Embedded single-board controller for Double Skin Facade: a co-simulation virtual test bed

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Abstract

Operational building performance of Double Skin Facades (DSFs) is highly sensitive on their control strategies. Due to the complexity of their operations, model-based controls could represent an opportunity to improve further the potential energy savings and occupant comfort. The present work explores the potential and applicability of rule and model-based control strategies implemented on a façade-embedded single-board controller. This is demonstrated by means on a virtual experiment, carried out by means of a co-simulative framework implemented on the controller itself, to replicate the real world implementation. The embedded controller has different tasks, from signal processing from low-cost sensors, to performing parametric on-line simulation to feed in the control decision making algorithm, to sending the control signal to the different DSF actuators. Two different control strategies are developed for the implementation, and their performance compared by means of co-simulation on the single board controller: a) a Rule-Based Control strategy, based on if-else rules depending on environmental conditions; b) a Model-Based Control strategy, aims at minimising the heating and cooling loads of the environment adjacent of the DSF, while maximising the autonomous Useful Daylight Illuminance. The results show that, compared to benchmark DSF configurations and control strategies, the MBC implemented on the embedded single board controller would be able to reduce total (heating, cooling and lighting) energy use between 11\% and 18\%, while improving useful daylight availability by 13\% without introducing potential glare risk.

Key Innovations

- Co-simulation framework has been implemented on a single-board controller to simulate performance of DSF;
- Rule-based controls and a model-based control can be implemented on façade embedded controllers;
- Model-based control leads to a higher reduction (-11\%) of the total energy needs compared to Rule Based ones and higher visual comfort;

Practical Implications

Controls based on model-supported decision-making algorithms can improve the energy and indoor environment performance of operations of dynamic envelope systems. Single-boards are promising for application as an embedded controller for decentralised online model-based control of such dynamic complex transparent system.

Introduction

Double Skin Façades are complex fenestration systems “which consist of two transparent systems separated by a cavity, which is used as an air channel” (Saelens, 2002). They usually contain ventilation openings and solar shading devices to actively manage different tasks in a building (e.g. controlling solar gains, ventilation and daylighting), thus impacting significantly building energy use and occupant comfort. Even though the concept of Double Skin Façade is not new, in the last two decades their use in buildings is increased leading to significant performance improvements. DSF technology evolved to achieve an even higher level of dynamicity, controlling to a greater extent incoming solar loads and ventilation flows (by means of integration of different and sometimes multiple shading devices, integrating multiple ventilation modes and air-paths within the cavity). The theoretical flexibility provided by such controllable building envelope components can allow the façade to act as a climate-responsive element able to optimise everchanging building requirements (i.e. occupant thermal and visual comfort, energy use etc.) with intrinsically dynamic boundary conditions (climate, occupancy etc.) (Loonen et al., 2017). This can be achieved by actuating on the ventilation mode (natural and or mechanical) and speed, different ventilation path (thermal buffer, to outdoor air curtain, supply air, exhaust air and inlet air curtain) (Catto Lucchino et al., 2019) and different height of the curtain shading (or angle of Venetian blind). However, these dynamic features require a decision-making system able to predict the best DSF configuration to ensure a certain building-level performance, as their performance strictly depend on the control strategies adopted during building operations (Bianco et al., 2018), which need to consider not only energy savings but also occupant comfort requirements.

Rule Based Control (RBC) strategies are the most common control type adopted, due to their simplicity and relative low cost (in terms of software and hardware). The decision making of this kind of control consists of a set of if-then rules, based on the comparison of sensors measurements with specific thresholds. Choi et al. (2012) for example proposed a RBC for a multi-storey double
skin facade based on occupancy, cavity air temperature and indoor air temperature, reaching low energy saving results compared to a benchmark poorly controlled DSF. Within the DSF, the most adopted solar shading control options are by far the ones preventing direct solar radiation within the indoor environment when occupied, such as the cut-off control for venetian blinds (Jain & Garg, 2018), which could reduce importantly the daylight availability. RBC is not able to predict the effect of the control decision on building performance but is only based on the information about the current state of the facade, the boundary conditions and related indoor environmental parameters, and its design is usually built upon expert knowledge (Yoon et al., 2011). Model-based controls (MBC), conversely, exploit the prediction of the impact of the control action on the indoor environment to perform its decision making, with the aim of maximising a specific building-level performance. Only a few examples exist in literature applied to dynamic facade systems: the Fener model aims at combining daylighting and thermal simulations for controlling shading devices (Bueno et al., 2015); Park et al. (2004) adopted a lumped model to find the optimal DSF configuration in an on-line control (actuating on blind slat angle, ventilation mode and cavity air-path); Yoon et al. (2011) presented a real-time self-calibrating model for the optimal control of a Double Skin Facade. Novel control architectures have been devised as well for MBC, leaving to the Building Management System the high-level decision making (i.e. optimal entering solar loads and HVAC configurations), and using decentralized low-level controllers to determine with more accuracy and less computational time the optimal configuration of their actuators (i.e. state of the facade to achieve a certain entering solar load or daylight level) (Mork et al., 2020).

In the framework of an international research project, a novel DSF prototype has been developed, with the aim to maximise the capability of modulating the overall heat transfer between the indoor and outdoor environment by means of this technology. The DSF prototype consists of two parallel transparent skins within an aluminium framing system. Both the inner and outer parallel skins, present an equally sized Insulated Glazing Units (IGUs), separated by a narrow (approx. 25 cm thick) air cavity that can be ventilated either naturally or mechanically (with the help of axial fans at the top of the cavity), and containing an operable shading to control solar loads and daylight. In order to control the air path between the indoor and outdoor environment, four ventilation openings are present on the inner (bottom and top) and outer (bottom and top) skins (above and below the IGUs).

In this way different ventilation air paths could be achieved in the DSF cavity bridging between the indoor and outdoor environment (Figure 1): i) thermal buffer (TB) when all the vents are closed; ii) outdoor air curtain (OAC); iii) indoor air curtain (IAC); iv) supply air (SA); v) exhaust air (EA). More specific information related to the DSF prototype are provided in the next sections. This prototype was installed in a South-exposed facade of the TWINS outdoor test cell facility (Fig. 1) of the Politecnico di Torino (Favoino et al., 2016), with the aim to perform a yearly experimental campaign (currently on-going) in order to (i) characterise the performance of the DSF in different configurations (different operable shading devices and different ventilation paths), (ii) to calibrate the building simulation models of the DSF, (iii) to implement real-time rule- and model-based control strategies and demonstrate them in a real-world application.

In fact, compared with a traditional Double Skin Façade, the flexibility of this new concept of Double Skin Façade allows the controller to vary the façade configurations according to the boundary conditions (i.e. weather and indoor conditions) to meet multiple performance requirements. The combination of the different actuators determines more than 18 different DSF configurations (without considering the slat angle nor the different percentage of openings or air speeds). To exploit such high flexibility, adequate DSF control is needed in order to increase energy savings and maintain a certain indoor daylight level. For this sake a single-board controller (based on Raspberry Pi 4) is devised for embedment in the DSF prototype to achieve the following control tasks:

a) Sensing DSF variables and boundary conditions;

b) Simulation and decision making at building component level: different rule- and model-based decision making algorithms could be implemented, whose performance will be tested in the present paper;

c) Actuating the following DSF elements: ventilation openings, fan speed and state of venetian blind (fully raised or fully lowered and slat angle);

d) Communication and interfacing with the building BMS.

The main objectives of this work are (i) to explore the potential and feasibility of RBC and MBC implemented on the embedded single board controller to optimize the DSF operations; (ii) to compare the performance of MBC and RBC with benchmark controls and DSF configurations. For this sake a virtual experiment, replicating the real world implementation of such control architecture was carried out, this is detailed in the next section. In the last section the results are presented, while the potentials and limitations for real-world implementation of the single-board for DSF MBC controls are discussed.
Methodology

A co-simulation framework was adopted to simulate the TWINS test cell with the DSF, which is controlled by means of the single board controller with different strategies. Within this co-simulation framework a “Master” energy model simulates the yearly conditions within the test cell, while the embedded single-board controller is represented by a “Slave” module, performing the tasks a) to c) in the Introduction, which is called at every control time step (hourly), as depicted in Figure 2. The whole co-simulation, as well as all the tasks of the single board controller and the alternative control strategies of the DSF, are programmed in Python. All the simulations are performed on the single board controller itself (Raspberry Pi 4, 4 GB 1.5 GHz quad-core 4 GB RAM), to explore and demonstrate the feasibility of real world implementation. In this section, the description and the setup of the EnergyPlus model are detailed, clarifying modelling assumptions and limitations. The alternative control strategies to control the DSF prototype are then presented, followed by the description of the co-simulation framework implementation and related considerations connected to real world application.

Model set-up, limitations and calibration

EnergyPlus version 9.2 is adopted to perform the energy and daylighting simulations. The building energy model replicates the TWINS test room (3.5 m x 3 m x 1.6 m) located on the rooftop of the university building (building context higher than the test room was modelled as external obstruction).

The thermostat set-point is fixed for heating and cooling (20 °C and 26 °C respectively) during working days from 8:00 to 18:00, and a set-back (12 °C and 40 °C respectively) otherwise. The infiltration is set to a constant value of 1.5 ACH (based on average characteristic values from blower door test measurements). The lighting power density is set to 11.84 W/m² and the artificial lighting system is dimmable to keep the minimum illuminance level (500 lux) at the reference daylighting point (central point of the room, 0.80 m height). The schedule for heating, cooling and lighting systems are defined according to the ASHRAE standard 90.1. A heat pump is used as heating and cooling system, with a COP of 3.5 for winter and Seasonal Energy Efficiency Ratio of 2.5 for summer. The primary energy factor for electricity is set to 2.42.

The Double Skin Façade model represents what has been installed on the test cell, consisting of two parallel IGUs of the same size (1.22 m x 2.00 m) and stratigraphy (6 mm internal and external glass, low emissivity coating on face #3, 16 mm Ar90% gap), integrated in a clear alluminium thermal cut structure. The 25 mm narrow cavity contains a centered aluminium venetian blind with 10 mm slats, and 4 axial fans (nominal flow 220 m³/h each) placed at 2.6 m height, to increase the ventilation flow when required. 4 ventilation openings (1.5 m x 0.3 m) allow different air-path configurations.

The DSF is modelled using the in-built EnergyPlus component “Airflow Control” which allows simulating forced airflow in the gap between adjacent glass layers. The source and destination of the DSF cavity airflow and its flow rate needs to be defined. In total, the “Airflow Control” can run five different air path configurations (all the possible configurations of the developed flexible DSF prototype). Although within this paper only two configurations are modelled to test the performance of the embedded controller: the “Outdoor Air Curtain” (OAC) mode (the source and destination airflow is the outdoor air node); the “Thermal Buffer” (TB), in which the inlet mass flow rate for the OAC mode is set equal to zero. Knowing the inlet flowrate is usually not a trivial task; for this work the inlet flowrate is derived by a multivariable linear correlation based on the climate condition (outdoor temperature, solar radiation and wind speed) based on measured data, resulting in a correlation index of more than 80%. These parameters have been calibrated for the 3 ventilation mode (OAC100F, OAC 50F, OAC0F).

Figure 2 Real system (left), replaced by the Master in the virtual experiment; Co-simulation workflow of RBC (center) and MBC (right): at each control time step (1 h).
Another limitation is due to the maximum number of layers that constitutes the Airflow Window construction (Gelesz et al., 2020). The Venetian blind is modelled as “Between glass blind” that allows the dynamic control of both the blind state (ON-OFF) and the slat angle during the simulation (from 0° to 90° with steps of 15°). Nevertheless, the aim of this work is to demonstrate the feasibility and the performance of the embedded controller, despite the simulation model adopted. In the future different in-built component (i.e. AirFlow Network) could be adopted, which could provide greater accuracy and flexibility (Catto Lucchino et al., 2019).

The SplitFlux Daylighting Method (DOE, 2014) is used to calculate the interior daylighting illuminance at the reference daylighting and then to determine how much the electric lighting system must be dimmed to maintain the target workplane illuminance level (500 lux). It is a simplified method that performs the illuminance calculation for two reference point and applies these values to the required points through weighting factors; Ramos and Ghisi (2010) highlighted a limitation of this method associated with light decay in deep rooms and in general it can be used for approximate calculation of the horizontal illuminance in simple geometry zones. The daylight model has not been calibrated and it is used only to demonstrate the feasibility of the framework.

The model of the test cell, equipped with Double Skin Façade, has been calibrated with measurements carried out for different DSF ventilation configurations (TB, OAC, EA and SA naturally and mechanically ventilated), and with different operations of the shading device (always deployed or not, and deployed at cut-off angles). The measurements lasted at least one week per different configuration. The calibration was mainly focused on the Double Skin Façade model, minimizing the difference between the measured and simulated air temperature of the DSF cavity, the DSF air temperature outlet, the surface temperature of the inner glass of the DSF, the total heat transfer (due to entering solar radiation and to temperature differences across the DSF), and the cavity air velocity. Provided the aim of this work, for the sake of brevity, the calibration procedure and related results are not reported within this paper and will be object of future communications.

**DSF control strategies**

Different control strategies for the hybrid ventilated Double Skin Façade are compared (Case 3 and Case 4 below), together to some benchmarks (Case 1 and Case 2), representing traditional DSF configurations controlled with benchmark controls:

1. **TB DSF:** Thermal Buffer (all closed vents) with 3 different shading state (without blinds, closed blinds, venetian blind controlled with slats always at to the cut-off);
2. **OAC100F DSF:** Outdoor Air Curtain (outer vents fully opened, inner vents closed and fan at maximum speed) with 3 different shading state (without blinds, closed blinds, venetian blind controlled with slats always at to the cut-off);
3. **Rule-Based Control (RBC) TB+OAC DSF:** the decision making is based on if-then rules, based on specific threshold values of boundary conditions (as detailed in Fig. 3).

**Figure 3 RBC flowchart:** a) ventilation configuration and b) blind state

This RBC is divided into two branches as per Figure 3, relating to the shading device (3.b) and the cavity ventilation (3.a). First the solar shading state (i.e. shading availability and slat angle) is defined (Fig. 3.b) based on occupancy, sky cloudiness (amount of horizontal diffused over horizontal global solar radiation), the solar angle, which defines the cut-off angle \( \beta_{cut-off} \) of the blind as follow:

\[
\beta_{cut-off} = \sin^{-1} \left( \frac{d}{w} \cos \gamma \right) - \gamma
\]

where \( d \) is the distance between slats, \( w \) is the slat width and \( \gamma \) is the profile angle of the sun on the window, defined as:

\[
\gamma = \tan^{-1} \left( \frac{\tan \delta}{\cos \Psi} \right)
\]

where \( \delta \) is the solar altitude and \( \Psi \) the surface azimuth. As far as the cavity ventilation is concerned, the airpath mode and air speed are defined based on the indoor-outdoor temperature difference and temperature difference within the height of the DSF cavity. The threshold values to switch from natural to mechanical ventilation (shown in Figure 3), have been optimised to minimise the total heating and cooling primary energy use, by means of a preliminary yearly parametric simulation.

4. **Model-Based Control (MBC) TB+OAC DSF:** the decision making is based on the output of a parametric simulation of the considered Energyplus model for a specific control time step, with the aim to evaluate what is the best DSF configuration (combination of actuators), among the ones which ensure a sufficient work-plane illuminance, that minimise the following cost function:

\[
\min \left\{ EP_{tot}(X) = EP_{heat} + EP_{cool} + EP_{light} \right\}
\]

\( X = (conf, \alpha) \)

No receding horizon is considered, so that the controller only minimises the heating and cooling energy of the current time step. The following hard constraint is applied, based on the autonomous UDI
(Nabil & Mardaljevic, 2006) so to ensure a daylight level which minimises artificial lighting energy use while preventing glare risk (where $\alpha$ is the slat angle):

$$\alpha = \begin{cases} 
\text{if } 300 \text{lux} < R_{\text{lit,hor}}(\alpha) < 3000 \text{ lux} \\
0 \text{ if } R_{\text{lit,hor}}(\alpha) > 3000 \text{ lux} \\
\text{blind up } \text{if } R_{\text{lit,hor}}(\alpha) < 300 \text{ lux} 
\end{cases} \quad (4)$$

In order to feed the decision making mechanisms of the controller with simulation results representative all the feasible sets of facade configurations, at each time step the following steps are performed:

I. Solar shading daylight pre-selection: given that daylight results are not affected by the DSF ventilation mode, initially the parametric simulation is performed only for TB mode, varying the shading configuration (deployment and slat angle). At this step the controller selects only the shading configurations meeting the daylighting constraints in (4);

II. Ventilation mode optimisation: for the selected solar shading options, a parametric simulation is performed by varying the possible ventilation states (TB, OAC mechanical ventilation at 50% or 100% fan speed, or natural ventilation);

III. The decision making algorithm select the configuration minimising the cost function (3). If the same minimum value is found for more than one configuration, the selection among these is based on: (i) the minimisation of the DSF configuration differences compared to the previous timestep (if present among the optimal solutions) to reduce changes in the state of the façade that may cause distraction for users and wear of actuators; (ii) the configuration entailing the maximum horizontal illuminance at the reference point to maximize the contribution of daylighting into the zone.

Co-simulation framework

In order to perform the virtual experiment, so that it could represent a possible real-world implementation, a co-simulation is performed directly on the single board controller, Raspberry-Pi (Figure 2). The whole co-simulation environment relies on the combination of EnergyPlus and Python, using the pyEp python library, allowing to use the EnergyPlus External Interface function within Python. The virtual experiment is realised by two models (Figure 2): a Master model of the building (in this case an office room representing the TWINS test cell with the integrated DSF prototype), which represents the physical reality of an environment operating in real weather conditions with an yearly duration (to simulate this the IWEC standard weather file of Turin is adopted, Torino 160590 IWEC); a Slave model, representing the operations and the decision making of the embedded controller (either for the different RBCs and for the MBC). In particular, for the implementation of the RBC, the Slave model is constituted by the flowchart of Figure 3 (written in Python language) in which the control variables are given in input from the Master model at each control timestep (1 hour). More effort has been given to the implementation of the MBC: in particular, the DSF configuration is varied in the Master model, mimicking DSF real world operations, while the on-line control optimisation is performed for each control time step (1 hour) in the Slave model. Within the single-board controller, the whole co-simulation framework is implemented, so that both the Master and Slave models are co-simulated, differently from what would happen in a real-world implementation in which only the Slave model would be running on the single-board controller. As the Slave model is separated from the Master one, thermal synchronisation of the two models is necessary at each control timestep; so the following measures are taken at specific control timestep: the Slave model is simulated for a pre-conditioning period of one week to reproduce exactly the conditions (zone air temperature, surface temperatures) of that specific control timestep in the Master model (one week pre-conditioning was selected after a preliminary parametric study analyzing the impact of it from 1 day to 1 month pre-conditioning); to do so, within the Slave, all the actuators states implemented in the Master in the preconinding period are considered.

Result and discussion

The Key Performance Indicators used to compare the different control strategies are:

- the total energy consumption (for heating, cooling and lighting), as defined in the MBC cost function;
- the Useful Daylight Illuminance index (UDI) (Nabil & Mardaljevic, 2006), which is the percentage of time during which the illuminance measured in the reference point is within specific thresholds. In particular fours classes are identified, among which UDI$_S$ (supplementary) and UDI$_A$ (autonomous) are the two classes positively contributing to reduce artificial lighting and preventing potential glare risk.

Figure 4 and Table 1 compare the performance of the different DSF configurations and control strategies in terms of annual primary energy (break-up in heating, cooling and lighting, and total). From the 2 air mode benchmark (TB and OAC with the blind slats to the cutoff angle) it is evident that the Thermal Buffer performs better.

Table 1 Annual primary energy demand comparison between RBC, MBC and benchmarks

<table>
<thead>
<tr>
<th>Control type</th>
<th>Primary energy demand [kWh/m$^2$/y]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PE$_{\text{heat}}$</td>
</tr>
<tr>
<td>TB + slat 0°</td>
<td>118.4</td>
</tr>
<tr>
<td>TB + blind-up</td>
<td>113.6</td>
</tr>
<tr>
<td>TB + cut-off</td>
<td>119.2</td>
</tr>
<tr>
<td>OAC + slat 0°</td>
<td>134.8</td>
</tr>
<tr>
<td>OAC + blind-up</td>
<td>123.3</td>
</tr>
<tr>
<td>OAC + cut-off</td>
<td>133.7</td>
</tr>
<tr>
<td>RB + cut-off</td>
<td>119.8</td>
</tr>
<tr>
<td>MB</td>
<td>117.7</td>
</tr>
</tbody>
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better for heating mode, while the Outdoor Air Curtain in fully-mechanical ventilation reducing the cooling energy use, due to the capability of the OAC mode to remove unwanted solar heat from the cavity thought the inlet flowrate.

From Figure 4, it can be deduced that the RBC has an intermediate behaviour between the two benchmarking control: the energy needs for heating is similar to the TB mode and the cooling one is equal to the OAC mode, resulting in a 7% reduction in primary energy compared to the 2 benchmark controls, in particular there is a reduction of 37% in cooling needs compared to the TB + cut-off and a reduction of 10% of heating needs compared to the OAC + cut-off.

The use of MBC instead has led to higher reductions in total energy needs, accounting for 18% compared to the benchmark controls, with a reduction of 53% for lighting energy needs and a maximum reduction of 12% (compared to the OAC + cut-off) for heating and of 28% (compared to the TB + cut-off) for cooling.

Figure 5 compares the UDI levels for the 4 shading control types. Due to its geometry, when the shading device deployed and completely closed illuminance higher than 100 lux are not achievable, while without the solar shading there could be a high risk of glare, presenting 11% of the time with illuminances higher than 3000 lux. By means of adopting a cut-off strategy (as for the RBC and for the TB and AOC benchmarks), a UDI-useful is achieved for 78% of the time. While when the MBC is implemented, this achieves 91% of the occupied time, providing enough natural light to replace the artificial light without causing potential glare discomfort for 84% of occupied hours.

Figure 6 shows the carpet plots the DSF configuration chosen from the two control strategies, in terms of air mode and blind slat angles respectively. During the heating season, both controls tend to choose the Thermal Buffer mode in order to reduce the heat losses through the façade and they favour the OAC mode during the cooling season. Moreover, it is clear that the two control strategies exhibit different behaviour: the RBC ventilation modes change regularly throughout the year, depending on climate boundary conditions, while in the MBC the climate pattern is less evident because the MB decision making is more influenced by the impact that the DSF has on the indoor environment, rather than by the climatic boundary conditions. Comparing the two control strategies, it is detectable that although the MB involves an increase of 13% for cooling needs compared to the RBC, it leads to a higher reduction (-11%) of the total energy needs by reducing especially the lighting energy need (-55%). As far as the blind slat angle is concerned, in the same way, it is possible to notice that the cut-off control angles follow the sun angles, while the MBC leads to an increase on the slat angles or even sometimes withdraw the blind when sufficient illuminance is not present in the space (sky conditions closer to overcast sky, and early morning and late afternoon hours). The MBC shows stagnation in the choice of configurations (both air mode and blinds state), reducing the number of changes during the day. This behaviour is due to the constraints imposed by the decision-making algorithm, which leads to the reduction of the configurations changes. This assumption was imposed for two reasons: first, decreasing the working hours of the actuators engines decreases their wear; in addition, it has been demonstrated that too frequent facade control results in distraction and a drop in concentration by the users (Bakker et al., 2014).

In order to better understand the aggregated results, one representative week for June is shown in Figure 6 in terms of heating and cooling hourly energy use, total energy use (sum of the heating, cooling and lighting), horizontal illuminance at Reference Point, DSF air path and slat angle. As far as the thermal aspects are concerned, during the summer week the MBC reduces the total energy use compared to the RBC one, although it involves a higher energy demand for cooling. This is caused by the daylighting constrain which forces the control to maximize the amount of natural light entering the zone, leading to increase horizontal illuminance (also shown in Figure 5) but also increased solar gains. However, the MBC cost function leads to minimize the primary energy demand for heating, cooling and lighting, meeting the energy saving with the visual comfort requirements. When it comes to the façade configuration, both controls aaaaad tend to choose the Outdoor Air Curtain naturally ventilated, with marginal differences during the week. The MBC has obtained a greater energy saving and excellent results for the visual comfort requirements. The bottleneck of such control is however the computational
time: at the design stage, the computational time must not be excessively high to allow the design and the cross-comparison of different controls with an adequate computational cost, while for real-time control the computational time must be less than the control timestep to control the façade actuators. The co-simulative framework implemented on Raspberry Pi takes more than 2 days for the annual simulation of the MB control; nevertheless, it is important to highlight that only 25 seconds are needed to perform an hourly time step (including all the parametric simulations for the MBC), which is suitable for on-line implementation compared to potential DSF control timestep (10-15 mins).

To improve the performance of the MBC control different solutions can be implemented. As mentioned above, the in-built component “Airflow Window” allows only a certain ventilation configuration to be modelled, with the ventilation flow rate as an input. It is only possible to alternate one ventilation mode with the TB mode (closing the cavity) but this does not lead to very significant results especially to reduce the heating energy demand. It is therefore necessary to implement more flexible models, able to simulate the flexible behaviour of the DSF, as for example adopting:
- in-built EnergyPlus component “Airflow Network”;
- other Building Energy Simulation softwares (TRNSYS and IDA-ICE), which could have greater capabilities to comprehensively simulate such a flexible DSF concept (Catto Luchino, 2019);
- simplified R-C and reduced order models, such as the one of the ISO 15099 (EN ISO 15099:2003), which is currently being implemented and validated by the Authors using experimental data. This could greatly reduce the computational time (thus compatible with the optimization time required in receding horizon or Model Predictive Control);

Figure 6. Air mode carpet plot (left) comparing RBC (top) and MBC (bottom); Slat angle carpet plot (right) comparing RBC (top) and MBC (bottom), in grey blind-up.

Figure 7 RBC and MBC comparison in terms of heating and cooling rate (first), total energy rate needs (second), illuminance amount at RP (third), DSF ventilation configuration (fourth) and venetian blind state (fifth)
Greater effort will also be given to the daylighting simulation through the use of more advanced method such as the Multi-Phase Method (Saxena et al., 2010).

Conclusions
This paper presents a framework for real-time control of a Double Skin Façade prototype by means of an embedded single-board controller. The main objective was to demonstrate the flexibility and the performance of such a controller by means of co-simulation framework, prior to real world application. Two different control strategies are devised and implemented (a rule- and a model-based one) and their performance is compared by means of key performance indicators at building level (total primary energy use and daylight comfort). The two control strategies have different computational cost (both in the implementation of the decision making and modelling, and in terms of computational effort), although they require the same level of hardware (controller, sensors and actuators). The model-based control obtained a greater energy saving (18% compared to the two benchmark controls, and 11% compared to optimized rule based control) and excellent results for the visual comfort requirements (UDI-u equal to 91 % of the time compared to the 78% for cut-off strategy). The presented single-board controller implementation requires few adaptations to achieve real world application as embedded controller of the prototype DSF, and the present work has shown the possibility and the potential to adopt the Raspberry Pi sigle board to for model based decentralized control of DSFs , and more in general for dynamic envelope systems.

Reference