SHORT TERM SCIENTIFIC MISSION (STSM) SCIENTIFIC REPORT

This report is submitted for approval by the STSM applicant to the STSM coordinator

Action number:	**TU1403 (Adaptive Façade Network)**
STSM title:	**An advanced integrated simulation procedure to evaluate the overall performance and control strategy of an active adaptive transparent façade component**
STSM start and end date:	**17/07/2017 to 14/10/2017**
Grantee name:	**Luigi Giovannini**

PURPOSE OF THE STSM:

Currently available Building Performance Simulation tools present two main limitations when assessing the performance of innovative adaptive façade components and their effects on the overall building performance:

i) difficulty in varying the thermo-optical properties of the component within the simulation process itself, making thus the evaluation of the effects of the component adaptive behaviour very complex.

ii) Inability to perform a simultaneous evaluation of the effects of an adaptive façade component on different physical domains (energy performance, thermal and visual comfort)

To overcome the methodological lacks highlighted the present STSM proposes to:

a) devise and design a novel simulation tool that, managing together thermal and lighting simulation softwares, is able to vary the thermo-optical properties of the adaptive façade component during simulation run-time, with a particular focus also on the user interface

b) use the novel methodology proposed to investigate the control strategy of an active adaptive transparent component. The purpose is that of conceiving an innovative control strategy, with the aim of optimising the visual comfort provided to the user whilst reducing the energy consumption of the building.

A secondary aim of the STSM is to explore the possibility of joint research projects between Politecnico di Torino, University of Cambridge, Eckersley O'Callaghan and others (involving national and international funding).

DESCRIPTION OF WORK CARRIED OUT DURING THE STSMS

The work carried out in order to achieve the primary objectives of the STSM can be divided in five different phases:

Phase 1: review of active adaptive transparent technologies features and control strategies.

A review of currently available and innovative adaptive components was carried out to select the most suitable technologies to be analysed in this STSM, depending on their properties and on the features of their active behaviour. A state of the art of the control strategies currently used to control active adaptive transparent components was also carried out in order to highlight the most common performance objectives and the way they are reached.

Phase 2: development of a novel methodology for spatial glare assessment.

Glare assessment is the heaviest computational part of an integrated simulation model. Moreover, the glare condition, being view-dependant, needs to be evaluated for every point of the space. A novel methodology to evaluate glare throughout a space by means of the vertical illuminance measured in a single point was devised, in order to reduce the computational time and at the same time being able to comprehensively assess the glare condition.

Phase 3: control strategy conception and implementation.

From the findings of the literature review performed, a series of different control strategies were conceived. The control strategies devised, all aimed at providing the best possible visual comfort to the user while reducing the energy performance of the analysed space, were based on different working logics and operating principles. In this phase they were tested in order to select the one which allowed the highest visual performance.

Phase 4: simulation tool implementation.

Through the previous phases a simulation framework was developed. This simulation method allows to: a) define the task of the different simulation softwares; b) define the building performance metrics to be calculated in each phase of the simulation process; c) define the workflow of the analysis to achieve accurate building performance results by coupling synergistically the different parts of the novel methodology. In this framework a simulation tool was implemented, partly in a flexible parametric environment (through *Rhinoceros* parametric plugin *Grasshopper*) and partly by means of a series of python scripts created on purpose to manage the complex computation process and to perform advanced data post-processing operations.

Phase 5: test of the simulation strategy on a case study.

The simulation methodology proposed was used to test the validity of the control strategy conceived for the different active transparent adaptive technologies selected. An enclosed office located in Turin, South-oriented and with a Window-to-Wall Ratio (WWR) of 50% was chosen as a case study. Visual comfort annual metrics relative both to the glare conditions and to the light penetration inside the room, as well as energy performance annual indicators were calculated for the different technologies considered. The visual performance of the different adaptive technologies considered was also analysed and compared to highlight the most promising technologies among the ones considered.

DESCRIPTION OF THE MAIN RESULTS OBTAINED

Phase 1: review of active adaptive transparent technologies features and control strategies.

The first phase of the STSM work consisted in a comprehensive literature reviewon two different topics:

i) Active adaptive transparent façade components and dynamic shading system control strategies
ii) Smart glazing technologies.

The state of the art relative to the control strategies was set up in order to highlight the main performance aspects the different control strategies had been devised to control and optimise and which environmental parameters were monitored to reach the different goals. This activity was particularly useful as, with more than 40 between research papers and whitepapers analysed, it was finally possible to understand which are the main parameters monitored by the different control strategies to ensure, in turn, an optimal visual comfort (daylight and/or glare control), an optimal thermal comfort or to reduce the different energy demands the building is subjected to. All the findings from this phase were summarised in a comprehensive synthetic table which resulted fundamental in phase 3, when a novel control strategy had to be devised.

The review of the active adaptive transparent façade technologies already on the market or under development was instead necessary to acquire a basic knowledge about the different features and possibilities relative to each of them. This part allowed choosing which technologies to consider in the STSM work, depending on their features and their behaviour, in order to study cutting edge components, based on different operating principles, allowing different operations. The adaptive components chosen are:

a) EC: an innovative electrochromic (EC) glazing technology able to switch between the darkest and clearer state within a few minutes. Moreover, when in the darker states, it is able to preserve the spectral properties of the transmitted light, not having a dominant blue component like traditional thermochromic technologies. The light transmission of this component remains specular within the whole switching range
b) LC: a liquid crystal glazing able to switch between its clearest and darkest state within just one second. Moreover, it has the possibility to have different zones of the same glazing controlled in different ways. This technology too presents a specular attitude in the light transmission in all its switching range, but also has the possibility to switch in a single static thermo-optical state with scattering properties and a high haze index.
c) LC+: a liquid crystal glazing similar to the previous one, with the only difference that it is able to switch either in a specular light transmission range or in a scattering light transmission range (not only one single state like the previous component).

Thanks to the technology review carried out, not only the behaviour features of the selected components were known, but also their detailed characterisations.

<u>Phase 2: development of a novel methodology for spatial glare assessment.</u>

Glare condition is one of the most important aspects to be considered when analysing visual comfort. In fact glare, when present in a working environment, can make the working activities impossible to be carried out by the worker. Annual glare computation though is one of the most heavy, computationally speaking, operations of an integrated simulation methodology. For this reason the common practice is that of analysing it, for all the year, for only one or few representative points in the room and a single direction of observation, extending then the obtained results to all the space considered. This operation, unfortunately, implies some simplification that may lead to results which are not representative of the reality:

i) The glare condition is view-dependant. This means that for the same point of view, a slightly different direction of observation may not imply the same results

ii) Visual comfort never presents a linear behaviour. Therefore analysing the glare condition for one point in the room and then extending this result to the whole space analysed may result in gross evaluation errors, as a point near to the one analysed may already present completely different visual comfort conditions.

Nevertheless a spatial evaluation of the glare sensation of the user was a fundamental step to be able to devise a proper control strategy that granted an optimal visual comfort.

In this context a novel methodology for the spatial assessment of glare able to overcome all the aforementioned limitations was devised. The most common metric to assess glare due to daylight conditions is the Daylight Glare Probability (DGP), introduced by Wienold and Christoffersen, which mainly depends on the vertical illuminance registered at eye level. By means of the application of a fault detection technique on a database of case studies simulated on purpose, for which DGP and relative vertical illuminance at eye level had been assessed, it was possible to directly correlate the glare condition perceived to the vertical illuminance detected. This operation was performed for an enclosed office, alternatively oriented towards South and West, for which three representative points in the room were chosen to assess DGP and relative vertical illuminance. To be able to understand the effect of the variability of adaptive components on glare sensation, 11 different glazings, with different light transmission and haze index, were alternatively considered for this study. Venetian blinds with different slat angles and two different roller shadings were considered in this study as well. A total number of 128 different case studies was taken into account in the validation process of the novel methodology conceived. The spatial glare assessment methodology was not only validated against a huge number of different case studies, but for each of them the absolute annual error, in terms of total number of hour in which glare condition was overestimated or underestimated, was also evaluated. The maximum error committed, in terms of glare underestimation (the most dangerous possibility when controlling an active component) results to be 8% of the year. This result is relative to only one case study, but for the greatest part of them the time for which glare is underestimated is lower than 2% of the year. From the results obtained it is possible to say that the methodology, for the enclosed office case study considered, is reliable for evaluating the glare conditions of a whole space by means of the vertical illuminance measured at eye level in only one point of the room. Apart from the fact that it is finally possible to assess glare in a spatial way, the methodology proposed has also the great advantage of reducing exponentially the computational time required, being necessary the annual glare evaluation only for one point.

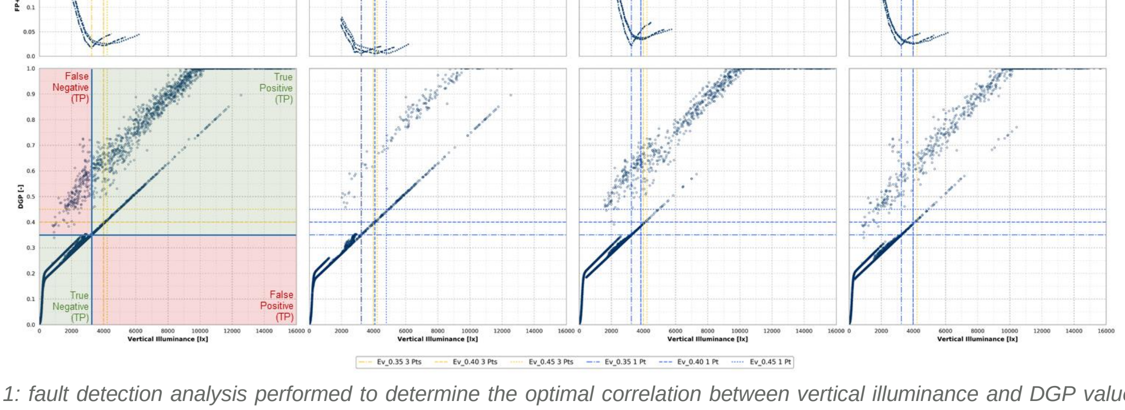

Figure 1: fault detection analysis performed to determine the optimal correlation between vertical illuminance and DGP values. The image is relative to one of the case studies analysed

Phase 3: control strategy conception and implementation.

By means of the critical literature review performed, and thanks to the spatial glare assessment methodology devised, it was possible to propose and evaluate a series of control strategies to be applied to the active adaptive transparent façade components selected. The main task of a transparent adaptive technology is that of always providing to the user the best possible visual comfort conditions. Starting from this premise, on the basis of the literature review carried out, different control strategies, based on different working principles and monitoring different parameters were conceived. All the control strategies devised are Rule-Based Control strategies (RBC), which means that a series of rules and thresholds for the different parameters accounted in the strategy must be set up, and that every different case considered must correspond to a different thermo-optical state of the adaptive component. The performance of the different control strategies proposed was evaluated, in terms of annual visual comfort provided to the user, in order to select the most suitable one.

The control strategy selected is a Rule-Based control strategy based on an optimising function that must be solved, at every time step of the year, for every thermo-optical state of the switchable glazing. The equation of optimisation takes into account different aspects of visual comfort at a time, allowing also to specify a hierarchical order between them. At each time step, the thermo-optical state that obtains the higher result solving the equation of optimisation is the one which provides the highest visual comfort to the user. In more detail the logic behind the optimisation equation is the following:

1) The thermo-optical state that is able to provide the highest percentage of space for which the glare is imperceptible is chosen
2) If two or more thermo-optical states provide the same percentage of glare-free space, the one able to maximise the daylight penetration is chosen. Daylight penetration is evaluated in this framework as horizontal illuminance on a horizontal plane located at a height of 0.75 m from the floor. Normative values are given, at European level, for the minimum illuminance allowed in a space, depending on the visual task performed in the considered space. Therefore the thermo-optical state allowing the highest daylight penetration is the one that provides the highest percentage of space for which the normative requirement for horizontal illuminance is met.
3) If two or more thermo-optical states provide the same percentage of glare-free space and also the same percentage of space in which the horizontal illuminance requirement is met, the most transparent one is chosen. This operation allows to maximise, when possible also the view to the outside allowed to the user.

The proposed equation takes into account all the three main aspects of visual comfort, giving a priority to the one that creates in the user the highest dissatisfaction or disability in performing its visual task. The equation of control optimisation is formulated in such a flexible way that it is also possible to give different priorities and weights to the different aspects, compared to the three main control rules outlined above.

Phase 4: simulation tool implementation.

Once established how to assess glare and how to actively control the transparent adaptive façade technologies selected, it was possible to implement a simulation tool able to perform an integrated evaluation of the visual comfort and energy performance of the components considered. The implementation of the tool starts from the results of a previous COST STSM, carried out on July 2016 by Emanuela Giancola, in collaboration with the grant holder himself and Fabio Favoino, at Politecnico di Torino. The outcome of that STSM was an innovative tool that, managing together thermal and lighting analysis softwares, was able to vary the thermo-optical properties of the adaptive façade component during simulation run-time. Being its development at a very early stage, it had some limitations:

a) it was only able to assess, in a simplified way, the integrated energy performance of a building (energy demands for heating, cooling and lighting), without taking into account the visual comfort provided by the component to the user
b) it was only tested for a passive adaptive façade technology component (i.e. thermochromic glazing)

In this STSM the simulation tool was further developed to be able to finally assess the annual visual comfort provided to the user, implementing in it the spatial glare assessment methodology described. Moreover, the possibility of controlling active technologies by means of user-defined control strategies was implemented in the tool as well. Since the beginning the tool has been developed in a flexible parametric environment, by means of *Rhinoceros* parametric plugin *Grasshopper*. Through its powerful add-on *Honeybee* a daylight simulation software (*Daysim*) and an energy/thermal simulation one (*EnergyPlus*) are managed in synergy in order to perform a correct integrated analysis of visual comfort and energy performance, to be used for adaptive façade components. By exploiting the EnergyPlus module *Energy Management System* (EMS) it is possible to perform a simulation on a *timestep-by-timestep* basis, overcoming thus all the limitations relative to currently available Building Performance Simulation Tools listed at the beginning of this document.

The simulation tool conceived has been developed by means of a series of custom-written Python scripts (consisting globally in circa 10.000 lines of code) with different purposes:

i) Manage the whole simulation process, allowing a synergic operation of the different softwares involved in it
ii) Use the EMS in the grasshopper environment (Honeybee does not allow the EMS utilisation when running EnergyPlus)
iii) Create a systematic parametrisation process of the component behaviour, in order to allow the tool performing also optimisation analyses on the most suitable component properties (once fixed the desired performance results)
iv) Processing the outcomes of the different softwares in order to guarantee, under any circumstance, a complete interoperability between daylight simulation and the energy/thermal simulation software
v) Post-Processing the raw outcomes of the two software involved in the integrated simulation process in order to eventually obtain specific annual performance metrics for visual comfort and energy performance, as well as spatial and temporal maps that allow a qualitative visualisation of the performance results.

It was possible to implement the great part of these scripts directly within grasshopper, but for a small part of them, due to the complexity of the calculations required, it was necessary to develop them within a pure python environment, as Grasshopper does not support python scientific analysis modules (Scipy and Numpy).

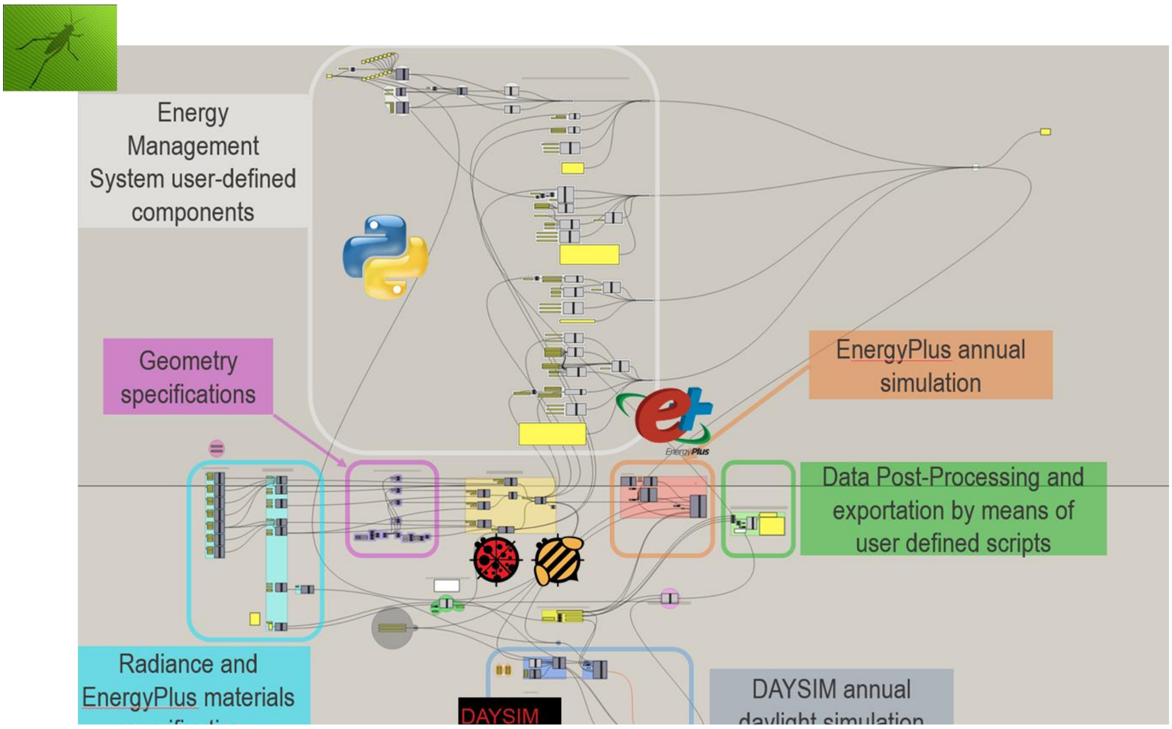

Figure 2: the simulation tool created in Grasshopper with the indication of the different sections composing it and the software used in each of them

Phase 5: test of the simulation strategy on a case study.
The methodology described was eventually tested on the active adaptive transparent façade components considered in this STSM work. The analysis had three main objectives:

i) Analyse the performance of the different adaptive components considered, in respect also to some traditional dynamic shadings and static glazings
ii) Test the validity of the control strategy proposed
iii) Test the methodology devised itself, in order to highlight possible problems in the workflow or in the results.

The enclosed office used in phase 3 was once again considered as case study.
In fig. 3 annual results relative to visual comfort for all the technologies considered are summarised. It is possible to see that also venetian blinds (VB) and two types of roller shading (RB) were simulated. For every adaptive technology or dynamic shading system, results relative to the most transparent and more opaque

static thermo-optical states are represented, as well as the results relative to the different technologies controlled by means of the control strategy proposed. On the x-axis of the chart it is represented the *DA*, i.e. the Daylight Autonomy, that represents the percentage of time for which the minimum horizontal illuminance requirement is met by daylight alone, without the need of artificial lighting. On the y-axis instead it is represented the *DGP_0.35*, i.e. the percentage of time for which the Daylight Glare Probability is below 35%, which means that the glare sensation perceived is intolerable. The diameter of the single points represents the energy demand for lighting associated to each case study.
From the results shown it is possible to see that for every technology analysed the control strategy proposed is able to improve the DA, without for this reducing the total hours in which no glare is perceived. From this it is possible to draw a first conclusion, that is to say that the control strategy proposed, for every case study analysed, is able to improve the annual visual comfort provided by increasing the daylight penetration while maintaining the same glare conditions of the darkest (and most performant) of the thermo-optical states the technology considered can assume.
Analysing then the performance of the single technologies considered, it is clear that, for the same control strategy applied, any adaptive technology considered performs better than all the traditional dynamic shadings. Among the adaptive components, the one able to provide the best visual comfort over the whole year is the LC+, that is to say the LCD component able to switch both in the specular and in the scattering range. The LCD component able to switch only in a specular range, but with the possibility to assume a single static scattering state, (LC) shows a better performance if compared to the innovative electrochromic glazing (EC). This trend can be explained by considering the variety of possibilities each component can choose among when switching state. The component with the highest number of possibilities, the LC+, is the one with the best annual performance because it is the one that to any daylight condition can provide the best answer, i.e. it can minimise the glare sensation while allowing a higher daylight penetration if compared to the other two adaptive technologies.
Fig. 4 summarises the annual energy performances for heating (EPh), cooling (EPc) an lighting (EPl) relative to the only adaptive technologies considered, compared with the most transparent and more opaque static thermo-optical states every technology can assume. It is possible to see that for all the three technologies, the control strategy is able to reduce the energy consumption required by the most transparent state, but the darkest static state always shows a higher energy performance. This happens because for darker states a lower part of the solar radiation is allowed inside the analysed space, reducing thus summer overheating and the correlated energy demand for cooling. It is important to highlight that although the most opaque state for every technology shows a higher energy performance than the controlled case studies, their annual visual performance is far below the one provided to the user by means of the devised control strategy. Comparing then the energy performance relative to the case studies controlled by means of the control strategy proposed, it is possible to see that the same trend highlighted in the annual visual performance results is valid here too.
In conclusion it is possible to state that the control strategy devised is able to sensibly improve the visual comfort conditions provided to the users, in respect to static glazings and traditional dynamic shading, by maintaining the same levels of imperceptible glare as the most opaque thermo-optical state of every technology, but allowing at the same time a higher presence of daylight. In terms of annual energy performance instead, the control strategy proposed is able to reduce the energy demands for heating, cooling and lighting in respect to static clear glazings.

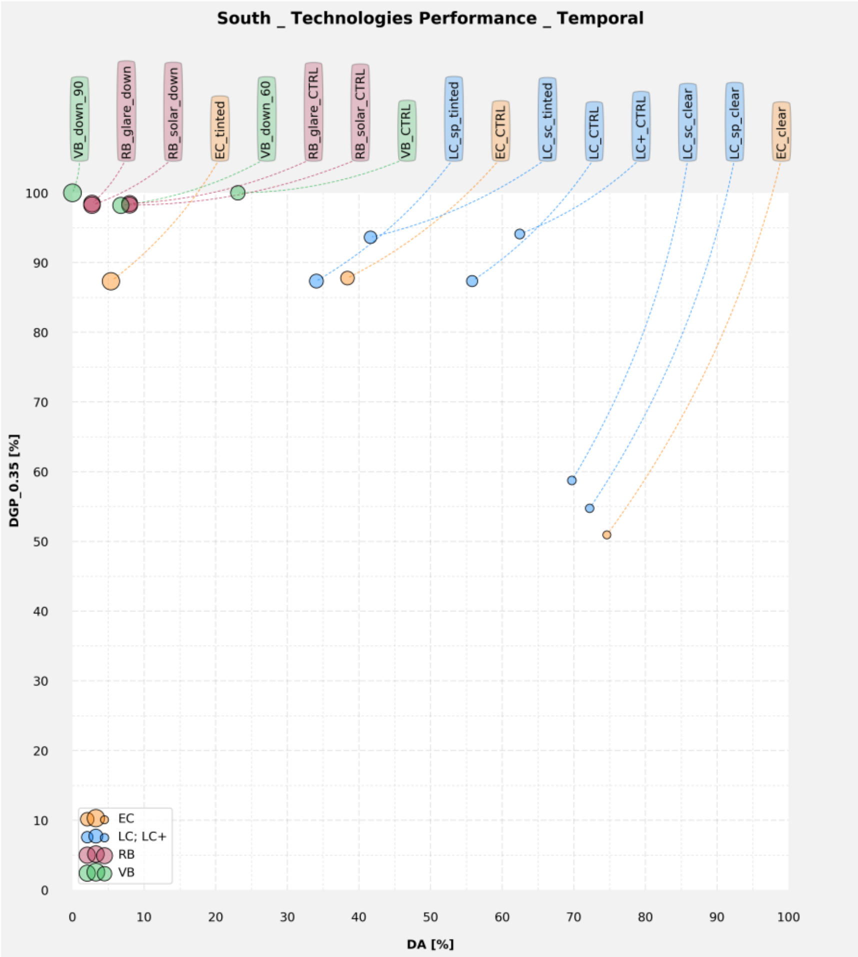

Figure 3: Chart summarising the results relative to the annual visual comfort provided by the different case studies considered in this analysis

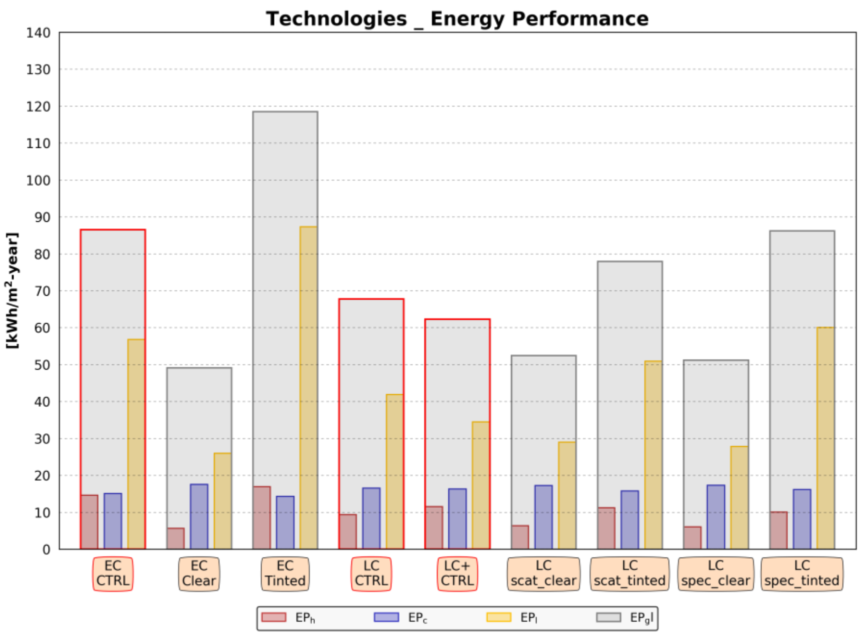

Figure 4: chart summarsing the final annual energy performance results relative to the case studies considered in this analysis

It is important to highlight that the results shown here are just a part of the results obtained during the STSM and that the implementation of the control strategy and of the simulation tool, as well as a broader study that includes different climates, geometries and orientations, are still in progress and will be object of one or more dedicated manuscripts.

FUTURE COLLABORATIONS (if applicable)

The STSM has been useful to consolidate the relationship between the three institutions involved. Future collaborations, all relative to the work carried out within the STSM, include:

a) the writing of a literature review about the different currently available control strategies to control the smart glazings with different purposes
b) The development of the spatial glare assessment methodology and its validation against different climates, geometries orientations and different adaptive components;
c) the further implementation of the integrated simulation methodology here created, in order to:
    i) include the energy aspects within the control strategy itself (now they are only evaluated ex-post)
    ii) implement the possibility of simulating Model Predictive Control (MPC) strategies
    iii) improve the simulation workflow
    iv) allow a more user-friendly utilisation of the simulation tool
d) the improvement of the control strategy proposed, by means of:
    i) the introduction, in the optimization function, of thermal comfort aspects
    ii) a comprehensive sensitivity analysis on the weights assigned to every component of the optimization function.
e) A possible experimental campaign activity aimed at validating the methodology and the control strategy proposed against a real case.

An abstract about the spatial glare assessment methodology has already been submitted to the 7th International Building Physics Conference (IBPC2018), to be held in Syracuse, USA, in September 2018.
Part of the work carried out in this STSM will also be submitted to the COST Action Tu1403-Adaptive Façade Network final conference, to be held in late 2018.
The outcomes of the STSM will also be presented in joint publications in international journal papers.