# A Modular Multifunctional Climate Adaptive Façade for Shopping Centers Retrofitting

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Existing shopping centres offer a great opportunity thanks to their retrofit for the reduction of the energy consumption. The partners of the European FP7 CommONEnergy project are developing a modular multifunctional façade for the retrofit of shopping malls, capable to adapt to different climates and to the existing building features both by the presence of movable components and by proper sizing of the fixed ones. In particular, the curtain- wall façade is equipped with a fixed shading system, a photovoltaic panel with a battery feeding the automated openings for natural ventilation. The aim of this work is to define a reliable parametric model for a multi-functional façade system, supporting designers with a set of useful data for the proper design of the façade configuration depending on climate, orientation and building use. Firstly, a reference zone model for the façade has been set; this had to be both representative of the real case and smartly defined for simulation software implementation. Besides the definition of the façade model parameters, all free design variables have been settled as minimum and maximum values, depending on different possible applications and environmental conditions in which the façade could be applied. Inputs for the model have been defined in a parametric matrix and they include facade module size, façade orientation, climate, window typology (thermal transmittance and g-value), distance between the shading lamellas and tilt angle, openable window size. The simulation engine is decoupled: visual comfort and artificial lighting use have been assessed with Radiance, while the façade thermal behaviour is evaluated by means of building energy simulations in TRNSYS, taking into consideration the Radiance results. For each simulated configuration, a set of relevant outputs in the field of Indoor Air Quality, thermal and visual comfort, and energy performance have been chosen. The main considered performance indicators are the long-term percentage of people dissatisfied, the number of hour when $CO_2$ concentration is within the recommended values for each of the categories defined by EN 15251:2007, the illuminance provided by daylight, the energy consumption due to lighting, ventilation, heating and cooling, energy generated by the PV panel. Moreover, all outputs have been collected in a user-friendly database and gathered in a simple tool. The work highlights the role of thermal and daylighting simulation in the design of an adaptive multifunctional façade.

**Keywords:** Façade, Multifunctional, Parameterization, CommONEnergy, Trnsys

# 1 Introduction

CommONEnergy project (Commonenergyproject.eu, 2016) aims at re-conceptualizing shopping malls through deep retrofitting, developing a systemic approach made of technologies and solution sets as well as methods and tools to support their implementation. Modern shopping centres tend to include glazed envelopes in their design ensuring daylighting and offering a more seamless connection between the indoor shopping space and the outdoor environment. However, glazed envelope features need to be carefully evaluated in order to limit the energy consumption for air conditioning. Within the CommONEnergy project, among other retrofitting solutions for shopping centres, research and industry partners (Acciona, Bartenbach, EURAC, Sunplugged) are developing a modular multifunctional climate adaptive façade system. The newly developed modular climate adaptive (Attia, Favoino, Loonen, Petrovski, & Monge-Barrio, 2015) façade system is based on a properly designed natural ventilation and daylight control, light-weight substructure, enriched by rapid assembly possibilities. Thanks to its flexibility and modularity, this façade system is suited for retrofit applications offering the opportunity to adjust the façade design according to climate and building features.

The high number of design possibilities rose the need of a tool which enables designers to make informed decisions about façade configuration, glazing materials and shading geometry depending on the building design constraints, such as climate, façade orientation, facade module size and indoor space usage. The aim of this work is to define a parametric simulation model to evaluate the performance of all the possible configurations of the modular multifunctional climate adaptive façade from both energy and indoor environment quality perspective.

## 1.1 The modular multifunctional climate adaptive facade

The proposed system consists of a modular frame made of mullion and transom with flexibility on their position, enabling easy integration of possible technologies such as photovoltaic or thermal solar panels. In principle, the anchorage system allows double screen installation, and it easily adapts to multiple designs, creating different geometric, aesthetic and energy solutions. The modular multifunction climate adaptive façade system is a general replicable concept, adjustable for different applications: in particular, in the model discussed in this work, automated openings are located in the lower and upper part of the façade enhancing single-sided stack ventilation (see Figure 1). A thin-film PV panel is integrated in the façade to generate the electricity needed for windows automation. The thin-film photovoltaic panel included in the module has the same length of the façade and it is 0.3 meters high. The energy provided

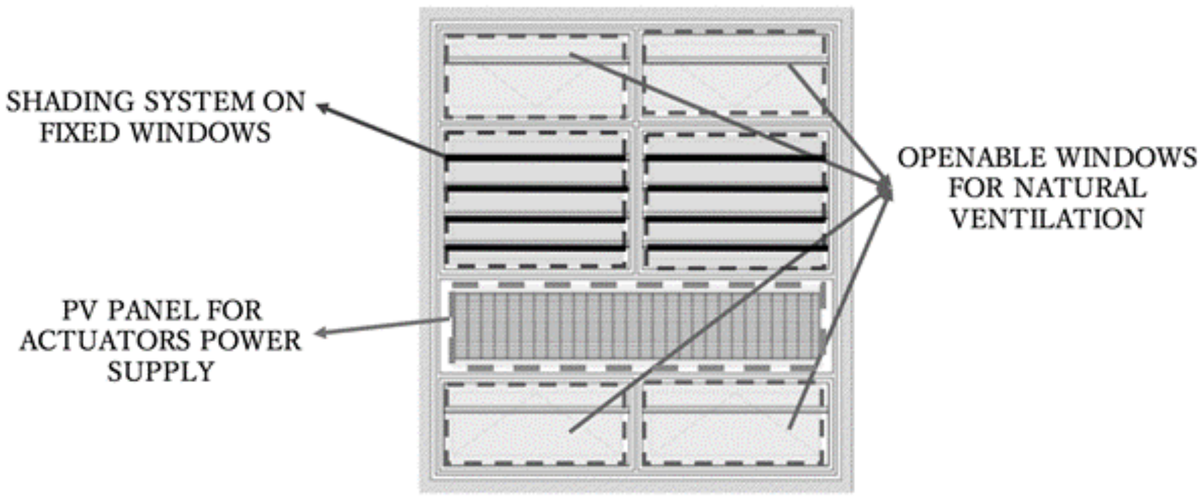


**Fig. 1 Main components in the façade designed by Acciona.**

by the PV supplies the power needed for automated windows; moreover, in order to store power when not directly needed by the actuators, a battery is integrated in the façade module, behind the PV panel. Moreover, a shading system with fixed lamellas controls solar gains. Façade module width can range between 2 and 3 m, whereas façade module height can range between 2 and 6 m.

## 2 Methodology

Model parameterization enables to define a set of results and to have hints on the performance of the façade for each configuration possible.

The parametric simulation model is based on a mono-zone model, intended to be representative of typical shopping mall environments. The reference zone is 15-meters deep with adiabatic boundary conditions on all the walls, except for the one including the multifunctional façade. The multifunctional façade module covers entirely the external wall of the reference zone model. As far as the façade module is concerned, it has been drawn considering a distinction between the fixed mullion and transom and the assigned frame's percentage of windows installed in the module. The model geometry has been drawn with SketchUp using Trnsys3D plug-in and then imported in the Trnsys simulation environment (Klein et al, 2010); in particular, the thermal behaviour of the reference zone is modelled by TYPE 56. The standard radiation model (Seem, 1987) of Trnsys has been used through the simulation process. The PV power production has been evaluated using the model of Trnsys TYPE 94 (Klein et al, 2010). Three volume sizes of the zone have been considered in the study: 60 $m^3$, 90 $m^3$ and 270 $m^3$ for the façade module dimensions of 2[m]x2[m], 2[m]x3[m] and 3[m]x6[m], respectively. The fixed glazed part of the window is provided with a fixed lamella shading system. Thermal transmittance of façade elements, such as mullions and window frames, have been set in accordance to data provided by the façade designer (U-value 'frame&mullion'=3.588 $W/m^2K$). The first part of the process which led to model definition has been dedicated to the setting of the reference zone parameters and the application of the building physics principles:

- set point temperature values for the heating and cooling system are the one recommended by the EN 15251-2007;
- the natural ventilation rate has been assessed using the single-sided, two vents, buoyancy driven model (CIBSE,2005)
- the infiltration rates depend on indoor-outdoor temperature difference and wind speed according to (Coblenz & Achenbach, 1963);
- internal gains due to people, appliances and artificial lighting system have been provided by an Italian shopping malls design company.

As second step, the input data have been defined in order to include all the possible choices simulating the desired condition in each configuration and can be distinguished in three categories:

- climatic condition and façade orientation;
- application, depending on the space's circumstance of use;
- façade module size and characteristics (glazing system and shadings configuration).

Finally, the simulation results have been post-processed in order to represent Indoor Air Quality, thermal and visual comfort and energy performance of the reference zone. The main considered performance indicators are the long-term percentage of people dissatisfied (LPD) (Carlucci, 2013), the number of hour per IAQ category, the energy consumption due to lighting, ventilation, heating and cooling demand and energy generation form the PV panel.

The developed tool shows simulation results using different plots guiding users in the selection of the optimal facade configuration.

### 2.1 Building energy simulation model

The first step of the work concerned the implementation of the façade model in the Trnsys simulation environment. Different possible algorithms where available for the modelling of the heat transfer and solar radiation exchange between the façade and the indoor and outdoor environment. Given the high number of simulation runs for the parametric analysis, a trade-off between computation time and model accuracy has to be considered. Thus, two geometry modelling approaches (standard and detailed model geometry) and two radiation calculation mode (detailed (Gebhart, 1971) or 'standard' (Seem, 1987)) have been analysed and compared in order to quantify the influence of the different model approaches on simulation results, in particular concerning windows and frame geometry inputs. The deviation in output trend showed the need to use a detailed model geometry which considers the geometrical distinction between frame of windows and mullion and transom of the module. Furthermore, the standard radiation model leads to a reduction in the computational time of the simulation (29 seconds and 71.93 seconds) compared to the detailed radiation model, without affecting in a critical way the results (Pinotti, 2016).

## 2.2 Inputs definition

Table 1 reports the facade configurations used in the parametric analysis. Façade module size and configuration results in different proportions between openable windows and fixed ones, with a consequent change in the percentage of frame in each window.

**Table 1: Possible configuration of the facade module**

| Façade width | Façade height | Zone depth | Frame % openable window | Frame % fixed window | Openable window width | Openable window height | Openable window area | Fixed window area | PV area |
|---|---|---|---|---|---|---|---|---|---|
| [m] | [m] | [m] | [-] | [-] | [m] | [m] | [m$^2$] | [m$^2$] | [m$^2$] |
| 3 | 6 | 15 | 22% | 9% | 1.5 | 0.60 | 0.90 | 6.40 | 0.9 |
| 3 | 6 | 15 | 17% | 9% | 1.5 | 0.90 | 1.35 | 5.97 | 0.9 |
| 3 | 6 | 15 | 14% | 9% | 1.5 | 1.20 | 1.80 | 5.54 | 0.9 |
| 2 | 3 | 15 | 31% | 15% | 1 | 0.42 | 0.42 | 1.74 | 0.6 |
| 2 | 3 | 15 | 24% | 16% | 1 | 0.63 | 0.63 | 1.54 | 0.6 |
| 2 | 3 | 15 | 21% | 17% | 1 | 0.85 | 0.85 | 1.33 | 0.6 |
| 2 | 2 | 15 | 36% | 21% | 1 | 0.35 | 0.35 | 0.85 | 0.6 |
| 2 | 2 | 15 | 27% | 23% | 1 | 0.52 | 0.52 | 0.69 | 0.6 |
| 2 | 2 | 15 | 23% | 27% | 1 | 0.69 | 0.69 | 0.53 | 0.6 |

Three different typologies of building application have been considered in the parameterization: 'Shops' (SHP), 'Common Area' (CMA) and 'Restaurant' (RST); different building application implies different lighting, appliances and occupancy density and profiles, and, therefore different internal gains. It must be noticed that, in case of 'Shop', no shading system has been applied on the façade because each façade module is supposed to be a shop window. All the orientation (North, South, East and West) for each configuration of the reference zone have been simulated. It must be noticed that for north-oriented façade no shading system has been applied on the façade.

A literature review has been carried out on U-values and g-values in order to define the most likely value ranges of these parameters for glazed components in several European countries. The result of this part of study has given realistic thermal transmittance and the respective solar gain values, from the point of the reliability at the current state of the art in the field of windows and glasses technologies and in compliance with the current regulation framework. Upper limit for U-values refers to the minimum requirements of national regulations. The lower limit refers to the minimum U-value recommended by the standards set by energy efficient buildings certification schemes. Feasible ranges of g-values have been assigned to each U-value, taking into account the state of the art of glazing industry (agc-glass.eu, 2016). Window glazing systems models have been developed using WINDOW 7.4 database (Lawrence Berkeley National Laboratory, 2011). Table 2 reports glazing U-values and g-values ranges for several locations.

**Table 2: Glazing U-values and g-values ranges.**

| Country | Reference city | HDD | $U_w$-value [W/m$^2$ K] (max) | g-value (max) | g-value (min) | $U_w$-value [W/m$^2$ K] (min) | g-value (max) | g-value (min) |
|---|---|---|---|---|---|---|---|---|
| Norway | Trondheim | 5211 | 1.20 | 0.67 | 0.20 | 0.80 | 0.63 | 0.25 |
| UK | London | 2800 | 1.80 | 0.52 | 0.29 | 0.85 | 0.63 | 0.25 |
| Austria | Wien | 2844 | 1.90 | 0.73 | 0.25 | 0.85 | 0.63 | 0.25 |
| Italy | Modena | 2529 | 2.20 | 0.52 | 0.29 | 1.30 | 0.67 | 0.22 |
| Italy | Palermo | 585 | 3.00 | 0.77 | 0.40 | 1.30 | 0.67 | 0.22 |
| Spain | Seville | 1460 | 4.20 | 0.61 | 0.37 | 1.25 | 0.67 | 0.20 |

In order to prevent direct sunlight from entering the zone, a fixed shading system has been considered for all the big central windows of façade's modules, except for the 'shop' application and for north-oriented cases. Among the parameterization variables we considered also lamellas tilt and distance (Figure 2). In order to calculate the shading effect due to the shading system, a dedicated model, and the related parameterization, have been done using the Radiance plug-in for GRASSHOPPER (McNeel, Rutten, & Associates, 2007) combined with RHINOCEROS (Robert McNeel & Associates, 2015). Practically, the effect induced by shading lamellas has been translated in the Trnsys model as a reduction of direct and diffuse solar radiation entering the zone.

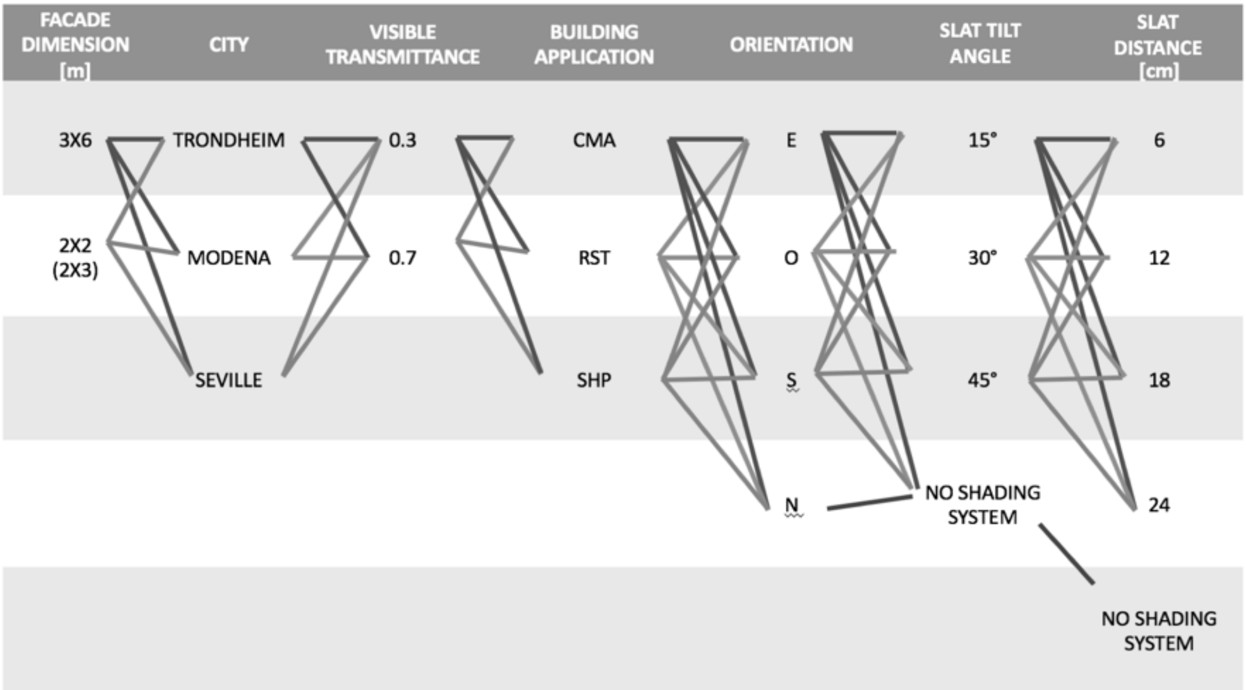


**Fig. 2 Parameterization combinations for the shading system (Trondheim, Modena and Sevilla cases)**

The entering level of luminous flux predicted by the Radiance model is also input in Trnsys to control artificial lighting dimerization.

The parametric analysis is run through the JE+ software (Zhang & Korolija, 2010) in full-factorial mode. Therefore, for each possible combination of inputs, one simulation had to be run. The parametric analysis led to 8424 façade configurations, or simulation runs (Figure 3), 2808 for each climate.

## 2.3 Outputs definition

| OREINTATION | APPLICATION | REFERENCE CITY | U-value | g-value | FACADE WIDTH | FACADE HEIGHT | OPENABLE WINDOWS FRAME | FIXED WINDOWS FRAME | OPENABLE WINDOWS WIDTH | OPENABLE WINDOWS HEIGHT | SLAT TILT ANGLE | SLAT DISTANCE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | - | - | [W/m²K] | - | [m] | [m] | - | - | [m] | [m] | - | [cm] |
| N | SHP | TRONDHEIM | 1.2 | 0.67 | 3 | 6 | 22% | 9% | 1.5 | 0.60 | 15° | 6 |
| S | CMA | | | 0.2 | | | 17% | 9% | 1.5 | 0.90 | 30° | 12 |
| O | RST | | 0.8 | 0.63 | | | 14% | 9% | 1.5 | 1.20 | 45° | 18 |
| E | | | | 0.25 | 2 | 3 | 31% | 15% | 1 | 0.42 | no shadings | 24 |
| | | MODENA | 2.20 | 0.52 | | | 24% | 16% | 1 | 0.63 | | no shadings |
| | | | | 0.29 | | | 21% | 17% | 1 | 0.85 | | |
| | | | 1.30 | 0.67 | 2 | 2 | 36% | 21% | 1 | 0.35 | | |
| | | | | 0.22 | | | 27% | 23% | 1 | 0.52 | | |
| | | SEVILLE | 4.20 | 0.61 | | | 23% | 27% | 1 | 0.69 | | |
| | | | | 0.37 | | | | | | | | |
| | | | 1.20 | 0.67 | | | | | | | | |
| | | | | 0.2 | | | | | | | | |

**Fig. 3 Summary of parametric analysis variables (Trondheim, Modena and Sevilla climate)**

Table 3 reports the key performance indicators out coming from the simulation results post-processing.

**Table 3: Output from the simulation**

| OUTPUT | UNIT | DESCRIPTION | REFERENCE |
|---|---|---|---|
| SPECIFIC HEATING DEMAND | $kWh/m^2$ | - | |
| SPECIFIC COOLING DEMAND | $kWh/m^2$ | - | |
| LONG-TERM PERCENTAGE OF DISSATISFIED | - | The necessity of using such an indicator instead of the most known PPD is due to the will of having an output for each simulated configuration, summarizing the result of all the considered period. | (Carlucci, 2013) |
| LIGHT CONSUMPTION | kWh | Calculation of the lighting consumption has been possible thanks to combined parameterizations regarding the shading system, giving as result the overall luminous flux entering the zone from daylight and considering a designed enlightenment value. | |
| MECHANICAL VENTILATION CONSUMPTION | kWh | The electric energy required by fans for providing airflows required to keep an acceptable IAQ, considering a specific fan power of 0.75 $Wh/m^3$. | |
| N° HOURS WITH NATURAL VENTILATION | h | Number of hours over the occupied period when natural ventilation can be activated. | |
| N° HOURS WITH EFFECTIVE NATURAL VENTILATION | h | Number of hours over the occupied period when natural ventilation can be activated and provides same or higher airflows than mechanical ventilation | |
| N° HOURS IAQ CATEGORY 1 | h | $CO_2$ concentration in the air has been calculated and Indoor Air Quality categories have been assigned to the environment | (EN 15251,2007) |
| N° HOURS IAQ CATEGORY 2 | | | |
| N° HOURS IAQ CATEGORY 3 | | | |
| N° HOURS IAQ CATEGORY 4 | | | |
| N° HOURS THERMAL CATEGORY 1 | h | Thermal categories have been assigned to the room environment after having compared the running outdoor mean temperature with the operative temperature inside the room | (EN 15251,2007) |
| N° HOURS THERMAL CATEGORY 2 | | | |
| N° HOURS THERMAL CATEGORY 3 | | | |
| OVERHEATING HOURS | h | Overheating and overcooling number of hours exceeding thermal categories limits | (EN 15251,2007) |
| OVERCOOLING HOURS | | | |

| | | | |
|---|---|---|---|
| OVERHEATING DEGREE | °C | Estimation of the severity of overheating and overcooling | (EN 15251,2007) |
| OVERCOOLING DEGREE | | | |
| PV POWER GENERATED | kWh | PV power generated by the façade PV module | |
| PV POWER DIRECTLY TO LOAD | kWh | Power generated by the PV being directly used by the actuators of windows | |
| POWER SUPPLY FROM GRID | kWh | Electric energy supplied from the grid to accomplish window automation demand when battery is not charged and no energy is generated by PV | |

All the outputs and their trends have been analysed using Matlab-based filtering methods. The graphs generator will be the base of the graphical user-interface for the façade designers support tool. Therefore, using the software Matlab, a series of filters on input and output parameters have been arranged and users can select their own preferences excluding undesired ranges for specific variables, thus obtaining the optimal facade configuration for stated boundary conditions. Users can define the optimisation parameter, depending on their design targets. For instance, designers can decide to give priority to comfort level of occupants over energy consumptions. By filtering selection, users can set their order of priorities. Table 4 summarizes two different filtering selection procedures available in the tool. So, following one of the two filtering procedures, designers can go through all the possible configurations for the façade and end up with just few cases, whose characteristics depends on the filters applied.

The graph for the LPD filtering relates the percentage of hours with an IAQ in categories 1 or 2 (y-axis) with the percentage of LPD (x-axis); moreover, the colour of the indicator gives information on the characteristic of the type of glazing used in each facade configuration (U-value, g-value and Visible Transmittance).

As far as the LIGHT CONSUMPTION filter is concerned, it has been decided to use data on light consumptions as indirect indicators of the value of daylighting inside the zone. Obviously, the lower the light consumption results, the higher daylighting is. The second filter is used in order to ensure good level of daylight. By applying this filter, the light consumption (y-axis) is related with the configuration of the shading system: distance between lamellas (x-axis) and lamellas angle degree (colour of the indicator).

Remaining configurations are filtered on the base of total consumptions available, choosing cases with lowest energy demand: heating system, cooling system, mechanical ventilation, light consumptions are considered; moreover, power demand from the grid is taken into account in the total amount of energy consumptions. Therefore, in the TOTAL CONSUMPTION filter's graph, the total energy consumption (x-axis) is related with the percentage of hours with an IAQ in categories 1 or 2 (y-axis) and LPD value can be identified using the colour scale.

Finally, a few cases remain, all with very similar comfort and consumption characteristics; therefore, the ultimate selection is related to designer's preferences on shading configurations (slat orientation angle and distance), proportions in the façade module and type of the glazing to be used.

**Table 4: Different filtering procedures depending on the design priority of the designer**

| COMFORT PRIORITY | LOW CONSUMPTION PRIORITY |
|---|---|
| 1. LPD filter | 1. TOTAL CONSUMPTIO+POWER FROM GRID filter |
| 2. LIGHT CONSUMPTION filter | 2. LIGHT CONSUMPTION filter |
| 3. TOTAL CONSUMPTIO+POWER FROM GRID filter | 3. LPD filter |
| 4. FINAL DESIGN CHOICE | 4. FINAL DESIGN CHOICE |

## 3 Example application of the design tool

One applicative example of the façade configuration selection process is showed below: it has been supposed to design a 3x6 south-oriented façade in a ‘restaurant’ building application in Seville. The priority in the choice of allowed ranges has been given to the occupants’ comfort level.

- Step 1: LPD filtering

The first filter selected is the one regarding thermal comfort (LPD). So, after evaluating the available range for the LPD in the specific case and trying to keep lowest values (PPD<10% as recommended by ANSI/ASHRAE Standard 55-2013), filters on LPD are applied. In Figure 4, all the configurations for ‘restaurant’ 3x6 south-oriented Seville facade are reported and a filter on **LPD<11** is selected.

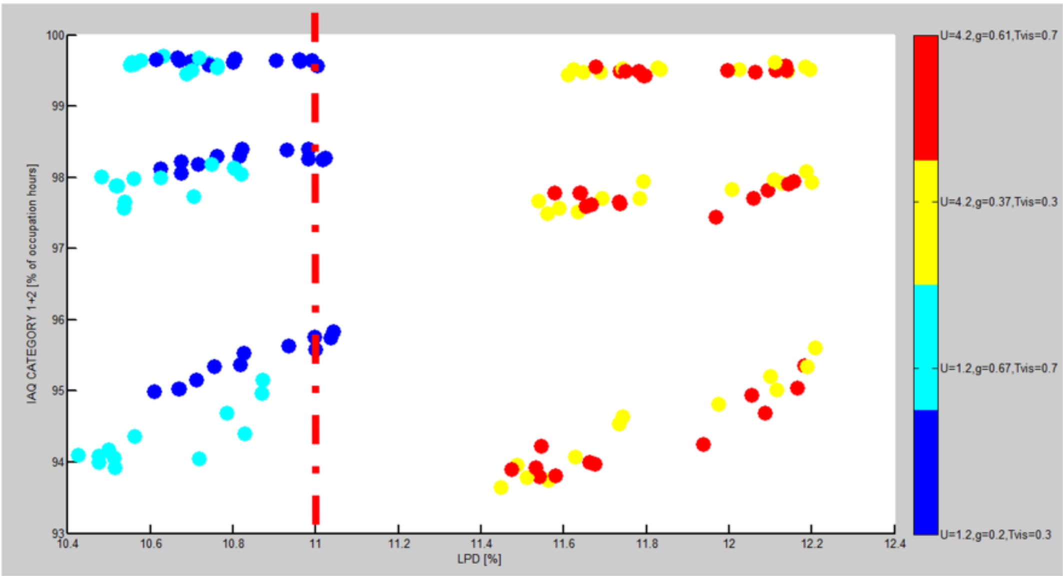


**Fig. 4 LPD % - Seville_3x6_RST_S**

- Step 2: Light consumption filtering

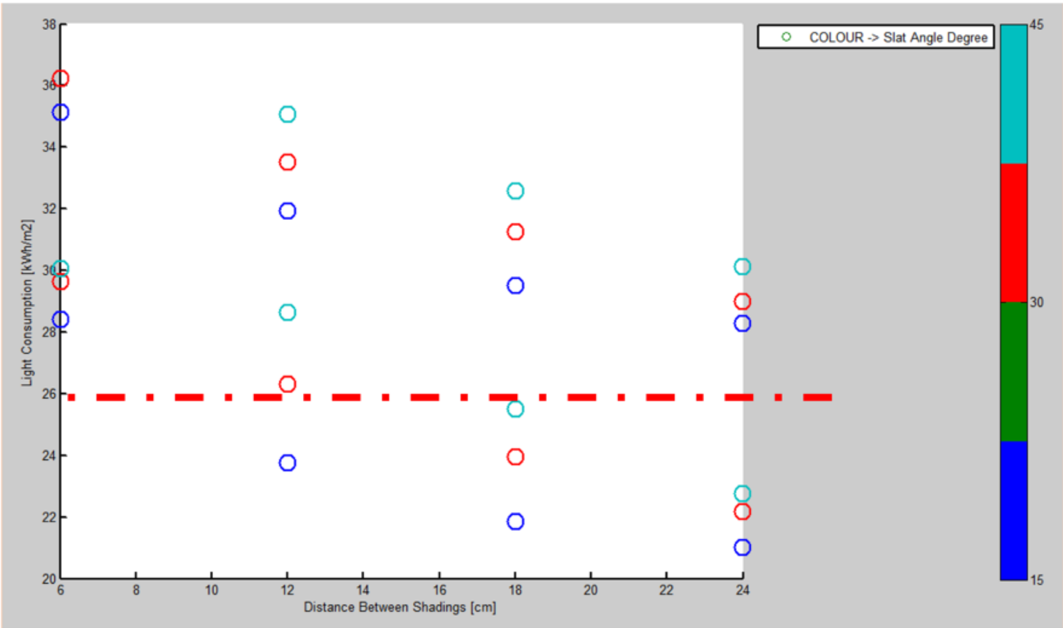


**Fig. 5 Light consumption and shading configuration - Seville_3x6_RST_S**

Among the façade configurations with higher thermal comfort, a filter on light consumption is applied setting with a threshold of **26 kWh/m$^2$** (Figure 5); this value is leaving a good number of cases for the final choice, and, at the same time, it is largely reducing available configurations.

- Step 3: Consumption filtering

In this example, on the base of consumption range showed in Figure 6, total energy consumption filter will be set to 147 kWh/m$^2$ as maximum value. The remaining configurations are reported in Figure 7.

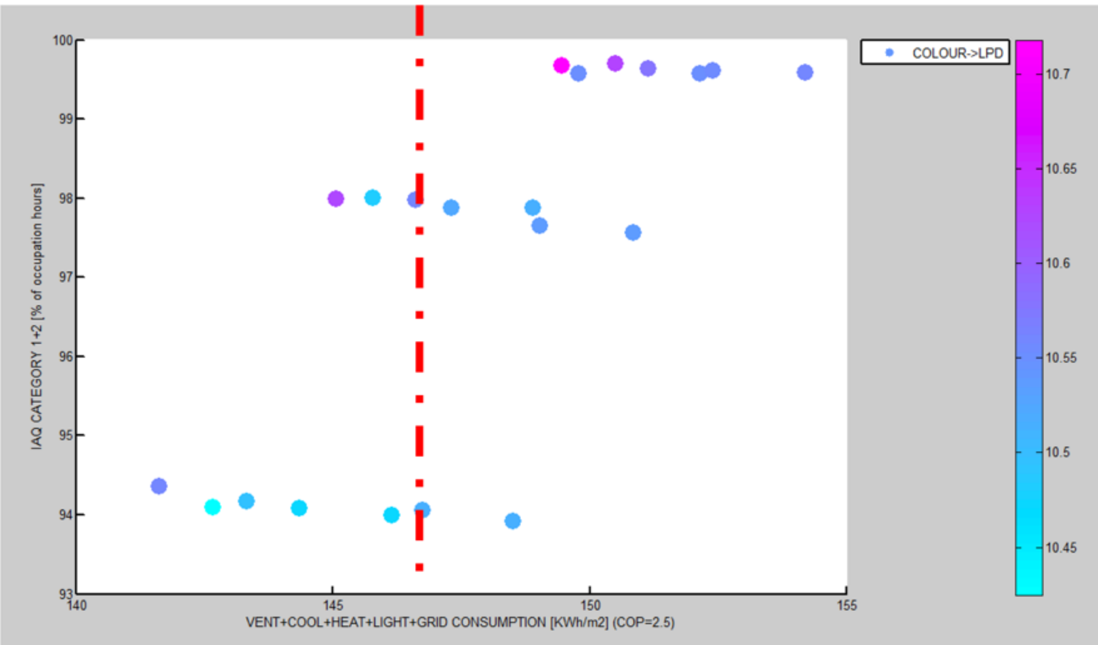


**Fig. 6 Total consumption related to IAQ and LPD - Seville_3x6_RST_S**

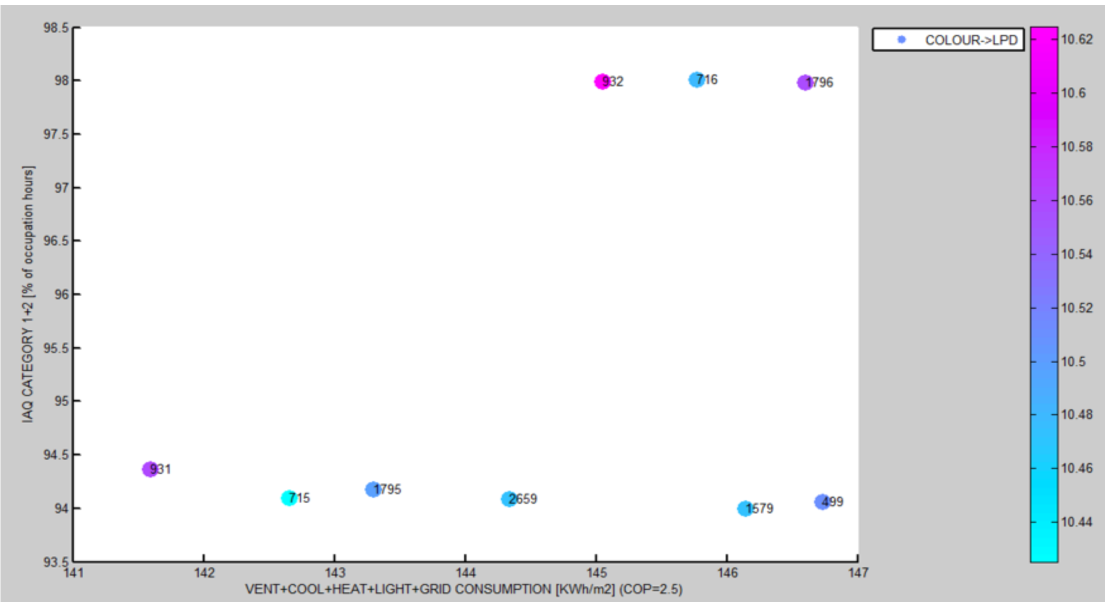


**Fig. 7 Remaining cases after filtering on consumptions, ID simulation displayed - Seville_3x6_RST_S**

- Step 4: Design choice

Table 5 summarizes the filtering process for the application example described and lists the resulting optimal façade configurations among which the designer can choose.

**Table 5: Summary of the filters applied in the example described and available configurations**

<table>
<tr><td>STARTING CONDITION</td><td colspan="5">Seville<br>3x6 module<br>'RST' application<br>South-oriented</td></tr>
<tr><td>DESIGN PRIORITY</td><td colspan="5">COMFORT</td></tr>
<tr><td>FILTER</td><td>LPD</td><td colspan="4">< 11%</td></tr>
<tr><td>FILTER</td><td>LIGHT CONSUMPTION</td><td colspan="4">< 26 kWh/m²</td></tr>
<tr><td>FILTER</td><td>TOTAL CONSUMPTION</td><td colspan="4">< 147 kWh/m²</td></tr>
<tr><td rowspan="10">FINAL DESIGN CHOICE</td><td rowspan="10">SHADING CONFIGURATION AND FAÇADE PROPORTIONS</td><td>ID SIMULATION</td><td>SLAT ANGLE DEGREE</td><td>DISTANCE BETWEEN SHADINGS [cm]</td><td>AREA OPENABLE WINDOW [m²]</td></tr>
<tr><td>499</td><td>15°</td><td>12</td><td>SMALL</td></tr>
<tr><td>715</td><td>15°</td><td>18</td><td>SMALL</td></tr>
<tr><td>716</td><td>15°</td><td>18</td><td>MEDIUM</td></tr>
<tr><td>931</td><td>15°</td><td>24</td><td>SMALL</td></tr>
<tr><td>932</td><td>15°</td><td>24</td><td>MEDIUM</td></tr>
<tr><td>1579</td><td>30°</td><td>18</td><td>SMALL</td></tr>
<tr><td>1795</td><td>30°</td><td>24</td><td>SMALL</td></tr>
<tr><td>1796</td><td>30°</td><td>24</td><td>MEDIUM</td></tr>
<tr><td>2659</td><td>45°</td><td>24</td><td>SMALL</td></tr>
</table>

## 4 Conclusions

The paper presents a parametric tool, suited to support the design process of a modular multifunctional façade giving the façade itself the possibility of being climate-adaptive. The tool is based on a filtering procedure, generating graphs and driving the user to identify the most optimal façade configurations. All the possible configurations of the façade module – i.e. façade orientation, façade proportions and dimensions and glazing characteristics - have been firstly modelled in TRNSYS and secondly simulated through a fully-factorial parameterization. Therefore, a smart graphical organization of data has been fundamental in order to manage the huge amount of results. The choice of the most performing configuration in a specific condition depends on the priority of the designer which has been assumed low-consumption or high-comfort oriented. The results show that the methodology is necessary for the realisation of the "façade adaptive" concept. Further research developments would be a detailed study of the retro-ventilation behind the integrated photovoltaic panel and a development of the filtering tool, making it more smart and interactive.

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