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Multi-domain model-based control of an adaptive façade based on a flexible double skin system

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ABSTRACT

Adaptive envelopes have the potential to significantly reduce energy use in buildings while ensuring high performance. These envelopes interact with multiple interconnected domains, such as daylight, indoor air quality, thermal comfort, and energy use, which can often conflict with one another. Identifying and developing suitable control strategies that can optimally manage the envelope's impact on many domains and avoid sub-optimal operations is an open challenge. Conventional approaches commonly adopted in buildings and building envelope control based on schedules or relatively simple decision trees may be unable to tackle the dynamic behaviour of adaptive envelopes. Due to their complexity, more advanced control approaches based on simulation-informed decision-making are scarce in both research and practice. In this work, we propose a multi-domain model-based control (MBC) algorithm for an adaptive façade concept based on a flexible Double Skin Façade (DSF). The proposed method, which aims for a balanced performance over different comfort domains and energy use, employs a co-simulation approach where the DSF is modelled in a Building Energy Simulation (BES) tool and the control algorithm to manage the simulation and optimize the control of the façade is developed in a generic programming language. To the best of our knowledge, this is one of the first attempts to design and demonstrate the effectiveness of a simulation-informed control strategy that can handle and optimise the behaviour of a complex façade by considering multiple performance objectives. The innovation of this approach lies in the MBC algorithm that selects the optimal façade state among over seventy possible states at each timestep, the practical demonstration of the feasibility in a BES tool, and the complexity of the controlled façade system. To verify the effectiveness of the proposed control approach, we compared the innovative MBC to more traditional control strategies, such as schedule and rule-based controls, revealing how it enabled the façade to achieve a better performance in all the analysed domains. By applying the MBC to three different year periods, we showed that the energy and environmental performance was within the selected comfort criteria for all the domains for>80% of the occupied hours, and an energy reduction of up to 70% was simultaneously obtained if compared to more traditional approaches. The control approach presented in this study and the simulation method employed can be used not only to improve the performance of advanced adaptive façades by providing an effective solution to the challenge of balancing multiple conflicting performance domains but also for more conventional building envelope systems that exhibit a certain degree of dynamic behaviour.

1. Introduction

1.1. Background

Adaptive façades are envelope systems that dynamically adjust their physical properties in response to transient boundary conditions [1]. Adaptive facades can exploit a large range of possibilities enabled by different technologies; among them, double skin façades (DSFs) are highly transparent façades that can exhibit adaptive capabilities thanks to the cavity ventilation flow [2] and shading systems in the cavity. These adaptive properties may be

Abbreviations: ***API***, Application Programming Interface; ***BES***, Building Energy Simulation; ***DSF***, Double Skin Facade; ***EA***, Exhaust Air; ***IAC***, Indoor Air Curtain; ***MBC***, Model-Based Control; ***MPC***, Model-Predictive Control; ***OAC***, Outdoor Air Curtain; ***RBC***, Rule-based control; ***SA***, Supply Air; ***SBC***, Schedule-Based Control; ***SK***, Single Skin facade; ***TB***, Thermal Buffer; ***TB_v***, Ventilated Thermal Buffer.

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Nomenclature

AFP	Airflow paths
$\Delta CO2$	difference between the outdoor and room CO2 concentration level [ppm]
$\bar{E}_{plane}$	illuminance on the working plane [lux]
φ	angle of the slats [°]
F	Fan settings
Q_{heat}	Heating deand [W]
Q_{cool}	Cooling demand [W]
Q_{SOL}	Solar radiation on the façade [W/m^2]
SH	shading position
T_{op}	operative temperature in the room [°C]
Tmr	Running medium temperature [°C]
T_{GAP}	Airgap temperature [°C]
V_{min}	Minimum airflow [l/s]
V_{mid}	Medium airflow [l/s]
V_{max}	Maximum airflow [l/s]

benifitial for reducing energy use for building climatisation [3] and improving thermal and visual comfort conditions compared to a traditional single-skin façade [4].

The mere presence of adaptive capabilities in a building envelope does not directly guarantee its successful operation. The adaptive behaviour has to simultaneously satisfy multiple interdependent performance requirements, which often conflict with one another. Therefore, the correct operation of an adaptive façade is as crucial as the chosen materials and technologies that enable a dynamic behaviour, but this aspect is quite often neglected. For example, in most cases, DSFs are run using simple, rule-based controls (e.g. "*if this, do that*" under certain circumstances) focusing on a single criterion. This control structure intrinsically limits the optimal performance of a DSF since it is pre-set (hence cannot fully adapt to what really happens) and is by necessity linked to a limited number of output states. As a result, it is not unusual that the potential performance of DSFs is not met [5].

More advanced forms of control for adaptive envelopes that can foster a better and more balanced performance across different domains can be based on the exploitation of (real-time) simulation to identify the most effective state for the façade at each timestep. An example of such an approach for a DSF is present in Park et al.'s work, where the optimal control is the solution of a cost function that optimises energy use [6,7]. However, the development and application of advanced control strategies is relatively little explored in research and practice, where RBC are still largely employed.

1.2. Research aims and questions

In the research activity presented in this paper, we aimed to develop a model-based control method able to fully exploit an adaptive facade's abilities across several different performance domains–indoor lighting, air quality, thermal comfort, and energy consumption (not just minimising the energy consumption). The dynamic facade concept linked to the control approach in this study is a flexible DSF module capable of switching between different cavity ventilation flow paths, driving force and interplaying with the HVAC plant of the building. However, the control approach developed in this research is generally valid for any adaptive façade tackling a balanced behaviour across different domains and can be scaled and expanded further to meet performances that were not selected in this specific case.

We developed this innovative control approach, which goes beyond the current practice in control of building envelope systems, using a building energy simulation (BES) tool, as we believe that this class of tools best ensures an integrated simulation between the envelope system and the building energy and environmental systems. By doing this, we also demonstrated how recent developments in building performance simulations (e.g. the increasing availability of APIs or software interfaces for external control of BES tools) greatly enhance the possibility of developing more advanced control architectures.

In a nutshell, the research presented in this paper addresses a gap in the current knowledge and practice for control of (advanced) building envelopes, and tackles the the research question of *how adaptive envelopes can be controlled effectively by exploiting the flexibility that these building enclosure systems have.* The element of novelty in this research covers both *i) a new approach to multi-domain optimal control* of adaptive facades by exploiting a model-based control and *ii) a demonstration of the feasibility of such an approach by leveraging the latest developments in co-simulation schemes for BES*. At the best of our knowledge, this study is the first of its kind demonstrating the use of model-based control for an adaptive façade system characterised by a very large range of possible states, which is a system that clearly cannot be efficiently controlled using common control strategies conventionally adopted for building envelopes.

1.3. Article structure and readership

The article is structured as follows: in *Section 2–Control structures and control simulation for adaptive building envelopes,* we provide the reader with an overview of the current control possibilities for adaptive facades, highlighting the challenges and limitations and building the case for a more sophisticated approach in the case of a façade system with many degrees of freedom; in *Section 3–Adaptive façade concept and its numerical model in a BES tool,* the concept of flexible DSF is explained in detail, together with the simple case-study building used in this study; *Section 4–Control strategy definition* presents the multi-domain model-based control strategy developed for this work and the more conventional control approaches used as a baseline. Section 5–*Implementation of MBC in a BES tool via co-simulation* presents the workflow for implementing the model-based control in co-simulation with IDA ICE. The interaction between IDA ICE and the optimal control algorithm in Python is described together with the process automation. In *Section 6–Results,* the results for all the control strategies used in three different analysed periods are presented and compared. This is followed by *Section 7–Discussion,* where we reflected on the results and expanded the assessment of the outcomes of the work. Finally, the conclusive summary of the article is presented in *Section 8–Conclusion*.

2. Control structures and control simulation for adaptive building envelopes

2.1. Current possibilities for control structures for building envelope systems

The automation of actively controllable dynamic envelope systems is, in principle, based on two alternative approaches [10]: rule-based control (RBC) and model-based control (MBC). RBCs represent the majority of control decision-making currently adopted in building automation [11]. A set of pre-determined rules with time schedule could also be considered a very simple form of RBC. MBC is a relatively novel way emerging in building control, especially for the control of envelope systems. Nevertheless, it still requires a lot of development before reaching a mature state and achieving widespread implementation. Henceforth in this workwe refer to schedule RBC as Schedule Based Control (SBC), while we use the term RBC to refer to threshold-base control.

Defining time schedules to control active elements of a façade is straightforward and easy to implement, but they may not be as flexible or responsive to changes in the system as more advanced control methods. This type of control is often used in systems where the desired outcome is known, and the timing of the various elements is critical to achieving that outcome. Schedule-based control is based on the assumed performance of a system given "average" or "common" conditions. While this approach can be suitable for systems with binary values (e.g. deployed/not deployed, open/-closed) in domains with high predictability, it cannot truly exploit the potential of an adaptable system. Simple control strategies for shading devices, deployed or tuned following the progression of time during the day, are a good example of this type of control.

Taking the complexity to a slightly higher level, embedded or building-level sensors can be used to include environmental parameters in the decision process. RBC consists of a set of *if-then* rules where input data derived from sensors are compared against specific threshold values to determine the state of one or more actuators. Controlling the position of solar devices based on the amount of solar irradiance on the façade is a common application of this approach. If the reading from the irradiance sensor is combined with other input data, such as outdoor temperature, occupancy sensor, or a schedule, more complex decision trees can be created [12].

RBCs can use signals from environmental monitoring in combination with a more or less complex decision tree to realise the so-called *open-loop* or *closed-loop* controls. In open-loop RBCs, the control action does not affect the control input signal. For example, when using an outdoor irradiance sensor to control the state of a shading device, the controller has no information on the effect of shading on the indoor environment [13]. Conversely, in a closed loop the input sensor signal depends on the control action. For example, when a shading system is deployed due to the indoor illuminance exceeding a certain threshold value, the closed-loop control is based on the effect of the control action [14]. Open-loops are usually simpler to realise and are hence widely adopted in controlling adaptive facades [15], but closed-loops could provide more effective management as the control is done on the final effect of the system [16–18].

Even if rule-based control can easily be made more complex, for example, by combining sensor-based input with schedule-based rules or using variable threshold values depending on the season or the room occupancy level [19], they still suffer from several limitations. Any rule-based control (scheduled, open- and closed-loop) only allows a limited number of alternative states, as making a decision tree with many output states is neither trivial nor too functional. Particularly for those control strategies that tackle multiple domains (e.g. thermal environment and light environment) and have contrasting objectives, a rigid structure makes it challenging to provide the right answer for any combination of conditions and objectives. Moreover, understanding meaningful threshold values might be challenging [20], especially in open-loop algorithms.

MBC strategies generally employ a linear and differentiable system model to describe the behaviour of the system and choose the best strategy to reach predefined goals. This provides higher flexibility than RBC as an indirect logic approach is employed [21]. They exploit the prediction (through simulation) of the impact of the control action on the indoor environment to perform decision-making, aiming to maximise one or more building-level performances [22], thereby improving upon the performance of closed-loop controls. This usually requires a high-level optimal objective definition (e.g. minimisation or maximisation of a particular performance) combined with suitable optimal search algorithms to ensure that the computational load remains within a suitable range [20]. In the case of a limited number of states, a full-factorial search might still be an option. In contrast, if the number of states is high and/or a prediction functionality is included in this control strategy (with a certain future prediction horizon, as for model predictive control), the need for a more intelligent search of the desired performance in a given solution space is a must [23].

Implementing MBCs to improve the operational performance of a building by integrating adaptive building envelopes is complex (and expensive), not only in real-life but even in the context of a simulation study. Different examples of implementations of MBCs (and model predictive control, MPC) to control adaptive building envelope systems are available in literature. Nevertheless, these are limited to research applications [24] and, most of the time, only to simulation studies [25–28]. This is mainly due to the high cost and effort in designing and implementing MBC strategies linked to the modelling and automation requirements [10]. Models (of the façade element, of the building in which it is integrated to evaluate its impact, and for forecasting the system disturbances, i.e. weather and occupancy) are required to be accurate and fast at the same time (enabling the possibility to perform extensive exploration in a time compatible with the control action). Only very few studies have analysed the influence of control on multi-comfort domains [29,30]; most works focus on daylight and visual comfort performance and energy minimisation by controlling the position of blind slats [31–33] or the properties of electrochromic glazing [21,34,35]. Only a few studies have applied MBC on DSFs [8,36], where the interaction of multiple domains plays a key role.

2.2. Current state and limitations of advanced control of adaptive facades in BES tools

Simple control approaches and routines are commonly implemented in BES tools. For example, schedule controls or controllers based on threshold values for shadings systems are available in the most commonly adopted tools (EnergyPlus [37], Trnsys [38], IES VE [39], IDA ICE [40], etc.). The implementation of open-loop controls over a certain element is often restricted to a particular domain without taking into consideration the effect that it could have on other domains (e.g. the threshold for controlling the shading device is often set in terms of radiation hitting the facade and not linked to the thermal domain). EnergyPlus allows users to control shading, openings, HVAC and other active systems via the implementation of diverse pre-set controls, with the option of accounting for more than one variable (commonly the presence of occupants, incident solar radiation and temperature of the room). IES VE provides basic controls for most of the building components (like time schedule or threshold values to apply basic open-loop algorithms), and some more developed controllers for the HVAC system. Trnsys has quite an extensive control library that allows implementing complex open and closed-loop controls without having to recur to co-simulation. Similarly, IDA ICE offers highly customizable control strategies when using the "Advance level", providing diverse elements (NMF library) to create advanced strategies and allowing access to most of the models' inputs and outputs [41]. These features are indispensable when more advanced control routines are required. However, when there are many levels for the states of the actuators/functions, the number of possible permutations can quickly reach hundreds. Even without considering how suitable this control strategy is, implementing very complicated decision trees in BES tools is challenging. Tools like IDA ICE or Trnsys are more suitable for this use as they provide greater flexibility in creating complex control structures without the need to use advanced functions, such as the Energy Management System (EMS) module in EnergyPlus.

Moreover, given the current level of development of BES tools, no simulation environment allows straightforward implementation of model-based control routines [42,43]. To have a simulation that includes MBC, it is necessary to have a model that represents the physical system and a control-oriented model that is used to take decisions on the best operations of the system. While the former model can be easily made in a BES tool, control-oriented models often take the form of a reduced-order model [44], and the control performance is determined using a forecasting horizon [6,45,46]. Calibrated reduced-order models are commonly used to achieve a good balance between speed and accuracy. Implementing a MBC algorithm with BES tools thus requires two simulations to proceed in parallel and exchange information within the simulation runtime (co-simulation). The primary simulation replicates the system's performance given the selected operational mode and computes the evolution of the energy and mass balances in the building. A secondary simulation explores at each time step the ranges of performance that can be achieved in a particular time-window, given a set of boundary conditions, and the past states (this is usually relevant only for some domains, i.e. thermal and mass balance, while it might be neglected for others that are not affected by the previous history). Co-simulating the two models relies on the possibilities of a specific BES tool to be integrated into a co-simulation framework either directly or using middleware software. While co-simulation for BES has been in the field for a while, co-simulation targeting control for building envelope systems is relatively new.

Co-simulation infrastructures can be realised between a BES tool and other external scripts in different ways that depend on the individual features of the simulation environment. In Energy Plus, for example, this can be achieved with a high-level control method, the Energy Management System (EMS). Using the EMS, it is possible to access a wide variety of "sensor" data and use this data to direct various types of control actions with co-simulation [47]. Moreover, using the software *EnergyPlusToFMU* it is possible to perform co-simulation with all tools that support an FMI (Functional Mock-Interface), e.g. Modelica [48]. Similarly, Trnsys allows co-simulation control using a dedicated FMI via Python [49,50] or other programming languages. Similar integrated access to the software APIs is provided by IES VE, where an in-built Python interface allows the extraction of the simulation data and access to some of the variables of the model [51]. Finally, IDA ICE also allows interaction over socket communication, providing a library with API functions accessible with general-purpose programming languages, e.g. Python, Matlab, Excel, C++, Java or similar [52]. A commonly adopted environment for co-simulations is the BCTVB Toolbox, where BES tools like Energy Plus or Trnsys can be coupled with MATLAB/Simulink control sequences [53].

This study tackles the challenge of setting up a multi-domain control for an adaptive façade concept characterised by a large variety of possible states. The investigated façade concept can modify its performance by changing the state of three actuators, each of which can assume multiple states. In a reduced version of the façade concept, this equals 69 possible different states to be explored when the best control sequence needs to be found.

Examining different options for controlling such a system revealed that advanced control strategies such as model-based control architecture are needed to fully utilize the potential of flexible façade concepts, as opposed to traditional RBC structures, which can currently be directly implemented in BES [54,55].

Therefore, in the following sections, we will demonstrate the coupling between the adaptive façade model and a multi-domain optimisation control algorithm thanks to the co-simulation features accessible in a BES tool. A suitable simulation workflow was developed for this purpose in IDA ICE to enable the MBC of the adaptive façade concept, leveraging the possibilities to automate the workflow process, the start/stop of simulation runs and co-simulation functionality. Moreover, more traditional rule-based controls described in the previous sections (schedule-based and open-loop control) are also applied to the same model for a more comprehensive comparison.

3. Adaptive façade concept and its numerical model in a BES tool

3.1. Adaptive façade concept

The adaptive façade concept exploited in this research has been presented in detail in a previous study [9], which focused on the challenge of building a suitable physical–mathematical representation of the façade concept and its validation using comparison with experimental data. It is a façade based on the architecture of a double-skin façade, with different cavity ventilation paths achievable thanks to a dedicated inlet and outlet section. The cavity can have an airflow driven by mechanical devices (fans) and naturally-induced phenomena (natural ventilation). The façade concept also allows one to close the cavity fully and either decouple the indoor from the outdoor in terms of mass exchange or bypass the ventilated cavity and allow air exchange between indoor and outdoor through openings at the bottom and the top of the façade element. The facade manages the direct solar and luminous gains through an integrated shading system in coordination with the building energy management system.

In the framework of such an integrated façade concept that needs to interact dynamically with the building services, the coupled simulation of the whole building and the specific building components is an essential prerequisite to correctly assessing the overall energy and comfort performance and replicate the complex interaction between airflow in the façade, the HVAC system, and the building energy management system.

The physical–mathematical representation of the façade concept was developed using the BES tool IDA ICE, employing the in-built model '*Double Glass Façade*', which was modified to switch between all the air path configurations. This in-built module, described more in detail in [9], is already integrated into the thermal and airflow network of the BES tool and allows the combined simulation between the façade component and the indoor space (and the HVAC). The existing model was further developed to model all the natural and mechanical airflow paths and to control the facade within the same simulation.

The presented model (Fig. 1) allows the modeller to change the configuration of the façade by controlling the actuators of each opening and fan and integrate this control with the building HVAC system. Each controlled element receives different input from the controller: a) the openings' actuators allow the setting of the opening percentage (from 0–closed to 1–fully open); b) the fans' actuators receive two inputs: a *centralMode* control that sets the fan ON or OFF and a flow *control* that controls the amount of mechanical flow (max*(centralMode*(m_max*control + m_min*(1-control)), c_low*m_min)*) with c_low detailing the behaviour of the fan as crack when it is off; c) the shading device' actuator receives two input: a 1/0 control that sets the shading ON/OFF and an *ANGLE* input that sets the position of the slats in case a blind is used.

As explained in more detail in the next section, the model of the adaptive façade was combined with three different types of control

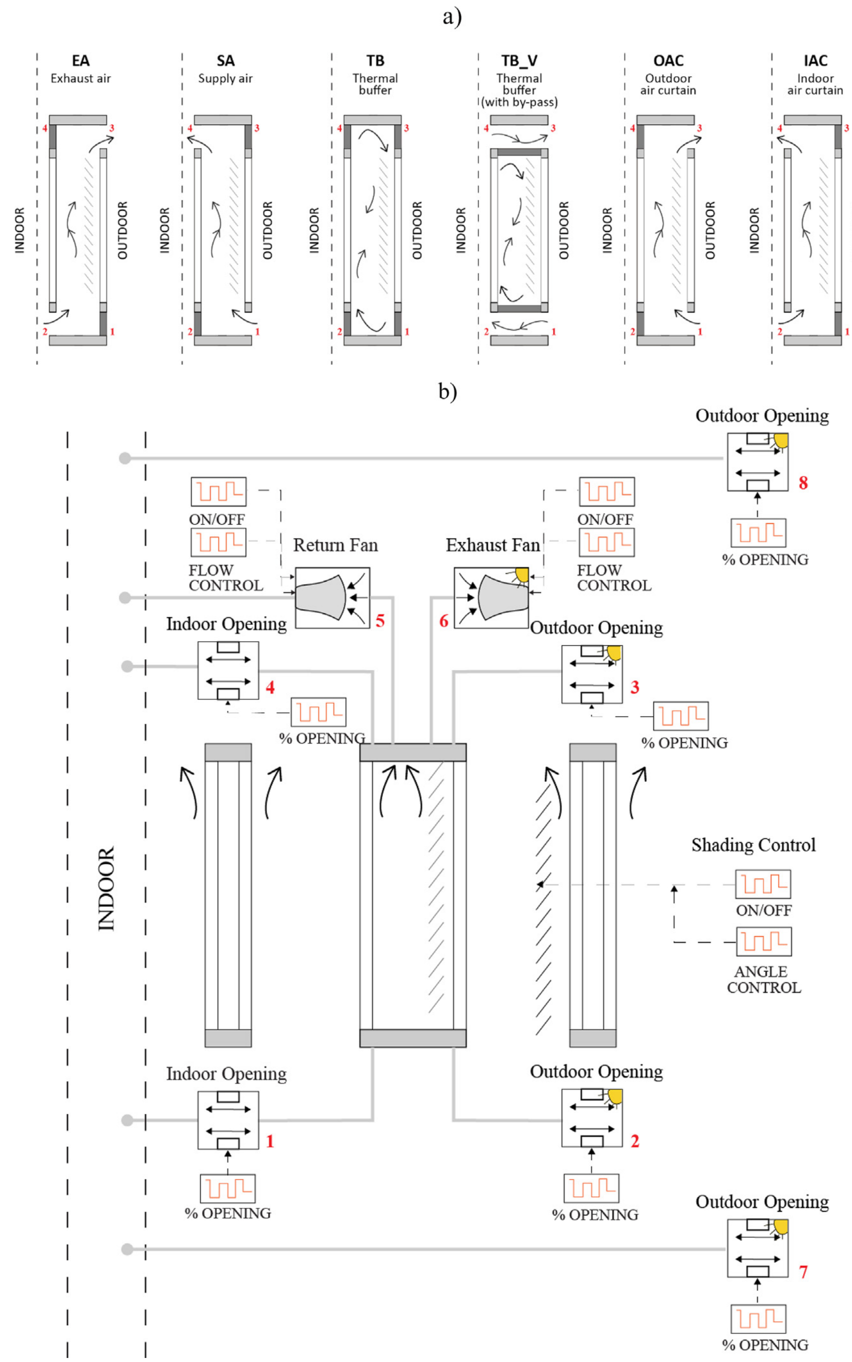

Fig. 1. A) Ventilation strategies implementable in a fully flexible DSF module; b) Schematic view of the fully flexible DSF model implemented in IDA ICE [9].

architectures: i) a MBC, ii) a RBC, iii) a SBC. While the first approach represents the key theoretical contribution of this research, the other two approaches were chosen to perform as a reference baseline to compare the functioning (and potential advantage) of the more advanced control approach to managing the façade.

In order to apply the MBC, a specific routine involving running a script from an external programming language tool was necessary, and the procedure is described in detail in Section 5. When using the last two types of controls (scheduled and RBC control), the control happened within the BES tool. While applying schedules to each actuator is straightforward, the definition of the rules to control each element was possible by employing a component in IDA ICE called '*Macro*'. In this area of the simulation environment, the modeller can use predefined controls or create new ones. By using different logical operators, it was possible to define the control logic that established a connection between the boundary conditions (indoor, cavity, outdoor, solar radiation, CO2, etc.) and the configuration to choose from.

3.2. Case study definition

We tested and demonstrated the working of the advanced control approach developed in this study by using a case study building equipped with the adaptive façade concept and alternative control routines. The simple building used in this research was adapted from the BESTEST Building–Base Case 600 [56]. The base building is a single-story 48 m^2, low-mass building with a rectangular prism geometry and two south-facing windows of 12 m^2. The opaque walls, floor and roof were set to reach a U of 0.28 W/m^2K– corresponding to the required U-value for the German building reference building [57] -. The two regular windows of the BESTEST were modelled using the adaptive façade model developed in the previous study [9], where the transparent part was made of two low-e double glazing units (one on each of the two skins of the double façade structure), leading to an overall window system with the reference building values (U = 1.4 W/m^2K, g = 0.48, τ = 0.72). The geometry was kept as in the Base Case 600 (2 m wide and 3 m high), and the frame ratio was set to 10 %. The ventilated gap of the adaptive façade concept based on a flexible DSF architecture was set to 25 cm, and a venetian blind in the ventilated gap was added. The size of the openings was set to 5 % of the total glazed area, one at the bottom and one at the top of each ventilated window. The extraction fans connected to the ventilated cavity were set to have the same flow, which is calculated according to the conditions of class II as described in Table B.8 of EN 16798–1 [58] for occupied hours and set to the minimum value of 0.15 l/s m^2 when the room is empty [58]. When using MBC, the fans were allowed to also work with a higher setting, which was circa twice the airflow for the occupied hours.

The building was located in Frankfurt, and the weather file used was the default one for the location. The reason for this location was to select a climate characterised by both cooling and heating load in order to test the performance of the control over a large range of boundary conditions and not only for one or the other case (heating or cooling). The heating and cooling system was modelled as an ideal heater and cooler of 10 kW, with an ON/OFF thermostat control that would control the temperature according to the heating or cooling season as described in Table B.5 of EN 16798-1 [58] for naturally ventilated buildings (Table 1).

The occupancy was set ON during working days with schedules 8-18. The calculation for the occupancy was carried out according to the CEN/TR 16798–2 [59] for a landscape office. The artificial lighting was set to 12 W/m^2 [60] and set ON during the occupied hours only if the outdoor conditions allowed maximum illuminance values lower than 300 lx on the plane. The equipment loads were set to 300 W and set to 100 % during occupied hours and 25 % during unoccupied ones.

4. Control strategy definition

In this section, the multi-domain trade-off algorithm that is at the core of the model-based control (MBC) is presented (Section 4.1). The objectives and procedures of this innovative approach are explained, while its implementation in IDA ICE is described in the following chapter, Section 5. Adopting a MBC requires the modeller to control the tool from an external script via its API.

In the rest of the chapter, the other two control strategies applied are presented: first, the RBC–Section 4.2 - defined to adopt a set of rules that accounted for the outdoor conditions and the cavity temperature only, as would be recorded by an onboard control; and last the SBC–Section 4.3 - defined to reflect the common usage of DSF. Applying these two approaches requires the development of more or less complicated construction to be compatible with the BES tool, but no co-simulation is needed.

Table 1
A) indoor temperatures range as a function of the running mean temperature [58]; b) Internal Loads; c) Airflows values for fans (for each window) calculated according to the conditions of Class II [58].

a)		
	T_{mr}	Indoor Temperature
Heating Season	<10 °C	20–24 °C
Cooling Season	>15 °C	23–26 °C
Mid - Season	10° C < Tmr < 15 °C	20–26 °C
b)		
	Loads	Schedule
Occupants	3 persons	Weekdays 8–18
Lighting	48 W	Weekdays 8–18–if $E_{plane\_achievable}$ < 300
Equipment	300 W	Weekdays 8–18 *100 %* - Rest of the time *25 %*
c)		
	Vunoccupied	*Voccupied*
Mechanical Airflow	3.6 l/s	27.3 l/s

4.1. Multi-domain model-based control–multi-objective trade-off algorithm

The principle behind control-based modelling is that the behaviour of a controlled element is stirred by the prediction, through a model, of the desired performance. Ideally, the strength of this type of control is that after evaluating all possible performances over a certain time range as a result of the degree of freedom of the system, the chosen configuration is the one that fulfils a specific range of requirements, and/or optimises an objective function. The control applied in the MBC proposed in this work covers four different domains. For this reason, an overarching control tree was developed to set priorities among the different domains as we preferred not to formulate the optimisation problem as a single objective by weighting the different domains. Because of considerations about how the adaptive façade works and its possible interaction with the surroundings, the following priorities were developed: indoor lighting, indoor air quality, thermal comfort, and minimum energy consumption (see Fig. 2).

The first step in the MBC is to run parametric simulations over the entire domain of possibilities for the given timestep and to calculate the selected KPIs: i) illuminance on the working plane - $\bar{E}_{plane}$; ii) CO2 concentration in the room - $\Delta CO2$; iii) operative temperature in the room - T_{op}; and iv) the heating and cooling demand - ($|Q_{heat}| + |Q_{cool}|$). The presence of occupants in the room affected which domains were further analysed utilizing the control tree. In the case of an occupied room, the first domain that filtered the results was the *'natural light domain';* all the configurations that fulfilled the minimum requirements set for the values on the illuminance plane were used to check the following domain requirements '*air quality domain*'. In case none of the simulated cases gave results within the criteria, the filter was disregarded and all the configurations were used for the next step. This happens because there is no minimisation (maximation function) in any of the filtering domains (except for the last one) to avoid the risk of selecting a solution at the beginning that only satisfies (or partially satisfies) the requirements of one domain. After the '*air quality domain*', the '*thermal domain*' filtered the results; here, the operative temperature in the room was checked with the tolerance levels. Finally, the configurations that respected all these domains were filtered by the last condition:´"*minimum energy consumption*". This last condition imposed a minimisation function to end up with a unique set of configurations to apply to the analysed timestep. Once the optimal multi-domain solution was found for the specific timestep, the values were stored to build the history of the simulation period; this process was followed to find the optimal configuration for each time step (1 h) of the analysed period.

The described algorithm can be applied to any controlled element (a window, HVAC system, heating and cooling device, etc.). For the presented case, a flexible DSF coupled with the HVAC system, a wide range of parameters for the control was available. The proposed adaptive façade can work by adopting six different ventilation strategies (Fig. 1a), and four (EA, IAC, OAC, SA) can work either mechanically or naturally. The openings of the operable win-

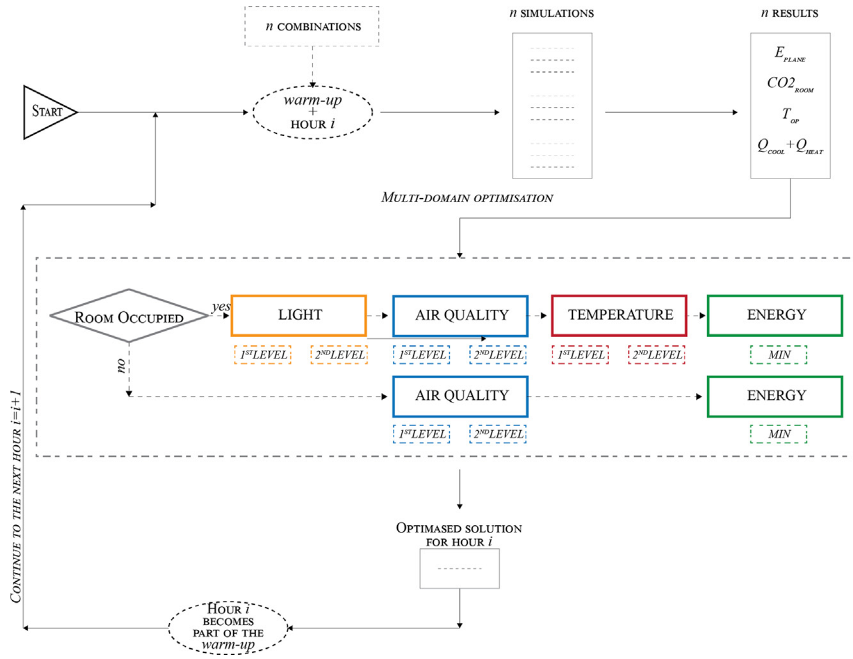

Fig. 2. MBC scheme: the simulated cases are filtered by the multi-domain trade-off algorithm to obtain the optimised solution for the i[th] timestep.

dow were controlled to three different positions: 0 % - CLOSED, 50 % OPEN, and 100 % OPEN. This *'opening'* input was used to control the flow path by closing the openings not used in that specific flow path and adjusting the degree of openness. The fan received two inputs: i) ON–if the façade was run mechanically, or OFF–naturally ventilated. ii) if the fan was ON, the flow was set as: V*min, Vmid* or *Vmax. Vmin* corresponded to the minimum airflow necessary to ventilate the room if not occupied, as described in Table 1-c, while *Vmid* to the value during occupation; *Vmax* was set to 2* *Vmid* + V*min.* Finally, the shading device was controlled with an ON/OFF control and by choosing 3 different angle positions: 0° - *cut*-off – 90° angle. The cut-off angle is calculated from eq. 10 and 11 of [61] taken from the work of [62].

The control optimisation problem can be formulated as the combination of Eqs. (1) and (2):

$$\min\left(|Q_{heat}|+|Q_{cool}|\right)[Occ, AFP, OP, F, SH, \varphi] \tag{1}$$

With $|Q_{heat}|+|Q_{cool}|$ - the sum of heating and cooling demand; Occ–the presence of the occupants; AFP–the possible airflow paths; OP–openings position; F–fan settings (operation and flow); SH–shading position; φ–angle of the slats.

Moreover, the KPIs were subject to the following constraints:

$$\begin{cases} \bar{E}_{plane} > 1^{st}LEVEL_{limit} else \bar{E}_{plane} > 2^{nd}LEVEL_{limit}; \\ \Delta CO2 < 1^{st}LEVEL_{limit} else \Delta CO2 > 2^{nd}LEVEL_{limit}; \\ 1^{st}LEVEL_{low-limit} < T_{op} < 1^{st}LEVEL_{high-limit} \\ else \\ 2^{nd}LEVEL_{low-limit} < T_{op} < 2^{nd}LEVEL_{high-limit}; \end{cases} \tag{2}$$

Being $\bar{E}_{plane}$–illuminance on the working plane [lux]; $\Delta CO2$–difference between the outdoor and room CO2 concentration level [ppm]; T_{op}–operative temperature in the room [°C]. The threshold values for the 1st and 2nd LEVEL are presented in Table 3.

This set of parameters led to 69 different combinations that had to be simulated for each time step (1 h). To reduce the computational effort required by this control approach, a reduced number of cases was simulated for the nighttime. In particular, the position of the shading was kept ON and fixed at 90° when there was no radiation hitting the façade or if there was not enough natural light to guarantee 300 lx (indoor lights were ON). Moreover, when the room was empty (but with solar radiation hitting the facade), the shading position could vary between OFF and ON and fixed at 90° (Table 2).

Once all the simulations were run, their results were filtered according to the hierarchy shown in Fig. 2 and Eq. (2). The multi-domain filters were applied with two fulfilment levels: for the indoor lighting, the thresholds were set according to the ISO 8995 [63] for office space; for the indoor air quality and thermal comfort, the thresholds were set according to the EN 16798-1 [58]; finally, the energy consumption for cooling and heating was minimised.

4.2. Rule-based control

The definition of the rules for the RBC strategy is based on a previous work [64], where a similar concept of façade was controlled to reduce the room's heating and cooling gains. This work further detailed the strategy to include the air quality domain in the algorithm. Figs. 3 and 4 show which thresholds and conditions choose the state of the façade. The proposed algorithm in Fig. 3 is a closed-loop algorithm that has two independent variables (the TMR–mean running temperature - and the Q_SOL–the solar radiation hitting the vertical south facade) and two dependent variables (T_GAP–the airgap temperature of the DSF–and the CO2 in the room). The algorithm shown in Fig. 4 is an open-loop control based only on the external radiation on the façade (Q_Sol). For each time step of the simulation, the independent variables are checked and fed into the algorithms, while, in order to reduce the instability of the control, the dependent variables have a time delay element that takes the average value over the previous hour. The two algorithms are executed independently. The algorithm that controls the shading device's solar absorption affects the temperature of the cavity (T_GAP), which is one of the control variables used by the algorithm that controls the openings. However, this latter algorithm does not influence the decision-making process to deploy and tilt the blades of the venetian blinds at a given angle.

These algorithms allowed us to explore all the available ventilation paths that the flexible DSF described in section 3.1 allows, both

Table 2
Possible combinations of all the controlled parameters in the model-based controlled DSF.

Conditions	Parameters	Combinations
OCC: ON $SOL_{facade} > 0$	$\left\{\begin{array}{l} \left\{\begin{array}{l}SA\\IAC\\OAC\\EA\end{array}\right. \times \left\{\begin{array}{l} N\times\left\{\begin{array}{l}50\%\\100\%\end{array}\right.\\ M\times\left\{\begin{array}{l}Vmin\\Vmid\\Vmax\end{array}\right.\end{array}\right. \times \left\{\begin{array}{l}OFF\\ ON\times\left\{\begin{array}{l}0^{\circ}\\cut-off\\90^{\circ}\end{array}\right.\end{array}\right. \\ TB \\ TB_V\times\left\{\begin{array}{l}50\%\\100\%\end{array}\right.\end{array}\right.$	69
OCC: OFF $SOL_{facade} > 0$	$\left\{\begin{array}{l} \left\{\begin{array}{l}SA\\IAC\\OAC\\EA\end{array}\right. \times \left\{\begin{array}{l} N\times\left\{\begin{array}{l}50\%\\100\%\end{array}\right.\\ M\times\left\{\begin{array}{l}Vmin\\Vmid\\Vmax\end{array}\right.\end{array}\right. \times \left\{\begin{array}{l}OFF\\ ON\times\left\{90^{\circ}\right.\end{array}\right. \\ TB \\ TB_V\times\left\{\begin{array}{l}50\%\\100\%\end{array}\right.\end{array}\right.$	46
OCC: OFF $SOL_{facade} < 0$	$\left\{\begin{array}{l} \left\{\begin{array}{l}SA\\IAC\\OAC\\EA\end{array}\right. \times \left\{\begin{array}{l} N\times\left\{\begin{array}{l}50\%\\100\%\end{array}\right.\\ M\times\left\{\begin{array}{l}Vmin\\Vmid\\Vmax\end{array}\right.\end{array}\right. \times \left\{ON-90^{\circ}\right. \\ TB \\ TB_V\times\left\{\begin{array}{l}50\%\\100\%\end{array}\right.\end{array}\right.$	23

Table 3
KPI selected for each set of simulations and their thresholds values.

$\bar{E}_{plane}[lux]$		ΔCO2[PPM]		T_{op}°C	
1st level	2nd level	1st level	2nd level	1st level	2nd level
Office space [63] 500	Circulation [63] 300 lx	II Class [58] 800	III Class [58] 1350	II Class [58] 20–24 23–26 20–26	III Class [58] 19–25 22–27 19–27

*The thresholds of the operative temperature differ according to the season.

with mechanical and natural ventilation, as well as the control of the shading device in the cavity. The openings were controlled as open/closed (0 % - CLOSED and 100 % - OPEN), similarly to how the fan was controlled (0 % - OFF and 100 % - ON). When the fan was on, the airflow was set as the flow required to ventilate the room when it was occupied or unoccupied (Table 1-c). The cut-off angle is calculated as described in the model-based case.

4.3. Scheduled-based control

The SBC of the DSF was applied on two elements: i) the ventilation strategy adopted and ii) the operation of the shading device. The schedules shown in Table 4 to be applied to the façade were decided according to the following principles: the DSF should reduce the heating load in winter and the cooling load in summer. At the same time, it should also provide fresh air during the hours of occupation. Since the facade conditions are usually unknown at the time of the schedule definition, the DSF was run only with mechanical ventilation to ensure sufficient airflow on every occasion. During the occupied hours, the fans were working with the V*occupied* airflow (Table 1-c), while the value for non-occupied hours was used for the rest of the time. The angle of the shading device was always varied throughout the day and the seasons, aiming to maximize the indoor lighting in the first and last hours of the day and reduce glare during the rest of the time.

5. Implementation of MBC in a BES tool via co-simulation

The challenges of implementing a MBC with a whole building model developed in a BES tool are connected to the structure and interoperability of these simulation environments. This type of control is a one-step at-a-time model predictive control, i.e. where the prediction horizon is set equal to the timestep under assessment and does not include optimising a given performance over a longer time horizon. This approach requires both parallel runs to explore the impact of each controllable parameter and a time-dependent correlation. The crucial aspect of implementing this type of control is being able to run simulations to explore a domain of possibilities and keep the thermal memory of the previous runs for the following timestep. Moreover, ensuring that the initial conditions are kept the same for each simulation for the exploration domain is essential. To establish the optimal length of the preconditioning horizon, a parametric study was carried out to quantify the influence of the length of preconditioning. A 10-daypreconditioning horizon was sufficient to ensure convergence of the energy balance of the room.

Considering the high degree of freedom that a DSF allows and the relatively low time step usually adopted in simulations, the number of simulations necessary for just a few days was in the order of hundreds. By limiting the prediction horizon to the present timestep, the size of the exploitation domain can still be kept to a number that, though requiring a certain computational effort, makes it possible to perform a full-factorial search of the domain. This allowed us to avoid using an optimal search algorithm to reduce the exploration domain, a non-trivial procedure that might lead to very different results. The relatively high number of runs necessarily requires automation of the process that is not available within the structure of the BES tool. Therefore, the use of co-simulation is needed. In this case study, the physical model was run in IDA ICE 5.0 and the optimisation engine in Python 3.8.

MBC can only be implemented if the process of setting up, running, and analysing multiple simulations is automatised. To do

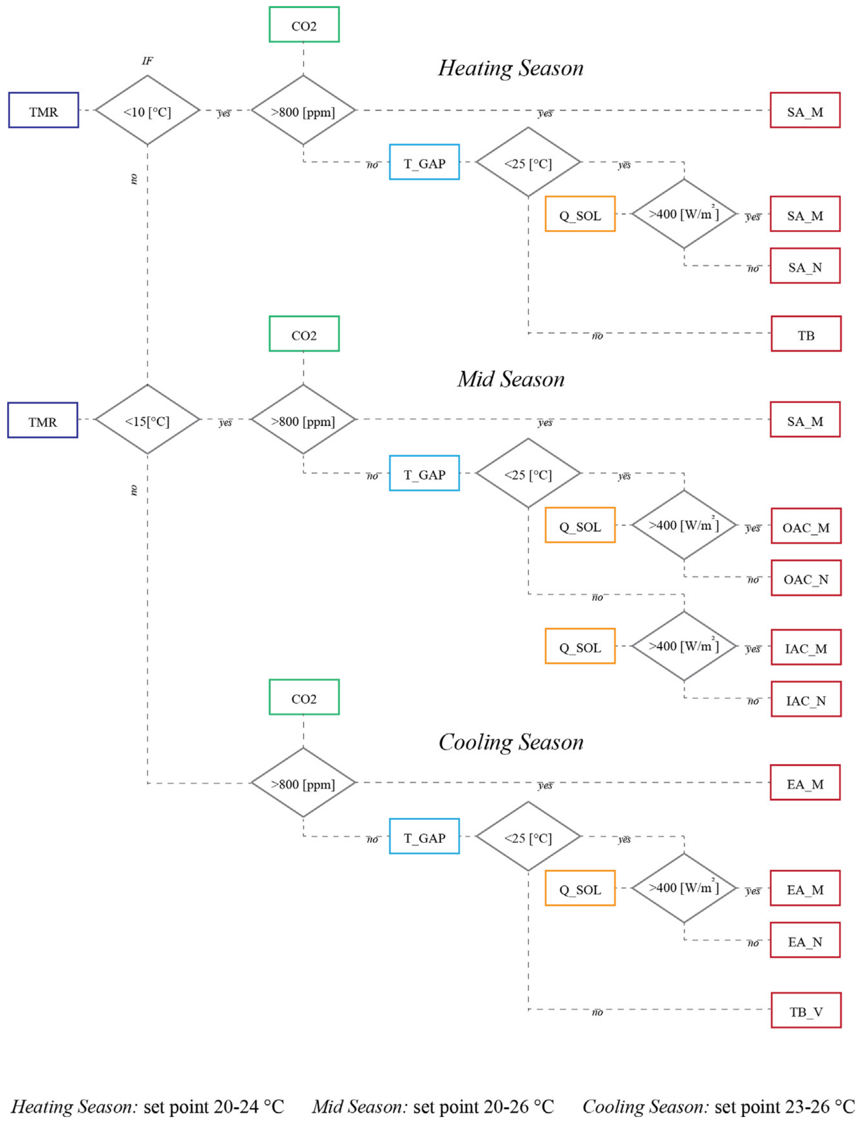

Fig. 3. RBC strategy for the thermal and air quality domain. TMR–Running medium temperature [°C]; T_GAP–Temperature inside of the DSF airgap [°C]; Q_SOL–Solar radiation hitting the façade on which the DFS is installed [W/m^2]; CO2-Amount of CO2 in the occupied room [PPM].

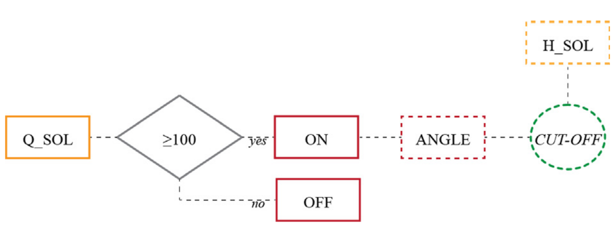

Fig. 4. RBC strategy for the visual domain; Q_SOL–Solar radiation hitting the façade on which the DFS is installed [W/m^2]; H_SOL–Solar altitude [°].

this, the model in IDA ICE was run via the IDA ICE API (Application Programming Interface). IDA ICE provides API functions in C programming language through a dynamic-link library *idaapi2.dll*. With direct calls to API functions, it is possible to load a previously developed model into IDA ICE and perform operations using Python scripts. The IDA Message Broker Service communicates with IDA ICE and the external program. The functions available in the API allowed both to connect to IDA ICE (opening the model, saving the model, etc.) and to manage the model objects.

It was necessary to adopt a programming language to automate the process and to carry out the data analysis of the obtained results. The version of Python 3.8 64bit was used. The Python library *win32process* and *ctypes* enabled the IDA ICE process in Windows environment and interacted with the API, calling API functions.

The data structure of an IDA ICE model (IDM) is represented as a hierarchical tree, where branches have subtrees of children with parent nodes. The tree of an IDM starts from the building object and then goes down to the level of the building body, zones, HVAC components, etc. It is possible to access each branch of the tree by calling the children of nodes. Objects of each node have attributes made up of names and values. These values can be accessed, read, and manipulated by using the LISP language [65].

The workflow used to apply the MBC is illustrated in Fig. 5, and the functions used in the Python code are collected in Table 5. The baseline IDM was created manually, as described in Section 3.2, and then accessed by the algorithm implemented in Python.

Manipulating the values of a node via the LISP language, as also underlined by Chenglong [52], requires a high computational time. For this reason, this method was limited to modifying the simulat-

Table 4
Schedule definition for the SBC of the DSF flow path and shading position.

	Flow path	Airflow	Blind ON/OFF	Slat Angle
Winter				
	Flow path	Airflow	Blind ON/OFF	Slat Angle
00:00–08:00	TB	–	ON	90°
08:00–10:00	IAC_M	*Voccupied*		0°
10:00–12:00				Seasonal average cut-off angle
12:00–16:00	SA_M			
16:00–18:00	TB	–		0°
18:00–24:00				90°
Summer				
	Flow path	Airflow	Blind ON/OFF	Slat Angle
00:00–05:00	EA	*Vunoccupied*	ON	90°
05:00–08:00	SA_M			
08:00–10:00		*Voccupied*		0°
10:00–16:00	OAC_M			Seasonal average cut-off angle
16:00–18:00				0°
18:00–24:00	EA	*Vunoccupied*		90°
Mid-Season				
	Flow path	Airflow	Blind ON/OFF	Slat Angle
00:00–06:00	TB	–	ON	90°
06:00–08:00	SA_M	*Vunoccupied*		
08:00–10:00		*Voccupied*		0°
10:00–12:00				Seasonal average cut-off angle
12:00–15:00	OAC_M			
15:00–16:00	SA_M			
16:00–18:00				0°
18:00–24:00	TB	–		90°

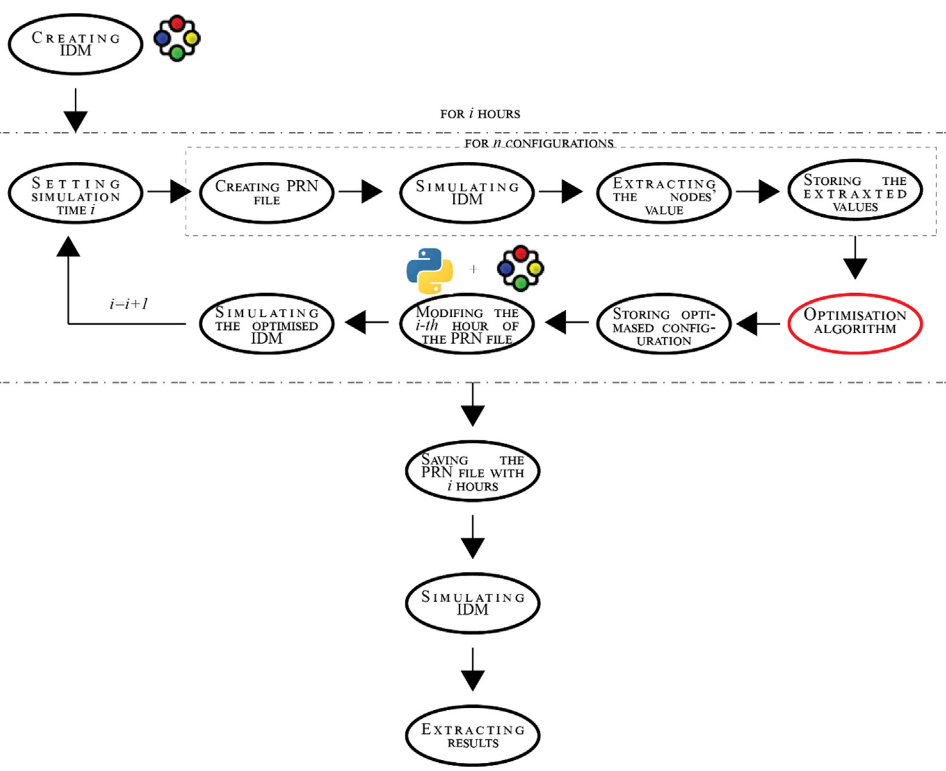

Fig. 5. Workflow of the automated process to adopt the MBC. The interaction between IDA ICE and Python is carried out by the API's functions called directly via Python.

ing time. The controlled parameters were modified by using an external *PRN* file. This approach was also necessary to replicate the same preconditioning time for each parametric run since the previous facade state can be stored in the PRN file. IDA ICE uses these formatted text (space delimited) files to read external data such as weather files and write the simulation results. To be read by the software, these files require time-stamped columns with the hours of the year (it is possible to define the fraction of the hour if necessary). Creating PRN files in Python was more efficient and allowed the automation of the process to simulate all the necessary configurations. In fact, the different state of the opening, fan, shading etc., was defined as a number in the PRN file. Once loaded in

Table 5
List of API functions used in the Python workflow.

Function	Description
connect_to_ida	Perform the connection to the IDA message broker.
call_ida_api_function	Call any IDA function with given parameter values in json format.
ida_disconnect	Terminate the connection to IDA message broker.
openDocument	Open the building specified in path. Return the building object
saveDocument	Save the building object to a path.
runSimulation	Run simulation for the building object.
runIDAscript	Execute a general IDA script with node as base object.
getZones	Return a list of the node's zones.
findNamedChild	Return the object of the child that has a particular name.
getAttribute	Return the value of the attribute of node.

IDA ICE, this number was interpreted by a function defined in a *Macro*, and the correct signal was sent to the actuator of the opening, fan, shading, etc.

The simulation was run using the "*Advanced level*" simulation, and the results of the simulation at the end of each parametric run are accessed directly from the model by reading the node value of the analysed element (room temperature, CO2 level, etc.). This action reduces the computational time compared to saving the file and reading the PRN result file but has the drawback of only giving the instantaneous value at the last moment of the simulation (not averaged over the hour). This operation is done automatically for each hour of the analysed period (two weeks per season). The use of hourly timesteps is connected to the computational time, but it could be either lowered or increased. Once the script had run for the whole simulation period, the script's output was a PRN file with the optimal configuration for the selected period, which was then used to run a continuous simulation for each period and obtain the results shown in the next section.

6. Results

6.1. Model-based control

The MBC was applied for two weeks in three different seasons. In this study, we first want to focus on whether or not the controller enabled the full exploitation of the flexibility that the adaptive façade concept offered (i.e. up to 69 different functioning modes). As a second goal for this analysis, we wanted to assess whether or not the full complexity of the façade was necessary to offer the best performance or if a façade with a reduced domain of possibilities could have performed equally well–in other words, if there were sub-domains in the domain of possibilities that were either never used or hardly used. Fig. 6 shows how the adaptive facade was run during one week of the winter period. The analysis of the different configurations used during this period shows that the most recurring ventilation path was the thermal buffer (TB–87 % of the not occupied hours and 40 % of the occupied ones - Table 6). During the occupation, IAC_M, IAC_N and OAC_N configurations were each used around 10 % of the time. During mechanical ventilation, the fan mainly used the minimum flow (42 %), while in natural ventilation, the openings were mostly fully open (60 % of the time). The shading device was rarely deployed during

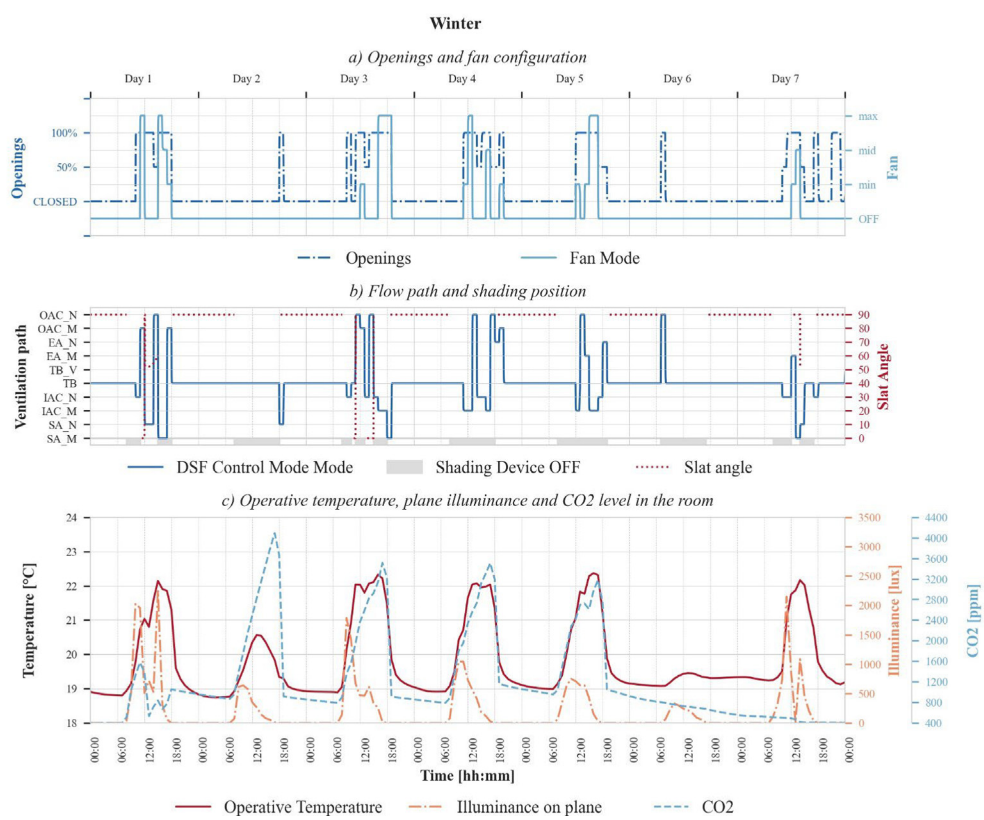

Fig. 6. MBC results for the winter period. a) The openings often shifted between CLOSED, 50 % and 100 % during the occupied hours, while both the fan and the openings were OFF/CLOSED since the façade mainly worked as a thermal buffer. When the façade was mechanically ventilated, all the airflow settings were used with equal frequency; b) the main flow path adopted in winter was TB, with few hours during the occupied period, run in SA or OAC mode. The shading device was mainly OFF during the day. c) the operative temperature was within the 2nd level range [19–25 °C] during most of the occupied hours, while the CO_2 level in the room reached very high values (above 1350 ppm) during the occupied hours. The level of illuminance on the working plane was above 300 lx for most of the occupied hours, remaining under the 3000 lx threshold set for avoiding glare.

Table 6
Ventilation strategies adopted during the different simulated periods.

Mode	Winter [%]		Summer [%]		Mid-Season [%]	
Occupation	ON	OFF	ON	OFF	ON	OFF
SA_M	6	3	3	4	4	2
SA_N	6	2	2	5	5	4
IAC_M	*10*	2	3	6	*10*	5
IAC_N	***12***	2	1	2	3	3
TB	**40**	**87**	4	**54**	***19***	**63**
TB_V	1	0	**45**	8	**37**	***12***
EA_M	7	1	***24***	8	*10*	*9*
EA_N	1	1	*11*	5	9	3
OAC_M	6	1	1	2	1	0
OAC_N	10	1	6	6	2	1

the daytime (20 %), and during these few hours, the slats angle was set to 0° for most of the time (60 %); during the rest of the time, the cut-off angle was used. The results for the multi-domain optimisation showed that while the lighting and thermal requirements were met (Eq. (3)–winter season), the CO_2 levels grew relatively high (always above 1350 ppm when the room was occupied), and the control algorithm was not able to choose the right configuration to reduce the CO_2 to under 800 ppm during the nighttime. This resulted in a high baseline for the following day without the possibility of reducing it further once the room was occupied again.

During the summer period (Fig. 7), the operational modes adopted varied more, even though approximately 40 % of the simulated time used the thermal buffer configuration. This is because, during the unoccupied hours (which correspond to 54 % of the time), the facade was run in TB. During occupation, the most recurring configurations were the ventilated thermal buffer (45 %), the mechanical (24 %) and natural exhaust-air facade (11 %). All the other configurations were used, but for very short periods. When the facade was run mechanically, the fan setting was mainly on the mid-flow (60 %), followed by the maximum flow (25 %). In natural ventilation, the openings were mostly fully open (80 %). During the summer, the shading device was ON half of the occupied time (49 %) with the slat position set at 0° (94 %). The indoor conditions showed a better fulfilment of the multi-domain criteria than the winter case did. Besides the temperature being controlled within the set point of the 2nd level as indicated by Eq. (3). for the summer season, the CO_2 level was within the 1st level threshold most of the occupied time. It is interesting to notice that the temperature inside of the room was mainly controlled by the façade ventilation since the shading

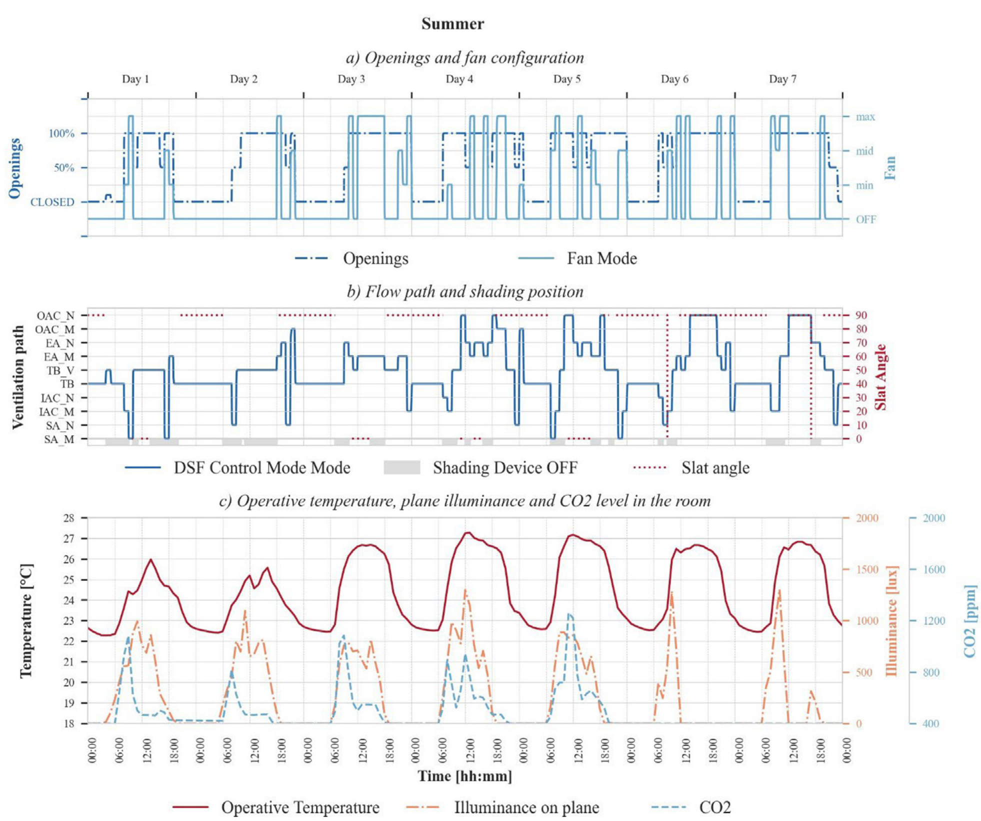

Fig. 7. MBC results for the summer period. a) During occupied hours, the openings were modulating the flow, often shifting between 50 % and 100 %. When the façade was run with mechanical ventilation, the fan mostly worked with the maximum flow setting. B)during the night the optimal configuration was the thermal buffer, while during occupation the flowpath switched among many different configurations, mainly EA, SA and OAC. The shading device was mostly OFF during the daytime c) the operative temperature was within 22–27 °C for most of the time. The CO_2 levels were always under 1350 ppm and the illuminance on the work plane was above 300 lx during most of the occupied hours.

device was mostly OFF during the occupied hours. Consequently, the illuminance values on the workplane were within the requirements.

Similar to the summer season, during the mid-season weeks (Fig. 8), the most adopted configuration strategies were the thermal buffer (50 %), the ventilated thermal buffer (19 %) and the mechanical exhaust air (9 %). Looking at the difference between occupied and unoccupied times, the distribution shifts a bit. The most adopted configuration during occupied hours was the TB_V (37 %), followed by the TB (19 %), while during the unoccupied time it was the TB (63 %). Other configurations were evenly used during occupation: IAC_M, EA_M and EA_N were used around 10 % of the time. Compared to the winter season, the mild outdoor temperatures guaranteed an exchange of fresh air to control the CO2 level without affecting thermal comfort; in this way, the CO2 levels were mainly under the acceptable threshold for most occupied hours (2nd level = 1350 ppm). When the fans were used, the airflow chosen was mostly the mid-flow (48 %), and the rest of the time was equally split between the minimum and maximum settings. Similar to the other simulated periods, the openings were fully open during naturally ventilated modes (69 %). The shading device was mostly unused during the occupied time (63 %), but when ON, the slats were always set to 0°(99 %). Similar to the summer case, the comfort requirements were also met during the mid-season weeks. The CO2 and the illuminance level were within the boundaries identified by Eq. (3)., as was the operative temperature. Also, during this period, the shading device did not play a crucial role in controlling the room conditions, as it was activated only for a few hours per day to allow daylight to enter the room.

6.2. Comparison of the performance with different control strategies

The results shown in this section are compared the three controlled strategies presented in Section 4. The criteria for the comparison are defined as the percentage of the occupied hours that fulfil the requirements for natural lighting, indoor air quality and operative temperature presented in Eq. (3). Moreover, the energy necessary for cooling and heating when the air temperature did not meet the dual set points defined in Table 1-a was considered (Eq. (4)).

$$\%ofoccupiedhours \left| \begin{array}{l} \bar{E}_{plane} > \begin{cases} 500lux\ 1^{st}level \\ 300lux\ \ 2^{nd}level \end{cases} \\ \Delta CO2 < \begin{cases} 800ppm 1^{st}level \\ 1350ppm\ \ 2^{nd}level \end{cases} \\ \begin{cases} 20^{\circ}C \\ 19^{\circ}C \end{cases} < T_{op_{winter}} < \begin{cases} 24^{\circ}C 1^{st}level \\ 25^{\circ}C\ \ 2^{nd}level \end{cases} \\ \begin{cases} 23^{\circ}C \\ 22^{\circ}C \end{cases} < T_{op_{summer}} < \begin{cases} 26^{\circ}C 1^{st}level \\ 27^{\circ}C\ \ 2^{nd}level \end{cases} \\ \begin{cases} 20^{\circ}C \\ 19^{\circ}C \end{cases} < T_{op_{mid-season}} < \begin{cases} 26^{\circ}C 1^{st}level \\ 27^{\circ}C\ 2^{nd}level \end{cases} \end{array} \right. \quad (3)$$

$$\sum Q_{heating} and \sum Q_{cooling} \quad (4)$$

The results of Table 7 show that the control strategies used impacted the different domains differently; the illuminance on the working plane ($\bar{E}_{plane}$) was highly under reached with a tradi-

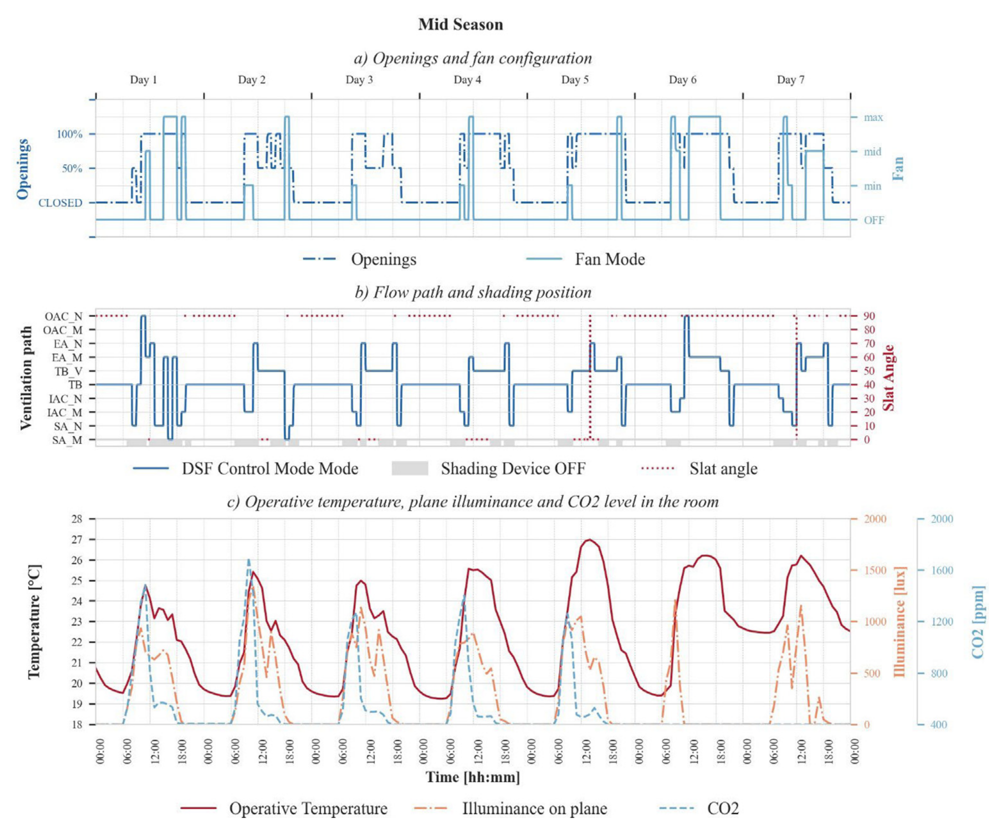

Fig. 8. MBC results for the mid-season. a) When the façade was not in thermal buffer (CLOSED), the openings were mostly open 100 %, and the fan worked with maximum flow settings; b) the thermal buffer was predominant during night hours, while during the day the flow often switched to TB_V, holding the settings for a few hours. Other paths frequently adopted are IAC, EA and SA. c) The operative temperature fluctuated between the thresholds 20–26. The CO2 levels were under 1350 ppm, and the illuminance on the plane was above 300 lx during most of the occupied hours.

Table 7
Fulfilment criteria for the different control strategies adopted during the combined three simulation periods. The KPIs $\bar{E}_{plane}$, ΔCO2 and T_{op} are calculated only during the occupied hours. Q is calculated for the whole simulation hours.

Control	$\bar{E}_{plane}$		ΔCO2		T_{op}		Q	
	1st level $\%_{occ\_hours}$	2nd level $\%_{occ\_hours}$	1st level $\%_{occ\_hours}$	2nd level $\%_{occ\_hours}$	1st level $\%_{occ\_hour}$	2nd level $\%_{occ\_hour}$	Heating *kWh*	Cooling *kWh*
SBC	30	73	38	65	46	90	206	143
RBC	47	91	100	100	35	94	711	163
MBC	81	96	68	81	68	91	210	69

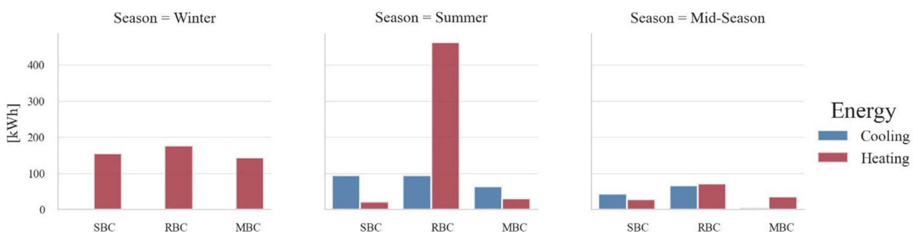

Fig. 9. Energy uses from the different control strategies in the three simulated periods. SBC, RBC and MBC control.

tional SBC. Better results were obtained when a rule-based control was adopted, even though the values were below 500 lx>50 % of the occupied time. Conversely, adopting the MBC yielded satisfactory results (80 % of the occupied hours meet the 1st-level requirements).

As for the indoor air quality domain, the results of the SBC show a very low percentage of compliance with the CO^2 values in the room. Even considering the 2nd level criteria (1350 ppm), only 66 % of the occupied hours satisfied this requirement. For the case of the RBC, this 100 % value is explainable with the rigid control in the algorithm tree (Fig. 3); in fact, whenever the CO2 level reached a value above 800 ppm, the DSF would run with mechanical ventilation to bring fresh air inside the room at the expense of the room temperature, and consequently of the energy use. Conversely, the MBC worked towards a solution that was a trade-off of all three domains; the results for the air quality were lower than the other two strategies but still satisfactory (above 65 % for the 1st level and 80 % for the 2nd level).

For both the SBC and RBC the thermal domain values were<50 % of occupied hours within the boundaries defined for the 1st level of the operative temperature, while the model-based control results approached 70 %. When checking the 2nd level, the values became much more similar due to the ideal heating and cooling action; this good achievement resulted in much higher energy consumption for the RBC case to maintain the set point temperatures. Remarkably, the RBC results showed an extremely high heating demand during summer (more than twice that in winter - Fig. 9). This is probably connected to the rule definition for the cooling season (Fig. 3), which would run the façade in exhaust mode–thus extracting heat from the room whenever the TMR was above 15 °C. Most likely, for the weather conditions of Frankfurt, this was not the optimal ventilation strategy - as Table 7 shows, the thermal buffer was the most adopted configuration, even in summer. During winter, all three control strategies performed similarly (with the MBC consuming less energy), while during summer and the mid-season, the MBC outperformed the other two control strategies in terms of cooling loads.

7. Discussion

This work originates from the challenge and limitation of using traditional control strategies to properly manage an adaptive façade with high degrees of freedom. We defined a simple SBC for the façade that aimed at reducing the room heating load in winter and the cooling load in summer while providing fresh air during occupation hours and guaranteeing indoor natural light without glare. It was already obvious from the development of the algorithm that this would not take full advantage of the flexibility of the façade; the DSF was only run in mechanical mode with a fixed flow and fixed openings. We also developed an RBC algorithm for this work that only used the airgap temperature and the CO_2 level in the room as dependent variables and external air temperature and the solar irradiance on the facade as the independent variables of the. The assumptions made related to the model, and the RBC control, were based on the authors' experience with the main aim of demonstrating the functionality of the developed model and based on previous work [64]; with this decision tree, all the available flow paths were explored, and the control of the shading device in the cavity was also controlled with a more advanced strategy than the scheduled case. Nevertheless, not even this algorithm allowed the fully exploitation of the flexibility that this model offered since it could only account for a limited number of states. Not even rather advanced RBC approaches could effectively exploit the full potential of a complex adaptive façade.

The analysis of the results also highlighted the importance of defining the correct thresholds for RBCs; the proposed algorithm led to sub-optimal thermal and indoor comfort performance, despite having been developed with this goal in mind. Choosing the most appropriate control strategy as a function of the climate condition is critical. Indeed, RBC solutions not optimised for the climate can lead to worse results than the classical use of the DSF, as clearly shown by this work's results.

The developed model, adopting a full factorial MBC, demonstrated instead how it it possible to fully exploit the flexibility of the façade while aiming at a multi-domain optimisation that was not reached with the other control strategies. The approach presented in this paper shows how MBC and multi-domain control can be combined. It is, of course, an open question of how different domains should be prioritised. In addition to great flexibility, the proposed control algorithm showed that the optimal configuration of the façade varies a lot within the same period. The strength of this type of control is that it does not require prior knowledge of the performance of the controlled element to be defined. It differs from the other types of control because it only sets the target

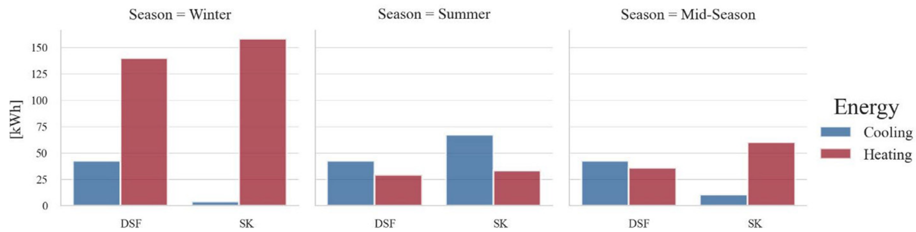

Fig. 10. Comparison of the energy requirements for cooling and heating between the DSF and SK models.

Table 8
KPIs of the MBC applied to the flexible DSF and to a simpler single skin (SK). $\bar{E}_{plane}$, ΔCO2 and T_{op} were calculated only during the occupied hours. Q was calculated for the whole simulation hours.

Control	$\bar{E}_{plane}$		ΔCO2		T_{op}		Q	
	1st level $\%_{occ\_hours}$	2nd level $\%_{occ\_hours}$	1st level $\%_{occ\_hours}$	2nd level $\%_{occ\_hours}$	1st level $\%_{occ\_hours}$	2nd level $\%_{occ\_hours}$	Heating *kWh*	Cooling *kWh*
DSF	81	96	68	81	68	91	210	69
SK	84	100	65	79	71	95	274	81

rather than defining the ways to reach it, leaving open the exploitation of the façade's flexible behaviour as the means to reach the desired target. All the results showed that, in all analysed domains, the MBC performed better than the more traditional control strategies.

Due to its nature, this multi-domain, MBC strategy is suitable for controlling every type of façade that exhibits some degree of adaptability–hence requiring control. To exemplify the possibility of using the presented control approach with a wider range of façade systems, we applied the same MBC strategy to a more conventional façade system. Fig. 10 shows the application of the MBC for a single skin façade (SK) with equivalent glass properties to the DSF, two operable openings and a between-glass shading device. Compared to the DSF model proposed, this type of façade has much less degree of freedom, yet it can be beneficial to control the way this façade is operated using a multi-domain MBC. The single skin façade simulated to demonstrate the wider applicability of our method had similar features to the adaptive façade in terms of optical and thermophysical properties. The energy need results and indoor comfort performance (Table 8) show similar results to the adaptive façade when controlled with the MBC proposed in this study. When the single skin was controlled with an advanced type of control, and its performance was compared to that of the adaptive façade controlled with more traditional control strategies (e.g. schedules and RBCs), the single skin outperformed the more complex adaptive façade, not only in terms of comfort performances but also in terms of energy. This demonstrates that adaptive facades can only perform better than more traditional envelopes if properly controlled and that an advanced façade characterised by a large degree of freedom requires more advanced control methods.

One of the main drawbacks of the MBC approach, as formulated in this study, is the computational time required to run an explicit physical model for a full-factorial exploration. The full factorial exploration adopted was already a reduced from of a more exhaustive analysis where, ideally, the openings of the façade or the position of the shadings could have even more intermediate settings. Due to the heavy computational load, the analysis had to be limited only to a few weeks of the year. In order to overcome these limitations, a solution could be the use of this approach to identify the most adopted configurations over a limited period (like the one in this study) and then run the model over an extended period or in real applications, with a reduced amount of states. For example, from the simulated weeks, it could be deducted that at night, no matter the season, the predefined configuration is the thermal buffer, reducing the exploration domain to only the hours with considerable solar gains. The number of simulation runs (hence the total simulation time) could also be reduced by adopting an algorithm for optimal search (e.g. a genetic algorithm) instead of performing a full-factorial exploration. .

Combining a MBC and RBC could also lead to suitable performance. Particularly in real building applications, a development of the presented MBC control could be combined with the more traditional control, like hierarchical rule-based control to reduce the search domain based on a series of pre-set rules. Developing a control-oriented model of the flexible double skin system with significantly shorter simulation time is however a prerequisite to take this approach to in-field, real-time applications. Alternatively, MBC-enhanced RBC strategies, which are proved of being a cost-effective solution, can allow to reach the optimal control with a decrease in operational time [35,66] by means of rule extraction from an MBC simulation dataset [10].

8. Conclusion

Thanks to the increasing capabilities to interface BES tools with external simulation environments, we developed in this study an innovative model-based control (MBC) for adaptive facades that can adjust their physical properties to satisfy multiple interdependent performance requirements (across multiple domains–i.e. energy, thermal comfort, natural lighting, indoor air quality). To the best of our knowledge, this is one of the first attempts to conceive and demonstrate how an adaptive facade characterised by a large variation in its operational model can be effectively managed by exploiting a simulation-informed control. The multi-domain MBC was applied to a double skin façade highly capable of switching between different ventilation flow paths and interconnecting with the HVAC plant of the building. The specific case presented a very large number of possible states for the operation of the façade (in the order of one hundred), thus making this system unsuitable for conventional control approaches adopted for building envelopes. This approach takes advantage of the capabilities of BES tools to replicate the behaviour of adaptive envelopes and to explore the full potential of an optimal management of their dynamic features. In this work, we have not only demonstrated how traditional control strategies are inappropriate for achieving high performance goals in facades characterised by a large freedom in their operation, but we addressed a knowledge gap by proposing a method that can outperform the current approaches and contribute to the know-how for advanced building envelope controls. Furthermore, it has been shown that this approach is not only suitable for complex facades; it can be easily transferred to more conventional facade configurations, characterised by a lower degree of freedom, but targeting multiple performance domains. Applying this MBC to a less complex (with a minimum of automatization) envelope showed how a good control strategy plays an equal role as the technology chosen. Overall, the proposed method can be applied to various typologies of adaptive facades, allowing optimal integration with the HVAC system of the building.

The proposed approach control has only been tested through simulations thus far. Only parallel tests in identical (laboratory or in-field) environments would be suitable to give an empirical demonstration of the effectiveness of one control approach against another. Though we have access to such experimental facilities that allow this type of investigation (i.e. [67]), such tests are expensive and very time consuming. Simulation-based studies are normally carried out in the first stages of a research activity to investigate a new approach or technology, while experimental assessments and demonstrations are carried out once the new technology has been numerically verified. In the next steps of the research, we will apply the method proposed in this study, pending suitable modifications to make it possible run in real-time, to control a mock-up of a flexible DSF system. Furthermore, we will keep developing the proposed method to optimise the performance of the façade considering future states too (so-called model-prediction control).

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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