# cultural E+

*Climate and cultural based design and market valuable technology solutions for Plus Energy Houses*

## Active Window configurator tool

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## List of Abbreviations

| | |
|---|---|
| AWS | Active Window System |
| IGU | Insulating glazing unit |
| KPI | Key Performance Indicator |
| TV | Trickle Vents |
| VM | Ventilation machine |
| BSDF | Bidirectional Scattering Distribution Function |
| FEM | Finite Element Method |
| CFD | Computational Fluid Dynamic |
| IAQ | Indoor Air Quality |

## 3   Executive summary

This document aims to provide and overview of the different Active Window System (AWS) configurations and its main key performance indicators (KPI). These performance indicators are gathered in an ad-hoc database, which is the AWS configurator tool. Therefore, this document is a complementary manual to that tool, so that it can support a better understanding and use of the tool during the AWS design process.

Results consists of a series of KPIs belonging to different physical domains (window performance, thermal, daylight, Indoor Air Quality (IAQ)) and assessed for a number of different configurations. These configurations take into account different climatic conditions (with implications also on the window frame and glazing thermal characteristics), shading configurations (external shadings, shadings integrated in the Insulated Glazing Unit (IGU) or electrochromic glazing), ventilation typology (no ventilation, Trickle Vents (TV) or Ventilation Machine (VM)) and eventual integration between the ventilation and the shading system. All these configurations will be better explained in the following paragraphs. Nonetheless, this variability allowed to assess the behavior of the AWS with a multidisciplinary perspective and taking into account a large number of potential applications in real cases.

The AWS configurator tool might be extremely useful at the early stages of a design process, since a synthetic yet complete picture of the Active Window System behavior and its implications in the considered case study is drawn through simple KPIs. Therefore, comparisons among different configurations can be easily performed, as well as climate implications on the same system.

Beside the final result of the AWS configurator tool, this document describes the methodology used to obtain the results, with interesting insights on how to deal with simulations at different scales (component/system or building).

The following chapters will describe:

- *Chapter 2*: Active Window System
- *Chapter 3*: the methodological approach
- *Chapter 4*: a practical explanation on the configurator tool
- *Chapter 5*: conclusions
- *Annex 1* and *Annex 2*: technical details about the methodology used in simulation

## 4   Active Window System (AWS)

### 4.1   Introduction

The Active Window System is a new window system that aims at changing the traditional window concept to an active element that promotes energy efficiency, indoor air quality and user comfort. This new window system is based on the following technological pillars:

1. *Modular wood frame system:* The wood frame new design was conceived to be easily adaptable to different configurations, such as different climates, different insulating glazing units (IGU) or integration of different shading devices. It was designed to be easy to manufacture and to install both, in-wall and insulated block installation.

2. *Movable adaptive shading system:* The AWS can integrate different shading systems, such as external shading, electrochromic glass or integrated venetian blinds. In the latter case, the venetian blinds are allocated in a semi-ventilated external chamber in front of the insulating glass unit and protected by an external openable glass. This configuration allows to easily maintain the system. Moreover, shading control strategies were optimized between visual/thermal comfort and winter/summer energy savings.

3. *Integrated decentralized ventilation device:* The AWS, as a multifunctional window system, allows the integration of decentralized ventilation devices, such as passive trickle vents for assuring certain natural ventilation or active compact mechanical ventilation machines with heat recovery.
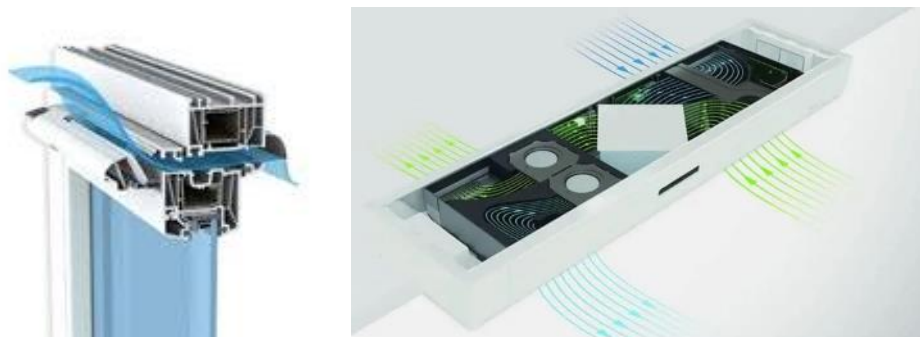


**Figure 1. Decentralized ventilation devices: Trickle vents (left – Source: Renson), Ventilation machine (right – Source: Thesan)**

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4. *Interaction between shading semi ventilated cavity and decentralized ventilation device:* The most advanced configurations of the AWS would include the venetian blinds in the semi ventilated cavity and the ventilation device in a way that they would collaborate between themselves, with the aim of exploiting the shading cavity ventilation for optimizing indoor air quality and energy consumption. This could be done in different ways depending on the type of ventilation device (passive or active) and the season. After an extensive analysis of these possibilities, part of these AWS configurations were considered only as theoretical possibilities, as they are still not technically ready to be implemented in real cases.

This new window system was developed in collaboration by Eurac Research and Eurofinestra.

## 4.2    Active Window System configurations

Based on the different AWS design possibilities mentioned before, the most interesting combination of design parameters were selected to identify the main AWS configurations, as shown in Table 1.

**Table 1. Active Window System different design possibilities**

| AWS different solutions | | |
|---|---|---|
| **Window type: frame + IGU (3)** | **Shading (3)** | **Ventilation (5)** |
| Mediterranean: frame1 + IGU1 | External | No Ventilation device |
| Continental: frame2 + IGU2 | Integrated - ventilated* | Ventilation Machine  independent |
| Nordic: frame3 + IGU3 | Electrochromic | Trickle Vents independent |
| | | Ventilation machine coupled with the ventilated shading cavity* |
| | | Trickle vents coupled with the ventilated shading cavity* |
| Total: 33 possible AWS configurations | | |

In order to cover the main European climates, three different window frames and IGUs were selected (Mediterranean, Continental and Nordic), based on their application zones and therefore the required thermal features, such as $U_{frame}$, $U_{glazing}$ and g-value:

The second design parameter is the shading device to be integrated in the AWS, among the three selected options (external, integrated in the semi-ventilated cavity and electrochromic).

The last design parameter is the ventilation device to be integrated in the AWS, among the three selected options (window with no ventilation device, with active ventilation machine (VM) or with passive trickle vents (TV)). For the last two cases the ventilation devices could work independently or coupled with the ventilated shading cavity, when applicable. For this reason, it is worth to be noted that, in Table 1, the last two ventilation solutions (*Ventilation machine coupled with the ventilated shading cavity* and *Trickle vents coupled with the ventilated shading cavity*) are only applicable with the integrated shading (all are in facts highlighted in purple followed by an asterisk).

The full combination of these different design parameters result in 33 different AWS possible configurations: 18 configurations regarding the external and electrochromic cases (3 window types x 2 shadings x 3 ventilations) and 15 configurations regarding the integrated shading (3 window types x 1 shading x 5 ventilations).

Figure 2 shows the schemes of some of the analysed AWS configurations to give a better understanding of the different possibilities. Option d) and e) integrate an external shading, with no ventilation or with trickle vents respectively. Option a), b) and c), on the other hand, integrate the shading in the semi ventilated cavity combined with different ventilation schemes:

5. *Option c):* No ventilation device is included in the AWS, therefore the shading cavity is ventilated naturally with external air

6. *Option b):* Integration of independent trickle vents, therefore the shading cavity is ventilated naturally with external air and the two ventilation flows (of the shading and the trickle vents) do not cross each other.

7. *Option a):* A trickle vent is coupled with the shading cavity ventilation, which is used to preheat the air before passing through the trickle vent and entering the indoor environment.
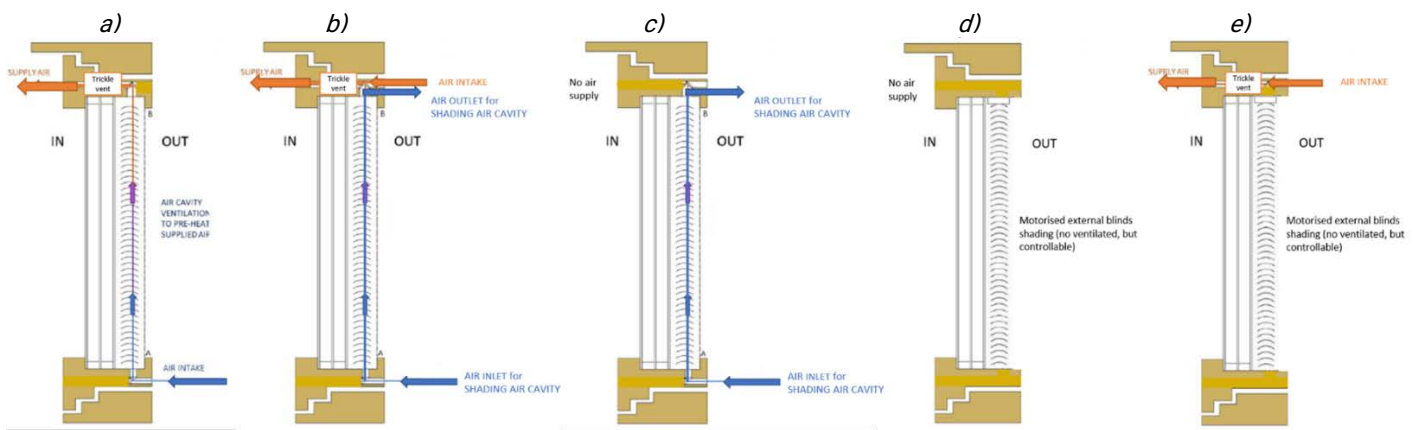
**Figure 2. Schemes of some of the possible AWS configurations**

It is worth to be mentioned that the previous scheme shows just some of the possible AWS configurations and that the option numbers do not correspond to the ones shown in the next chapter, which goes more in detail about the methodological approach used in the simulations.

The different AWS configurations were deeply analysed in terms of technical feasibility, condensation risk, as well as thermal, daylighting and indoor air quality performance. The main results of these parametric analysis were then gathered in a AWS configurator tool to support the AWS design phase, as explained in the following sections.

## 5    Methodology

The AWS behaviour in all its configurations is assessed both in at system scale (i.e. with detailed analysis on its thermal behaviour, air movement in the cavity, condensation risk, etc.) and at building scale (i.e. evaluating its impact on the indoor environment according to several KPIs). To this purpose, in the next paragraphs it will be shown how the two scales are tackled with different tools and approaches and how this two levels of analysis are interconnected through calibrations and checks between the used modelling tools.

### 5.1    Building case study

In order to properly create the performance database for the AWS configurator tool, a thermal model of the building case study was set up in TRNSYS 18. The model is a 80 m2 apartment (five rooms) as shown in Figure 3, in which all the windows represented in each room (with the expectation of the bathroom) are the AWS, the focus of this study.
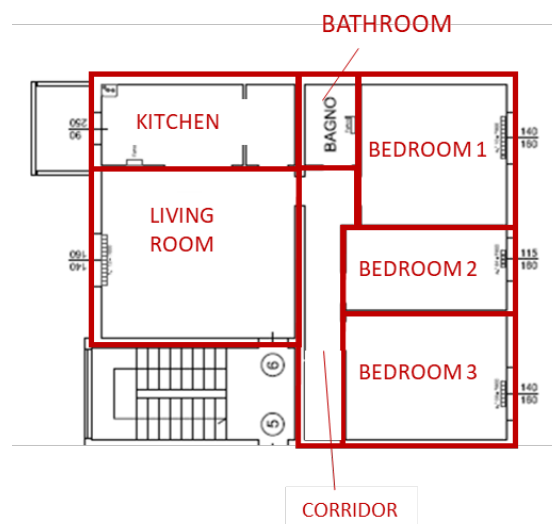


**Figure 3. Case study**

The windows were modelled using the Type56 CFS based on the thermal model of ISO 15099. It is a simplified model of complex fenestration systems which allows the integration of adaptive windows systems (ventilated windows, smart glazing, venetian blinds) into the building model in TRNSYS by using the BSDF matrix (bidirectional scattering distribution function) for each configuration of the active window. The Type 56 CFS has been meant to model only mechanically ventilated windows, just requiring

as input the inlet mass flow rate and its temperature. In the case of naturally ventilated cavity, the inlet mass flow rate is unknown and not so trivial to determine; therefore, for the implementation of the AWS with integrated shading and ventilated cavity (Figure 2. Option a), b) and c)) in the TRNSYS model it was necessary to develop an ad-hoc Type, able to calculate the inlet flow rate due to the stack effect according to the ISO 15099:2003 [1].

## 5.2   Modelling approach

To support the modelling and simulation of the different AWS configurations with the TRNSYS software and to assess the system's performance in detail, the COMSOL Multiphysics [2] software was used. The Finite Element Method (FEM) based software COMSOL allows to compute the coupled heat transfer, moisture transport and fluid flow phenomena of a specific system, in this case the AWS. To simplify the model and decrease the computational time, the AWS was reduced to a vertical cross section and modeled as 2D domain. This assumption was supported by the study performed by Pasut and De Carli [3] stating that the 3D modelling of a fenestration system does not provide a substantial improvement in the results, considering the increased complexity and computational time.

The discretization of the domain, necessary to solve the equations of heat transfer, fluid flow and moisture transport, occurred through the creation of a calculation grid (mesh). For the creation of the mesh, the AWS geometry was divided into various domains so that different types and sized of the mesh could be adopted, according to the geometric and material characteristics of each domain. Particular attention was given to the refinement of the mesh at the interfaces between the solid and fluid volumes, in order to better simulate the passage from a non-zero velocity inside the fluid to a zero velocity on the wall. The discretization of the domain varied a bit for the different AWS configurations, mainly due to the geometrical differences. To find the correct grid size and ensure that the solution is independent from the calculation grid, a mesh refinement

study was done for each AWS configuration. In Figure 4 an example of the calculation grid adopted for the naturally ventilated AWS cavity with external air is shown.
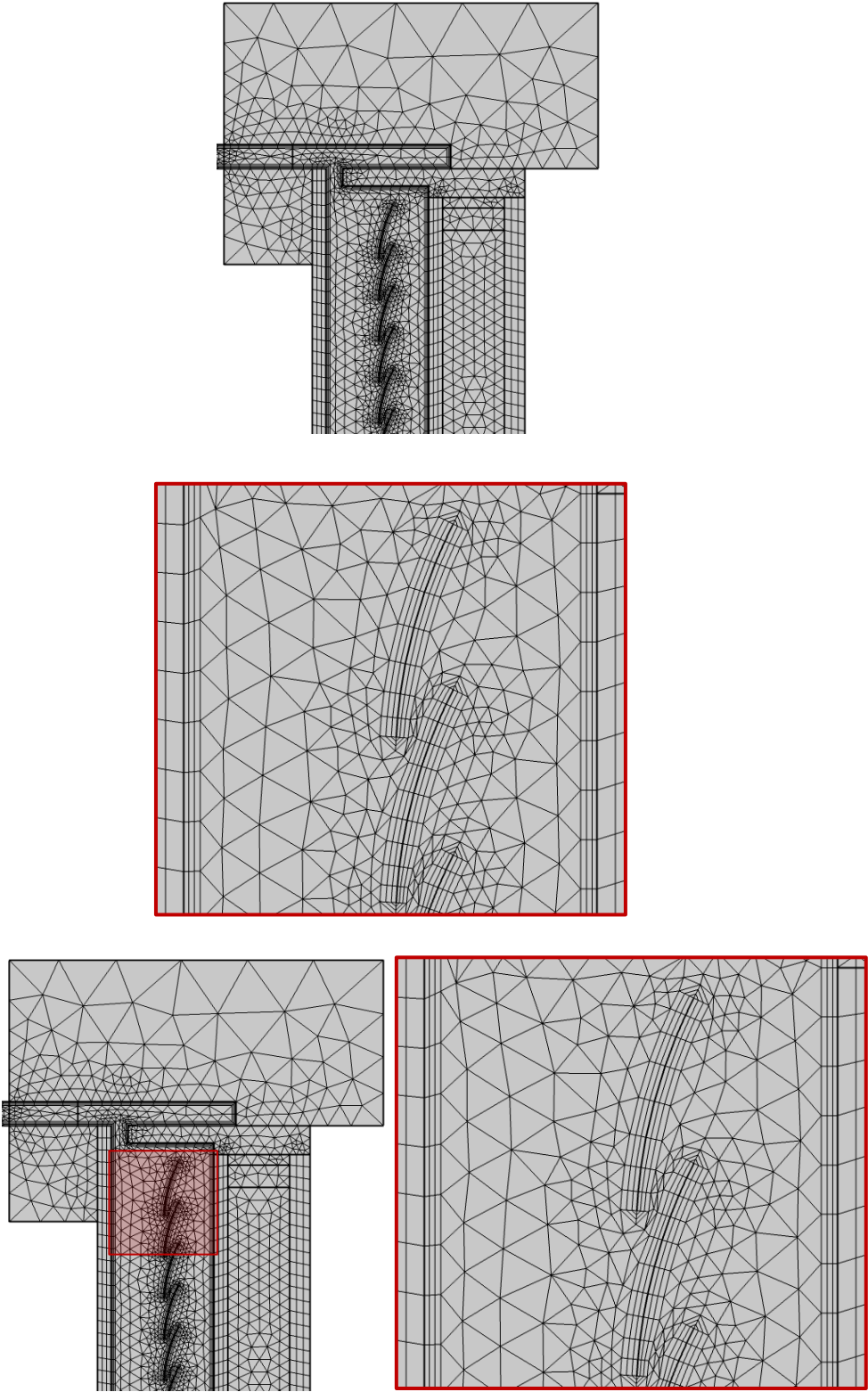
**Figure 4: Example of calculation grid of configuration 1 with naturally ventilated AWS cavity with external air**

The optical calculation, to account for the short-wave radiation exchange due to solar irradiance, was done apart from the Computational Fluid Dynamic (CFD) simulation with a detailed optical calculation using Radiance [4]. For each glazing and shading configuration, the Bidirectional Scattering Distribution Function (BSDF) was calculated and the solar absorption data for each glass pane and for the shading system were derived. These percentages of incident solar irradiance that are absorbed by each layer of the window system were assigned to the CFD simulation.

Depending on the scope of the study, steady-state or dynamic simulations were done. Also the setup of the boundary conditions varied a bit according to the aim of each study, but in all the cases convective and radiative heat flux boundary conditions on the internal and external glazing surface were considered, while adiabatic conditions were assumed for the top and bottom boundaries.

In the following paragraphs the simulation setup of the three major configurations modelled with COMSOL Multiphysics is reported.

### 5.3 Configuration 1: No ventilation device included in the AWS (shading cavity naturally ventilated with external air)

For this naturally ventilated configuration of the AWS the purpose of the COMSOL simulation was twofold: on one side the simulation was aimed at determining the performance in terms of condensation risk of the naturally ventilated AWS with external air, on the other side the COMSOL model was used as reference to calibrate the model of the AWS in TRNSYS.

The configuration of the AWS with the ventilated air cavity presents two types of openings, one external vertical opening and another internal horizontal opening, as represented on the vertical cross section of the AWS (Figure 5). The internal horizontal opening is continuous along the entire AWS width, while the external vertical opening is discontinuous and interrupted by solid (closed) parts along the AWS width (Figure 6). Additionally, the external openings are covered by a squared mesh to avoid the entry of insects or dirt.
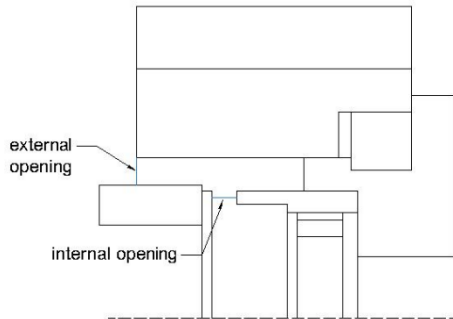
**Figure 5. Layout of openings of AWS with ventilated cavity**
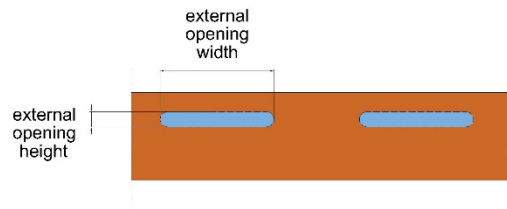


**Figure 6. Front view of AWS frame with external vertical openings**

### 5.3.1 Design optimization with COMSOL

The aim of the first analysis was to optimize the dimensions of the external and internal opening sizes in order to minimize the risk of condensation of water vapor on the internal glazing surface of the external glass pane (face 2). The optimization criterion was to spatially and temporally minimize relative humidity values of 100% on face 2, while ensuring also an acceptable thermal performance in winter and summer season and a technical feasibility of the system. In total 36 different combinations of external opening height and width and internal opening depth dimensions were analyzed. Table 2 reports the minimum and maximum values of the analyzed openings' dimensions.

**Table 2. Minimum and maximum values of the analyzed openings' dimensions**

|  | Min | Max |
|---|---|---|
| External Opening Height [mm] | 10.7 | 26 |
| External Opening Width [mm] | 40 | full width (140) |
| Internal Opening Depth [mm] | 5 | 15 |

A first set of steady-state simulations with critical temperature and relative humidity boundary conditions for the location of Bolzano (Text = 7.8°C and RHext = 85.1%)[1] was carried out and the minimum surface temperature on face 2 was compared with the dew point temperature. For all combinations of opening dimensions, the minimum

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[1] 10-year average of daily minimum temperature and 10-year average of daily maximum relative humidity from Meteonorm V7.1 for the reference period of 2000-2009

surface temperature was higher than the dew point temperature, meaning that in none of the cases the condensation criterion was fulfilled. However, it could be noticed that the opening dimensions influenced the difference between the two temperatures and that the overall trend was an increasing minimum surface temperature on face 2 (i.e., decreasing condensation risk) at decreasing opening area, where the internal horizontal opening dimension was the parameter that mostly affected the glazing surface temperature.

To enhance the analysis, for three specific opening configurations dynamic simulations were run for three periods of 8 hours each. The three opening dimensions' configurations were the most closed one (case 1), an intermediate dimension (case 2) and the most open one (case 3), as reported in Table 3.

**Table 3. Opening dimensions of the configurations analyzed in dynamic conditions**

|  | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| External Opening Height [mm] | 10.7 | 18 | 26 |
| External Opening Width [mm] | 40 | 80 | Full width (140) |
| Internal Opening Depth [mm] | 5 | 7 | 10 |

Temperature and humidity boundary conditions were taken from extreme hourly weather data from Meteonorm V7.1 using two criteria, that must be fulfilled contemporarily, to filter the data and find the most critical period:

1. RH > 93% for at least 3 consecutive hours during night-time (6pm – 8am)
2. $(T_{air,ext} - T_{sky}) > 7°C$ for at least 3 consecutive hours during night-time (6pm – 8am)

Finally, a dynamic heat transfer, fluid flow and moisture transport simulation for two selected periods was carried out. For all three cases, the dynamic trend of the maximum relative humidity of face 2 was computed and is reported in Figure 7. Also in this analysis the most closed opening configuration (case 1) is characterized by the lowest relative humidity values.
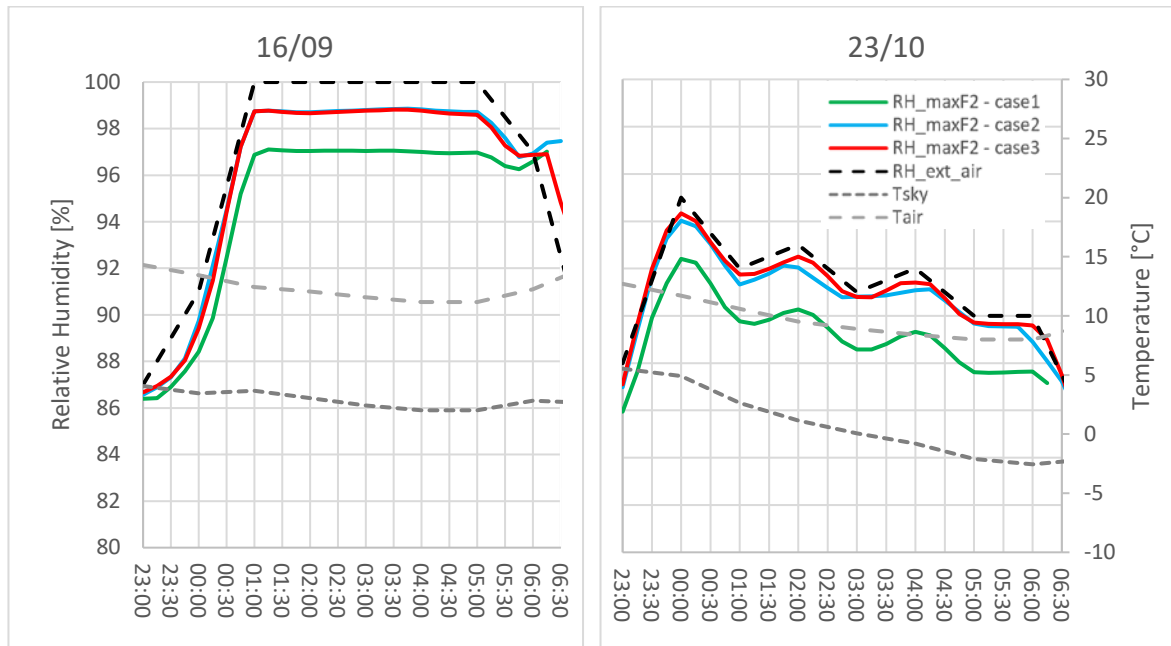
**Figure 7. Dynamic trend of maximum relative humidity on face 2 for the openings' configurations**

In addition to the condensation risk analysis, the thermal performance was analyzed through two indicators: the thermal transmittance (U-value) for the winter climate and the internal solar heat gain for the summer climate. Figure 8 shows the variation of U-value and solar gain as a function of the external (vertical) opening area and the internal (horizontal) opening area. It can be observed that case 1 performs best in winter and worst in summer. However, the solar gain shows very little variations between the best and worst performing case.
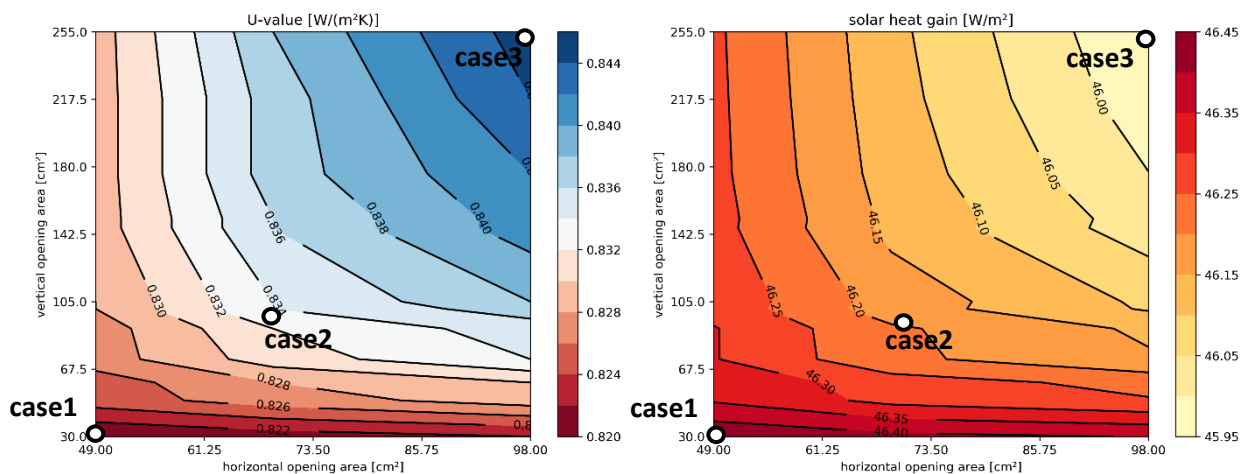


**Figure 8. U-value and solar heat gain versus external (vertical) and internal (horizontal) opening area**

Finally, in terms of condensation risk and winter thermal performance, the optimal combination of opening dimensions among the technically feasible ones, resulted to be that of case 1 (external opening height: 10.7 mm, external opening width: 40 mm, internal opening depth: 5 mm). However, to optimize the construction process a slightly different ratio of the external opening height and width was preferred but the same equivalent opening area was maintained. Thus, the final opening dimensions are the following:

- external opening height: 7 mm,
- external opening width: 80 mm,
- internal opening depth: 5 mm.

A final verification of condensation risk and thermal performance was carried out also with these opening dimensions.

### 5.3.2  Calibration of TRNSYS model

In addition to the design optimization, the COMSOL model of the naturally ventilated AWS cavity with external air was used to calibrate and the TRNSYS model. In particular, the model calibration was carried out increasing step by step the complexity, focusing on the inlet ventilation flowrate parameter: firstly, the CFD flowrate value was provided as input to the TRNSYS model to tune the model parameter and then it was calculated by the ad-hoc Type and provided as input to the TRNSYS building model in order to calibrate the natural flowrate Type and compare the outcome of the model at the component level.

The validation of the ad-hoc Type was focusing on the tuning of the pressure loss factor Z of the cavity, which should take into account the pressure losses caused by:

- Inlet and outlet openings;
- Square mesh grille;
- Integrated blind;

the pressure losses are estimated as follow:

$$Z_i = \left( \frac{A_{s,i}}{0.6 * A_{eq,i}} - 1 \right)^2$$

where $A_{s,i}$ is the cross section of the ventilated gap and $A_{eq,i}$ is the equivalent loss area which depends on the pressure loss sources along the air-path.

In the configuration without shading the $A_{eq,i}$ is equal to the area of the ventilation openings. The comparison of the data with the COMSOL outcome showed the need to

calibrate this parameter. First, the factor K was added for the estimation of the pressure loss due the grille:

$$K = 0.98\,((1 - \sigma_s)^{-2} - 1)^{1.09}$$

where $\sigma_s$ is the ratio of blocked area to total are of the screen.
Then, the calibration parameter k was introduced to tuning the openings area in order to take into account the discontinuity of the ventilation openings as follows:

$$A^*_{eq,i} = k * A_{eq,i}$$

The value k has been parametrically varied from 0.1 to 1 in order to find the optimal value minimized 2 statistical values: RMSE (Root Mean Squared Error) and MAPE (Mean Percentage Error) estimated for both inlet flow rate and the total heat flux exchanged from the AWS (by convection and long-wave radiation) to the other surfaces. The optimal value is k=0.5 as shown in Figure 9 (k3).
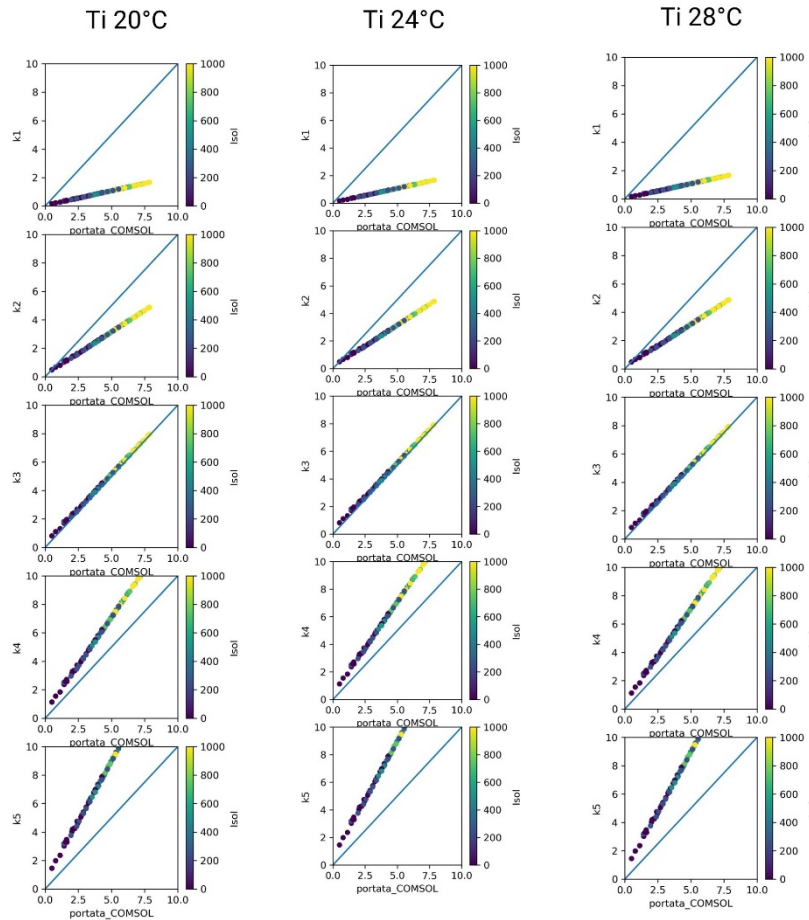
**Figure 9. TRNSYS vs COMSOL COMPARISON OF INLET AIRFLOW RATE IN OPEN CAVITY (SHADING FULLY RAISED) BY TUNING K PARAMETER**

When the shading is deployed, the $A_{eq}$ formulation becomes:

$$A_{eq,ISO} = A^*_{eq,i} + \frac{1}{4}A_h$$

Where Ah is the total area of the holes in the shading surface and for the estimation this value, the formulation proposed in [5] has been used. It is a function of the blind tilt angle and geometrical properties of the blind. Also this parameter was calibrated following the same procedures as described above. In particular, the calibration parameter x has been parametrically varied from 0.1 to 10 by changing also tilt angle of the blind in 3 configurations (0°, 30° and 75°). The optimal values is x=0.7 as shown in Figure 10 (k5). Therefore, the final formulation of the different pressure losses due to openings and integrated shadings is:

$$\Delta P_Z = \frac{1}{2}\rho_i v_i^2 (2Z_i + K)$$

$$A_{eq,ISO} = 0.5 * A_{eq,i} + \frac{0.7}{4} A_h * Y_{SHD}$$

where $Y_{SHD}$ indicates the availability of the shading (1if it is deployed, 0 if it is fully raised) and the $A_h$ is a function of tilt blind. In this way it is possible to use the same formulation for all the possible configurations.
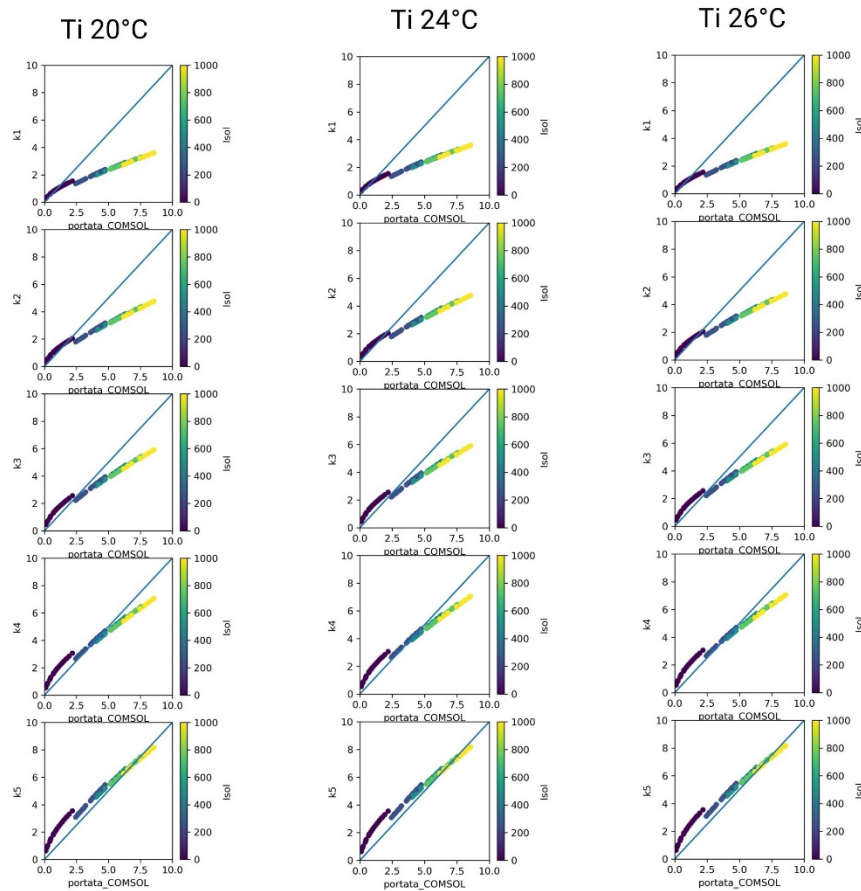


**Figure 10. TRNSYS vs COMSOL COMPARISON OF INLET AIRFLOW RATE IN OPEN CAVITY AND TILT ANGLE AT 30° BY TUNING x PARAMETER**

## 5.4 Configuration 2: Integration of decentralized mechanical ventilation system in the AWS frame

The second AWS configuration studied in detail involves a decentralized mechanical ventilation system that is integrated in the top frame of the AWS. The exhaust air of the decentralized ventilation machine is forced through the ventilated AWS cavity with the aim to increase the window's thermal performance: since the exhaust air of the mechanical ventilation is warmer than the external air during the winter season, while it is cooler during the summer season, it might improve the thermal performance of the AWS by reducing heat losses in winter and heat gains in summer. The layout of the AWS with the integrated mechanical ventilation system is shown in Figure 11.
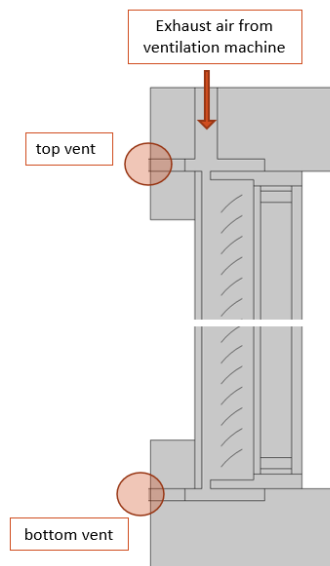


Figure 11. Layout of the AWS with the integrated mechanical ventilation system

Also for this configuration the purpose of the COMSOL simulation was twofold: on one side the simulation was aimed at determining the thermal and hygrothermal performance of the AWS with the integrated mechanical ventilation system, on the other side the COMSOL model was used to support the setup of the TRNSYS model.

### 5.4.1 Design optimization with COMSOL

To better understand the thermal and hygrothermal performance of this system, different layouts in terms of blind tilt angle (0°, 30° and 75°), ventilation openings (top and bottom vent open or top vent closed and bottom vent open), depths of ventilated

cavity (5mm, 30mm and 40mm) and exhaust airflow of the ventilation machine (15 m³/h, 30 m³/h and 41 m³/h) were analysed.

The major result concern the condensation risk: due to the high moisture content and the cooling of the air coming from the internal ambient due to the heat recovery, the exhaust air forced through the AWS cavity is characterized by a high relative humidity that results in condensation of water vapour on the external glazing surface. In particular, during the winter period, if no dehumidification is applied, the water vapour condensation on the façade cannot be avoided. The condensation risk is minimized only when the external air temperatures is higher than a certain threshold value, that depends on the AWS configuration in terms of lamella, ventilation openings, cavity depths and airflow. For instance, in case of 30° blind tilt, 30mm cavity depth, open top and bottom vents and airflow of 30 m³/h, this threshold amounts to 19°C. The integration of a dehumidification system would be necessary if the system was to be used also in winter conditions.

As for the condensation risk, also the thermal performance depends on the AWS configuration. However, it can be concluded that the integration of the decentralized mechanical ventilation system improves the summer performance in terms of solar heat gain with respect to the naturally ventilated AWS layout, for the majority of analysed configurations, while the impact on the winter performance (U-value) depends on the AWS configuration itself: for some configurations, like low airflow (15 m³/h), blind tilt of 0° or 30° or low cavity depth (5mm) the winter thermal performance is reduced, while it is slightly improved for higher airflow rates (30 and 41 m³/h), blind tilt of 75° or larger cavity depths (40mm).

### 5.4.2 Calibration of TRNSYS model

Thanks to the accurate modelling of fluid flow, the COMSOL model was used to determine the fraction of exhaust air *a1* (Figure 12) that enters and flows through the ventilated cavity, as a function of three parameters: difference between indoor and outdoor temperature ($\Delta T$), incident solar irradiance ($I_{sol}$) and blind tilt angle (Table 4).
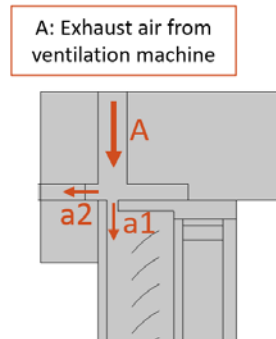
**Figure 12. Schematic representation of exhaust airflow entering the window cavity and exiting the top vent**

**Table 4. Variables that affect the fraction of exhaust air that enters the ventilated window cavity**

| $\Delta T$ [°C] | $I_{sol}$ [W/m²] | Blind tilt [°] |
|---|---|---|
| -15 | 0 | No blinds |
| -5 | 250 | 0 |
| 5 | 500 | 10 |
| 15 | 750 | 25 |
| 25 | 1000 | 40 |
| | | 75 |

The fraction of airflow entering the window cavity was found to be correlated to the parameters listed in Table 4 by means of a multiple linear regression. In particular, one equation for each blind tilt angle was written having as input variables $\Delta T$ and $I_{sol}$; at each timestep, the TRNSYS model is thus able to calculate the airflow entering the window cavity.

In this configuration, the AWS works as ventilated cavity thus the parameters required as input by the Type 56 CFS are the outputs of the decentralized mechanical ventilation system in terms of inlet flow rate (which is obtained from the fraction of the exhaust air *a1*) and the inlet temperature. In order to validate this model, a parametric simulation was performed for the purpose of comparing the window parameters (in terms of air temperature and heat fluxes) which influence the thermal balance of each thermal zone. The analysis showed a good fitness model with the outcomes of the COMSOL model.

## 5.5 Configuration 3: Integration of trickle vents coupled with the shading cavity ventilation

The third AWS configuration analysed in this study involves a trickle vent that is integrated in the top frame of the AWS. The peculiarity of this system is the coupling of the trickle vent with the window cavity. In particular, the airflow from the external ambient to the internal one first crosses the window cavity and then the trickle vent, before entering the internal room. In this way the air entering the building is preheated thanks to the passage through the AWS cavity. This is expected to have a positive impact on the heating demand during winter, while it might increase the cooling demand during the day in the summer period. To control the ventilation rate, the apartment is equipped with a centralized mechanical extraction ventilation system (MEV) that extracts air from the apartment based on the $CO_2$ concentration in the air. Thus, the airflow passing through the window cavity and the trickle vent depends on the airflow rate of the MEV. The MEV adopted in this study is characterized by the static pressure curve described in Table 5.

**Table 5. MEV static pressure curve**

| Airflow [m³/h] | Pressure [Pa] |
|:---:|:---:|
| 135 | 0 |
| 122 | 25 |
| 91 | 70 |
| 61 | 112 |
| 30 | 140 |
| 0 | 168 |

For this AWS configuration, the COMSOL model was used in a first phase to run some preliminary simulations to analyse the overall working principle of the AWS and to verify airflow rates and pressure distributions inside the window cavity and along the trickle vent. Once these preliminary verifications were done, the COMSOL model was used to support the setup of a TRNSYS model of the AWS with the integrated trickle vent.

### 5.5.1 Design optimization with COMSOL

In the COMSOL model, when the MEV is on, the total airflow was assumed to be distributed over the single window proportionally to the window width. In total, the

apartment was assumed to have four AWS with integrated trickle vent. Three of them are installed in the bedrooms and are characterized by a window width of 1.192 m, the fourth one is installed in the living room and has a window width of 2.192 m. Thus, the maximum airflow amounted to 27.9 and 51.3 m³/h, respectively (Table 6). Due to the 2D model with a unitary depth of 1m, a specific maximum airflow per unit depth of 23.4 m³/h was considered in the simulation.

**Table 6. Airflow distribution over aws in single rooms**

|  | Window width [m] | Max airflow [m³/h] |
|---|---|---|
| Living room | 2.192 | 51.3 |
| Bedroom 1 | 1.192 | 27.9 |
| Bedroom 2 | 1.192 | 27.9 |
| Bedroom 3 | 1.192 | 27.9 |
| Kitchen | NO TV | NO TV |

The wind-induced pressure difference was not considered in the COMSOL model, and the focus was placed on (1) the thermally driven ventilation only (when the MEV is off) and (2) combined thermally and mechanically driven ventilation (when the MEV is on). In these two cases, due to the limited airflows and pressure drops, the trickle vents were modelled as a localized pressure drop depending on the airflow. The trickle vent's self-regulating mechanism, aimed at avoiding high airflow and draught due to high wind-induced pressure differences, starts working at 2 Pa, while for lower values the pressure difference can be assumed to be proportional to the airflow.

$$dp = \frac{airflow\ [kg/s]}{C_s\ [\frac{kg}{sPa}]}$$

$$C_s = 0.013\ \frac{kg}{s\ Pa}$$

Where $C_s$ : airflow @ 1 Pa

To evaluate the advantages in terms of thermal performance of the integrated trickle vent coupled with the window cavity ventilation (option 1), a comparative analysis between the AWS with the integrated (option 1) or non-integrated (option 2) trickle vent was carried out.

The AWS with the non-integrated trickle vent is naturally ventilated with external air and independent from the trickle vent through which air can directly flow from outdoor to indoor ambient and vice-versa (option 2).

In both cases, the thermal contribution to the interior environment can be divided in (1) heat flux resulting from heat exchange with the surface ($q_{sf}$) and (2) heat flux coming from the airflow entering the building through the trickle vent ($q_{air}$).

$$q_{air} = \dot{m}_{air} c_p (T_{inlet} - T_{int})$$

where

$\dot{m}_{air}$: mass flow rate entering the building through the trickle vent [kg/s]
$c_p$: heat capacity at constant pressure [J/(kgK)]
$T_{inlet}$: temperature of air entering the building through the trickle vent [°C], $T_{inlet}$ equal to external air temperature ($T_{ext}$) for option 2: $T_{inlet} = T_{ext}$


In Figure 13 the heat flux resulting from heat exchange with the surface and from the airflow entering the building for the AWS with integrated trickle vent (option 1) is shown, while in Figure 14 the same results for the AWS with the non-integrated trickle vent (option 2) are reported. It can be noticed that the heat entering the building through the heat exchange with the AWS surface is almost the same for the two configurations, while the heat entering the building by means of the airflow is different for the two systems: while there is no dependence from solar irradiance in case of non-integrated trickle vent, when the trickle vent is coupled with the window cavity, the air inside the cavity is heated up by solar radiation before entering the room through the trickle vent. In fact, the impact of solar radiation on the heat flux resulting from the airflow entering the building can be observed on the right graph of Figure 13. It can be noticed that the integration of the trickle vent coupled with the window cavity (option 1) makes the system much more sensitive to solar radiation: it has a positive impact in winter by increasing the solar heat gains, while the system becomes less convenient in summer as the solar heat gains are enhanced.
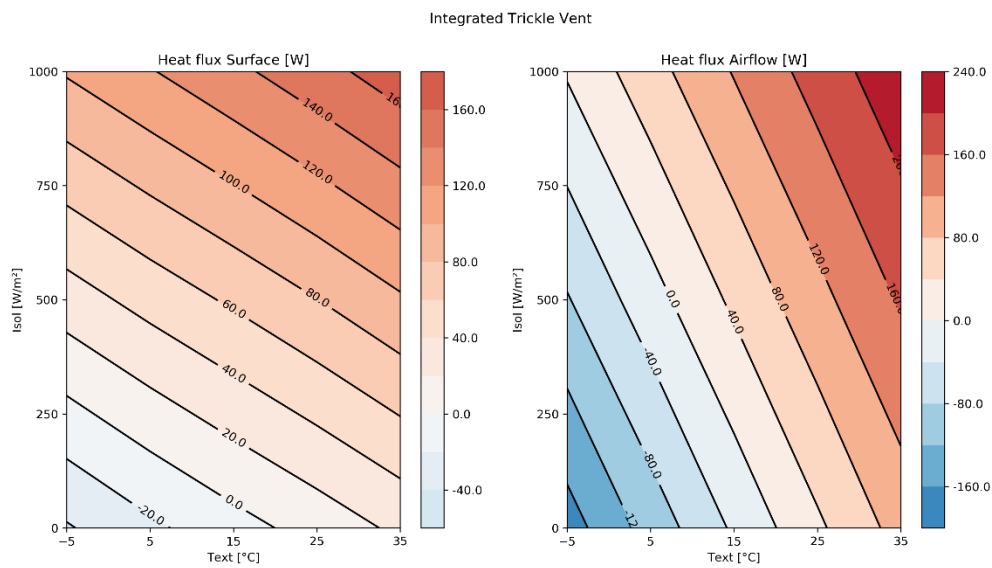
**Figure 13. Heat flux resulting from heat exchange with the surface (left) and from the airflow entering the building (right) for the AWS with integrated trickle vent (option 1)**
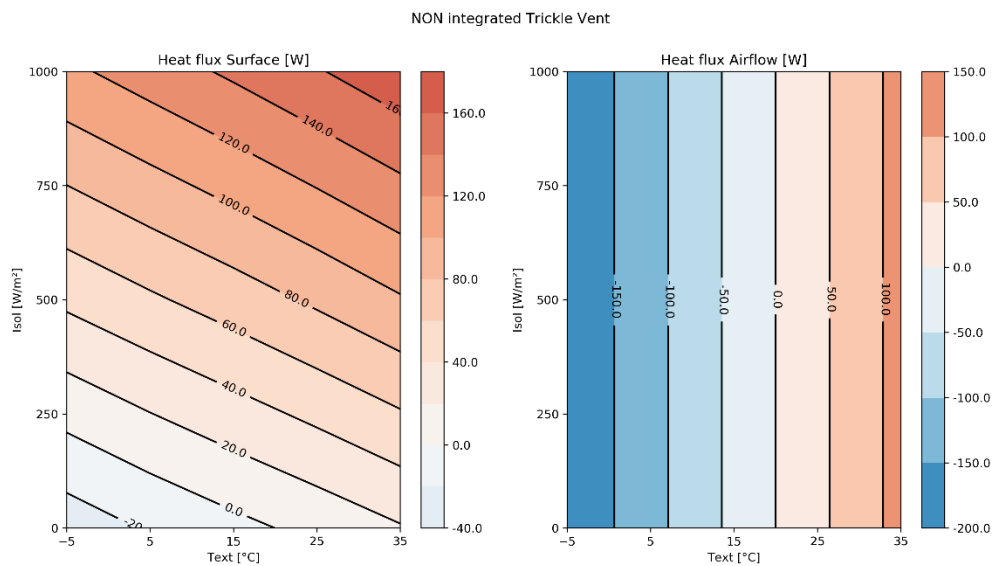


**Figure 14. Heat flux resulting from heat exchange with the surface (left) and from the airflow entering the building (right) for the AWS with non-integrated trickle vent (option 2)**

To better understand the suitability of the two configurations for different climatic conditions, the total heat flux (surface + airflow) was compared (Figure *15* and Figure *16*). It results that the AWS with the integrated trickle vent (option 1) typically performs better than the one with the non-integrated trickle vent (option 2) for climatic conditions

that are characteristic for the winter season, while the opposite occurs for summer conditions, especially under solar radiation.

In case of none or very little solar irradiances, the AWS with the integrated trickle vent performs slightly better than the one with the non-integrated trickle vent.



Figure 15. Best performing AWS configuration: integrated vs non-integrated TV (purple colors: AWS with integrated TV performs better, orange colors: AWS with non-integrated TV performs better)
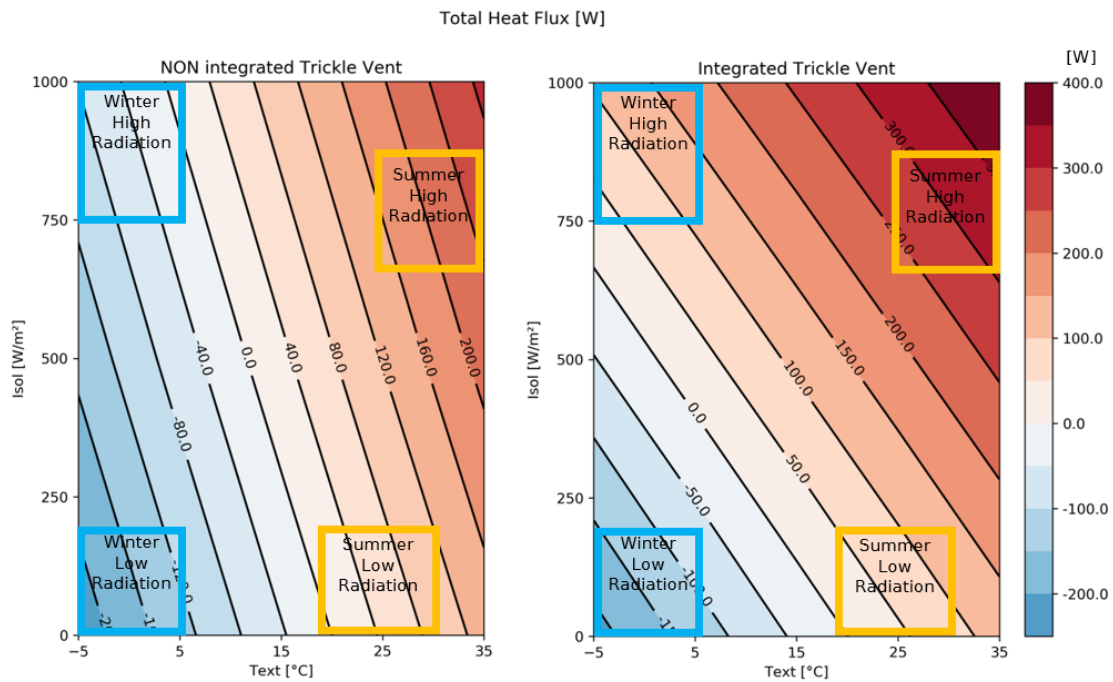
**Figure 16. Total Heat flux comparison integrated (right) vs non-integrated (left) trickle vent**

### 5.5.2 Limitations for TRNSYS modelling

For the integration of the ventilated AWS cavity with the trickle vents in the TRNSYS model, simplifying hypotheses have been made in order to find fictitious components which would describe the AWS behaviour the airflow network of the building (in terms of outlet temperature of cavity and pressure drop). Regarding the pressure drop, two alternatives were evaluated (either a dummy crack or fan) but without a reference (simulated or measured data) it was not possible to validate the methodology used. For this reason, the results of this kind of configurations are not reported in the AWS configuration tools, but for the performance considerations of this technology configuration, please refer to the comments on the COMSOL outcomes.

## 6    AWS configurator tool

### 6.1    Database

The results of these parametric simulations were structured in a Microsoft Excel workbook. Since the parametric analysis involved a large number of cases (climatic conditions, shading solutions, ventilation strategies) and since the aim of the simulations was multidisciplinary (energy consumption, thermal comfort, visual comfort, etc.), a large amount of data was collected at the end on the numerical campaign, and a organized database structure was needed. In this way, results can be easily accessible by users (e.g. building designers at the early design stage), with the possibility to filter information based on key inputs (e.g. climate, ventilation strategy, etc.) and obtain key results belonging to different domains.

The input parameters, outputs and some examples are better described in the following paragraphs.

### 6.1.1    Inputs/filters

Inputs are the means by which the user can filter data. Two main categories of inputs were defined: the boundary conditions and the AWS configuration.

The boundary conditions are described through the *climate* and the *orientation*: the four climatic conditions considered are Italy (Mediterranean), France and Germany (Continental) and Norway (Nordic); regarding orientations, the cardinal directions (North, East, South and West) were taken into account.

AWS Configurations involve four different inputs:

- *Window type*, related to the climatic condition (Mediterranean, Continental, Nordic);
- S*hading type*, that as in Table 1 can be External, Electrochromic or Integrated;
- *Ventilation*, that can involve Trickle Vents, Ventilation Machines or no devices;
- *Interaction shading with ventilation*, defined as a Boolean value describing the presence or absence of interaction between the shading cavity and the ventilation system

All inputs are summarized in Table 7

<p align="center">**Table 7. Input parameters**</p>

| BOUNDARY CONDITIONS | | AWS CONFIGURATION | | | |
|---|---|---|---|---|---|
| Climate | Orientation | Window type | Shading type | Ventilation | Interaction shading with ventilation |

### 6.1.2  Outputs/Key performance indicators

In order to evaluate the performance of the different cases, with changing window technologies, configurations, climates and orientations, a series of Key Performance Indicators (KPIs) have been selected in order to assess the outcomes of the performed simulations.

The selected KPIs are divided into five categories, since their quantities are related to different physical aspects:

- *Window*: describe the thermal performance of the window system
- *Thermal*: provides information on energy needs and a measure of thermal comfort in the indoor environment
- *Daylighting*: assess the exploitation of daylight in the indoor environment
- *Indoor Air Quality*: describes the air quality by means of $CO_2$ levels
- *Ventilation*: measures the ventilations rates and consumption in both natural and mechanical cases

A thorough description of the chosen KPIs is here provided:

- *Thermal transmittance - U-value [W/$m^2$K]*

Average thermal transmittance of the AWS.

- *Solar heat gain coefficient – g-value [-]*

Solar heat gain coefficient, assessed as the ratio between the transmitted solar radiation through the glazed component and the incident solar radiation.

- *Annual heating demand [kWh/$m^2$]*

Heating demand referred to the entire case study (all rooms composing the apartment) assessed on an annual basis.

- *Annual over-heating hours (T>26°C) [h]*

Amounts of hours, on an annual basis, in which the indoor temperature is above 26°C. Values above this threshold are considered to cause discomfort to the occupants, so the higher the value of this KPI, the longer is the time in which occupants experience discomfort in the considered case study.

- *Annual over-heating degree [°C]*

Similarly to the previous KPI, the annual over-heating degree measures the discomfort taking into account the temperature difference with respect to the threshold of 26°C. In particular, it consists of a summation for the entire year of the difference between the indoor temperature and the considered threshold (26°C), when the indoor temperature is above the threshold. This means that if the indoor temperature never goes above 26°C, this KPI will be 0°C; otherwise, the difference between the indoor air and the threshold provides a quantitative information on the intensity of the discomfort. Reading this KPI with the annual over-heating hours is thus crucial to get a complete picture of the quantity and intensity of the thermal discomfort.

- *Daylight autonomy [%]*

Percentage of occupied hours with an illuminance above a certain threshold (in this case 300 lx), generally sufficient not to use artificial light.

- *UDI [%]*

The Useful Daylight Illuminance is the percentage of annual occupied hours having an illuminance value on the work-plane that falls into a specific range, going from 0 to 3000 lx. This is an index that attempts to consider both the illuminance level and the glare occurrence. In fact, an illuminance below the inferior limit forces the occupants to use artificial light, while an excessive illuminance could lead to glare issues. UDI indicators are structured as follows:

  o *UDI-s* (below 300 lx) – additional artificial lighting could be required to supplement the daylight;
  o *UDI-a* (300 to 3000 lx) – electric lighting is most likely not needed. In this range of illuminance the natural light is sufficient and at the same time not excessive;
  o *UDI-x* (above 3000 lx) –amount of light is considered excessive, generating possible glare and overheating.
- *$CO_2$ [%]*

This KPI, used to assess the Indoor Air Quality, is the percentage of annual occupied hours in which the $CO_2$ level is below or ranges between certain thresholds. In particular, four categories of $CO_2$ levels are identified:

- o Category 1 (CAT1): $CO_2 \leq 950$ ppm
- o Category 2 (CAT2): $950$ ppm $< CO_2 \leq 1200$ ppm
- o Category 3 (CAT3): $1200$ ppm $< CO_2 \leq 1750$ ppm
- o Category 4 (CAT4): $CO_2 > 1750$ ppm

- *Air change rate [1/h]*

Average air changes per hour throughout the year considering the whole case study.

- *Hours natural ventilation [h]*

Annual hours in which there is natural ventilation by window openings.

- *Mechanical ventilation consumption [kWh/m²]*

Energy consumption of the mechanical ventilation system, referred to 1m² of floor area.

Table 8 summarizes all the above described KPIs.

**Table 8. Key Performance Indicators (KPIs)**

| WINDOW | | THERMAL | | | DAYLIGHT | | | |
|---|---|---|---|---|---|---|---|---|
| U-value | g-value | Annual heating demand | Annual over-heating hours (T>26°C) | Annual over-heating degree | Daylight autonomy | UDI-s | UDI-a | UDI-x |
| [W/m²K] | [-] | [kWh/m²] | [h] | [°C] | [%] | [%] | [%] | [%] |

| INDOOR AIR QUALITY | | | | VENTILATION | | |
|---|---|---|---|---|---|---|
| $CO_2$ CAT1 | $CO_2$ CAT2 | $CO_2$ CAT3 | $CO_2$ CAT4 | Air change rate | Hours natural ventilation | Mechanical ventilation consumption |
| [%] | [%] | [%] | [%] | [1/h] | [h] | [kWh/m²] |

Both Daylight and Indoor Air Quality results are further divided for the four rooms of the considered case study (LR for Living Room and BR for the Bedrooms).

## 6.2 Examples of AWS configurator tool use

This database, containing all the obtained simulations results, can be a very useful tool to get a general idea about the performance of the analysed AWS configurations. Applications can be many: for example, if the AWS has to be installed in a Mediterranean climate and the risk of overheating is expected, it is possible to filter the simulations output and visualize only the outcomes with the Italian weather data and with the window oriented towards South. In this way, it is possible to visualize which combination of ventilation system and shading system is more appropriate to reduce the overheating time.

| INPUT | | | | | | WINDOW KPIs | | THERMAL | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Boundary conditions | | AWS Configuration | | | | | | | | |
| Climate | Orientation | Window type | Shading type | Ventilation | Interaction shading with ventilati | U-value | g-value | Annual heating demand | Annual over-heating hours (T>26°C) | Annual over-heating degree |
| IT | S | Mediterranean | External | No | No | 1.38 | 0.47 | 29.26 | 11.33 | 0.80 |
| IT | S | Mediterranean | External | TV | No | 1.37 | 0.47 | 20.72 | 2.25 | 0.30 |
| IT | S | Mediterranean | Electrochromic | No | No | 1.39 | 0.38 | 30.00 | 29.25 | 2.36 |
| IT | S | Mediterranean | Electrochromic | TV | No | 1.33 | 0.38 | 20.84 | 2.42 | 0.41 |
| IT | S | Mediterranean | Integrated | No | No | 1.43 | 0.53 | 28.40 | 216.00 | 62.70 |
| IT | S | Mediterranean | Integrated | TV | No | 1.37 | 0.53 | 19.50 | 99.20 | 19.00 |

**Figure 17. AWS configurator tool - Example use 1**

At the same time, it is possible to take a look at the daylight performance and at the indoor air quality that the ventilation system ensures. The overall view of all these indicators can be a very interesting tool especially in the preliminary design phase, when stakeholders and especially building designers must be directed towards one type of AWS solution.

Another possible application could be the need of building designers to improve as much as possible the indoor air quality selecting the optimal ventilation system. If the AWS configurations are filtered according to the climate, the orientation of the building and the shading type, it is possible to evaluate the best AWS for their needs. Indeed, the indoor air quality parameters can be easily analysed.

| INPUT | | | | | | OUTPUTS | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boundary conditions | | AWS Configuration | | | | INDOOR AIR QUALITY | | | | | | | | | | | | | | |
| | | | | | | LR | | | | BR1 | | | | BR2 | | | | BR3 | | | |
| Climate | Orientation | Window type | Shading type | Ventilation | Interaction shading with ventilati | CO2 CAT1 | CO2 CAT2 | CO2 CAT3 | CO2 CAT4 | CO2 CAT1 | CO2 CAT2 | CO2 CAT3 | CO2 CAT4 | CO2 CAT1 | CO2 CAT2 | CO2 CAT3 | CO2 CAT4 | CO2 CAT1 | CO2 CAT2 | CO2 CAT3 | CO2 CAT4 |
| FR | S | Continental | External | No | No | 99.96 | 0.04 | 0.00 | 0.00 | 99.90 | 0.07 | 0.00 | 0.00 | 99.98 | 0.00 | 0.00 | 0.00 | 99.98 | 0.00 | 0.00 | 0.00 |
| FR | S | Continental | External | TV | No | 83.04 | 16.67 | 0.30 | 0.00 | 53.66 | 43.85 | 2.46 | 0.00 | 69.53 | 30.43 | 0.02 | 0.00 | 70.40 | 29.58 | 0.00 | 0.00 |
| FR | S | Continental | External | VM | No | 99.55 | 0.45 | 0.00 | 0.00 | 99.54 | 0.44 | 0.00 | 0.00 | 99.96 | 0.02 | 0.00 | 0.00 | 99.98 | 0.00 | 0.00 | 0.00 |

**Figure 18. AWS configurator tool - Example use 2**

# 7    Conclusions

In this report, the Active Window configurator tool is presented: the considered AWS configurations are described, the methodology used to assess each configuration is shown and the results are collected in an easily accessible database. The outcome is a tool that can be used in early design stages to make performance-based evaluations for different window configurations and boundary conditions.

From a methodological point of view, two main tools associated with two different scales were used: on the one hand, COMSOL allowed to assess the thermal behavior at component/system scale, providing crucial information on the potential of a given configuration and its weak points; through TRNSYS, on the other hand, it was possible to extend the previous information at building scale (an apartment was used as case study), with the result of providing useful information concerning different physical domains.

The multi-physical KPIs provide a complete picture of the considered cases: the outputs are in fact given in terms of window performance, thermal demand and comfort, daylight parameters, Indoor Air Quality and ventilation characteristics.

Next steps will include the development of the most promising AWS prototypes to be tested in an experimental facility. This will allow to verify the assumptions made in this study, further calibrate the built models and get more insight on how this complex widow systems behave under real conditions.

# 8 References

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## Annex 1. Discontinuous openings along the AWS width

As described in chapter 3.2, the external vertical opening is discontinuous along the AWS width, as it is interrupted by solid (closed) parts. Additionally, the external openings are covered by a squared mesh.

These discontinuities along the AWS width could not be modelled directly nor in COMSOL, due to its bi-dimensional model, nor in TRNSYS. Thus, the phenomenon was described analytically with a localized pressure drop and assigned through a function to the COMSOL and TRNSYS models.

To quantify the pressure drop, several 3D models of the discontinuous opening, including also the squared mesh, were created with COMSOL for the different combinations of vertical opening width and vertical opening height dimensions. Then, a parametric study with variable pressure difference between inlet and outlet was run, in order to determine the relation $f$ between the pressure difference $\Delta p$ and the velocity $u$: $\Delta p = f(u)$. To verify the correctness of this analogy, the resulting pressure drop function was assigned to an equivalent 3D model in which the geometric discontinuity was replaced by a volume force quantified by the pressure drop function. In Figure 19 the 3D model with the geometrical opening used to determine the pressure drop function and the 3D model with the domain to which the analytical volume force is assigned as verification are shown.
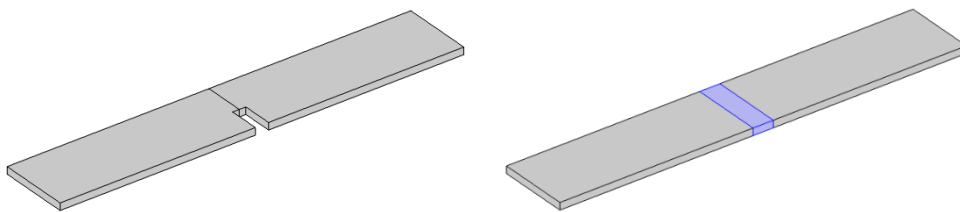


**Figure 19. 3D model with geometrical opening (left) and analytical representation of opening (right)**

## Annex 2. ISO 15099:2003 to treat naturally ventilated window

In the case of natural ventilation, the air velocity is caused by the stack effect and depends on the driving pressure difference and the resistance to the airflow to the airflow of the opening and space itself. The driving pressure difference is approximated as follow:

$$\Delta P_T = \rho_0 * T_0 * g * H_i * \frac{|T_{gap,i} - T_{gap,k}|}{T_{gap,i} * T_{gap,k}}$$

he airflow in the cavity is modelled as a pipe flow and therefore the driving pressure difference is set equal to the total pressure losses along the air path. The losses of pressure are the following:

Bernoulli pressure loss:

$$\Delta P_B = \frac{1}{2}\rho_i v^2$$

Hagen-Poiseuille pressure loss:

$$\Delta P_H = 12\,\mu_i \frac{H_i}{b_i^2} v^2$$

Pressure loss in the openings

$$\Delta P_Z = \frac{1}{2}\rho_i v_i^2 (Z_i + Z_o)$$

Therefore, the air velocity in the cavity is obtained by solving the equation:

$$\Delta P_T = \Delta P_B + \Delta P_H + \Delta P_Z$$

It is clear that the model has an inter-dependence between the air gap temperature and air velocity and for the calculation of these two unknown variables an iterative calculation is performed until the convergence limit of 1% is achieved.