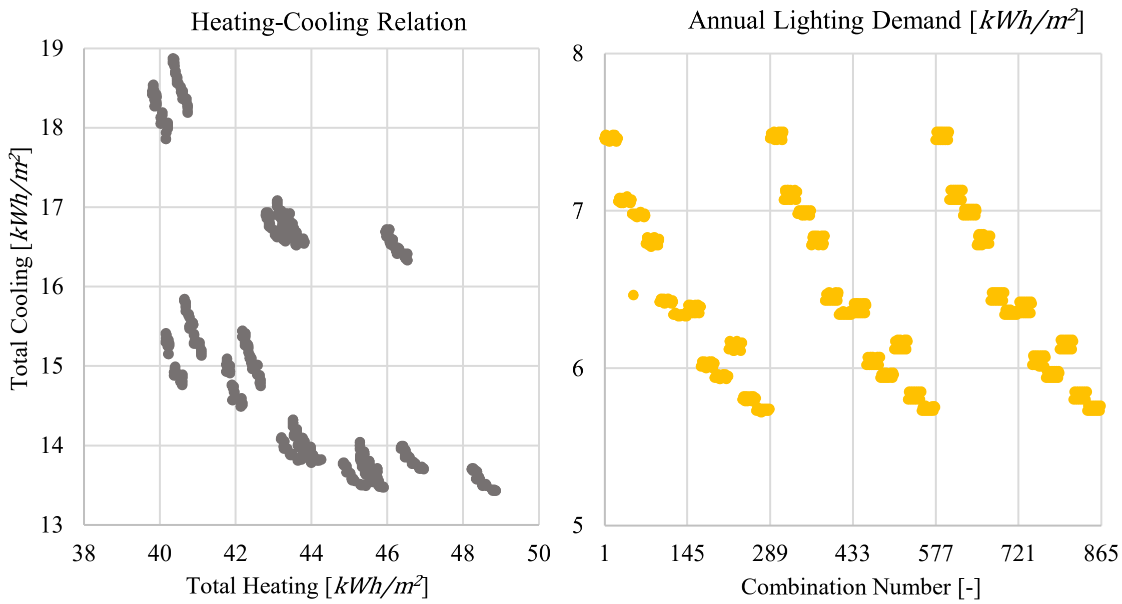


Figure 136: Heating/Cooling energy need relation (left) and artificial lighting energy need variation (right) for the 864 different combinations

The variation of the delivered and primary energy for the room is reported in *Figure 137*. It is visible a progressive reduction of the total primary energy required by the room if the number of the combination increases (i.e. the temperature difference value for the seasonal switch of *DSF* operating strategies is increased).

The reduction in the total delivered energy for the room follows the reduction in the heating energy need observed for the different combinations (this is of course the largest energy use for the room during the year). The total delivered energy in this case is comprised between the values of about *26 kWh/m²* and *31 kWh/m²*. For this, reason, the minimization of the overall primary energy for the room corresponds to one for the heating energy need (in the last implemented combinations).

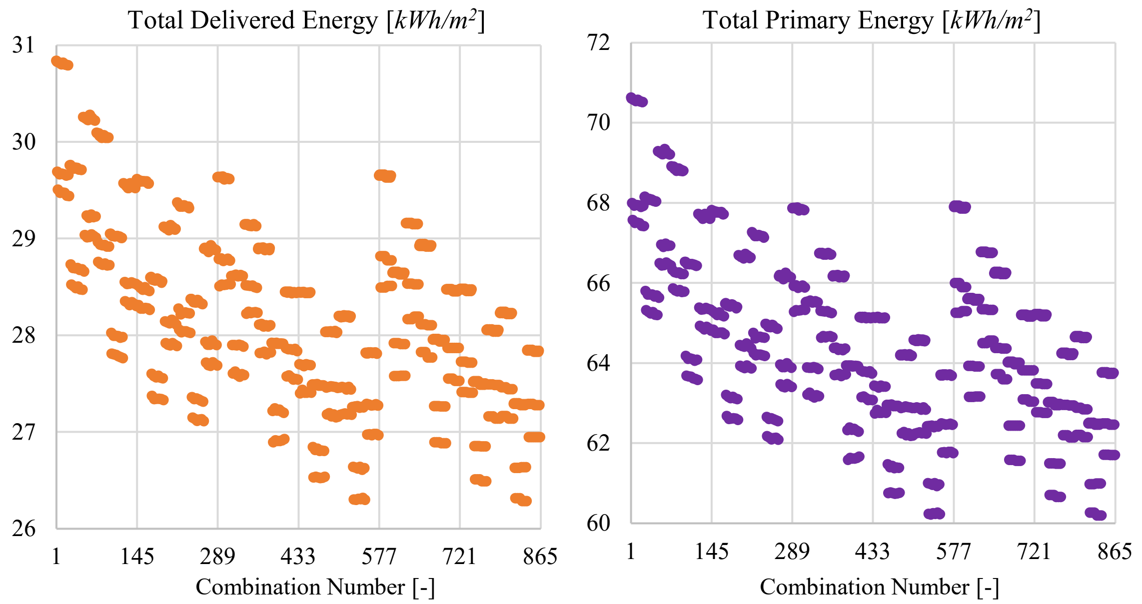


Figure 137: Delivered energy (left) and primary energy (right) variation for the 864 different combinations

7.3. Selection of the optimal combinations and testing

The selected combinations, in function of the results provided by the annual simulations, are the following ones:

1) Combination 10: for this combo there is a minimization of the cooling energy need of the room
2) Combination 844: for this combo there is a minimization of the heating energy need of the room
3) Combination 264: for this combo there is a good balance between the heating and the cooling energy needs of the room
4) Combination 832: for this combo there is a minimization of the total primary energy use of the room, which considers all the different energy uses (heating, cooling and artificial lighting).

For the different combinations of values, the overall performance of the system and the operating strategies assumed by the *DSF* have been analysed. The performance comparison, as mentioned before, has been made considering the *SSF* system and the traditional *DSF* as reference systems. According to the selected combinations, the following modifications have been applied to the two reference systems:

1) For the *SSF*, just the two parameters referred to the activation of the shading (the incident solar radiation on the façade and the indoor air temperature) have been modified in function of the selected combination.
2) For the traditional *DSF*, with the two parameters referred to the activation of the shading, also the temperature difference for the seasonal switch in the operating strategies (*OAC* and *TB*) has been modified in function of the selected combination of values.

In this way, the performance comparison between the different reference systems is more reliable and robust, since the common parameters for the control of the different façade systems are set equal.

7.3.1. Combination number 10

For the minimization of the cooling energy need the selected combination is 10. Among the different implemented combinations, this is the one which minimize the energy consumption for cooling (space and ventilation).

The values adopted in the combination are reported in *Table 104*.

Combination number	Control variable	Values for the control variable
	`temp_switch`	*-10°C*
	`rad_shad`	*200 W/m²*
	`temp_shad`	*20°C*
10	`CO2_Summer`	*500 ppm, 700 ppm* and *900 ppm*
	`TCav_Summer`	*26°C*
	`CO2_winter`	*800 ppm*
	`TCav_Winter`	*4 °C, 21°C, 24°C* and *27°C*

Table 104: Combined values for the combo number 10 (Cooling energy need minimization)

The comparisons with *SSF* and the traditional *DSF* are here reported. Under the point of view of the reduction of the heating energy need (*Table 105* and *Figure 138* on the left), the optimal combination for the cooling energy need produces an increase (*+11.2%*) of the energy need for heating (space and ventilation).

For the Frankfurt climate, this is most consistent compared to the cooling energy need of the room (1.4 times in the case of *SSF*). On the other hand, the traditional *DSF* system reduces the overall energy need for heating (-*9.5%*).

	TOTAL ENERGY NEED [kWh]			*TOTAL ENERGY NEED [kWh/m2]*			[%]
Facade configuration	Space heating	Ventilation heating	TOT	Space heating	Ventilation heating	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 10)	2194.00	149.00	2343.00	45.71	3.10	48.81	**11.2**
Traditional DSF	1859.00	46.21	1905.21	38.73	0.96	39.69	**-9.5**
Reference Single Skin	***2066.00***	***40.12***	***2106.12***	***43.04***	***0.84***	***43.88***	***REFERENCE***

Table 105: Heating energy need variation (Combo 10)

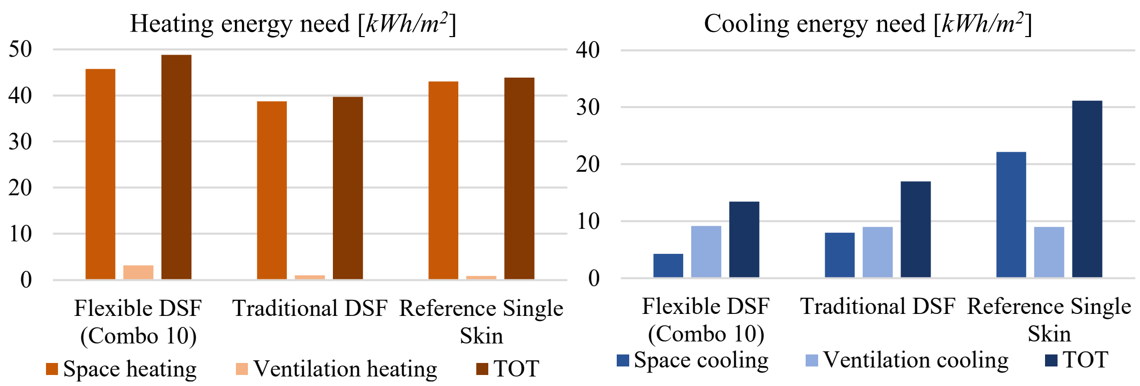


Figure 138: Heating (left) and cooling (right) energy need variation (Combo 10)

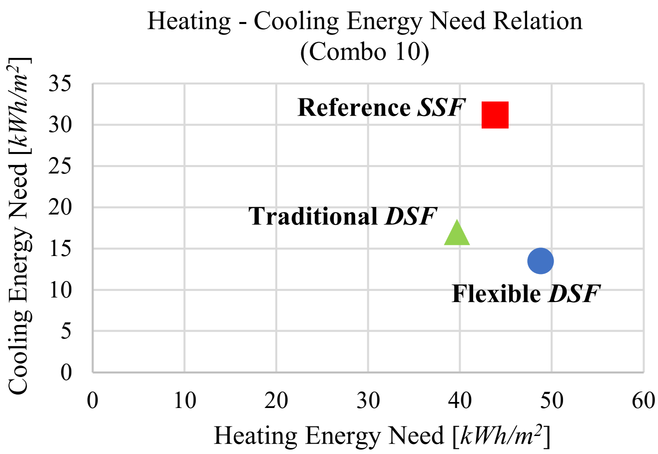
The reduction of the cooling energy (*Table 106* and *Figure 138* on the right) in comparison with *SSF* system is evident (*-56.9%*). The reduction is also much more consistent than the one generated by the traditional *DSF* (-*45.5%*). However, the difference in terms of performance is not so evident as seen for the heating energy need variation.

	TOTAL ENERGY NEED [kWh]			*TOTAL [kWh/m2]*			[%]
Facade configuration	Space cooling	Ventilation cooling	TOT	Space cooling	Ventilation cooling	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 10)	204.60	440.40	645.00	4.26	9.18	13.44	**-56.9**
Traditional DSF	382.80	431.90	814.70	7.98	9.00	16.97	**-45.5**
Reference Single Skin	***1063.00***	***432.50***	***1495.50***	***22.15***	***9.01***	***31.16***	***REFERENCE***

Table 106: Cooling energy need variation (Combo 10)

For this, reason, if the combination number 10 is considered, the overall performance of the flexible *DSF* is worse compared to the one of the traditional one. Both produces a reduction of the overall thermal energy (cooling and heating) that is required by the room through the year, but this reduction is more consistent in the case of the traditional *DSF*.

This is mainly caused by the fact that the flexible *DSF* produces an increase of the heating energy need (*Figure 139* on the left). The minimization of the cooling energy need in Frankfurt is not consequently effective since this energy use is anyway lower compared to the heating.



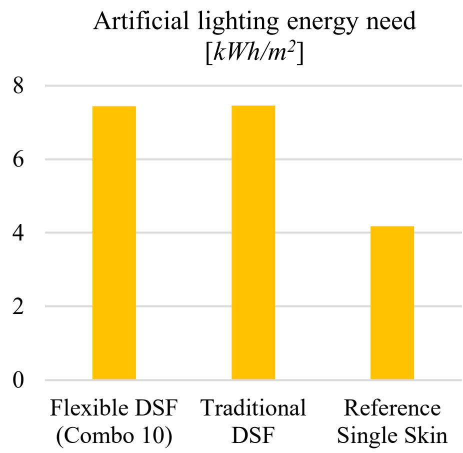


Figure 139: Relation between the heating and the cooling energy needs for Combo 10 (left) and related artificial lighting energy needs (right)

The most critical aspect of the energy performance for the *DSF*, both flexible and traditional, is the increase of the required energy for artificial lighting (*Table 107* and *Figure 137* on the right).

This is the same problem already observed during the single month simulations (especially July). In this case, the radiation control coupled with the cut off produces an overall increase of about *78%* for the *DSF* systems.

Facade configuration	Artificial lighting [*kWh*]	**Artificial lighting [*kWh/m²*]**	Variation [%] (Single Skin)
Flexible DSF (Combo 10)	357.30	7.44	**78.1**
Traditional DSF	358.20	7.46	**78.6**
Reference Single Skin	***200.60***	***4.18***	***REFERENCE***

Table 107: Artificial lighting energy need variation (Combo 10)

The ineffectiveness of the combination is also showed analysing the delivered and primary energy values for the different façade systems (*Table 108* and *Figure 140*). While the flexible *DSF* configuration does not change it significantly the traditional *DSF* can reduce it of about *8%* compared to *SSF*.

Consequently, given the not good performance under the point of view of the heating energy need for this combo, the overall effects on the primary energy need are negative (slightly increase compared to *SSF*).

Facade configuration	**Delivered energy [*kWh/m²*]**	**Primary energy [*kWh/m²*]**	**Variation (Single Skin) [%]**
Flexible DSF (Combo 10)	30.81	70.55	**0.57**
Traditional DSF	28.19	64.55	**-7.98**
Reference SSF	***30.63***	***70.15***	***REFERENCE***

Table 108: Variation of the primary and delivered energy needs (Combo 10)

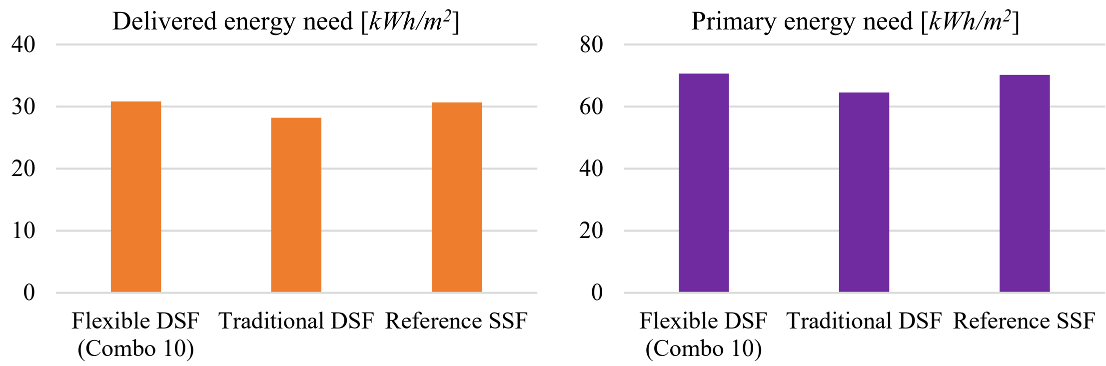


Figure 140: Variation of the primary (right) and delivered (left) energy needs (Combo 10)

About the different strategies and configurations of the *DSF* through the year (*Figure 141*), in the case of the combination number 10, there is a good balance between heating and cooling season strategies: heating season strategies are applied for *53.1%* of the year duration, while the cooling seasons ones for the *46.9%* of the overall year duration.

This is mainly caused by the fact that this combination uses the lowest value of temperature difference for the seasonal switch (*-10°C*).

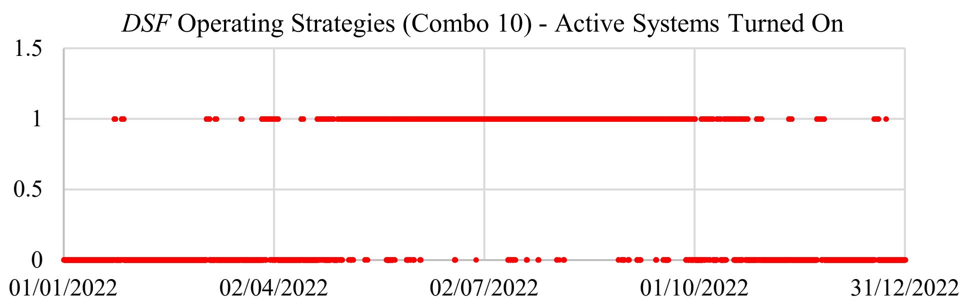


Figure 141: Application of the heating and cooling strategies through the year (Combo 10). 0 = heating season strategies, 1 = cooling season strategies

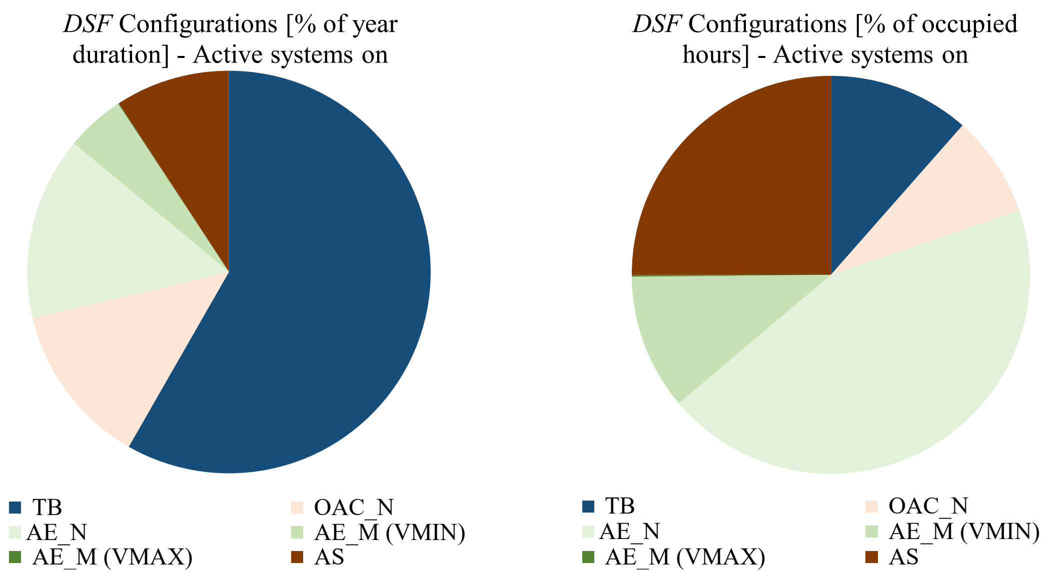


Figure 142: Flexible DSF configuration through the year for combo 10: overall month duration (left) and occupied hours (right)

The *TB* configuration (*Figure 142*) is the most adopted through the year (about *60%*), while the remaining ones (*OAC*, *AE* and *AS*) are adopted with considerably lower frequency (under *20%*). Looking at the occupied hours only, the situation is of course different: The most adopted configuration is *AE* natural, followed by the *AS*. The other configurations (*TB*, *OAC* natural and *AE* mechanical) are applied with a considerably lower frequency.

7.3.2. Combination number 844

For the minimization of the heating energy need the selected combinations is 844. The values adopted in the combination are reported in *Table 109*.

Combination number	Control variable	Values for the control variable
844	`temp_switch`	*0°C*
	`rad_shad`	*500 W/m²*
	`temp_shad`	*26°C*
	`CO2_Summer`	*500 ppm, 700 ppm* and *900 ppm*
	`TCav_Summer`	*20°C*
	`CO2_Winter`	*1000 ppm*
	`TCav_Winter`	*4 °C, 21°C, 24°C* and *27°C*

Table 109: Combined values for the combo number 844 (Heating energy need minimization)

The optimal combination for the heating energy need (*Table 110* and *Figure 143* on the left) of the room produces a good reduction (*-9%*) of this energy demand. Anyway, the overall reduction generated by the traditional *DSF* in this case is more consistent (*-15.2%*). Anyway, the performance under the point of view of the heating energy need is better compared to the one generated by the combination number 10.

The optimal combination for the heating energy need is also quite effective in the reduction of the cooling energy need for the room (*Table 111* and *Figure 143* on the right), as observed for the optimal combination for the cooling energy need. The reduction (*-43.5%*) is anyway less consistent compared to the one observed in the combo number 10. Also in this case, the flexible *DSF* system is more performant than the traditional one in this reduction.

	TOTAL ENERGY NEED [kWh]			*TOTAL ENERGY NEED [kWh/m2]*			*[%]*
Facade configuration	Space heating	Ventilation heating	TOT	Space heating	Ventilation heating	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 844)	1829.00	81.72	1910.72	38.10	1.70	39.81	**-9.0**
Traditional DSF	1735.00	45.57	1780.57	36.15	0.95	37.10	**-15.2**
Reference Single Skin	***2060.00***	***40.21***	***2100.21***	***42.92***	***0.84***	***43.75***	***REFERENCE***

Table 110: Heating energy need variation (Combo 844)

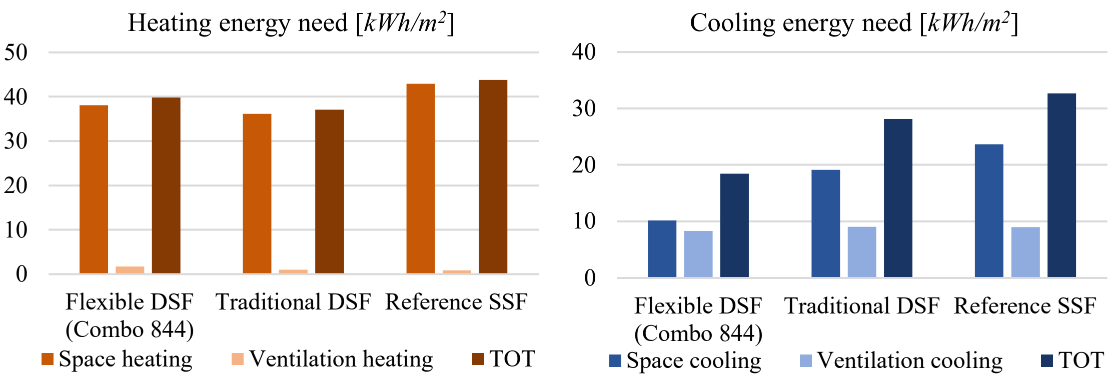


Figure 143: Heating (left) and cooling (right) energy need variation (Combo 844)

	TOTAL ENERGY NEED [kWh]			*TOTAL [kWh/m2]*			[%]
Facade configuration	Space cooling	Ventilation cooling	TOT	Space cooling	Ventilation cooling	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 844)	486.90	399.40	886.30	10.14	8.32	18.46	**-43.5**
Traditional DSF	917.40	432.60	1350.00	19.11	9.01	28.13	**-13.9**
Reference Single Skin	***1136.00***	***432.00***	***1568.00***	***23.67***	***9.00***	***32.67***	***REFERENCE***

Table 111: Cooling energy need variation (Combo 844)

Consequently, in the complex the performance of the combination 844 is much better than the one of the combination 10 (*Figure 144* on the left). There is in fact an overall reduction of the required energy for heating and cooling, greater than the one generated by the traditional *DSF*: for a climate as Frankfurt is consequently more effective to minimize the energy required for heating, compared to the one necessary for cooling purposes. Also under the point of view of the energy requirements for artificial lighting (*Table 112* and *Figure 144* on the right), a consistent improvement of the performance is visible. As it is possible to see, the increase of the required energy for the artificial lighting is limited to less than *40%* for the *DSF* systems. In the case of the combination number 10, the increase was in the order of *80%*, almost the double. The performance improvement under this point of view is consequently evident.

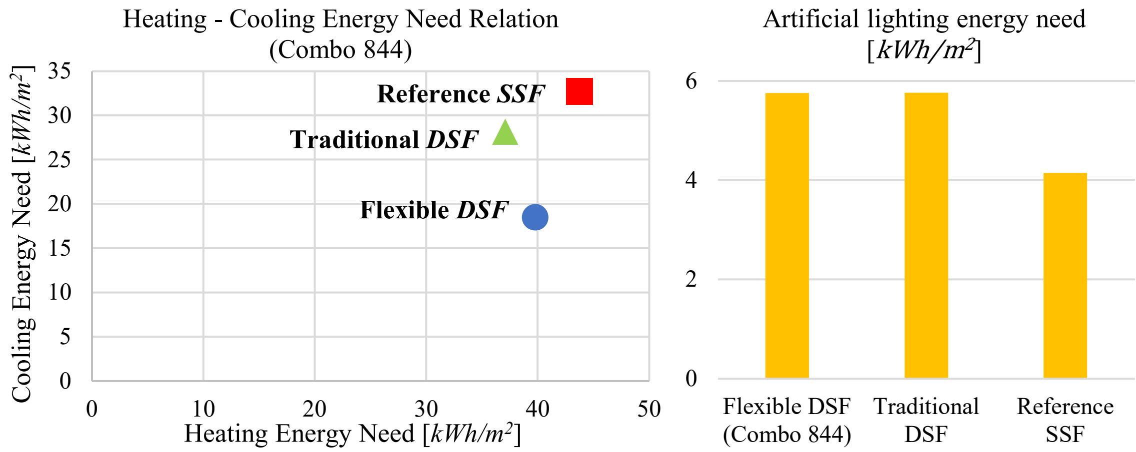


Figure 144: Relation between the heating and the cooling energy needs (left) for Combo 844 and related energy needs for artificial lighting (right).

Facade configuration	Artificial lighting [*kWh*]	**Artificial lighting [*kWh/m²*]**	Variation [%] (Single Skin)
Flexible DSF (Combo 844)	276.20	5.75	**38.8**
Traditional DSF	276.30	5.76	**38.8**
Reference Single Skin	***199.00***	***4.15***	***REFERENCE***

Table 112: Artificial lighting energy need variation (Combo 844)

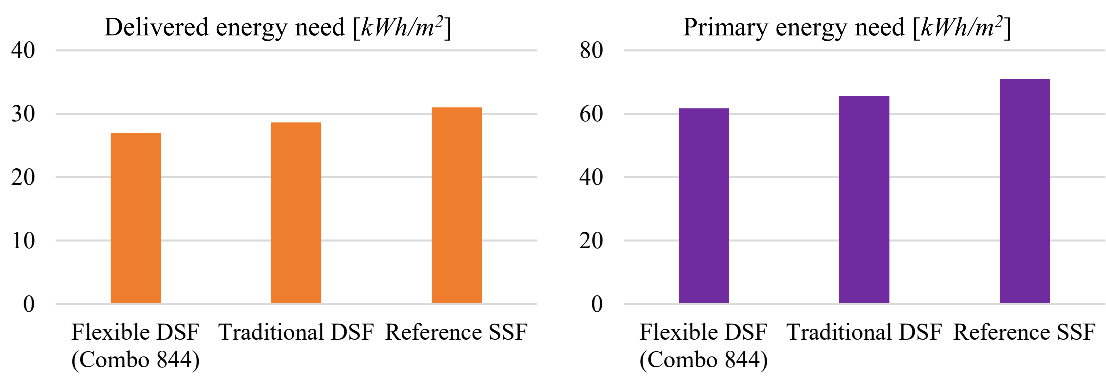


Figure 145: Variation of the primary (right) and delivered (left) energy needs (Combo 844)

Given the results of the energy analysis for the three performance domains (heating, cooling and lighting) it is possible to say that the combination 844 is the best option for the overall energy efficiency of the room. This is also evident considering the primary energy need variation for the different façade solutions (*Table 114* and *Figure 145*). The overall reduction generated by the flexible *DSF* is *13%* while the one of the traditional *DSF* is about *8%*. This combination of values is consequently associated with a better performance improvement of the flexible *DSF* compared with a traditional one. The greater effectiveness is caused by the better performance under the point of view of the reduction of the heating energy need for this combination.

Facade configuration	Delivered energy [kWh/m^2]	Primary energy [kWh/m^2]	Variation (Single Skin) [%]
Flexible DSF (Combo 844)	26.95	61.72	**-13.00**
Traditional DSF	28.63	65.56	**-7.59**
Reference SSF	***30.98***	***70.95***	***REFERENCE***

Table 113: Variation of the primary and delivered energy needs (Combo 844)

About the different strategies and configurations of the *DSF* through the year (*Figure 146*), there is a minimization of the adoption of the cooling season strategies through the year: they are used only for the *2.1%* of the overall year duration, as it is reported in the graph. Basically, only the heating season strategies are applied through the year using the combination number 844. This is mainly caused by the fact that the temperature difference of *0°C* between indoor and outdoor environment is used for the seasonal switch: this temperature difference is reached with a considerably lower frequency compared to *-10°C* and *-5°C*. Therefore, the overall heating energy of the systems can be consequently reduced.

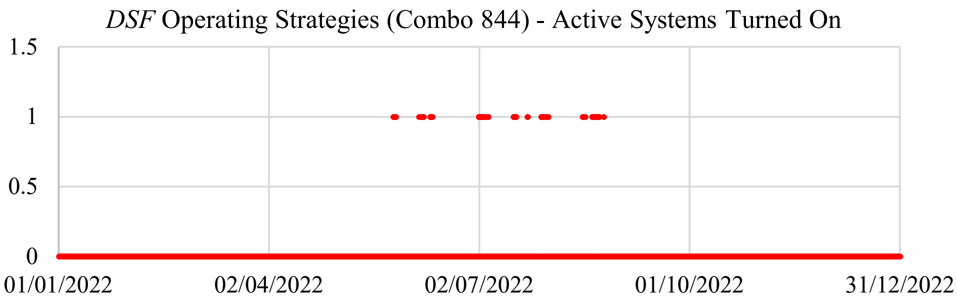


Figure 146: Application of the heating and cooling strategies through the year (Combo 844): 0 = heating season strategies, 1 = cooling season strategies

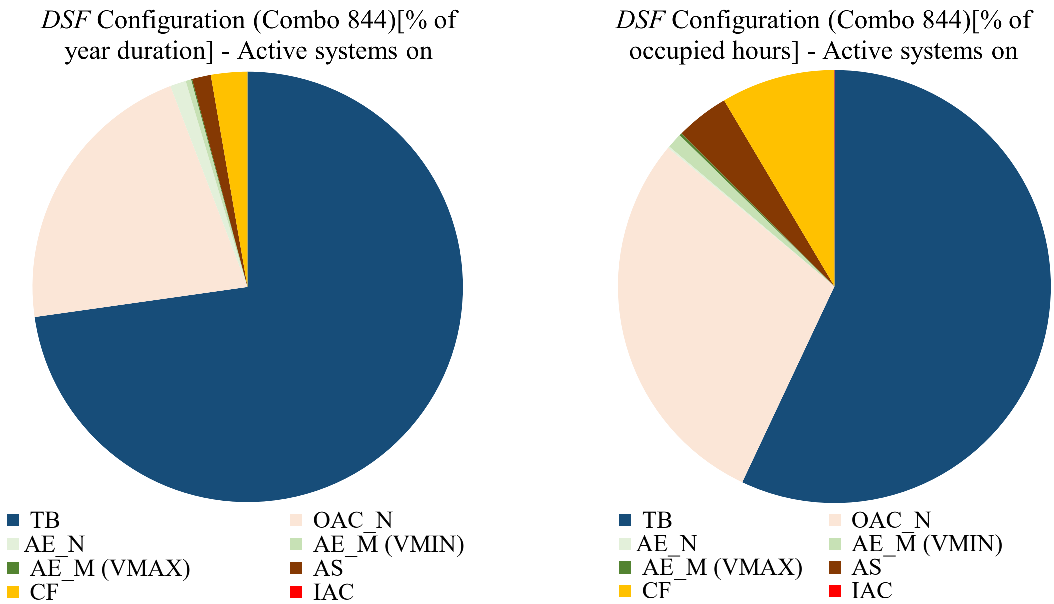


Figure 147: Flexible DSF configuration through the year for combo 844: overall month duration (left) and occupied hours (right)

There is a consistent increase (*Figure 147*) of the adoption of *TB* through the year (above *70%*), compared to the other *DSF* configurations (in particular, *OAC*, *AS*, *AE* and *CF*).

The same trend is also visible looking at the occupied hours only: *TB* remains the main adopted configuration by the flexible *DSF*, followed by *OAC* natural. Other configurations are in this case *AS* (used with considerably lower frequency compared to combination number 10) and *CF* (not used at all by the combination number 10). *IAC* is almost never used in this case.

7.3.3. Combination number 264

For the balance between the heating and the cooling energy need the selected combination is 264. The values adopted in the combination are reported in *Table 114*.

Combination number	Control variable	Values for the control variable
264	`temp_switch`	*-10°C*
	`rad_shad`	*500 W/m²*
	`temp_shad`	*23°C*
	`CO2_Summer`	*600 ppm, 900 ppm* and *1000 ppm*
	`TCav_Summer`	*26°C*
	`CO2_Winter`	*1000 ppm*
	`TCav_Winter`	*4 °C, 21°C, 24°C* and *27°C*

Table 114: Combined values for the combo number 264 (Balance between heating and cooling energy demand)

The comparisons with *SSF* and the traditional *DSF* are here reported. Considering the heating energy need of the room (*Table 116* and *Figure 148* on the left), flexible *DSF* produces a reduction of the energy need for heating (*-1.5%*) considerably less consistent than the one produced by the traditional *DSF* (*-12%*).

	TOTAL ENERGY NEED [kWh]			*TOTAL ENERGY NEED [kWh/m2]*			*[%]*
Facade configuration	Space heating	Ventilation heating	TOT	Space heating	Ventilation heating	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 264)	1913.00	160.40	2073.40	39.85	3.34	43.20	**-1.5**
Traditional DSF	1807.00	45.76	1852.76	37.65	0.95	38.60	**-12.0**
Reference Single Skin	***2065.00***	***40.16***	***2105.16***	***43.02***	***0.84***	***43.86***	***REFERENCE***

Table 115: Heating energy need variation (Combo 264)

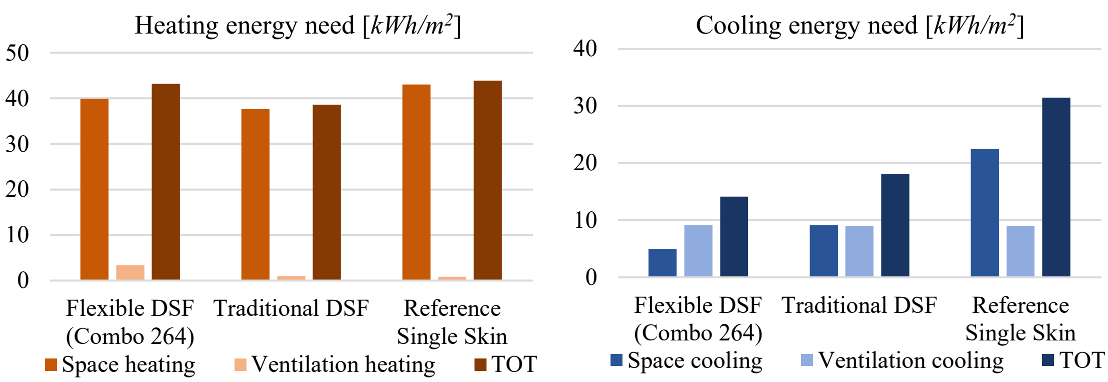


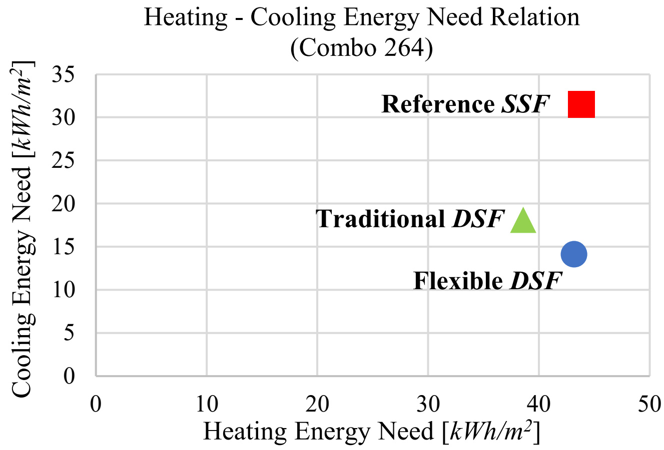
Figure 148: Heating (left) and cooling (right) energy need variation (Combo 264)

Considering the cooling energy need for the room (*Table 116* and *Figure 148* on the right), the reduction produced by the flexible *DSF* is more evident compared to the effect on the heating energy need (*-55.2%*).

However, in this case, compared to the combinations 10 and 844, the performance of the traditional *DSF* is much better (*-42.5%*).

	TOTAL ENERGY NEED [kWh]			*TOTAL [kWh/m2]*			[%]
Facade configuration	Space cooling	Ventilation cooling	TOT	Space cooling	Ventilation cooling	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 264)	238.00	437.90	675.90	4.96	9.12	14.08	**-55.2**
Traditional DSF	436.80	431.60	868.40	9.10	8.99	18.09	**-42.5**
Reference Single Skin	***1077.00***	***432.60***	***1509.60***	***22.44***	***9.01***	***31.45***	***REFERENCE***

Table 116: Cooling energy need variation (Combo 264)



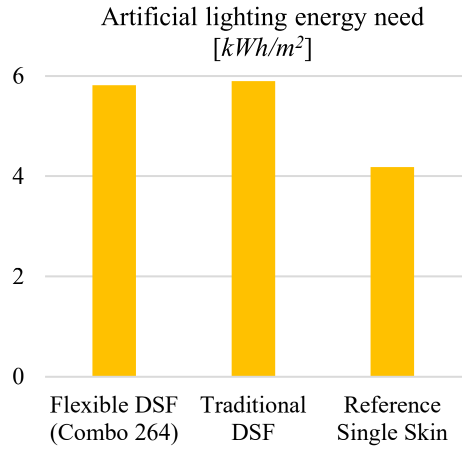


Figure 149: Relation between the heating and the cooling energy needs (left) for Combo 264 and related energy needs for artificial lighting (right)

For this reason, the overall performances of the two systems (traditional and flexible) are almost the same, considering the total reduction of heating and cooling energy required by the room through the year (*Figure 149* on the left).

It is not consequently visible the evident difference in performance observed in the combination 844, in which the overall reduction produced by the flexible *DSF* was more consistent and evident.

As said before, it is possible to say that for a climate as Frankfurt it is better to minimize the overall energy need for heating, instead of searching a possible compromise between heating and cooling requirements.

From the point of view of the energy requirements for artificial lighting (*Table 117* and *Figure 149* on the right), the increase compared to *SSF* is about the same observed in combination 844 (about *40%*) because the same radiation level for the activation of the blind is adopted in the two combinations (*500 W/m²*).

Facade configuration	Artificial lighting [*kWh*]	**Artificial lighting [*kWh/m²*]**	Variation [%] (Single Skin)
Flexible DSF (Combo 264)	*278.90*	*5.81*	***39.0***
Traditional DSF	*283.00*	*5.90*	***41.0***
Reference Single Skin	***200.70***	***4.18***	***REFERENCE***

Table 117: Artificial lighting energy need variation (Combo 264)

The lower effectiveness of the selected combination compared to the combination 844 can be observed also looking at the overall primary energy of the room (*Table 118* and *Figure 150*).

In this case, both the solutions have about the same percentages of reduction of the overall primary energy need, but for the traditional *DSF* this is slightly higher (*-13.7%* against *-11.7%*).

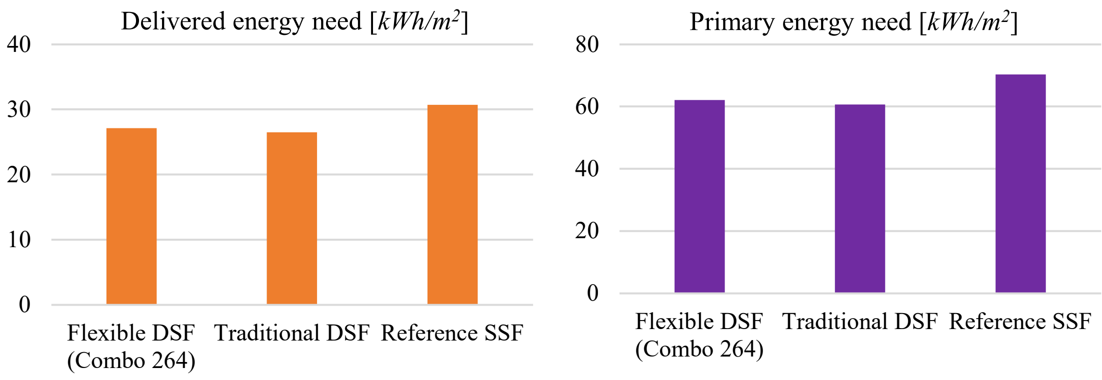


Figure 150: Variation of the primary and delivered energy needs (Combo 264)

For the flexible *DSF*, however, it is possible to see a reduction in the effectiveness of the minimization of the primary energy need, compared to combination 844. This is of course caused by a reduced effectiveness in the reduction of the heating energy need (which is, as said before, the most relevant energy use for the Frankfurt climate).

Facade configuration	**Delivered energy [*kWh/m²*]**	**Primary energy [*kWh/m²*]**	**Variation (Single Skin) [%]**
Flexible DSF (Combo 264)	27.11	62.09	**-11.72**
Traditional DSF	26.50	60.70	**-13.69**
Reference SSF	***30.71***	***70.33***	***REFERENCE***

Table 118: Variation of the primary and delivered energy needs (Combo 264)

Regarding the different strategies adopted by the *DSF* through the year (*Figure 151*), the percentages are analogue to the ones observed in the combination 10: *54.4%* of the year duration for the heating season strategies and *45.6%* for the cooling season strategies. This is caused by the fact that the temperature difference value used for the seasonal switch (*-10°C*) is the same for the two combinations.

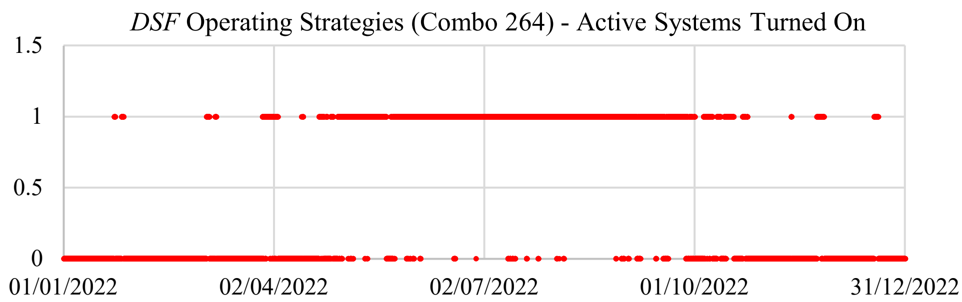


Figure 151: Application of the heating and cooling strategies through the year (Combo 264). 0 = heating season strategies, 1 = cooling season strategies

In terms of configurations (*Figure 152*) there are anyway some substantial differences because different threshold values for the control are anyway adopted. As it is possible to see, there is an increase in the adoption of *TB* and *OAC*, with a reduction in the use of *AE*. Also the adoption of *CF* and *IAC* is visible.

The use of *AS*, on the other hand is similar. Looking at the occupied hours, *TB* is the most adopted configuration (instead of *AE* natural) followed by *AS*, which is used for the same percentage of occupied hours. The adoption of *OAC* natural is slightly higher and the applications of *CF* and *IAC* are visible (the latter almost never is used).

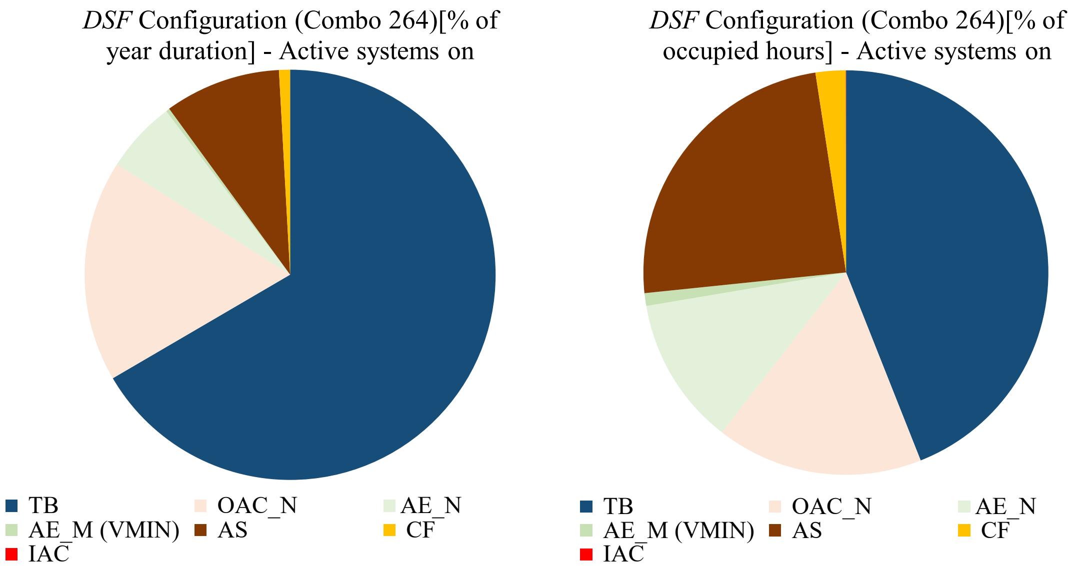


Figure 152: Flexible DSF configuration through the year for combo 264: overall month duration (left) and occupied hours (right)

7.3.4. Combination number 832

The last combination to be selected is the one which minimize the overall primary energy need of the room (*Table 119*). As it is possible to see, they are the same adopted in the combinations 832 (except for the activation temperature of the shading and CO_2 levels during the heating season).

Combination number	Control variable	Values for the control variable
832	`temp_switch`	*0°C*
	`rad_shad`	*500 W/m²*
	`temp_shad`	*23°C*
	`CO2_Summer`	*600 ppm, 900 ppm* and *1000 ppm*
	`TCav_Summer`	*20°C*
	`CO2_winter`	*1000 ppm*
	`TCav_Winter`	*4 °C, 21°C, 24°C* and *27°C*

Table 119: Combined values for the combo number 832 (Primary energy need minimization)

For this reason, the performance of the combination 832 is almost the same of the of the combination 844 and the *DSF* configurations with the two combos are not so different: the minimization of the heating energy need is consequently linked with a minimization of the overall primary energy use in a climate as Frankfurt.

844 is more effective in the reduction of the heating energy need (*-9%* against *-8.4%*) while 832 is more efficient for the cooling energy need (*-51.3%* against *-43.5%*). The increase of the artificial lighting energy need is comparable (around *40%*). In terms of overall primary energy need reduction (*Table 120*), the combination 832 is better, with an overall reduction of *-14.4%* (in the combination 844 the reduction is *-13%*).

Facade configuration	**Delivered energy [*kWh/m²*]**	**Primary energy [*kWh/m²*]**	**Variation (Single Skin) [%]**
Flexible DSF (Combo 832)	*26.29*	*60.20*	***-14.40***
Traditional DSF	*27.68*	*63.38*	***-9.88***
Reference SSF	***30.71***	***70.33***	***REFERENCE***

Table 120: Variation of the primary and delivered energy needs (Combo 832)

7.4. Testing of the optimal combinations in the free running configuration

The selected optimal control combinations have been also tested for the evaluation of the effects on the indoor environmental quality for the occupants. For this purpose, the cell model with the active systems turned off has been used (as done for the simulations performed in July, January, April and October). An additional condition for the seasonal switching between heating and cooling *DSF* control strategies is anyway necessary for this typology of room model.

The cooling season strategies (*SAC#5*) are activated if the indoor air temperature is above a certain threshold (*20°C*, *23°C* or *26°C*). The lower the temperature limit is, the larger is the application of the cooling season strategies compared to the heating season ones: the condition must be satisfied with the temperature difference between indoor and outdoor air already implemented for the flexible *DSF* system in the model with the active systems turned on (*Figure 153*). The switching to the cooling season strategies for the *DSF* is consequently applied only if the two conditions are true.

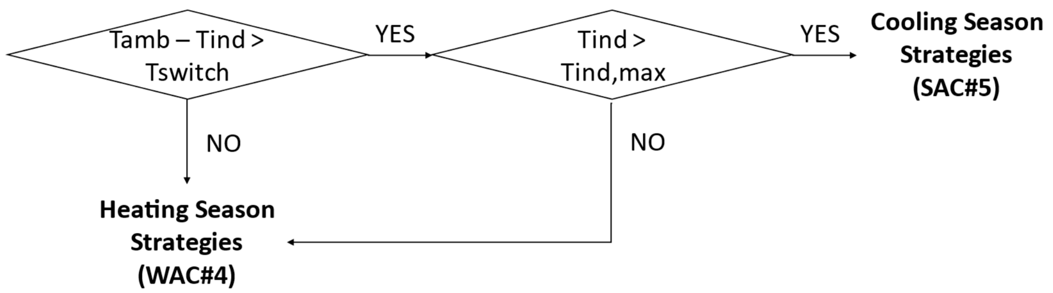


Figure 153: Selection of the cooling and heating season strategies for the DSF operations in function of the temperature difference between indoor and outdoor environment (active systems of the room turned off)

This additional condition is necessary since no active systems for heating and cooling are present in the room: for this reason, the temperature difference profile through the year is different from the one observed if the active systems are turned on (*Figure 154*). In general, the temperature difference quite never reaches the $0°C$ level.

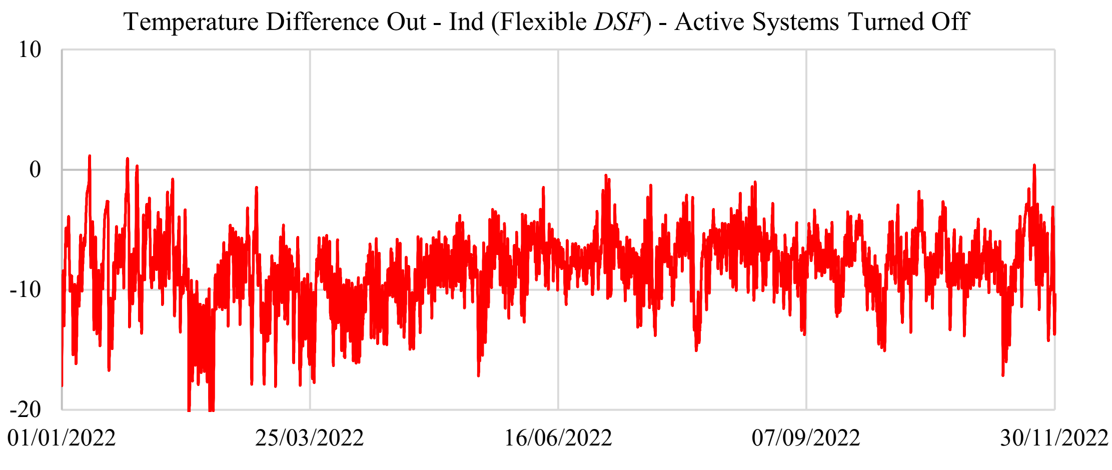


Figure 154: Variation through of the air temperature difference between the outdoor and the indoor environments, if the free running configuration of the model is considered (the flexible DSF system is considered)

Among the different combinations of values, 844 (*Figure 156*) is the one which shows the highest percentages of occupied hours above the limit of $PPD = 10\%$, for all the three selected levels of indoor air temperature for the seasonal switch ($20°C$, $23°C$ and $26°C$). This is mainly caused by the fact that quite never the temperature difference between outdoor and indoor is above $0°C$ in the free running configuration and consequently the heating season strategies (which are not the optimal one for the indoor comfort conditions, as showed during the simulations performed in April and October) are the only ones adopted through the year in the case of this combination. This fact has of course negative aspects linked with the indoor thermal comfort conditions.

Considering the Fanger's comfort indices variation, combination 844 shows percentages of $PPD > 10\%$ near 80%, caused mainly by a potential overheating risk for the occupants (the average increase for the three temperature levels is about 50%). Anyway, the performance compared to the traditional *DSF* system is better (if the limitation of the increase of the possible overheating risk for the occupants is considered). Similar results are also visible in the combination 832, which adopt almost the same *DSF* configurations of 844.

The other two selected combinations (10 and 264) show largely better results in terms of indoor thermal comfort conditions, mainly because they adopt a lower value of temperature difference for the seasonal switch ($-10°C$). In this way, a more balanced adoption through the year of the heating and cooling season strategies is possible, with positive effects on the indoor comfort conditions (however, in the combinations 10 and 264, the adoption of the cooling season strategies is considerably reduced compared to the case in which the active systems are turned on).

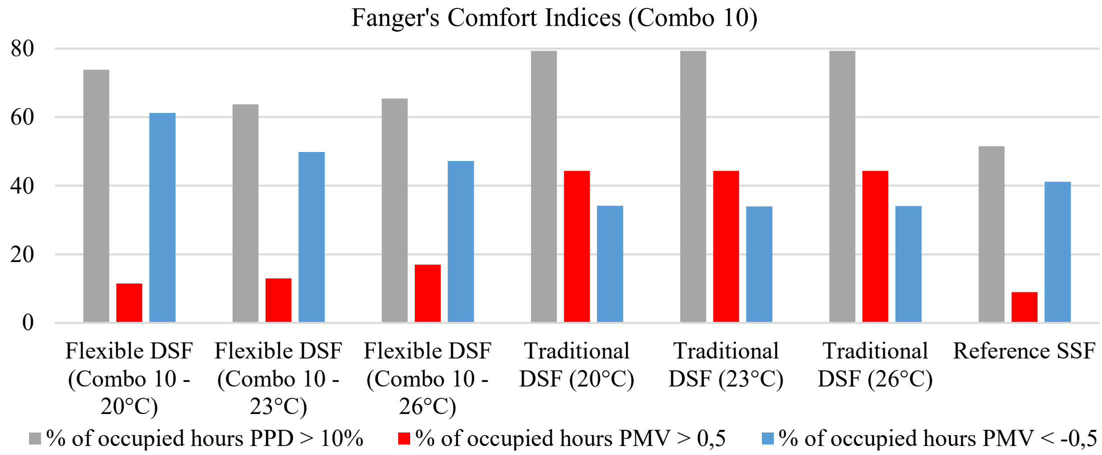


Figure 155: Variation of the Fanger's comfort indices for the combination 10

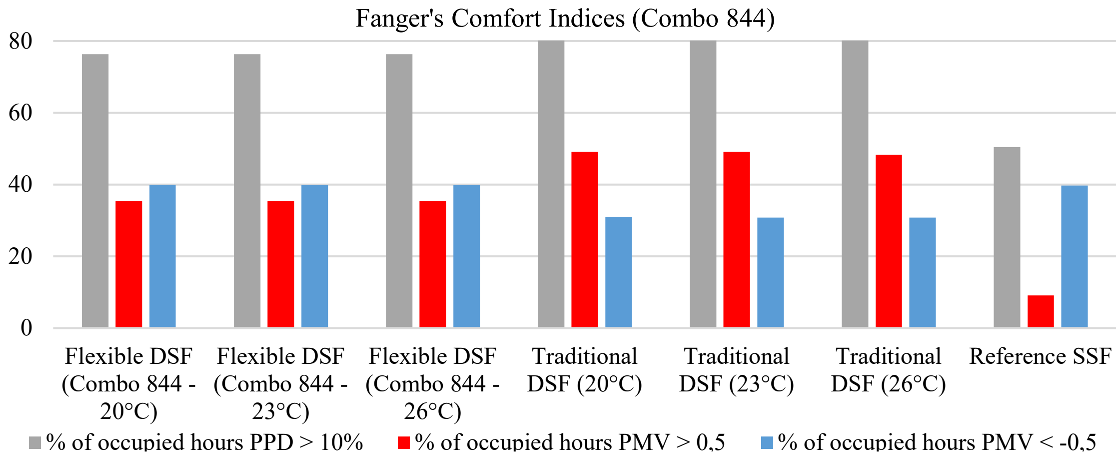


Figure 156: Variation of the Fanger's comfort indices for the combination 844

Considering the Fanger's comfort indices variation (*Figure 155* and *Figure 157*), the influence of the three different temperature levels is evident. Among the three different values, the lowest increase of the number of occupied hours above the limit of $PPD = 10\%$ is associated with the use of the indoor air temperature equal to $23°C$ (the intermediate solution between the heating and the cooling setpoints of the room). In both the cases (combinations 10 and 264) the increase is limited to only 23% (considerably lower than the one of the traditional *DSF* system).

It is consequently better to adopt an intermediate value of indoor air temperature for the switching between the different operating strategies. The other two options for the indoor air temperature ($20°C$ and $26°C$) are associated in the first case to a larger overcooling risk and in the second case to a larger overheating risk, because it is present a not well-balanced adoption of the heating and the cooling season strategies. Consequently, it is possible to say that the combinations 264 and 10 (with the additional condition on the indoor air temperature set to $23°C$) are the best solution in terms of thermal comfort.

The same observations can be of course done also analysing the indoor operative temperature limits (*20°C*, *26°C* and *30°C*), as in the single month simulations. The combination 844 is associated with the largest increase of the number of occupied hours above *26°C* and *30°C*, compared to combinations 10 and 264.

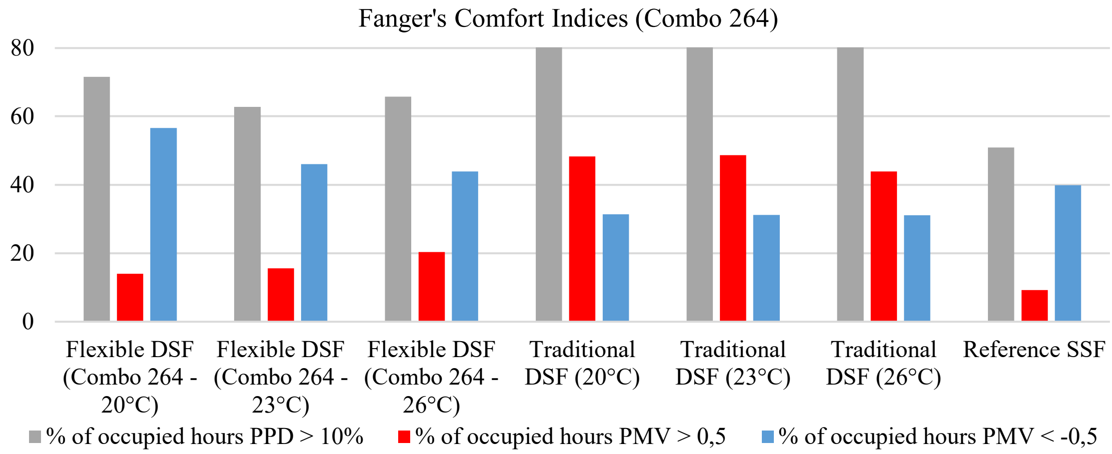


Figure 157: Variation of the Fanger's comfort indices for the combination 264

The opposite situation is of course visible analysing the overcooling risk (*Table 121*): the combination 844 can limit the increase of the number of occupied hours below *20°C* (about *+10%*) while combinations 10 and 264 are associate to larger increases of the number of occupied hours below the limit of *20°C* (for the combination 10 in particular).

This is evident analysing the variations of *PMV < -0.5* in *Figure 155*, *Figure 156* and *Figure 157*, where only combination 844 shows analogue numbers comparable to the ones in *SSF*. In these cases, the traditional *DSF* is more effective in the reduction of the number of occupied hours below the limit of *20°C*.

Facade configuration	***% of occupied hours Top < 20°C***	***Variation (Single Skin) [%]***
Flexible DSF (Combination 10 - 20°C)	54.9	**44.00**
Flexible DSF (Combination 10 - 23°C)	47.3	**24.03**
Flexible DSF (Combination 10 - 26°C)	46.0	**20.71**
Flexible DSF (Combination 264 - 20°C)	*49.6*	***34.85***
Flexible DSF (Combination 264 - 23°C)	*43.9*	***19.33***
Flexible DSF (Combination 264 - 26°C)	*42.6*	***15.99***
Flexible DSF (Combination 844 - 20°C)	*40.8*	***11.36***
Flexible DSF (Combination 844 - 23°C)	*40.7*	***10.89***
Flexible DSF (Combination 844 - 26°C)	*40.7*	***10.89***

Table 121: Variation of the number of occupied hours below the limit of 20°C for the different façade configurations

Almost the same trend in the performance of the three selected combinations is visible analysing the indoor air quality in the room: the heating season strategies are not the optimal solutions for the reduction of the CO_2 peak concentrations in the room.

The combination 844 (*Figure 159*), with a consistent adoption of the heating season strategies, produces an increase of the indoor CO_2 concentrations during the occupied hours compared to *SSF*. Almost all the occupied hours in the room are above the limit of *1000 ppm*.

The performance is almost the same of a traditional *DSF*, for which no air exchange between the cavity and the thermal zone is supposed to be present. The increase of occupied hours above the limit of *1000 ppm*, compared to *SSF*, is in this case in the order of *65%*.

This is mainly caused by the fact the *AS* configuration is quite never used by the *DSF* during the occupied hours, with a subsequent worsening of the indoor air quality conditions. As observed for the thermal comfort conditions, the influence of the three different temperature levels (*20°C*, *23°C* and *26°C*) is not visible.

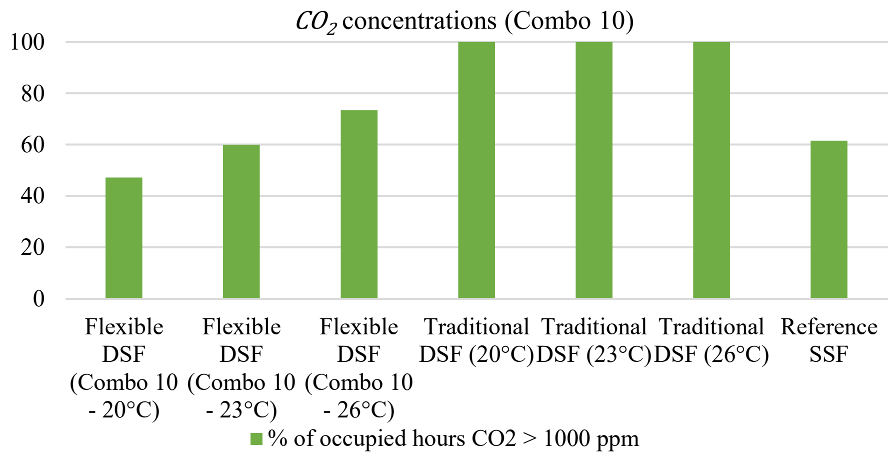


Figure 158: Percentage of occupied hours above the limit of 1000 ppm for the combination 264

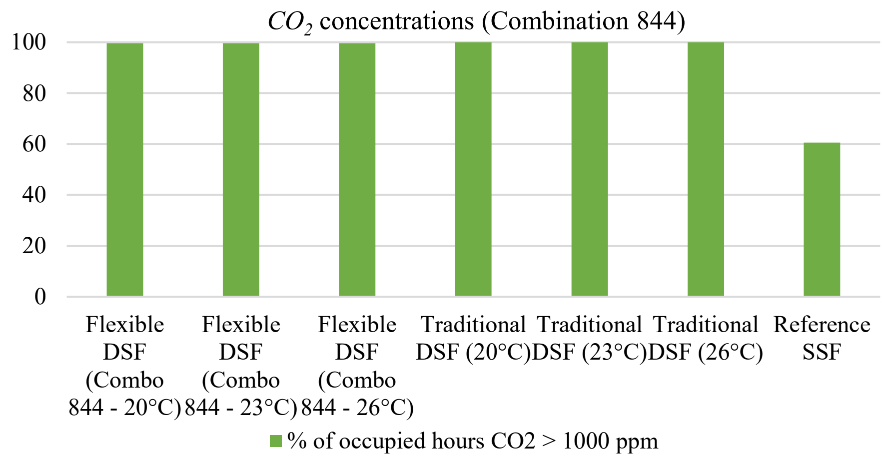


Figure 159: Percentage of occupied hours above the limit of 1000 ppm for the combination 844

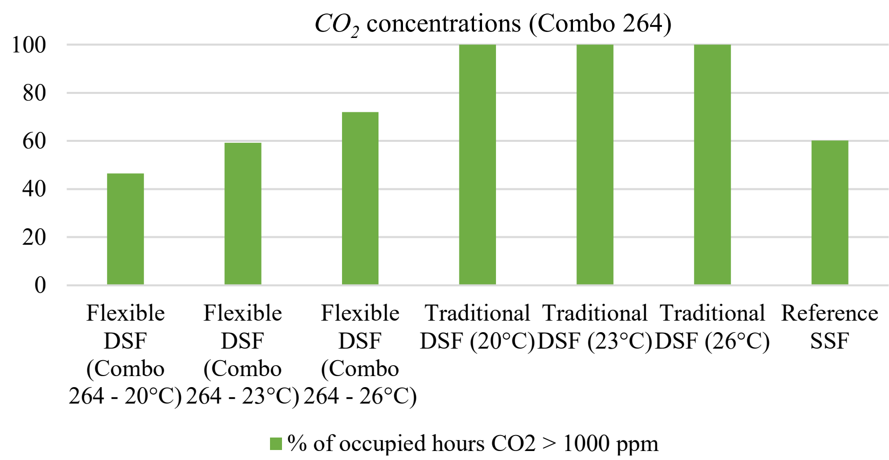


Figure 160: Percentage of occupied hours above the limit of 1000 ppm for the combination 264

The performance of the other two combinations of values (10 and 264) is considerably better (*Figure 158* and *Figure 160*) if the temperature values of *20°C* and *23°C* are used. On the other hand, it is visible an increase of the indoor CO_2 concentrations if the temperature limit of *26°C* is in use (anyway lower than the one generated by the traditional *DSF*). The main difference is in the adoption of the *AS* configuration during the occupied hours, which is higher if the adopted temperature limit is lower (with a larger use of the cooling season strategies). The best results in terms of indoor air quality are for this reason reached with the adoption of the temperature level of *20°C* (average reduction of *23%* of peak CO_2 concentrations in the cases of combinations 10 and 264) while in the case of the application of the *23°C* level the reduction is in the order of only *2%*.

For the indoor illuminance levels, the performance is not depending on the kind of strategy used by the *DSF,* but the incident solar radiation level used for the activation of the blind (as observed for the artificial lighting energy consumptions). Combination 10, which uses the lowest solar radiation limit (*200 W/m²*) is associated with a larger increase of the number of occupied hours below *500 lux* (around *80%*). Combinations 264 and 844, which both adopt the radiation level of *500 W/m²*, are on the other hand associated with a lower increase of the number of occupied hours below the limit (in the order of *40%*).

7.5. Critical points in the application of the rule-based for the whole year control

After the testing of the optimal control combinations for the annual control of the *DSF*, it is now possible to underline some conclusions as already done for the analysis in the months of July, January, October and April. The analysis of the critical points is subdivided in the two main performance domains of the system, energy efficiency and comfort for the occupants since the analysis have been conducted on both the two versions of the room model.

Energy performance optimization

1) In general, the performance under the point of view of the reduction of the cooling energy need for the room is very good for all the selected combinations of threshold values.

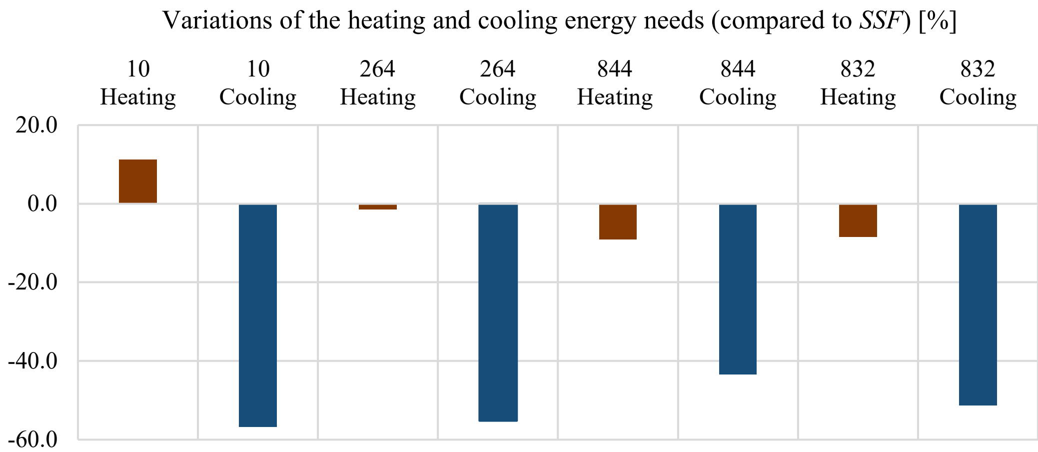


Figure 161: Variations (compared to SSF) of the heating and cooling energy needs generated by the different combinations of values.

However, there is an increase of the required energy for heating in the case of the optimal combo for cooling energy need (10). Also in the case of the optimal combinations for heating energy need and primary energy use (844 and 832) the reduction of the heating energy need is anyway less consistent than the one generated by the traditional *DSF*. Consequently, the optimization of the heating energy need of the room (compared to *SSF*) is much more difficult than the reduction of the energy requirements for cooling (*Figure 161*).

2) The selected combination for the balance of the heating and cooling energy need (264) produces an overall performance of the system which is comparable to the one of the traditional *DSF,* if the energy requirements for cooling and heating are considered. It is not consequently visible the performance gap observed with the adoption of the of the combo for the minimization of the heating energy need of the room (844), which is consequently the best option under the point of view of the energy efficiency.

3) It is visible an increase of the energy for artificial lighting for all the combos, as observed in the single month simulations. The most evident increase is in the case in which the radiation control of the blind is lower (for example *200 W/m²*), as in the case of the combo 10: the increase of the requirements with this combination in in the order of *80%.* The reduction can be considerably reduced if the radiation control of the blind is increased to *500 W/m²:* this is evident in the combos 844, 832 and 264, which the increase is reduced to less than *40%.*

4) However, in the complex, it is visible a reduction of the total delivered and primary energy of the room for the selected combinations (except for 10), considering all the energy uses of heating, cooling and lighting (*Figure 162*). In the cases of the combinations 832 and 844, which showed the lowest values of overall primary energy use, the reduction is more consistent than the one generated by the traditional *DSF*.

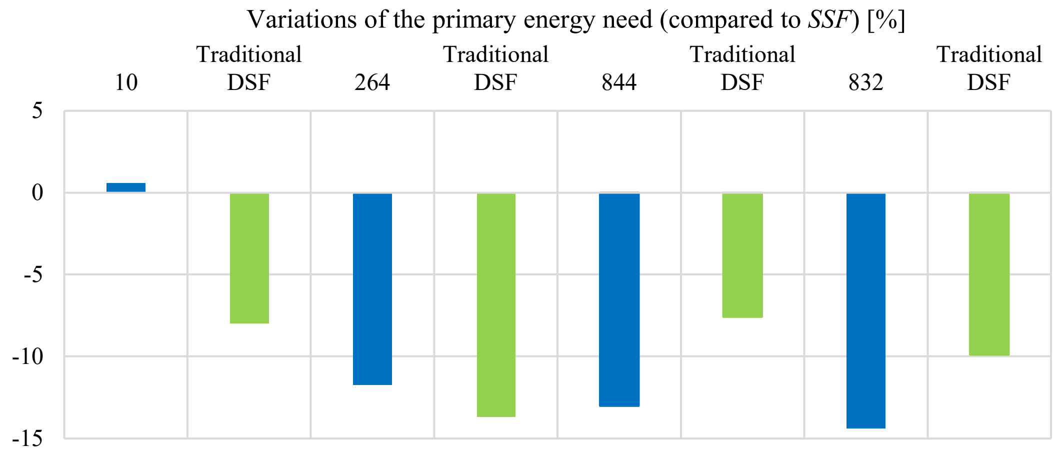


Figure 162: Variations (compared to SSF) of the primary energy need generated by the different combinations of values for the flexible DSF (green columns) and the traditional DSF (blue columns)

Indoor environmental quality improvement

1) All the combinations of values, if tested in the free-running configuration of the model, are unable to improve the indoor comfort conditions, in comparison with the *SSF* system. In particular, the heating season strategies (*WAC#4*), which are particularly effective in the energy optimization of the system (as observed in the combinations 844 and 832) are particularly ineffective in the improvement of the overall comfort conditions of the occupants, both considering the thermal comfort (Fangers's indices) and the indoor air quality (number of occupied hours above the limit of *1000 ppm*): for the combinations 844 and 832 the increase of the number of occupied hours above the limit of *PPD = 10%* is in the order of *50%* compared to *SSF* while almost all the occupied hours of the room show CO_2 levels above *1000 ppm.*

   For this reason, the optimal combinations for the energy efficiency of the room (844 and 832) are less effective for the indoor comfort conditions compared to the other two combinations (10 and 264), which are the not optimal ones for the energy efficiency. These two combinations, on the other hand, show a larger application of the cooling season strategies (*SAC#5*) also in the *free running* configuration of the model: the increase of the number of occupied hours above the limit of *PPD = 10%* can be limited to *23%* and the peak CO_2 concentrations can be reduced of about *20%* compared to *SSF*.

   This performance gap between energy efficiency and indoor environmental quality is the same problem already emerged in the analysis performed during the single months of July, January, October and April, for which it is not possible a multi-domain (energy efficiency and indoor environmental quality) optimization of the system. In fact, the most optimal air flow control for the overall energy efficiency of the system (*WAC#4*) is also the less effective under the point of view of the indoor comfort (as observed in April and October). However, the worsening of the indoor environmental conditions is larger in the case of the application of the traditional *DSF*. The flexible *DSF* is consequently more effective in the limitation of the worsening of the indoor comfort conditions.

2) In analogue way to the increase of the energy requirements for artificial lighting, in the *free running* configuration of the model it is possible to see an increase of the number of occupied hours below the limit of *500 lux*. The increase is much more evident if a lower radiation level is used for the activation of the blind. This is linked with the increase of the artificial lighting requirements already discussed.

8. Findings and conclusions for the selected boundary condition

From the analysis performed in the previous chapters, it is possible to introduce the final considerations regarding the obtained results of the control application for the performance improvement of the flexible *DSF* system.

8.1. Limitations in the use of the rule-based control for the multi-domain optimization

The results of the simulations performed in the single months (July, January, October and April) and through the whole year, have showed some criticalities in the application of the rule-based control for the performance optimization of the *DSF*. The final considerations are specifically linked with the research hypothesis illustrated in *1.7*. Under this point of view, the results of the simulations have been already discussed in detail in *5.2*, *6.3* and *7.5*. In this first section of the last chapter, a general recap of the main aspects is reported.

8.1.1. Heating and cooling season periods simulations

The peak summer and winter conditions (corresponding to the months of July and January) showed the most critical aspects for the control of the *DSF*, as illustrated in the sections *5.1.2.*, *5.1.4.* and *5.2.* However, it was possible to select the two optimal control solutions for the heating and cooling season (*SAC#5* and *WAC#4*). It was also possible to see how different control combinations (defined with the different air flow control logics) can influence the behaviour of the *DSF* and consequently the overall performance of the system (as stated in the second research hypothesis listed in *1.7*).

For the cooling season (July), as observed in *5.1.2.*, the good reduction of the cooling energy need generated by *SAC#5* is linked with an increase of the heating demand of the room (which is anyway considerably lower in absolute terms than the cooling demand). In the summer performance, the effects of the static *OAC* configuration, as illustrated, are considerably better compared to the ones produced by the flexible *DSF*. In addition, despite a good performance under the energy point of view, if the room model with the active systems turned off is considered (*free run* configuration) a worsening of the indoor comfort parameters is visible (only under the point of view of the *IAQ* it is visible a consistent improvement of the performance compared to *SSF* and static *OAC*).

For the winter season (January), as illustrated in *5.1.4.*, the reduction of the heating energy need produced by all the different combinations of control is not particularly significant but at least it is not visible an increase of the cooling energy need for the room. Consequently, under this point of view the energy performance during the winter season is better compared to the summer. The most adopted configuration during the month of January is anyway *TB*, as illustrated in *4.1*, and for this reason the overall performance is comparable to the one of static *TB*. Also considering the indoor comfort conditions, the overall performance of the control is better, with a less critical worsening compared to *SSF*, with respect to July.

Common problems related to the control of the *DSF* in summer and winter conditions, widely discussed in *5.2,* are the increase of the energy need for artificial lighting and the linked reduction of the indoor illuminance levels during the occupied hours of the room (the problem is more evident in July than January), generated by the adoption of two glass skins instead of only one.

The first critical point is consequently the difficulty in the optimization of both, energy efficiency and indoor environmental quality for the occupants, considering the 2 different configurations of the *BESTEST* cell model (active systems turned on and *free run*): if the *DSF* operates with the active systems of the room turned on, an improvement of the energy performance (heating and cooling) is visible but the worsening of *IEQ* is evident if the active systems are turned off.

The second critical point (under the point of view of the energy optimization), during the peak conditions of summer and winter seasons, is that the performance of the static *DSF* configurations (*TB* in winter and *OAC* in summer) is better compared to the one of the different combinations of control implemented for the flexible *DSF*. *TB* is more effective for the heating energy need reduction in January, while *OAC* is better for the cooling energy need lowering in July.

For these peak conditions, the adoption of a static *DSF* configuration produces consequently best results under the energy efficiency point of view, compared to a more flexible one (with an higher configurations variability).

8.1.2. Mid-season periods simulations

As mentioned in *6.3*, the overall performance of the *DSF* optimal control combinations for heating and cooling seasons (*SAC#5* and *WAC#4*) during the months of April and October is considerably better compared to the summer and winter conditions, both under the point of view of the energy efficiency and the indoor environmental quality for the occupants. Moreover, the overall performances of the flexible *DSF* system (considering both heating and cooling energy needs) are better compared to the ones of static *TB* and *OAC*.

Consequently, during the mid-season periods the flexibility of the system is better than the static behaviour of the façade cavity (both as *OAC* or *TB*),

In addition, the selected control combinations for the mid-season tests (*SAC#5* and *WAC#4*) showed a good response and overall flexibility to the change of the system's boundary conditions (in this case, the operating season), by varying the different configurations assumed by the *DSF* respect to the ones observed in July and January. The responsivity of the system is evident in both the two configurations of the *BESTEST* cell model, as illustrated in *6.1.1.1*, *6.1.2.1*, *6.2.1.1* and *6.2.2.1*: the configurations assumed by the flexible *DSF* are different from the one adopted in peak winter and summer conditions, due to the changed environmental conditions.

This is linked with the fourth research hypothesis listed in *1.7*.

However, some critical points are present in the application of the rule-based control also during the mid-season periods. The main one, illustrated in *6.3,* is that the best air flow control for the energy efficiency of the system in April and October (*WAC#4*) is not effective under the point of view of the indoor environmental quality (if the free running configuration of the room is analysed), compared to the less effective control under the point of view of the energy efficiency (*SAC#5*).

Consequently, linked to which has been discussed for the summer and winter seasons (*8.1.1*), the main difficulty in the control (also during the mid-season periods) is the optimization of both, energy efficiency and indoor environmental quality for the occupants, considering the 2 different configurations of the *BESTEST* cell model.

This aspect is evident also considering the simulations referred to the whole year with the adoption of the optimized decision tree, as illustrated in *7.5*. Anyway, despite the critical points, in the complex the overall performance of the flexible *DSF* façade system, compared to a traditional one (both *OAC* and *TB*), is largely better if the mid-season periods are analysed, considering both the overall energy efficiency of the system and the indoor environmental quality.

8.1.3. Whole year simulations

The simulations performed through the whole year for the annual control of the *DSF* (in *7.3* and *7.4*) showed opposite results in terms of energy efficiency and indoor environmental quality.

Three of the selected combinations (264, 844 and 832) are effective in the reduction of the overall primary energy which is required by the room through the year. The flexible *DSF* is consequently a good solution if applied to the model with the active systems turned on, especially for the reduction of the cooling energy need of the room (for which it is more effective than the traditional *DSF*). For the reduction of the heating energy need, on the other hand, the flexible *DSF* showed some limitations and the traditional *DSF* is always more performant in the reduction of this energy use.

If a duration period of one year is considered, however, the overall advantages offered by a flexible *DSF* (compared to a traditional one) are evident, despite the critical points which can emerge during the peak summer and winter conditions: in particular, if the correct combination is selected it is possible to see an overall reduction of the primary energy needs requirements for the room, which are more consistent than the one generated by the traditional *DSF* (this is in case of the application of the combinations 844 and 832).

The main negative aspect is that, as showed in *7.5*, all the different selected combinations have been showed a substantial worsening of the indoor comfort conditions compared to *SSF*. This is the same critical point already discussed for the single month simulations in April, October, July and January: the implemented combinations of rule-based controls are quite effective under an energy efficiency point of view, but some consistent criticalities are visible in the application to the model with the active systems turned off.

Despite this, a positive aspect is that considering the whole year duration the worsening of the indoor comfort conditions produced by the traditional *DSF* is much more evident compared to the one of the flexible *DSF* (analysing the thermal comfort and indoor air quality performance domains in particular).

8.1.4. Adoption of the model-based control as possible solution

All the conclusions reported in *8.1.1*, *8.1.2* and *8.1.3* underlined the difficulty of the use of the rule-based control for a multi domain optimization of the *DSF* performance (considering both, energy efficiency and *IEQ*). As mentioned in *2.2.5*, the innovative concept of the selected *DSF* model used in the Thesis work is the ability to change their configuration to ensure the best fit to a certain boundary condition.

Anyway, traditional concepts of control as the rule-based have showed substantial limitations and criticalities in the fully exploitation of the façade flexibility. This is the confirmation of the third research hypothesis listed in *1.7*, related to the possible ineffectiveness in the adoption of the rule-based control for the performance optimization of a *DSF*: one of the objectives of the Thesis, as already said in the introduction of the work (see *1.4*), is in fact the one to show the limitations in the use of less advanced forms of control in the performance optimization of a flexible *DSF* system, for which more sophisticated forms of control are required.

The intrinsic limitation in the use of the rule-based approach, as already said, is that it is entirely based on the designer knowledge about the physical behavior of the system (in this case, a flexible *DSF* system). Many different combinations of rule-based controls can be defined following the approach illustrated in this Thesis (varying for example the control variables, the related threshold values and the configurations assumed by the *DSF*) but it is anyway impossible to know a priori which the effects on the overall system performance will be. It could be consequently good for simpler adaptive façade systems (electrochromic glazing or movable shading systems), but not for a flexible *DSF*.

Consequently, more innovative, and flexible forms of control are required for such a kind of envelope solutions. The *model-based* approach could be a possible alternative: as mentioned before in *1.4*, it is a more sophisticated form of control for the *DSF* since the optimal asset of the system is defined by means of the simulations carried out on the virtual model for different boundary conditions and time steps. For the actuation of this control strategy, it is necessary to define a priori some criteria that will be used by the simulation environment to address the control of the façade and the definition of its optimal asset.

These criteria correspond to the priority performance targets that the *DSF* must guarantee (already defined in the first step of the control implementation process in *2.2.1*): thermal comfort, visual comfort, indoor air quality and overall energy efficiency for the system. The application of this typology of control could be therefore the right path to follow for the fully exploitation of the façade flexibility in several climatic contexts.

However, due to the larger effort which is necessary for the implementation of efficient *model-based* control solutions and the consistent computational time which is required for all the embedded simulations (as illustrated in the introduction of the Thesis work) the focus of the research was the implementation of *rule-based* strategies.

A possible further development of the Thesis work could be consequently the implementation of *model-based* control solutions for the optimization of both, energy efficiency and *IEQ* for the occupants, applied to the flexible *DSF* model (considering the same climate and the same façade orientation already analyzed in this context).

In this way, a comparison between the effectiveness of the two control approaches could be possible, allowing a more accurate evaluation of the advantages offered by the flexible *DSF* system if more sophisticated forms of control are applied.

9. Control optimization for other climates

A possible further development of the Thesis work is the application of the optimization process of the annual rule-based decision tree for the *DSF* (illustrated in *3.7* and *7.1*) in other boundary and operating conditions (different from the ones in Frankfurt for a South exposed façade): in this way, it could be possible to understand if the critical aspects emerged with the rule-based approach for a certain boundary condition are present also in other contexts (for example a different climate).

In fact, the same optimization process can be applied for example for other climates or façade orientations, keeping the same flexible *DSF* model already implemented for Frankfurt. This is linked with the fourth and last research hypothesis illustrated in *1.7*, already tested with the simulations performed in April and October.

Using the same flexible *DSF* model, in fact, with the proper modifications of the thermal transmittances of the opaque envelope components (floor, roof and walls) due to the different climatic contexts, it is possible to optimize the *DSF* control structure, selecting the optimal combination of values among the proposed 864 (as done in *7.1*). The structure of the optimization script implemented in Python is the same (the possible threshold values for the control variables can be of course changed in function of the different boundary conditions) and different yearly simulations can be run for each one of the implemented combinations (as showed for Frankfurt).

Different climates and locations (according to the *Kopper-Geiger* classification) for the evaluation of the *DSF* performance can be used for this purpose. Possible examples of new climates to consider in the control implementation can be for example:

- Madrid, Spain (*Hot-summer Mediterranean* Climate, *Csa*)
- Oslo, Norway (*Humid-continental* Climate, *Dfb*)

These two are example of climates that are more similar and closer to the *Artic* (Oslo) and the *Saharan* ones (Madrid), therefore they can be considered as more "extreme" cases in which it could be possible to evaluate the *DSF* performance. Frankfurt is exactly in the middle between the two other selected locations and consequently it is characterised by the most temperate and mild environmental conditions.

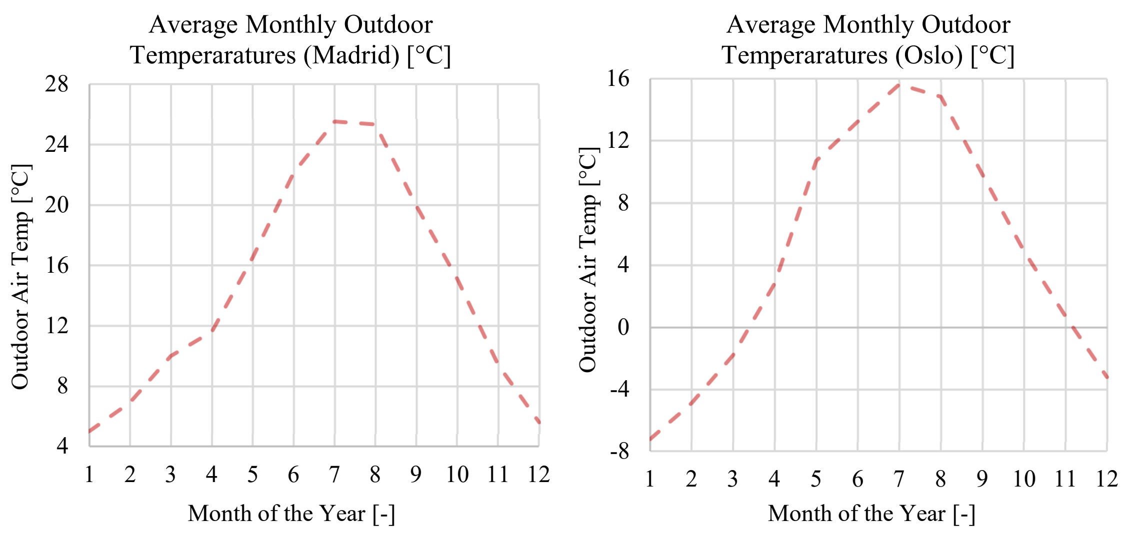


Figure 163: Average monthly values of outdoor air temperature for Madrid (left) and Oslo (right)

An idea about the difference in climate conditions for the two locations can be given by the analysis of the average monthly outdoor air temperature values (*Figure 163*), which are considerably different in the 2 selected locations (and from the ones observed in Frankfurt).

The same is of course for the incident solar radiation on the façade and the cloudiness of the sky.

9.1. Whole year control optimization for Madrid

The same optimization script has been applied to Madrid. Only 2 modifications have been performed with respect to the case of Frankfurt. Firstly, the thermal transmittances of the external opaque enclosures (walls, floor and roof) of the *BESTEST* cell have been modified in accordance with the different climate.

The thermal transmittance values have been taken from the Spanish reference standard regarding the energy efficiency of buildings [38] and they are reported in *Table 122*. They are of course higher than the ones used for Frankfurt.

Enclosure	**Madrid, Spain** (from *Documento Básico HE, Ahorro de Energía*)
External Walls	*0.41 W/m²K*
Floors	*0.65 W/m²K*
Roofs	*0.35 W/m²K*

Table 122: Thermal transmittance values of the opaque enclosures used for Madrid

Moreover, according with the different outdoor air temperature and incident solar radiation on the façade (higher compared to the ones in Frankfurt), the possible values for `TAir_switch` have been modified to *-5°C*, *0°C* and *+5°C* (as is it possible to see in the temperature profile in *Figure 164*) while the possible values for `Rad_shad` have been modified to *300 W/m²*, *400 W/m²*, *500 W/m²* and *600 W/m²* (also in this case higher values compared to the ones used in Frankfurt).

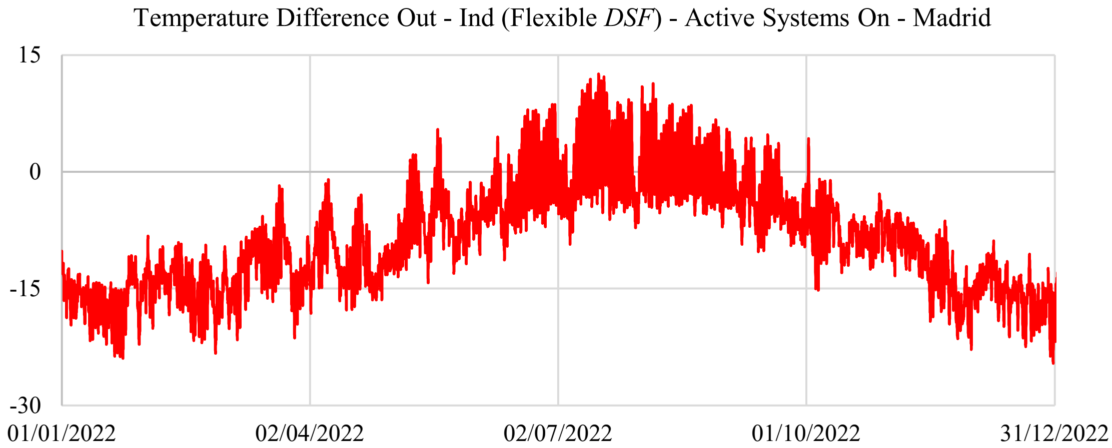


Figure 164: Variation through of the air temperature difference between the outdoor and the indoor environments, if the active systems of the room are on (the flexible DSF system is considered) in Madrid

For the calculation of the total primary energy of the room, the same primary conversion factor of 2.29 has been used. Compared to Frankfurt, the heating energy need is slightly lower, ranging from a minimum of about *33 kWh/m²* to a maximum value of about *37 kWh/m²* (*Figure 165* on the left).

As it possible to see, differently from Frankfurt, it has a constant trend even if the number of the combination is increased: it is not consequently possible to progressively reduce the heating demand as observed in Frankfurt.

The cooling, on the other hand, is considerably higher, as it could be expected in a warmer location as Madrid (*Figure 165* on the right): the values are comprised between a minimum of about *40 kWh/m²* to a maximum of over *54 kWh/m²*. The trend is completely opposite to the one observed in Frankfurt, with a progressive reduction of the overall cooling demand for the room if the number of the combination is increased.

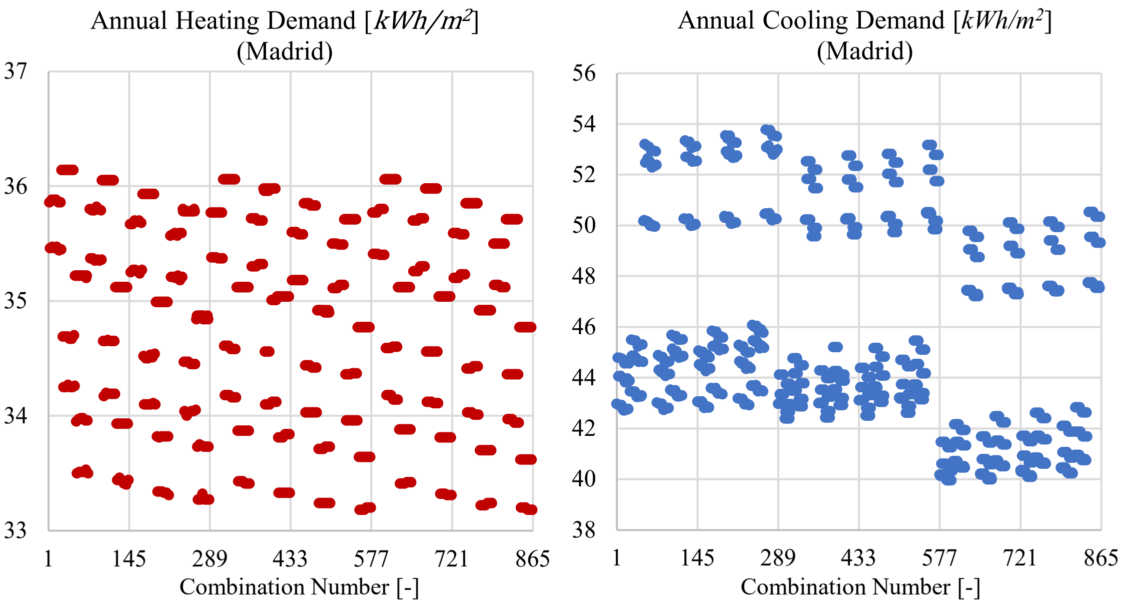


Figure 165: Heating (left) and cooling (right) energy need variation for the 864 different combinations in Madrid

The artificial lighting energy need, thanks to the larger natural light availability in Madrid, compared to Frankfurt, is slightly lower (*Figure 166* on the right).

The variation of the heating and cooling demands for the different combinations of values is reported in *Figure 166* on the left.

Differently from Frankfurt, it is easier to select an optimal combination which can be a compromise for the heating and the cooling energy need of the room.

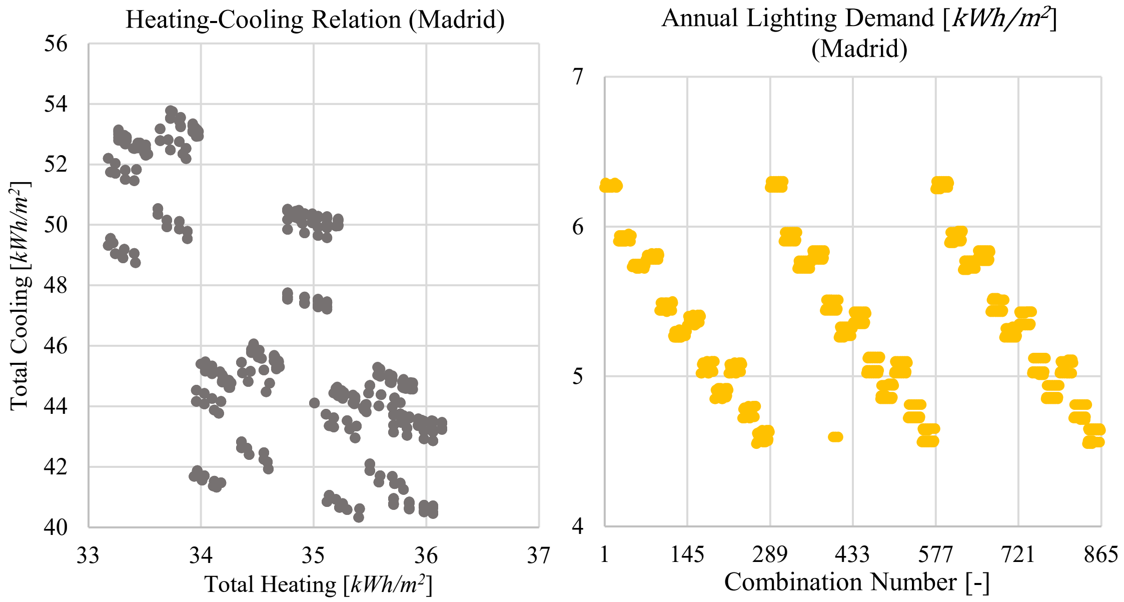


Figure 166: Heating/Cooling energy need relation (left) and artificial lighting energy need variation (right) for the 864 different combinations in Madrid

As observed in Frankfurt, analysing the total delivered energy and the related total primary energy for the room, there is a reduction of them if the number of combinations is increased (*Figure 167*). This can be linked to the progressive reduction of the cooling energy need of the room during, as it was for the heating demand in the Frankfurt climate.

It is consequently more effective to reduce the overall cooling demand of the room (instead of the heating) for a climate as Madrid if the purpose is the minimization of the overall primary energy need.

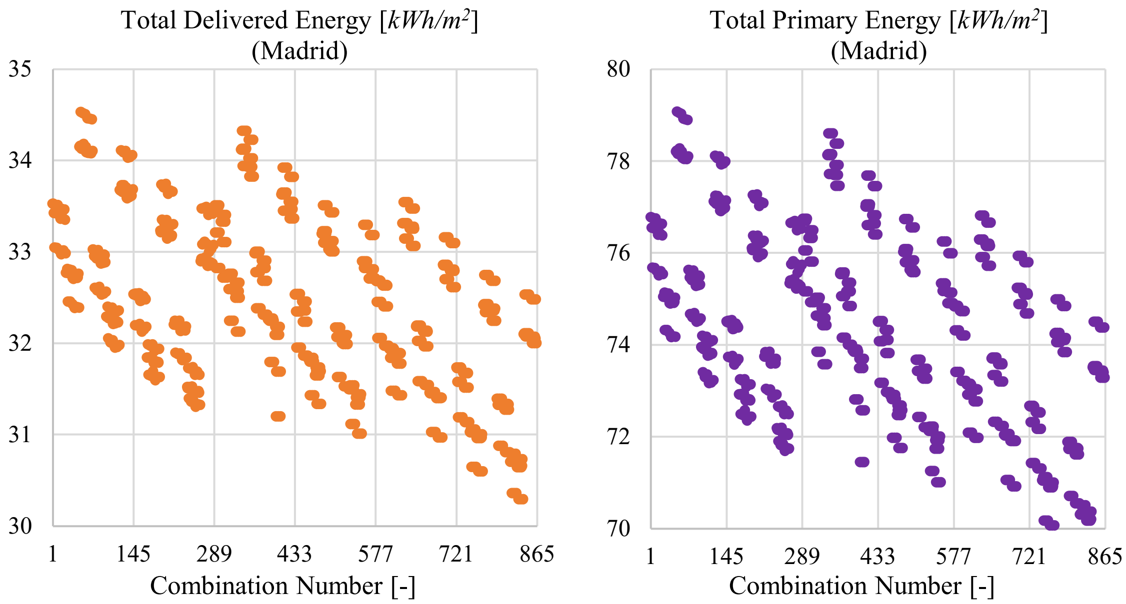


Figure 167: Delivered energy (left) and primary energy (right) variation for the 864 different combinations in Madrid

The first combination to be selected is the number 764, for which it is visible a good balance between heating and cooling energy needs (*Table 123*). This combination is the analogue to the number 264 in Frankfurt, which showed a good reduction in both, heating, and cooling requirements of the room. It is also one of the combinations with the minimum overall values of primary energy consumptions.

Combination number	**Control variable**	**Values for the control variable**
764	`temp_switch`	*5 °C*
	`rad_shad`	*500 W/m²*
	`temp_shad`	*23°C*
	`CO2_Summer`	*600 ppm, 900 ppm* and *1000 ppm*
	`TCav_Summer`	*23°C*
	`CO2_winter`	*1000 ppm*
	`TCav_Winter`	*4 °C, 21 °C, 24 °C* and *27 °C*

Table 123: Combined values for the combo number 764 (Balance between heating and cooling energy demand) for Madrid

The comparisons with *SSF* and the traditional *DSF* are here reported. Regarding the heating energy need of the room (*Table 124* and *Figure 168* on the left), the selected combination keeps unvaried the heating energy need of the room (variation on *+0.3%*, almost null). On the other hand, the traditional *DSF* is more effective in the reduction of the heating energy need of the room (about *-11%*).

As observed in Frankfurt, therefore, the reduction of the heating energy need produced by the traditional *DSF* is more consistent. However, in this case the balanced combination of values produces a slight increase in the energy consumption for heating of the room, while for the combination 264 in Frankfurt a reduction of the heating energy need was visible.

	TOTAL ENERGY NEED [kWh]			*TOTAL ENERGY NEED [kWh/m2]*			*[%]*
Facade configuration	Space heating	Ventilation heating	TOT	Space heating	Ventilation heating	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 764)	1555.00	77.60	1632.60	32.40	1.62	34.01	**0.3**
Traditional DSF	1433.00	17.33	1450.33	29.85	0.36	30.22	**-10.9**
Reference Single Skin	***1613.00***	***14.31***	***1627.31***	***33.60***	***0.30***	***33.90***	***REFERENCE***

Table 124: Heating energy need variation (Combo 764) in Madrid

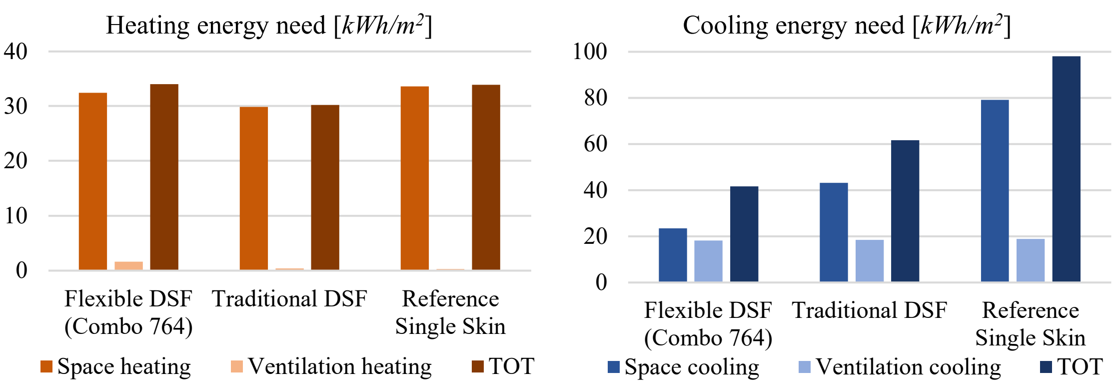


Figure 168: Heating (left) and cooling (right) energy need variation (Combo 764) in Madrid

The cooling energy need (*Table 127* and *Figure 168* on the right), on the other hand, has been reduced by a significant extent by the adoption of the flexible *DSF*. As observed in Frankfurt, the flexible *DSF* is more effective in this reduction compared to the traditional one (*-57.6%* against *-37.1%*). In this case the difference between the two façade configurations is analogue to the one generated by the combination 264 in Frankfurt, but the difference in performance compared to the traditional *DSF* is more evident.

	TOTAL ENERGY NEED [kWh]			*TOTAL [kWh/m2]*			[%]
Facade configuration	Space cooling	Ventilation cooling	TOT	Space cooling	Ventilation cooling	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 764)	1124.00	870.70	1994.70	23.42	18.14	41.56	**-57.6**
Traditional DSF	2073.00	882.00	2955.00	43.19	18.38	61.56	**-37.1**
Reference Single Skin	***3800.00***	***900.20***	***4700.20***	***79.17***	***18.75***	***97.92***	***REFERENCE***

Table 125: Cooling energy need variation (Combo 764) in Madrid

In the complex, consequently, the overall performance of the flexible *DSF* configuration (considering both energy for heating and cooling) is better compared to the one of the traditional *DSF*, as illustrated in *Figure 169* on the left.

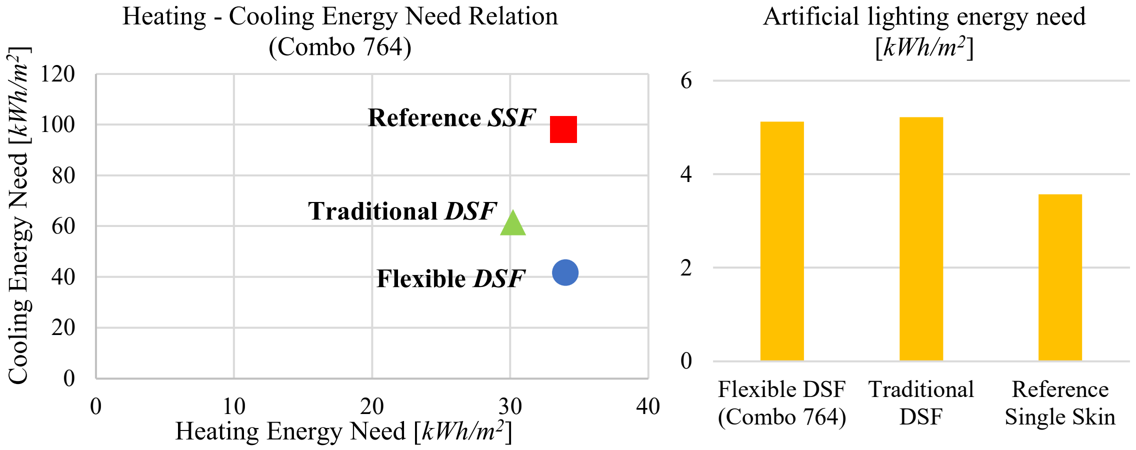


Figure 169: Relation between the heating and the cooling energy needs (left) for Combo 764 and related energy needs for artificial lighting in Madrid (right).

From the point of view of the energy requirements for the artificial lighting of the room (*Table 128* and *Figure 169* on the right), as seen in Frankfurt it is visible an increase of this energy need.

The increase is of course the same for the two different *DSF* systems, in the order of *45%*, slightly higher than the one observed in the combinations 844 and 264 in Frankfurt (which showed a good performance under this point of view).

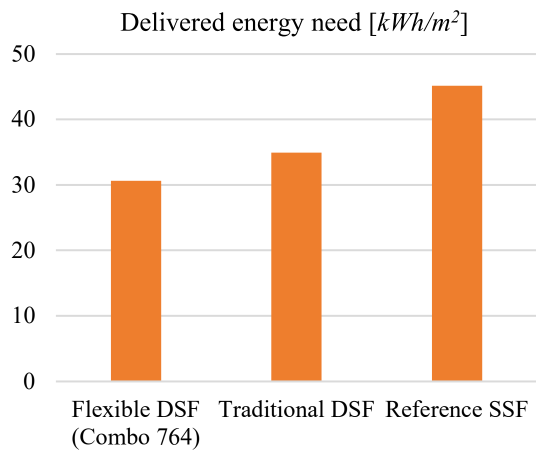
Facade configuration	Artificial lighting [*kWh*]	**Artificial lighting [*kWh/m²*]**	Variation [%] (Single Skin)
Flexible DSF (Combo 764)	246.00	5.13	**43.7**
Traditional DSF	250.70	5.22	**46.4**
Reference Single Skin	***171.20***	***3.57***	***REFERENCE***

Table 126: Artificial lighting energy need variation (Combo 764) in Madrid

Differently from Frankfurt, it is possible to notice a more consistent reduction of the primary energy need for both the two *DSF* configurations (traditional and flexible). As it is showed in *Table 129* and *Figure 170*, the reduction for the flexible *DSF* is over *-32%* while for the traditional one the reduction is in the order of *-23%.* The balance between heating and cooling energy uses is consequently a good solution for a climate as Madrid (characterized by a larger cooling demand compared to Frankfurt).

Facade configuration	**Delivered energy [*kWh/m²*]**	**Primary energy [*kWh/m²*]**	**Variation (Single Skin) [%]**
Flexible DSF (Combo 764)	30.60	70.08	**-32.15**
Traditional DSF	34.90	79.92	**-22.63**
Reference SSF	***45.10***	***103.29***	***REFERENCE***

Table 127: Variation of the primary and delivered energy needs (Combo 764) in Madrid



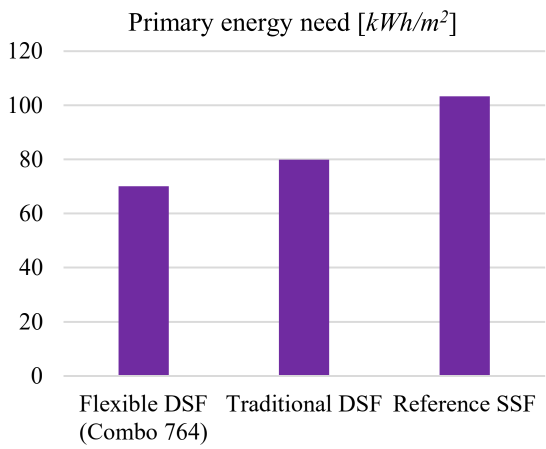


Figure 170: Variation of the primary (right) and delivered (left) energy needs (Combo 764) in Madrid

Regarding the different strategies adopted by the *DSF* through the year (*Figure 171*), it is clearly visible that for the greatest part of the year the heating season strategies are applied (*95.5%* of the overall year duration). Compared to the combination 264 in Frankfurt, there is a consistent reduction in the application of the cooling season strategies.

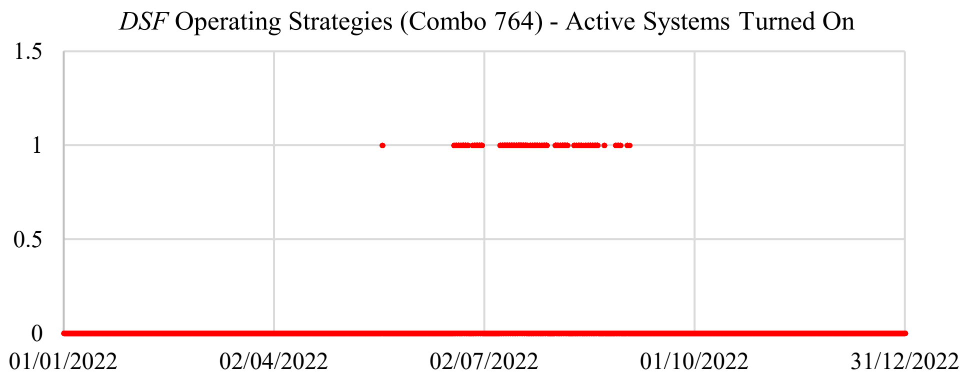


Figure 171: Application of the heating and cooling strategies through the year (Combo 764) in Madrid. 0 = heating season strategies, 1 = cooling season strategies.

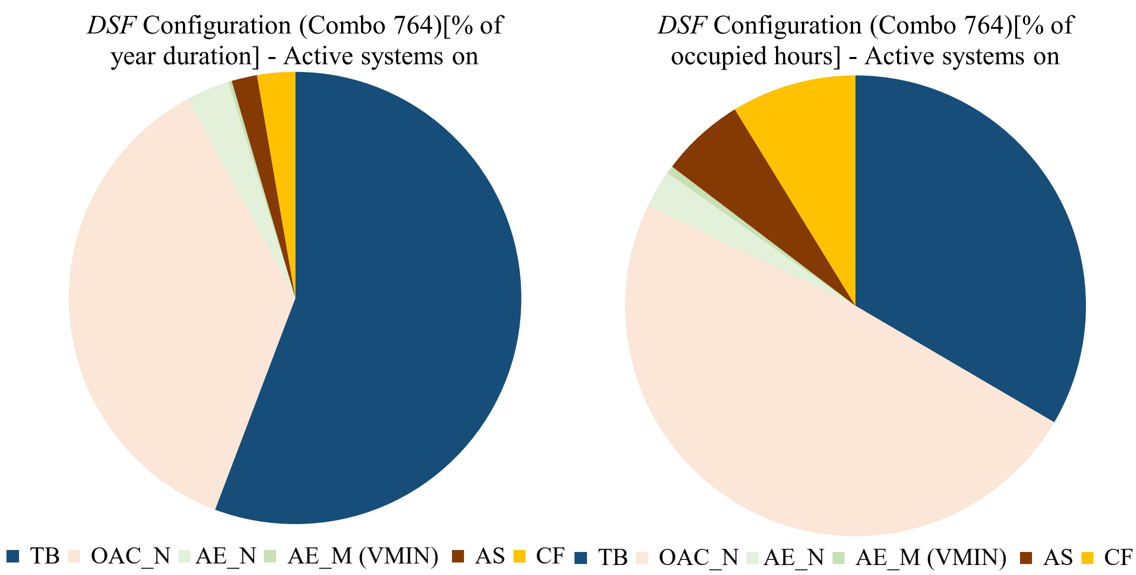


Figure 172: Flexible DSF configuration through the year (% of year duration) for combo 764 in Madrid: overall month duration (left) and occupied hours (right)

In terms of configurations (*Figure 172*), *TB* is applied with a lower frequency than in combination 264 in Frankfurt. On the other hand, *OAC* natural is present with a larger frequency. It is also visible a reduction in the application of *AS* configuration (due to the higher temperature inside the cavity in a location as Madrid).

Considering the occupied hours only, the change in configurations compared to the Frankfurt case is more evident: there is a reduction in the application of *TB* and *AS*, while *OAC* is natural is applied with a larger extent. Given the not good results in the reduction of the heating energy need for the room, another combination can be selected.

In this case, the number 556, which showed the minimum values for the heating energy need among the different implemented combinations (*Table 128*).

Combination number	**Control variable**	**Values for the control variable**
556	`temp_switch`	*0°C*
	`rad_shad`	*600 W/m²*
	`temp_shad`	*26°C*
	`CO2_Summer`	*500 ppm, 700 ppm* and *900 ppm*
	`TCav_Summer`	*20°C*
	`CO2_Winter`	*1000 ppm*
	`TCav_Winter`	*4°C, 21°C, 24°C* and *27°C*

Table 128: Combined values for the combo number 556 (Minimization of the heating energy need) for Madrid

Regarding the heating energy need for the room (*Table 129* and *Figure 173* on the left), it is possible to see a reduction of the heating energy need (*-1.3%*) with the application of the combination 556. However, also in this case the reduction of the heating energy need is more consistent in the case of the application of the traditional *DSF*. This is the same situation already observed in the combination 764 and in the Frankfurt case.

	TOTAL ENERGY NEED [kWh]			*TOTAL ENERGY NEED [kWh/m2]*			*[%]*
Facade configuration	Space heating	Ventilation heating	TOT	Space heating	Ventilation heating	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 556)	1515.00	77.58	1592.58	31.56	1.62	33.18	**-1.3**
Traditional DSF	1413.00	17.35	1430.35	29.44	0.36	29.80	**-11.3**
Reference Single Skin	***1599.00***	***14.29***	***1613.29***	***33.31***	***0.30***	***33.61***	***REFERENCE***

Table 129: Heating energy need variation (Combo 556) in Madrid

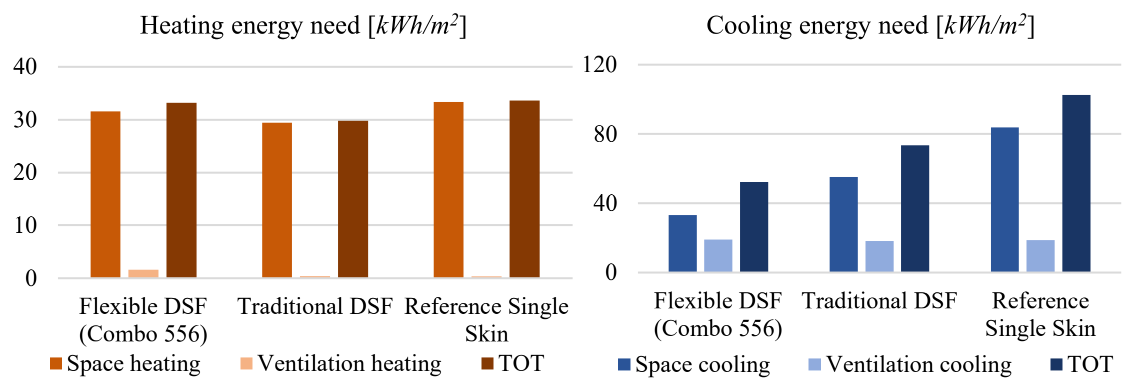


Figure 173: Heating (left) and cooling (right) energy need variation (Combo 556) in Madrid

Regarding the cooling energy need for the room (*Table 130* and *Figure 173* on the right), the selected combination is less effective than 764 in the reduction of the cooling energy need for the room (*-49%* against *-57.6%*). However, also for this combination the reduction of the cooling energy is considerably more evident in the case of the application of the flexible *DSF*.

	TOTAL ENERGY NEED [kWh]			*TOTAL [kWh/m2]*			[%]
Facade configuration	Space cooling	Ventilation cooling	TOT	Space cooling	Ventilation cooling	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 556)	1592.00	913.80	2505.80	33.17	19.04	52.20	**-49.0**
Traditional DSF	2644.00	881.90	3525.90	55.08	18.37	73.46	**-28.3**
Reference Single Skin	***4016.00***	***899.70***	***4915.70***	***83.67***	***18.74***	***102.41***	***REFERENCE***

Table 130: Cooling energy need variation (Combo 556) in Madrid

Also in this case, the overall performance of the flexible *DSF*, considering the heating and cooling energy need of the room, is better, as reported in *Figure 174* on the left.

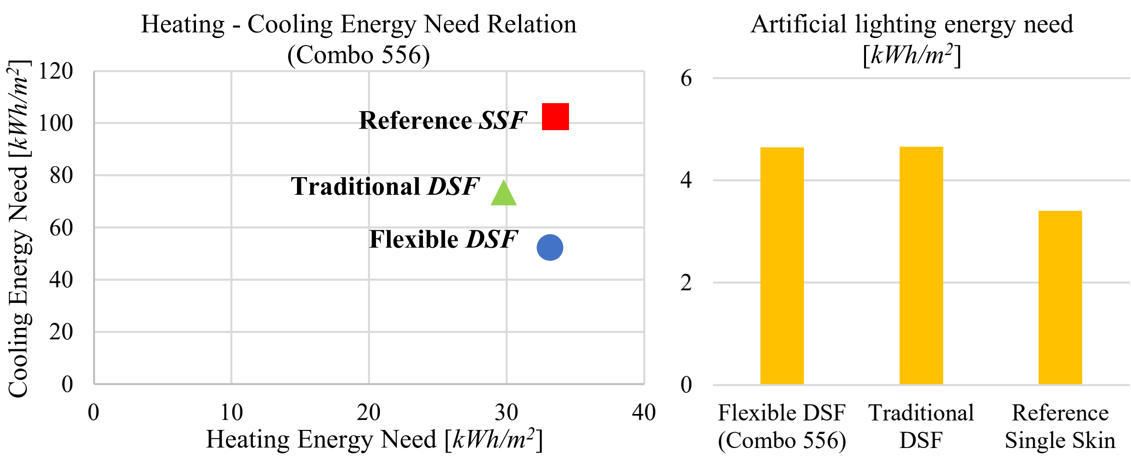


Figure 174: Relation between the heating and the cooling energy needs (left) for Combo 556 and the related energy needs for artificial lighting (right).

Regarding the artificial lighting energy need (*Table 131* and *Figure 174* on the right), the increase is in the order of *37%* for both the *DSFs* (static and flexible), comparable to the one observed in the combinations 844 and 264 in Frankfurt (anyway lower than *40%*).

Facade configuration	Artificial lighting [*kWh*]	**Artificial lighting [*kWh/m²*]**	Variation [%] (Single Skin)
Flexible DSF (Combo 556)	222.90	4.64	**36.5**
Traditional DSF	223.50	4.66	**36.9**
Reference Single Skin	***163.30***	***3.40***	***REFERENCE***

Table 131: Artificial lighting energy need variation (Combo 556) in Madrid

As observed for the previous combo, a more evident reduction of the primary and delivered energy need for the room (compared to *SSF*) can be observed (*Figure 175* and *Table 132*). Also in this case, the reduction of the primary energy for the flexible *DSF* is more evident compared to the one of the traditional solution.

However, the generated reduction is slightly lower compared to the one of the combination 764: the minimization of the heating energy need is consequently not optimal for the reduction of the overall primary energy need for a climate as Madrid: the performance of the combination 764 is better under this point of view.

Facade configuration	**Delivered energy [*kWh/m²*]**	**Primary energy [*kWh/m²*]**	**Variation (Single Skin) [%]**
Flexible DSF (Combo 556)	32.83	75.18	**-28.79**
Traditional DSF	37.56	86.02	**-18.53**
Reference SSF	***46.11***	***105.58***	***REFERENCE***

Table 132: Variation of the primary and delivered energy needs (Combo 556) in Madrid

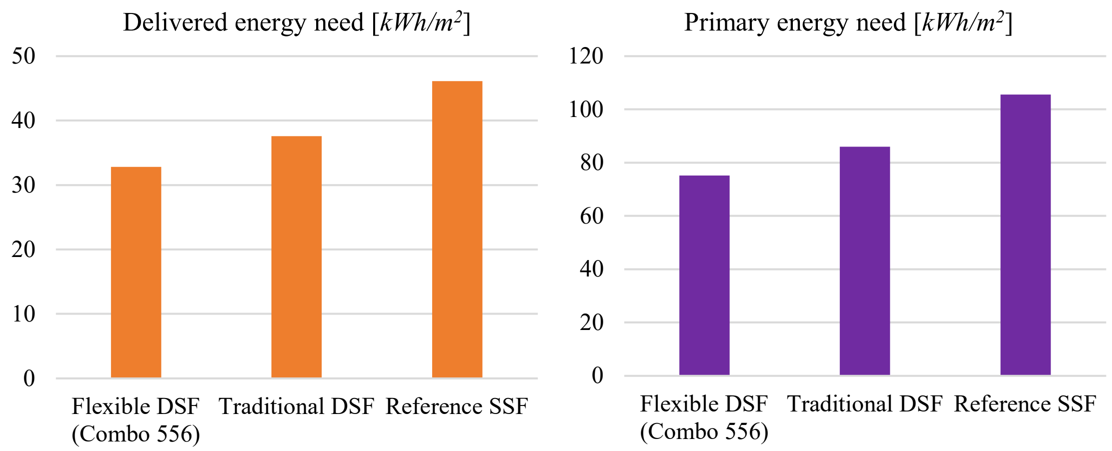


Figure 175: Variation of the primary (right) and delivered (left) energy needs (Combo 556) in Madrid

Regarding the different strategies adopted by the *DSF* through the year (*Figure 176*), it is visible a larger application of the cooling season strategies (*12.4%* of the overall year duration).

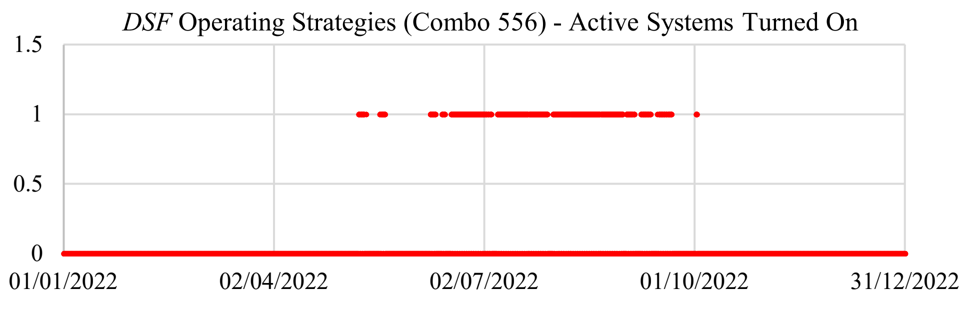


Figure 176: Application of the heating and cooling strategies through the year (Combo 556) in Madrid. 0 = heating season strategies, 1 = cooling season strategies

Regarding the different configurations adopted by the *DSF* through the year (*Figure 177*), the configurations are almost the same observed for the combination 764. The percentages for the adoption of *TB* and *OAC* are similar, while only an increased application of the *AE* mechanical configuration is visible.

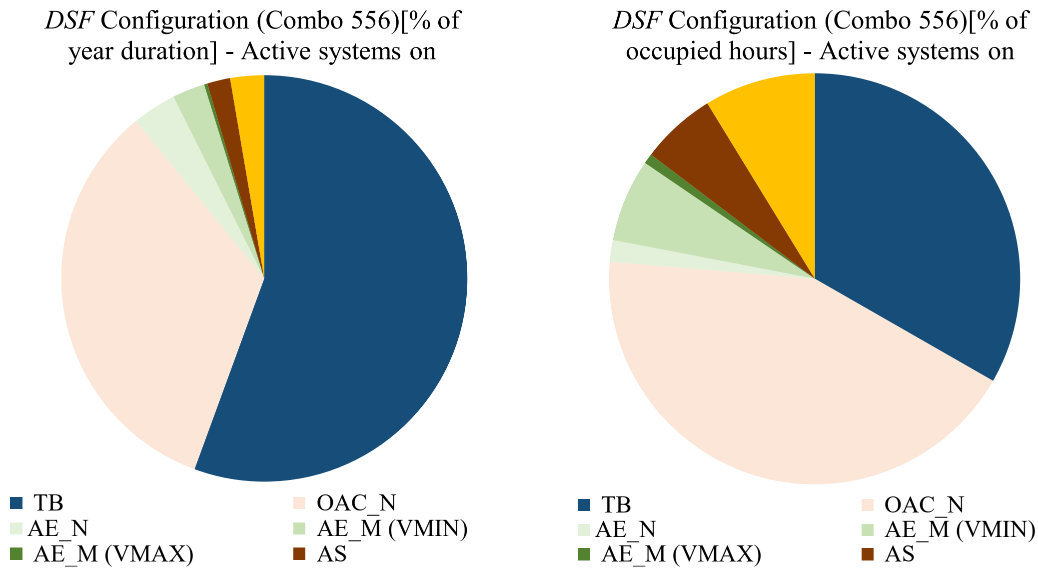


Figure 177: Flexible DSF configuration through the year for combo 556 in Madrid: overall month duration (left) and occupied hours (right)

Considering the occupied hours only the same trend is visible: the percentages of the adoption of *OAC*, *TB*, *AS* and *CF* are almost the same, while it is visible an increased application of the *AE* mechanical configurations (especially the one with the minimum air flow implemented inside the cavity). In the complex, it is consequently possible to say that the overall performance of the flexible *DSF* system in Madrid is considerably better compared to the one observed in Frankfurt, if the primary energy need reductions are considered.

The flexible *DSF* system (as observed in Frankfurt), is considerably more performant in the reduction of the cooling energy need, compared to the heating. For this reason, given the necessity to reduce the cooling energy need of the room if the purpose is the minimization of the overall required primary energy, the reductions in terms of primary energy (for the selected combinations) are of course larger (in the order of *30%*).

The selected combinations have been also tested for the free running configuration of the model, to evaluate the effects on the indoor comfort conditions. The results, however, are like the ones observed for the combination 844 in Frankfurt, with a consistent worsening of both thermal comfort and *IAQ*: the increase of the number of occupied hours above the limit of *PPD = 10%* is in the order of *50%* while almost all the occupied hours of the room are above the threshold limit of *1000 ppm* (same situation observed in Frankfurt for the combination 844).

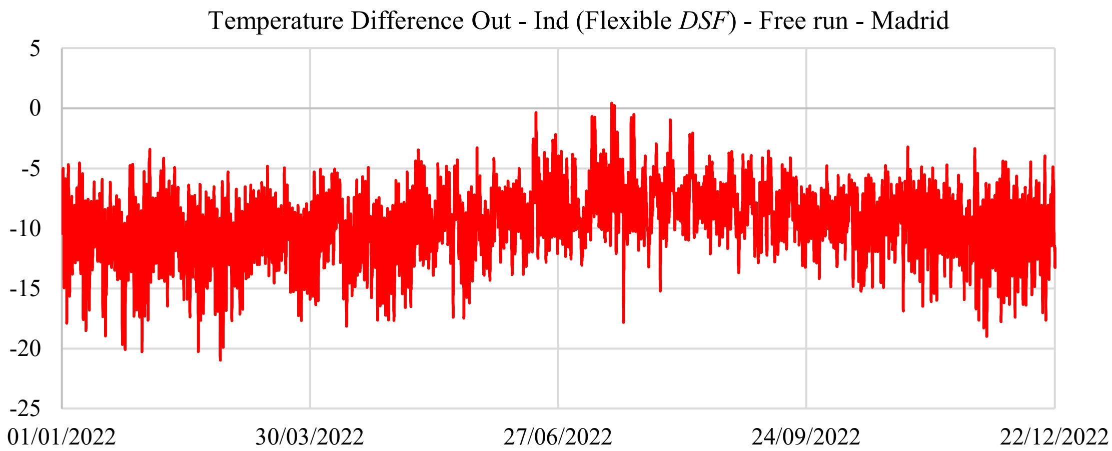


Figure 178: Variation through of the air temperature difference between the outdoor and the indoor environments, if the free running configuration of the model is considered (the flexible DSF system is considered) in Madrid

This is of course caused by the fact that the temperature difference value used for the seasonal switch is too high if the free running configuration of the model is considered (*Figure 178*). For this reason, only the heating season strategies are applied, which have been showed negative effects on the indoor environmental quality of the room (as already illustrated in *7.5* and *6.3*). The same results are produced if all the three different indoor air temperature levels (*20°C*, *23°C* and *26°C*) are applied for the seasonal switch between heating and cooling season strategies (*Figure 179*). Therefore, also for Madrid, as seen for Frankfurt, is consequently visible a substantial worsening of the indoor environmental quality conditions of the optimal combinations for the energy efficiency of the room are applied to the free running configuration of the model.

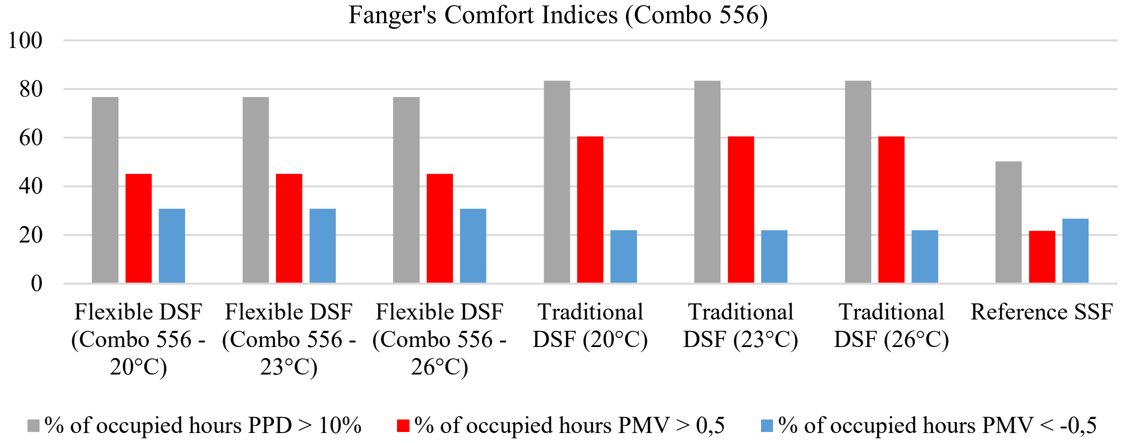


Figure 179: Variation of the Fanger's comfort indices for the combination 556 in Madrid

9.2. Whole year control optimization for Oslo

The same optimization script has been applied to Oslo. Only 2 modifications have been performed with respect to the case of Frankfurt: the thermal transmittances of the external opaque enclosures (walls, floor and roof) of the *BESTEST* cell have been modified in accordance with the different climate (as done for the case of Madrid). The thermal transmittance values have been taken from the Norwegian reference standard [18] regarding the energy efficiency of buildings and they are reported in *Table 133*.

Enclosure	***Oslo, Norway*** (from *TEK 17*)
External Walls	*0.22 W/m²K*
Floors	*0.18 W/m²K*
Roofs	*0.18 W/m²K*

Table 133: Thermal transmittance values of the opaque enclosures used for Oslo

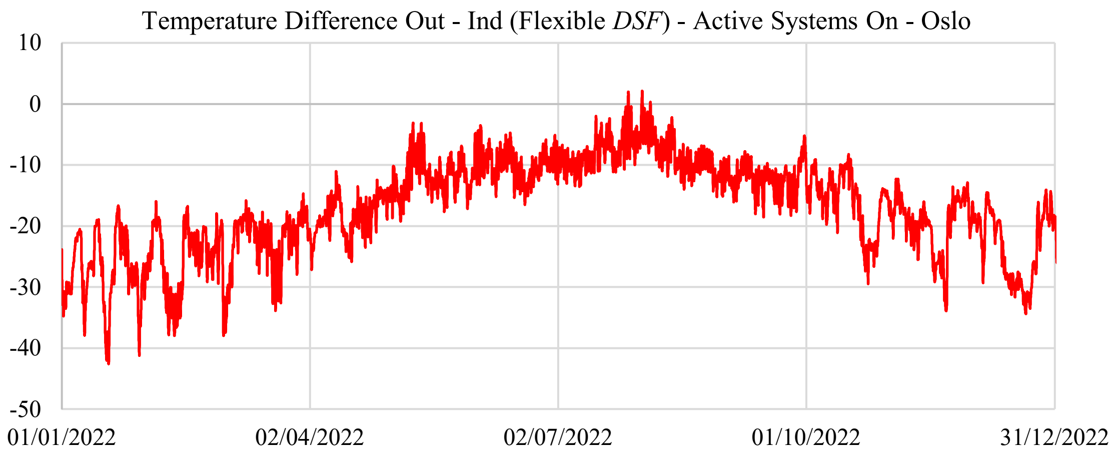


Figure 180: Variation through of the air temperature difference between the outdoor and the indoor environments, if the active systems of the room are on (the flexible DSF system is considered) in Oslo

Moreover, according with the different outdoor air temperature and incident solar radiation on the façade (lower compared to the ones in Frankfurt), the possible values for `TAir_switch` have been modified to *-15°C*, *-10°C* and *-5°C*, given the different temperature profile observed in Oslo (*Figure 180*).

The possible values of incident solar radiation on the façade on the other hand have been not changed (differently from the case of Madrid) adopting the same already used for Frankfurt.

The results of the 864 different simulations performed on the flexible *DSF* system in Madrid are here reported. In the case of Oslo, a primary energy conversion factor equal to 1 has been used, instead of 2.29 (adopted for Madrid and Frankfurt).

This is because the greatest part of electrical energy in Norway is produced using hydropower plants and other renewable sources (wind or solar), with a considerably lower adoption of fossil fuels compared to the European context. Consequently, the conversion factor can be assumed equal to the unity [37] [39] [40] [41]. Hence, delivered and primary energy needs are corresponding.

As it is possible to see, the overall heating energy need is considerably higher compared to the other two locations (*Figure 181* on the left), while on the other hand the cooling energy need is almost not significant in comparison with the heating energy need (*Figure 181* on the right).

This could a problem for the performance of the flexible *DSF*, which showed some limitations in the reduction of the heating energy need both in Madrid and Frankfurt. The behaviours of the different energy uses are anyway similar to the ones observed in Frankfurt, with a progressive (and more evident also) reduction of the heating energy demand with the increase of the combination number (in opposite way, the cooling demand has an incremental trend).

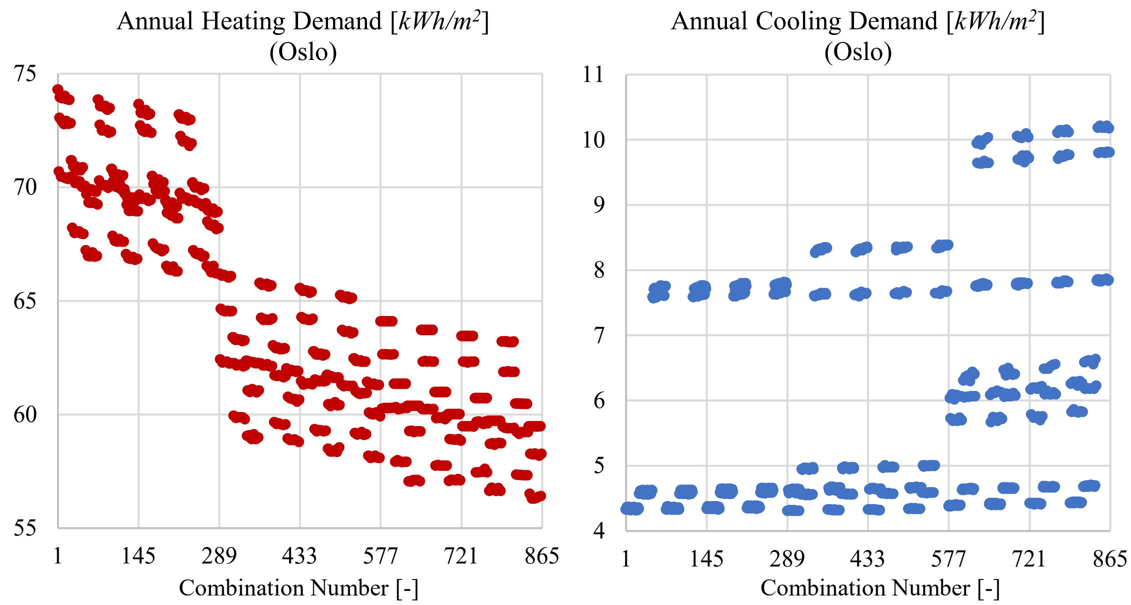


Figure 181: Heating (left) and cooling (right) energy need variation for the 864 different combinations in Oslo

The relation between heating and cooling energy needs with the different configurations of control is reported in *Figure 182* on the left.

The trend is the one already observed in Frankfurt and Madrid: the highest energy needs for heating are associated with the lowest energy needs for cooling (and vice-versa). Also artificial lighting energy needs (*Figure 182* on the right) the results are very similar.

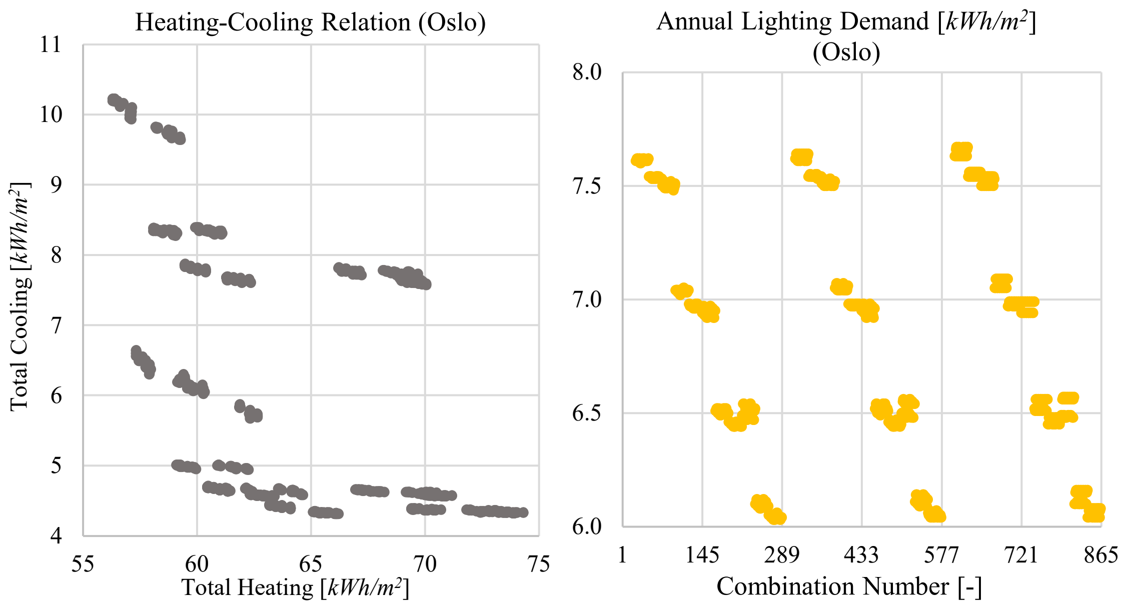


Figure 182: Heating/Cooling energy need relation (left) and artificial lighting energy need variation (right) for the 864 different combinations in Oslo

The delivered and primary energy needs in Oslo showed a different trend compared to Madrid and Frankfurt (*Figure 183*): the reduction in terms of total delivered energy with the increase of the combination number is more evident. This a consequence of the progressive reduction of the heating energy need of the room.

As observed for the other two locations, the minimum values of delivered energy are reached with the highest numbers of combinations: in this case, the minimum delivered (and primary) energy is reached with combination 835, which is also among the ones with the lowest values of heating energy need (which is the most relevant in Oslo).

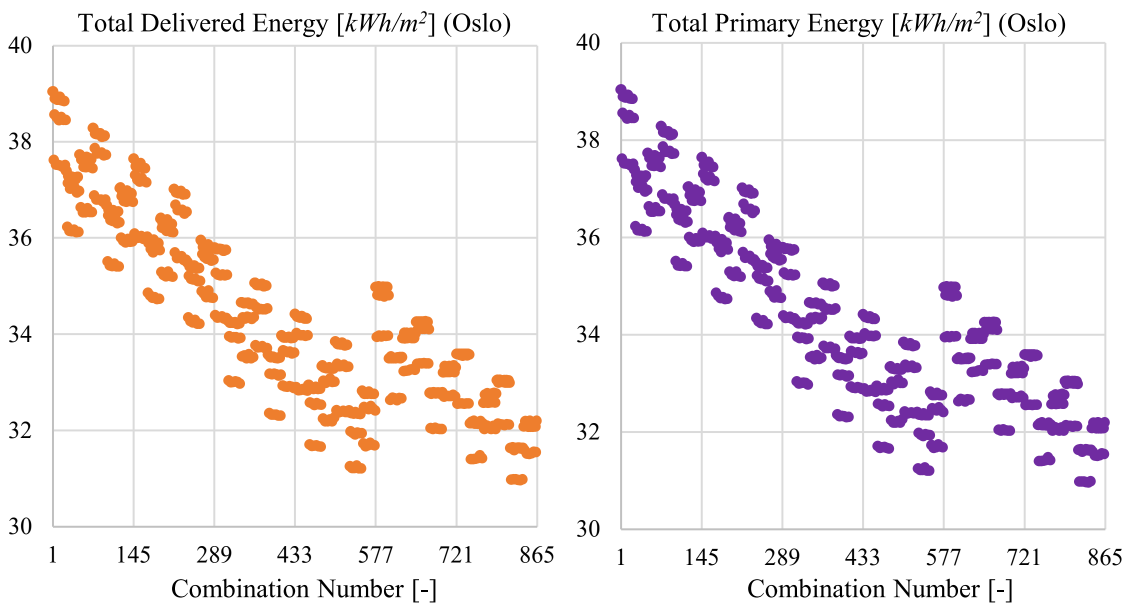


Figure 183: Delivered energy (left) and primary energy (right) variation for the 864 different combinations in Oslo

For these reasons, combination 835 has been selected as optimal one for Oslo. The combined values inside the combination are reported in *Table 134*.

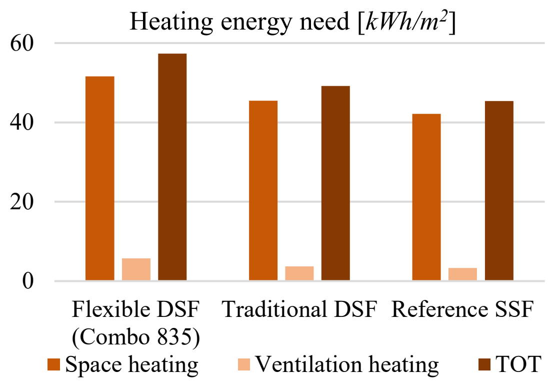
Combination number	Control variable	Values for the control variable
835	`temp_switch`	*-5 °C*
	`rad_shad`	*500 W/m²*
	`temp_shad`	*23 °C*
	`CO2_Summer`	*600 ppm, 900 ppm* and *1000 ppm*
	`TCav_Summer`	*23 °C*
	`CO2_winter`	*1000 ppm*
	`TCav_Winter`	*2 °C, 19 °C, 22 °C* and *25 °C*

Table 134: Combined values for the combo number 835 (Minimization of primary energy need) for Oslo

The most critical aspect of the flexible *DSF* performance is the heating energy need, as already observed in Frankfurt and Madrid (*Figure 184* on the left and *Table 135*). Given the colder climate, the flexible *DSF* system applied in Oslo produces an increase of the annual heating demand (*+26.3%*). Also the traditional *DSF* shows a negative performance under the point of view of the heating energy need, but the increase in the demand is less consistent (*+8.3%*). Both the double skin systems are consequently ineffective in the reduction of the heating energy need in a climate as Oslo.

	TOTAL ENERGY NEED [kWh]			*TOTAL ENERGY NEED [kWh/m2]*			*[%]*
Facade configuration	Space heating	Ventilation heating	TOT	Space heating	Ventilation heating	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 835)	2477.00	275.10	2752.10	51.60	5.73	57.34	**26.3**
Traditional DSF	2183.00	175.50	2358.50	45.48	3.66	49.14	**8.3**
Reference Single Skin	***2022.00***	***156.50***	***2178.50***	***42.13***	***3.26***	***45.39***	***REFERENCE***

Table 135: Heating energy need variation (Combo 835) in Oslo



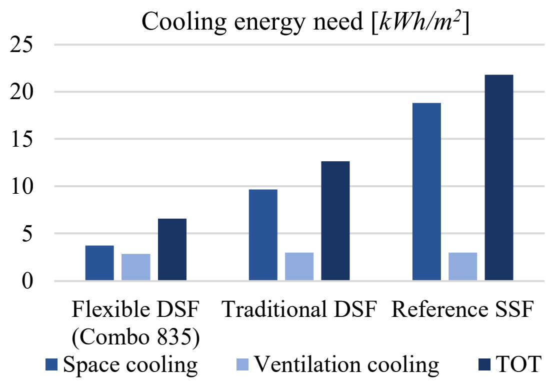


Figure 184: Heating (left) and cooling (right) energy need variation (Combo 835) in Oslo

On the contrary, the reduction of the cooling energy (*Figure 184* on the right and *Table 136*) need is good if the double skin system is applied: in the case of the flexible *DSF* reduction is about *70%* compared to *SSF*. However, the cooling energy need for a climate as Oslo is considerably less consistent compared to the heating energy need. For this reason, this aspect of the performance is not so relevant (as it was for example in Madrid).

The relation of the performance under the point of view of heating and cooling energy needs for the double skin systems is reported in *Figure 185* on the left.

	TOTAL ENERGY NEED [kWh]			*TOTAL [kWh/m2]*			*[%]*
Facade configuration	Space cooling	Ventilation cooling	TOT	Space cooling	Ventilation cooling	**TOT**	Variation (Single Skin)
Flexible DSF (Combo 835)	178.20	136.80	315.00	3.71	2.85	6.56	**-69.9**
Traditional DSF	464.20	143.20	607.40	9.67	2.98	12.65	**-41.9**
Reference Single Skin	***903.00***	***142.90***	***1045.90***	***18.81***	***2.98***	***21.79***	***REFERENCE***

Table 136: Cooling energy need variation (Combo 835) in Oslo

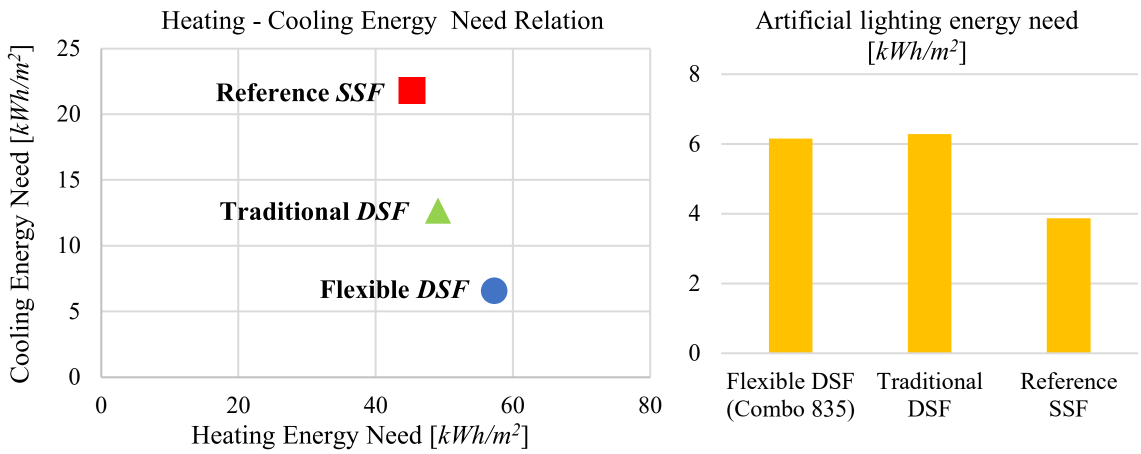


Figure 185: Relation between the heating and the cooling energy needs (left) for Combo 835 and related energy needs for artificial lighting in Oslo (right).

Also under the point of view of the energy need for the artificial lighting, the performance is considerably worse compared to the locations of Madrid and Frankfurt. Even if the radiation level for the activation of the shading is quite high, the increase in the overall energy need for artificial lighting is in the order of *60%* if the double skin system is applied (*Table 137* and *Figure 185* on the right). For these reasons, the overall performance under the point of view of the primary (and delivered) energy needs in negative for both the *DSF* systems (*Table 138* and *Figure 186*): the annual increase is not particularly relevant (less than *10%*) but it is anyway a worsening if compared with the application of the *SSF*. In particular, the increase generated by the application of the flexible *DSF* is almost the double of the one of the traditional solution. In the complex the application of the flexible *DSF* system does not produce good results in a climate as Oslo.

Facade configuration	Artificial lighting [*kWh*]	**Artificial lighting [*kWh/m²*]**	Variation [%] (Single Skin)
Flexible DSF (Combo 835)	295.20	6.15	**59.1**
Traditional DSF	301.40	6.28	**62.5**
Reference Single Skin	***185.50***	***3.86***	***REFERENCE***

Table 137: Artificial lighting energy need variation (Combo 835) in Oslo

Facade configuration	**Delivered energy [*kWh/m²*]**	**Primary energy [*kWh/m²*]**	**Variation (Single Skin) [%]**
Flexible DSF (Combo 835)	30.96	30.96	**9.61**
Traditional DSF	29.55	29.55	**4.62**
Reference SSF	***28.24***	***28.24***	***REFERENCE***

Table 138: Variation of the primary and delivered energy needs (Combo 835) in Oslo

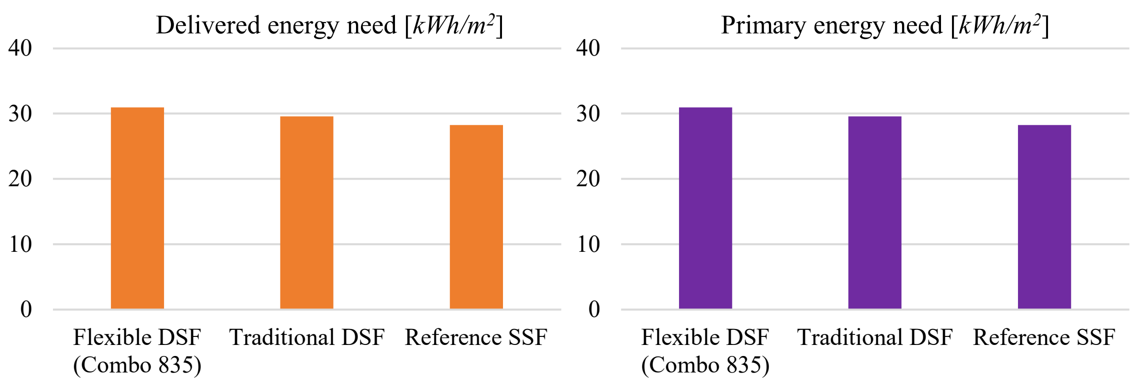


Figure 186: Variation of the primary (right) and delivered (left) energy needs (Combo 835) in Oslo

Regarding the different strategies which are applied through the year (*Figure 187*), there is of course a consistent application of the heating season strategies, used for about *97%* of the year. For this reason, the configurations adopted by the flexible *DSF* are mainly the one referred to the heating season (*Figure 188*), with a reduction in the use of *OAC* and *AE*. On the contrary, the percentage of the use of *CF* during the occupied hours is considerably higher and it is also visible the application of *IAC* (almost not adopted in warmer climates as Frankfurt and Madrid).

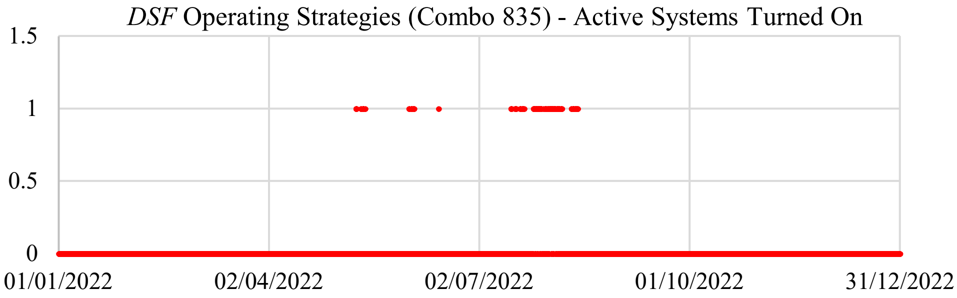


Figure 187: Application of the heating and cooling strategies through the year (Combo 835) in Oslo. 0 = heating season strategies, 1 = cooling season strategies

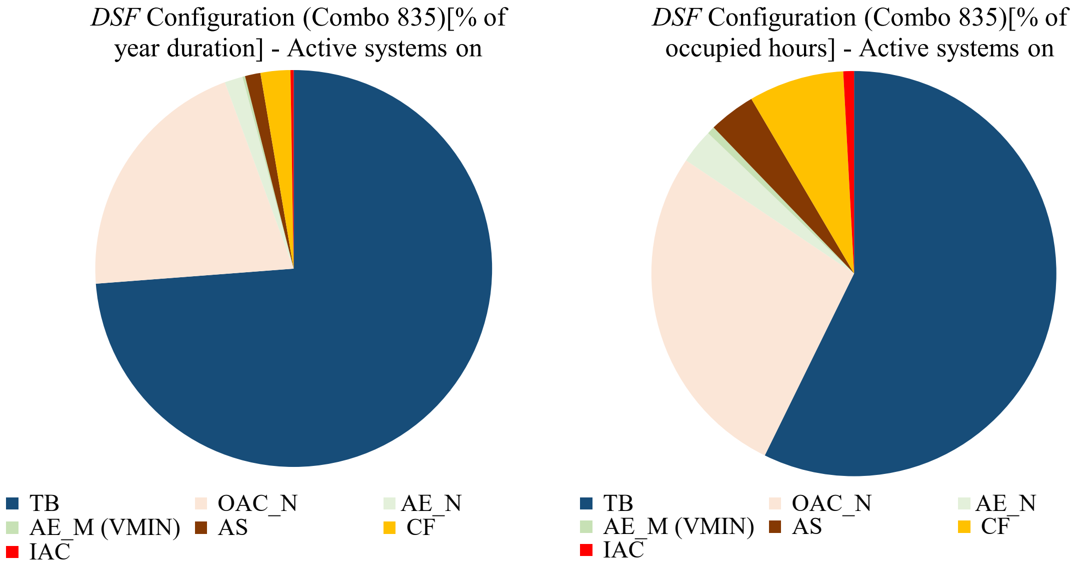


Figure 188: Flexible DSF configuration through the year for combo 835 in Madrid: overall month duration (left) and occupied hours (right)

Unfortunately, it was not possible to perform *IEQ* evaluations using the free running configuration of the model in the Oslo climate, due to persistent numerical instability problems (see *Appendix D*): for Oslo more variable and transient boundary conditions for the control variables are present and as a consequence the software cannot complete a indoor climate simulation for the whole year (the simulation ends at the beginning of March).

It is consequently not possible to get the results regarding indoor operative temperature, CO_2 concentrations, Fanger's comfort indices and indoor illuminance levels, as already done for Madrid and Frankfurt.

Given the large application of the heating season strategies, it is however expected to see a general worsening of the indoor thermal comfort and air quality conditions, as already observed in the case of the combination 844 in Frankfurt (7.4) and 556 in Madrid (9.1) or for the monthly simulations in April and October (6.1.2 and 6.2.2).

9.3. Comparison between the three selected boundary conditions

It is now possible to compare the effectiveness of the annual *DSF* control structure and subsequent optimization process in the three selected locations (Frankfurt, Oslo and Madrid). For this comparison, the reduction of the overall primary energy (with respect to *SSF*) for the selected optimal combinations in the three selected locations is considered (*Figure 189* and *Table 139*).

Both the *DSF* systems, traditional and flexible, have been considered, with the purpose to evaluate the advantages and disadvantages in the use of the flexible *DSF* in the different climates.

The selected combinations in the different locations are:

- Combination 832 for Frankfurt
- Combination 764 for Madrid
- Combination 835 for Oslo

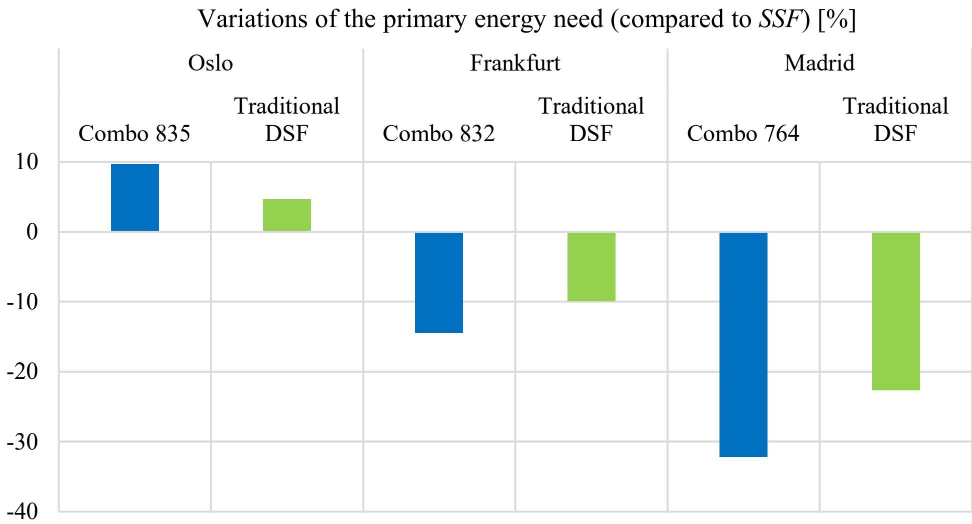


Figure 189: Reduction of the overall primary energy use (with respect to SSF) produced by the selected optimal combinations in Frankfurt, Madrid and Oslo

Location	**Climate classification**	**Primary energy requirements (respect to *SSF*)**	**Heating energy requirements (respect to *SSF*)**	**Cooling energy requirements (respect to *SSF*)**
Oslo	*Humid continental*	**+ 9.6 %**	**+ 26.3 %**	**- 69.9 %**
Frankfurt	*Temperate-Oceanic*	**- 14.4 %**	**- 8.4 %**	**- 51.3 %**
Madrid	*Hot-summer Mediterranean*	**- 32.2 %**	**+ 0.4 %**	**- 57.6 %**

Table 139: Variation of heating, cooling and overall primary energy requirements generated by the flexible DSF in Oslo, Madrid and Frankfurt (with respect to SSF)

In the three selected locations (*7.3, 9.1* and *9.2*), the flexible *DSF* is more effective in the reduction of the cooling energy need of the room, compared to the heating energy need. In all the locations this reduction is above the *50%*, with peaks of *70%* in Oslo. On the other hand, the heating energy need is reduced only in Frankfurt, while in Frankfurt this is almost unchanged and in Oslo increase of over one quarter. This fact has of course different effects in function of the considered climate.

For this reason, the best results in terms of reduction of the overall primary energy are in Madrid (in which the most consistent energy use is the cooling): for Madrid, if the combination 764 is used, the reduction of the overall primary energy need of the room is above *30%*, considerably better than the traditional solution (around *20%*).

The worst performance, on the other hand, is for Oslo, in which the annual cooling demand is almost insignificant compared to Madrid: in this case both the *DSF* systems (flexible and traditional) produce an overall increase of the primary energy need of the room. The consistent reduction of the cooling energy need is consequently not effective in the Oslo climate, compared to the increase of the annual heating energy need.

In the case of Oslo, in particular, the increase of the primary energy need generated by the flexible *DSF* is more consistent than the one of the traditional solution. Frankfurt is in an intermediate situation, but the overall results are of course worse better than Oslo: the reduction is in this case in the order of *15%*, better than the one of the traditional *DSF*.

From the energy performance point of view, consequently, the adoption of the flexible *DSF* is particularly better for a *Hot-summer Mediterranean* climate as Madrid than for a *Temperate-Oceanic* climate like Frankfurt. On the contrary, the adoption of the flexible *DSF* configuration (with this control structure and the implemented optimization process) is not recommended for a colder *Humid-continental* climate as Oslo.

Regarding the *IEQ* analysis, in Madrid (*9.1*) and Frankfurt (*7.5*) a general worsening of the indoor climate conditions has been observed, compared to *SSF*. For Oslo, on the other hand, the simulations on the free running configuration of the room have not been performed due to numerical instabilities problems (see *Appendix D*).

However, it is possible to say that for all three selected climates the most critical aspect is the application of the control in the free running configuration of the model, especially in terms of thermal comfort and indoor air quality.

Appendix A - The use of BPS tools for the modelling of RBEs and IDA ICE features

In this Appendix, the features related to the *BPS* tools and their use for the modelling of *RBEs* is illustrated to the reader. The dynamic behaviour of *RBEs* is the main reason of the intrinsic complexity which designers must deal with working on these typologies of systems. If for conventional and static envelope systems it is always possible to use common simulation tools, in the case of *RBEs* and dynamic façade systems (as the flexible *DSF* system analysed in the Thesis work), the evaluation of the performance is much more complex and difficult: consequently a successful design of proper control strategies for these dynamic systems is a difficult task [9].

The use of simulations carried on virtual models of the adaptive systems can be however useful in the design phase. Two are the main reasons for which a performance prediction by means of simulation tools of *RBEs* is crucial during the design phase:

- Simulation tools can be used for an investigation of the impact of the adoption of adaptive technologies on the whole building energy performance and indoor comfort conditions
- Simulation tools can be also used for a further optimization of possible control strategies for such kind of elements, evaluating the effects of different control logics on the whole system efficiency

Consequently, the prediction of the dynamic behaviour of adaptive systems by means of computer models can be useful for the entire design and optimization process. In this field, the *Building Performance Simulation* (*BPS*) is defined as a computer based, multi-disciplinary and problem oriented mathematical model of several aspects of building performance, based on the adoption of fundamental physical principles and engineering models. *BPS* is nowadays a useful and widely diffused tool for the multi-domain performance assessments of buildings [42].

It is however necessary to say that *BPS* tools have been firstly developed without considering the adaptability capacity of building components [9]: in fact, these tools are used mainly to replicate convectional and static building envelope systems (for example the traditional walls or windows) and it is difficult to predict how much they can be accurate in the description of the behaviour a *RBE* [43]. In addition, *BPS* tools in general do not focus on the description of the physical behaviour behind each building component but on the evaluation of the energy needs of the entire building (heating, cooling, lighting, etc.) and on the interaction between its various parts (envelope and technical systems) [44]. Consequently, the performance prediction of adaptive façades in some cases can be a complex and difficult task, leading to possible errors and uncertainness.

The main disadvantage linked to the use of *BPS* in the performance prediction of adaptive envelope systems is that modelling the behaviour of adaptive systems is not a so common task, therefore not so large information on this topic is present now. *BPS* tools can be anyway a solution that can be adopted to investigate the behaviour of adaptive and dynamic envelope systems in the framework of the overall building energy efficiency (evaluating in this way the different energy needs of the buildings) and to test in a quick and efficient way different control alternatives for these kinds of elements [45] (as in the workflow followed during the Thesis work).

Some advantages [9] offered by the adoption of *BPS* tools for the performance prediction are consequently:

- The capability to develop different control strategies for the *RBEs* performance optimization.
- The ability to simulate the dynamic interaction of the *RBEs* with the other building services (for example the *HVAC* system or the artificial lighting system).
- The possibility to virtually test the robustness of the adaptive system with respect to occupant behaviour and variable weather conditions.

To sum up, *BPS* tools, despite some limitations and difficulties in their use for the modelling of advanced envelope technologies, are anyway the right solution for the multi-domain performance evaluation of these systems.

IDA ICE general features

The commercial *BPS* tool that has been used for this Thesis work for the control implementation and the performance evaluation, as already written, is IDA ICE. *IDA Indoor Climate and Energy* is a flexible, whole year detailed and dynamic multi-zone performance simulation tool that is mostly used in Nordic and Central European countries [9], such as Sweden, Finland, Germany and Norway. It has been initially developed in 1998 by the Swedish company *EQUA Simulation AB* and now it reached the 5th release (used during this Thesis work as *beta* version). In the following sub-section, the main features and characteristics of the simulation environment will be analysed.

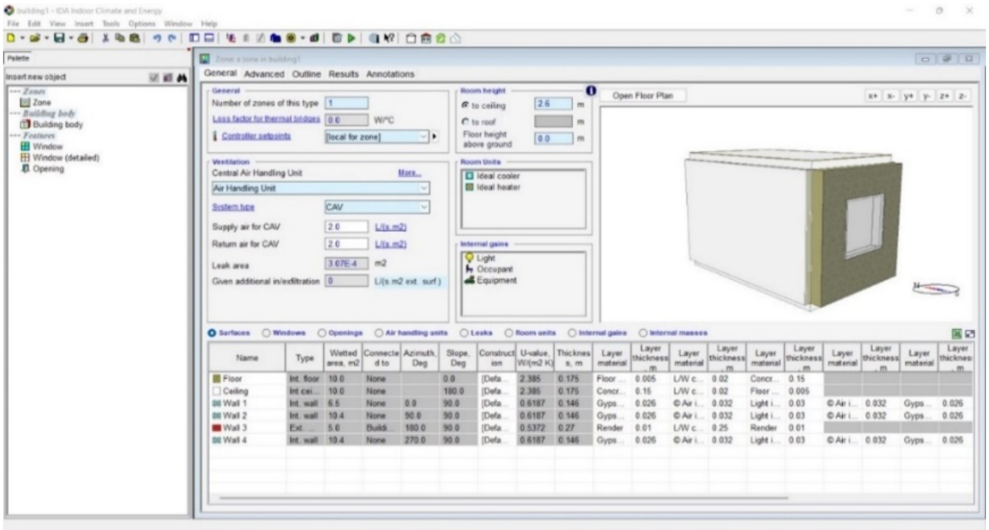


Figure 190: Graphic user interface of IDA ICE

Compared to other *BPS* tools, the IDA ICE user interface is designed to make easier the work of the designer, while still offering full modelling flexibility [46]. The simulation engine and the user interface are therefore already implemented inside the software, without the need to use external interfaces realized by other developers (as in the case of EnergyPlus and Design Builder, other widely diffused *BPS* tool).

This is a clear advantage in terms of easiness of use for the designer (*Figure 190*).

IDA ICE is a *general-purpose* simulation environment: it manages the mathematical models of all the building components (envelope and technical building systems) as input data, allowing a user to simulate a wide range of system designs and configurations (as the case of different *DSF* operating strategies implemented for this Master Thesis).

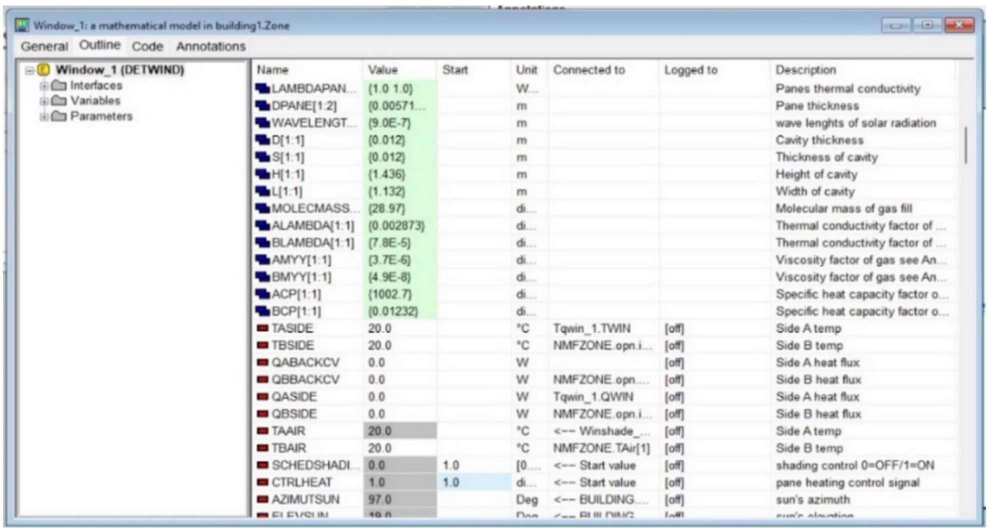


Figure 191: Mathematical model of a window in IDA ICE: list of interfaces, variables and parameter in the Outline tab of the element.

Its main advantage is consequently the flexibility: almost anything that can be associated to mathematical modelling can be simulated. One of the most attractive features of the general-purpose simulation tools is that the user can build successively large component model libraries and independent researchers can develop compatible solutions [47].

The different building components inside the simulation environment can be described using a so-called *text-based modelling language* [48]: the *Neutral Model Format* (*NMF*). Using the *NMF* the mathematical models, the building components are expressed in separate modules that can be interconnected in different ways, to define the customized system [49]. In particular, the entire model library of IDA ICE is written using the *NMF* [50].

More in detail, the standardized elements of a *NMF* model are the following ones (*Figure 191*) [50]:

- Equations: they describe the behaviour of the physical system, defining in a mathematical way the interconnection between variables and parameters used inside the system.
- Links (or interfaces): they are the interfaces with the other modules contained inside the whole system. They can be used for the information exchange between the different components of the building and the façade system, as in the case of the control implementation for the flexible *DSF*.
- Variables: computed by the simulation environment for each defined time-step. They represent therefore the output of the simulation performed by the software.
- Parameters: given by the user as simulation input and used for the variable calculations.

The control implementation in IDA ICE

In IDA ICE, expert users can implement adaptive features and rule-based control strategies directly into the mathematical model using the *advanced level* interface (as in the workflow of this Thesis work) [9].

In general, there are two different typologies of advanced control that can be implemented inside the *BPS* tool:

- Time-scheduled: control actions are in this case pre-determined as a function of time, instead of being based on boundary conditions or state variables. Time schedule control can be used successfully to represent the dynamic operations of building components, but the responsivity of the system to varying boundary conditions cannot be implemented.

- Script-based: a script-based control can directly be coded by the user in the simulation tool. Script-based control gives consequently the possibility to test a specific control approach defined by the designer. This last form of advanced control can be applied in IDA ICE by means of user defined *Control Macros* (*Figure 192*), in which different logical operators can be adopted.

Using the *Control Macros*, the users is able to implement custom control strategies for different devices and adaptive components in the building (for example the ventilation system or the lighting system) or in the façade element (openings, fans or shading systems).

The main elements of the control-macros are in fact the two interfaces that are used for the information exchange between the different model components:

1) Signal Sources: they can be used as input to the control algorithm provided by the different control variables (for example the outdoor air temperature or the incident solar radiation on the façade).

2) Control Targets: the output from control macros should be connected to a control target object (for example a particular actuator of the façade).

Signal sources and control targets can be linked and managed in different ways according to the typology of control to be implemented and the actuator to which the control is focused. The IDA ICE *Control Macros* in fact have been used for the rule-based control implementation of the façade system in this Master Thesis work.

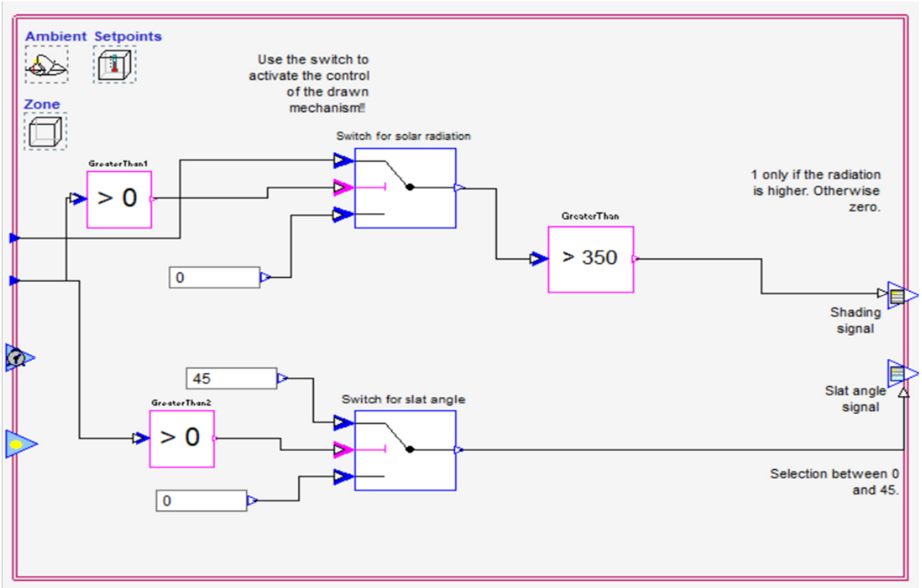


Figure 192: Control macro example from IDA ICE for the control of the shading system

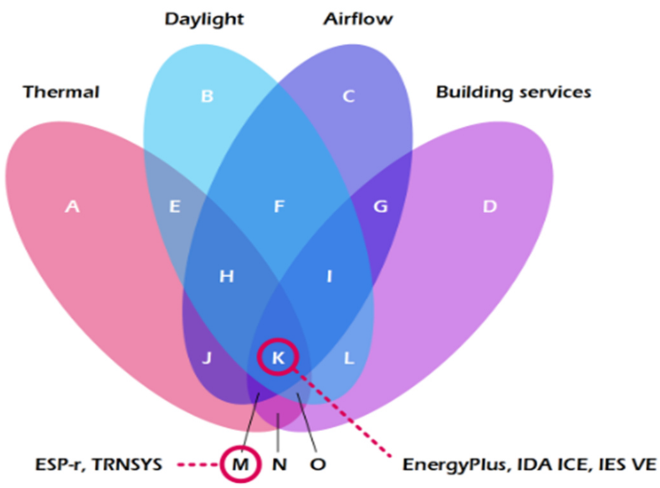


Figure 193: Intersection of all the different domains for different BPS tools [9].

The application of the *Control Macros* for the control implementation of adaptive façade has been discussed more in detail in *Appendix D - Rule-based control implementation in IDA ICE.* IDA ICE is a simulation environment that can be used for the study of the indoor thermal climate as well as the energy consumption of the whole building [9].

In fact, it is one of the few *BPS* tools nowadays developed that can cover all the different physical domains that are present inside the whole building performance (*Figure 193*):

- Thermal comfort analysis
- Air-flows domain study
- Building services dynamic operations implementation
- Artificial and daylight models

For all these listed features, this *BPS* tool has been selected for the modelling of an adaptive envelope system and its subsequent multi-domain performance evaluation.

Appendix B - The DSF system: history and state of the art

Since the year of construction of the first glass architecture, the *Crystal Palace* in 1851, glazed façades in modern architecture have become the norm [51]. From the half of the 20th century, with the diffusion of the so-called *International Style* and the improvement of new technologies in the construction sector, the glass became one of the most iconic materials to be used in the new skyscraper façades [52].

Fully transparent building envelopes therefore have become common since the *50s* (especially among office and commercial buildings), with an increasing popularity of the industrialized curtain wall solution [4]. The two main reasons for the increased adoption of the glazed façades were the greater aesthetical appeal offered by this envelope solution compared to a traditional opaque one and the better indoor daylight conditions ensured by the glass transparency [53].

However, some relevant disadvantages are related to the extensive use of glass in the building façade [54] [55]:

- Higher thermal transmittance compared to a traditional opaque partition, that can be cause of higher heat losses during the winter.
- Higher passive solar heat gains, linked to the higher visible transmittance of the glass.
- Higher glare discomfort risk if the incoming solar radiation is not managed in the proper way.

As a result of these disadvantages, buildings with large use of glass in the façade usually are characterized by not good indoor comfort conditions (due to the high energy loss in winter, the excessive thermal gain in summer and the visual discomfort caused by large amount of indoor daylight) with also relevant energy uses [4].

In fact, fully glazed façades tend to have higher space conditioning loads from heat transfer through the building envelope because windows have lower resistance to heat transfer than traditional insulated opaque walls [56]. From these considerations, with the increasing need of a better energy performance within the building sector (as mentioned at the beginning of *1.1*), new solutions have been developed with the aim to overcome the gap between traditional opaque façades and fully glazed ones.

In particular, the introduction of the *DSF* systems in the contemporary architectural language from the *80s* is a clear design effort in this direction.

Explanation of the concept of DSF

The *DSF* is an architectural trend (mainly diffused in European countries but anyway adopted all over the world) driven mostly by four reasons [12]:

- The aesthetic desire of architects for an all-glass façade that leads to increased transparency of the building envelope.
- The practical need for improved indoor environment among buildings with fully glazed façades.
- The need for improving the acoustics and indoor air quality in buildings located in noise and polluted areas.
- The reduction of the energy use during the occupation stage of the building.

The use of the *DSF* is mainly caused by the need to design a fully transparent envelope with a good performance from the point of view of both energy efficiency and comfort for the occupants [23]. Moreover, this improvement of the façade performance is also linked with the concept of dynamicity and responsivity of the building envelope: since outdoor weather and occupancy are dynamic boundary conditions, the façade solution must have the capacity to respond and adapt in a dynamic way to variable exterior conditions and to changing occupant needs [57].

According to this view, the *DSF* is based on the notion of exterior walls that respond dynamically to variable and transient ambient conditions and that can incorporate a range of integrated sun-shading and natural ventilation devices or strategies [58]. Many different definitions of *DSF* systems have been defined in the decades within the scientific literature.

One of the most complete is the following one, provided in [12]:

"The DSF is a pair of glass skins separated by an air corridor (also called cavity or intermediate space) ranging in width from 20 cm to several meters. The glass skins may stretch over an entire structure or a portion of it. The main layer of glass, usually insulating, serves as part of a conventional structural wall or a curtain wall, while the additional layer, usually single glazing, is placed either in front of or behind the main glazing. The layers make the air space between them work to the building's advantage primarily as insulation against temperature extremes and sound."

The functioning is therefore based on the doubling of the glass layer of a traditional fully glazed façade, with the purpose of using in an active way the air contained inside the gap between the two façade skins [8]. In addition, the cavity offers the possibility to insert shading devices for the control of the incident solar radiation (*Figure 194*).

To sum up, the main advantages provided by the *DSF* are the reduction of the heat losses during the winter (thanks to the thermal buffer created by the still air inside the cavity) and the reduction of the overheating risk in summer (thanks to the air circulating inside the cavity) [4].

Probably, the first concept of *DSF* has been originally developed in the 1849, when Jean-Baptiste Jobard, director of the *Industrial Museum* in Brussels (Belgium), described an early version of a mechanically ventilated multiple skin façade: in winter hot air should be circulated between two glazing skins to increase the insulation capability of the façade, while in summer it should be cold air for cooling purposes [59].

However, no significant improvement in the *DSF* construction field has been performed until the early *80s* of the 20th century when this type of façades started to get popularity in Europe and *USA*: the consciousness of the environmental costs of construction, the evidences of the relationship between inefficient façades and energy consumption and some practical problems determined an increased interest in this typology of advanced envelope: consequently, it was during the *90s* that this architectural system started to become more popular among high-rise commercial buildings [60].

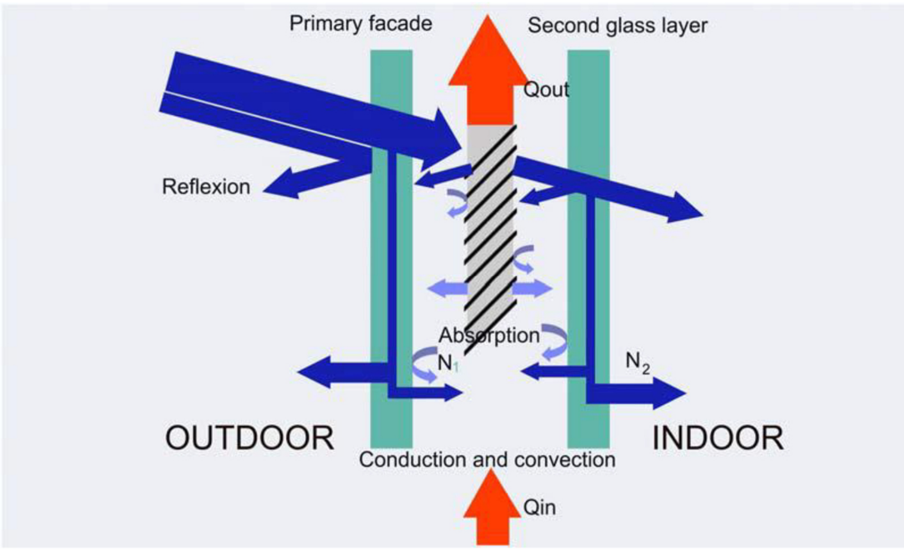


Figure 194: Structure of a DSF, with the different components of the system: primary façade (outer skin), second glass layer (inner skin), cavity and integrated solar shading device [61].

The use of this typology of façade, if well designed and integrated with the other building systems, can allow to some significant advantages, in particular [12]:

- Efficient use of the solar gains during the winter season.
- Acceptable thermal comfort during the whole year.
- Overall primary energy savings for heating, cooling, ventilation and lighting.
- Solar control and subsequent better visual comfort conditions thanks to the use of the integrated shading devices.

The components of the DSF and their influence on the system functioning

As said in the previous sub-section, *DSFs* can allow a better performance than a traditional glazed façade. Anyway, this is possible only if the *DSF* is properly designed and operated by effective control strategies. Otherwise, the potential benefits of this system can be deleted. For this reason, the physical phenomena that can occur inside a *DSF* (and their relationship with the *DSF* components) must be well understood [20].

Starting from the *DSF* components, the main ones can be listed as:

- Exterior glazing skin, that can be both a single glazing unit and a double-glazing unit. In some case, the outer skin can be composed by movable transparent glass louvers.
- Interior glazing skin, that can be both a single glazing unit and a double-glazing unit.
- Air cavity, with a depth usually comprised between *4 cm* and *2 m*. It can be both, naturally or mechanically ventilated.
- Integrated solar shading devices, usually venetian blinds, or roller blinds. In general, roller blinds are more effective in blocking the light, but the venetian blinds usually are more flexible in the daylight management of the indoor environment, thanks to the variable slat angle.

The physics governing the behaviour of a dynamic system as a *DSF* is not particularly easy to understand. Phenomena in the cavity are highly dynamic and in constant interaction, influenced by indoor and outdoor temperature fluctuations, wind speed and directions, solar radiation intensity and pressure difference between the cavity and the surrounding environments [20].

The main phenomena that can influence the performance of the façade system are:

- The heat transfers through the façade, both radiative and convective
- The air flows in the cavity, generated by natural or mechanical ventilation
- The optical properties of the façade

The heat transfer trough the façade is the sum of both, convective and longwave radiative heat fluxes, that must be considered in separate way during the behaviour analysis of the *DSF*. In particular, the convective heat transfers coefficients are not easy to define since the air flows in the cavity can be difficult to be understood and evaluated [45].

The presence of integrated shading devices inside the cavity can be an additional element of complexity in the *DSF* behaviour prediction: shading systems are in fact able to absorb the direct short-wave solar radiation before it reaches the indoor environment, releasing in a second moment the absorbed heat to the cavity air, influencing in this way its temperature [57]. The shading systems in addition divide the cavity in two separate sub-cavities, for each one it is necessary to define a flow regime and the corresponding convective heat transfer coefficient [12].

Regarding the ventilation, the calculation of the airflows between the two skins in case of naturally ventilated cavities is not an easy task, since it is influenced by the stack effect, pressure difference between the different environments and wind action [12]. In addition, the ventilation inside the cavity has an influence on the cavity heat transfers, since it influences the air velocity [20].

About the optical and solar properties of the façade system, they are highly influenced by the shape (venetian or roller blind) and the position of the shading system and by the solar and optical properties of the two glass skins [45].

All these elements influence the transmission and the absorption phenomena inside the *DSF* and consequently the heat transfers and the air flows. Given these considerations, it is understandable how complex the behaviour of this dynamic system is.

The intercorrelation between the physical behaviour of the *DSF* and the configuration of its components (for example the venetian blinds, the cavity openings or the ventilation fans) must be of course known *a priori* if the designer has the task to set proper control strategies for the façade system.

Possible classifications of the DSF

Many different classifications for the *DSF* have been proposed in the last decades. In fact, a correct understanding of them is crucial for a correct design process and a good control implementation for the façade actuators.
In function of the partitioning of the cavity space, there are four main possible configurations [60] (*Figure 195*):

- *Box window (a)*: in this case the façade is characterized by a simple window doubled inside or outside by a single glazing or by a second window itself. This specific typology of *DSF* has been adopted for the simulations during the Thesis work.

- *Shaft-Box (b)*: the cavity is in this case closed in the horizontal direction, but not in the vertical one. Therefore, the cavity is designed as a vertical ventilation duct connecting different floors together.

- *Corridor façade (c)*: this is the opposite case of the shaft-box layout because the cavity is divided in the vertical direction only (usually at the level of each storey). Consequently, the cavities for each storey are independent.

- *Multi-storey façade (d)*: this case is characterized by a cavity which is not partitioned either horizontally or vertically. In some cases, the cavity can run all around the building without any interruption.

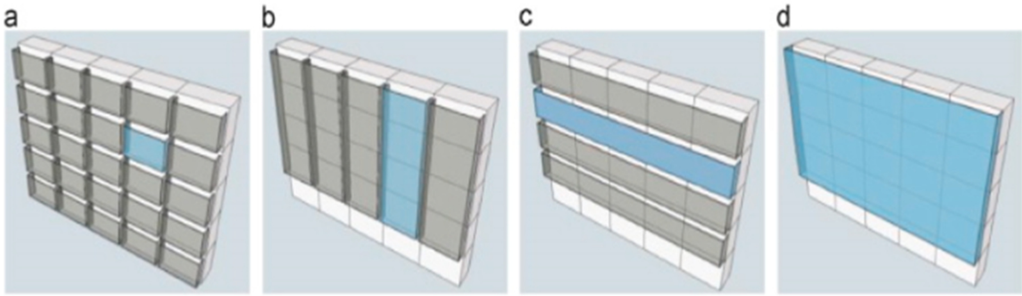


Figure 195: Pictures of the DSF layouts: a) box window, b) shaft-box, c) corridor façade and d) multi-storey façade [20].

Another important distinction, as said in the previous sub-section, is the one regarding the air driving force inside the cavity [6]:

- *Natural ventilation*: the driving force is the pressure difference generated by stack effect and wind action inside the cavity.

- *Mechanical ventilation*: the air is forced into the cavity by means of mechanical devices, for example fans.

Finally, a crucial classification is the one regarding the ventilation mode (*Figure 196*), corresponding to the origin and the destination of the air flowing inside the ventilated cavity. The same ventilation mode can be implemented both in natural and mechanical way.

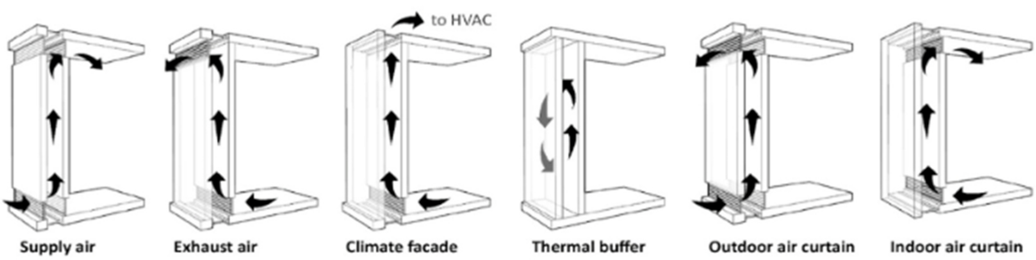


Figure 196: DSF ventilation modes classification [20].

The main ventilation modes for *DSFs* are [60]:

- *Outdoor Air Curtain* (*OAC*): in this ventilation mode, the air introduced into the cavity comes from the outside and is immediately rejected towards the external environment. The ventilation of the cavity therefore forms an air curtain enveloping the outside façade. Usually, the inlet opening is located at the basis of the cavity, while the outlet one at the top of it: this configuration amplifies the cavity air flows and makes a more uniform rate inside the cavity [45]. For the cooling season period it can be used for cooling the cavity air and remove in this way the excess of heat accumulated from the incident solar radiation [12]. To improve the air flow rates inside the cavity could be necessary to use the mechanical ventilation in the cavity, if the naturally generated air flows are not large enough.

- *Indoor Air Curtain* (*IAC*): the air comes from the inside of the room and is returned to the indoor environment. The ventilation of the cavity therefore forms an air curtain enveloping the indoor façade. This configuration can be used for the pre-heating of the air that is re-introduced inside the indoor environment (if enough incident solar radiation is present). The application of this kind of façade is more effective in countries with a colder climate, since in milder conditions it can be cause of a significant increase of the cooling demand [62].

- *Air Supply* (*AS*): the air is introduced in the cavity from the bottom opening. This air is then brought to the inside of the room. The cavity of the façade thus makes it possible to supply the building with fresh air, that can be pre-heated by using the solar gains. This configuration is good for the winter days or during the mid-seasons in which it is present a certain amount of incident solar radiation and the outdoor air temperature is not so low, but it can be applied also in summer if the cavity temperature is not high enough [6].

- *Air Exhaust* (*AE*): the air comes from the inside of the room and is evacuated towards the outside. The ventilation of the façade thus makes it possible to evacuate the air from the building, ensuring a good indoor air quality condition in the indoor environment. At the same time, the air movement can be used for removing the excess of heat inside the room and in the cavity. This feature can be useful especially during the summer season for night cooling purposes. In this case the cavity is used to extract and remove the heat loads accumulated during the daytime, cooling down the thermal mass of the building [57].

- *Thermal Buffer* (*TB*): in this configuration, all the openings of the cavity are closed, with the main aim to make the façade airtight. The cavity in this way forms a buffer zone between the indoor and outdoor environment thanks to the still air inside it. This configuration consequently is optimal for the winter days with very low outdoor temperature and low incident solar radiation on the façade or more in general for the night periods [6]. It is also good for the reduction of the heat losses through the façade during the nights.

- *Climate Façade (CF)*: the configuration is like the one of the indoor air curtains, but in this case the air is returned to the ventilation system of the building. As seen for the *AS* configuration, air is preheated in the cavity but used in this case for the ventilation system, for the pre-heating of the ventilation air of the mechanical ventilation plant.

All these ventilation modes can be implemented in the operations of the façade during the different seasons, ensuring dynamicity and flexibility features to the system, that can adapt to different weather and operational conditions of the building.

All these ventilation modes (with both natural and mechanical ventilation) have been implemented inside the flexible *DSF* model adopted during the Thesis work, as illustrated in *2*.

Appendix C - DSF modelling in IDA ICE: characteristics and workflow

In this Appendix, the modelling of the *DSF* systems inside IDA ICE is illustrated. After a general description of the *DSF* system, it is necessary to deal with the modelling of such kind of systems inside the *BPS* tools and with the IDA ICE simulation environment in detail.

DSF system in IDA ICE

Actually, *BPS* tools are widely used to assess the energy performance of buildings which are characterized by the presence of a *DSF* in their envelope [45] but anyway, there are several doubts about how accurately *BPS* tools can describe the complex environment of a *DSF*, since these tools have been developed to replicate conventional building envelope components, not dynamic ones [44], as already mentioned in *Appendix A - The use of BPS tools for the modelling of RBEs and IDA ICE features.*

According to the existing scientific literature about this topic [9], the main issues that are faced by *BPS* tools in the performance evaluation of *DSF* are the following ones:

- Underestimation of the cavity air temperature
- Errors in the prediction of the natural air flows inside the cavity
- Underestimation of the solar radiation entering in the indoor environment

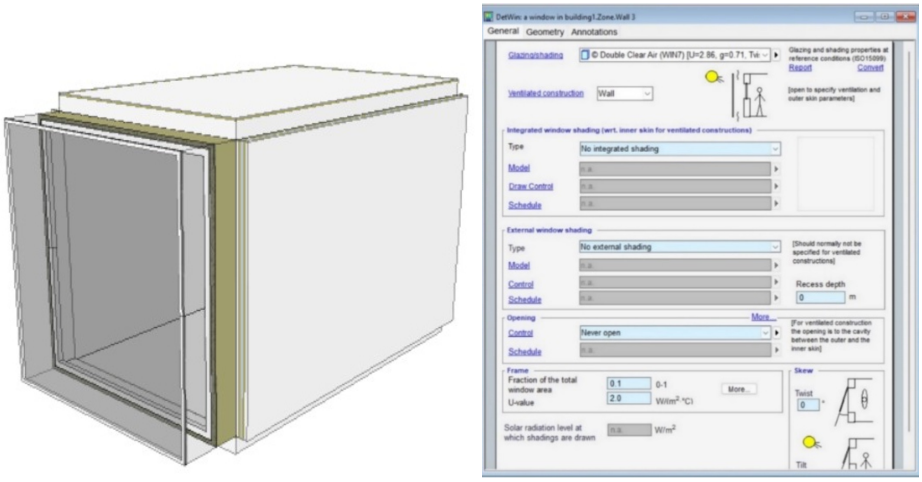


Figure 197: 3D view of the DSF in-built model from the IDA ICE graphic interface (left) and Detailed window form in IDA ICE. The glazing properties are referred to the inner skin of the DSF. In the "Ventilated construction" field the selection "Wall" enables the creation of the DSF model (right).

However, since this Thesis does not deal with the comparison of different *BPS* tools in the performance prediction of *DSF*, the focus of this sub-section is the description of the modelling capabilities that are implemented inside IDA ICE. In particular, the *DSF* implemented inside IDA ICE (*Figure 197* on the left) is an *in-built model*: with this configuration the user can directly enter specific input information by means of the graphic user interface of the simulation environment. No additional modelling effort is therefore required from the user [45].

For these reasons, IDA ICE has been selected as simulation environment for the modelling and the testing of the *DSF* system for this Thesis.

In IDA ICE, the *DSF* can be defined using the *Detailed Window* model and a custom additional component called *Double Glass Façade*. The user can define the properties of the inner skin (such as glazing configuration and frame fraction) using the *Detailed Window Form* already implemented inside the graphic user interface of the program (*Figure 197* on the right).

Using the *Opening* link in the same form, it is also possible to set the dimensions of the first opening that connects the cavity to the indoor environment, with the related control. The dimensions (length and width), in this case, are set in terms of percentage with respect to the overall dimensions of the inner skin.

On the other hand, in the field *Ventilated Construction* it is possible to specify the properties of the external skin and the cavity depth of the *DSF*: clicking on the field it is possible to open the *Double Glass Façade Form* (*Figure 198*).

Inside it the user can define the parameters related to:

- External skin glazing type (*DGU* or *SGU*)
- Cavity depth
- Integrated shading (Venetian or roller blinds)
- Air paths between the different environments (Indoor environment, cavity and outdoor environment).

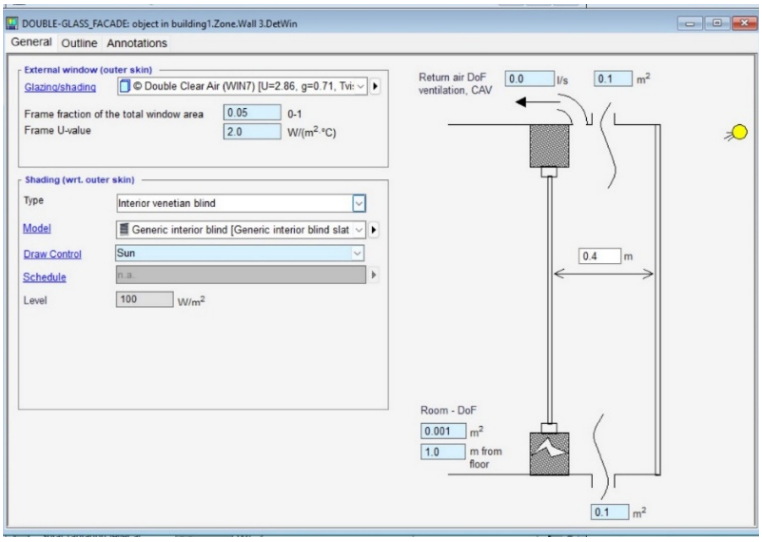


Figure 198: The form referred to the double glass façade component: here it is possible to define the properties of the external skin, the cavity and the integrated shading system.

By default, 4 different air paths are considered inside the form:

- A leak at the floor level (bottom of the cavity) for the connection of the cavity itself with the outdoor environment.
- A leak at the ceiling level (top of the cavity) for the connection of the cavity itself with the outdoor environment.
- A leak between the room and the cavity, for which it is possible to set a given height. This leak represents the second connection between the indoor environment and the cavity of the DSF.
- A connection with the *HVAC* system of the linked thermal zone, assisted by a fan.

While the last opening can be directly expressed in terms of l/s, the first three air paths are expressed by default by means of the *equivalent* or *effective leakage area* A_{eff}. From this, it is possible to define the ventilation air flow through the opening using the following relation [34]:

$$Q = A_{eff} C_d \sqrt{\frac{2\Delta p}{\rho_{air}}}$$

Where:

- C_d is the discharge coefficient, set equal to 1.
- Δp is the pressure difference across the opening, set equal to $4\ Pa$.
- P_{air} is the air density, set equal to $1.161\ kg/m^3$.

Conventionally, the shading system of the DSF is defined as internal shading of the outer skin, using the *Shading* link in the *Double Glass Façade Form*. More details about the shading system can be defined in the dedicated section (*Figure 199)*: slat material, spacing and width, ventilation gap, default slat angle and distance from the outer skin. The advanced control of the shading system (drawn mechanism and slat angle variation) can be implemented using the IDA ICE *Control Macro* in the *Drawn Control* link.

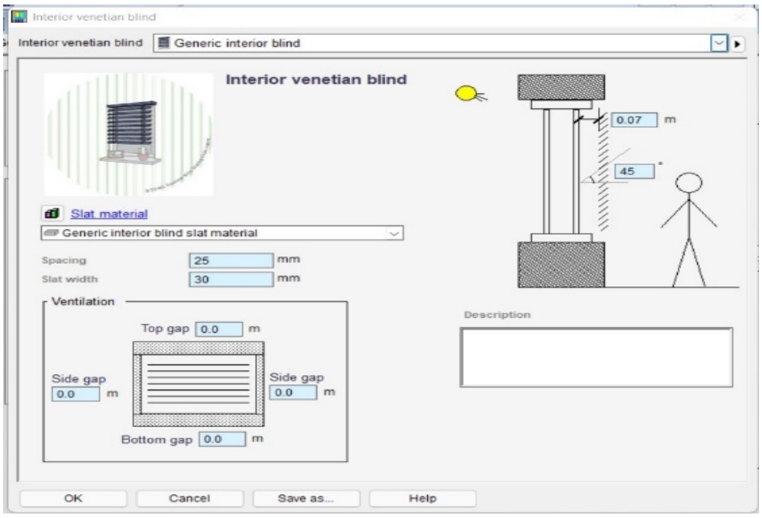


Figure 199: Definition of the shading system properties (in this case a venetian blind): materials, slat angle, distances.

<u>*The flexible DSF system*</u>

Anyway, some additional modification of the standard *DSF* model in IDA ICE must be performed if more advanced control strategies must be implemented by the designer (as in the case of this Master Thesis). The form dialog implemented in the graphic user interface, in fact, does not allow to specify more detailed information about the double skin characteristics.

For this reason, a more complex modelling approach is required. By creating the *Schematic* view of the DSF using the *Build Model* function in the *Simulation* tab of IDA ICE (*Figure 200*), it is therefore possible to view all the different modules that constitute the envelope and their connections with other building systems (for example the *AHU* of the zone).

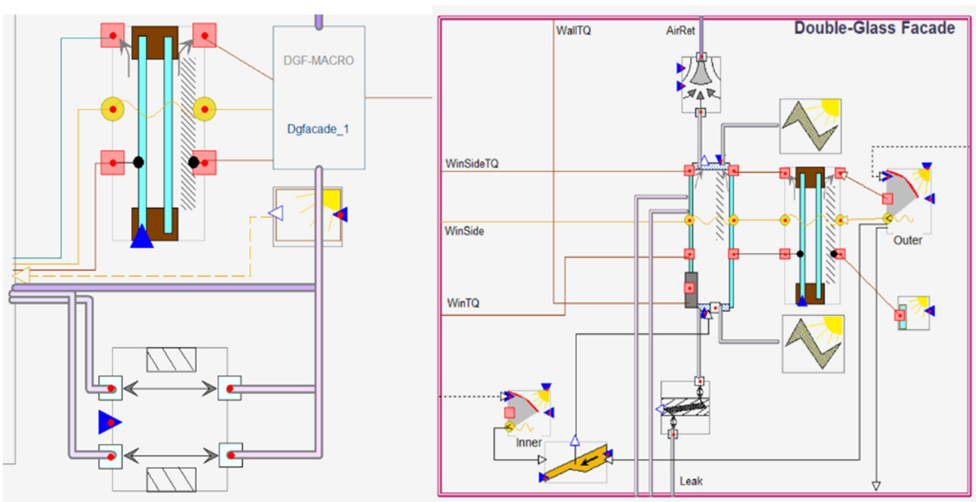


Figure 200: Schematic view of the DSF created on IDA ICE. On the left, it is visible the inner skin and the opening towards the zone, while on the right it is possible to see the ventilated cavity and the outer skin.

In this way, the connections of the cavity to the outdoor environment and the upper connection of the cavity to the linked zone can assumed two different configurations (open and closed) according to the ventilation modes of the façade.

The second step is the connection of the cavity with a fan that can be used for the implementation of the mechanical ventilation inside the cavity. As seen for the openings, the fan can be linked to a *Control Macro* that can manage its operations.

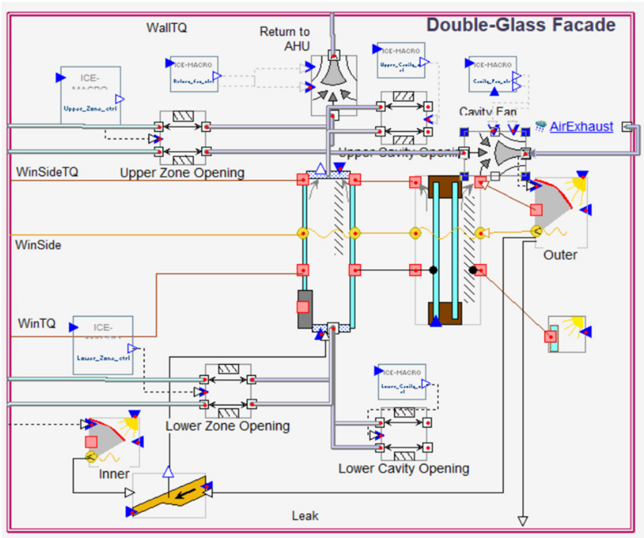


Figure 201: The modified configuration of the DSF system implemented inside IDA ICE

With this advanced interface, it is possible to customize the typologies and the interconnections of the different modules of the *DSF* according to the designer needs, enabling a more detailed modelling of the envelope system.

The most important modification, in fact, is the substitution of the leaks defined in the *Double Glass Façade Form* with some openings, that enable the possibility to implement an *open-closed* control using the IDA ICE *Control Macros* (*Figure 201)*. This approach has been developed and adopted by Elena Catto Lucchino in her PhD Thesis work and used also in this Master Thesis for the implementation of the rule-based control of the *DSF*.

Appendix D - Rule-based control implementation in IDA ICE

In this appendix, it is illustrated the implementation of the rule-based control inside the simulation environment IDA ICE. As illustrated in the *Appendix A*, IDA ICE offers advanced functionalities for the control implementation by using the so-called *Control Macros*. The Control Macros have been linked to the different actuators of the flexible *DSF* already described in *Appendix C*.

The *Control Macros* receive a certain input from an *interface*, linked to a specific variable of the model (for example, the indoor air temperature or the incident solar radiation), and defined a certain *output signal* (*On/Off* or *Open/Close* for example) that is send to an actuator.

Consequently, using the *Control Macros* it is possible to link a specific configuration of the *DSF* to a certain actuator state. Using the IDA ICE *Control Macros* it has been possible to define the decision trees illustrated in *2.3.1*, *2.3.2* and *2.3.3:* an example is reported in *Figure 202*.

As explained in *2.2.4*, the control targets of the façade system are 2:

1) <u>Cavity air flows</u>, corresponding to the zone and cavity openings and cavity fans

2) <u>Shading system</u>, corresponding to the drawn mechanism of the venetian blind and the slat angle regulation

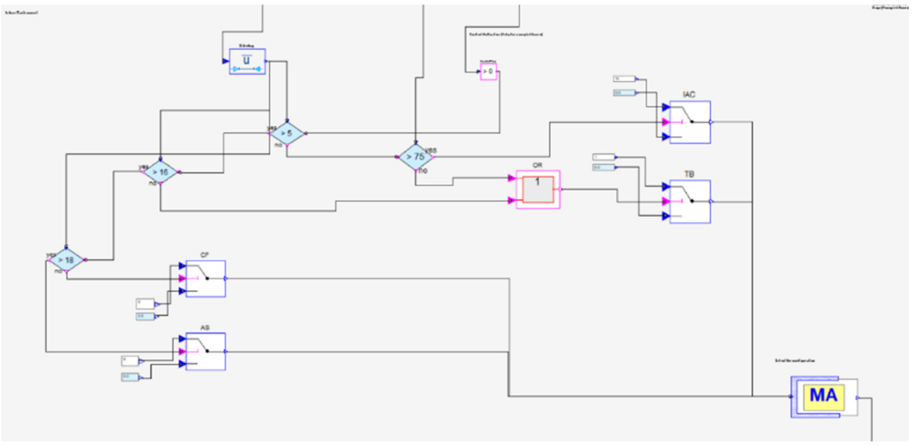


Figure 202: Example of decision tree for the cavity air flows built in IDA ICE

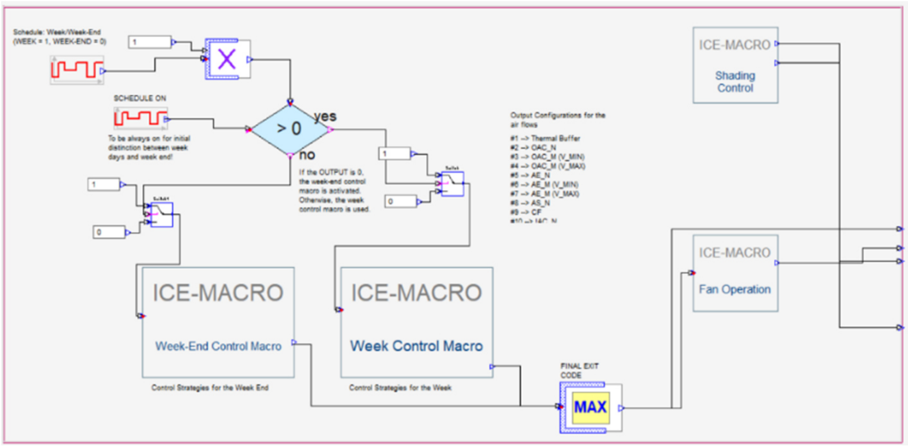


Figure 203: Control implementation for the cavity air flows (on the left) and the shading system (on the right) in the central Control Macro of the DSF

The 2 control targets are independent from each other and therefore their control is applied with the use of different *Control Macros* inside IDA ICE, as visible in *Figure 203*. Inside the two *Control Macros*, for the shading and the cavity air flows, the different decision trees of the control groups *SAC*, *WAC*, *SSC* and *WSC* have been defined.

In the *Control Macros* it is possible to use a wide range of logical operators (*Modules*) that allow the constriction of complex decision trees: the most largely used during the Thesis work are of course the *if-else* operators for the selection of the different configurations of the façade actuators.

Control Macros definition for the air flows

For the control of the cavity air flows, the involved actuators are:

1) The openings between the zone and the cavity
2) The openings between the cavity and the external environment
3) The return fan to the *AHU*
4) The cavity fan

The total number of involved actuators is consequently 6. To each one of the actuators, a certain state can be set in IDA ICE:

1) *Open = 1*, *Closed = 0* for the openings

2) *On =1*, *Off = 0* for the fans
3) *VMIN = 0*, *VMAX =1* for the air flows generated by the fans if activated (respectively, a minimum and a maximum one).

As mentioned in *2.2.4* the total number of configurations for the *DSF* is 10 and to each one of them it is possible to assign a code from 1 to 10 (*Table 140*). Therefore, to each actuator it is possible to associate a state in function of the number of the selected configuration (*Table 141*).

The decision trees implemented inside IDA ICE provide some *exit codes* from 1 to 10, corresponding to the selected configuration for the DSF system. The codes are then sent to the different façade actuators that in this way can change their state in accordance to the output of the decision tree.

	Facade actuator	***State***
Thermal buffer ***(CODE=1)***	Upper cavity opening	Closed
	Lower cavity opening	Closed
	Upper zone opening	Closed
	Lower zone opening	Closed
	Cavity fan	Off
	Return to the AHU	Off
Outdoor Air Curtain (Natural) ***(CODE=2)***	***Facade actuator***	***State***
	Upper cavity opening	Open
	Lower cavity opening	Open
	Upper zone opening	Closed
	Lower zone opening	Closed
	Cavity fan	Off
	Return to the AHU	Off
Outdoor Air Curtain (Mechanical) ***(CODE=3)***	***Facade actuator***	***State***
	Upper cavity opening	Open
	Lower cavity opening	Open
	Upper zone opening	Closed
	Lower zone opening	Closed
	Cavity fan	On (VMIN)
	Return to the AHU	Off
Outdoor Air Curtain (Mechanical, increased air flow) ***(CODE=4)***	***Facade actuator***	***State***
	Upper cavity opening	Open
	Lower cavity opening	Open
	Upper zone opening	Closed
	Lower zone opening	Closed
	Cavity fan	On (VMAX)
	Return to the AHU	Off
Air Exhaust (Natural) ***(CODE=5)***	***Facade actuator***	***State***
	Upper cavity opening	Open
	Lower cavity opening	Closed
	Upper zone opening	Closed
	Lower zone opening	Open
	Cavity fan	Off
	Return to the AHU	Off
Air Exhaust (Mechanical) ***(CODE=6)***	***Facade actuator***	***State***
	Upper cavity opening	Open
	Lower cavity opening	Closed
	Upper zone opening	Closed
	Lower zone opening	Open
	Cavity fan	On (VMIN)
	Return to the AHU	Off
Air Exhaust (Mechanical, increased air flow) ***(CODE=7)***	***Facade actuator***	***State***
	Upper cavity opening	Open
	Lower cavity opening	Closed
	Upper zone opening	Closed
	Lower zone opening	Open
	Cavity fan	On (VMAX)
	Return to the AHU	Off

	Facade actuator	State
Air Supply ***(CODE=8)***	***Facade actuator***	***State***
	Upper cavity opening	Closed
	Lower cavity opening	Open
	Upper zone opening	Open
	Lower zone opening	Closed
	Cavity fan	On
	Return to the AHU	Off
Climate Façade ***(CODE=9)***	***Facade actuator***	***State***
	Upper cavity opening	Closed
	Lower cavity opening	Closed
	Upper zone opening	Closed
	Lower zone opening	Open
	Cavity fan	Off
	Return to the AHU	On
Indoor Air Curtain ***(CODE =10)***	***Facade actuator***	***State***
	Upper cavity opening	Closed
	Lower cavity opening	Closed
	Upper zone opening	Open
	Lower zone opening	Open
	Cavity fan	Off
	Return to the AHU	Off

Table 140: Exit codes for the DSF configurations and related actuators states

Façade actuator	Code of the configuration	State of the actuator	Façade actuator	Code of the configuration	State of the actuator
Upper cavity opening	**#1**	*Closed*	Lower zone opening	**#1**	*Closed*
	#2	*Open*		**#2**	*Closed*
	#3	*Open*		**#3**	*Closed*
	#4	*Open*		**#4**	*Closed*
	#5	*Open*		**#5**	*Open*
	#6	*Open*		**#6**	*Open*
	#7	*Open*		**#7**	*Open*
	#8	*Closed*		**#8**	*Closed*
	#9	*Closed*		**#9**	*Open*
	#10	*Closed*		**#10**	*Open*
Lower cavity opening	**#1**	*Closed*	Cavity fan	**#1**	*Off*
	#2	*Open*		**#2**	*Off*
	#3	*Open*		**#3**	*On (VMIN)*
	#4	*Open*		**#4**	*On (VMAX)*
	#5	*Closed*		**#5**	*Off*
	#6	*Closed*		**#6**	*On (VMIN)*
	#7	*Closed*		**#7**	*On (VMAX)*
	#8	*Open*		**#8**	*Off*
	#9	*Closed*		**#9**	*Off*
	#10	*Closed*		**#10**	*Off*
Upper zone opening	**#1**	*Closed*	Return to the AHU	**#1**	*Off*
	#2	*Closed*		**#2**	*Off*
	#3	*Closed*		**#3**	*Off*
	#4	*Closed*		**#4**	*Off*
	#5	*Closed*		**#5**	*Off*
	#6	*Closed*		**#6**	*Off*
	#7	*Closed*		**#7**	*Off*
	#8	*Open*		**#8**	*Off*
	#9	*Closed*		**#9**	*On*
	#10	*Open*		**#10**	*Off*

Table 141: States of the different actuators in relation to each configuration code

The configuration number in each decision tree is define using the *Switch* module. If the conditions are respected, the number of the configuration is selected. In this way, each decision tree will have certain number of *exit codes*, but only one will be different from zero: it will be the selected configuration for the *DSF* system. In *Figure 204* it is visible the application of the *Switch* module inside the *SAC#1* decision tree.

Only one code different from zero can be the output of the selected switch mechanisms: in this case the selection is between the codes 5, 6 and 7.

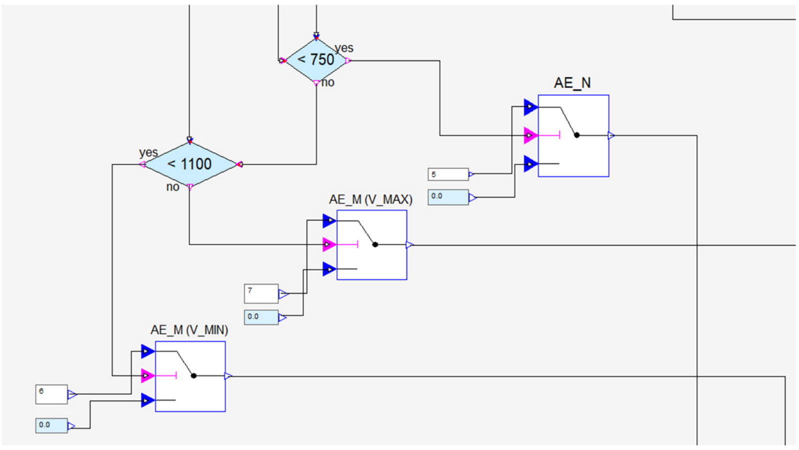


Figure 204: Example of switch modules at the end of a decision tree implemented in IDA ICE for the selection of the confirmation number (in this case 5, 6 and 7).

For the selection of the code from the *Control Macro*, the *Max* module is adopted: being all the exit codes equal to zero except for the selected configuration, the final exit code will be always the greatest one. After the *Max* module, the *exit code* can be sent to the façade actuators.

In *Figure 205* it is showed the application of the *Max* module in the same decision tree: the *Max* modules receives all the exit codes sent by the *Switch* modules, defining in this way the output of the *Macro*.

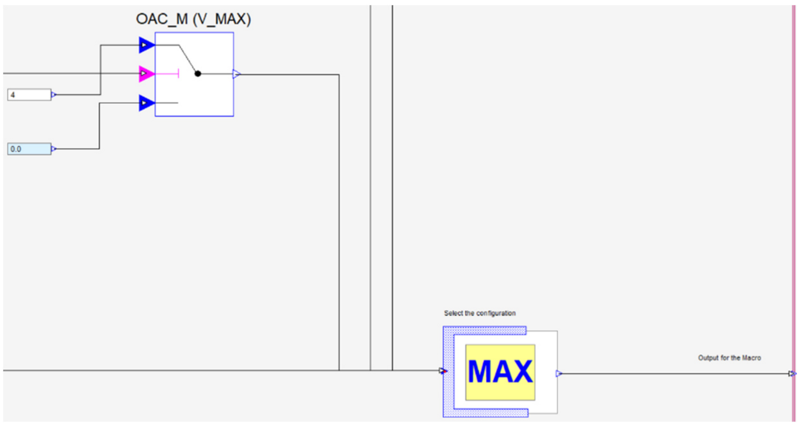


Figure 205: Application of the Max module for the definition of the output of the Macro

After the definition of the *DSF* configuration, it is necessary to associate the exit codes to a specific actuator state. For the definition of the related state, each actuator is associated with another *Control Macro*, which receives the exit code sent from the decision tree and by means of *Lessthan* and *GreaterEqual* modules define the related state of the façade actuator. In the case of the openings, the possible states defined by means of the *Control Macro* are 1 and 0, corresponding to the open and closed configurations. The state also in this case is defined using a *Switch* module between 0 and 1.

In *Figure 206* it is visible the application of this method in the case of the upper zone opening. Using the logical operators of IDA ICE the open state (corresponding to the number 1) is selected only if the exit code from the decision tree is 8 or 10. Otherwise, the opening is kept closed (corresponding to the number 0). For the fans in similar way the *On/Off* selection is performed using the codes 1 and 0 respectively.

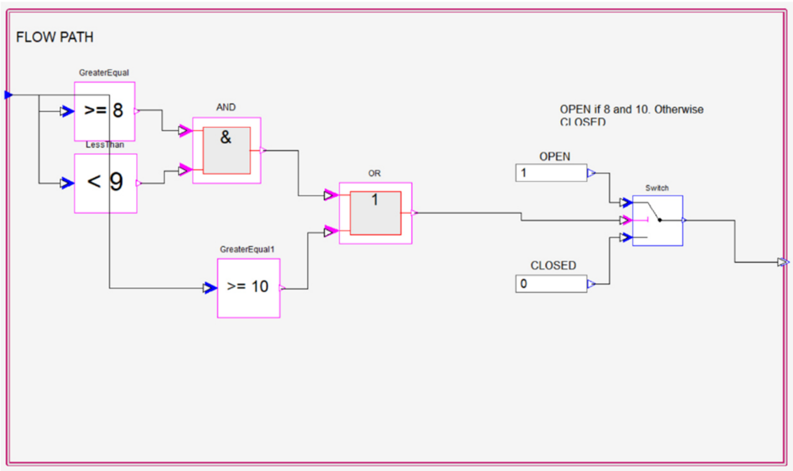


Figure 206: Definition of the actuators state in function of the decision tree

For the fans, an additional *Control Macro* defines the required air flow when the fan is on. In this way it is possible to also define the air flows in the cavity if the fan is in function. The selection of the air flows of the fan is sent to an additional *Switch* module that defines the velocity for the fan.

The *Multiplier* module in this case is used to consider a possible schedule of the fan: if the fan is turned off automatically because of a schedule, the code 1 is multiplied by zero and the resulting configuration of the fan is *Off*. In *Figure 207* it is showed the application of this system for the cavity fan activation.

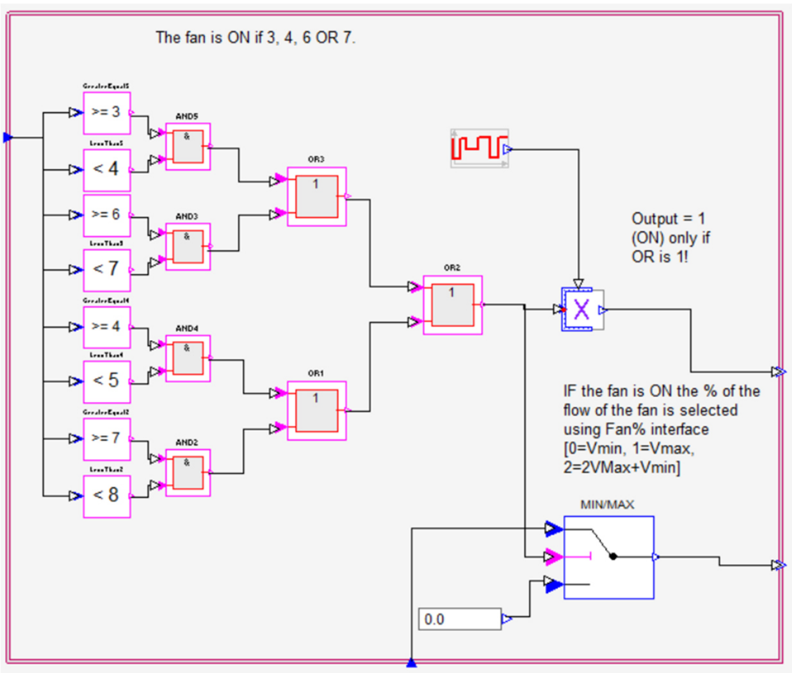


Figure 207: Definition of the fan configuration (on/off) and the related air flow (min/mx) inside the cavity fan Control Macro

Control Macros definition for the shading system

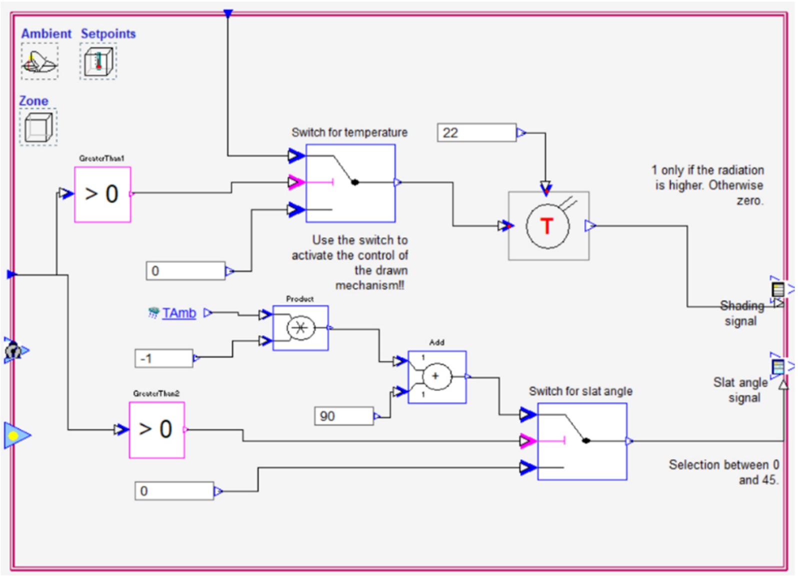


Figure 208: Use of the IDA ICE Control Macro for the application of the shading control

As mentioned before, the control of the shading is focused on the drawn mechanism of the blind and the regulation of the slat angle. Being the control of the shading system independent from the one of the cavity air flows, another *Control Macro* is adopted. The 2 outputs of the Control Macro are in this case the activation of the blind (1 for the drawn blind, 0 for the not drawn blind) and the slat angle (variable from *0°* to *90°*).

In *Figure 208* it is visible the implementation of the *WSC#3* control: the activation of the blind is performed by means of the temperature control, using the *Thermostat* module already present in IDA ICE. If the blind is activated, the cut off position is implemented for the slats. The exact angle is calculated using the logical operators *Product* and *Add*, using the value of solar elevation angle for a given time step of the simulation. This variable is sent as input to the *Control Macro* using the *TAmb* link, related to the climate file of the selected location.

Control of the AHU of the room

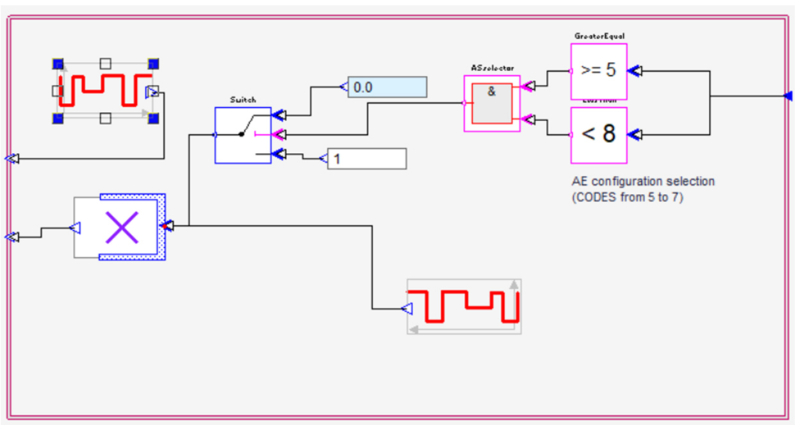


Figure 209: The Control Macro for the supply fan of the AHU

Using the functionalities of the *Control Macros* it is also possible to connect the decision tree for the air flows control to the *AHU* components the supply and return fans. When the façade is operating in *AE* configuration, the return fan can be switched off. On the other hand, when the façade is operating in *AS* configuration, the supply fan can be switched off. In the other configurations, the *AHU* can operate in accordance with the building operations.

The control is implemented creating additional *Control Macros* in the standard one already implemented for the *AHU* in IDA. This additional control macro regulates the *On/Off* mechanism of the fans, in function of the exit code of the decision tree, and the required air flow (*VMIN* and *VMAX*).

To make the operations of the supply and the return fans independent, each fan is connected to a separate control macro, which defines the operations in function of the exit code of the decision tree. In *Figure 209* is reported the example for the return fan, for the summer configurations of the façade. The *On/Off* state is defined by means of a Switch module between 0 and 1.

The presence of the occupancy schedule (0 for unoccupied periods, 1 for occupied ones) allows to consider the operational time of the fan during its control, using the *Multiplier* module.
When the façade is operating in the *AE* configurations, the supply fan is turned off, as it is possible to see from the selected exit codes (from 5 to 7). The velocity of the fans (*VMIN* and *VMAX*) is regulated using the occupancy schedule for the thermal zone (occupied and unoccupied hours).

<u>*Control Macros for the unoccupied hours*</u>

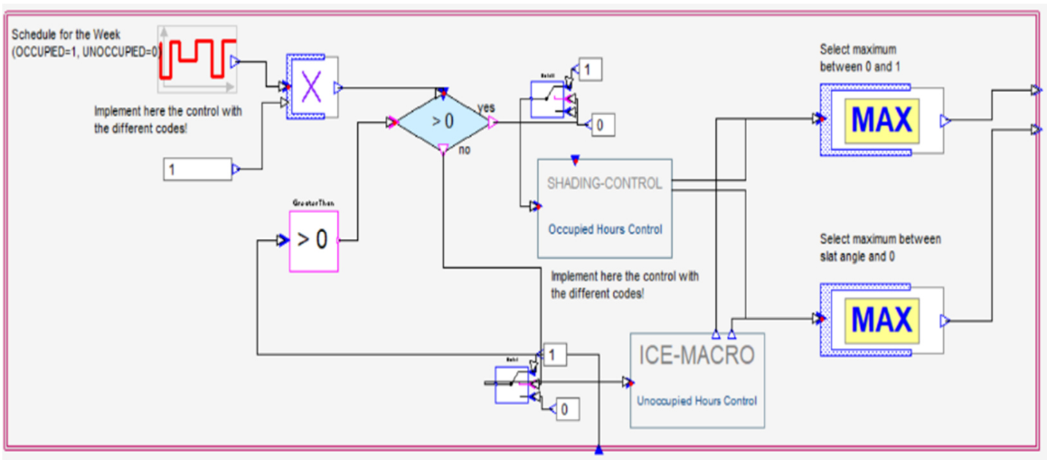


Figure 210: Distinction between the operating strategies for the shading system during the weekdays

The distinction between control strategies for the occupied and unoccupied hours and for the working and weekend days is performed by means of schedules. Using the *Multiplier* module, it is possible to define if a given time step is inside an occupied time (code 1) or unoccupied one (code 0). Using the *If* module an activation signal (0 or 1) is sent to the control macros for the occupied and unoccupied hours. Only if the activation signal is positive, the control inside the *Control Macro* is activated and the blind state and the slat angle can be defined.

Otherwise, the exit code for blind drawn mechanism and slat angle from the *Control Macro* is set null. In this way, using the *Max* module, it is possible to select the right configuration of the shading for a given time step. In *Figure 210* the application of this system is showed for the control of the shading during the working days in the winter season. The same approach has been adopted during the weekend to perform a distinction between night and daytime.

<u>*Control Macros for the artificial lighting system*</u>

Following the same approach adopted for the other components of the model, also the control of the lighting can be defined (*Figure 211*): in this case, during the occupied hours, the light is turned off if the indoor illuminance levels on the working plane are below the limit of *500 lux*.

Otherwise, during the unoccupied hours, the artificial lighting is turned off. Also in this case the *Sliding Average* operator have been used to calculate an average of the illuminance levels at the working plane, to reduce of a certain extent the required time for the different simulations.

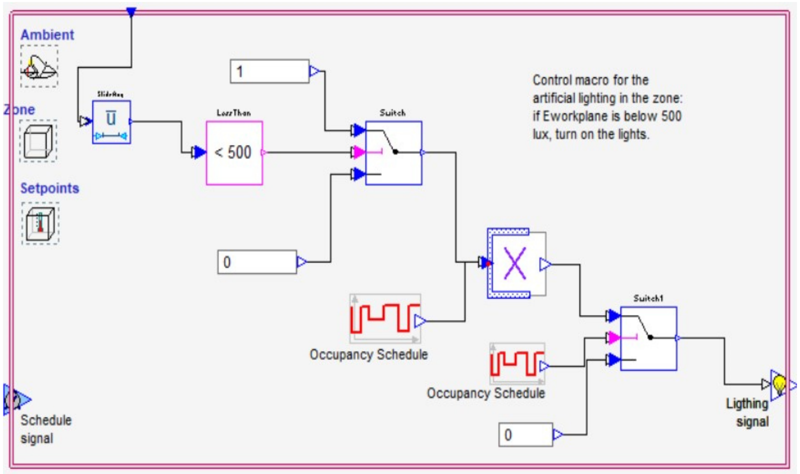


Figure 211: Definition of the control macro for the artificial lighting system of the room

<u>*Resolution of possible numerical instabilities and too long simulation times*</u>

During the simulations of the control in IDA ICE, there could be possible problems caused by too long times required for the analysis. This can be caused by too frequent changes of the façade configurations, that modify the thermo-physical behaviour of the system, increasing the computational effort required by the simulation environment. The main causes of a too frequent configuration change of the *DSF* are:

- High variability of the control variables during the simulation time (for example the cavity temperature of the *DSF*), that can increase the instability of the simulation

- Too narrow threshold limits of the control variables for the configuration switches of the façade actuators

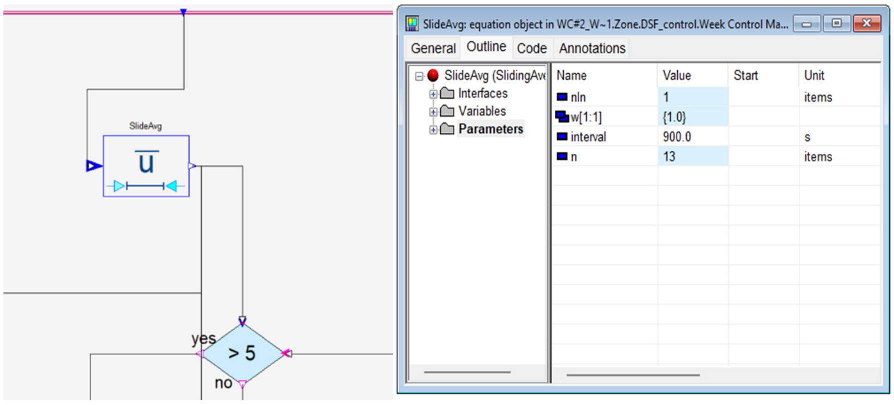


Figure 212: The Sliding Average module (left) and the definition of the interval parameter (right) in the Outline view

The solution to the first problem is the use of the *Sliding Average* module (*Figure 212*): this module calculates the average of the selected control variable, referred to a previous period, defined by the user. The module has been used for example in the decision trees for the selection of the air flow configurations, for the calculation of the sliding average of the cavity air temperature used as control variable (both in summer and winter conditions). The selected time in this case is *900 sec* (*15 minutes*).

This solution can reduce in a significant way the time that is required for the simulation of the control decision tree, without affecting too much the results of the analysis performed on the model (the interval of time must be anyway short enough).

For the second problem, the only solution is the one to "enlarge" the distance between the different threshold limits of the control variables, avoiding in this way too fast changes in the façade configurations: also this option has been adopted, in case of too large simulation periods required by IDA ICE.

The *Sliding Average* operator have been used in other several cases during the definition of the *Control Macros*, the ensure proper simulation times for the different façade configurations.

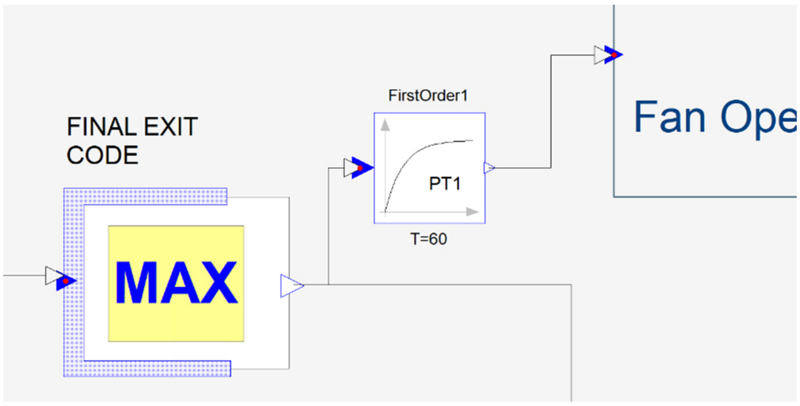


Figure 213: The First Order Operator module adopted to retard the response of the façade actuators. In this case the selected period is 60 seconds.

Another possible solution for the limitation of the numerical instabilities problems is the adoption of the *First Order Operator* module (*Figure 213*): this mathematical module can retard the variation of the actuator's states in response to a certain output signal given by the decision tree. Selecting a certain period, the actuator will change its configuration only after the passing of the preferred period of time.

In some cases, however, it is not possible to perform the simulation due to the consistent presence of numerical instabilities problems, even if the *Sliding Average* and *First Order Operator* modules have been used. The only solution in this case is to modify the threshold limits of the control variables or directly change the control structure.

This is of course a longer and more complex procedure, especially if long simulation periods are considered: in the case of the annual simulations in Oslo, for example, it was not possible to perform indoor climate simulations referred to the whole year because of numerical instability problems, given the fact that the only approach to follow was the modification of the *DSF* control structures and the related threshold values selected for the control.

Appendix E - Optimization scripting in the IDA ICE API

The optimization script used for the definition of the different combinations of threshold values for the control variables of the annual decision tree is here reported (the optimization script is the one defined for Frankfurt, South façade).

```
from msilib.schema import ComboBox
from tokenize import Token
from turtle import setheading
from winreg import SetValue
from util import *
from calendar import c
from re import X
from shelve import DbfilenameShelf
from util import *

#file path to the flexible DSF model
```

```
file_path_0 = "C:\\Users\\[…]\\Flexible DSF.idm
file_path = file_path_0.encode()

DSF = call_ida_api_function(ida_lib.openDocument, file_path)

fileidm = ida_get_name(DSF)
print("Opening case: " + fileidm)

#Possible threshold values for the parameters initialized in different lists

TempRange = [-10, -5, 0]
RadRangeShad = [200, 300, 400, 500]
TempRangeShad = [20, 23, 26]
CO2LevelRangeSummerCode = [1, 2]
TempRangeCavSummer = [20, 23, 26]
CO2RangeWinter = [800, 1000]
TCavLevelRangeWinterCode = [1, 2]

#Empty lists with the values of the different parameters

TempSwitchList = []
RadiationShadList = []
TemperatureShadLunchList = []
TemperatureShadWeekEndList = []
CO2Summer1List = []
CO2Summer2List = []
CO2Summer3List = []
TCavMaxSummerList = []
CO2WinterList = []
TCavWinter1List = []
TCavWinter2List = []
TCavWinter3List = []
TCavWinter4List = []

#Empty lists for the results referred to heating, cooling and artificial lighting

TotalHeatList = []
TotalCoolList = []
TotalLightList = []

ComboNumber = []

n_iter = 0

#start of the for loops (7 in total)

#1st for loop (temperature difference value for the seasonal switch)

for temp_switch in TempRange:

      changeTempDiff = "(:UPDATE [@](:PAR :N THRESHOLD_SEASON :V "+ str(temp_switch) +"))"
      call_ida_api_function(ida_lib.runIDAScript, DSF, changeTempDiff.encode('utf-8'))


#2nd for loop (solar radiation level on the façade for the blind activation)

for rad_shad in RadRangeShad:

      changeRadShad = "(:UPDATE [@](:PAR :N RAD_SHAD :V "+ str(rad_shad) +"))"
      call_ida_api_function(ida_lib.runIDAScript, DSF,changeRadShad.encode('utf8'))

#3rd for loop (indoor temperature level of for the blind activation in the unoccupied hours)

for temp_shad in TempRangeShad:

      changeTempShad = "(:UPDATE [@](:PAR :N TEMP_SHAD :V "+ str(temp_shad) +"))"
      call_ida_api_function(ida_lib.runIDAScript, DSF, changeTempShad.encode('utf-8'))

#4th for loop (CO2 indoor levels for the switching between the different AE configurations)

for CO2_level_summer_code in CO2LevelRangeSummerCode:

      if CO2_level_summer_code == 1: #first option of values
```

```
        changeCO2TempSummer1 = "(:UPDATE [@](:PAR :N CO2_SUMMER_1 :V "+ str(500) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeCO2TempSummer1.encode('utf-8'))

        changeCO2TempSummer2 = "(:UPDATE [@](:PAR :N CO2_SUMMER_2 :V "+ str(700) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeCO2TempSummer2.encode('utf-8'))

        changeCO2TempSummer3 = "(:UPDATE [@](:PAR :N CO2_SUMMER_3 :V "+ str(900) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeCO2TempSummer3.encode('utf-8'))

       else: #second option of values

        changeCO2TempSummer1 = "(:UPDATE [@](:PAR :N CO2_SUMMER_1 :V "+ str(600) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeCO2TempSummer1.encode('utf-8'))

        changeCO2TempSummer2 = "(:UPDATE [@](:PAR :N CO2_SUMMER_2 :V "+ str(900) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeCO2TempSummer2.encode('utf-8'))

        changeCO2TempSummer3 = "(:UPDATE [@](:PAR :N CO2_SUMMER_3 :V "+ str(1000) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeCO2TempSummer3.encode('utf-8'))

#5th for loop (maximum cavity air temperature for the adoption of AS in summer)

for tcav_max_summer in TempRangeCavSummer:

       changeTCavMaxSummer = "(:UPDATE [@](:PAR :N TCAV_MAX_SUMMER :V "+ str(tcav_max_summer)
       +"))"
       call_ida_api_function(ida_lib.runIDAScript, DSF, changeTCavMaxSummer.encode('utf-8'))

#6th for loop (CO2 indoor levels for the adoption of AE in winter)

for CO2_winter in CO2RangeWinter:

       changeCO2Winter = "(:UPDATE [@](:PAR :N CO2_WINTER :V "+ str(CO2_winter) +"))"
       call_ida_api_function(ida_lib.runIDAScript, DSF, changeCO2Winter.encode('utf-8'))

#7th for loop (cavity air temperatures for the adoption of the winter configurations)

for TCav_level_winter_code in TCavLevelRangeWinterCode:

       if TCav_level_winter_code == 1: #first option of values

        changeTCavWinter1 = "(:UPDATE [@](:PAR :N TCAV_WINTER_1 :V "+ str(2) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeTCavWinter1.encode('utf-8'))

        changeTCavWinter2 = "(:UPDATE [@](:PAR :N TCAV_WINTER_2 :V "+ str(19) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeTCavWinter2.encode('utf-8'))

        changeTCavWinter3 = "(:UPDATE [@](:PAR :N TCAV_WINTER_3 :V "+ str(22) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeTCavWinter3.encode('utf-8'))

        changeTCavWinter4 = "(:UPDATE [@](:PAR :N TCAV_WINTER_4 :V "+ str(25) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeTCavWinter4.encode('utf-8'))

       else: #second option of values

        changeTCavWinter1 = "(:UPDATE [@](:PAR :N TCAV_WINTER_1 :V "+ str(4) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeTCavWinter1.encode('utf-8'))

        changeTCavWinter2 = "(:UPDATE [@](:PAR :N TCAV_WINTER_2 :V "+ str(21) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeTCavWinter2.encode('utf-8'))

        changeTCavWinter3 = "(:UPDATE [@](:PAR :N TCAV_WINTER_3 :V "+ str(24) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeTCavWinter3.encode('utf-8'))

        changeTCavWinter4 = "(:UPDATE [@](:PAR :N TCAV_WINTER_4 :V "+ str(27) +"))"
        call_ida_api_function(ida_lib.runIDAScript, DSF, changeTCavWinter4.encode('utf-8'))


print("All the parameters have been changed!")

n_iter = n_iter + 1

ComboNumber.append(n_iter)

print("Now start the iteration number: ", n_iter)
```

```
#verify the substitution of the values

Zone = ida_get_named_child(DSF, "ZONE")
season_selector = ida_get_named_child(Zone, "SEASON SELECTOR")
temp_diff_object = ida_get_named_child(season_selector, "TEMPERATURE DIFFERENCE SEASON")
temp_diff = ida_get_named_child(temp_diff_object, "threshold")
temp_diff_val = ida_get_value(temp_diff)


DSF_control = ida_get_named_child(Zone, "DSF_control")
shading_control = ida_get_named_child(DSF_control, "Shading Control")
shading_week_control = ida_get_named_child(shading_control, "Week")
shading_occupied_control = ida_get_named_child(shading_week_control, "Occupied Hours")
radiation_shading_limit_object  =  ida_get_named_child(shading_occupied_control,  "Radiation
Limit")
radiation_shading_limit = ida_get_named_child(radiation_shading_limit_object, "threshold")
radiation_shading_limit_val = ida_get_value(radiation_shading_limit)


shading_unoccupied_control = ida_get_named_child(shading_week_control, "Unoccupied Hours")
shading_lunch_break_cooling_control = ida_get_named_child(shading_unoccupied_control, "Lunch
Break")
temperature_shading_limit_lunch_object=ida_get_named_child(shading_lunch_break_cooling_contr
ol, "Temperature Limit Lunch")
temperature_shading_limit_lunch = ida_get_named_child(temperature_shading_limit_lunch_object,
"threshold")
temperature_shading_limit_lunch_val = ida_get_value(temperature_shading_limit_lunch)


shading_weekend_control = ida_get_named_child(shading_control, "Week End")
temperature_shading_limit_weekend_object    =    ida_get_named_child(shading_weekend_control,
"Temperature Limit Week End")
temperature_shading_limit_weekend=ida_get_named_child(temperature_shading_limit_weekend_obje
ct, "threshold")
temperature_shading_limit_weekend_val = ida_get_value(temperature_shading_limit_weekend)


week_control = ida_get_named_child(DSF_control, "Week")
occupied_control = ida_get_named_child(week_control, "Occupied Hours")
CO2_limit1_Sum_object = ida_get_named_child(occupied_control, "CO2_limit_cooling1")
CO2_limit1_Sum_limit = ida_get_named_child(CO2_limit1_Sum_object, "threshold")
CO2_limit1_Sum_val = ida_get_value(CO2_limit1_Sum_limit)

CO2_limit2_Sum_object = ida_get_named_child(occupied_control, "CO2_limit_cooling2")
CO2_limit2_Sum_limit = ida_get_named_child(CO2_limit2_Sum_object, "threshold")
CO2_limit2_Sum_val = ida_get_value(CO2_limit2_Sum_limit)

CO2_limit3_Sum_object = ida_get_named_child(occupied_control, "CO2_limit_cooling3")
CO2_limit3_Sum_limit = ida_get_named_child(CO2_limit3_Sum_object, "threshold")
CO2_limit3_Sum_val = ida_get_value(CO2_limit3_Sum_limit)


TCav_limit_Sum_object = ida_get_named_child(occupied_control, "CavityTemp_limit_cooling1")
TCav_limit_Sum_limit = ida_get_named_child(TCav_limit_Sum_object, "threshold")
TCav_limit_Sum_val = ida_get_value(TCav_limit_Sum_limit)


CO2_limit_Win_object = ida_get_named_child(occupied_control, "CO2_limit_heating")
CO2_limit_Win_limit = ida_get_named_child(CO2_limit_Win_object, "threshold")
CO2_limit_Win_val = ida_get_value(CO2_limit_Win_limit)


TCav_limit1_Win_object = ida_get_named_child(occupied_control, "CavityTemp_limit_heating1")
TCav_limit1_Win_limit = ida_get_named_child(TCav_limit1_Win_object, "threshold")
TCav_limit1_Win_val = ida_get_value(TCav_limit1_Win_limit)
TCav_limit2_Win_object = ida_get_named_child(occupied_control, "CavityTemp_limit_heating2")
TCav_limit2_Win_limit = ida_get_named_child(TCav_limit2_Win_object, "threshold")
TCav_limit2_Win_val = ida_get_value(TCav_limit2_Win_limit)
TCav_limit3_Win_object = ida_get_named_child(occupied_control, "CavityTemp_limit_heating3")
TCav_limit3_Win_limit = ida_get_named_child(TCav_limit3_Win_object, "threshold")
TCav_limit3_Win_val = ida_get_value(TCav_limit3_Win_limit)

TCav_limit4_Win_object = ida_get_named_child(occupied_control, "CavityTemp_limit_heating4")
TCav_limit4_Win_limit = ida_get_named_child(TCav_limit4_Win_object, "threshold")
```

```
TCav_limit4_Win_val = ida_get_value(TCav_limit4_Win_limit)

#print the combined values in the n combo

print("Combined values in this iteration are: ")

print("Temperature difference for the seasonal switch: ", temp_diff_val, " °C")
print("Incident solar radiation for the shading activation: ", radiation_shading_limit_val, " W/m2")
print("Indoor air temperature for the shading control in the lunch break: ", temperature_shading_limit_lunch_val, " °C")
print("Indoor air temperature for the shading control during the week end: ", temperature_shading_limit_weekend_val, " °C")
print("CO2 level 1 for the summer control: ", CO2_limit1_Sum_val, " ppm")
print("CO2 level 2 for the summer control: ", CO2_limit2_Sum_val, " ppm")
print("CO2 level 3 for the summer control: ", CO2_limit3_Sum_val, " ppm")
print("Cavity temperature for the summer control: ", TCav_limit_Sum_val, " °C")
print("CO2 level for the winter control: ", CO2_limit_Win_val, "ppm")
print("Cavity temperature 1 for the winter control: ", TCav_limit1_Win_val, "°C")
print("Cavity temperature 2 for the winter control: ", TCav_limit2_Win_val, "°C")
print("Cavity temperature 3 for the winter control: ", TCav_limit3_Win_val, "°C")
print("Cavity temperature 4 for the winter control: ", TCav_limit4_Win_val, "°C")


print("Now performing simulation number: ", n_iter)

#Simulation run for the n combo

sim_res = call_ida_api_function(ida_lib.runSimulation,DSF,5)

print("Simulation done...")
print("Here there are the results... ")

#Get space cooling demand

emeterloccool = ida_get_named_child(DSF, "EMETERLOCCOOL")
tot_cool = ida_get_named_child(emeterloccool, "TOTENERGY")
tot_cool_val_neg = ida_get_value(tot_cool)
tot_cool_val = ((-1 * tot_cool_val_neg))/48
print("TOTAL SPACE COOLING DEMAND:")
print(tot_cool_val, " kWh/m2")

#Get ventilation cooling demand

tot_vent_cool_emeter = ida_get_named_child(DSF, "COOLING_AHU")
tot_vent_cool = ida_get_named_child(tot_vent_cool_emeter, "TOTENERGY")
tot_vent_cool_val = (ida_get_value(tot_vent_cool))/48
print("TOTAL VENTILATION COOLING DEMAND:")
print(tot_vent_cool_val, " kWh/m2")

#Calculate total cooling

total_cooling_start = tot_cool_val + tot_vent_cool_val
total_cooling = round(total_cooling_start,2)
print("TOTAL COOLING DEMAND:")
print(total_cooling, " kWh/m2")
TotalCoolList.append(total_cooling)

#Get space heating demand

emeterlocheat = ida_get_named_child(DSF, "EMETERLOCHEAT")
tot_heat = ida_get_named_child(emeterlocheat, "TOTENERGY")
tot_heat_val = (ida_get_value(tot_heat))/48
print("TOTAL SPACE HEATING DEMAND:")
print(tot_heat_val, " kWh/m2")

#Get ventilation heating demand

tot_vent_heat_emeter = ida_get_named_child(DSF, "HEATING_AHU")
tot_vent_heat = ida_get_named_child(tot_vent_heat_emeter, "TOTENERGY")
tot_vent_heat_val = (ida_get_value(tot_vent_heat))/48
print("TOTAL VENTILATION HEATING DEMAND:")
print(tot_vent_heat_val, " kWh/m2")

#Calculate total heating
```

```
total_heating_start = tot_heat_val + tot_vent_heat_val
total_heating = round(total_heating_start,2)
print("TOTAL HEATING DEMAND:")
print(total_heating, " kWh/m2")
TotalHeatList.append(total_heating)

#Get artificial lighting energy need

emeterqlight = ida_get_named_child(Zone, "EMETERQ_LIGHT")
tot_light = ida_get_named_child(emeterqlight, "TOTENERGY")
tot_light_val_start = (ida_get_value(tot_light))/48
tot_light_val = round(tot_light_val_start,2)
print("TOTAL LIGHTING DEMAND:")
print(tot_light_val, " kWh/m2")
TotalLightList.append(tot_light_val)

data_energy = {'TOT HEATING [kWh/m2]': [round(total_heating,2)],
'TOT COOLING [kWh/m2]': [round(total_cooling,2)],
'LIGHTING [kWh/m2]': [round(tot_light_val,2)]}


data_energy_df = pd.DataFrame(data_energy)
print("Here there are the overall values for the iteration number: ", n_iter)

print(data_energy_df)

#Save .csv in the related folder (1 for each combo)

data_energy_df.to_csv("C:\\Users\\[…]\\DataEnergy_"+str(n_iter)+"_Overall.csv",index = False)

print("Start a new iteration... ")

#end of all the for loops

print("All the iterations are concluded!")

#Final Tables of the results: variation in function of the combo number

Heating_df = pd.DataFrame({"Total Heating [kWh/m2]":TotalHeatList,"n combo [-]":ComboNumber})
print(Heating_df)
Heating_df.to_csv("C:\\Users\\[…]\\Heating.csv", index = False)

Cooling_df = pd.DataFrame({"Total Cooling [kWh/m2]":TotalCoolList,"n combo [-]":ComboNumber})
print(Cooling_df)
Cooling_df.to_csv("C:\\Users\\[…]\\Cooling.csv", index = False)

Lighting_df = pd.DataFrame({"Total Lighting [kWh/m2]":TotalLightList,"n combo [-
]":ComboNumber})
print(Lighting_df)
Lighting_df.to_csv("C:\\Users\\[…]\\Lighting.csv", index = False)


#Put all the results in a common table

final = {

'N Combo [-]': ComboNumber,
'TOT Heating [kWh/m2]': TotalHeatList,
'TOT Cooling [kWh/m2]': TotalCoolList,
'TOT Lighting [kWh/m2]': TotalLightList,

}

final_df = pd.DataFrame(combos)

#print(final_df)

#Save in a .csv file the final results

final_df.to_csv("C:\\Users\\[…]\\FinalValues.csv", index = False)
```

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