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Review

Multi-Skin Adaptive Ventilated Facade: A Review

Darya Andreeva, Darya Nemova * and Evgeny Kotov

Institute of Civil Engineering, Peter the Great St. Petersburg Polytechnic University, 195251 Saint Petersburg, Russia; andreeva_ds@spbstu.ru (D.A.); ekotov.cfd@gmail.com (E.K.)
* Correspondence: nemova_dv@spbstu.ru

Abstract: Multi-skin ventilated facades with integrated building elements that respond to climatic conditions (mechanized openings and automatic shading with intelligent control) present the potential of improving overall annual energy savings by adapting the thermal properties of buildings. This paper presents a literature review on multi-skin adaptive ventilated facades. Additionally, this article presents a literature review on building envelopes that contain inner-air layers. The operation modes of the air layer used in building enclosure structures are classified and summarized and the thermal performance and benefits of climate-adaptive facades are discussed and reviewed. The existing operation modes of the air layer used in building envelopes are summarized, outlined and roughly classified into the following types: the enclosed type, the naturally ventilated type and the mechanically ventilated type. One of the sustainable development trends is the investigation and application of energy-efficient climate-adaptive facades. In this study, the energy modeling of a high-rise office building was calculated using the Green Building Studio. The annual energy, the annual CO_2 emissions, and life cycle energy for the following three types of facade were estimated: a single-layer facade made of three-layer glass with argon, a double ventilated facade, and a triple ventilated facade with a double chamber. The calculation results show that the annual energy of the building with an adaptive triple-skin facade could be reduced by 15% compared with buildings with a single skin facade.

Keywords: adaptive facade; multi-skin facade; double-skin ventilated facade; triple-skin ventilated facade; numerical modeling; carbon emission; heat and mass transfer; energy efficiency; building

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1. Introduction

A variety of factors will shape the future of buildings and cities. Among the most influential drivers that will affect the way we design and operate buildings is the need for decarburization as well as for supplying energy from clean and renewable sources. Globally, all energy produced is consumed by several main sectors: the residential sector, the commercial sector, the industrial sector, and the transport sector [1]. The built environment is partly responsible for the current situation and offers opportunities for new solutions to address the societal challenges of climate change and sustainable development [2,3]. The United Nations Environment Program [4] has determined that buildings consume 30–40% of the world's total primary energy costs. With the acceleration of urbanization and the constant improvement in residents' standard of living, the construction sector will continue to dominate the process of energy conservation and emission reduction. Reducing environmental pollution (CO_2 emissions) throughout the life cycle (production, operation, and disposal) of buildings is an urgent and important problem. The European Commission (EC) has identified the building sector as a key enabler in its long-term decarburization strategy by targeting a reduction in CO_2 emissions of at least 80% by the year 2050 [5–7].

The loss of thermal energy through the external enclosing structures of buildings is one of the main components in the structure of the costs of thermal energy spent on heating and cooling and accounts for 30–50% of all heat energy loss [8]. The loss of thermal energy directly depends on the thermal characteristics of the external enclosing structures.

The thermal conductivity, the thermal resistance and thermal transmittance are very important parameters in the evaluation of the energy efficiency of buildings. In this work, the authors offer a method for determining the thermal characteristics based on cooling measurements, using a multiple regression mode. The results show that the model can be used to define the thermal characteristics of building structures [9]. Development U-value of window and glazing facade is illustrated at Figure 1.

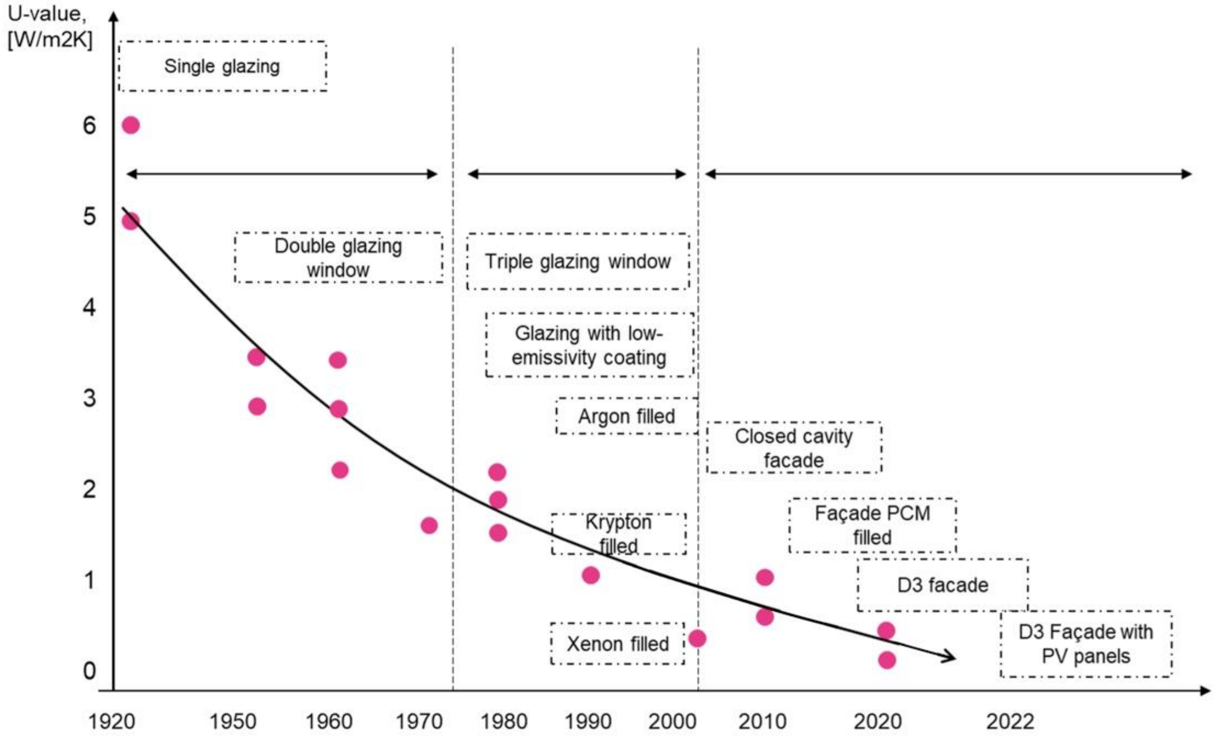


Figure 1. Development U-value of window and glazing façade.

To improve the energy efficiency of facade systems it is possible to use the air layers as an internal structural layer of a building's enclosing structures. The use of enclosing structures with air layers has gained popularity [10,11].

The concept of double skin facades (DSF) was first proposed in the early 1900s [12]. DSF is gaining popularity as an architectural element as more translucent facades are used in modern office buildings. A double-ventilated facade consists of an outer facade layer, an inner layer, and an air layer between them. The outer layer (tempered glass) protects the building from external conditions and provides additional sound insulation from external noise, while the inner layer consists of either double glass or thermal insulation material. The width of the air space between the two shells, called the air channel, ranges from 20 mm to more than 1 m [13]. An adjustable shading device (blinds) can be installed in the air channel to protect from the sun and control solar radiation [14]. DSF can work both in the mode of an absence of air convection (closed air layer) and in the mode of natural or forced convection (with air ventilation). The closed air layer mode provides additional thermal insulation of the outer shells to reduce heat transfer in winter. The mode with air ventilation solves the problems of overheating in summer, removes moisture from the insulation materials, and helps to achieve energy savings in winter. Several different facade systems are characterized by the presence of one or more air layers between the exterior cladding and thermal insulation (which is continuous throughout the entire height of the facade). There is a growing interest in triple ventilated facades consisting of outer, middle, and inner layers separated by two air layers [15].

The use of convective air movement in ventilated channels of facades provides several advantages for the entire building, such as passive cooling, room heating, natural ventilation, a fresh air supply to the room, and the prevention of insulation destruction. Numerous studies and publications have detailed the effects of using air layers in the enclosing structures of buildings. Several studies have been conducted on passive energy saving in buildings [16,17], the energy efficiency and thermal characteristics of ventilated facades with double cladding triple-ventilated facades [18–21], closed cavity facade, ventilated facades using phase-change materials (PCM), ventilated facades with solar photovoltaic (PV) panels [22–34] and convective currents in air layers [35–42].

In this study, the accumulation of thermal energy was applied to the building structure using the intelligent heat accumulation of materials with a high thermal mass. The research is directed towards the introduction of materials for storing latent heat, which, if used correctly, can have a real effect in reducing energy costs without taking up the space needed for accumulation. The authors review the heat energy accumulation of passive systems that have been integrated in building structures, and classify them [43].

The simulation results can help designers make the right choice in terms of the location of PCM wall panels, the planned ventilation rate at night and the maximum melting point value for a particular PCM.

This study explored a fencing system that uses 50% recycled polystyrene foam (EPS) to generate lightweight foam concrete panels. A comprehensive study was performed to define the embodied energy of these panels. A comparable study that was performed using a single-storey building and different materials indicated that a prefabricated foam concrete panel is a good component and can be considered as the main enclosing material. This article presents research defining changes in the physical characteristics of expanded polystyrene supplemented with graphite when subjected to solar radiation. When subjected to a higher intensity of synthetic solar radiation, the extensible force improved and the materials absorption increased. The material subjected to a higher rate of solar radiation had a higher compressive strength than the material subjected to a lower rate of solar radiation [44].

2. Scientometric Literature Analysis

A scientometric analysis of the literature over the last 5 years was carried out using the Scopus database. Visualization of the scientific landscape was made possible by using the VOS Viewer program. In Figure 2, a map based on keywords in the literature on enclosure structures is presented. The analysis shows that the research-relevant topics for building enclosing structures are energy efficiency, sustainable development, photovoltaic cells, and intelligent buildings. However, with a detailed analysis of the literature, it becomes clear that the research mainly focuses on the external adaptive elements of buildings. Overheating from solar radiation is solved primarily by using intelligent climate-adaptive dynamic facades. The purpose of dynamic facades is to promote the development of sustainable architecture. Dynamic facades act as filters between the room and the street, providing appropriate shade, sunlight, ventilation, and visual unification. However, according to the authors, a modern facade should be developed as a flexible and efficient shell that responds to external climatic conditions while simultaneously determining internal requirements by controlling the movement of airflows in the air channels between the facade shells. The creation of multi-skin ventilated facades with controlled modes of air currents under various climatic conditions is a promising research avenue.

The Topic Prominence percentile for topic «T.18162 Facades; Blinds; Natural Ventilation» (Scopus Database) is equal to 94.7% (Figure 3).

The most active institutions for the topic «T.18162 Facades; Blinds; Natural Ventilation» are shown at Figure 4.

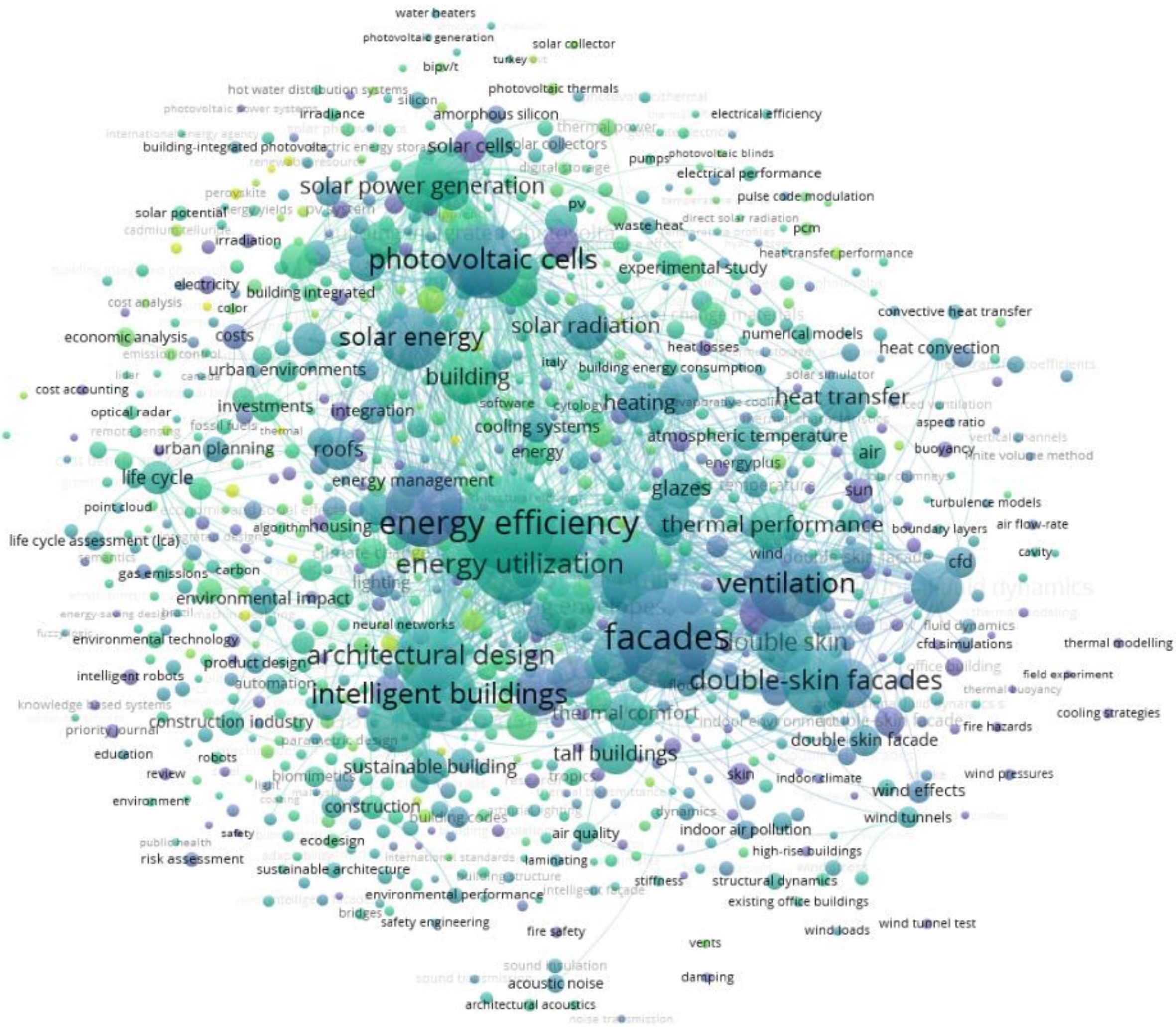


Figure 2. Visualization of scientific landscapes by indexed keywords, SCOPUS (VOS Viewer).

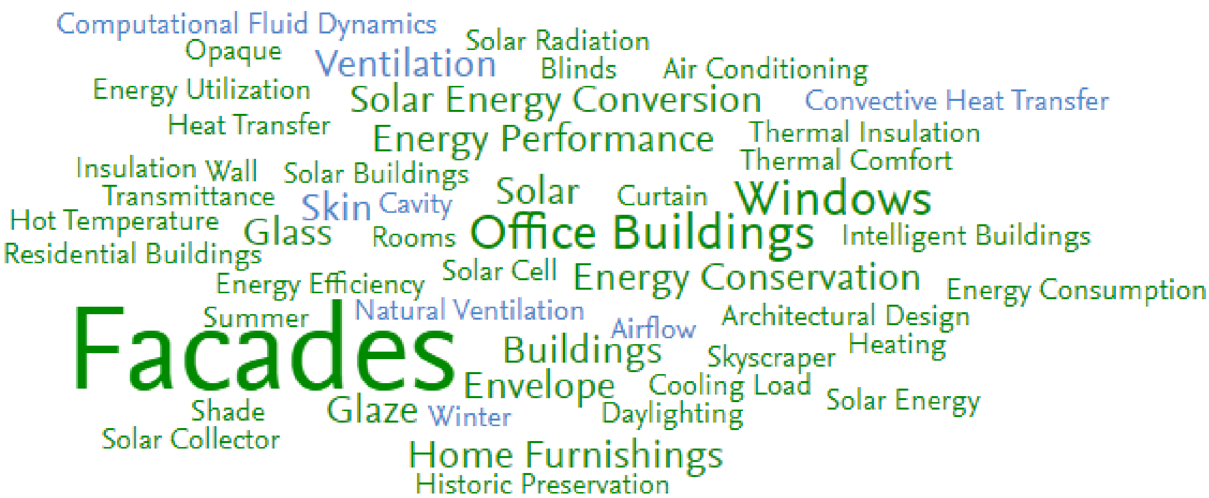


Figure 3. Visualization of scientific landscapes by indexed keywords.

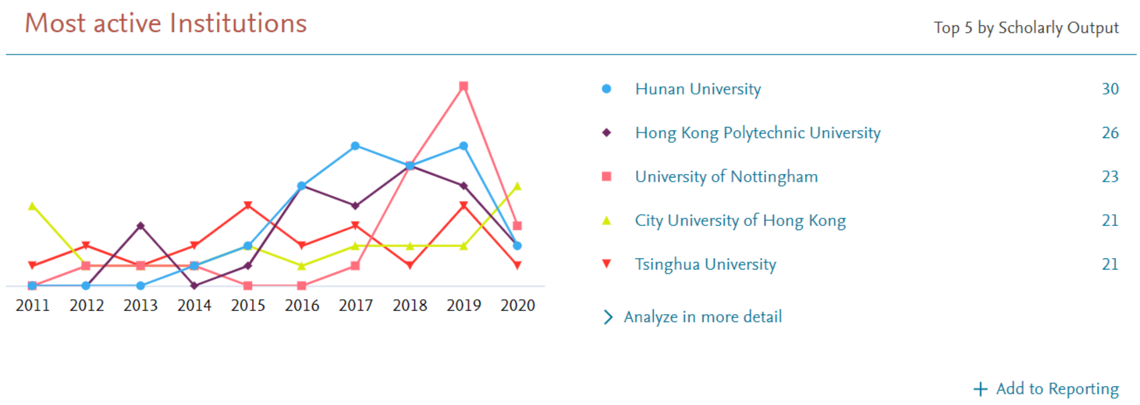


Figure 4. Most active institutions for the topic «T.18162 Facades; Blinds; Natural Ventilation».

The most active Countries/Regions for the topic «T.18162 Facades; Blinds; Natural Ventilation» are shown at Figure 5.

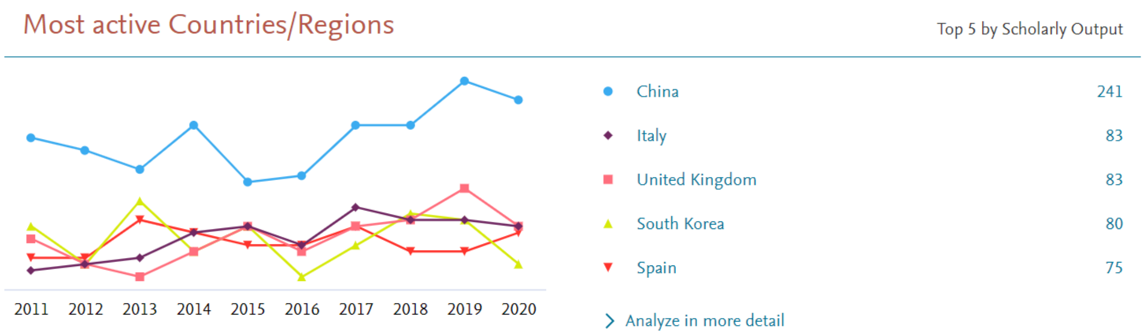


Figure 5. Most active Countries/Regions for the topic «T.18162 Facades; Blinds; Natural Ventilation».

The most active Authors for the topic «T.18162 Facades; Blinds; Natural Ventilation» are shown at Figure 6.

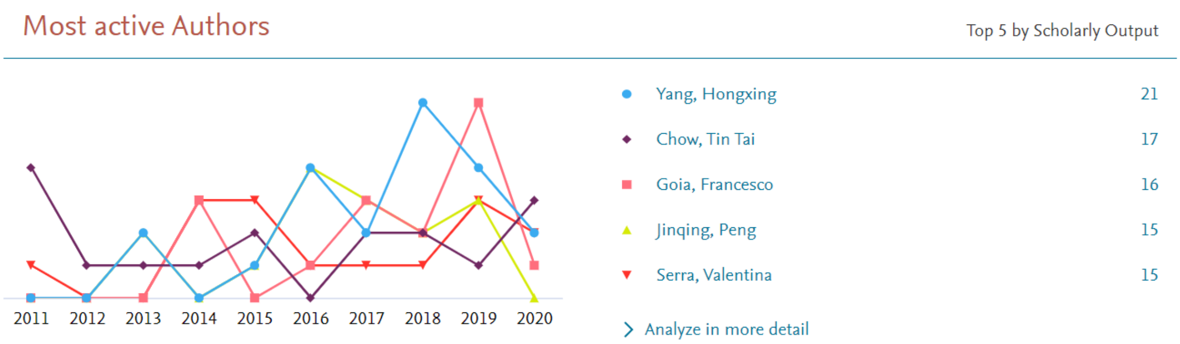


Figure 6. Most active Authors for the topic «T.18162 Facades; Blinds; Natural Ventilation».

The most active Authors for the topic «T.18162 Facades; Blinds; Natural Ventilation» are shown at Figure 7.

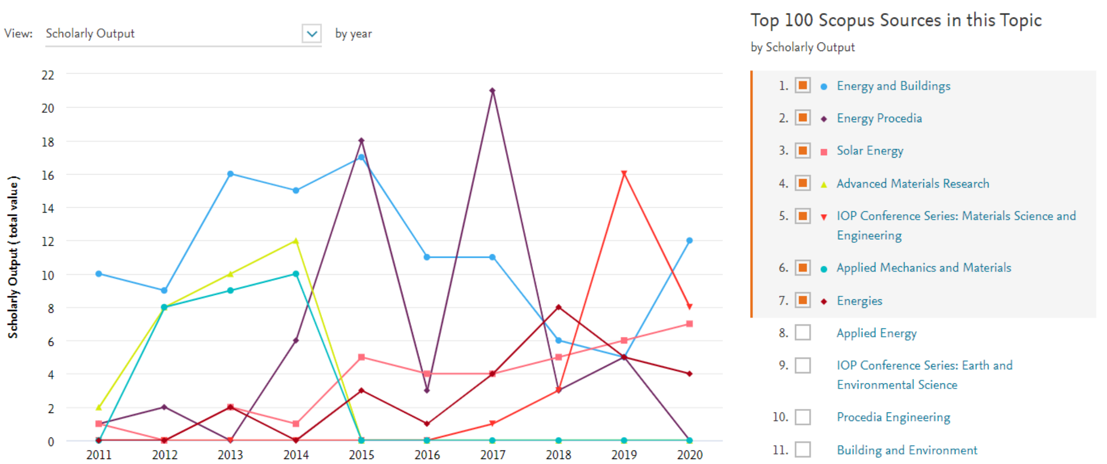


Figure 7. Most active Scopus Sources for topic «T.18162 Facades; Blinds; Natural Ventilation».

3. Classification of Ventilated Facades

Figure 8 shows the classification of ventilated facades.

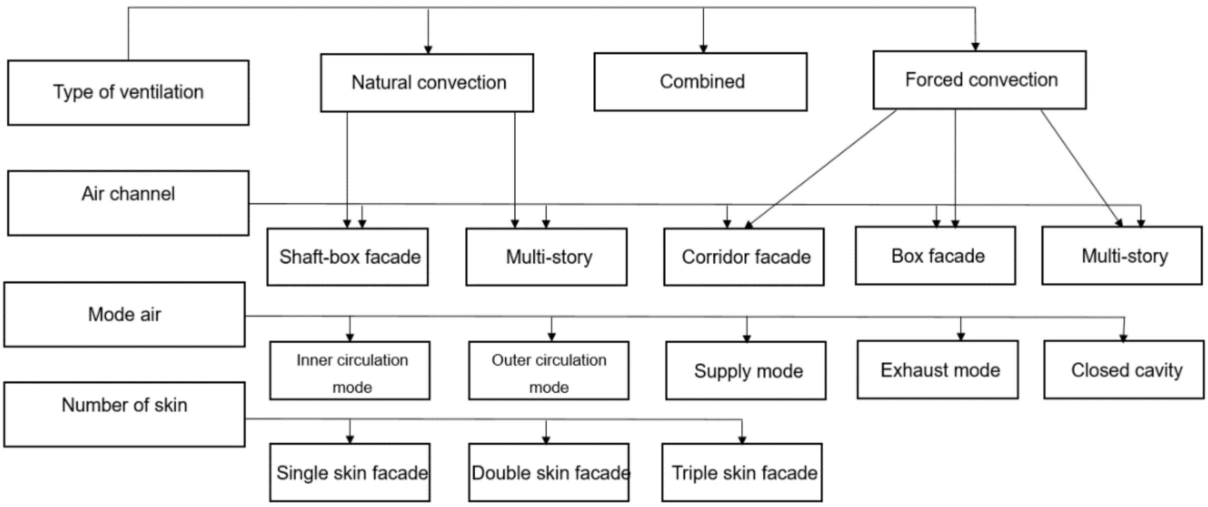


Figure 8. Classification of ventilated facades.

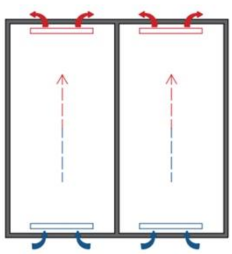
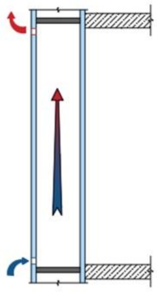
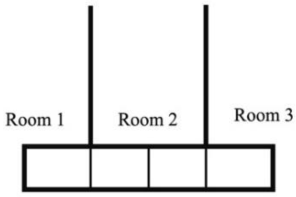
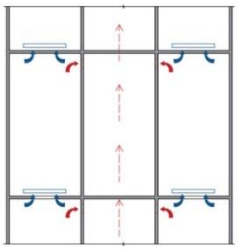
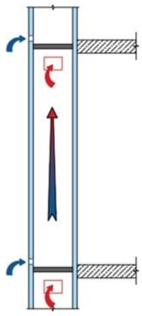
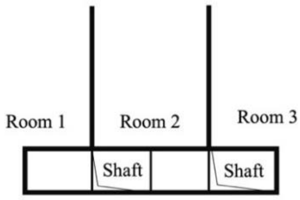
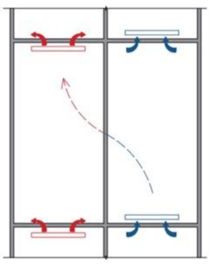
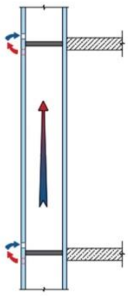
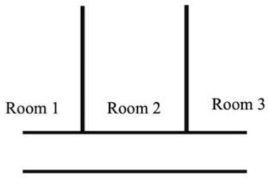
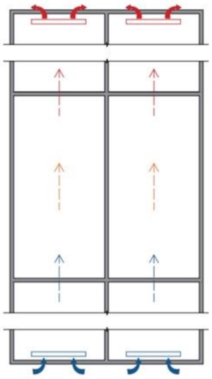
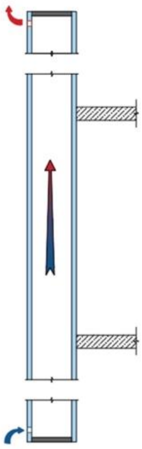
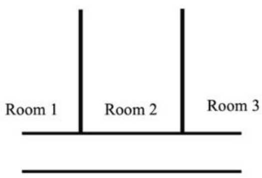
3.1. Different Connection Types of Ventilated Facades

The ventilated facades are classified into different connection types according to the type of airflow system, such as the Box-window, the Shaft-box, the Corridor, and the Multi-story system [45]. Connection types for ventilated facades are presented at the Table 1.

Ventilated facades can be classified into facades (a) with open rusts (seams) and (b) with closed rusts or without rusts. Ventilated facades with open rusts provide free air circulation between the air chamber and the external environment through the seams between the exterior cladding panels. In facades of this type, air enters the chamber from the outside through the rust of the lower part of the facade and then exits through the upper joints [46,47]. The energy efficiency of the facade was explored by developing numerical models, CFD [48], and experimentally using non-intrusive methods to measure the airflow [49].

There are no open rusts between the parts of the exterior cladding in ventilated facades with a closed connection, so air enters the chamber through a hole or grate located in the lower part of the facade and exits through a vent in the upper part of the facade. The thermal characteristics of ventilated facades with a closed connection were studied using computational fluid dynamics modeling [50] and energy modeling [51].

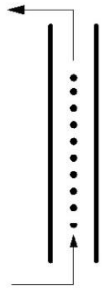
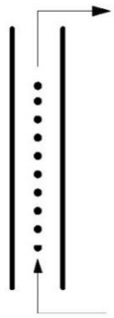
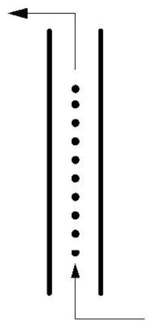
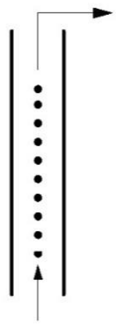
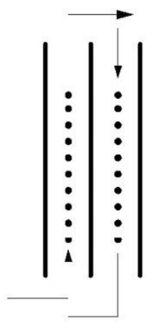
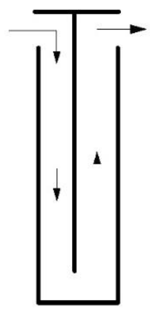
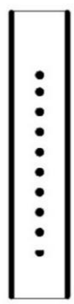
Table 1. Connection types for ventilated facades.

<table>
<tr><th>Type</th><th>Facade</th><th>Section</th><th>Plan</th><th>Construction</th><th>Air Circulation</th></tr>
<tr><td>Box</td><td></td><td></td><td>
</td><td>Horizontal and vertical split</td><td>Through horizontal and vertical rusts</td></tr>
<tr><td>Shaft-box</td><td></td><td></td><td>
</td><td>Combined split</td><td>Combined</td></tr>
<tr><td>Corridor</td><td></td><td></td><td>
</td><td>Horizontal split</td><td>Through horizontal rusts</td></tr>
<tr><td>Multi-story</td><td></td><td></td><td>
</td><td>No division</td><td>Through the air channel over the entire height</td></tr>
</table>

3.2. Working Air Modes of the Ventilated Facade

Free and forced convection processes can develop in the building structure. Natural convection in a permeable and porous medium occurs when there is a temperature or pressure gradient and, accordingly, different air densities at different points of the thermal insulation material. Modes of ventilation of the air layers of the façade is presented at Table 2.

Table 2. Modes of ventilation of the air layers of the facade.

Air Mode		Description	Principal Scheme
Ventilated air gap	Outside air	The internal air enters the air cavity from the room and is removed through the exhaust ventilation duct or directly into the environment.	
	Internal air	The air from the room passes into the interstitial space and is then removed through the exhaust duct or directly into the environment.	
	Air supply by the ventilation system	(a) Air is passed between the panes before it is fed into the room from the supply channels of the ventilation systems. (b) Air enters the cavity from the premises of the building and is then ejected outside.	 
	Combined	For multi-skin façade.	 
Non-Ventilated air gap	Closed cavity facade	The cavities form a buffer zone between the street and the premises, the cavities are not ventilated.	

Forced convection in a porous medium occurs if the directional movement (flow) of air relative to the boundary surface in the space bordering the material and the boundary is permeable.

Facade systems can be classified according to the mode of ventilation of the air space (Figure 9), as follows:

(1) Air from the room;
(2) Outside air;
(3) Supply air from the ventilation-conditioning system;
(4) Combined air supply.

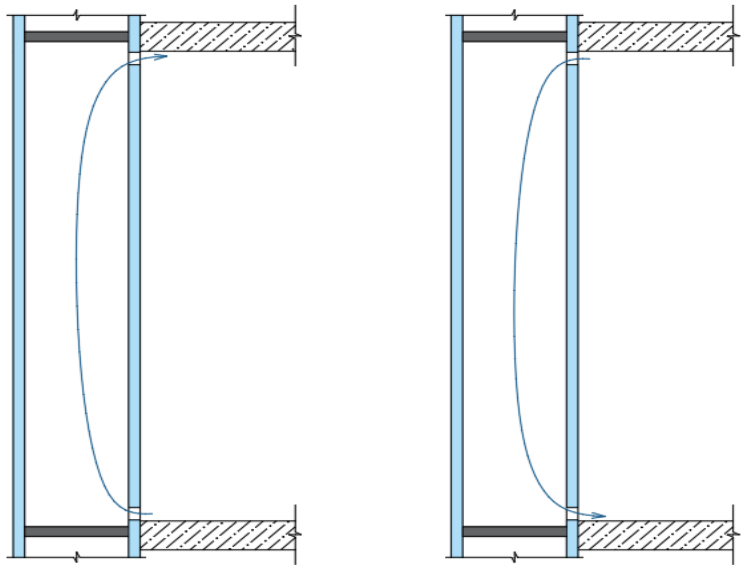


Figure 9. Facade systems with ventilation of the interstitial space with internal air (internal air curtain).

Figure 9 presents a scheme of facade systems ventilated with indoor air from a room. Air from the room passes into the interstitial space and is then removed through the exhaust duct or directly into the environment.

The heated air between the glazing layers is extracted through the cavity; thereby, the inner layer of glazing performs cooling. The outer layer of insulating glass minimizes heat-transfer losses.

The amount of heat from the outside air and solar radiation during the warm season is reduced, which significantly reduces the load of the cooling system. Part of the heat of the air removed from the room is utilized during the cold season, which reduces the load of heating systems.

The heat input from the outside air and solar radiation decreases in hot climates and during solar radiation, and the load of cooling systems of buildings is reduced. The shading blinds are often installed in the interstitial space for ventilated translucent structures in hot climates. Blinds shade the room and absorb the heat from solar radiation.

The translucent structures ventilated with air from the room have an internal surface temperature equal to the indoor air temperature, which increases indoor comfort.

Figure 10 shows schematic diagrams of facade systems ventilated by outdoor air. Internal air enters the air cavity from the room and is removed through the exhaust ventilation duct or directly into the environment. The interstitial space is connected with the outdoor air in the upper and lower parts.

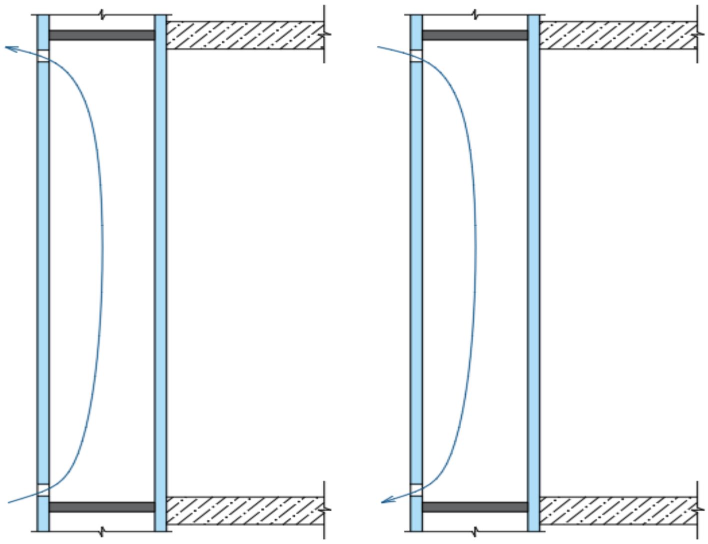


Figure 10. Facades with ventilated air gap by external air (external air curtain).

During the cold season, the heat leaving the room through the interstitial space heats the air entering the room for further use in ventilation systems. The amount of heat required to compensate for the room's heat loss is reduced. Such facade systems are rational to use in hot climates.

Figure 11 presents the principal scheme of facade systems integrated with the ventilation system. Air is passed between the windows before it is fed into the room from the supply channels of the ventilation systems. It is supposed to carry out air heating of buildings in winter and air conditioning in summer.

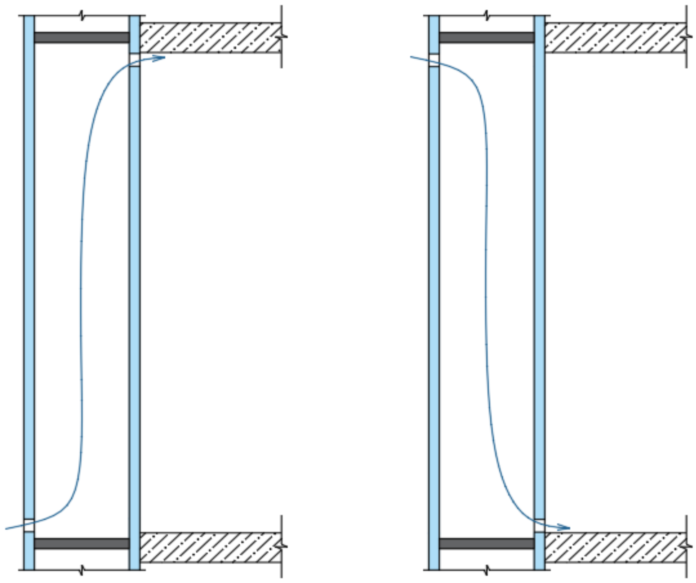


Figure 11. Facade systems with air mode.

Air enters from the environment into the cavity and then into the building through the facade or ventilation system. It becomes possible to update the indoor air with fresh air from the environment.

Figure 12 illustrates that another type of ventilation of the air space is possible if air enters the cavity from the premises of the building and then is removed. In this scheme, the exhaust air is removed from the premises.

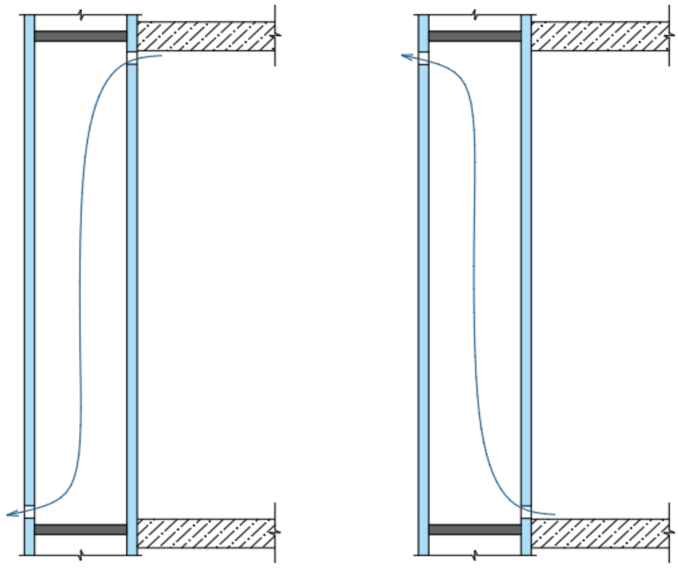


Figure 12. Facade systems with exhaust mode.

Figure 13 shows the principal scheme of a facade with a closed air cavity. The complete tightness of the facade characterizes this type of facade. The air cavity forms a buffer zone between the environment and the premises and the cavity is not ventilated. The low coefficient of thermal conductivity of the air (λ = 0.024 W/m·K) allows for the use of air as a thermal insulation layer. Air is an excellent heat insulator if it is in a stationary state.

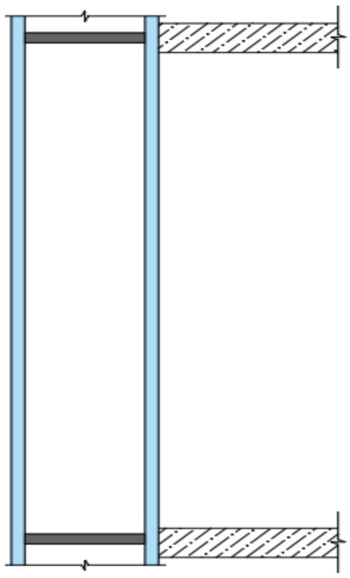


Figure 13. Facade systems with closed air layers (buffer zones).

Multi-skin facade systems can take into account climatic conditions due to configurable and controlled airflow modes to reduce heat loss and increase the comfort of the room.

The multi-skin facade consists of three glass panels bounding a U-shaped channel (Figure 14). The air flow is controlled by forced or mixed convection connected to the air exhaust system from the building (mechanical or natural) [52,53].

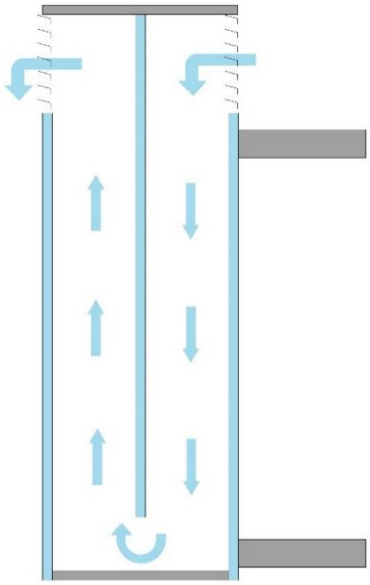


Figure 14. Triple ventilated facade with U-shaped airflow.

The incoming air moves down between the two panel, rises between the second and third panels, and enters the heated space. The incoming outdoor air is preheated because of heat-loss recovery and absorbed solar energy. Such an effect reduces energy costs.

A triple ventilated facade filled with PCM material can effectively prevent the phenomenon of overheating and has advantageous characteristics for heat preservation and insulation [54,55].

In a different study, the authors proposed a ventilated translucent structure for exhaust ventilation with triple glazing [56]. The structure presents three panels, air cavities, and built-in blinds. The study results show that the proposed design can significantly reduce heat loss/heat inflow through the window during peak winter and summer days, respectively.

The combined ventilation schemes increase the comfort level in the room, protection from hypothermia in the cold season and protection from overheating in the warm season.

4. Type of Multi-Skin Ventilated Facades

4.1. Single Skin Facade

A single skin facade presents a double-glazed unit (DGU) or triple-glazed unit (TGU). The facade can include internal blinds and a low-E coating on the glass.

4.2. Double Skin Facade

Double skin facades present outside a double-glazed unit and inside a single-glazing unit form an air cavity. The blinds can be used in a ventilated air cavity.

4.3. Closed Cavity Facade

A closed cavity facade is a double-skin facade present on the outside of a single-glazing unit or inside a DGU or TGU. It forms a ventilated cavity where blinds can be integrated.

4.4. D3 Facade

A D3 facade consists of two separated, closed or ventilated air cavities, which are supplied with clean and dry air and prevents condensation. The dry and clean-faced cavities are equipped with a high-quality, robust, and automated solar-shading and air mode system, which can be operated individually based on climate zones and boundaries. The benefit is a unique architectural feature—the visual appearance of the facade changes in line with the position of the solar shading (e.g., summer or winter appearance).

A D3 facade dynamically adapts to the varying external weather conditions, the comfort of building occupants, and energy needs. The shading system behavior can be designed for each specific building in moderate climates using project-specific control algorithms and building-users can override such possibilities. Furthermore, a D3 facade provides energy savings in combination with natural light transmittance and thermal comfort for the occupants. It contributes to achieving high scores in energy rating systems (BREAM, LEED, etc.) [57].

4.5. Ventilated PV Facades

Photovoltaic (PV) panels are commonly used in buildings to produce energy from solar radiation [58]. A photovoltaic system can be integrated into the building. A photovoltaic system that consist of a building enclosure structure and PV panels can create electricity and reduce the heating costs in winter and cooling costs in summer [52,53]. The energy efficiency of the photovoltaic system can be estimated with different ventilation modes (non-ventilated, naturally ventilated, and recovery ventilated mode).

Figure 15 illustrates a passive ventilated facade with photovoltaic panels [59]. The photovoltaic panels are combined with a double-glazed facade. The facade system can implement different operation modes for summer and winter depending on the adjustment of the ventilation openings on the external and internal panels.

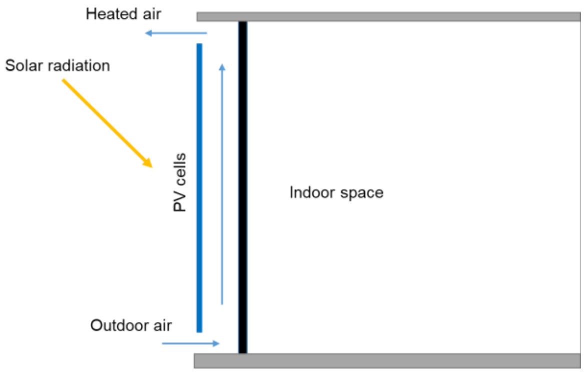


Figure 15. Scheme of ventilated passive PV facade.

Figure 16 presents an active ventilated PV facade, which combines the benefits of a BIPV system and a solar thermal system [60].

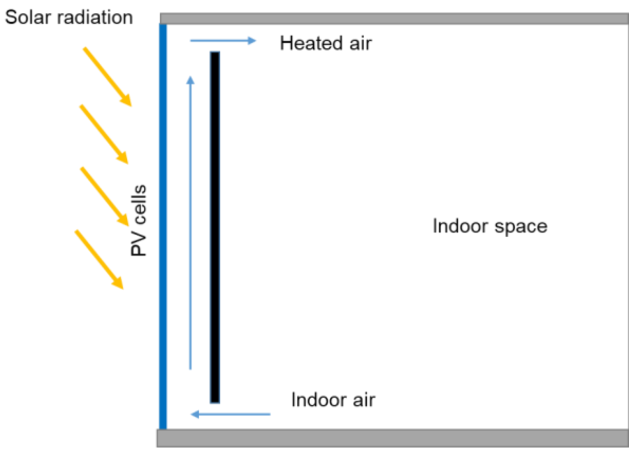


Figure 16. Scheme of ventilated active PV facade.

This facade is designed to achieve the most efficient activity of the photovoltaic panels by generating electricity and by solar air heating.

The results of the investigation indicate that a PV–TSF system with a narrow air cavity (50 mm wide and 20% perforations) can provide suitable thermal performance for buildings in hot climates, achieving a significantly lower solar heat gain than wider PV-DSF systems, without a significant loss of natural daylight in indoor spaces. For countries such as India where land prices are very high, the PV–TSF system provides better performance at a 50 mm air cavity as compared to the PV–DSF system operated at a 200 mm air cavity to reduce the energy consumption of the building [61].

In their study, the authors found that the triple-skin facade with PV modules with a narrow air cavity (50 mm wide and 20% perforation) can ensure appropriate thermal characteristics in the buildings. The triple-skin facade with a PV-modules system ensures better thermal characteristics with a 50 mm air cavity compared to the system with a 200 mm air cavity [62].

In another study, the authors found that the succession of PCM configuration layers significantly affects the thermal characteristics of building enclosing structures, and the developed model provides a perspective with which to optimize PCM envelope configurations [63].

Types of multi-skin ventilated facades is presented at Table 3.

Table 3. Types of multi-skin ventilated facades.

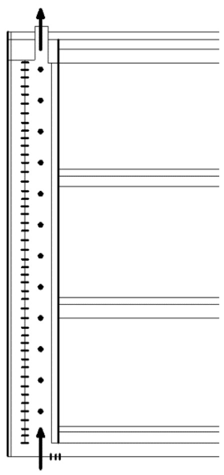
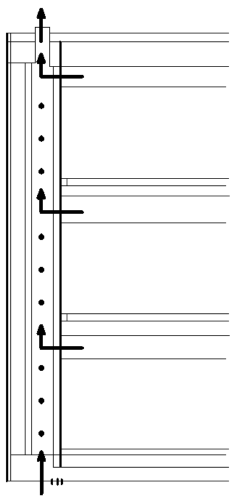
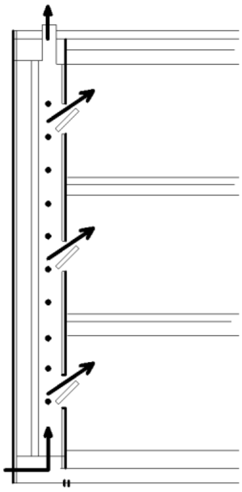
№	Principal Scheme	Air Gap	Description
1		Single glazing with a distance of 250–900 mm from each other. Shading device.	Increased thermal insulation and sound insulation properties of the structure, protection from solar radiation.
2		The outer layer of insulating glass minimizes heat transfer losses.	Increased thermal insulation and sound insulation properties of the structure, protection from solar radiation.

Table 3. *Cont.*

№	Principal Scheme	Air Gap	Description
3		The thermal insulation properties of the inner layer minimize heat loss.	Natural ventilation.
4	Hybrid system	A combination, or variation, of any of the previous.	Multi-skin façade.

5. Adaptive Ventilated Facades with Controlled Thermal Characteristics

Adaptive facades provide buildings with flexibility so that they can respond to varying weather conditions and occupant preferences. It is increasingly recognized as a promising option for achieving a high indoor environmental quality while offering the potential for low-energy building operation.

Ventilated facades with integrated building elements that respond to climatic conditions (mechanized openings and automatic shading with intelligent control) present promising potential in improving the overall annual energy savings by adapting the thermal properties of the structure to contradictory climatic conditions throughout the year.

Figure 17 introduces an example of an automated mode of control of the thermal properties of the facade depending on the climate.

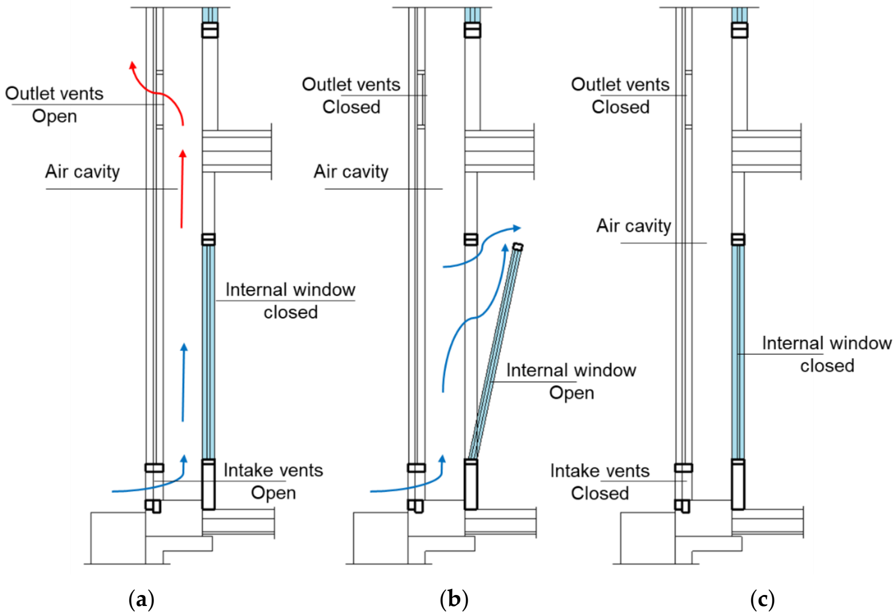


Figure 17. Adaptive ventilated facades with controlled thermal characteristics. (**a**) summer daytime, (**b**) summer night, (**c**) winter.

6. Methods of Thermomechanical Calculation

The existing methods of thermomechanical calculation are as follows: (1) a method based on solving the heat balance equation in a ventilated interlayer; (2) a method based on solving a system of heat balance equations on the glass surface; (3) a method of calculation using empirical formulas; and (4) Computational Fluid Dynamics modeling (CFD) methods.

6.1. Calculation Using Equation of Heat Balance in a Ventilated Layer

Scheme of a ventilated facade for calculation using the heat balance equation in a ventilated layer is illustrated at Figure 18.

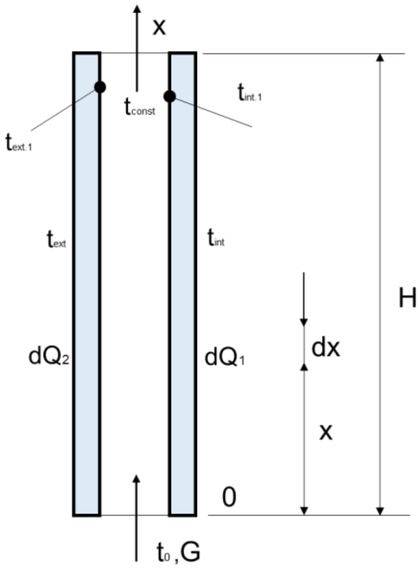


Figure 18. Scheme of a ventilated facade for calculation using the heat balance equation in a ventilated layer.

The heat balance equations are as follows [56]:

$$\begin{aligned} dQ_1 + dQ_2 &= dQ_3 \\ dQ_1 &= k_{\text{int}}(t_{\text{int}} - t)dx \\ dQ_2 &= k_{ext}(t_{ext} - t)dx \\ dQ_3 &= cGdt \end{aligned}$$

dQ_1 and dQ_2 are heat transferred through the inner and outer parts of the fence, c is the heat capacity of air, G is the mass flow rate of air,

k_{int} and k_{ext} are internal and external heat transfer coefficients of the structure.

The following differential equation can be used:

$$(k_{\text{int}} + k_{ext})(t_{const} - t)dx = cGdt$$

Air temperatures at a distance x from the entrance to the layer are calculated as follows:

$$t = t_{const} + (t_0 - t_{const})e^{-Kx}.$$

t_{const} is the constant air temperature in the interlayer, which is established at a certain distance x and does not depend on the air temperature at the inlet to the interlayer.

$$k = (k_{\text{int}} + k_{ext})/cG$$

Relative heat transfer coefficient of the ventilated facade is illustrated at Figure 19.

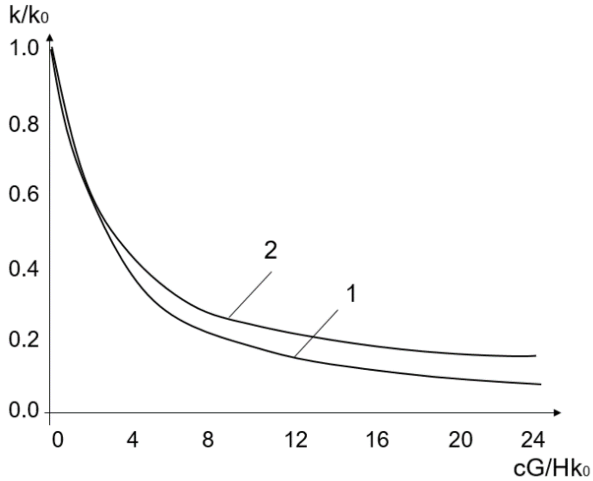


Figure 19. Relative heat transfer coefficient of the ventilated facade: 1—double glazing, 2—triple glazing.

The calculation is not suitable for facades with numerous large interlayers, such as triple glazing.

6.2. Calculation Using the System of Heat Balance Equations on Glass Surfaces

This method of computer calculation for ventilated facades was developed in Canada [57]. Each glass is represented as node i with temperature T_i. Scheme of a ventilated facade for calculation according to the heat balance equations on glass surfaces is illustrated at Figure 20.

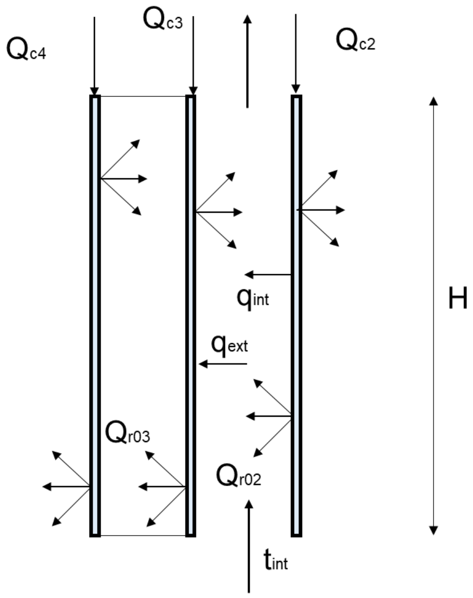


Figure 20. Scheme of a ventilated facade for calculation according to the heat balance equations on glass surfaces.

The heat balance equation for each zone is established by taking into account long-wave radiative heat exchange with the following connected surfaces: a weather-side radiosity $Q_{r.ext}$ and a room-side radiosity $Q_{r.\text{int}}$, convection between solid zones and adjacent air Q_c and absorbed solar radiation Q_{sol}.

For the surface of the outer glass, the heat balance equation is written as follows:

$$Q_{r.ext3} + Q_{r.\text{int}5} - Q_{r.\text{int}4} - Q_{r.ext4} + \alpha_{k34}(t_3 - t_4) + \alpha_{k45}(t_5 - t_4) + Q_{sol4} = 0.$$

The thermal balance on the surface of the middle glass can be calculated as follows:

$$Q_{r.ext2} + Q_{r.\,\text{int}\,4} - Q_{r.\,\text{int}\,3} - Q_{r.ext3} + \alpha_{k34}(t_4 - t_3) + q_{ext} + Q_{sol3} = 0.$$

The thermal balance on the surface of the inner glass can be calculated follows:

$$Q_{r.ext1} + Q_{r.\,\text{int}\,3} - Q_{r.\,\text{int}\,2} - Q_{r.ext2} + \alpha_{k12}(t_1 - t_2) + q_{\text{int}} + Q_{sol2} = 0.$$

$\alpha_{k12}, \alpha_{k34}, \alpha_{k45}$ are heat transfer coefficients on the inner and outer surface of the facade and the glass surfaces inside the double-glazed facade; q_{ext} is heat transferred from the inner glass to the airflow of the ventilated layer, q_{int} is heat transferred from the airflow to the middle glass.

The radiant heat flux from the design nodes towards the room and towards the outside air can be calculated using the following formulas:

$$\begin{aligned} &Q_{r.\,\text{int}(i)} = \varepsilon\sigma T_i^4 + (1 - \varepsilon - \tau)Q_{r.ext(i-1)} + \tau Q_{r.\,\text{int}(i+1)} \\ &Q_{r.ext(i)} = \varepsilon\sigma T_i^4 + (1 - \varepsilon - \tau)Q_{r.\,\text{int}(i+1)} + \tau Q_{r.ext(i-1)} \\ &Q_{sol(i)} = I_{sol}\alpha_i. \end{aligned}$$

where ε is a emissivity of the glass, τ is transmissivity of the glass, σ is Stefan-Boltzmann's constant, I_{sol} is the incident solar radiation; α_i is the absorptance of the outer glass pane.

Because of the joint solution of equations, it is possible to obtain average temperatures and heat flux densities for all glasses in an exhaust ventilated facade. Using the same method, the authors propose to model the thermal characteristics of conventional non-ventilated and ventilated facades. The calculation methods have sufficient computational complexity.

6.3. Calculation by Empirical Formulas

To quickly assess the heat-shielding properties of ventilated windows, various researchers have proposed semi-empirical formulas for calculating the heat transfer coefficient obtained based on experimental data.

The following formula is proposed for calculating the heat transfer coefficient of an exhaust ventilated window with double glazing [64]:

$$k = \frac{0.02}{\omega} + 0.0015(10 - t_{ext}).$$

The value k depends linearly on the air velocity in the interlayer and the calculated outside air temperature. A method for calculating the heat transfer coefficient of an exhaust window with triple glazing was proposed. According to the Figure 21, the increment of the heat transfer coefficient can be determined, and, further, the value of the heat transfer coefficient of the ventilated façade is as follows:

$$k = k^0 - \Delta k_{\text{int}}.$$

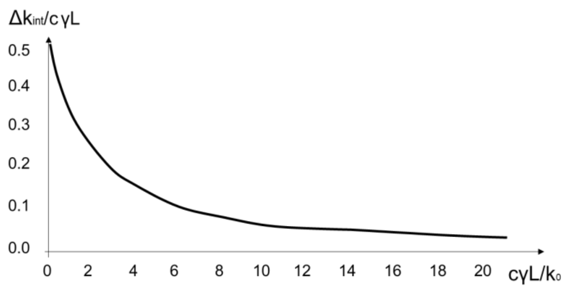


Figure 21. Dimensionless increment of the heat transfer coefficient of a ventilated facade with triple glazing.

The following formula is used to determine the value Δk_{int} [42]:

$$\Delta k_{\mathrm{int}} = 0.24 c \gamma L \left[1 - e^{\left(1 - \frac{k^0}{0.24 c \gamma L}\right.} \right].$$

The calculation makes it possible to obtain only average values of physical parameters characterizing heat transfer in glazing systems.

6.4. Numerical Calculation Methods, Computational Fluid Dynamics Modeling

The numerical solution method of the following equations describes the movement and heat transfer of air in the cavity: continuity Equation (1), Navier–Stokes Equations (2) and (3), and energy conservation Equation (4).

For the equations used in the calculation procedure, the following assumptions are usually made: the physical properties of air are assumed as constant; the compressibility and viscous dissipation for air are not taken into account (Boussinesq approximation).

The Boussinesq approximation $\frac{\partial p}{\rho} + g dz = 0$ is as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial \tau} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = v \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{\partial p}{\rho \partial x} \tag{2}$$

$$\frac{\partial v}{\partial \tau} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = v \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - \frac{\partial p}{\rho \partial y} + g\beta (T - T_{evg}) \tag{3}$$

$$\frac{\partial T}{\partial \tau} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = a \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \tag{4}$$

The finite difference method divides the calculated cavity into finite elements, whereby with a greater number of elements, a more accurate solution can be obtained. However, an increase in the number of grid nodes dividing the cavity into elements leads to an increase in the computation time of the task on the computer.

7. Energy Modeling of a Building with Different Type of Ventilated Facades

To determine energy efficiency and thermal characteristics, three different configurations of ventilated facades were adopted, which have been discussed above in the article, including Single-skin facades, Double-skin facades and D3 facades. The heat transfer resistances for the facades' U-value are presented in Table 4. To calculate the energy efficiency of the building, the energy consumption and thermal energy costs of an office building was modeled with the Autodesk Revit. A model of a high-rise building is shown in Figure 22.

Table 4. Design characteristics of the multi-skin facade.

Specifications	Single Skin Facade	Double Skin Facade	D3 Facade
U value, W/m2·K	1.34	0.71	0.5
Annual Energy Cost, $	93,688	82,958	82,336
Annual CO2 emissions (the equivalent of a large off-road vehicle)	6.8 off-road vehicle/year	5.7 off-road vehicle/year	5.8 off-road vehicle/year
Annual energy (electric, kWh/fuel, MJ)	548,299/1,358,111	489,719/1,147,359	484,715/1,156,228
Life cycle energy (electricity, kW/fuel, MJ)	16,448,973/40,743,330	14,691,570/34,420,770	14,541,459/34,686,840

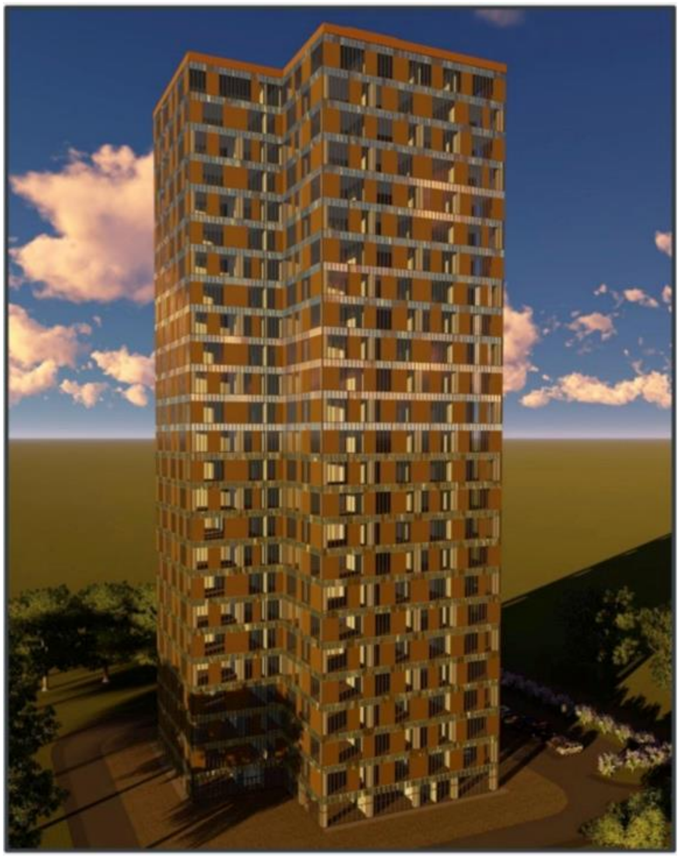


Figure 22. A model of an office high-rise building with a height of 121.7 m with the Autodesk Revit program.

The modeled high-rise building was exported from Autodesk Revit to the Green Building Studio software. The results of calculations in the Green Building Studio software for various configurations discussed above are presented in Table 4, Figures 23–25. Figures 23–25 illustrate the energy consumption of the high-rise building.

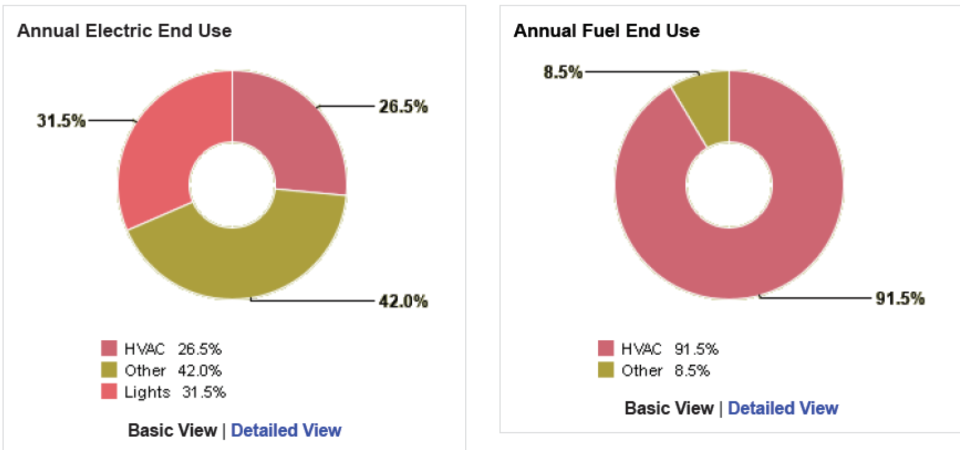


Figure 23. Annual costs of Single skin facade (Green Building Studio).

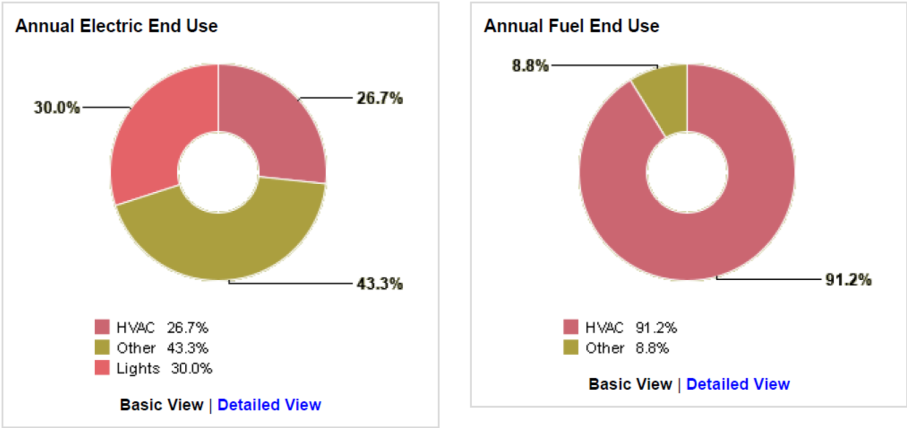


Figure 24. Annual costs of Double skin facade (Green Building Studio).

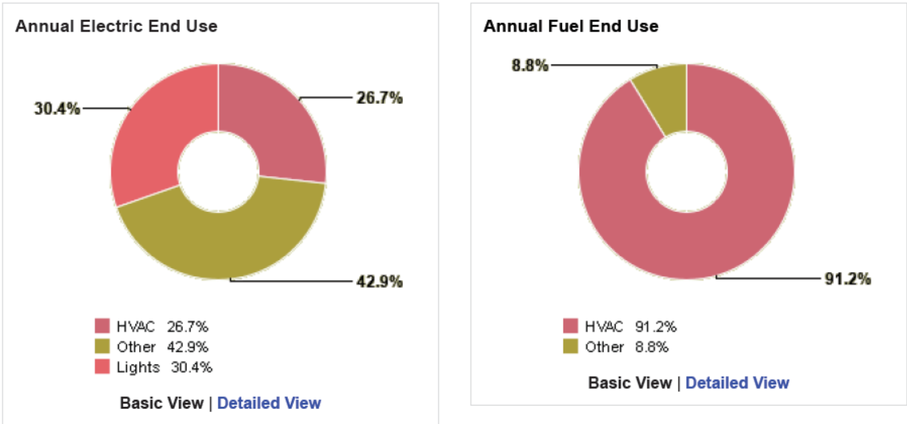


Figure 25. Annual costs of D3 facade (Green Building Studio).

Based on the results of energy modeling, it can be concluded that the cost of thermal energy for office buildings with climate-adaptive triple facade structures decreased by 15%, and CO_2 emissions decreased by 16%.

Thus, the study of climate-adaptive facade structures presents great potential for the further study of energy efficiency and a reduction in CO_2 emissions, and constitutes an urgent topic of research.

The annual energy cost of the high-rise office building with different facade types was estimated using the Green Building Studio to determine the energy efficiency of a multi-skin adaptive facade. For comparison, the annual energy cost calculation was performed for a single-layer facade made of three-layer glass with argon, a double ventilated facade, and a triple ventilated facade with a double chamber. The calculation results are summarized in Table 4.

The calculation results show that the annual energy use of the building with an adaptive triple-skin facade was reduced by 15% compared to the same building with a single-skin facade.

8. Discussion

In this study, a review and analysis of the literature have illustrated the scientific problem, due to the lack of methods and calculations, associated with determining the influence of various parameters (climatic, geometric, etc.) on the thermal characteristics of facade structures, leading to the absence of scientific and technical evidence of the effectiveness of the use of multi-zone structures with triple glazing with adjustable thermal characteristics by the climatic zone. There is great potential to create an algorithm for controlling convective airflows to control thermal characteristics.

Thermal conductivity, thermal resistance and thermal transmittance are essential parameters in the evaluation of the energy efficiency of buildings. For buildings with a Trombe envelope, the annual energy heating cost is about 20%. With electrical heating, the energy payback period is 8 years [6].

The authors in the research compare the energy characteristics of a ventilated facade with a double air cavity and flow control device with a conventional ventilated facade system with a closed join. The thermal and hydrodynamic characteristics of the proposed system and the conventional ventilated facade system with a closed joint, at different climate conditions, were investigated. The results present that the proposed system can increase efficiency by 38% in summer time, and 333% in winter, compared with a ventilated facade with a closed joint [12].

The authors found that the triple-skin facade with PV modules with a narrow air cavity (50 mm wide and 20% perforation) can ensure appropriate thermal characteristics of the buildings. The triple-skin facade with a PV module system ensures better thermal characteristics with a 50 mm air cavity compared to the system with a 200 mm air cavity.

An assessment of the thermal characteristics of the building with a double-skin facade with PV panels with shading blinds and without shading blinds was carried out.

The results show that the energy savings in summer of the double skin facade with PV panels is about 12.16% compared to the double skin facade with shading blinds and 25.57% without them [65–67].

The authors of the study demonstrated that the succession of PCM configuration layers significantly affects the thermal characteristics of building enclosing structures, and the developed model provides a perspective with which to optimize PCM envelope configurations [8].

The application of a PCM in the air cavity of a double skin facade with a PV layer can reduce energy consumption by 20–30%. The performance of electricity increases by 5–8% [68]. DSF with PCM reduces the energy consumption by 11.5% in the winter period and by 5.6% in the summer period compared to a DSF without PCM [68,69].

The DSF with PCM effectively collects solar energy. The use of DSF with PCM reduces energy use by more than 50% compared to a traditional facade in the warm period [70].

This article presents a comprehensive study of the effectiveness of PCM wall panels to improve summer thermal comfort in existing lightweight buildings. The study is based on dynamic modeling conducted using the Energy Plus software on a sample office building [71]. The authors reviewed the phase change materials used in passive heat thermal energy storage systems and provided an overview of how these solutions are associated with the energy efficiency of buildings. The numerical simulation of heat transfer using phase change and heat transfer improvement methods was discussed. Studies on dynamic energy modeling in buildings were reviewed. Life cycle assessments were also discussed. This research illustrates that passive construction solutions with PCM provide the opportunity to reduce energy costs and increase thermal comfort in the building [72,73].

For comparison the results of a multi-skin adaptive facade obtained by the authors were reviewed [74,75]. The total heat transfer resistance of a triple-skin facade was calculated with CFD modeling and equaled U = 0.55 $W/m^2 \cdot C$, which is close to the value obtained by other authors. The triple facade can recuperate and efficiently use the energy from the extracted air, reduce the inflow and loss of heat through the window and improve the thermal comfort of the air-conditioned room. During the warm season, absorbing solar panels absorb thermal energy from the sun, and the flow of outside air, in turn, cools the glass. This prevents overheating in the room. The heated "exhaust" air between the glazing layers is extracted through the cavity, thereby cooling the inner glazing layer, while the outer layer of insulating glass minimizes heat-transfer losses. In the warm season, the amount of heat from the outside air and solar radiation is reduced, which significantly reduces the load on the cooling systems. In the cold season, part of the heat of the air removed from the room is utilized, which reduces the load on the heating systems. For warm climates, it is recommended to install solar panels around the perimeter of the building, as well as shading devices [76–80].

Despite the fact that a lot of work has been conducted to investigate the performance of multi-skin adaptive facades, there are still many problems that need to be solved during their application and development.

9. Conclusions

In this paper, a literature review on building envelopes that contain inner air layers was presented. The operation modes of the air layer used in building envelopes were roughly classified and summarized and the thermal performances and benefits of the climate-adaptive facade were discussed and summarized. One of the sustainable development trends is the investigation and application of energy-efficient climate-adaptive facades.

The results of the review and analyses are as follows:

1. The existing operation modes of the air layer used in building envelopes were summarized and outlined. The operation modes of the air layer used in building envelopes were roughly classified into the following types: the enclosed type, the naturally ventilated type and the mechanically ventilated type. The enclosed type acts as an extra insulation layer; the naturally ventilated air layer is often adopted in passive cooling systems and some of the space-heating systems; and the mechanically ventilated type is applied in space-heating systems or the ventilated facades in which the flow resistance is larger than the buoyancy effect.
2. A scientometric analysis was conducted using the tools SciVal and VosViewer and revealed some trends. The theme was «Climate-adaptive facades», and «Facades, Blinds, Natural Ventilation» represents a trend in China according to the level and number of publications from Chinese organizations and institutions.
3. The energy calculation results derived using the Green building Studio software show that the annual energy usage of a building with an adaptive triple-skin facade reduced by 15% compared to the same building with a single-skin facade.
4. In a building with Trombe walls, the annual final energy savings in heating is about 20%. For the electrical heating and optimum core thickness, the energy ratio is around 6 and the energy payback period is 8 years.
5. Our analysis of research works on facades shows that multi-skin adaptive facades with PV panels are more energy efficient than other traditional systems. The energy resources required for air conditioning the building is reduced by 15–20%.
6. The literature review shows that integrating PCM layers in multi-skin facades with PV panels will significantly affect the thermal performance of building envelopes, effectively reduce the cooling load and increase the conversion efficiency of solar energy into electrical energy.

Using the multi-skin climate-adaptive facade with PV panels and PCM materials, multiple benefits can be achieved, including a reduction in the thermal load of a building, the provision of auxiliary heating for the indoor air and improved indoor thermal comfort and indoor air quality. This review outlined the current state of research, existing gaps and possible future research directions for air-layer technologies in building envelopes.

The investigation of multi-skin climate-adaptive facades with PV panels and PCM materials provides great potential for the further study of energy efficiency, increased thermal resistance of enclosure structures and a reduction in CO_2 emissions, thereby representing an urgent topic for further study.

Author Contributions: Conceptualization, D.A. and D.N.; methodology, E.K.; software, E.K.; resources, D.A.; writing—original draft preparation, D.A.; writing—review and editing, D.A.; visualization, E.K.; supervision, D.N.; project administration, E.K.; funding acquisition, D.N. All authors have read and agreed to the published version of the manuscript.

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