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Deployment and control of adaptive building facades for energy generation, thermal insulation, ventilation and daylighting: A review

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Deployment and control of adaptive building facades for energy generation, thermal insulation, ventilation and daylighting: A review

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A R T I C L E I N F O

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A B S T R A C T

A major objective in the design and operation of buildings is to maintain occupant comfort without incurring significant energy use. Particularly in narrower-plan buildings, the thermophysical properties and behaviour of their façades are often an important determinant of internal conditions. Building facades have been, and are being, developed to adapt their heat and mass transfer characteristics to changes in weather conditions, number of occupants and occupant's requirements and preferences. Both the wall and window elements of a facade can be engineered to (i) harness solar energy for photovoltaic electricity generation, heating, inducing ventilation and daylighting (ii) provide varying levels of thermal insulation and (iii) store energy. As an adaptive façade may need to provide each attribute to differing extents at particular times, achieving their optimal performance requires effective control.

This paper reviews key aspects of current and emerging adaptive façade technologies. These include (i) mechanisms and technologies used to regulate heat and mass transfer flows, daylight, electricity and heat generation (ii) effectiveness and responsiveness of adaptive façades, (iii) appropriate control algorithms for adaptive facades and (iv) sensor information required for façade adaptations to maintain desired occupants' comfort levels while minimising the energy use.

1. Introduction

HVAC and artificial lighting often have solely met occupant comfort requirements where (i) in deep plan buildings, the façade is small when compared with the floor area or (ii) building façade characteristics are effectively a fixed boundary for HVAC sizing that intentionally decouples the indoor and outdoor environments. These, together with thermally inefficient materials and systems, lead to 40% of global energy consumption [1,2] being used to heat, cool, light and ventilate buildings. In marked contrast, as one approach to achieving new and refurbished near-zero energy buildings (nZEB) [3], adaptive façades combine features, materials and technologies that alter their properties with changing weather and/or occupancy to maintain internal occupant comfort whilst incurring minimal energy demand [4-6]. Particular adaptive façade systems provide different combinations of actively and selectively managed (i) energy and mass transfer between the building and its external environment [7,8] (ii) thermal insulation, natural ventilation, shade and daylight [9-11] and (iii) locally harnessing of solar energy to produce electricity and heat air and water. To do this, adaptive façades need to; (i) be flexible and reversible in response to changing occupancy and weather conditions, (ii) control concurrent physical processes, for example, solar heat gain and ventilation mass transfer of air [12] and (iii) be reliable and durable, with in-built fault-indication to enable ease of maintenance [13]. With low operational energy use, the energy embodied in extraction and processing of building materials becomes a greater proportion of overall energy and greenhouse gas emissions associated with buildings [14]. Minimal use of new materials thus reduces environmental impacts of construction, so, rather than demolition and disposal, façade elements should be designed to be readily (i) refurbished, (ii) repurposed, (iii) reused on another building and/or (iv) fully or partially recycled.

As shown in Fig. 1, in this paper the distinct aspects of adaptive facades are reviewed in the following sections;

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Nomenclature

Symbol	Definition [Unit]
A	External fabric area [m^2]
C	Specific heat capacity [$J\ K^{-1}\ kg^{-1}$]
m	Mass [kg]
p	Size ratio
Q	Heat power input [W]
R_i	Thermal resistance [$K^{-1}W^{-1}\ m^2$]
t	Time [s]
T	Sensor output temperature [^oC]
T_{ai}	Indoor air temperature [^oC]
$T_{ai\ d}$	Design steady-state indoor air temperature [^oC]
T_{ao}	Outdoor air temperature [^oC]
$T_{ao\ d}$	Design steady-state outdoor air temperature [^oC]
T_w	External wall temperature [^oC]
U	Overall heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]

- Section 2 compares façade technologies in terms of their adaptive features.
- Section 3 explains the wide range of techniques and parameters used to control how adaptive facades adapt.
- Section 4 discusses the response times of both the façade and adaptive technologies.
- Section 5 concludes the paper by identifying future challenges adaptive façade technologies, as well as areas that need to be explored in the future.

Irrespective of construction type, use, performance, architectural style, occupancy and construction location and period, all buildings are instances of a generic enclosure as shown in Fig. 2. As the form of a purpose-built building would normally follow its function, so a building's use determines the most appropriate façade. Quite distinct façade attributes arise from whether the functions of the enclosure are determined by (i) people; as in residential, office and institutional buildings, (ii) processes; as in factories, warehouses and data centres or (iii) plants; as in protected horticulture.

2. Adaptive façade technologies and features

By combining passive and active features, an adaptive building façade can transmit, capture, convert, distribute and store solar energy for electrical power generation, daylighting, space heating, water heating and ventilation [19]. Passive façade systems rely on (i) buoyancy-driven air flows, (ii) unmediated sensible heat storages in wall and floor materials, (iii) continuous insulation throughout the entire building envelope (iv) low heat loss windows and doors and (v) fixed shading devices to mitigate overheating and glare. As passive façades respond largely to diurnal changes in weather conditions, they are thus not usually responsive to rapidly changing weather conditions nor to changes in buildings occupancy. Advances in materials technologies and control systems enable passive façade features to become integral elements of adaptive façade systems [20]. Actively adaptive façades incorporate in-built combinations of;

(i) fans and louvers to manipulate ventilative and solar heated airflows [21],
(ii) recovery of heat from air via heat exchangers,
(iii) controlled transmittance of daylight luminance and solar heat gain [22–24],
(iv) building integrated photovoltaics for electricity generation.
(v) thermal conversion of solar energy [25,26],
(vi) sensible or latent heat thermal energy and/or
(vii) battery storage of electricity.

Adaptive façade technologies are categorized in Tables 1 and 2.

3. Adaptive façade control

This section outlines the methods and parameters used to control adaptive facades. To enable an adaptive façade system to satisfy comfort, a control system intervenes in flows of energy between the building, its occupants and the external environment [72]. The generic system control architecture shown in Fig. 3 encompasses both the building's services and its adaptive façade.

These uncertainties are the crucial problem which faces any adaptive technology, uncertainties can be caused mainly because (i) the uncertain weather conditions [74], (ii) and uncertain occupant behaviour.

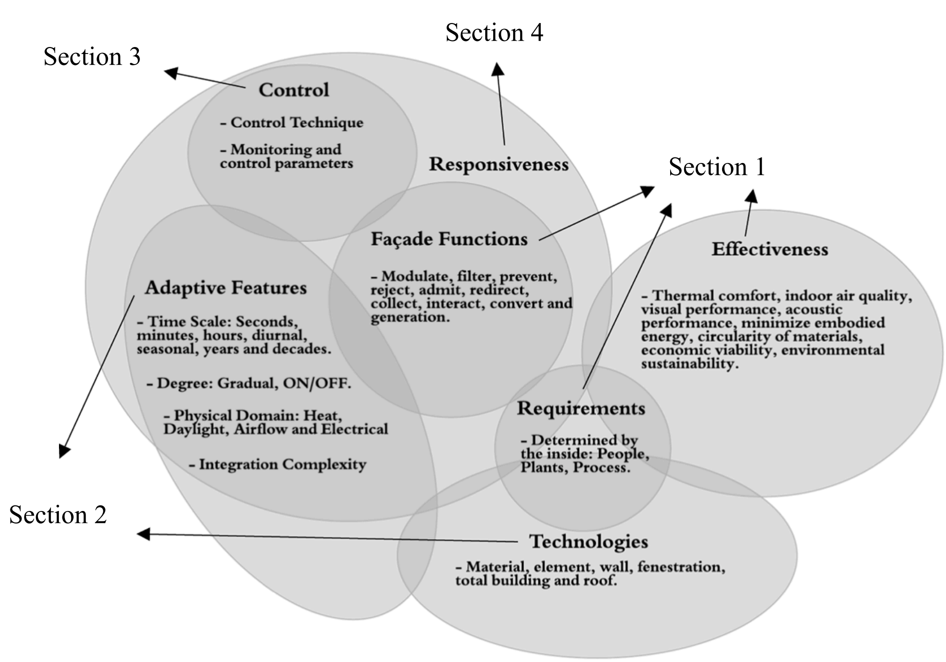


Fig. 1. The interrelationship between many aspects of an adaptive façade [15–18].

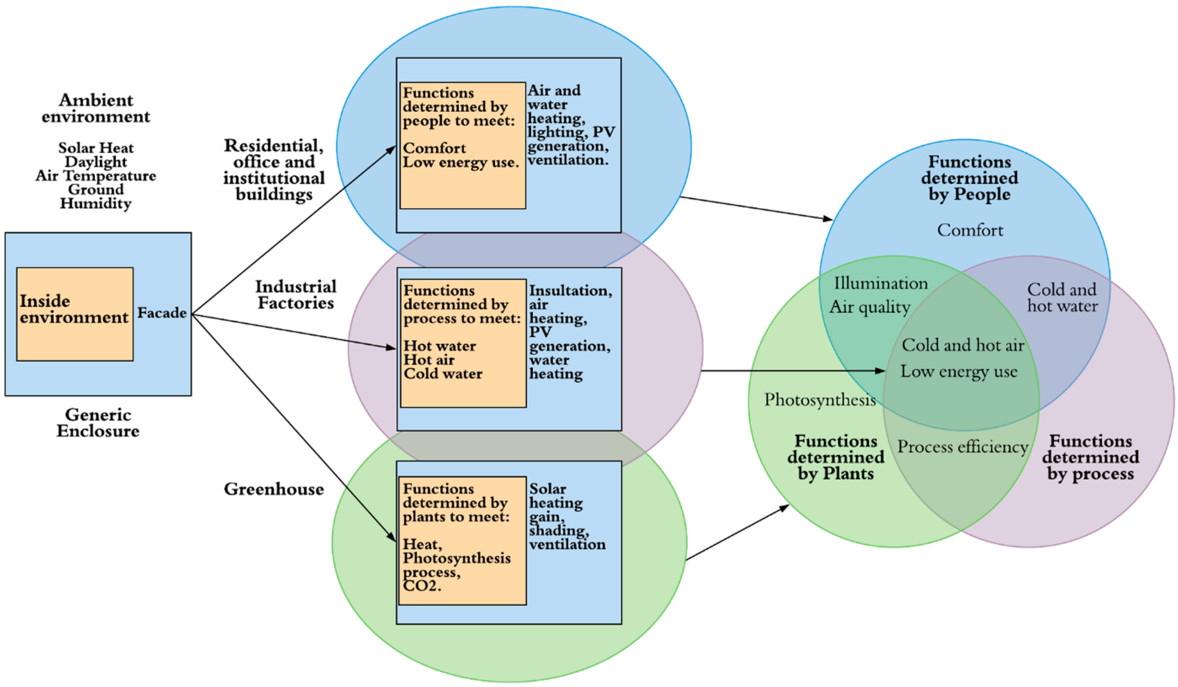


Fig. 2. Relationship between the façade and functions in different building types.

Occupants influence building energy consumption by the way they (i) use building equipment's (HVAC and lighting), (ii) move, (iii) open doors and windows [75], these actions influence energy use in a direct and indirect way. For that reason, some of the control strategies are centred around occupancy behaviour [76–78]. To minimize uncertainties, machine learning algorithms can be used. They have the ability to learn, these algorithms requires data to train them [79]. That is why buildings that learn are entering the market.

Uncertainties or changes in the conditions applied to an adaptive façade will result in a deviation from desired performance. The ideal control strategy minimizes the size of such deviations [80]. To achieve this, adaptive facade control sensors, processing and actuator/switching systems should have (i) appropriate response times and (ii) an ability to learn [81] enabling adaptation to changing (i) outdoor conditions and (ii) comfort requirements [82]. Control techniques used for adaptive building façades are categorized in Fig. 4.

The adaptive façade control techniques in Fig. 4 can be either;

- Extrinsic, or closed-loop, control (illustrated by continuous lines in Fig. 3) uses feedback to adjust the system continually and actively, Extrinsic control can (i) react to different conditions even if those conditions were not expected at the design stage and (ii) react with different systems in the building and in other buildings [4].
- Intrinsic, direct or open loop, control (illustrated by dashed lines in Fig. 3) makes decisions directly from the environmental conditions without external decision-making inputs, so (i) can act immediately with less driving energy and (ii) requires fewer components as there is no need for control management hardware [4].

Computational tools can examine the effectiveness of control strategies at different spatial scales and time resolutions [83]. For this, the most appropriate building performance simulations tools must be able to (i) simulate an open-ended set of adaptive façade technologies (ii) integrate with other tools, (iii) include occupancy influences and (iv) include the full range of possible control strategies [73].

Classical control

There are two types of classical control techniques; rule-based methods and proportional integral derivative (PID). Both are simple in their implementation but can be energy inefficient compared to other controlling techniques as they do not incorporate continuous adaptation. [84,85].

Rule-based (or On/Off) methods use upper and lower set points to control processes within given boundaries. Rule-based methods are used mostly for temperature control. Use of rule-based methods can lead to energy inefficient operation of an adaptive façade because they do not (i) learn, so a complicated system requires complicated rules, (ii) handle incomplete data, (iii) solve control challenges not considered at the design stage and (iv) cope with variables with infinite numbers of possibilities [78,79]

Proportional integral derivative (PID) controllers use feedback "errors" from sensors on the adaptive facade [86,87]. PID comprises three controllers [88] (i) proportional controller that produces an output proportional to the error by comparing the feedback signal with the set point, (ii) integral controller that removes error by integrating the error over time until the value of the error comes to zero and (iii) derivative controller that increases system response and minimizes overshooting by slowing down the correction factor. PID controller must be tuned before its use in a building.

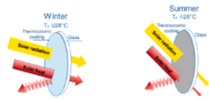
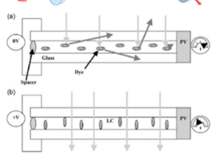
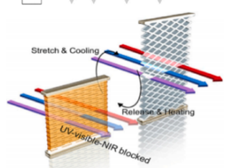
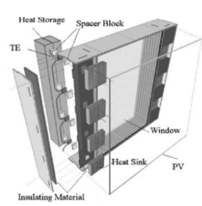
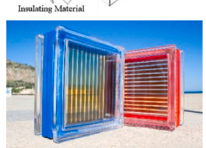
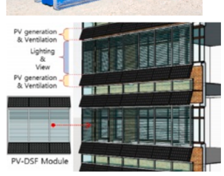
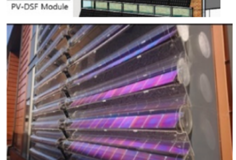
Model-free control use weather prediction based on historical weather data, to change the settings of actuators on an adaptive facade. Model-free control does not use data from a building simulation model nor past measured data from the building. Model-free control can be used to control the grid pricing by continuously updating the model using the knowledge of the input–output relationship. If model-free control is used to control temperature, it is recommended to predefine temperature set-points for the zone [89-91]. Intelligent PID (i-PID) controller is an example of a model-free control system, it works as a normal PID but without any modelling procedure [92,93].

Advanced control

Advanced controls determine future action of an adaptive façade based on a building model. There are five main types of advance control; (i) Adaptive control [94], (ii) Optimal control [95], (iii) Model predictive control (MPC) [89], (iv) Feedforward/feedback [96] and (v) Robust controls [97].

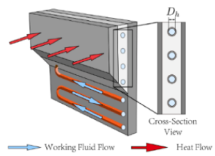
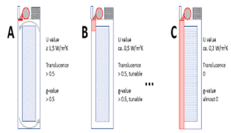
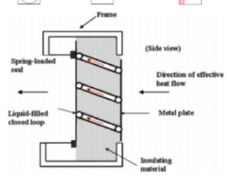
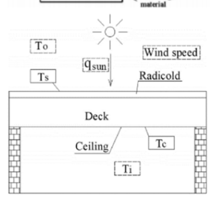
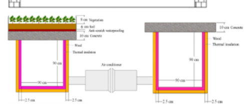
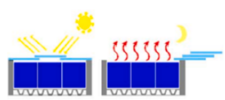
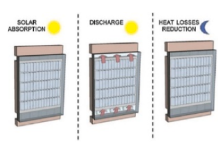
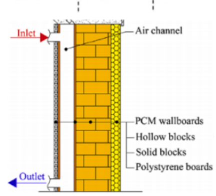
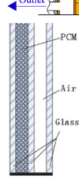
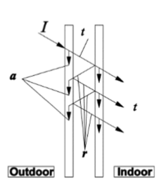
Adaptive control is used in processes that change dynamically and are subjected to disturbance; it can handle unknown model uncertainty

Table 1
Adaptive façade technologies.

Technology	Description	Illustration	Benefits	Drawbacks	Application	Ref.
Technologies controlling daylight transmission						
Thermochromic glazing	Changes transmissivity at a specific temperature.		Controls solar heat gain and glare. No power needed.	Coating controlled solely by glass temperature.	Primarily Offices.	[27]
Electrochromic glazing	Changes transmissivity at a specific applied voltage		Controls solar heat gain and glare. Power only needed to modify the transmission state.	Low transparent transmissivity. Delay changing from clear to opaque. Expensive.	Primarily offices.	[28]
Photovoltaic window with adjustable transmission	Using liquid–crystal with PV panel, to generate electricity and control the light transmitted into the building.		When opaque, produces electricity.	Costly to implement in existing buildings. Lowers heat gain in winter.	Primarily offices	[23,29,30]
Innovative Window blinds.	Reconfigurable transition separately controlling daylight and heat gain.		Controls solar heat gain and glare	Long-term durability has yet to be demonstrated.	Office and domestic buildings	[31]
Coloured fluid window	Coloured fluid pumped between window panes to changes transmissivity to reflect or transmit solar radiation as required.		Heat extracted by the fluid can be stored for use. Fluid redirects daylight.	Complex with many parts to maintain.	Office and domestic buildings. Greenhouses	[32-34]
Reflective external panels	Movable reflective panels on the building façade.		Provide heat gain control can be linked to building integrated pv.	When retrofitted, changes building façade appearance. Significant response time. Care for the directionality of reflected light needed.	Residential, particularly apartments	[35]
Daylight filtering coatings	Changing day-light transmission by Filtering near-infrared [36-39] or diffuse it [40] or block UV [41-43].		Enhance the photosynthetic rate.	The coating may need be changed if the plant grown is changed	Greenhouse	[36-43]
Technologies generating electricity						
Combined photovoltaic thermo-electric window (PV-TE)	Module photovoltaic thermoelectric system.		Produces and stores electricity.	Complex design that exists only as a small prototype.	Office Buildings	[44]
Window-integrated photovoltaic.	Photovoltaics mounted on the façade generate electricity and modulate solar gain		Regulate the light and heat transmission through the window. Generates electricity on-site.	Lower solar heat gain in winter.	Residential and office buildings	[45]
Photovoltaic powered blinds	Module consists of blinds in the middle part and PV on the upper and lower parts.		Produces electricity. Controls daylight. Allows ventilation.	Limited to specific building types.	Residential, primarily apartments	[46]
Photovoltaic thermal solar collector	Combines a photovoltaic absorber with heat removal by air or water flow.		Produces both electricity and heat	Can have high initial cost.	Office, industrial and residential buildings. Greenhouses.	[47–51]

(*continued on next page*)

Table 1 (*continued*)

Technology	Description	Illustration	Benefits	Drawbacks	Application	Ref.
Technologies controlling heat loss from windows, walls and roofs						
Switchable opaque wall insulation	Walls change between being insulation and thermally conductive states.		Regulates heat transfer between indoor and outdoor environments.	Difficult to install on existing buildings. Requires significant maintenance.	All building types	[52,53]
Switchable translucent wall insulation.	Translucent insulation panel inside a glazed closed cavity. Varies thermal insulation by enabling or suppressing convection.		Variable overall heat loss coefficient. Daylight directed deeper into the building.	Mechanical parts require regular maintenance.	All building types	[54]
Thermal diode	Bi-directional thermal diode allows heat transfer to change from one direction to another. depending on need.		Control direction of the heat flow.	Limited range of operation. Long response time.	All building types	[55]
Cool Roofs	High reflectance or high emissivity coatings placed on flat roofs.		Reduces peak roof overheating to save cooling energy.	A summer cooling coating can lead to higher energy use in winter.	Residential	[56,57]
Green Roofs	Green roofs or living roofs are roofs that are covered fully or partially with vegetation.		Can be used in building and urban scales, it saves energy by reducing the cooling load.	Initial, management and irrigation costs are high, needs irrigation to be perform well.	Institutional, office and residential Buildings.	[58-60]
Roof pond	Roof ponds store and release heat		The sensible heat stored in water can be used for heating or cooling.	Additional structural support required for large rooftop area. Needs regular maintenance.	Residential	[61]
Sensible heat storage in water in walls.	Water storage mounted on walls.		Stores heat for later release	Requires structural integration.	Residential	[62,63]
Wall incorporated phase change material	Phase change material integrated into wall fabric,		Stores heat for later release.	Can be costly to install	Residential	[64,65]
Window incorporated phase change material	Phase change material in a multiple-pane window.		Stores heat for later release.	Controlled only by the external weather conditions	Residential	[66]
Technologies that heat air						
Ventilated double window	Double pane window with air path between them.		Provides preheating of ventilation air.	Performance depends on the outside wind conditions.	Residential	[67]
Air heating solar collector	Solar air heaters with glazed absorber plate mounted in walls or roof.		Provides heating	Most effective in cold weathers.	Domestic buildings. Greenhouses.	[68-70]
					Residential	[71]

(continued on next page)

Table 1 (*continued*)

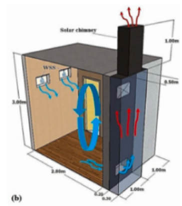
Technology	Description	Illustration	Benefits	Drawbacks	Application	Ref.
Advanced Trombe-Michel wall	Integrated sensible heat storage in masonry with ventilation heat gain or cooling.		Diurnal heat storage is useful in climates with high solar heat gain followed by cold nights	Construction cost is high.		

Table 2
Adaptive features of façade technologies.

Technology	Physical Process				Response Time	Control Type		Readiness			Integration Complexity		Ref.
	Heat	Day-light	Air-flow	PV	H: hours M: minutes S: seconds	Int: Intrinsic Ext: Extrinsic		C: Concept P: Prototype I: Industrial			Inv: Invasive Sup: Superficial		
						Int.	Ext.	C	P	I	Inv.	Sup.	
Thermochromic glazing	✓	✓			M	✓				✓		✓	[27]
Electrochromic glazing	✓	✓			S		✓			✓	✓		[28]
Photovoltaic module with adjustable transmission	✓	✓		✓	S		✓	✓			✓		[23,29,30]
Innovative Window blinds.	✓	✓			M		✓	✓			✓		[31]
Coloured fluid window	✓	✓			S		✓		✓		✓		[32-34]
Reflective external panels	✓	✓		✓	S		✓		✓			✓	[35]
Daylight filtering coatings	✓	✓								✓		✓	[36-43]
PV-TE window	✓	✓		✓	S	✓			✓		✓		[44]
Window-integrated photovoltaic	✓	✓		✓		✓			✓		✓		[45]
Photovoltaic powered blinds	✓	✓		✓	M	✓			✓			✓	[46]
Switchable translucent wall insulation.	✓	✓			S		✓	✓			✓		[54]
Photovoltaic thermal solar collector	✓			✓	M		✓			✓		✓	[47-51]
Switchable opaque wall insulation	✓				H		✓	✓			✓		[52,53]
Thermal diode	✓				M		✓		✓		✓		[55]
Cool Roofs	✓								✓			✓	[56,57]
Green Roofs	✓									✓		✓	[58-60]
Roof pond	✓				M		✓	✓			✓		[61]
Sensible heat storage in water in walls.	✓				M		✓		✓		✓		[62,63]
Wall incorporated phase change material	✓				M	✓		✓			✓		[64,65]
Window incorporated phase change material	✓				M	✓			✓		✓		[66]
Ventilated double window	✓	✓	✓		S		✓		✓		✓		[67]
Air heating solar collector	✓		✓		M		✓		✓		✓		[68]
Ventilated Roofs	✓				S		✓	✓			✓		[69,70]
Advanced Trombe-Michel wall	✓		✓		H		✓		✓		✓		[71]

by comparing the current status of an adaptive facade with that desired to realign status continuously. There are two types of adaptive control: gain scheduling where feedforward adaptive control is based on a-priori knowledge and self-adjusting control based on parameter estimation [94,98-101].

Optimal control determines the best control law for a dynamic adaptive facade. It achieves the minimization or maximization of a real function by choosing the controlled values from a defined range of values. For example, it can pursue the least possible energy cost that will guarantee healthy inside conditions, taking into account the changing outdoor and indoor conditions along with the response times active façade elements [95,101].

Model predictive control (MPC) predicts the upcoming states of an adaptive façade to then take an optimal control action, MPC consists of six elements (i) an objective function, (ii) a prediction horizon, (iii) decision time steps, (iv) manipulated variables, (v) an optimization algorithm and (vi) a feedback signal [89]. Referred to as a "Gray Box" model, an MPC algorithm combines both accuracy and simplicity in its prediction processes. [102]. MPC constantly adjust control parameters based on the future and current conditions of the facade. MPC has the potential to adjust and adapt multiple times per hour responding to any change in the outdoor and internal conditions. MPC control strategies have been used to maintain predefined indoor conditions while minimizing primary energy costs [103,104]. An MPC uses the most effective strategy by producing several time-bounded predictions; in each step, an MPC solves a control problem over those predictions to satisfy both dynamic and comfort constraints [105]. An MPC requires a model that accurately describes an adaptive façade's control variables. There are three main types of MPC model;

(i) data-driven model predictive controls (DDMPC) use output and input data to determine the behaviour of an adaptive façade. DDMPC (i) cannot handle external disturbance and occupant behaviour and (ii) is challenging to find the best solution in large buildings with receding horizon problems [106].
(ii) hybrid models based on energy balance equations require measured data from the façade and the building. State-space models are a good example of a hybrid model most used in MPC, and

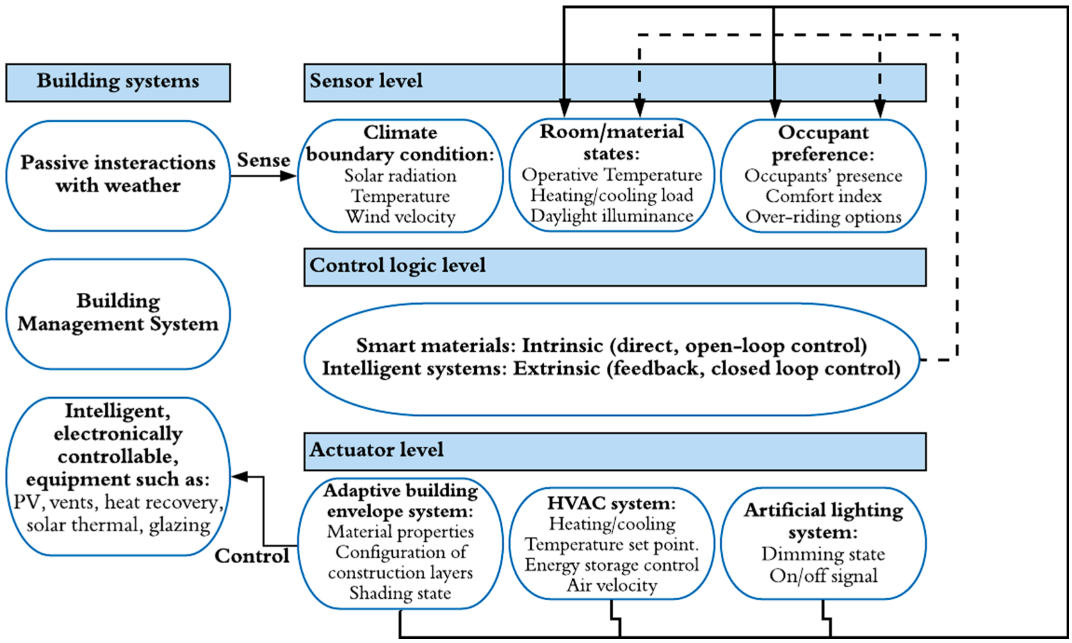


Fig. 3. An overall control architecture (adapted from [73]).

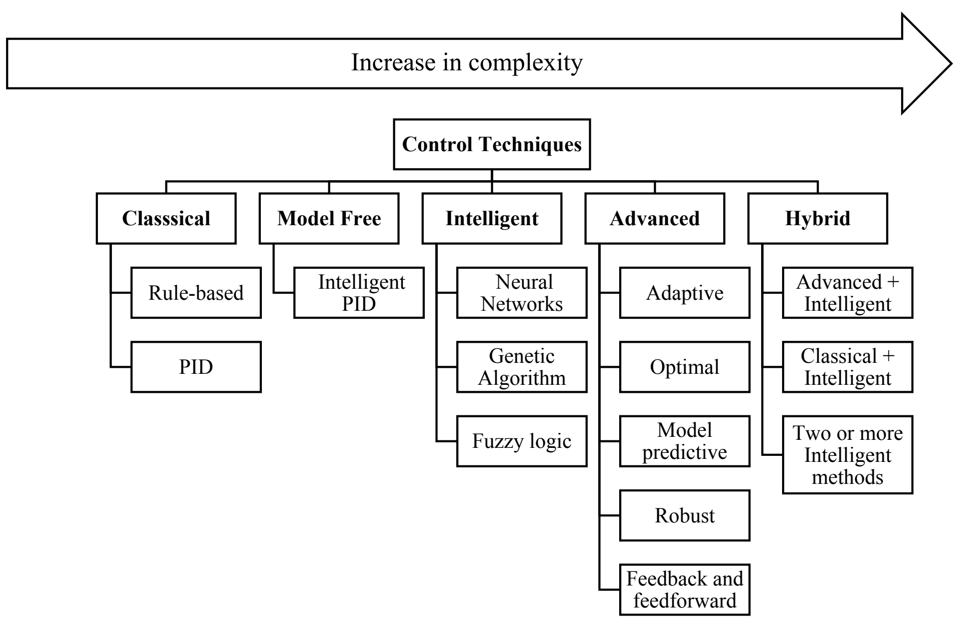


Fig. 4. Taxonomy of control techniques.

(iii) first-principle models use detailed heat and mass balance equations. They have been used rarely because of their computational requirements [96].

Robust control is an approach that intends to design a stable controller despite the disturbances and uncertainties affecting the adaptive façade. It requires an assumed process uncertainty beforehand that provides a description of the system under all conditions. Robust control is stable over the given operation range [97,107,108].

Feedback/Feedforward control combines both feedback control and feedforward control together. Feedback is outputs from the adaptive facade used as control inputs as seen in Fig. 5. Feedback is vulnerable to errors as it can deviate from the defined set-point during disturbance and has response delays. Feedforward, as shown in Fig. 5 depends

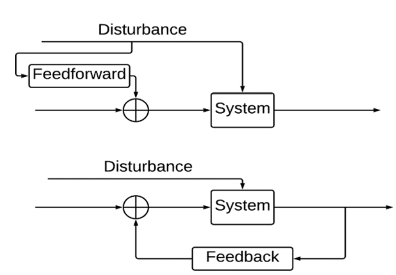


Fig. 5. Feedforward and feedback systems.

heavily on the system model with the output of the system depending on user commands. Feedforward cannot make a correction on the input if the adaptive façade behaviour deviates from that wanted [109-111]. Merging feedback and feedforward combines their advantages to give enhanced overall performance [96].

Intelligent control

Intelligent controllers use data from previous adaptive façade actions and scenarios to inform future control. Intelligent controllers are connectionist systems that learn to perform tasks from past examples without being programmed with specific rules [112]. There are three main intelligent control types (i) genetic algorithms (ii) artificial neural networks and (iii) fuzzy logic.

Genetic Algorithms or evolutionary algorithms use metaheuristic optimization algorithms inspired by reproduction, recombination, selection and mutation. Evolutionary algorithms start with an initial first-generation population of adaptive façade control laws. Those initial laws can be produced by many techniques that can be categorized based on (i) compositionality, (ii) generality and (iii) randomness [113]. After initialization, facade control laws compete to see how effective each law is and rate them accordingly. Thus highly-rated control laws breed more effective next-generation control laws using genetic operations [114,115].

Artificial Neural Network (ANN) is a machine learning tool consisting of multiple layers of nodes that respond dynamically to external inputs using an activation function. An ANN learns the relationships between outputs and inputs to predict adaptive façade performance. In effect, ANN are black-box models within which are input, output, neuron and hidden layers [116].

Fuzzy logic control (FLC) uses continuous values between 0 and 1. FLC is based on fuzzy sets. FLC has three steps: fuzzification, defuzzification and inference engine [117,118].

Hybrid control is a combination of intelligent control with advanced/classical control or a combination of two intelligent control methods. Hybrid control can solve problems facing adaptive façade that are unsolvable by a single façade control system. Training a hybrid system often needs extensive data. Hybrid controls that use classical or advanced controllers are stable whilst also being fast and expert when combined with an intelligent controller [96,119].

Adoption of adaptive façade control techniques

A review of research studies has been performed to determine the most used façade control methods. In the twenty-seven research studies reviewed [120-147]. As shown in Fig. 6, MPC was the most used to control adaptive facades. Table 3 provides a summary of the key attributes of alternative control techniques for adaptive facades.

3.1. Control parameters

Control parameters, sensor outputs that activate a response from a control strategy [156], can be divided into the three main types shown in Fig. 7. Each type contains several parameters that can be chosen to control the adaptive facade [73].

A particular adaptive façade technology may be most effectively controlled by (i) more than one parameter, (ii) different parameters over time, for example, for day and night and (iii) different parameters depending on building location or façade orientation. Given interdependencies between possible control parameters, one parameter may be a proxy for a set of linked parameters. For example, when outdoor air temperature, room air temperature, solar radiation incident on a window and global horizontal irradiance were compared for the control of smart windows in six USA locations, it was found that outdoor air temperature is the best control parameter for smart windows [157]. For adaptive façade technologies that generate electricity that can be sold to a utility, grid pricing may be a relevant control parameter to achieve (i) optimal price (ii) comfort (iii) grid stability and (iv) coordination between the grid and the building [158-162]. Possible control parameter(s) for an adaptive façade technology can be tested for appropriateness and optimized either via computational simulations [163] or in a physical test cell.

4. Responsiveness

The most suitable control strategies for façade technologies is often determined by the dynamic response time. The dynamic response time of the adaptive façade can be split into (i) response time of the building

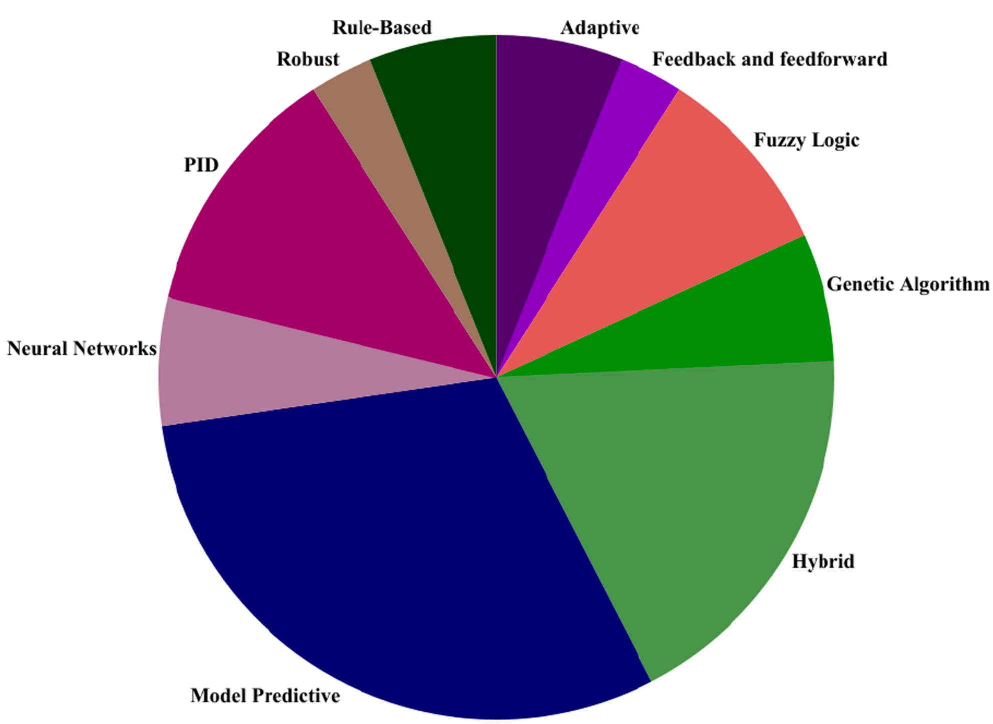
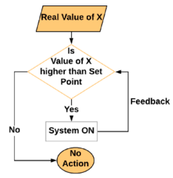
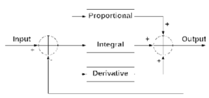
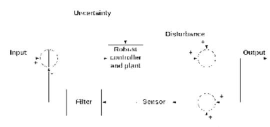
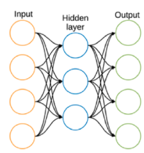
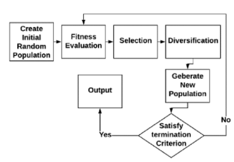
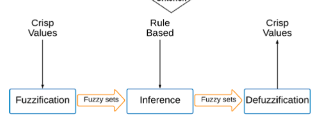
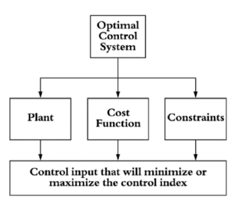
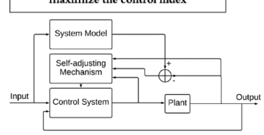
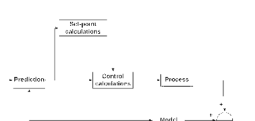
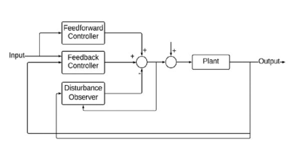


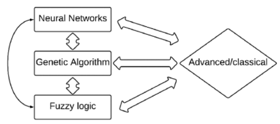
Fig. 6. Control techniques frequency in studies on residential and greenhouse façades [120–147].

Table 3
Control methods for adaptive facades.

Control Method	Operation	Diagram	Advantages	Disadvantages	Ref.
Rule-based	Uses a set of rules to create set-points and schedules.		• Fast response. • Easy to implement. • Low cost. • Overshoot the desired condition.	• Depends heavily on the engineer's knowledge. • Reliability decreases when the rules get complicated. • Not able to follow the set point accurately. • Not good for the long term. • Does not achieve optimum energy saving.	[148,149]
Proportional Integral Derivative (PID)	Proportional controller produces an output which is proportional to the error, Integral controller removes the error, Derivative controller minimizes the overshooting.		• Avoids overshooting the desired condition. • Derivative term handles sudden changes.	• Can make the system unstable. • Takes a long time to be tuned.	[150,151]
Robust	Generates control rules that form the response of the system to the desired behaviour and maintain that operation constant against fluctuations.		• Can handle noise and disturbance. • Stable operation. • Does not require previous knowledge from the uncertain input.	• Cannot handle big changes in behaviour.	[95]
Neural Networks	Tests certain problem with previous records to find solutions to the problem.		• Can process a large dataset. • Can work with incomplete knowledge. • Have some fault tolerance. • Good performance when used for prediction over a short term.	• Requires a large amount of data. • Hardware dependence. • Large number of parameters need to be known.	[152,153]
Genetic Algorithm	Generate possibilities in which the most appropriate solution is selected.		• Quick to implement. • Good way to solve hard optimization problems.	• Sometimes it does not work well with real-time HVAC applications. • The computational cost can be high.	[95,114]
Fuzzy logic	Consists of three steps: fuzzification, inference engine and defuzzification.Preform action in the form of "if-then-else" statements.		• Accurate. • Fast response. • Does not need detailed knowledge of the system model.	• Cannot handle large input data. • Creating the exact number of rules can be slow. • Requires good knowledge of the plant's functioning.	[154]
Optimal	Optimizes the technology parameter to select the best control strategy.		• Handles multiple control variables. • Enhance the energy saving. • Fast response.	• Good system model is required. • Can be complex unless the system has a special configuration.	[86]
Adaptive	It changes the technology's operation to the best mode possible by comparing the current stats with the desired one and report the stats continuously.		• Fast response. • Easy to implement. • Stable. • It changes the parameters quickly.	• Good system model is required. • The resulting control system is non-user-friendly. • Sensitive to noise.	[86,98]
Model predictive	Consists of six main elements: objective function, prediction horizon, decision time step, manipulated variable algorithm and feedback signal.		• Predict future changes and disturbance. • Enhance energy-saving, disturbance prediction, the efficiency of the technology and decrease the fluctuation from the desired behaviour.	• Expensive installation. • Requires a good system model.	[86,155]
Feedback and feedforward	Combination of feedback and feedforward. The feedforward generates the input required to achieve the desired performance and the feedback corrects for errors.		• Enables a linear controller to solve nonlinear problems, • Can be combined with PID and MPC to enhance their performance.	• Does not perform well with large parameter variation.	[96]
Hybrid			• Has a fast response.		[154]

(continued on next page)

Table 3 (*continued*)

Control Method	Operation	Diagram	Advantages	Disadvantages	Ref.
	Combines Classical or advanced control methods with an intelligent control method. Or it can be a combination of two or more intelligent methods together.		• Solves complicated problems. • Stable.	• Needs user experience, • Need a lot of data to be trained • Hard to tune the classical/advanced controller.	

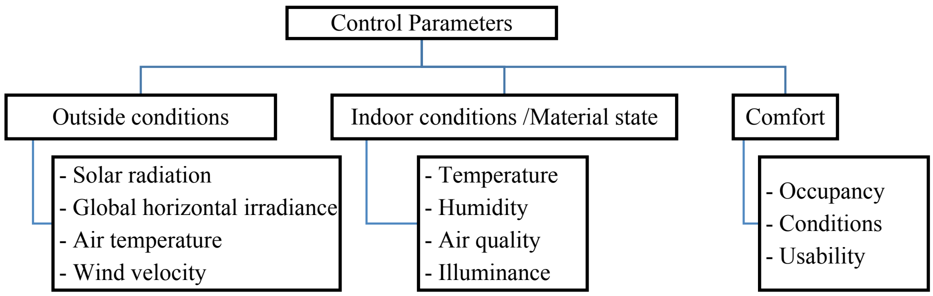


Fig. 7. Types of Control parameters.

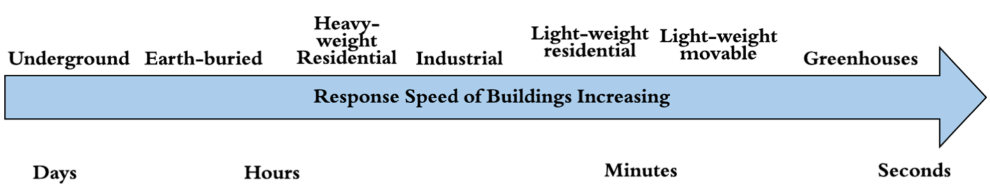


Fig. 8. Response times of different building types.

fabric and (ii) response time of the adaptive and conventional façade technologies.

A building's thermal mass exposed to the internal or external environment responds in a time-dependent way. The heavier a building façade's thermal mass, the longer it takes to react to changes. Fig. 8 compares the response time of different building types.

To understand the effect of the building envelope on the response time of the building, a simple thermal time constant, τ, that indicates the time taken for a building to heat-up or cool-down [164-168] can be derived by considering a thermal system described by equation (1):

$$Q - UA(T_{ai} - T_{ao}) = mC\frac{dT_{ai}}{dt} \quad (1)$$

Then assuming that the differential term is zero, equation (1) becomes:

$$Q = pUA(T_{aid} - T_{aod}) \quad (2)$$

Combining Eqs. (1) and (2) gives:

$$(T_{ai} - T_{ao}) + \frac{mC}{UA}\frac{dT_{ai}}{dT} = p(T_{aid} - T_{aod}) \quad (3)$$

The coefficient $\frac{mC}{UA}$ is the time constant τ or steady-state heat-up time. Integrating Eq. (3) gives:

$$T_{ai} = pT_{aid}\left[1 - exp\left(-\frac{T}{\tau}\right)\right] \quad (4)$$

The time constant can be defined from Eq. (4), the time constant is the time for the temperature to rise 63.2% of the final temperature when $t = \tau$, so $T_{ai} = 0.63p\ T_{ai\ d}$, when $t = 2\ \tau$ then the time constant becomes 86% of the final temperature.

The thermal mass of a wall affects the time constant [169]. Assuming that the thermal mass of a wall can be represented by two resistances and one capacitance ignoring surface resistance, the differential equation becomes [164]:

$$T_w = \frac{R_1 T_{ai}}{(R_1 + R_2)}\left[1 - exp(-\frac{t(R_1 + R_2)}{R_1 R_2 C})\right] \quad (5)$$

Assuming that $R1 = R2 = R$ the time constant of the wall becomes $T_{extwall} = \frac{RC}{2}$, the differential equations mentioned above can respond to different input functions. Three main inputs functions shown in Fig. 9 can be applied to the first-order system (i) step function input, (ii) ramp input, (iii) impulse input. Each input function results in a different output. Accurately predicting response time can be done by knowing how a certain building fabric responds to different inputs.

An important response time in adaptive facades is the adaptive technology response time. Different adaptive technologies can response at second, minute, hour, day timescales as shown in Table 4 [73].

To achieve the best performance, control strategies should align with the technology's and envelope's response times. Correct matching between the control strategy and the technology's response has a huge effect on the performance of some adaptive technologies, for example choosing the right control strategy for the PV tracking can lower the response time which can enhance the performance of the PV [173]. On the other hand, sometimes the response time will have a negligible effect

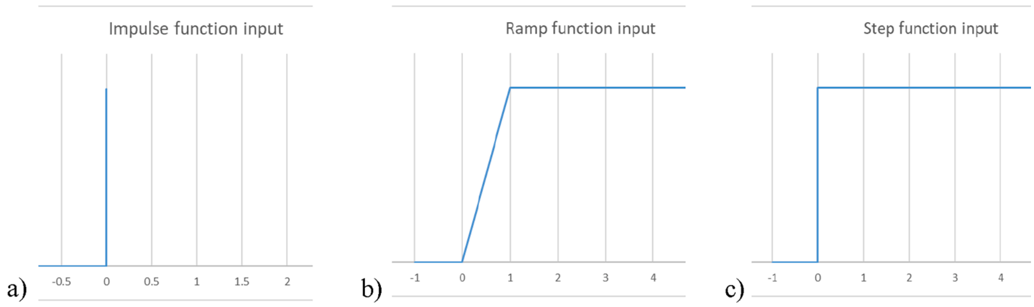


Fig. 9. (a) Impulse function input. (b) Ramp function input. (c) Step function input [170].

Table 4
Indicative response times of specific adaptive technologies.

Indicative response time	Example of fluctuation	Example of reacting façade element
Second	Very short-term changes in wind speed	Breathing panel reacts to changes in wind pressure [171]
Minute	Short-term changes in cloud cover and solar radiation	Switchable glazing [9]
Hour	Diurnal changes in incident solar radiation	PV with two-axis tracking [172]
Day	Changes in occupancy; day-night temperature cycles	Thermal storage using thermal roof ponds [61]

on the performance, for example electrochromic windows tinting speed was shown to have almost no effect on the energy consumed in the building [174].

The response time of the technology depends heavily on how fast the control parameters (mentioned in section 3.1) are being measured by the sensor, so lower response time can be achieved by having high frequency sensing. Computational tools can also be used to accurately predict the response time of both the fabric and the technology.

5. Conclusion

The range and diversity of adaptive façade technologies is growing. However, many adaptive façade technologies remain designed for, and used in, single projects. There has not been widespread commercialization of adaptive façade technologies for either new or existing buildings. As the majority of the building stock is not energy efficient and must be refurbished following the EU "renovation wave", the development of adaptive facades for retrofitting buildings will have a faster and more significant reduction on the energy use and greenhouse gas emissions than a sole focus on new buildings. Excluding greenhouses, there has been limited research on adaptive industrial building façade technologies and their control probably because industrial buildings typically dissociate the use of the façade and the industrial process rather than exploiting the façade for the process or because occupants' comfort is secondary to the design of such building. Particularly promising adaptive façade technologies are [175]: (i) dynamic shading (ii) chromogenic glazings (iii) solar active facades and (iv) active ventilation facades.

Future residential adaptive facades should:

- be easily integrated into a wide range of existing building types,
- arise from human-centred design,
- use smart/intelligent and scalable control techniques that holistically integrate façade technologies/systems performances with the overall-building performance, and
- be adopted in building types in which they have to-date been underused, such as industrial buildings.

There are many available simulation tools that can be used for selecting and optimizing the most suitable mix of adaptive features and their control. Adaptive features must have an effective control algorithm driven by both external and internal control parameters connected to other systems in the building. MPC is the most used control strategy in residential buildings and greenhouses. The relative merits of the wide range of possible alternative control algorithm and parameter combined actions remain to be fully investigated.

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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