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and Principles of Construction

Edited by Silvia Brunoro



Facade Engineering - Concepts, Materials, Techniques and Principles of Construction

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IntechOpen Book Series

Civil Engineering

Volume 15

Aims and Scope of the Series

Civil engineering is a traditional field of engineering from which most other branches of engineering have evolved. It comprises traditional sub-areas like transportation, structures, construction, geotechnics, water resources, and building materials. It also encompasses sustainability, risk, environment, and other concepts at its core. Historically, developments in civil engineering included traditional aspects of architecture and urban planning as well as practical applications from the construction industry. Most recently, many elements evolved from other fields of knowledge and topics like simulation, optimization, and decision science have been researched and applied to increase and evolve concepts and applications in this field. Civil engineering has evolved in the last years due to the demands of society in terms of the quality of its products, modern applications, official requirements, and cost and schedule restrictions. This series addresses real-life problems and applications of civil engineering and presents recent, cutting-edge research as well as traditional knowledge along with real-world examples of developments in the field.

Meet the Series Editor



Professor Assed N. Haddad is a Civil Engineer with a degree from the Federal University of Rio de Janeiro (UFRJ) earned in 1986, as well as a Juris Doctor degree from the Fluminense University Center earned in 1993, and a Master's degree in Civil Engineering from the Fluminense Federal University (UFF) obtained in 1992. He completed his Ph.D. in Production Engineering from COPPE / Federal University of Rio de Janeiro in 1996. Professor Haddad's academic pursuits have taken him to postdoctoral stays at the University of Florida, USA in 2006; at the Universitat Politècnica de Catalunya, Spain in 2010; and at the University of New South Wales Sydney, Australia in 2019. Currently, he serves as a Full Professor at the Federal University of Rio de Janeiro. He has held visiting professorships at various institutions including the University of Florida, Universitat Politècnica de Catalunya, Universitat Rovira i Virgili, and Western Sydney University. His research expertise encompasses Civil, Environmental, and Production Engineering, with a primary focus on the following topics: Construction Engineering and Management, Risk Management, and Life Cycle Assessment. He has been the recipient of research grants from the State of Rio de Janeiro, Brazil: CNE FAPERJ from 2019 to 2022 and from 2023 to 2025. Additionally, his research grants obtained from the Brazilian Government CNP since 2012 last to this date. Professor Haddad has been involved in several academic endeavors, being the Guest Editor of the International Journal of Construction Management; MDPI's Sustainability, Energies, and Infrastructures; Associate Editor at Frontiers in Built Environment / Sustainable Design and Construction; Guest Editor at Frontiers in Built Environment / Construction Management; and Academic Editor of the Journal of Engineering, Civil Engineering Section of Hindawi. He is currently a Professor of the Environmental Engineering Program at UFRJ and the Civil Engineering Program at UFF.

Meet the Volume Editor



Silvia Brunoro is an Associate Professor of Technology in Architecture in the Department of Architecture at the University of Ferrara, where she teaches Environmental Design and the Design and Construction Laboratory. She received a Ph.D. in Technology of Architecture in 2003 and has been involved in international and national research projects and networks since 2004, with a primary focus on integrated technologies for safe, resilient, efficient, sustainable, and durable building renovation. Her primary areas of research include sustainable refurbishment, energy efficiency, and innovation in technologies and materials for façade design. She is an editorial board member and reviewer for several scientific journals (*Energy*, *Buildings*, *Sustainability*, *Energy Research and Social Science*). She is the author of several publications concerning energy efficiency and sustainable design, mainly related to the envelope of the building, such as “Energy efficiency of façades. Standards, needs and examples for the refurbishment”.

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Preface

Façades play a crucial role in architecture, as they represent the building's image. They also account for approximately 60 % of a building's energy consumption and play a crucial role in meeting energy-saving and carbon reduction targets outlined in recent global policies on Climate Change.

The building envelope is the boundary between the external and internal environments, and it is responsible for important requirements, including thermal insulation, thermal inertia, lighting, weatherproofing, load distribution, and sound insulation. In the last twenty years, façades have become increasingly complex to meet both structural and energy efficiency regulations.

“Dynamic”, “smart”, “intelligent”, “climate-active”, and “adaptive” façades using self-regulating systems to respond to changing light and weather conditions have become more and more diffuse. Multiple objectives are required for these building systems that concern the development of innovative design concepts and new technologies.

Therefore, façade systems can play a significant role in developing high-performance buildings at scale. Key criteria for selecting an appropriate façade system include structural performance, constructability, cost, and environmental impact.

This book presents a selection of research contributions from international scholars and façade experts regarding new strategies, technologies and materials of façade design, and it is divided into two sections: Section 1, *Materials and Techniques*, which offers an overview of the main solutions and façades applications, by considering glass and opaque materials and their main characteristics. Section 2, *New Technologies, Design Planning and Tools for Sustainable Design and Energy Efficiency*, focuses on innovative solutions and design procedures to improve global quality, safety, and energy efficiency.

These aspects are investigated through the application of innovative procedures to fulfil new requirements, the use of smart materials, and the development of innovative design concepts.

The selected book chapters are the result of recent research efforts by several authors, as well as the support and input from a team of experts on the topic.

I would like to gratefully acknowledge the authors and reviewers for sharing their time and experience.

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Section 1

Materials and Techniques

Stone Materials in Facades: Most Important Deterioration and Treatment

Rubén Rodríguez Elizalde

Abstract

Stone materials are widely used in facades due to their durability and esthetic appeal, yet they are subject to various deterioration processes that compromise structural integrity. This chapter examines the most commonly used stones (granite, limestone, sandstone, and marble) and their physical and mechanical properties, including absorption, density, compressive strength, flexural resistance, and abrasion resistance. A comprehensive review of facade pathologies reveals that porosity plays a critical role in degradation, particularly under aggressive environmental conditions. Using advanced diagnostic techniques, this research evaluates the performance of stone materials in historical and contemporary buildings. Key findings indicate that sandstone and limestone exhibit higher vulnerability to pollution-related decay, while granites demonstrate superior resistance but require precise specification to avoid anisotropic failures. Additionally, the effectiveness of various cleaning and conservation treatments is assessed, highlighting the risks of over-aggressive cleaning methods. This chapter underscores the necessity of standardized selection criteria to enhance facade longevity and proposes guidelines for sustainable maintenance strategies. The findings provide essential insights for architects, conservation specialists, and engineers aiming to optimize the use and preservation of stone facades in both heritage and modern constructions.

Keywords: stone facades, weathering, material degradation, conservation strategies, diagnostic techniques

1. Introduction

Natural stone, including block stone, ashlar, cut stone, and rubble stone, has been a fundamental material in the construction of significant historical structures such as cathedrals, monasteries, castles, palaces, bridges, and aqueducts. Due to their inherent durability, stone-built monuments have withstood the test of time, becoming an essential part of the cultural heritage that requires conservation.

The advent of structural steel in the late nineteenth century, followed by the development of Portland cement and the widespread use of reinforced concrete, significantly reduced the role of stone as a primary construction material. Today, stone is mainly used as an ornamental material for façade cladding, roofing, and

certain structural elements. However, despite this limited application, stone remains economically significant in countries such as Spain, which possesses a rich variety of natural rock types, particularly in the export sector.

Stone is among the most sustainable construction materials, extensively used for cladding, paving, and other architectural applications. Its use dates back to the earliest civilizations, maintaining its relevance through modern times. Moreover, the resurgence of its popularity, combined with advancements in quarrying technology, has made its extraction more cost-effective than ever before [1].

A fundamental classification of stone materials, particularly those used in façades, is based on their geological origin. Natural stones can be categorized into three primary groups: igneous, metamorphic, and sedimentary rocks [2]. This classification reflects the distinct formation processes of each type, from the crystallization of magma to the transformation of pre-existing materials under pressure and temperature conditions. **Figure 1** illustrates the genesis of these rock types, tracing their formation from an initial magmatic state [3].

Igneous rocks originate from the solidification of magma. Depending on the depth at which this process occurs, they are classified as intrusive (plutonic) when crystallization takes place beneath the Earth's crust, or extrusive (volcanic) when it occurs on the surface. Among igneous rocks, granite is the most widely used in façade construction. Granite is a coarse-grained, acidic intrusive rock with a high quartz content (>60%), which provides exceptional strength. Intrusive rocks, particularly granite, are highly valued for their low porosity when intact. Consequently, granite has been a preferred building material since ancient times (**Figures 2 and 3**).

Sedimentary rocks are classified into two main groups based on their formation processes: clastic (detrital) and non-clastic.

Clastic sedimentary rocks result from the transportation and deposition of weathered rock fragments, which may remain unconsolidated (loose sediments) or undergo compaction and cementation (solid rocks). Sandstone, a compacted clastic rock, is one of the most frequently used materials in construction (**Figure 2**).

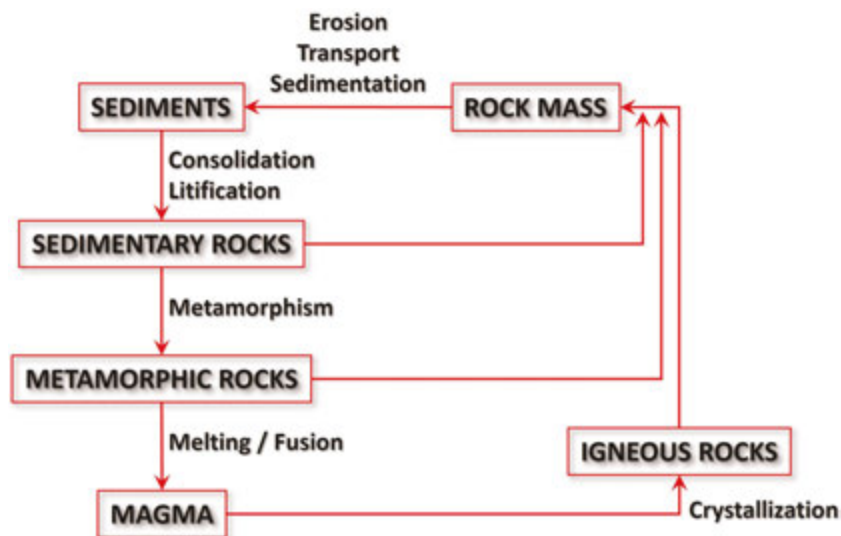


Figure 1.
Types of rocks according to their origin (diagram by the author).

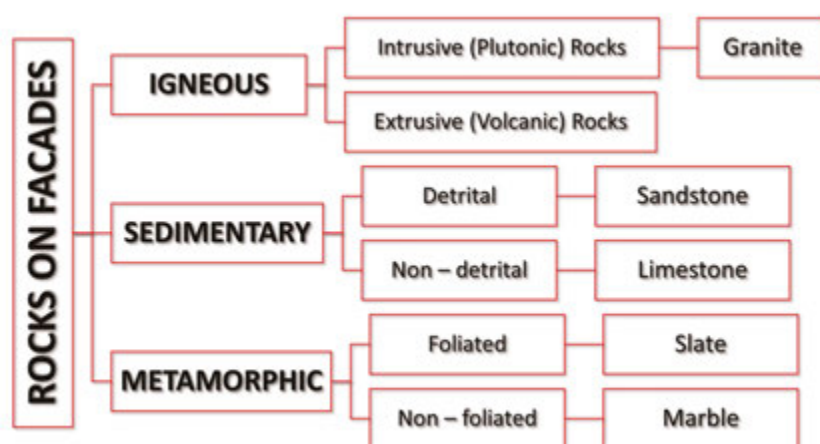


Figure 2.
 Classification of rocks and identification of the main types used in building facades (diagram by the author).



Figure 3.
 Roman aqueduct of Segovia, built with granite ashlars between the second half of the first century and the beginning of the second century (photo by the author).

Non-clastic sedimentary rocks primarily form through the precipitation of dissolved substances in sedimentary basins, followed by lithification. This category also includes rocks formed from the accumulation of biological remains, such as shells and skeletal fragments. Limestone, a prominent example (**Figure 2**), has been widely used in construction since antiquity (**Figure 4**).



Figure 4.
Roman aqueduct of Tarragona, built with limestone ashlars during the first century BC (photo by the author).

Metamorphic rocks result from the transformation of pre-existing sedimentary or igneous rocks due to high pressure and temperature conditions deep within the Earth's crust. These transformations modify mineral composition and rock structure.

On the one hand, foliated metamorphic rocks originate from clay-rich sediments and exhibit a layered texture. Slate, a widely used cladding and roofing material, falls into this category.

On the other hand, non-foliated metamorphic rocks primarily derive from carbonate rocks, such as limestone, and include marble, which has been extensively used in façade applications.

Beyond geological classification, other criteria are used in civil engineering to evaluate stone materials. Two key mechanical properties for defining their suitability in construction are uniaxial compressive strength and modulus of deformation.

Over the past two decades, global production of ornamental stone has increased rapidly, particularly in architectural projects where designers leverage the extensive variety of colors, textures, and finishes available. As the demand for natural stone rises, improvements in cutting and processing techniques have significantly expanded the range of materials supplied to the market.

For façade applications, stone must meet specific performance criteria defined by internationally recognized standards to ensure long-term durability and structural integrity [2].

2. Methodology

This chapter aims to describe a comprehensive methodology for the evaluation and treatment of stone materials used in facades. Their physical and mechanical properties, such as absorption, density, compressive strength, flexural strength, and abrasion resistance, are thoroughly evaluated to determine their suitability for facade applications.

Extraction and processing of stone involve both traditional and modern methods. Traditional methods include leveraging natural joints and fractures in rock masses to

detach blocks, while modern techniques employ diamond wire saws to extract large stone blocks efficiently. Stones are then processed into various shapes, including ashlar, cut stone, rubble stone, slabs, and slate shingles, each serving different architectural purposes.

Key properties for evaluating stone materials include absorption, density, uniaxial compressive strength, modulus of rupture, flexural strength, and abrasion resistance. These properties are assessed through direct tests on stone samples, such as the Schmidt rebound hammer test, which provides supplementary data on the stone's mechanical behavior. Weathering resistance is particularly important for slate, which is tested through sulfuric acid immersion to simulate environmental conditions.

The document establishes specific requirements for different types of stone used in facades. For instance, granite must meet high standards for compressive strength and low absorption to ensure durability. Sandstone, limestone, and marble also have defined specifications for properties like density and abrasion resistance, tailored to their unique characteristics and applications.

Deterioration of stone in facades is a significant concern, driven by external agents such as climate and environmental conditions. The document highlights the importance of permeability and porosity in the rate of stone alteration, with higher porosity leading to faster degradation. The mineralogical composition of the stone also plays a crucial role in its chemical stability and resistance to weathering.

To protect stone facades, the document recommends a two-phase approach: cleaning and surface treatment. Cleaning methods vary based on the stone's condition, ranging from aggressive techniques like sandblasting for hard, healthy stones to gentler methods like water vapor jets and detergents for altered or soft stones. Surface treatments involve the use of fluid monomers that penetrate the stone and polymerize to form a cohesive, durable layer, enhancing the stone's resistance to further deterioration.

Overall, the methodology provides a detailed guide for the selection, evaluation, and conservation of stone materials in facades. It emphasizes the need for standardized criteria to ensure the long-term durability and esthetic appeal of stone facades, offering valuable insights for architects, conservation specialists, and engineers involved in both heritage and modern construction projects.

3. Shape of stone elements

The extraction and processing of natural stone for various architectural applications follow both traditional and modern methodologies. Traditionally, stone blocks were quarried by leveraging the natural joints and fractures in rock masses, allowing the detachment of blocks of varying sizes. These blocks were then processed into usable stone pieces using either mechanical (saws) or manual tools (hammers and chisels).

In contemporary quarrying operations, advanced techniques have significantly improved efficiency. Wire saws with diamond segments (**Figure 5**) are now employed to extract large stone blocks directly from the quarry face, optimizing material yield. This method is particularly effective in producing stone slabs, which currently represent the highest volume of processed stone used in construction.

Depending on their shape and processing method, cut stones are categorized as ashlar, cut stone, rubble stone, slabs, and slate shingles.

Ashlar and cut stone are parallelepiped blocks with precisely finished surfaces, allowing seamless fitting in masonry (**Figures 6 and 7**). Due to their size, ashlars require mechanical handling.

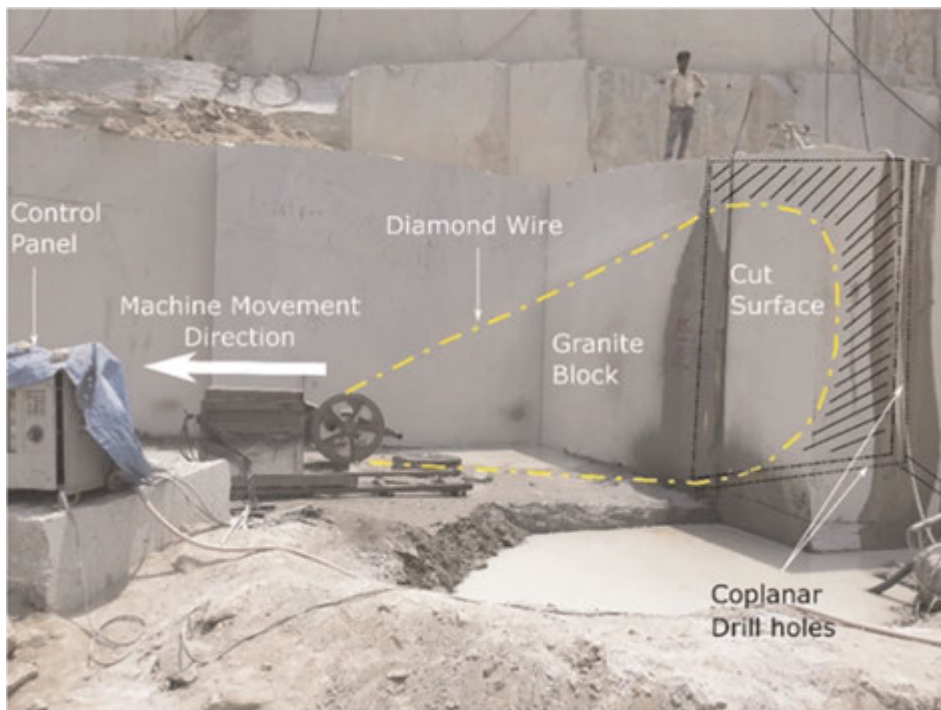


Figure 5.
Sawing blocks in stonework using wire ropes with diamond [4].

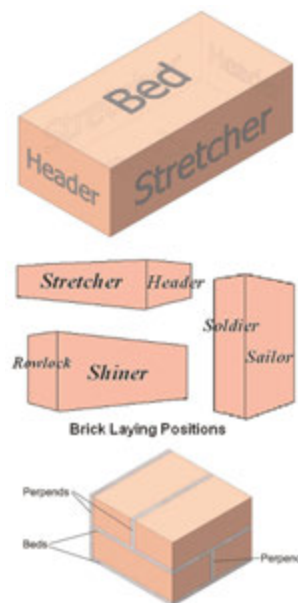


Figure 6.
Faces of brick and mortar terminology, showing perpend and bed (graphics by Wikipedia [5]).

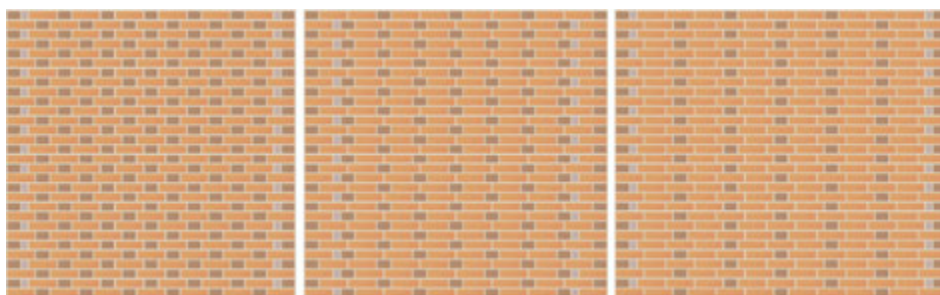


Figure 7.
 Different types of brick rigging: flemish bond, monk bond, and sussex bond (graphics by Wikipedia [5]).



Figure 8.
 Masonry wall with two exposed faces, with ordinary and concerted work (graphics by Generador de Precios. Spain [6]).

Rubble stones are irregularly shaped and unprocessed, making them suitable for dry-stone or mortar-bound masonry (**Figure 8**). They are typically obtained directly from block division.

Stone slabs are characterized by a thickness significantly smaller than their other dimensions [7]. They are cut from large blocks and finished through polishing, often using abrasives of varying grain sizes. In some cases, an additional buffing process is applied using a mixture of lead and polishing agents. Slabs are primarily used for façade cladding [8], wall coverings, and flooring, requiring strict quality control standards (**Figure 7**).

Slate shingles are thin, rectangular pieces (4–6 mm thick) used for roofing applications. Their production relies on the natural exfoliation properties of slate, eliminating the need for additional shaping. Slate shingles hold a substantial market share both domestically and internationally.

This classification underscores the diverse applications of natural stone in construction, highlighting the importance of both traditional craftsmanship and modern technological advancements in stone processing.

4. Criteria for evaluating stone materials in facades

The selection of stone materials for façade cladding and paneling requires high-quality, durable, and structurally sound rocks [9]. For exterior applications, these characteristics are essential due to varying degrees of environmental aggressiveness. In contrast, interior cladding does not demand such stringent specifications, offering cost advantages, as harder stones are more difficult to process, increasing unit costs.

Stone used in pavements must meet distinct performance criteria, particularly wear resistance, which differs from the requirements for vertical cladding and roofing

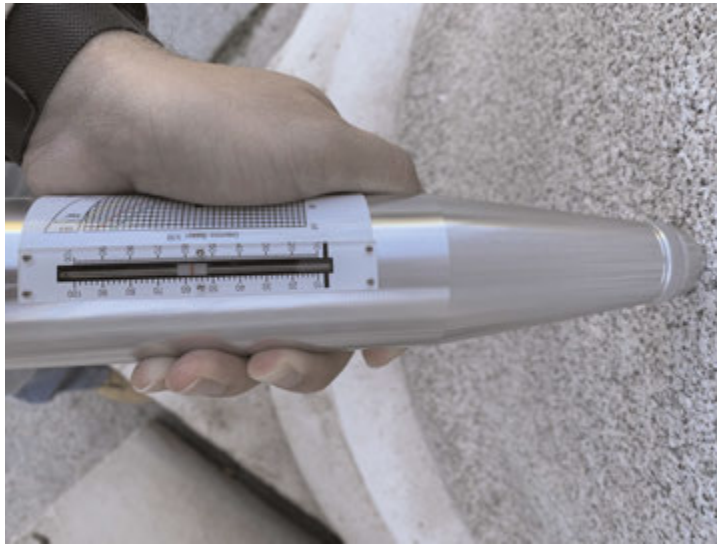


Figure 9.

Schmidt sclerometer to determine the strength of the granite used in the columns of the main entrance to the Prado Museum in Madrid (photo by the author [9]).

slates [10]. Roofing slates, due to their specific composition and application, must comply with additional technical specifications.

The primary properties used to evaluate stone materials for facade applications [11] include [12]:

- Absorption
- Density
- Uniaxial compressive strength
- Modulus of rupture
- Flexural strength
- Abrasion resistance

For slate, an additional requirement is softening resistance, ensuring that the material's deterioration remains within specified limits when immersed in a solution.

All these properties are determined using parallelepiped samples, directly extracted from the stone slabs intended for installation. In addition to direct tests [13], indirect methods, such as the Schmidt rebound hammer test, provide valuable supplementary data (**Figure 9**) [14].

4.1 Density and absorption

Density refers to the apparent density, which represents the mass per unit volume of a stone sample, reflecting the pore volume and fissures within the rock. The solid density varies among rock types, depending on the density of their constituent minerals. Apparent density decreases as the volume of voids within the rock increases [15].



Figure 10.
 Balance for determining the weight of submerged rock samples (graphic by Goyojo).

Water absorption is defined as the ratio of absorbed water weight to the dry weight of the sample [11]. This parameter correlates with the volume of accessible pores and serves as an indicator of permeability and weathering susceptibility.

Testing procedures follow standardized protocols, using three parallelepiped specimens ($50 \times 50 \times 70$ cm). The absorption coefficient (a) is calculated as:

$$a = \frac{w_2 - w_1}{w_1} \quad (1)$$

w_2 = saturated weight (after 48 hours of water immersion); w_1 = dry weight (after 24 hours in an oven at $105 \pm 5^\circ\text{C}$).

The apparent density (γ_{ap}) [16] is calculated as:

$$\gamma_{ap} = \frac{w_1}{w_2 - w_3} \quad (2)$$

w_3 = weight of the saturated sample when submerged.

A precision balance, such as the one illustrated in **Figure 10**, is used for these measurements.

4.2 Uniaxial compressive strength

The uniaxial compressive strength (UCS) of stone used in façade applications is determined using parallelepiped samples, rather than cylindrical specimens, which are conventionally used for uniaxial compressive strength tests in other materials [11].

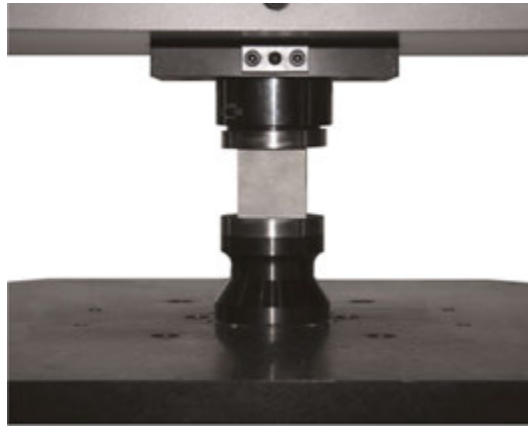


Figure 11.
Simple compressive strength test on cubic rock specimens (graphic by Instron [17]).

As a result, uniaxial compressive strength values obtained for stone façades may differ from standard values assigned to the rock type.

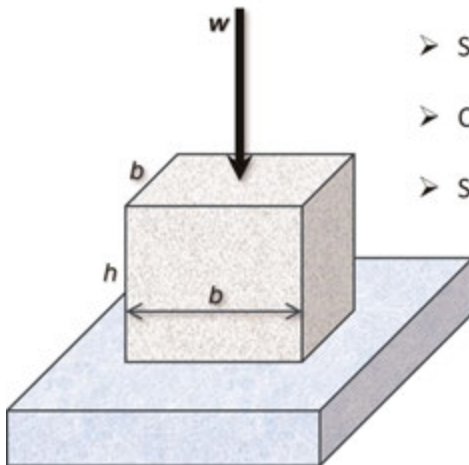
Testing is conducted on five cubic specimens, which are oven-dried for 48 hours at $60 \pm 2^\circ\text{C}$ before undergoing compressive testing (**Figure 11**).

When stone specimens deviate from a perfect hexahedral shape (**Figure 12**), it is recommended to calculate the equivalent uniaxial compressive strength (c_c) using the following expression:

$$c_c = \frac{c_p}{0.778 + 0.222 \frac{b}{h}} \quad (3)$$

c_p = measured uniaxial compressive strength in the test.

$$c_p = \frac{w}{A} \quad (4)$$



- Sample tubes: cube or cylinder (x 5)
- Condition: oven-dried at $60 \pm 2^\circ\text{C}$
- Saturated: in water for 48 hours

Figure 12.
Determination of uniaxial compressive strength (graphic by the author).

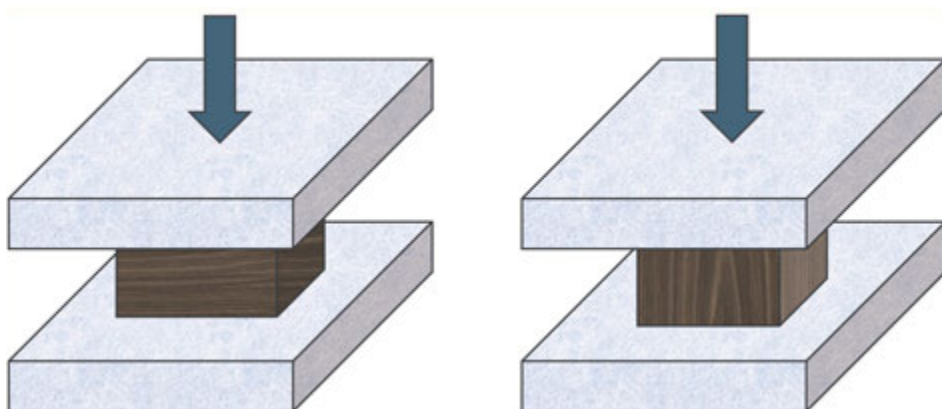


Figure 13.
 Simple compressive strength test on cubic rock specimens in a direction perpendicular to the discontinuity planes and in a direction parallel to the discontinuity planes (graphics by the author).

where w is the applied load and A is the cross-sectional area; b = width of the specimen; h = height of the specimen.

For anisotropic rocks with bedding planes or schistosity, compressive strength should be determined in two orientations:

- Perpendicular to the planes of discontinuity (Figure 13, left).
- Parallel to the planes of discontinuity (Figure 13, right).

4.3 Modulus of rupture

The modulus of rupture (R) represents the tensile strength of the rock under bending stress. It is determined using a three-point flexural test performed on parallelepiped specimens ($50 \times 100 \times 200$ mm) [11]. The test applies a central load, creating a bending moment that induces failure at the most stressed fiber, which is the farthest from the neutral axis (Figure 14) [15].

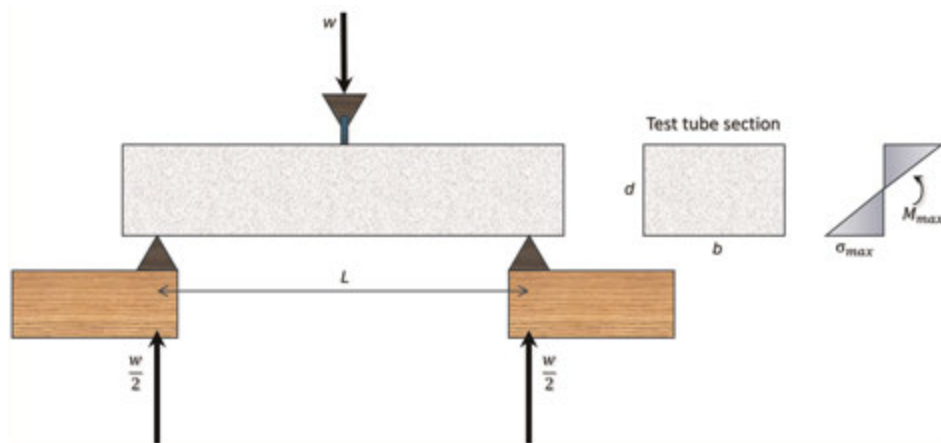


Figure 14.
 Test to determine the modulus of rupture (graphic by the author).

The modulus of rupture is calculated using the following formula:

$$M_{\dot{m}ax} = \frac{w}{2} \frac{L}{2} = \frac{w L}{4} \quad (5)$$

$$M_{\dot{m}ax} = \frac{1}{2} \frac{d}{2} b \sigma_{\dot{m}ax} \frac{d}{3} 2 = \sigma_{\dot{m}ax} \frac{b d^2}{6} \quad (6)$$

By equating both expressions:

$$\frac{w L}{4} = \sigma_{\dot{m}ax} \frac{b d^2}{6} \quad (7)$$

Solving for $\sigma_{\dot{m}ax}$:

$$\sigma_{\dot{m}ax} = R = \frac{3 w L}{6 b d^2} \quad (8)$$

where:

$M_{\dot{m}ax}$ = maximum bending moment in the central section; R = modulus of rupture; w = load at failure.

The test must be performed on five specimens. If the stone is anisotropic, two sets of tests should be conducted:

- With discontinuity planes perpendicular to the loading direction.
- With discontinuity planes parallel to the loading direction [11].

4.4 Flexural strength

The modulus of rupture provides an estimate of the tensile strength of the stone, but it is measured in a highly localized region—specifically, at the center of the specimen [11] where the maximum bending moment occurs (**Figures 15 and 16**).

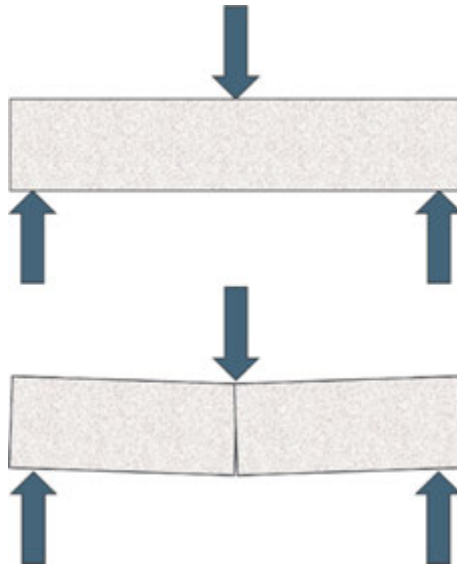


Figure 15.
Representation of the bending process in a stone test tube (graphic by the author).



Figure 16.
 Fractures in the granite lintel above the main entrance to the Monastery of El Escorial, the result of a complex bending process (photo by the author [18]).

To account for rock heterogeneity, a four-point bending test is used to determine the flexural strength (**Figure 17**) [15]. In this test, the specimen is subjected to two symmetrical loads applied at points separated by half the total span ($L/2$) (**Figure 18**). This setup ensures that the central section of the specimen experiences a uniform bending moment, leading to failure at its weakest point.

The flexural strength is calculated using the following equation (**Figure 18**):

$$M_{\max} = \frac{w}{2} \frac{L}{2} - \frac{w}{2} \frac{L}{4} = \frac{wL}{8} \quad (9)$$



Figure 17.
 Test to determine the flexural strength (graphic by Alicante University [19]).

$$M_{\max} = \sigma_{\max} \frac{b d^2}{6} \quad (10)$$

By equating both expressions:

$$\frac{w L}{8} = \sigma_{\max} \frac{b d^2}{6} \quad (11)$$

Solving for $\sigma_{\max}$:

$$\sigma_{\max} = \frac{3 w L}{4 b d^2} \quad (12)$$

The standard dimensions for flexural strength testing specimens are $25 \times 38 \times 300$ mm [20]. Similar to the modulus of rupture test, five specimens should be tested. If the stone is anisotropic, two series of tests should be conducted:

- With discontinuity planes perpendicular to the load direction.
- With discontinuity planes parallel to the load direction [11].

4.5 Abrasion resistance

When natural stone is used in pavements, assessing abrasion resistance is essential to ensure long-term durability. This property is also relevant for stone materials applied in façades, where surface wear may occur due to environmental exposure [21].

The Böhme abrasion test, standardized in international regulations, is commonly used to determine this property [22]. This method subjects a prismatic stone specimen, under a specified load, to the action of a rotating abrasive disk (**Figure 19**).

The test apparatus consists of a cast iron rotating wheel (750 mm in diameter) with a defined test track where white corundum abrasive is applied. The specimen holder ensures stability, and a dual-arm loading system applies a constant force of 294 ± 3 N.

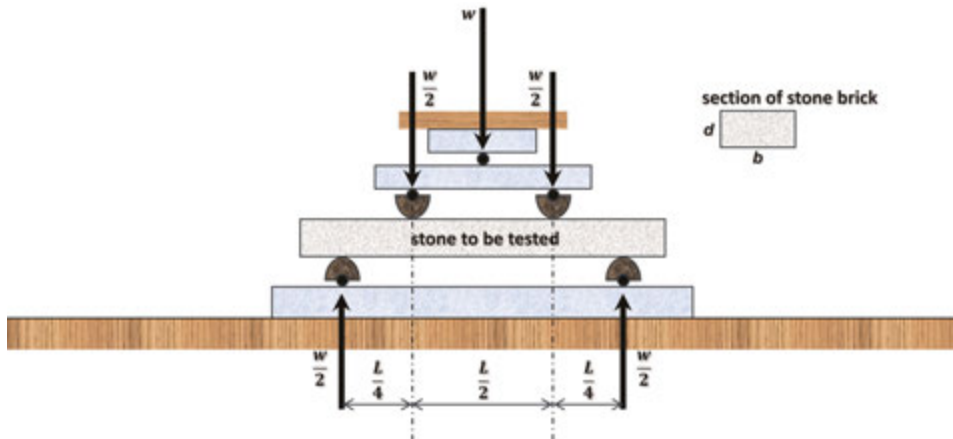


Figure 18.

Test to determine the flexural strength (graphic by the author). w = load at failure; L = distance between supports; d = specimen depth; b = specimen width.

Once the abrasive is evenly spread, the disk rotates at a controlled speed for a predefined number of cycles, in accordance with testing standards.

The machine is equipped with a digital control panel, allowing operators to set rotation speed and cycle count. Once started, the test runs automatically until the preselected number of cycles is completed.

The test evaluates abrasion resistance by quantifying material loss, either as thickness reduction or volume loss. A dial gauge (0.01 mm resolution), mounted on a stable reference base, is used to measure thickness at nine predefined points (**Figure 19**). This alternative measurement method is recognized by EN 13892-3 and DIN 52108 standards, where:

$$H_a = \frac{10}{V_{des}} (1 + \alpha) \cdot 2.5^3 \quad (13)$$

H_a = abrasion resistance index; V_{des} = volume loss (cm^3); 2.5^3 = unit conversion factor (cubic inches to cubic centimeters); α = weight correction factor.

α = weight correction factor, calculated as:

$$\alpha = \frac{\frac{1}{2}(w_i + w_f)}{2000} \quad (14)$$

The value of α ranges from 0.05 to 0.10 ($0.05 \alpha < 0.10$), where: w_i = initial specimen weight (grams); w_f = final specimen weight (grams).



Figure 19.
 Device for determining the abrasion resistance of rocks used in facades (graphic by Normatest [23]).

The abrasion resistance is inversely proportional to the volume loss during the test. Thus, higher resistance values indicate superior durability.

4.6 Weathering resistance of slate

Slate is primarily composed of clay minerals, but it may also contain calcite and pyrite [24]. These secondary minerals are susceptible to chemical weathering, particularly when exposed to environmental conditions that promote oxidation or dissolution. Additionally, clay minerals exhibit swelling behavior upon water absorption, potentially compromising the structural integrity of slate panels.

For slate used in roofing and façade cladding, it is essential to assess weathering resistance against atmospheric agents [25]. Standardized procedures have been established to quantify this property [26].

The sulfuric acid immersion test exposes a slate specimen, prepared at its intended application thickness, to a 1% sulfuric acid solution for seven days [26].

The degree of alteration is quantified by measuring the increase in indentation radius caused by a steel cylinder pressed against the specimen edge under a standardized force. The difference in indentation radius before and after acid exposure provides a measure of slate weatherability, with greater increases indicating higher susceptibility to chemical degradation.

5. Specifications for different types of stone

The tests in the previous section aim to determine the characteristics of stone materials that can be used in building facades. **Table 1** summarizes the required specifications for various stone types used in building cladding and facade applications.

Granite has been widely used in architectural facades, as evidenced by its presence in numerous historical monuments (**Figures 16** and **20**). A key requirement for granite is its high uniaxial compressive strength (131 MPa). This criterion typically

Property	Granite	Sandstone			Limestone			Marble			
		I	II	III	I	II	III	I	II	III	IV
Maximum absorption (%)	0.4	20	3	1	12	7.5	3	0.2	0.2	0.2	0.2
Minimum density (N/m ³)	25.105	21.185	23.535	25.105	17.260	21.185	25.105	25.450	27.460	27.460	22.605
Minimum uniaxial compressive strength (MPa)	131	13.8	68.9	137.9	12	28	55	52	52	52	52
Minimum modulus of rupture (MPa)	10.34	2.1	6.9	13.9	2.9	3.4	6.9	7	7	7	7
Minimum abrasion resistance	—	8	8	8	10	10	10	10	10	10	10
Minimum flexural strength	—	—	—	—	—	—	—	7	7	7	7

Table 1.
Required properties for stone materials used in facades (table compiled and prepared by the author).



Figure 20.
Granite ashlars on the facade of the Tower of Hercules (photo by the author [27]).

determines its suitability, as granites meeting this standard also exhibit low absorption and high density ($>2560 \text{ kg/m}^3$ or $25,105 \text{ N/m}^3$). Consequently, only unaltered granite is considered acceptable [28].

Sandstone has been extensively used in facade construction over centuries (**Figure 21**). Sandstones are classified into three categories based on their quartz content:



Figure 21.
Sandstone ashlars from Marés on the facade of the Cathedral of Palma de Mallorca (photo by the author [29]).



Figure 22.
Limestone ashlars with varying degrees of deterioration on the facade of the bell tower of the Cathedral of Murcia (photo by the author).

- Type I sandstone: quartz content $>60\%$.
- Type II (quartzitic sandstone): quartz content $>90\%$.
- Type III (quartzite): quartz content $>95\%$.

The highest-quality sandstones (Type III) must meet a compressive strength of 137 MPa, while lower-quality varieties may have values as low as 13.8 MPa [30].

Limestone has also been widely used in facade construction (**Figure 22**). It is classified into three groups based on density:

- Type I (low-density limestone).
- Type II (medium-density limestone).
- Type III (high-density limestone).

High-density limestones (Type III) exhibit superior mechanical properties, but due to their high porosity, density is the primary determining factor [31].

Marbles are categorized into four groups based on their mineral composition and metamorphic origin [32]:

- Type I: calcitic marble.
- Type II: dolomitic marble.
- Type III: serpentized marble.
- Type IV: travertine.

Property	Cladding slates		Roofing slates		
	I	II	Grade S ₁	Grade S ₂	Grade S ₃
Maximum absorption (in %)	0.25	0.45	0.25	0.36	0.45
Minimum transverse modulus of rupture (MPa)	62.1	62.1	62	62	62
Minimum longitudinal modulus of rupture (MPa)	49.1	49.1	—	—	—
Maximum abrasion index	8	8	—	—	—
Maximum acid softening (in mm)	0.35	0.64	0.05	0.20	0.36

Table 2.
 Required characteristics of slates to be used in buildings (table compiled and prepared by the author).

Dolomitic marbles, for example, must have a minimum density of 2800 kg/m³ (27,460 N/m³). Regardless of type, all marbles must meet a strict absorption limit of 0.2%.

The abrasion resistance of sandstones, limestones, and marbles must be greater than $H = 10$, which means that the wear measured in the test must be less than 6 mm. This is an important restriction for limestones, the softest of all the rocks listed in the table (Mohs hardness = 3).

As we said before, slate is a fine-grained metamorphic rock, commonly used for façade cladding and roofing. The properties required for architectural slates differ based on application type. **Table 2** summarizes the specifications for cladding slates and roofing slates.

Slates used in cladding are classified as Type I (interior) and Type II (exterior). Exterior slates must exhibit lower water absorption to prevent frost damage and chemical degradation.

Roofing slates are categorized into three grades based on expected service life:

- Grade S₁: high durability, expected lifespan >75 years.
- Grade S₂: moderate durability, lifespan 40–75 years.
- Grade S₃: lower durability, lifespan 20–40 years.

The highest-quality slates (Grade S₁) must maintain:

- Maximum absorption of 0.25%.
- Acid softening below 0.05 mm, ensuring resistance to acid rain and pollution.

6. Stone facades

Natural stone has been used for centuries in facade construction, both as a structural and decorative element. The different ways in which stone is employed include ashlar masonry, rubble masonry, and stone cladding. The choice of technique depends on the architectural style, structural requirements, and material availability (**Figures 7** and **21** [11]).

Ashlar masonry consists of precisely cut and dressed stone blocks that fit tightly together with minimal mortar (**Figures 7, 20–22**). This technique provides high

structural stability and a refined esthetic, making it prevalent in monumental architecture. Ashlars can be arranged in two main configurations:

- “Stretching” (soga): the longest dimension of the stone is parallel to the wall surface.
- “Heading” (tizón): the longest dimension of the stone is perpendicular to the wall surface [11].

Ashlar masonry was extensively used in historical buildings until the twentieth century when reinforced concrete became the dominant construction material. Despite its durability, the main challenge today is the conservation of these structures due to stone weathering and degradation.

Rubble masonry consists of irregular, unshaped stones arranged with or without mortar (**Figures 8 and 23**). It is classified into two types:

- Dry rubble masonry: No mortar is used; stability relies on careful stone placement and weight distribution.
- Mortared rubble masonry: Stones are bonded using lime or cement mortar, improving structural integrity [11].

In thicker walls, two exterior stone layers are constructed with an inner core filled with smaller stones (cuttings, **Figure 24**). Large stones called perpend stones extend through the wall, ensuring structural cohesion.

Stone cladding involves attaching thin stone slabs to an underlying structural surface. These slabs are often arranged to mimic ashlar masonry but can also be installed with continuous joints. Cladding is used for both interior and exterior surfaces, offering esthetic appeal and weather resistance.



Figure 23.
Granite masonry wall in Famoselle, Zamora, Spain (photo by the author).



Figure 24.
Detail of a sandstone wall in Soria, Spain, where cemented cuttings can be seen (photo by the author).

Slate has been widely used for roofing, particularly in regions with high precipitation. The standard slate sizes range from 30×15 cm to 60×30 cm. Slates are secured using galvanized iron nails or zinc hooks to ensure stability and longevity.

7. Deterioration of stone used in facades

The main problem of stone in facades is the alteration of the material [33]. The conservation of the world's cultural heritage made up of cathedrals, churches, palaces, funerary monuments, bridges, aqueducts, dams, etc. is a constant concern of each of the nations and international organizations that watch over what is declared a World Heritage Site [11, 12, 21].

The action of external agents on the rocky materials used in the building over time produces their alteration [34].

This action causes processes of different nature in the rocks, which for their study are divided into two groups. One is made up of those alteration processes in which no chemical transformations occur, and the other group is made up of those processes of alteration of the rock in which it is chemically transformed [35].

The alteration of rocky materials due to environmental actions occurs over time. This alteration will begin from the first moment, but the effect that interests us is that which occurs after a certain time, in particular the period of life of the building.

The life periods of the construction are different, and often its situation of Service is prolonged when it transcends to be a work of art. This would be the case of the assets referred to above.

The actions that a rock used in building can undergo may come either from the climate of the area where the work is located or from environmental actions specific to the type of work that is being built. Even depending on the type of work, these actions can be different depending on the place that the rocks occupy within it.

The alteration of the stone used in the building is the set of phenomena that occur on these materials due to the action of external agents over time. This action is influenced by the type of material, but also by the specific surface on which external agents act. Therefore, the degree of accessibility of these agents to the interior of the material will be important, as well as its composition and cohesion, with accessibility having a great influence on the speed at which the alteration occurs.

The action of external agents on the stone materials depends on the accessibility of the agents to the interior of the rocks, as well as on the composition and cohesion of the rock.

The accessibility of external agents is a function of the permeability and porosity of the rock. Permeability facilitates the access of external agents, and porosity facilitates its action in a larger volume. It is true that permeability is difficult to measure, but it is related to porosity: the more permeable a rock is, the higher its porosity; similarly, the lower the permeability, the lower the porosity. The porosities of the five most commonly used rocks in building facades have then been collected (**Table 3**). These values would correspond to rock samples without alteration. These are reference values: even in this state, porosities will vary in an interval, and in addition, as the degree of alteration increases, porosity will increase.

From a practical point of view, this ease of access by external agents to rocks is usually qualified by absorption, which is easier and more common to measure, as we saw in Section 3.1.

Other characteristics of the rocks used in facades that have a significant influence on their alterability are their composition and cohesion. On the one hand, mineralogical composition is directly related to the alteration processes in which chemical transformations occur. Thus, in the case of instructive rocks, such as granite, in 1938, Goldich established a scale of chemical alterability based on the silicates present in the rock [36], as opposed to quartz, mica, or potassium feldspars, which are more stable.

The minerals that make up detrital sedimentary rocks, such as sandstone, are chemically very stable, as they come from stable elements of natural rocks. Its stability is also given by the Goldich scale [36]. On the other hand, in non-detrital sedimentary rocks, minerals (or a significant part of minerals) originate from chemical precipitates with compositions different from those of the constituent minerals of intrusive rocks. Limestone is composed mainly of calcium carbonate, usually calcite, although

Rock type	Porosity (%)
Sandstone	18
Limestone	10
Slate	8
Granite	1
Marble	< 1



Table 3.
Influence of porosity on the alterability of the rocks most commonly used in facades (table compiled and prepared by the author).

sometimes it has traces of other carbonates; carbonates have a lower stability than siliceous compounds, and the Goldich scale is not applicable in their case.

In metamorphic rocks, when minerals from intrusive rocks and sedimentary rocks intervene in their composition, their chemical alterability will be conditioned by the presence of siliceous compounds or compounds of lower stability.

Another important aspect in alterability is the increase in volume due to the absorption of water. This characteristic has very low magnitudes in the minerals that make up healthy intrusive rocks. However, it can reach very high values in sedimentary and metamorphic rocks, which can influence the stability of the facade material as a whole.

Therefore, the alteration suffered by stone materials depends on the characteristics of the rocks used and the environment in which the monuments are located. The action of these agents develops such alteration processes in the stones used in facades. These processes can cause its weakening, its fissuration, its disintegration, and variations in its chemical composition.

Nowadays, certain characteristics are required of stones in order to be used in construction, but the stone materials with which our current heritage was built were not subjected to these tests and probably were not built with an indefinite service life in mind, but it is their valuation as a work of art that is forcing us to know the mechanisms of alteration of the stone and try to protect it.

The different alterability of the different types of rocks was commented on, in particular the alterability to water presented by sedimentary rocks. The protection of walls built with these types of rocks is normally carried out with a previous cleaning, followed by a treatment.

Another less frequent and less serious problem that can occur in ashlar built with the same type of rock is the different resistance of some ashlars in different directions, particularly sedimentary rocks. In some cases, it may be necessary to replace them with ashlars placed in the way they present the greatest resistance, usually with the strata perpendicular to the direction of the load.

In facades, we must take into account the different actions to which the rocks located on the exterior façade are subjected, from those used in interior coverings, which are protected from the direct action of atmospheric agents. Even within the rocks used as masonry or exterior coverings, alteration phenomena occur in different intensities between the south-facing facades (the sunniest) and those facing north, with fewer variations in temperature and, in general, more humid.

8. Protection of stone facade walls

Protection against alteration of stone protection elements in buildings is carried out in two phases: cleaning and surface treatment [37]. Obviously, the treatment will always depend on the type of stone we have (granite, sandstone, marble, slate ...) and its degree of alteration [22].

In a work that has already been altered, before treatment, it is necessary to clean the surface particles that are either not esthetic or will reduce the effectiveness of the treatment [38].

The main mission of these cleaning operations, therefore, is to remove the accumulated material and dirt, which stains the stones in different colors. Cleaning should not be too aggressive to avoid lifting undesirable stone thicknesses, due to the alteration it has (**Figure 25**) [11].



Figure 25.
Cleaning operations with water jet and detergent on the pink granite cladding of a building in Madrid (photo by the author).

On healthy and hard rocks, an aggressive cleaning method such as sandblasting can be used, but on altered or soft rocks, a gentle cleaning method must be used, which does not definitively erode the material. In the case of altered rock, the most commonly used cleaning methods are the following [39]:

1. Water vapor jet.
2. Water vapor jet + detergent.
3. Water vapor jet + detergent + cellulosic product.

There are other cleaning methods that are studied for each specific case by specialized factories. For example, in Park Güell, a glass perlite jet mixed with water was used [40, 41].

The consolidation and protection of the stone, once cleaned, are done by means of products with high penetrating power that can give cohesion and permeability to the material. In these cases, very fluid monomers are playing a very important role and once inside the stone, they polymerize, giving a compact and hard product that has hardly changed its external appearance.

Each facade, depending on the type of stone and its condition, requires special treatment, and poor application can have irreparable consequences. Think, for example, of the case of a stone in which the monomer does not go deep enough to the healthy area, and can create a hard superficial crust, which soon comes off the entire wall.

9. Conclusions

The study highlights the importance of understanding the physical and mechanical properties of stone materials used in facades, such as granite, limestone, sandstone, and marble. These properties include absorption, density, compressive strength, flexural resistance, and abrasion resistance. The research emphasizes that porosity plays a critical role in the degradation of stone materials, especially under aggressive environmental conditions.

The study underscores the necessity of standardized selection criteria to enhance the longevity of facades and proposes guidelines for sustainable maintenance strategies. These findings provide essential insights for architects, conservation specialists, and engineers aiming to optimize the use and preservation of stone facades in both heritage and modern constructions.

Key findings indicate that sandstone and limestone are more vulnerable to pollution-related decay, while granite shows superior resistance but requires precise specification to avoid anisotropic failures. The effectiveness of various cleaning and conservation treatments is also assessed, with caution against over-aggressive cleaning methods that can damage the stone. Various cleaning and conservation techniques were evaluated, emphasizing that overly aggressive methods can be counterproductive and cause more harm than good. Appropriate treatments should be selected based on the type of stone and its deterioration state.

The research highlights that porosity is a critical factor in the deterioration of stone materials in facades, particularly in aggressive environmental conditions. Stones with higher porosity, such as sandstone and limestone, are more susceptible to degradation by environmental agents.

The study stresses the need for standardized criteria in selecting stone materials for facades to enhance their longevity. Proposed maintenance guidelines include proper material selection, regular evaluations, and suitable cleaning methods.

The research underscores that many historical buildings were constructed without subjecting materials to durability tests. Therefore, understanding deterioration mechanisms and applying appropriate protection treatments are essential for preserving cultural heritage.

Conflict of interest

The author declares no conflict of interest.

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Glass Curtain Wall: A Systematic Review

Ilaria Spasari, Fabio Conato and Habtamu Bayera Madessa

Abstract

Global climate change and resource limitations are critical contemporary challenges. Since the building sector accounts for about 30% of global energy consumption, many countries are implementing policies to enhance energy efficiency in both new and existing buildings. These measures aim to provide cooling solutions with minimal energy demand while maintaining thermal comfort. The Program for Energy Efficiency in Buildings (PEEB) highlights strategies such as optimizing building design based on the local microclimate, including orientation, shape, openings, and solar shading devices. These measures enhance building envelope performance but often depend on mechanical systems for internal comfort. With increasing awareness of circularity and raw material scarcity, maximizing the potential of façade systems has become essential. Transparent curtain wall systems, introduced in the nineteenth century, have significantly influenced architectural identity and technological advancement. However, even the most efficient systems fail to meet the 2022 UN Environment Program's goal of a 95% energy consumption reduction. Achieving such targets requires transformative changes in both materials and design principles. This study explores contemporary applications of transparent curtain wall systems developed by leading international manufacturers. Using databases like Scopus and Web of Science and applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, a systematic review will be conducted. The collected data will be structured through the innovative concept of the meta-module, an informational core that integrates key indicators of smart façade modules.

Keywords: glass curtain wall, smart façades, systematic review, meta-module, smartness indicators

1. Introduction

Currently, the building sector accounts for approximately 40% of global energy consumption, primarily driven by rising living standards worldwide [1]. Within this sector, air conditioning alone constitutes 20–40% of a building's energy use [2, 3]. As the modern construction industry has evolved, priorities such as occupant comfort, esthetic appeal, and environmental equilibrium have increasingly shaped architectural design. In this context, transparent building envelopes, such as Glass Curtain Wall (GCW), have become prominent features in large public buildings [4–6]. While glass curtain walls offer significant architectural and visual appeal, they are often criticized for their low energy performance, especially in terms of thermal insulation.

Their popularity surged in the 1950s and 1960s due to their association with modernism and their ability to enhance natural daylighting, thereby reducing reliance on artificial lighting [7]. However, this benefit is counterbalanced by their inadequate thermal resistance, a growing concern in light of contemporary sustainability goals.

In response, non-residential buildings increasingly adopt high-performance transparent façades with adaptive features capable of dynamically responding to changing environmental conditions. Reducing overall building energy demand—particularly for heating, cooling, and lighting—requires the development of integrated façade systems that function effectively across seasonal variations. Glazing components, as a critical part of the building envelope, significantly influence solar heat gain, thermal losses, daylight distribution, and visual comfort [8–11]. When properly designed and specified, these systems can substantially enhance energy efficiency and indoor environmental quality. Additionally, the efficient use of interior space has led to the growing adoption of radiant heating systems, which are gaining traction across the industry [12]. The development of façade technologies is shaped by various factors, including architectural trends, technological advancements, and evolving user demands. Increasingly, context-specific environmental considerations are becoming as important as functional or esthetic requirements. While modern trends such as ecological design, energy efficiency, and automated control systems have started to influence façade development, there remains a need for greater integration of renewable energy sources in line with broader ecological objectives across the European construction sector.

The scope of this review is not to classify the GCW components and materials but to shed light on the typology and methodology in investigating contemporary applications of transparent curtain wall systems. Starting from the main research databases, such as Scopus and Web of Science, and by means of the application of the PRISMA method, systematic research has been conducted. The systematization of information has been achieved through the innovative concept of the meta-module, conceived as an informational core encompassing the key indicators characteristic of a smart architecture and, consequently, of smart façade modules.

2. Methodology

The presented paper is a review article using the systematic literature review method, with a meta-analysis [1]. The following subsections describe in detail the process of SE conducted following the PRISMA protocol rules. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method provides a standardized framework to ensure transparency and rigor in systematic reviews [13–15]. It structures the literature selection process into four phases: identification, screening, eligibility, and inclusion. The use of a flow diagram ensures clear documentation and helps minimize bias, enhancing the reliability and reproducibility of the review. The PRISMA protocol constitutes a methodological framework that integrates systematic literature review with quantitative meta-analytical techniques [2].

The following sections offer an in-depth explanation of how the reports included in this review were selected, along with an analysis of their quantitative features. This review draws on data collected from major international scientific databases—Web of Science (WoS) and Scopus—with the most recent search completed in May 2024. Scholarly interest in the GCW field has grown substantially, as reflected in the increasing volume of related publications.

The study defined its search terms, inclusion and exclusion criteria, and data extraction process in advance. The analysis focused on peer-reviewed articles published in English between 2016 and 2023. In the last 3 years, there has been a notable increase in the volume of papers (between 75 and 90). The observed pattern signifies a heightened recognition of the topic's academic significance, accompanied by a substantial growth in research engagement. This is illustrated in **Figure 1**.

The presented review included studies identified with “transparent façade,” “glass curtain wall,” and “adaptive façade.” All analyzed publications were written in English. Keywords were identified by examining the titles and abstracts of previously reviewed studies focused on GCW systems.

The literature search was conducted using the Web of Science and Scopus databases, covering the period from 2016 to the present. This initial search yielded 538 records from Web of Science and 30 from Scopus.

After removing duplicates, the remaining records were selected for further refinement. Titles and abstracts were meticulously reviewed to assess their relevance to the research focus.

Given the manageable number of records, each abstract underwent a double screening process to enhance the reliability and consistency of the selection.

In this first phase, 14 articles have been removed. The screening phase excluded 493 reports for these reasons: they treat different disciplines, different constructive technologies, full text not available, and no English text. Previous reviews have also been excluded, as well as the research about economic and structural aspects, in order to avoid misunderstood interpretations due to their being outside the author's area of expertise. Ultimately, 66 papers were selected for inclusion in this review (**Figure 2**).

Additionally, a meta-analysis was conducted based on data from Web of Science and Scopus extracted for 2016–2024 (**Figures 3 and 4**).

The analytical approach employed in this study is transversal, as it is based on the theoretical framework of the stem-cell *meta-module* in smart architecture. The meta-module contains all the information that allows us to generate contemporary smart façades' modules. It is generated between the match of the current society's necessity and the design solution proposed [16]. For these reasons, meta-modules are developed around four impact categories of indicators that are intrinsic to smart

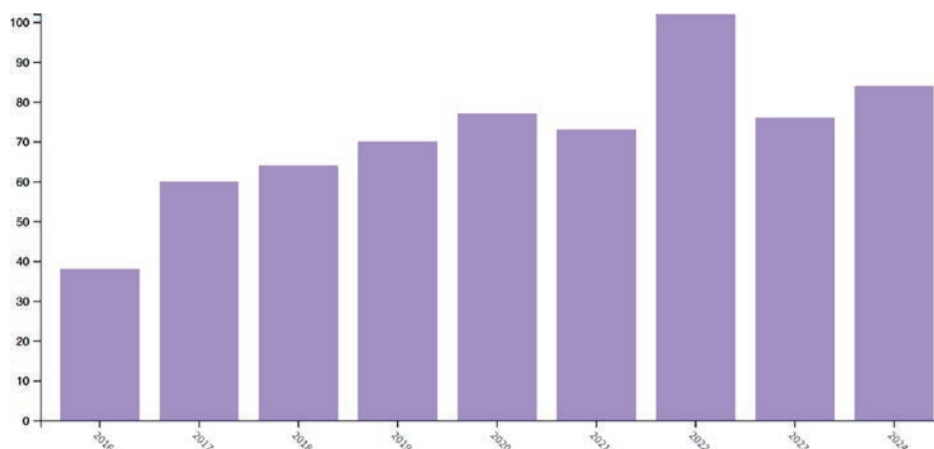


Figure 1.
Trend of publications about GCW from 2016 to 2024.

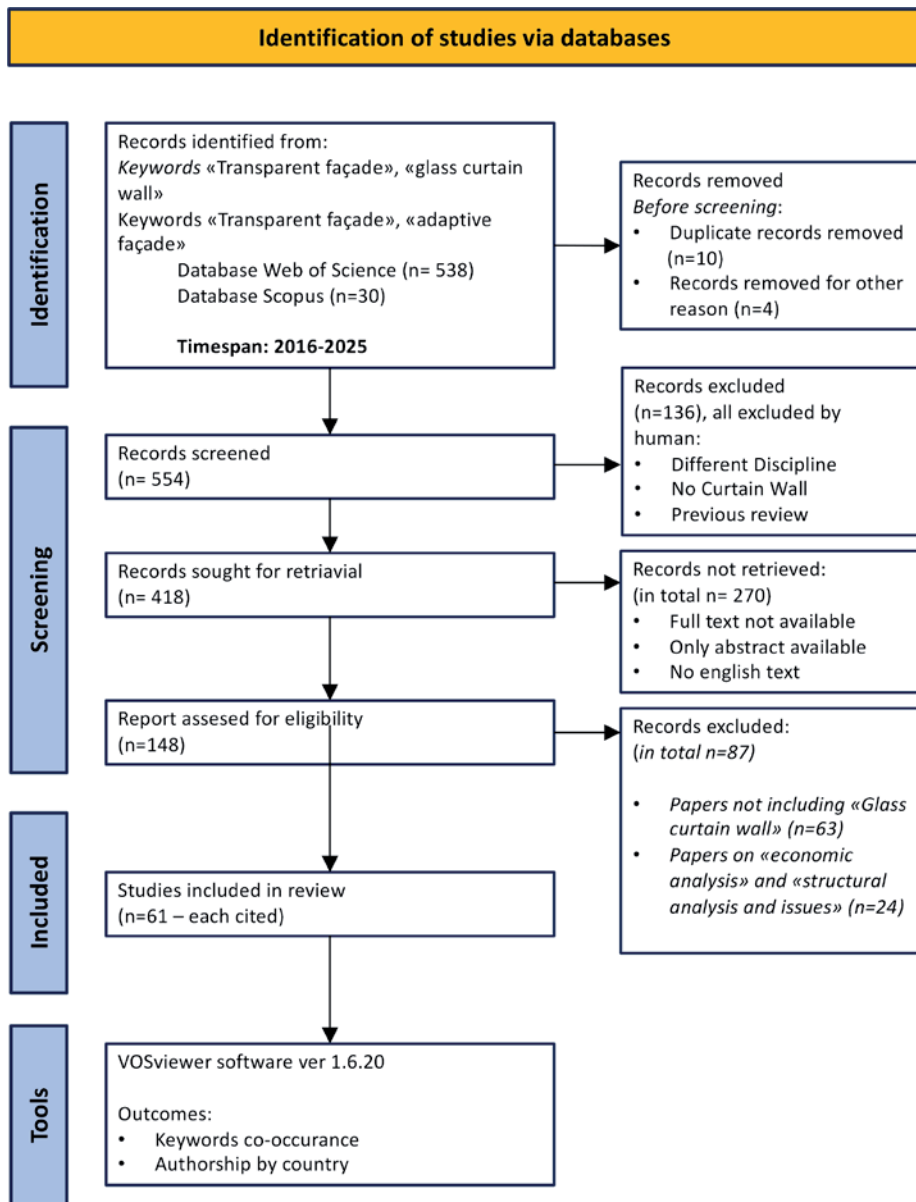


Figure 2.
PRISMA flow diagram.

architecture. These are identified, each corresponding to key contemporary issues that smart buildings—and by extension, façade systems—are required to address through targeted and innovative design strategies: sustainability, dynamicity, coherence, and controllability [4]. This review analyzes the design solutions and methods of smart GCWFs, systematizing them on the four meta-module blocks explained above.

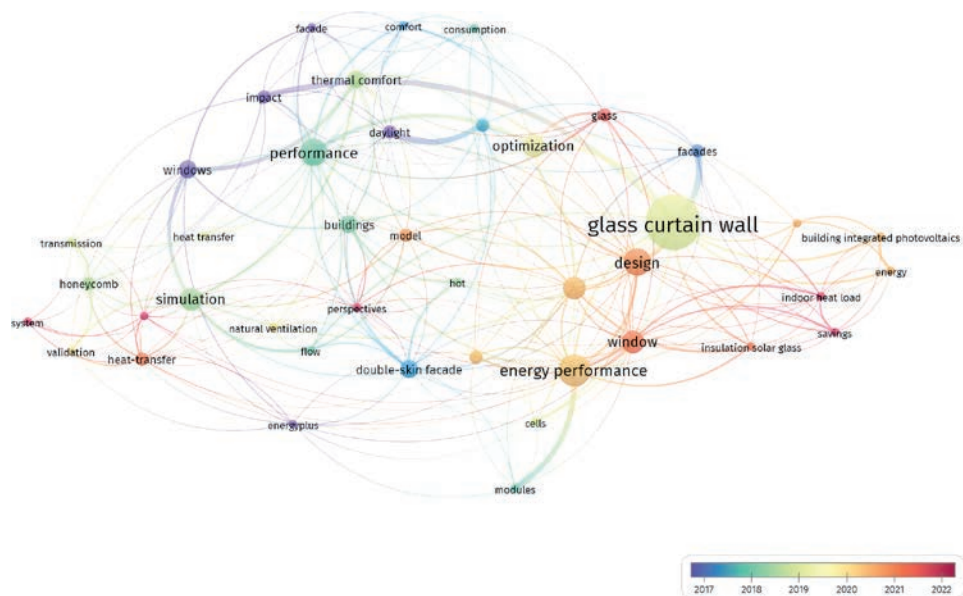


Figure 3. The network visualization, generated with VOSviewer in April 2024, displays keyword co-occurrences from titles and abstracts. Node size indicates term frequency, lines represent co-occurrence links, and colors denote thematic clusters.

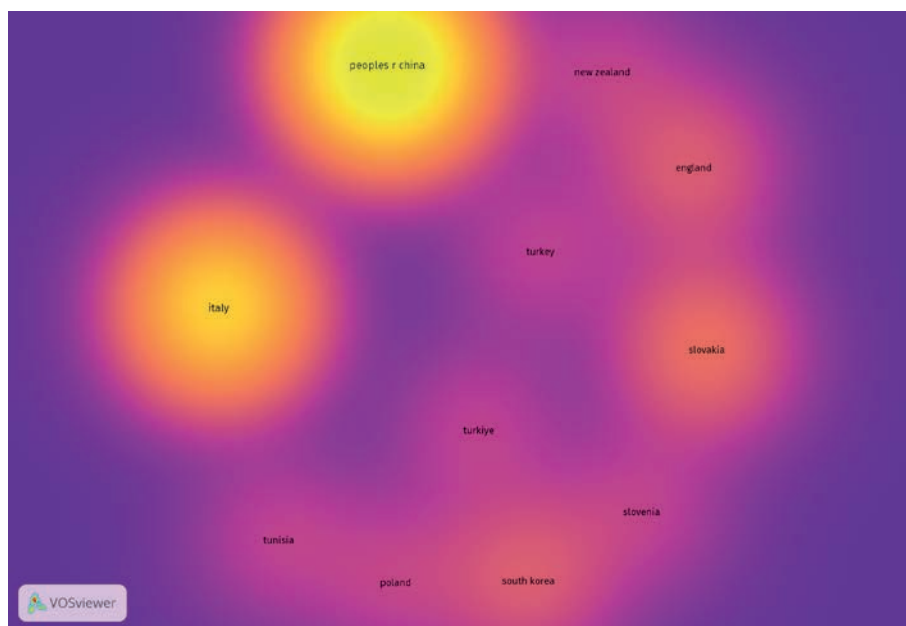


Figure 4. *Network visualization of co-authorship by country. Created by VOSviewer in April 2024.*

3. Results and discussion

The literature survey process resulted in a total of 41 relevant articles on GCWs. The four meta-module pillars are used in order to observe specific trends in GCWs analysis. The information presented in each article was examined according to the categorization described in the previous section (Appendix A).

The studies were distributed over six diverse climate zones (**Figure 5**). The geographical distribution of the reviewed case studies was mapped according to the Köppen climate classification, reflecting climate zones based on temperature and precipitation patterns, and the countries in which the studies were conducted.

The identified climates included Dwb (cold/dry winter, warm summer), Dfc (cold/without dry season, warm summer), Ar (tropical, rainforest), Dfb (cold/without dry season, warm summer), Bwh (arid, hot desert), and Cfa (humid subtropical). The climate zone most extensively studied was Dwb, corresponding to a significant portion of the Eastern European countries. Particularly, several Chinese and Korean research groups show a significant interest in the field.

The majority of studies neither identify the type of façade under analysis nor refer to buildings with a defined functional use; instead, they focus on specific façade components, independently of any specific architectural context (**Figure 6**). Regarding the façade's typology, the main area of interest concerns the double-skin façades (DSFs) and the structural glazing façades.

One of the principal advantages of Double-Skin Façades (DSFs) lies in their potential to significantly enhance a building's energy performance. Owing to their multi-layer configuration, DSFs function as a thermal buffer, effectively reducing heat loss during the winter months while mitigating the risk of overheating during summer.

This feature is particularly advantageous in temperate climates, in which the intermediate cavity acts as an insulating zone that contributes to improved indoor thermal comfort and reduced energy demand for space heating and cooling [17].

Moreover, the ventilated cavity within DSF systems enables natural air circulation, which facilitates passive cooling and contributes to better indoor air quality [18]. In addition to thermal and ventilation benefits, DSFs offer considerable acoustic insulation. By creating a physical separation between the interior and exterior environments, they attenuate environmental noise, rendering them particularly suitable for

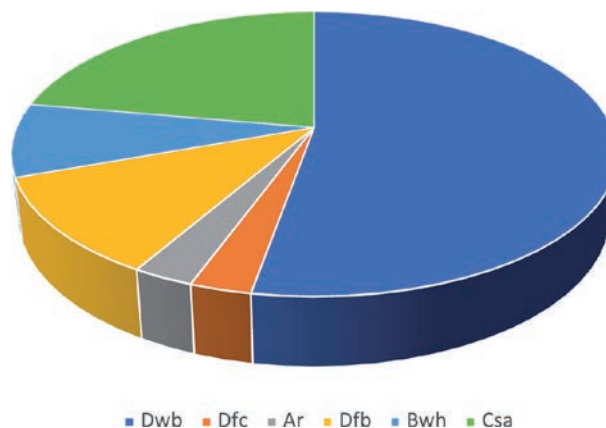


Figure 5.
Geographical distribution of the reviewed studies.

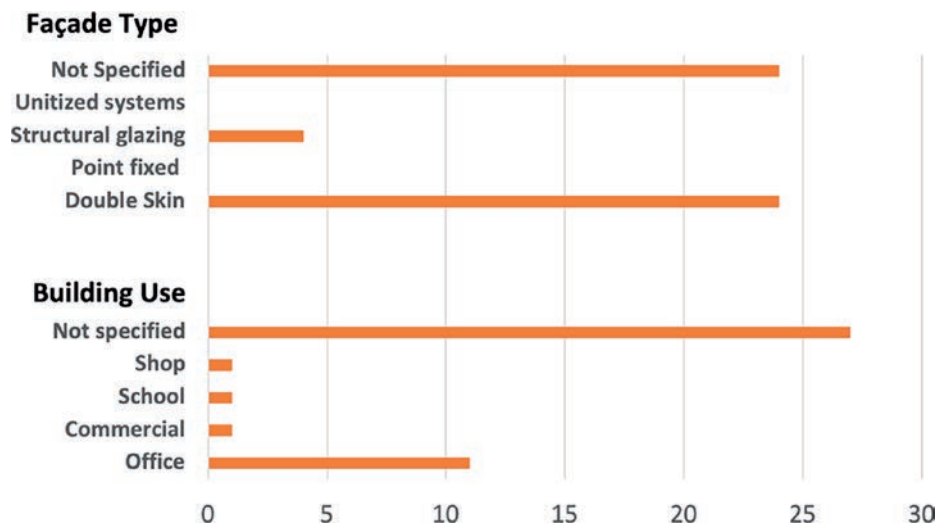


Figure 6.
 The graph shows the number of articles related to the façade type treated and the building use they refer to.

buildings located in urban or high-traffic areas [19]. The air gap between the glazing layers significantly contributes to sound attenuation, thereby enhancing occupant acoustic comfort [20].

Despite their numerous benefits, DSFs also present certain limitations. A commonly reported issue is the risk of overheating due to excessive thermal gain within the cavity during warm periods. This phenomenon can result in increased cooling loads, thereby undermining the overall energy-saving potential of the system [21]. In hot climatic zones, stagnant air in the cavity may further exacerbate this problem, necessitating intensive mechanical cooling to maintain indoor comfort [22]. Another challenge associated with DSFs is the complexity of their design, operation, and maintenance. Effective thermal and ventilation performance requires precise modeling, detailed simulation, and careful calibration of design parameters. Design inadequacies may lead to suboptimal performance, condensation issues, or unanticipated energy losses [23]. Furthermore, while DSFs can contribute to energy savings over the long term, the high capital investment associated with advanced materials, customized systems, and complex installation processes may deter some stakeholders from implementation.

In sum, although DSFs offer substantial advantages in terms of thermal regulation, ventilation, and acoustic control, their integration into building design must be approached with careful consideration of their potential drawbacks, including overheating risk, technical complexity, and elevated initial costs.

Structural Glazing Façades (SGFs) have also emerged as a prominent solution in contemporary architecture, primarily due to their minimalist esthetic and ability to enhance building transparency. These systems impart a visually lightweight and technologically advanced appearance to façades, improving both architectural expression and user perception. The high degree of transparency associated with SGFs allows for substantial daylight ingress, which has been linked to increased occupant satisfaction and enhanced visual comfort [24]. In addition, greater reliance on natural lighting contributes to energy savings by reducing artificial lighting requirements during daytime operation [25, 26].

The incorporation of energy-efficient glazing technologies—such as low-emissivity (Low-E) coatings—further optimizes thermal performance by limiting solar heat gain, with reported reductions in cooling demand ranging from 9 to 14% [24]. SGFs also demonstrate improved acoustic and thermal properties when combined with double- or triple-insulated glazing units (IGUs). These configurations enhance sound insulation and mitigate noise intrusion from the external environment [27]. The use of laminated or inclined glazing solutions further augments these benefits, supporting a comfortable and quiet indoor environment [27].

Nonetheless, SGFs present several technical and operational challenges. A primary concern is the risk of overheating due to increased solar radiation transmission. In the absence of external shading systems or intelligent solar control strategies, these façades may lead to elevated indoor temperatures and increased reliance on mechanical cooling [25], particularly when high-transparency glass is used. This may also result in visual discomfort due to glare [24].

Additionally, SGFs entail a high degree of constructional and operational complexity. Their installation demands specialized expertise, and their initial costs typically exceed those of traditional façade systems [24]. Long-term maintenance is another critical factor, as glass façades are vulnerable to soiling, weathering, and physical degradation, which may compromise both performance and esthetics over time. Moreover, safety considerations are paramount. The brittle nature of glass under impact or seismic loads requires the incorporation of advanced engineering solutions to ensure occupant protection and structural resilience [28].

While SGFs offer compelling benefits in terms of esthetics, daylight utilization, and environmental performance, their adoption should be grounded in a thorough analysis of site-specific conditions and long-term performance expectations. Consideration of potential limitations—such as thermal discomfort, maintenance intensity, and structural vulnerability—is essential to realizing a balanced and high-performance façade strategy.

With regard to building typologies analyzed in existing literature, a significant number of studies ($n = 27$) do not specify the type of façade system examined, nor do they reference an actual or hypothetical building scenario. Furthermore, these studies often omit consideration of the building's functional program or future use. Conversely, the remaining case studies are linked to well-defined building types, including 11 office buildings, one commercial facility, one educational institution, and one retail building.

The consistent application of glass curtain wall (GCW) systems in modern office buildings is attributed to their ability to integrate esthetic value, spatial flexibility, energy efficiency, and structural functionality. These systems provide a coherent and modern architectural language that enhances the visual identity of office buildings while simultaneously increasing their commercial appeal and environmental performance.

The extensive use of transparent glazing fosters a strong visual connection between indoor environments and the external context while simultaneously enabling deep penetration of natural daylight into interior spaces [29]. This increased availability of daylight has been correlated with improvements in user comfort, psychological well-being, and overall productivity. Empirical research has consistently demonstrated that access to natural lighting can elevate employee satisfaction and work efficiency while concurrently reducing reliance on artificial illumination during daytime periods, thereby contributing to lower operational energy demand [30].

In addition to their visual and experiential advantages, GCW systems significantly enhance the energy performance of buildings. Technological advancements in glazing—particularly the incorporation of high-performance low-emissivity (Low-E) coatings and insulated glazing units (IGUs)—have substantially improved the thermal resistance of glass façades, reducing heat transfer and mitigating energy losses through the building envelope [25]. As a result, buildings equipped with GCWs benefit from reduced heating and cooling loads, contributing to improved environmental performance and alignment with sustainable building standards.

Moreover, GCW systems are conducive to passive solar design strategies. By facilitating solar heat gain in colder seasons and enabling solar control in warmer climates (through the use of selective coatings or integrated shading devices), these façades support reduced dependence on active mechanical systems [31]. From a structural perspective, GCWs allow for expansive, column-free interior layouts that enhance spatial flexibility and enable reconfigurable workspaces suited to evolving functional needs [32]. The reduced self-weight of glass compared to opaque materials also leads to lower demands on the primary structural framework, potentially resulting in material savings in steel or reinforced concrete [33].

However, the structural integrity of GCW assemblies must be carefully engineered to resist dynamic loads such as wind pressure and seismic activity. Advances in façade engineering and materials science have enabled the development of robust systems capable of withstanding these challenges; nonetheless, risks associated with glass breakage under extreme loading conditions remain an area of ongoing concern [34].

Operational and maintenance considerations also present notable challenges. Glass façades are susceptible to the accumulation of dust, atmospheric pollutants, and water stains, which can compromise both optical clarity and thermal performance over time [35]. To address these issues, innovations such as photocatalytic self-cleaning coatings and automated façade maintenance technologies, including robotic cleaning systems, are being developed and implemented [35].

Additionally, in the absence of appropriate solar control strategies, extensive glazing can contribute to occupant discomfort due to glare or thermal gains, particularly in regions with high solar exposure [29]. Therefore, effective integration of shading elements and intelligent glazing selection is critical to ensuring indoor environmental quality.

In conclusion, glass curtain wall systems represent a key technological and architectural advancement in the domain of high-performance office buildings. Their ability to simultaneously fulfill esthetic, environmental, and structural objectives underscores their continued relevance in sustainable architectural practice. While several technical and operational challenges persist, ongoing innovations in materials engineering, façade design, and environmental control systems are progressively addressing these limitations, reinforcing the role of GCWs in the future of resilient and energy-efficient building design.

3.1 Sustainability in GCWFs

In addressing the three dimensions of sustainability, this review intentionally excludes studies related to the economic domain, as it falls outside the scope of the authors' expertise. Given the current context of climate change, a significant majority of the literature (73%) focuses on the environmental impact of glass curtain walls (GCWs), whereas only 27% considers the social dimension of sustainability.

From an environmental standpoint, 15 studies investigate potential energy efficiency benefits, four examine the influence of solar radiation on indoor environments, and three explore issues related to thermal comfort (**Figure 7**).

The remaining contributions address topics such as thermal sensitivity, life cycle assessment (LCA), visual performance, and indoor temperature regulation.

Energetically speaking, the integration of photovoltaic cells into CWF-s is one of the main topics investigated. It is worth noting that conventional photovoltaic materials exhibit relatively low energy conversion efficiency. Consequently, considerable research efforts in recent years have focused on enhancing PV system performance by employing light-concentrating technologies to increase the amount of solar energy incident on their surface [36]. Such a trend is also observable in the case of semi-transparent photovoltaic (STPV) and semi-transparent photovoltaic/thermal (STPV/T) façades. Barone et al. [37] proposed an innovative solution for smart building façades known as the Concentrating Photovoltaic Glazing (CoPVG) system. This system features a double-glazing panel embedded with a series of concentrating lenses, with a thin layer of photovoltaic cells positioned at the focal points of the lenses. The unique lens configuration exploits Total Internal Reflection (TIR) to achieve a seasonal effect: increased daylight penetration during periods of low solar incidence angles (e.g., winter) and enhanced electricity generation during periods of high incidence angles (e.g., summer). The implementation of this façade system demonstrated notable energy savings, ranging from 30–60% across the studied climatic zones. Xu et al. [38] evaluated the performance of double-skin façades integrated with semi-transparent photovoltaic glass (STPV-DSF), focusing on the combined effects of glass transmittance (τ) and natural ventilation on the system's dynamic thermo-physical behavior. The findings revealed that both parameters influence solar heat transmission through the façade; however, in summer daytime conditions, glass transmittance had a greater impact than natural ventilation. At night, the effect of natural ventilation became more pronounced, resulting in lower thermal transmittance (U-values). The study also indicated that a reduction in glass transmittance may diminish the overall energy efficiency of STPV-DSFs due to a greater seasonal

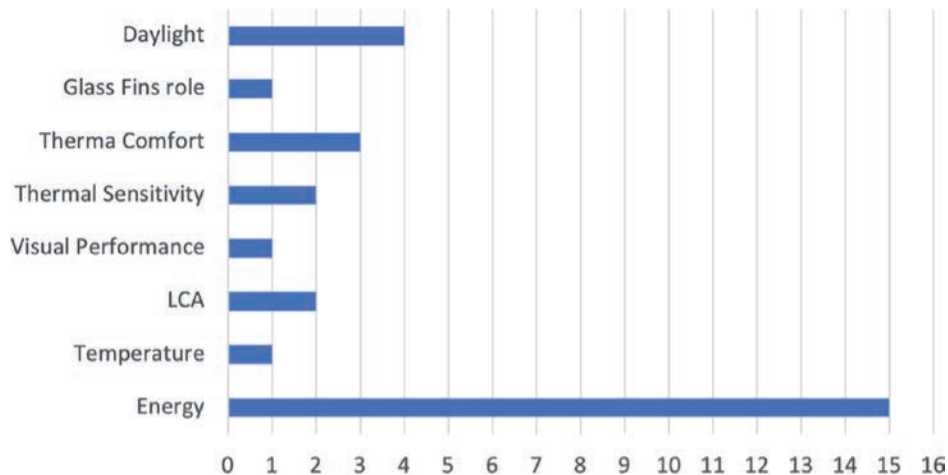


Figure 7.
The graph illustrates the main topic of the reviewed studies.

imbalance between reduced cooling demand and increased heating demand when compared to façades using clear glass. Arkar et al. [39] explored an alternative approach to reducing energy consumption through the development of a semi-transparent, modular building-integrated photovoltaic (BIPV) façade system. This configuration incorporates a forced-ventilated cavity and enhanced thermal storage capacity, achieved by embedding encapsulated phase change material (PCM) inserts on both the inner glass pane of the photovoltaic module and the building envelope. The results showed that, depending on climatic conditions during the heating season, this system can reduce energy demand by 40–55% compared to a reference façade. Moreover, the efficiency of solar energy utilization ranged between 44% and 63%.

To address the trade-off between indoor lighting and photovoltaic performance in BIPV/T (building-integrated photovoltaic/thermal) systems, a novel glass curtain wall design based on a micro-scale transmissive concentrator has been proposed [40–43]. The system consists of an upper and lower plate, side plates, and air and liquid inlet/outlet pipes, all fabricated from polymethyl methacrylate (PMMA). The upper cover integrates multiple micro-concentrating units with embedded fluid channels. These units feature a compound parabolic geometry with a hollow interior filled with a cooling medium. The micro-channel is thermally linked to a CPC (Compound Parabolic Concentrator) glass cover plate, where photovoltaic cells serve as the receiving element. This design effectively supports integrated photovoltaic and thermal energy generation while minimizing excessive solar heat gain within the building interior.

In order to reduce the global energy demand of a building, actively balance its energy use for heating, cooling, and lighting. Iennarella et al. [44] experimented with a novel concept of a responsive transparent façade module. The proposed façade module comprises three distinct glazing layers: a low-emissivity (low-E) selective glass, a double-pane glazing filled with phase change material (PCM) for solar control, and a double-pane glazing filled with aerogel for thermal insulation. These layers are dynamically reconfigured in response to external environmental conditions to minimize energy consumption for lighting and HVAC systems. The module functions as a smart adaptive system, where the low-E glass remains in a fixed position as the passive layer, while the PCM and aerogel glazings—classified as active layers—are automatically repositioned in front of or behind it. This dynamic arrangement enables optimal performance under varying boundary conditions, enhancing the overall energy efficiency of the building envelope.

To evaluate the environmental impact of GCW systems, the Life Cycle Assessment (LCA) methodology has been applied, although studies specifically targeting window systems remain limited. Notably, Kim [29] conducted a comparative LCA study of a Transparent Composite Façade System (TCFS) and a Glazed Composite Window System (GCWS). The findings indicate that the TCFS exhibits a total life cycle energy consumption equal to approximately 93% of that of an uncoated GCWS, while its total CO₂-equivalent emissions account for around 89% of those from the uncoated GCWS. In both systems, the operational (use) phase contributes most significantly to reducing environmental impact, whereas the effects associated with transportation and end-of-life processes are found to be minimal.

Only a few articles of this review investigated other aspects of GCW that have an impact on the environmental sustainability of the façades, such as the daylight performance [45], thermal comfort [46, 47], thermal sensitivity [48], temperature analysis [49], and glass fins' role [50].

3.2 Dynamicity in GCWFs

Dynamicity in building façades represents a crucial advancement in architectural and environmental design, responding to the necessity for energy efficiency and sustainability within the built environment. A variety of innovative approaches have emerged, highlighting the integration of advanced materials and responsive designs over recent years.

There are several means of dynamicity in building façades, such as the use of materials able to change their behavior according to the external stimuli or mechanical movement of some façade component related to solar radiation or other climatic conditions. In this review, as described in paragraph 2, the approach to examining the papers reviewed is to associate the dynamicity of building façades with the concept of multifunctionality, distinguishing three levels of it: level 1, if the façade's analysis responds to basic function (BF); level 2, to energy gaining (EG); and level 3, to supply function (Figure 8).

It is interesting to note that 14 papers treat research on BF façades, nine papers on EG façades, and just two of them investigate the supply functions of the façade considered for the study. Among the 14 papers, six associated the study with a specific building's use (five offices and one commercial building); just one office's façade is considered in its energy-gaining behavior, and two of them do not specify the building function. The analysis suggests that the transition from research activities to full-scale experimentation tailored to specific functional applications remains a significant challenge. Furthermore, it emerges that most studies concentrate on the investigation of fundamental façade functions. Approximately half of the research focuses on strategies for optimizing the use of renewable resources through the building envelope, whereas only a limited number of contributions address the integration of building services systems within façade modules.

3.3 Coherence in GCWFs

In architecture, the concept of coherence is generally defined as the ability of a project to remain aligned with its design objectives across all phases, from initial

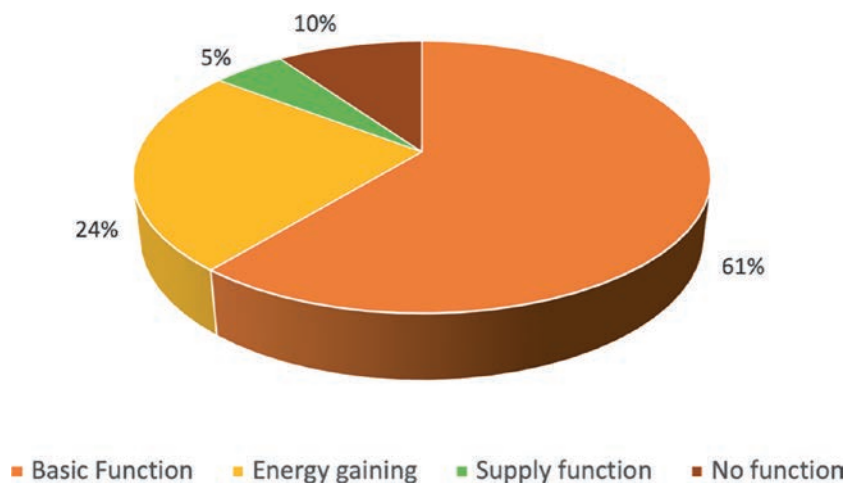


Figure 8.
The cake graph shows the percentage of studies that investigate GCWFs with different levels of multifunctionality.

conception through the various design scales. Since most of the studies included in this review do not reference a specific architectural project, evaluating coherence based on this definition would be inappropriate and not applicable to research lacking a real-world case study. Additionally, coherence was not assessed in terms of alignment between research outcomes and stated objectives, as all reviewed articles either respond to their research questions or contribute to the advancement of knowledge within their respective fields. For this reason, coherence is instead interpreted as a reflection of methodological rigor throughout the research process. This interpretation is articulated through a three-level framework depending on the typology of research that has been conducted or if more than one method has been applied. The analysis reveals that 76% of the reviewed articles present research findings based on software-based simulations, predominantly energy-related tools such as COMSOL or TRNSYS. Only 22% of the studies validate their simulation results through laboratory experiments, typically using custom-designed setups, while a mere 2% confirm simulation outcomes through both laboratory testing and the construction of a full-scale mock-up (Figure 9).

This limited validation at real scale may be attributed to several factors, including the high costs associated with prototype development, extended construction timelines that often exceed research project milestones or deliverables, the size and capacity of the research team, and the degree of collaboration between academia and industry. It is not suggested that studies lacking full-scale prototypes are inherently inconsistent with their research objectives. Rather, such studies may exhibit lower levels of coherence due to a range of influencing factors and potential margins of error in evaluation.

3.4 Controllability in GCWFs

The concept of controllability, in a broad sense, refers to the set of actions undertaken to ensure that a given activity achieves its intended outcomes. From this definition, the intrinsic connection between controllability and coherence becomes evident. The more controlled a process is, the higher the likelihood that its outcomes

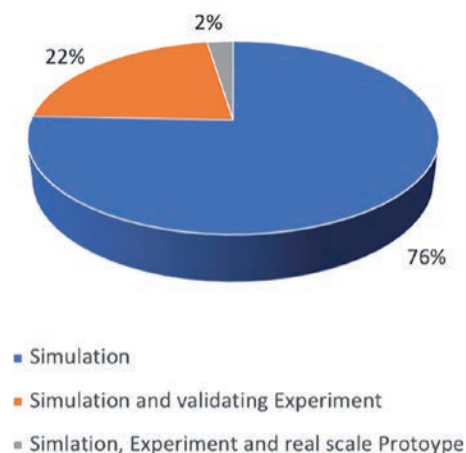


Figure 9.
 The image illustrates the percentage of papers according to the three levels of methodology applied.

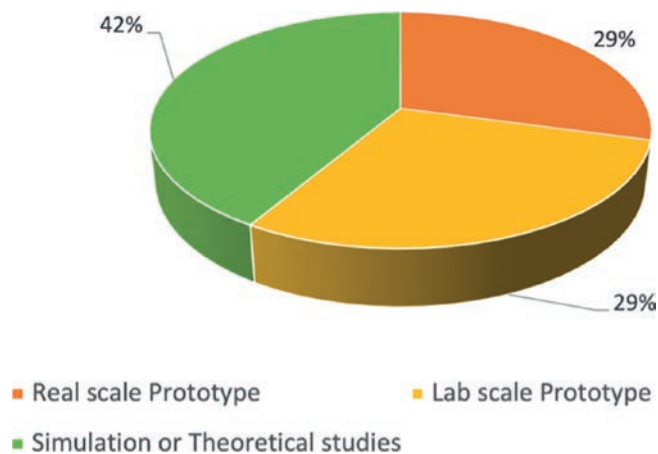


Figure 10.
Percentage of articles approaching different types of controllability levels.

will align with predefined objectives. When applied to the research context, the number and type of actions required to obtain coherent results increase progressively depending on whether a hypothesis is tested through computational simulations, laboratory-scale setups, or full-scale prototypes. Among the selected papers, there is a relatively balanced distribution across these levels of controllability assessment. Specifically, 12 articles present findings derived from full-scale prototypes, 12 from laboratory-scale setups, and 17 from computational simulations or theoretical studies (**Figure 10**).

While the controllability of any design or research process enhances the coherence of its outcomes, it also emerges as a response to the inherent complexity of the construction sector. The use of advanced materials inevitably requires designers to anticipate and manage phenomena of even greater complexity than those previously encountered. While the management of complex dynamics has long been integrated into architectural practice, the additional performance layers introduced by materials with novel or enhanced functionalities, such as smart, responsive, and active materials within building systems, demand an even more informed design approach. This approach must be capable of addressing both the potential and the risks associated with the increasingly widespread adoption of such materials. [51]. Baccarini [52] emphasizes that project complexity significantly influences various aspects of project management. It shapes planning, coordination, and control needs; complicates the definition of goals; impacts the choice of organizational structure and procurement methods; and determines the expertise required. Overall, greater complexity typically leads to increased time and cost [53].

4. Conclusions

This systematic review has highlighted the growing relevance of Glass Curtain Wall (GCW) systems in the context of contemporary architectural and environmental demands, particularly in non-residential buildings. Despite their esthetic and functional appeal, GCWs pose significant energy and environmental challenges, particularly regarding thermal insulation and solar control. However, the increasing

integration of adaptive features, advanced glazing technologies, and multifunctional components demonstrates a clear shift toward high-performance transparent façades that align with modern sustainability goals.

The meta-analysis revealed that research activity in this domain has intensified significantly in recent years, especially across diverse climatic zones, with a particular focus on cold and temperate regions. Among the façade typologies, Double-Skin Façades (DSFs) and Structural Glazing Façades (SGFs) emerged as the most investigated, with DSFs offering notable advantages in terms of energy efficiency, acoustic insulation, and ventilation, albeit with associated risks of overheating and complexity. SGFs, while esthetically advantageous and conducive to daylighting, also face technical challenges such as solar gain management, maintenance demands, and safety concerns.

Across the reviewed literature, a majority of studies relied on energy-based simulations, with fewer employing experimental validations or real-scale prototypes, indicating a methodological imbalance that may affect the robustness of some findings. The assessment of façades according to the four meta-module indicators—*sustainability, dynamicity, coherence, and controllability*—revealed critical insights into the current state of research. While sustainability is increasingly addressed, especially from an environmental perspective, the social dimension remains underexplored. Dynamicity is often limited to basic or energy-gaining functionalities, with few cases demonstrating supply-level adaptability. Similarly, coherence is largely dependent on simulation tools, and controllability is inconsistently applied, with varying levels of process validation. Notably, the integration of semi-transparent photovoltaic systems, phase change materials (PCMs), and responsive glazing solutions offers promising avenues for energy savings and environmental performance enhancement. Yet, their successful implementation requires addressing design complexity, high initial costs, and real-world performance uncertainties.

These studies might be implemented in several future perspectives. Research on Glass Curtain Wall (GCW) systems should be focused on bridging the gap between simulation and real-world performance through full-scale experimental validation and interdisciplinary collaboration. Expanding studies to a wider range of climates and building types will improve applicability, while integrating smart technologies, such as AI-based controls and real-time monitoring, can enhance responsiveness and efficiency. Emphasis on life cycle assessments, including environmental, economic, and social impacts, will also be crucial to support the development of GCWs as adaptive, sustainable components in the transition toward resilient and intelligent buildings.

In conclusion, GCWs are transitioning from passive architectural elements to active, smart systems capable of contributing significantly to energy efficiency and indoor environmental quality. Future research should prioritize interdisciplinary collaboration, full-scale experimental validation, and the integration of user-centric and context-specific design strategies. Such efforts will be critical in advancing GCW technologies toward more resilient, adaptable, and ecologically responsive building envelopes.

Conflict of interest

The authors declare no conflict of interest.

Acronyms and abbreviations

GCW	glass curtain wall
STGCW	semi-transparent glass curtain wall
DSFs	double-skin façades
PEEB	energy efficiency in buildings
SGFs	structural glazing façades
S	sustainability
D	dynamicality
C ₁	coherence
C ₂	controllability

A. Appendix

See **Table A1**.

Ref. no.	Year	Reserch type ¹	Building type	Façade type	Climate	Evaluation ²	S ³	D ⁴	⁵ C ₁	⁶ C ₂
[54]	2015	Ex	Office	DS	Dwb	IC	S	BF	A	A
[55]	2011	S	NS	NS	Dfc	LCA	E	0	A	C
[56]	2016	TA	NS	NS	Dwb	W	E	0	A	C
[40]	2022	Ex	NS	NS	Dwb	E	E	SF	A	B
[41]	2022	Ex	NS	NS	Dwb	E	E	SF	A	B
[57]	2019	S	NS	DS	Dwb	E	E	EG	B-C	A
[58]	2022	Ex	Office	SG	Dwb	TS	S	BF	A	A
[42]	2019	Ex	NS	NS	Dwb	E	E	EG	A	B
[59]	2013	Ex	NS	NS	Dwb	AI	S	0	BA	A
[30]	2020	TA	Commercial	US	Ar	UO	S	0	BA	C
[43]	2022	Ex	NS	NS	Dwb	E	E	EG	A	B
[60]	2023	Ex	NS	SG	Dwb	IC	S	BF	A	A
[61]	2006	Ex	NS	NS	Dwb	AC	S	BF	BA	A
[62]	2019	S	NS	NS	Dwb	E	E	EG	A	C
[50]	2022	S	Office	DS	Dwb	T	E	BF	A	A
[63]	2019	TA	Office	NS	Dfb	GFR	E	BF	BA	C
[64]	2017	Ex	NS	DS	Dfb	V	E	BF	A	B
[39]	2020	S	NS	NS	Dfb	E	E	EG	A	A

Ref. no.	Year	Reserch type ¹	Building type	Façade type	Climate	Evaluation ²	S ³	D ⁴	⁵ C ₁	⁶ C ₂
[65]	2007	S	Office	NS	Bwh	E	E	BF	A	C
[66]	2019	S	NS	DS	Csa	E-VP	E	BF	BA	C
[67]	2013	S	Office	NS	Csa	DL	E-S	BF	A	C
[49]	2016	S	NS	NS	Cfb	TS	E	BF	A	C
[44]	2015	S	NS	NS	Csa	E	E	BF	A	C
[68]	2015	Ex	NS	DS	Dwb	DL-E	E-S	EG	A	B
[69]	2017	S	NS	NS	Cfb	DL-E	E-S	BF	A	C
[70]	2017	S	Office	NS	Cfb	DL	S	BF	A	C
[71]	2017	S-Ex	Office	NS	Dwb	DL	S	BF	A	B
[45]	2019	Ex	NS	NS	Csa	E	E	BF	A	B
[72]	2023	S	NS	SG	Dwb	E	E	BF	A	C
[73]	2022	S	NS	DS	Dfb	E	E	BF	A	B
[74]	2022	Ex	Office	DS	Dwb	E	E	BF	A	A
[75]	2019	TA	NS	NA	Bwh	UO	S	BF	A	C
[37]	2022	Ex	NS	NS	Csa	E	E	EG	A	B
[38]	2023	Ex	NS	DS	Csa	E	E	EG	A	A
[47]	2023	Ex	Office	DS	Bwh	Th	E	BF	A	A
[76]	2013	Ex	NS	NS	Csa	Th	E-S	BF	A	B
[46]	2022	TA	NS	UG	Cfb	DL	E	BF	A	C

Ref. no.	Year	Reserch type ¹	Building type	Façade type	Climate	Evaluation ²	S ³	D ⁴	⁵ C ₁	⁶ C ₂
[77]	2016	Ex	NS	NS	Dwb	VP	E	EG	A	B
[78]	2016	Ex	School	SG	Csa	AB	S	BF	A	A
[55]	2011	S	Office	NS	Cfb	LCA	E	EG	A	C
[48]	2022	S	Shop	NS	Dwb	Th	E	BF	A	C

¹S—simulation, Ex—experiment; TA-Theoretical Analysis.

²DL—daylight, UO - User opinion, E—energy, T- Temperature, LCA, W-waste management, TS - Thermal sensitivity; AI – Automatized inspection, BGP - Basic Glass Performances, Automatized cleaning, GFR - Glass Fins Role, V - ventilation, VP – Visual Performance, Th -Thermal Comfort.

³IC- Indoor comfort, E- Environment, AB – Acoustic Behavior.

⁴BF – Basic function, EG- Energy gaining, SF- supply functions, 0 – no function.

⁵NA- Not Achieved–, BA- Barely achived, A- Achived.

⁶A = real scale experiment (prototype), B = lab scale experiment, C = simulations or theoretical analysis.

Point fixed = PF; Structural glazing = SG; Double-skin = DS; US = Unitized systems, Not Specified = NS.

Table A1.

The table summarizes the systematic review conducted on the 41 articles reviewed.

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Section 2

New Technologies, Design Planning and Tools for Sustainable Design and Energy Efficiency

Facade Retrofitting: Reclad and Overclad Typologies for High Performance

Mary Ben Bonham

Abstract

This chapter examines façade retrofitting strategies within the context of high-performance buildings. It explores motivations for façade retrofitting such as addressing failures, extending building lifespan, enhancing indoor environmental quality, and reducing energy consumption. Case studies of two International Style office towers in the United States illustrate the evolving performance criteria for façades. The case studies showcase innovative recladding and overcladding design solutions that respond to variables in building construction, condition, and tenancy. Additionally, the chapter highlights the growing importance of a multicriteria approach to guide retrofitting for high performance. Owner criteria for the case studies included blast-resistance and updated environmental performance targets tied to funding. Expanded criteria for retrofitting projects may include social cost of carbon, environmental justice, and embodied carbon in construction solutions. These broadened standards hold relevance for stakeholders in the public and private sectors who aim to upgrade existing building stock.

Keywords: façade retrofitting strategies, multicriteria approach, energy efficiency, building enclosure, cladding, construction techniques

1. Introduction

The greenest building is the one that already exists [1]. With a large percentage of real estate locked into existing buildings, an increase in energy efficiency upgrades is an essential step to reduce carbon emissions in the building sector. Around 80 percent of the current building stock will still be in use by 2050. The United Nations Global Status Report for Buildings and Construction 2024/2025 estimates the need to triple the rate of energy efficiency retrofits and upgrades to existing buildings by 2030 to meet Paris Agreement goals. Implementation of effective building codes for existing building energy performance is key to the success of global decarbonization efforts. Upgrades to walls, windows, and heating and cooling systems are central to the challenge of meeting higher performance targets [2].

As the barrier between exterior and interior environments - inclusive of facade, roof, and foundation - the building enclosure, or building envelope, is a critical

element of whole building design. Building enclosures have always been expected to be durable and provide some degree of environmental separation or moderation. Building enclosure design must account for conditions of local climate and building use, and comprehensively address issues like energy efficiency, daylighting, indoor air quality, fire safety, thermal comfort, and carbon footprint [3].

1.1 Methodology

The chapter's focus is on façade retrofitting strategies in the context of building renovations for high performance in energy and indoor environmental quality (IEQ). After addressing the research context regarding facades and energy efficiency regulations, this study turns to the topic of building retrofitting (Section 2) and façade retrofitting (Section 3). A Façade Retrofit Typology (**Table 1**) is proposed to organize and classify the variables and construction solutions encountered in façade retrofitting. Case studies (Section 4) focus on high-performance facades designed for the renewal of two International Style government office towers in the United States:

- The Edith Green-Wendall Wyatt Federal Building in Portland, Oregon was reclad in 2013.
- The A.J. Celebrezze Federal Building in Cleveland, Ohio was overclad to form a double-skin facade in 2015.

Discussion (Section 5) examines how the case studies demonstrate benefits of a multicriteria approach for façade retrofit. The case studies highlight how “one size does not fit all” in designing for retrofit. Innovation is required to address unique project conditions. While one of the challenges of retrofit is that design solutions may not be transferable to other sites, innovations nonetheless contribute to the industry's technical knowledge base. Bespoke design solutions for each building respect differences in facade age, condition, and location, and share owner-specific criteria for energy conservation and blast resistance. The social cost of carbon, financial risk, environmental justice, and embodied carbon in construction materials are newer criteria informing cost–benefit studies of building projects. The expanded criteria and the outcomes of these case studies hold relevance for public and private stakeholders aiming to safeguard investments and upgrade existing building stock.

1.2 Research context

Previous studies have explored the impact of energy efficiency regulations on the thermal performance of building enclosures [4]. Global implementation of energy performance regulations and standards for buildings began in the 1970s, driven by the oil crisis and rising energy costs. While specific regulations vary by country and region, the core concept of setting minimum energy performance requirements for new and existing buildings has consistently progressed over time. In the European Union, the first Energy Performance of Buildings Directive (EPBD, 2002/91/EC) introduced a unified methodology for achieving energy efficiency in the building sector and mechanisms for enforcing the regulations. A subsequent EPBD (2010/32/EU) imposed Nearly Net Zero Energy Building goals [4]. The latest EPBD (2024/1275/EU)

Motivating criteria for retrofit	Original façade construction	Extent of demolition	Façade retrofit classification	Façade retrofit construction
Historic preservation	Load bearing wall with windows (e.g., CMU, ICF, brick cavity wall, cladding on metal or wood stud framing)	Window only (wall remains)	COMPONENT	Replace windows or reglaze within existing frame
Extend building life		Cladding only (wall structure remains)		Replace cladding or repairs to system (e.g., re-caulk, repoint)
Remediate environmental problems		Other component (e.g., external shading)		
Code compliance (energy, accessibility)	Non-load bearing opaque wall with windows (e.g., precast concrete panels, non-glazed curtain walls of any material)	Complete wall and enclosure demolition	RECLADDING (wall replaced in full)	Stud or bearing wall with cladding
Performance enhancement (energy, thermal, luminous, acoustic, structural, fire-resistance)	Glazed curtain wall (e.g., stick, unitized, double skin)			Non-glazed curtain wall (e.g., metal or stone veneer panels)
Change related to repurposing building	Combination			Glazed curtain wall (e.g., stick, unitized, double skin)
Change related to aesthetics or space value	Other			External shading elements; green screens
		Partial or no wall demolition	OVERCLADDING (original façade materials remain behind new wall systems)	Direct (e.g., exterior thermal insulation, rainscreen system, green wall) Opaque offset (e.g., stone, brick, or metal on furring strips; ventilated rain screen systems) Glazed offset (double-skin facade) Screen offset (e.g., terra cotta fins, perforated metal panels, green screen)

The table integrates a multicriteria approach to façade retrofit with an organization that aims to classify the variables that lead to bespoke construction solutions. The list of original and new façade construction systems is not exhaustive. While common materials and façade systems are noted, emerging materials and construction technologies may be applied within the representative categories.

Table 1.
Façade retrofit typology.

intends to increase the rate of renovation, giving EU countries flexibility to decide on retrofit measures best suited to national contexts [5]. The EU’s Energy Efficiency Directive (2012/27/EU), established rules and obligations for member states to achieve EU energy efficiency targets for new construction and existing buildings among other sectors. The current recasting of the directive (2023/1791/EU) requires EU countries to renovate 3% of buildings owned by public bodies every year to upgrade their energy performance to a harmonized definition of nearly zero-energy building or zero-emission building standard [6].

The United States, while also aiming for net-zero emissions, takes a more decentralized approach with significant autonomy granted to individual states. Environmental legislation in the US operates primarily at the federal level through limits to emissions, clean air and water acts, and renewable energy subsidies [7]. The Energy Policy Acts of 1992 and 2005 [8] and the Energy Independence and Security Act of 2007, updated in 2022 [9] utilize a combination of mandates and tax incentives to promote use of renewable energy, high-efficiency lighting, heating and cooling systems, and building enclosure technologies, among other energy-related initiatives, within qualifying new and retrofit applications. Implementation of federal laws can fluctuate depending on the political administration in office, as demonstrated by shifts in environmental priorities between different presidential terms. Presidential executive orders can significantly influence how laws are enforced and how government agencies operate, effectively shaping policy [7].

By decree or incentive, these policies have transformed construction practices and raised the bar on building energy performance, driving progress in the field of building materials and systems. And in the other direction, research and development of efficient building technologies enables the successive tightening of regulations over time. Simple directives for building enclosure thermal transmittance have evolved to more complex regulations that acknowledge dynamic whole building hygrothermal interaction. Parameters of thermal insulation, thermal storage, ventilation, air tightness, solar gains, and sun protection interact to determine energy efficiency and indoor environmental quality related to the building enclosure. As buildings increasingly achieve low energy with high performance, further reduction of thermal loads becomes more challenging. To reach higher levels of performance, façade designs for new construction and innovation must employ innovative technologies and sustainable strategies [4].

Recent studies provide a review of advancements in building enclosure design, utilizing passive and active strategies that enhance performance and help reduce building carbon emissions. Innovative and sustainable strategies include kinetic facades with adaptive mechanisms, such as smart glazing and dynamic shading devices, double-skin facades, and building-integrated photovoltaic (BIPV) solutions [10–12]. Types of bio-facades, including living walls, planted balconies, green screens and algae bio-reactive facades, are also notable for providing functional benefits to thermal insulation, air quality and promoting biodiversity [10, 11, 13]. Other research assesses the life cycle impact of integrating non-conventional materials – polymeric textile, biogenic mycelium composite, and post-consumer textile waste – within External Thermal Insulation Composite System (ETICS) with the aim to develop lightweight solutions for the net-zero energy retrofitting of curtain wall systems [14]. Evolving methods of production are also driving change in façade technology as industry experiments with disruptive technologies such as use of 3D printing in manufacturing customized façade components and use of artificial intelligence in facade design or in training building management systems to optimize actions of façade and other building systems [11].

Retrofitting is the process by which existing buildings are upgraded for continued life and higher performance. The building enclosure is a core factor impacting building energy performance and indoor environmental quality. But with a vast variety of buildings to be considered, no singular strategy for façade retrofitting can be recommended. Innovations in façade engineering are necessary to advance and accelerate deep energy retrofitting of existing buildings.

2. Building retrofitting

2.1 Variables influencing building retrofitting

Existing buildings present uniquely individual narratives. The decision to retrofit, and to what extent, is based on tangible variables of the existing building in conjunction with project objectives and how costs and benefits balance in the perspectives of different stakeholders like developers, owners, tenants, and society.

In *Retrofit for Purpose: Low Energy Renewal of Non-Domestic Buildings* [15], Prasad outlines the following building variables that influence retrofit decisions:

- *Type*. How the building is used; variables such as occupancy, hours of operation, activities, and equipment.
- *Tenure*. The conditions under which the building is held; who will benefit and who will be willing to invest in retrofit.
- *Age and condition*. Factors used to diagnose the level of refurbishment or replacement of building structures, materials, and systems.
- *Historical significance and context*. Factors influencing decisions about the building's external and sometimes internal appearance [15].

2.2 Extent of building retrofitting

Depending on these variables, building retrofits might be planned to range from single measures such as window replacement to major renovations that address whole building systems in an integrated approach.

Stand-alone retrofitting measures must be considered for their impact on whole building functioning and purpose. For example, building air sealing may have implications for air quality if ventilation is not also considered. Interior lighting retrofitting may have an overly long payback period when only energy savings are quantified, but the upgrade may meet owner objectives when improved lighting quality and reduced maintenance are also considered [16].

On the other end of the spectrum are comprehensive retrofitting projects. Deep energy retrofit (DER) broadly describes major renovation projects that significantly reduce energy consumption and emissions while enhancing building energy performance. Definitions vary based on national contexts but generally entail coordinated upgrades to multiple building systems to reach specified energy reduction targets [17].

DER has been a subject of research under the International Energy Agency Energy in Buildings and Communities (IEA EBC) Program Annex 61. One of the program's outcomes, *Deep Energy Retrofit: A Guide to Achieving Significant Energy Use Reduction with Major Renovation Projects* [18] provides a valuable summary of lessons learned from 26 case studies of buildings that underwent major renovations across North America and Europe. The research was limited to public buildings such as dormitory, educational, and office buildings that were constructed before the 1980s. The analysis determined that deep energy retrofits can be cost-effective and successful in the context of a major building renovation when core energy-efficient technologies are bundled. When applied together, improvements in three categories

- building envelope, lighting and electrical systems, and HVAC systems - can reduce the total building site energy use by about 50% including plug loads. For maximum cost–benefit balance, the report advises that DER are best timed to coincide with major building renovation projects in which buildings are evacuated and gutted [18].

2.3 Multicriteria approach

Energy efficiency alone is not always sufficient motivation for retrofitting. A multicriteria or multiple project benefits (MPB) approach is promoted as a strategy to make the business case for office building deep energy retrofits. DER can provide returns on investment in multiple readily quantifiable areas such as building value, rental income increase, and energy and maintenance cost savings. Methods also exist to quantify the values of higher work productivity and avoided greenhouse gas emissions so that these benefits can be added to the cost–benefit analysis [19]. The IEA’s DER program researchers observed that buildings usually undergo renovations for reasons other than energy use reduction, including extension of building life, repurposing, code compliance, remediation, and adding value such as increasing useful space area, attractiveness or quality [16].

One of the biggest barriers to retrofit projects is the ‘split incentive,’ wherein tenants in a commercial lease enjoy the benefits of improvements financed by their landlords. Improvements to commercially leased structures may benefit tenants more directly than the building owner or developer under certain lease structures and given the generally shorter-term payback periods of commercial investments [19]. In contrast, owner-occupied properties such as corporate headquarters, university campuses, and public buildings traditionally have opportunity to plan and invest for the longer term.

Factors that are more difficult to quantify but nonetheless inform decision-making include owner goals for building image, green building designation, and benefits to society such as reduced environmental impact and preservation of historic or urban context [19]. A research study on office building retrofitting posits that the multicriteria method can be a “holistic approach to find solutions that are technically appropriate, environmentally sound, financially viable and socioculturally valuable [20].” To determine which retrofitting strategies are the most efficient, the study proposes a multicriteria approach based on the three dimensions of sustainable development:

- *Environmental* criteria include annual energy use and emissions.
- *Sociocultural* criteria include human thermal, acoustic, and visual comfort factors.
- *Economic* criteria include renovation investments costs and annual running costs [20].

Prasad’s variables of type, tenure, age and condition, and historical significance and context can be used to identify criteria that motivate and guide the extent of retrofitting besides cost. For example, it may not be practical to relocate building occupants or disrupt building operations. A building may have historical significance, leading a project to façade restoration rather than façade replacement. To capture the nuanced variables of individual retrofit projects, decision-making should be guided by a multicriteria or multiple project benefits approach.

3. Façade retrofitting

As discussed above, the building enclosure is one of the three key systems to be most effectively bundled to reduce building site energy use. Facades play a leading role among the variables and multiple criteria for determining the cost–benefit scenario of building retrofitting. The Façade Retrofit Typology (**Table 1**) unites these influences, offering a guide to track motivating criteria for façade retrofit alongside project-specific variables of existing and new construction.

3.1 Motivating criteria for façade retrofit

3.1.1 Context of aging building stock

Estimating a façade life cycle of 25–30 years, buildings built before the turn of the century will have reached the retrofitting phase, representing a large portion of existing building stock. The interwar and post-WWII eras ushered in the relatively new typology of buildings dedicated to administrative work [20]. New office buildings built in this era incorporated cladding technologies that were novel and state-of-the-art for their time. Cladding systems in precast concrete or metal panels were often uninsulated. With the rise of curtain wall technology, the ‘sealed and conditioned glass box’ became a signature building type for corporate architecture. These buildings relied on robust mechanical systems to manage thermal gains and losses. Understanding of bioclimatic architecture had been steadily developing in the field but had not dominated mainstream building practice. Concerns about energy conservation resurfaced into the mainstream in the wake of the 1970s energy crisis. While building structures in reinforced concrete and steel proved durable, mid-century building enclosures and energy-intensive mechanical systems became obsolete [21].

Nonetheless, aging existing buildings retain value. Many original facades hold historic significance for communities and society and warrant preservation. Other practical matters of investment may drive the investment in façade retrofit. With site development and utility infrastructures already developed, the underlying building structure is likely to remain viable much longer than the enclosure. Aged façades may be partially or fully replaced to extend the building life or enhance aesthetics and value of the space. A change in building use may also drive owners to make functional changes to façade components.

Remediation of failed enclosure elements is a primary driver of facade modification decisions. Facades in aging buildings can have multiple problems including leaks and thermal losses due to age, deferred maintenance, and deficiencies in original construction.

3.1.2 Context of high-performance facades

Facade improvements may be planned to ‘future-proof’ property for anticipated higher performance standards as regulated by building codes or local jurisdictions, or to revitalize existing buildings so they may compete with newer neighboring structures built to higher performance standards [22]. As described in the introduction (Section 1), regulations and code requirements for energy performance and expectations for comfort have risen in stride with better-performing building materials and methods. With lighting and HVAC systems, the building envelope is one of the core categories recommended to be bundled in a cost-effective deep energy retrofit model.

A shift in focus from operational energy to broader performance frameworks that assess source energy, carbon, and life cycle impacts has resulted in expanded criteria and incentives for retrofit projects. As buildings are being increasingly assessed for resilience from a life cycle perspective, many renovation projects and programs have the specific aim of significantly reducing energy consumption and related carbon emissions [23]. Building stakeholders may also aspire to higher building performance in categories related to risk, for example, fire and blast resistance in the event of natural disasters or attacks. Concurrently, owners may elect to develop project-specific criteria for occupant comfort related to the thermal, luminous, and acoustic environment of the building that exceed code requirements.

3.2 Façade retrofit classification and construction

Façade retrofit could be realized for existing buildings with a wide variety of base building structural systems (e.g., concrete, steel, timber) and façade constructions. Existing building facades may be classified as load-bearing or non-load-bearing walls with windows, curtain walls, or combination. When planning façade retrofit, it can be useful to understand the existing façade structural assembly (e.g., site-built, prefabricated, unitized), framing materials (e.g., aluminum, steel, wood, fiberglass) and glazing technologies (e.g., double- or triple-glazed IGU, structural sealant glazed, point-supported glazed, double windows, closed cavity façade).

Façade retrofit solutions vary greatly in scope, from targeted improvements to individual components, like window replacement or cladding repairs, to full facade replacement. The Façade Retrofit Typology (**Table 1**) proposes a simple classification nomenclature of Component, Recladding, and Overcladding to cover all the possible permutations of extent of demolition and new construction.

In component-based façade retrofit, selected elements such as windows or external shading devices may be replaced, removed, or modified. The enclosing wall, or at least the wall structure, remains.

In recladding façade retrofit, the original wall is completely demolished and replaced in full. Impact to occupied spaces could range from minor perimeter disturbance to structural or HVAC work necessitating relocation of occupants.

The new enclosure construction may be load-bearing or non-load bearing, infill or curtain wall. Facade materials may be glazed, non-glazed/opaque, or a combination of these. The new wall in a recladding retrofit is commonly a single-skin but may also be conceived as a double-skin or a multi-layer wall such as a single skin with an offset green screen, perforated screen, or other forms of external shading devices.

In overcladding façade retrofit, original façade materials remain in place behind new wall systems that are applied to the exterior. Fundamental differences are found in direct versus offset overcladding solutions. An example of direct overcladding is when exterior thermal insulation composite systems (ETICS), also known as exterior insulation finishing systems (EIFS), are applied to an original wall surface such as brick or masonry. Offset overcladding solutions create a gap or cavity between old and new construction layers. This could be in the form of a rainscreen system, or any materials like stone or brick supported by metal framing or furring strips. As with recladding, overcladding may result in a single skin or a double skin façade.

In both reclad and overlaid scenarios, combinations of opaque and glazed materials are expected. Fenestration may be punched windows in massive walls or glazed modules within curtain walls. Either reclad or overlaid walls can take advantage of advanced facade construction techniques including prefabrication and unitized

modules and employ high-performance materials and systems such as continuous insulation and air sealing, rainscreen and other water management systems, high-performance glazing including low-E coatings, ceramic frit, closed cavity façade, among other state-of-the-art technologies noted in the Introduction. While common materials and façade systems are noted in **Table 1**, the list is not intended to exclude emerging materials and construction technologies. These may be applied within the representative classifications of component, recladding, or overcladding.

4. Façade retrofit case studies

Case studies permit exploration of specific façade retrofit scenarios that evolved in practice. The two cases focus on high-performance facades devised for the renewal of two International Style government office towers in the United States. In each case, the Façade Retrofit Typology (**Table 1**) is applied to elucidate the motivations and methods for each retrofitting case.

4.1 Context of the government client

The case study retrofit projects were administered by the U.S. General Services Administration (GSA). Before getting into the architectural specifics of the case studies, this section outlines the underlying premise for the GSA façade retrofits by examining the environmental, sociocultural, and economic motivations of the government client. As the ‘government’s landlord,’ the U.S. GSA owns and leases over 363 million sq. ft. of space nationwide [24]. Government building agencies represent a special type of building investor that manages large volumes of real estate over the long term. Holding a combination of roles - to build, maintain, lease and manage office space for public service - government building agencies can be uniquely positioned to absorb risks and reap the benefits of reinvestment in real estate over the long term [25].

4.1.1 Leading by example

Over time, policy and executive office directives set ever-increasing performance requirements for federal facilities in the United States. Building on the foundations of the 1962 Guiding Principles for Federal Architecture, the GSA established the Design Excellence and Construction Excellence programs in the 1990s with an aim to improve the quality and performance of public buildings. Minimum security standards for federally owned or leased facilities were established after the 1995 bombing of the Alfred P. Murrah Building. While the objectives of the Excellence programs became intertwined with energy management and conservation measures as early as 1975 in the U.S. Energy Policy and Conservation Act (EPCA), the 1992 Energy Policy Act (EPAct) required federal agencies to demonstrate energy-conserving technologies in their buildings – to lead by example. Subsequent government projects became proving grounds for sustainable design, broadly considered to include energy and water conservation as well as superior indoor environmental quality. The 2005 EPAct included provisions for new federal building energy efficiency to be at least 30% better than ASHRAE 90.1 standards. The Guiding Principles also evolved, setting performance goals in areas of energy, water, environmental impact, greenhouse gas emissions, and operating costs, and providing guidance specific to sustainable new construction, major renovation, and existing buildings [8, 25–28].

4.1.2 Evolving performance standards

Renamed the Guiding Principles for Sustainable Federal Buildings in 2016, updated in 2020, the principles evolved to address environmental performance, climate resilience, and occupant health and wellness in addition to the operating efficiency of new and existing federal buildings. Per 2022 updates, the Energy Independence and Security Act [9] requires new and major renovations of federal buildings to reduce fossil-fuel-generated energy consumption from a 2003 baseline by 55% in 2010, 65% in 2015, 80% in 2020, 90% in 2025, and 100% in 2030. GSA uses the U.S. Green Building Council Leadership in Energy and Environmental Design (LEED) program for evaluating and measuring sustainable design, cross-listing LEED Gold requirements with the legislative acts when reporting compliance with the Guiding Principles [26]. These and other standards for energy, water, environmental protection, historic preservation, accessibility, flood resistant design, wildfire risk management, and security are consolidated in the GSA publication, P100 Facilities Standards for the Public Buildings Service [27]. The document, updated on a three-year schedule, contains both performance-based standards and prescriptive requirements to be used in the programming, design, and construction of GSA buildings.

Retrofitting and modernization triggers requirements for buildings to comply with more stringent structural system criteria than was in place at the time of the building's construction. This could have ramifications for façade factors like seismic load, wind load, and resistance to wind induced vibration. The goal of GSA alteration projects is to meet the same standards described for new projects. Equipment should not just be replaced but have enhanced performance and anticipate future changes. Life cycle cost analysis requirements impact the design process, requiring design alternatives, energy models, and three alternatives each for building enclosure, lighting, and HVAC systems.

Among the criteria pertinent to façade retrofit are wall and window thermal and airtightness performance, lighting quality (including daylight, views, glare control, and electric lighting controls), blast resistance of structure and façade. Façade design must also integrate aspects of HVAC system design including protection of air intakes, isolation of ventilation systems, and the interdependent relationship of HVAC system size and façade thermal performance. Requirements for façade mock-ups, window cleaning, and materials procurement (targets for use of low-embodied carbon materials and products sourced nationally) impact the design specifications and construction process [27].

The government client's evolving performance standards continue to evolve and influence retrofitting project scope and design solutions. For example, the 2024 P100 established new benchmarks related to electrification, embodied carbon, grid-interactive efficient buildings, construction decarbonization, and labor practices [28].

4.1.3 Funding mechanism

Performance requirements notwithstanding, many projects lack funding to implement needed renovations. The two case study office tower renovations, and many more GSA retrofit projects, were realized with funds from the 2009 American Recovery and Reinvestment Act (ARRA). ARRA was enacted in response to the economic downturn in the United States with goals to create new and save existing jobs, spur economic activity and investment in construction, real estate, and technology sectors, and foster new levels of accountability and transparency in government

spending. Of the total \$787 billion in stimulus funding, GSA received \$5.5 billion to renovate and construct new energy-efficient federal offices, courthouses and land ports of entry. The overwhelming majority of the funds, \$4.5 billion, was allocated to convert existing federal buildings into high-performance green buildings [29].

ARRA projects covered a variety of work including mechanical and lighting upgrades, window replacements, cool or green roofs, water-saving fixtures, onsite renewable energy, and importantly, necessary repairs. ARRA funding was an opportunity for the GSA to address deferred maintenance and make needed facility upgrades while meeting rising performance standards. Despite constantly ongoing work on properties including many major renovation projects, a backlog required the GSA to select from a “universe of projects” that met ARRA criteria [30]. The selection criteria were, in descending order of weight:

- High-performance features concentrating on energy conservation and renewable energy generation.
- Speed of construction start (creating jobs), with an emphasis on those projects that could begin within 120 days.
- Execution risk (ensuring that the projects will not fail due to unforeseen conditions).
- Facility condition. The Facility Condition Index is a standard real estate industry index that reflects the cost of the repair and alteration backlog of a particular building relative to the building’s replacement value.
- Improving asset utilization.
- Return on investment.
- Avoiding lease costs.
- Historic significance [30].

The funding was intended to be spent quickly. The original program planned for the full \$5.5 billion in projects to be awarded by 2011. When project costs came in lower than originally estimated, savings were reprogrammed to other projects to keep recovery funds flowing. Renovations, called ‘high performance green building modernizations,’ were grouped into a range of scales: full and partial building modernizations, limited scope (including energy projects), and small projects [30].

The timing of ARRA funding was a godsend for GSA’s stock of office buildings and courthouses. The boom of federal office space built in the 1950s, 60s and 70s today represent a veritable fleet of twentieth-century facades that are aging out and in need of repair or replacement. Many federal buildings from this era were built in the modern international style. Building enclosures whose lifespans may have been expected to be 30 years are now 50 years old, and historic preservation is a consideration for many. Modernization presented the opportunity to upgrade facades to meet newer energy standards and other criteria that have emerged including accessibility, seismic, and blast resistance [27]. Out of hundreds of federal projects funded by ARRA, approximately two dozen are listed as having significant facade upgrades. Facades

feature more prominently in the scope of the largest scale projects. Among 45 full and partial building modernization projects, 18 are listed as facade retrofits [31, 32].

The following two case studies are of similar *type* (urban government office towers) and *tenure* (managed by the GSA and eligible for ARRA funding). While there were differences in each building's *age*, both retrofit projects are examples of GSA's efforts to ensure the longevity of its landmark stock of aging office towers. Variables in *facility condition*, *historical significance and context*, climate zone, and the nature of building occupancy led to very different project approaches.

Discussion of the case studies emphasize the role of criteria and incentives in project decision-making that led to the reclad and overclad façade retrofit typologies. New criteria that have emerged in the policy landscape that will inform future facade retrofits are also introduced and discussed. Understanding the policy and construction dynamics of these retrofits can inform both public and private stakeholders on potential future strategies and policies for improving the performance of existing buildings.

4.2 Recladding case study

4.2.1 Condition and context

The Edith Green–Wendell Wyatt Federal Building (EGWW FB) is in downtown Portland, Oregon. The 18-story tower was completed in 1974 (**Figure 1**). The building had never received a substantial upgrade. One of the first ARRA-funded projects to be completed, the building underwent a complete facade replacement between 2010 and 2013 as part of a full building modernization project (**Table 2**).



Figure 1.
The Edith Green - Wendell Wyatt Federal Building in 2008 before renovation (Left) and during facade removal in 2011 (Right). Images: CC-BY-SA M.O. Stevens.

When the architects, Skidmore, Owings and Merrill, began design on the building in 1969, they planned a concrete-framed tower. Value engineering in 1972 changed the design to a steel-framed structure with an uninsulated precast concrete facade (**Figure 1**). Environmental systems guided by early building automation systems were efficient for the time period, but the technology became obsolete within a few decades. An energy-efficiency upgrade was planned for 2005 but ultimately was not funded by Congress [33].

4.2.2 Design criteria and process

The tower's upgrade project was revived with the advent of ARRA in 2009. To meet the deadline for obligating ARRA funds by 2010, the traditional design-bid-build contract was converted to a gross maximum price construction manager (GMP/CM) delivery contract. Advances in energy and water performance criteria required by EISA 2007 and ARRA meant that a complete rethinking of the renovation was in order. New criteria for seismic and blast resistance also had to be considered.

Edith Green-Wendell Wyatt Federal Building, Portland, Oregon. 18 stories. 525,000 GSF. Steel frame. Owner: U.S. General Services Administration (GSA). Climate: Warm summer Mediterranean (Köppen Csb).				
Motivating criteria for retrofit	Original façade construction	Extent of demolition	Façade retrofit classification	Façade retrofit construction
Regulatory compliance GSA PBS-P100 Facilities Standards for the Public Buildings Service (performance criteria for environmental protection, historic preservation, accessibility, energy, water, seismic, blast, etc. inclusive of Guiding Principles, EAct 2005, EISA 2007) Funding availability (ARRA 2009)	Non-load bearing opaque curtain wall Uninsulated precast concrete panels; single-glazed ribbon windows Forced-air heating and cooling system	Complete wall and enclosure demolition Major renovation; vacant building	Recladding Floor slab edges extended 55.9 cm to accommodate new curtain wall (add 3.066 sq. m. leasable area) Hydronic radiant heating and cooling system (raised interior ceiling height) Weight reduction (additional seismic retrofits unnecessary) Integrated design of enclosure and interior systems	Glazed curtain wall system with thermally broken aluminum frames 43% vision glass; 325 mm IGU triple-glazed blast-resistant laminated glass Spandrel zone; 325 mm IGU with 229 mm thermal insulation behind NW wall: curved vertical screen offset (aluminum rods) SE & SW walls: aluminum brise-soleil (horizontal light shelf / overhang; vertical rod screens; ground-based vines grow up to 3 stories)
<i>Original building 1974. Architect: Skidmore, Owings & Merrill. Retrofit 2010–2013. Architect: Cutler Anderson Architects and SERA Architects. Structural: KPFF Consulting Engineers. MEP: Stantec Consulting, PAE Consulting Engineers, Interface Engineering. Blast Consultant: Weidinger Associates. Construction Manager: GSA Region 10. General Contractor: Howard S. Wright. Curtain Wall Design-Assist Subcontractor and Fabricator: Benson Industries. Glass: Viracon. ARRA funding: \$133 M. Table compiled and prepared by the author from source [33].</i>				

Table 2.
Façade retrofit typology for EGWW federal building.

A cost-benefit analysis revealed that greater returns on investments in sustainable design could be realized with a vacant building instead of the occupied remodel originally planned [33]. The tower's 1240 employees would be relocated into 323,000 sq. ft. of leased space in other Portland buildings [34].

Early-stage computer modeling led the team to select a hydronic radiant heating and cooling system over a less efficient forced-air system. The state-of-the-art HVAC strategy, which included 100% DOAS and heat recovery ventilation, would not function efficiently without a higher-performing replacement building enclosure. The \$1.33 million ARRA project scope also included new lighting, daylighting, controls, building management system, rooftop photovoltaic canopy, and basement cistern to collect water for toilet flushing and irrigation [33].

4.2.3 Facade solution

The design team studied recladding options to passively reduce heat gain through solar shading integrated with a thermally broken aluminum frame insulated glass curtainwall system. Parametric modeling studies aimed to tune the facades for each elevation. Peak cooling loads were evaluated for northwest, southwest, and southeast exposures. A separate parametric study worked to balance shading with daylight harvesting of light to the interior. The studies were a collaborative effort between architects and curtainwall contractor. Additional criteria for aesthetics and biophilic design drove the details and final arrangement of sun-shading elements [33].

Building-high curved vertical screens made of reed-like aluminum rods protect the northwest facade from low-angle sun (**Figure 2**). A combination of light-shelf overhangs and vertical rod screens form a brise soleil on southwest and southeast facades (**Figure 2**). Vines trained to grow on the screens have reached as high as the third floor. The skin behind the screen is 43% vision glass. 1-1/4 in. (32.5 cm) thick IGU are fabricated with blast-resistant triple-laminated glass. Nine inches of insulation are strategically fit within spandrel zones [33].

The blast-resistant curtainwall design required a unique structural solution. Floor slab edges were extended to accommodate the necessary anchorage [35]. The replacement of the original precast concrete with curtain wall presented an opportunity for



Figure 2.
The Edith Green - Wendell Wyatt Federal Building during facade replacement in 2011 and after in 2012 (Middle) and 2014 (Right). Images: CC-BY-SA Another Believer.

the office floor plates to expand 55.9 cm in every direction. Floor space formerly dedicated to mechanical systems was also recovered, and interior ceiling heights raised. In all, the renovation garnered 3066 square meters of additional leasable space, an area equivalent to two floors. The recladding also reduced the overall building weight such that seismic retrofits were no longer needed [33].

4.2.4 Performance outcomes

Before modernization, the building's site EUI (energy use intensity) was in the range of 74–85 kBtu/ft²/yr. Whole building energy modeling predicted that the modernization project including tenant improvements would be in the range of 30–35 kBtu/ft²/yr., compared to a national office buildings average EUI of 94 kBtu/ft²/yr. [35] After the upgrades, GSA reported a net EUI of 30.6 million joules per square foot annually (29 kBtu/ft²/yr.), a figure that accounts for the onsite renewable energy production [33]. The net EUI represents a 70% reduction from the national average and a 63% reduction from pre-modernization performance, exceeding the reductions required by ARRA. EGWW FB earned a LEED New Construction 2009 Platinum certification in 2013.

GSA cites the EGWW as an example of GSA's efforts to ensure the longevity of its stock of mid-century buildings. It also set a precedent for buildings that lack historical merit architecturally. In this case, the EGWW's original facade was seen as an "unremarkable" example of Modernist architecture. The chance to reclad the building as an integrated part of a full building modernization meant that improvement in performance in terms of security, indoor environmental quality, and conservation of energy and water could be dramatic rather than incremental. Recladding also presented the opportunity to outwardly express the federal building as a symbol of a government that is environmentally aware and conscientious in stewarding taxpayer dollars [33].

4.3 Overcladding case study

4.3.1 Condition and context

The Anthony J. Celebrezze Federal Building (Celebrezze FB) is in downtown Cleveland, Ohio. The 32-story steel-framed building with stainless steel and glass skin opened in 1967 [36]. (**Figure 3**). The curtain wall had experienced significant deterioration over time and was not performing as an air and moisture barrier [37]. ARRA funds provided the opportunity to renovate the facade and reverse energy losses. Upgrades to the original facade and overcladding with a second skin occurred between 2012 and 2015 as part of a partial building modernization project (**Table 3**).

The federal building was part of a larger urban renewal project with master plan by I.M. Pei. Building architect Peter van Dijk designed the tower in the International Style. The original cladding panels are one-inch thick paper honeycomb sandwiched between a corrugated stainless-steel face and a backing panel (**Figure 3**). Modernization architect Charles Young explains that the building was designed during a period of curtain wall experimentation. The facade drainage system was erroneously sealed during installation. Moisture trapped in the wall could not escape causing some of the panels to delaminate. The wall's insulation value was minimal; frost was observed to form inside the exterior envelope in winter [37, 40].

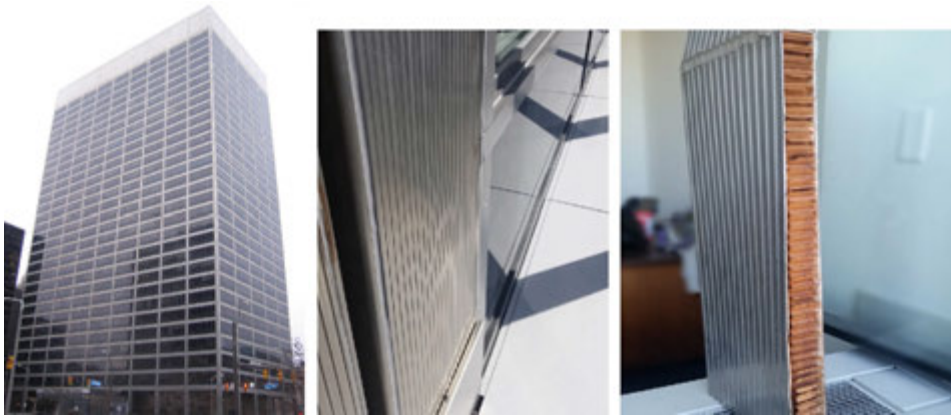


Figure 3. The Anthony J. Celebrezze Federal building in 2007 (Left). Image: CC-BY Jeramey Jannene. The Celebrezze's original stainless-steel cladding remains intact as seen inside the cavity formed by the overclad second skin (Middle). Image: Author. A sample of the cladding panel (Right). Image: Author.

4.3.2 Design criteria and process

Design decisions had to be more accelerated than usual due to the ARRA funding schedule. Project planning began in 2009, and contracts for the facade recladding and roof replacement projects were awarded later that year. The criteria were straightforward: maintain full building occupancy, upgrade for blast resistance, and improve energy efficiency while remediating the failing façade [37, 38]. Wind tunnel tests provided wind load criteria for the structure and cladding. Blast loading and performance criteria were established based on building risk and hazard [39, 41].

Historical significance was always an important factor in decisions about the facade, but preserving the original skin was not a foregone conclusion. GSA followed federal rules in historic assessment to determine that the tower was not eligible for landmark status but sought to balance goals for historic preservation with the project's other criteria. Simple window replacement was not an option due to the cladding flaws [42]. Early studies considered a range of options including replacing the facade and relocating tenants. A number of factors pointed to the overclad solution. The logistics and costs of relocating Celebrezze's high-security tenants was prohibitive [38]. Structural analysis determined early on that the existing steel superstructure could not accommodate all of the design loads of a new skin. The structure would need to be augmented with an outrigger-and-tube girt system at each level to support the new skin and accommodate wind, blast, and thermal loads [39, 41]. The 14-inch depth added by the girt system pointed to the strategy of a new skin offset from the original building perimeter. The team even considered the option of building a new outboard skin and later removing the original skin; however, an extension of the occupied floor plate would require more extensive renovations to building interior systems and finishes, disturbance to tenants, and added cost. The double-skin overcladding concept enabled multiple criteria to be resolved and was ultimately approved [38].

4.3.3 Facade solution

The design team intensively studied approaches to making the double wall viable. Computational fluid dynamic studies aided the team in understanding the temperatures

A. J. Celebrezze Federal Building, Cleveland, Ohio.

32 stories. 1,471,000 GSF. Structural steel moment frame, portions with concrete encasement. Owner: U.S. General Services Administration (GSA). Climate: Hot summer humid continental (Köppen Dfa).

Motivating criteria for retrofit	Original façade construction	Extent of demolition	Façade retrofit classification	Façade retrofit construction
Historic preservation (not required but a consideration)	Non-load bearing opaque curtain wall	No wall demolition	Overcladding	Double-skin façade formed by adding outer layer
Remediate environmental problems (cladding flaws)	Stainless steel panels with honeycomb paper core; single-glazed ribbon windows and spandrel panels	Original windows reglazed with monolithic laminated glass	Steel girt system added to augment existing steel superstructure	Non-ventilated glazed curtain wall system with thermally broken aluminum frames
Regulatory compliance (GSA P100 criteria for seismic and blast)	Forced-air heating and cooling system	Targeted renovation; Occupied building (relocating high-security tenants was cost-prohibitive)	Enclosure design concurrent with separate Energy Savings Performance Contract (energy, water, and lighting system upgrades)	Double-glazed blast-resistant laminated glass
Elective performance enhancement				NW & NE walls: Buffer type box-window DSF
(EISA 2007 and ARRA energy and water performance criteria)				SE & SW walls: Buffer type corridor DSF; solar control via ceramic frit on vertical glazing and horizontal glass sunshades/light shelves inside the cavity
Funding availability (ARRA 2009)				Maintenance access to DSF through original windows

Original building 1967. Architect: Peter van Dijk. Retrofit 2012–2015. Architects: Interactive Design/Eight Architects. Structural Engineers: Thornton Tomasetti. MEP Engineer: Jacobs. Blast Consultant: Hinman Consulting Engineers. Curtain Wall: Curtainwall Design Consulting. Building Envelope Consultant: Wheaton Sprague. Construction Manager as Agent (CMA): Gilbane Company. Construction Manager as Constructor (CMc): DCK North America. Building Envelope Commissioning: Sebesta. Curtain Wall Subcontractor: National Enclosure Company. Unitized Curtain Wall: Aluminum Curtainwall Systems. Glass: PPG Solarban 60 Starphire/Technoglass. Structural glazing tape: Saint-Gobain. ARRA funding: \$121 M. Sources: [37–39].

Table 3.
Façade retrofit typology for A. J. Celebrezze federal building.

that would occur inside the cavity and occupied spaces seasonally and in extreme temperature and solar conditions. Both actively ventilated and sealed cavity conditions were evaluated along with a variety of glass and shading configurations. Young notes that the relatively low winter humidity of building was a significant factor that permitted a sealed cavity system. Temperature and humidity in the buffer zone are allowed to ‘float’ in a wide range while still not impairing the performance of interior mechanical systems [37, 40]. CFD analysis established an operational case where temperatures in the cavity would range from 30 degrees F to 115 degrees F [39]. The outer skin consists of IGU with clear and low-E blast-resistant laminated glazing in aluminum framing. The new buffer significantly reduces the need for perimeter heating in winter. Ceramic frit on the glazing and fixed solar control devices inside the cavity manage solar gain [37].

Repairs to the original skin began in 2012. The original stainless steel cladding panels were retained, and the plate glass in the original windows was replaced with safer monolithic laminated glass (**Figures 3 and 4**). Work on the outer skin began in 2013. Steel girt tubes were welded onto steel outriggers welded to the existing

columns. Shifts in the old building structure required careful field surveying. The building's existing facade window-washing track on the roof was used with a custom hoist to set the units from the outside. Scheduling was critical, but benefited from extensive coordination between project team, building management, and tenants. Because of the building occupancy, daytime activity was limited to prep work, and glazing units were installed during a night shift [38].

Two different facade configurations respond to the building's solar orientation. On northwest and northeast elevations, the cavity is divided by story and structural bay to form box windows (**Figure 4**). The new skin is interrupted at each column line and floor line, revealing the new steel girt beam and accentuating the modernist grid of the original building. Facade cavities are partitioned as story-high corridors on southeast and southwest elevations (**Figure 5**). Here an ensemble of measures works to control heat and maximize useful daylight. Translucent glass shelves are mounted inside the cavity to the original window wall above vision height to work as dual sunshades and light shelves. A graduated pattern of ceramic frit on the outer skin's glazing reduces heat gain while maintaining views of the city and Lake Erie. The corrugations of the original facade are visible through the glazing at most view angles.

4.3.4 Performance outcomes

The ARRA-funded project (2012–2014) was done concurrently with another major project. As part of a 2013–2015 Energy Savings Performance Contract (ESPC)



Figure 4.

The Celebrezze's double-skin facades are partitioned as box-windows, divided by story and structural bay, on northwest and northeast elevations. View looking up at the northwest facade (Left). View inside the box-window double-skin facade cavity (Right). Images: Author.



Figure 5.
The Celebrezze's double-skin facades are partitioned as story-high corridors on southeast and southwest elevations. View of southwest facade (Left). View inside the corridor double-skin facade cavity (Right). Images: Author.

project the building's energy infrastructure was converted from district steam and chilled water to natural gas. The project included four new central heating and cooling plants, low flow restroom fixtures, and lighting retrofits. Siemens, the Energy Services Company (ESCO), reported that the \$37.2 million contract included design, installation, and operations and maintenance services. The four central plants are estimated to generate energy savings of \$2.5 million in the program's first year. The project is expected to reduce total CO₂ emissions by 51.3% annually [43]. Under the terms of the ESPC, the contractor guarantees cost savings sufficient to pay for the project improvements over the maximum 25-year term of the contract, after which all additional cost savings accrue to the GSA [44].

Pre-project studies estimated that the facade retrofit would result in energy savings around 17%. Savings related to facade improvements are not being measured separately, however, and improvements are due to the combined effect of the ARRA and ESPC projects. The building's total energy usage has been continuously monitored before, during, and after the renovations. Building site EUI was measured at 112 kBtu/ft²/yr. in 2011. After the facade and energy conservation upgrades, in 2016, EUI was measured at 75 kBtu/ft²/yr. [44] The drop in EUI represents a 33% reduction in energy usage compared to the building's previous performance. For reference, per CBECS 2003 data, average EUI for office buildings was 92.9 kBtu/ft²/yr. nationally and 120.1 kBtu/ft²/yr. for the east north central region [45].

The overclad solution yielded a successful facade renewal project given the constraints of a fully occupied building. Within the scope of a partial renovation, energy

consumption has been significantly lowered and interior comfort improved. A facade of local historical significance has been preserved and remains visible through the tower's new protective glass case.

5. Discussion

In both cases, the federal buildings were seen as opportunities to demonstrate the potential of retrofits to the private sector as well as to federal properties. The EGWW FB in Oregon is an example of very high building performance achieved through full building renovation, where recladding design is fully integrated with the design of HVAC, lighting, and other systems. The Celebrezze FB in Ohio represents a successful test case for the overcladding of existing facades, achieving substantial increases in building performance, preserving the existing enclosure, and maintaining continuous operation of an occupied building.

5.1 Criteria-driven decisions

Special convergences of criteria influence the decisions of how to retrofit a building skin. In the case of the EGWW FB, project objectives for energy performance drove the decision to replace rather than repair the existing enclosure: the heating and cooling system design required a completely new higher-performing skin to replace the precast concrete skin. In the case of the Celebrezze FB, the facade was failing. The need to keep tenants in place, the structural augmentation outrigger and tube girt system accommodate the strength demands of blast and thermal loads of the replacement skin, and the deterioration of the historic enclosure were all factors that combined to influence the decision to overclad rather than replace the building skin.

The office tower case studies demonstrate the importance of timing for retrofit projects. The scope and phasing of a facade retrofit must be studied for impact on occupied spaces. The extent of the disturbance depends on the project's design solution and may require owners to assess the costs of reduced productivity or in some cases, temporary relocation of tenants. It is unlikely that the EGWW FB could have achieved the Platinum level of performance without having a clean slate that allowed fully integrated design of enclosure and interiors. The Celebrezze FB avoided relocating tenants, but required a longer-term, phased approach to the work.

The necessarily bespoke designs of retrofit facades can facilitate progress in the industry as new methods and combinations of strategies are worked out in practice. However, the cost and performance risks associated with the non-standard construction can be seen as a barrier towards widespread adoption of similar designs. Celebrezze's facade with non-ventilated cavity was tuned specifically for that building's unique profile and interior/exterior microclimate. While it is hoped that the concept of overcladding will set a precedent for the modernization of other buildings, the specific design details of the Celebrezze may not be widely transferable. In the case of the EGWW FB, stripped bare to its structure for full building retrofit, the facade can initially be seen as having a more generic 'site' on which to be fixed. However, as was the case in the Celebrezze retrofit, the new enclosure required additional perimeter structure to anchor the facade and transfer loads to the building superstructure.

Although reports are limited in the number of buildings studied, the GSA has published studies of post-occupancy evaluation and building performance.

Contracted costs of GSA and many other public realm projects are readily available to the public. In the private sector, however, financial and performance information specific to facade improvement projects are generally not known or withheld. Due to these factors, facade retrofits can be negatively perceived as having uncertain return on investment [23].

Energy savings is an important benefit of facade retrofitting. As can be expected, the integrated design possible with a full-building renovation led to clearly higher performance benefits than the project with limited scope. Building simulation modeling can be used to predict the impact of different facade schemes on building performance. It is not feasible, however, to isolate the facade's contribution to measured whole building operational performance in projects where facade retrofits are combined with other renovations such as mechanical updates. This situation complicates efforts to 'close the loop' between predicted and measured performance when strategies are being considered for subsequent projects.

Due to the particular security concerns of tenants in these federal buildings, the ability of a new skin to meet criteria for blast protection added to the benefits of reinvesting in new skins. While physical security may be a lessor factor in the private sector, the federal case studies nonetheless underline the power of MPB as a strategy for realizing building improvements.

5.2 Evolving policies and criteria

Even as GSA's aging buildings have been stabilized and recovery funds have dried up, the future of facade retrofitting remains vitally important. Present-day stakeholders in public and private sectors alike are faced with the confluence of an aging building stock and the urgent need for resiliency and lower carbon emissions in the built environment. When simple payback schedules from energy and maintenance cost savings are insufficient to justify the cost of retrofitting, projects can broaden criteria and use MPB to make the business case.

Examples of expanding criteria that have influenced federal real estate decisions in the years since ARRA include measurement of the social cost of carbon, assessment of financial risks stemming from climate change, attention to environmental justice, and tracking carbon emissions in the building materials supply chain. While U.S. governmental action to reduce negative environmental impacts from building construction and operation has persisted through cycles of political and societal will, government efforts to enact a comprehensive climate policy fluctuate. With no time to waste, hurdles to implementation in one sector point to opportunities for other sectors to lead. State, municipal, and private building agencies, AEC firms, building material manufacturers, and other industry stakeholders can act to self-assess and update their internal policies and practices in light of the climate crisis. The social cost of carbon, financial risk, environmental justice, and materials with lower embodied carbon emissions are concepts that have global currency [46]. States, utilities, cities, and corporations have set independent policies on renewable energy, energy-efficiency, and carbon emissions [47].

5.3 Relevance to future retrofits

The government office tower case studies provide a number of strategies with relevance to future retrofits. The combination of project performance criteria and funding (through the ARRA program) was a classic 'requirement and reward' incentive

structure. An example of an alternative form of ‘requirement’ are the net-zero energy codes that have been adopted by states, municipalities, and private organizations. Alternative forms of ‘reward’ can include incentives related to taxation or zoning, or the valuation of a corporation’s triple bottom line to investors.

Sustainability plans that consider resiliency and adaptation to climate change as criteria can spur the decision to retrofit. Following a MPB strategy, projects can measure return on investment with measures unique to the project, such as the blast criteria required for the federal buildings studied above. Carbon emissions as a component of facade and building design is new frontier that is impacting the type and materials of the facade and its contributions to whole-building performance. The weighing of financial risks stemming from climate change and the social cost of carbon are among the newer criteria that can inform cost–benefit analysis of facade retrofits.

In addition to extending building life and reducing operational costs, reinvestments can be planned to provide MPB related to occupant wellness and productivity, increased building value, reduced environmental impacts, and preservation of historic context. Furthermore, the social cost of carbon, financial risk, environmental justice, and materials with lower embodied carbon emissions are among the newer climate-related criteria informing cost–benefit of building construction and renovation. These criteria hold relevance for facade retrofits in both public and private contexts in the effort to safeguard investments for the long term.

This chapter has investigated facade retrofitting as a cornerstone strategy to renew the operational vitality of buildings. As demonstrated by the reclad and overclad office tower case studies, a multicriteria approach, inclusive of but not limited to energy efficiency, is recommended to plan and execute innovative solutions. The novel façade solutions generated to resolve each building’s unique retrofitting profile contribute valuable technical knowledge to the façade industry. The future of façade design and engineering will continue to be shaped by novel materials and emerging technologies including the use of artificial intelligence and advanced manufacturing. To meet global climate goals, emphasis should be placed on developing technologies that are durable, cost-effective, and adaptable to evolving policies and standards that demand increasingly high performance in building design.

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Eco-Sustainable Double-Skin Facades with Respect to Fire Risk

Giacomo Di Ruocco

Abstract

Double-skin technology represents a sustainable and intelligent solution for both new construction and redevelopment of existing buildings. In fact, it allows to simultaneously satisfy multiple requirements, such as the thermo-hygrometric well-being of users and the redevelopment and esthetic redevelopment of the building. The case study analyzed concerns the development of a technological solution that takes into account the use of innovative materials (compressed rock wool finishing panel), an external finish adaptable to the context, and compliance with recent regulations on fire prevention of ventilated facades. This solution is particularly suitable for buildings nearing the end of their life, allowing for their energy-sustainable and esthetic redevelopment. The performance of this solution was compared with that of a traditional ventilated facade.

Keywords: ventilated facade, energy and environmental sustainability, fire risk, esthetic redevelopment, rock wool

1. Introduction

Sustainability in the construction sector and energy efficiency of buildings are among the key objectives of Agenda 2030. In the territory corresponding to the European Community, the resources committed to air conditioning of buildings represent approximately 50% of total energy consumption. This percentage is destined to increase because the consequences of global warming will lead to increasingly hotter summers and increasingly colder winters, with an obvious increase in the energy resources needed to guarantee internal comfort.

The building envelope, constituting the greatest incidence of dispersing walls, assumes a decisive role in the design of highly energy-efficient buildings in order to improve the comfort of the occupants.

From this perspective, double-skin facades (DSF) represent a particularly effective design solution for energy retrofit (intended as comfort of both the internal and external environment, through the possibility of mitigating the phenomenon of Urban Heat Islands) and the esthetic-formal redevelopment of multi-story buildings.

2. Methodological approach

Figure 1 shows the methodological scheme followed in this study, with reference to the areas investigated.

2.1 The eco-sustainability of the envelope system

There are various definitions of the DSF system. The research of Oesterle et al. [1] defines the double-skin façade as a multilayered façade envelope with an external and an internal layer, with an interposed cavity. This system allows the control of ventilation in order to mitigate the effects of external climatic conditions. According to the study of Ding et al. [2], the DSF is composed of an external skin, an intermediate space, and an internal skin. The external skin layer (transparent or opaque) guarantees protection from atmospheric events as well as better acoustic insulation from the external environment. An adjustable shading system allows to modulate the solar gain, allowing to heat (in winter) or cool (in summer) the air of the ventilated cavity. The research of Kim and Song [3] and Wong [4] argues that DSFs are multilayered technological systems, consisting of an external skin, an intermediate cavity, and an internal skin. The external and internal skins could be made with single glazing (for the interior) and double with laminated safety glass (for the exterior). Inside the cavity, a solar shading system allows the modulation of the thermal load toward the internal environment. According to the study by Baldinelli [5], compared to a single skin façade, a DSF consists of another external glazing integrated into the curtain wall, often equipped with a controllable shading system. In most cases, the external skin consists of a single safety glass, tempered or laminated, while the internal skin consists of a single or double glass, with fixed or openable windows. Chan et al. [6] identify the DSF as a layered system that covers one or more floors of the building. The skins can be hermetic or naturally/mechanically ventilated. The external skin is usually a single safety glass (tempered or laminated) and can be completely transparent. The internal skin can be a double insulating glass and is transparent only to the windowed portions of the facade. The thickness of the air gap can vary from 200 mm to more than 2 m. A double hermetic skin facade can

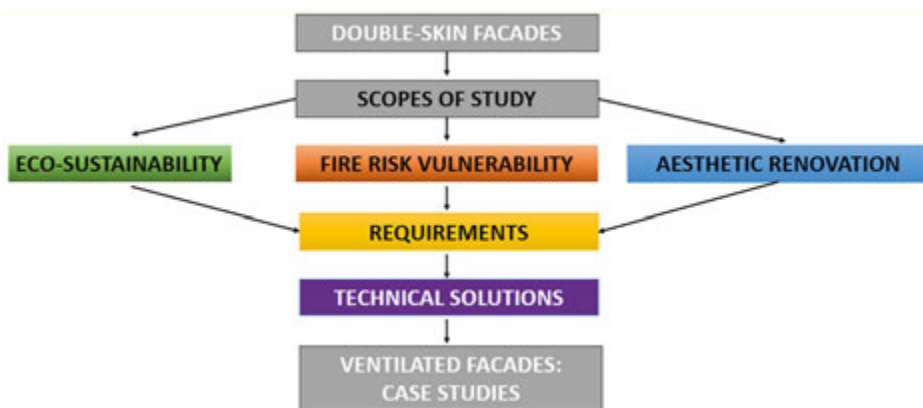


Figure 1.
Methodological framework.

provide greater thermal insulation. The convective movement of the air inside the gap can absorb the thermal energy resulting from the solar incidence on the external glass.

There is a large literature on passive ventilation in buildings and the thermal performance of double-skin façades. Although most of the research is mainly conducted in countries with moderate climate conditions, it has highlighted a close link between the design of the DSF connected to a natural ventilation system. According to the study by Oesterle et al. [1], DSF allows for obtaining significant energy savings only when the natural ventilation mechanism is used. In tall buildings, double-skin façades can help to reduce the effect of wind action. It is also noted that the natural ventilation system of the DSF is able to significantly reduce the load on the HVAC system, improving the comfort of the inhabitants. In fact, in hot seasons, DSF can promote passive night-time cooling of the building envelope, exploiting the thermal damping due to the expulsion of hot air, thanks to the chimney effect. The upward motion of the air also allows the hot air to be vented from the building upwards, improving the quality of the air that can penetrate the internal environment [7]. Gratia and Herde [8] analyzed the impact of a double-skin facade, facing south, in a temperate climate condition. The thermal analysis was carried out with the aid of simulation software, applied to the climatic conditions of the seasons of the year, to a low building, with and without a double-skin facade. It emerged that it is possible to obtain significant energy savings if natural ventilation is exploited through the use of DSF.

Many studies encourage the adoption of DSFs to control thermal gains in building design [9, 10]. Shameri et al. [11] indicate DSFs as an effective solution for the energy-saving objective in buildings. In principle, the DSF system identifies the combination of two layers of façade with an empty space inside (air cavity) [12]. The study by Gratia [13] highlights that DSFs are the natural technological evolution of the glass façade. The research by Mingotti et al. [14] highlights how the external and internal skins of a DSF must be equipped with versatile openings to appropriately control the ventilation of the air inside the cavity, favoring the exchange of air in the internal spaces. In consideration of this, the temperature and ventilation of the air are intrinsically related to the size of the cavity; in fact, the studies of Balocco and Colombari [15] and Balocco [16] confirm that the thermal benefits are proportional to the size of the cavity, especially in the hot period. DSFs also give the opportunity to add additional glass to the building, which could provide greater visual comfort and better daylighting, with a consequent reduction of consumption related to artificial light. The combined effect of the external and internal skins of the DSF can also have an impact on the greenhouse effect, as reported by the schemes represented in **Figure 2**.

Among the strengths of DSF, Yilmaz and Cetintas [17] highlight other positive effects, including acoustic insulation and improved esthetics, in addition to sustainable energy performance. Similarly, Byrd and Leardini [18] draw attention to the role of DSF as a prevention system for noise reduction, while recognizing, at the same time, the difficulty of measuring this effectiveness, by virtue of what was declared by Lawrence Berkeley National Laboratories [19]. Other studies have explicitly ascertained the effectiveness of DSF in reducing energy consumption, in particular with regard to the cooling of buildings. In any case, the literature highlights the need for further investigation, in the future, of the potential of the DSF system with a view to improving the energy performance of buildings.

Considering the local climatic conditions as input data, the façades could also be classified according to the type of construction and ventilation characteristics. Therefore, according to the types of construction, there are continuous and

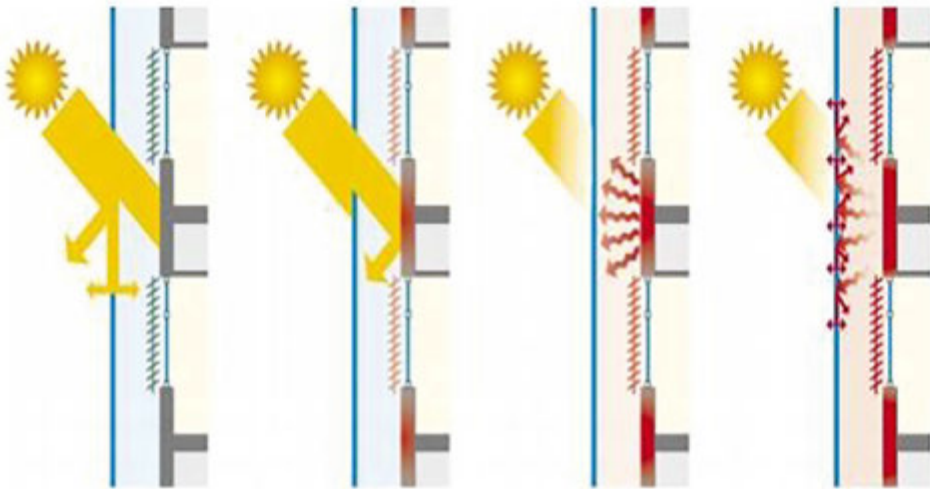


Figure 2.
Combined thermal behavior of the external and internal façade layers [13].

interrupted double-skin façades, while regarding ventilation, the façades are divided into naturally ventilated, mechanically ventilated, and mixed ventilated [4]. The studies of Yilmaz and Cetintas [17] and Chou et al. [9] highlight that the main benefit of DSF is obtained in the summer period, with the ability to reduce the amount of solar gain incident on the building; vice versa, in the winter period, DSF contribute to improve the thermal transmittance values with a consequent reduction of heat losses. Høseggen et al. [20] compare the energy behaviors of single and double-skin façades: the simulations developed confirm that the installation of DSF reduces the energy demand for heating in buildings. To improve the effectiveness of DSFs, compared to conventional DSFs, Ding et al. [2] propose adding a thermal accumulator as a solar chimney above the double skin layers to improve ventilation (**Figure 3**).

Andresen [21] highlights that the cost required for the implementation of a DSF is about 60–80% higher than conventional façades. On the other hand, however, it has also been found that DSFs provide long-term economic gain. The research of Shameri et al. [11] concludes that double-skin façades are essentially influential in improving the energy performance of buildings. They also highlight the criticality related to “fire risk” as another challenge in the application of DSFs, which requires further research and insights.

The study by Aruta et al. [22] investigates an innovative solution to reduce, and in some cases eliminate, the phenomenon of overheating, namely the reactive double-skin façade. The dynamism is obtained through the controlled opening of the window elements of the internal and external layers of the double-skin façade, which allows the establishment of air flows between the rooms. The aim is to trigger natural ventilation between the cavity and the external environment through the opening of the external windows. In this way, the overheating effect generated in the cavity of the DSF is counteracted. The reactive behavior allows one to exploit the effect of solar radiation in the winter season, thanks to the opening of the internal windows. The case study is a real building, for office use, located in Naples, in an area with a Mediterranean climate. The effects on heating and cooling consumption are therefore analyzed, as well as the effect produced by the urban context, the use of the systems, and proposing alternative solutions aimed at reducing energy consumption (**Figure 4**).

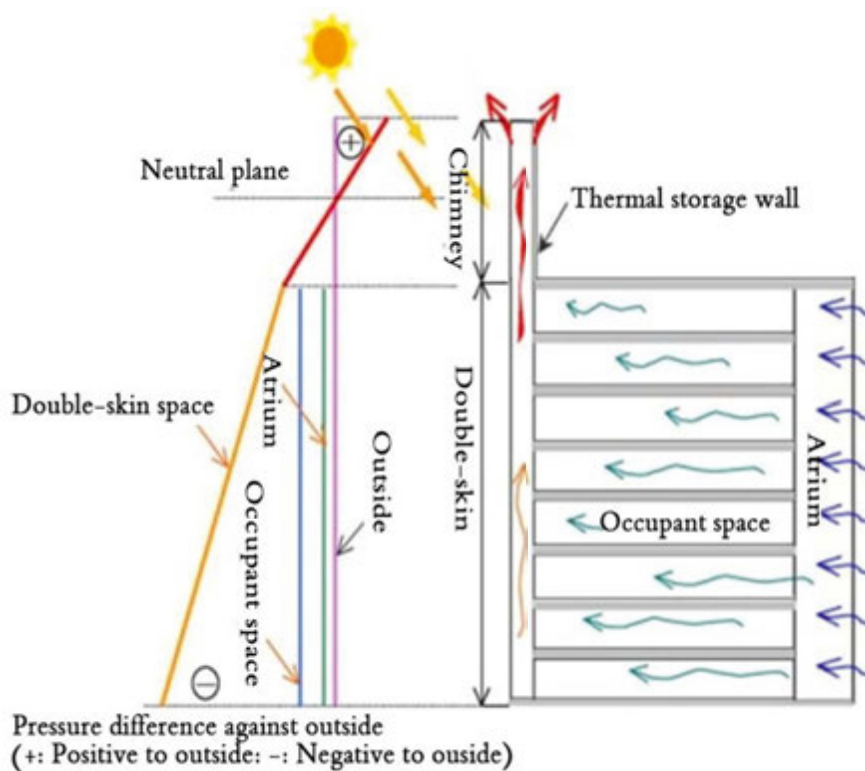


Figure 3.
 Exploitation of the solar stack as thermal storage in DSFs [7].

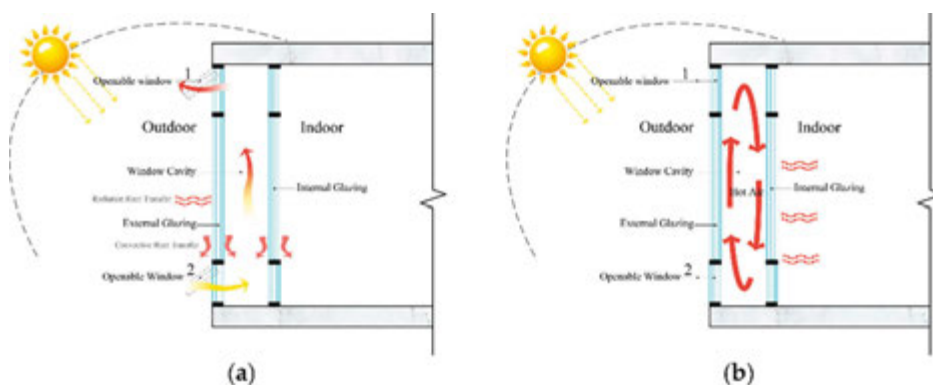


Figure 4.
 DSF operation mode. (a) Cooling season mode. (b) Heating season mode. [23].

2.2 Vulnerability to fire risk

In recent years, facades have represented an element of extreme interest for the building industry and also a point of tension between different needs.

On the one hand, the fire safety sector in Europe still has in its eyes the flames of the Grenfell Tower, and the impossibility of saving the occupants from a fire that

from the facade spread very quickly to the entire height of the building, invading the internal compartments. That event rang in 2017 like a strong alarm bell that pushed the national regulations of many countries to move to reduce the risk of a similar disaster repeating itself.

On the other hand, the strong push toward eco-sustainability and the uncertainties in energy supply have particularly recently supported redevelopment interventions aimed at increasing the thermal insulation of the building. The façade itself and, more generally, the perimeter of the building are the key elements of this strategy that has led to a more widespread use of thermal coats, and in some cases, in the presence of very tall buildings, to the creation of a ventilated façade, a “second skin” external to the building.

These are two trends that could partially conflict. The “urgent” installation of thermal coats (whose incombustibility in many cases remains to be verified) and the increasingly widespread use of a second facade (with the consequent risk of a “chimney” effect between the two skins) have, in fact, increased the possible dangers from the point of view of fire safety due to ignition and propagation.

With the still vivid images of the fire in London and more recently of the “Torre del Moro” skyscraper via Antonini in Milan (29 August 2021), the process for the approval of a new regulation on facades has received a new impetus, which has led to the approval of a new specific regulation in 2022.

In 2013, the Circular Letter of the Italian Ministry of the Interior n. 5043 was published, i.e., a guideline on fire safety requirements for the facades of civil buildings. This directive contains the foundations of RTV13 (vertical technical rule 13) for fire prevention for the enclosures of civil buildings.

The term “area closure of the civil building” refers to the external boundary of the building, with a horizontal or vertical orientation. It includes the facade, the roof, the ceiling of the pilotis floor, and the separation strips. Finally, it includes the underground external boundaries, boundaries between different areas of the building, or boundaries between different buildings that overlook an air volume.

Among the main factors characterizing the spread of a fire on a façade, there are therefore:

- property of fire reaction of the materials constituting the facade solution, which influence the speed of spread of the fire through the envelope;
- presence of cavities, which may be inherent to the façade solution or which are created due to the delamination of some layers during the fire itself;
- presence of openings in the facade (windows, doors, etc.) that allow flames to enter and/or exit the building at multiple points;
- absence of obstacles to the spread of fire on the façade and/or toward neighboring façades;
- possibility of detachment of burnt portions of the facade and involvement of portions of the facade that are still intact.

Fire risk prevention is therefore implemented through a strategy that takes into account suitable characteristics of both the individual materials and the technological system.

As regards materials, the determining factor is the fire reaction class: the use of materials with an adequate class allows for the reduction of the speed of fire propagation and increases the time available for evacuation. The main parameters that influence the fire reaction of a material are: Flammability; speed of flame propagation; heat development in the unit of time; production of harmful substances; smoke production; and dripping.

As regards the technological system, the propagation of the fire is linked to the characteristics of the cavity: if a flame enters a cavity, it can extend five to ten times its initial length due to the so-called “chimney effect,” regardless of the properties of the materials that make up the cavity itself. If specific fire barriers are not used, this effect can cause a faster and quicker vertical spread of the fire, initially not directly visible as it is “hidden” inside the cavity by the finishing coating.

The vertical cavity between the external and internal skins of double-skin façade systems, a fundamental feature for natural ventilation, can lead to the easy propagation of a fire, favored by the circulatory motion of air within the uninterrupted space of the cavity. It is essential, for the sustainability of buildings, to create works that protect the inhabitants from the possibility of propagation of a fire, with serious consequences in terms of diffusion of toxic gases released by the eventual phenomenon. In the literature, there are few studies that focus on the fire risk of DSF. Yildiz and Beyhan [24] developed a numerical model using computational fluid dynamics to monitor the propagation of smoke through the cavity of the double-skin façade and the temperature variations in the building. The effect of the modification of the slope of the external skin on the propagation of smoke and on the temperature variations was studied. The modeling took into account nine scenarios: four at an obtuse angle, four at an acute angle, and one at a right angle. While acute angle solutions increased the chimney effect in the cavity, increasing the speed of the air movements, obtuse angle solutions led to a reduction in the internal ambient temperature.

The study by Huang et al. [25] presents a methodology for simulating fire in the cavity of a naturally ventilated DSF, with an integrated Venetian blind system. The research uses a fire dynamics simulator (FDS) from the National Institute of Standards and Technology (NIST) and PyroSim. The data presented can provide reference parameters to operators in the sector for the integration of Venetian blind screening systems inside the DSF. The obtained modeling can also help firefighters in the theoretical evaluation of fire propagation in buildings equipped with this type of DSF.

The recent study by Yıldız and Ertosun [26] investigated the fire safety of some double skin façade (DSF) designs by developing a numerical model that includes the variation of natural airflow. Based on a three-story office building prototype, four DSF scenarios were simulated, varying the building typology (multi-story, gallery, shaft, and window box). The multi-story and shaft DSF designs, which create a continuous cavity in the vertical direction, lead to the highest consequences of the stack effect. In all simulated DSF cases, the internal room temperature did not reach the risk levels for the analyzed scenarios. On the contrary, the designs with a small cavity volume, associated with the fire chamber, caused an increase in internal temperature.

The study by Dong et al. [27] addresses an integrated approach to the three typical potential risks of DSF: solar overheating, structural risks, and fire risks. The manifestations, influencing factors, and possible preventive actions have been analyzed. The risk of overheating, mainly due to direct sunlight and incorrect ventilation, can be mitigated by optimizing the design parameters of the DSF by inserting additional

components. Wind-induced vibrations, earthquakes, or explosion impacts are the causes of possible structural damage to DSFs. Building shape and suitable sizing of ventilation cavities are factors that can mitigate the action of the internal and external airflow of the DSF, reducing wind-induced vibrations. Suitable dampers can be used to dissipate possible impacts from the outside. The fire risk can be reduced by using perforated plates and refractory glass. For safety purposes, it is important to evaluate the relevance of the thermal performances of various DSFs: some types of DSFs, in fact, present potential risks, so it becomes crucial to consider not only their energy performances but also the possible risk scenarios that such technological solutions may entail. In summary, this study defines possible guidelines for the design of DSFs, with a view to mitigating possible risk factors (Figure 5).

2.3 The esthetic-functional redevelopment of the building

At its plenary session in Strasbourg on 14 March 2023, the European Parliament (EP) adopted its position on the Energy Performance of Buildings Directive (EPBD) in order to achieve the objectives of reducing energy consumption while improving quality of life. The text introduces two new key elements:

- Minimum energy performance standards for existing buildings, with non-residential buildings having to reach class D by 2030 and residential buildings having to reach class D by 2033;
- Tools to mobilize renovation finance to support homeowners in their renovations (e.g., mortgage portfolio standards), in addition to the large EU funding already available for renovations.

The need to redevelop the existing building heritage requires the combination of a series of objectives [29]:

- Energy and environmental sustainability: energy and environmental requalification of buildings, promoting design strategies that favor the circular economy of the construction sector;

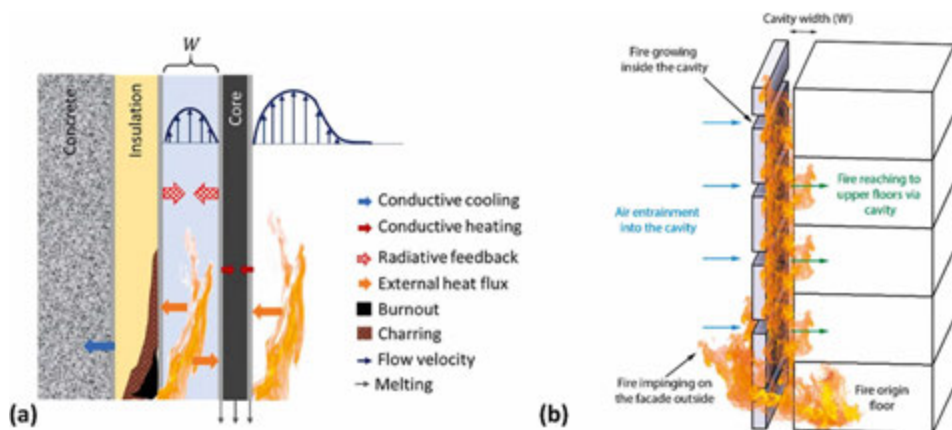


Figure 5.
(a) Physical phenomena in the upward propagation of flame in a cavity. (b) Flame propagation in a facade [28].

- Social sustainability: redevelopment of the building heritage through radical restructuring interventions aimed at improving the quality of life of the occupants, with their involvement through various forms of participation;
- Functional and esthetic sustainability (restyling): opportunities to improve the architectural and urban quality of the territorial context in which the building complexes to be redeveloped are located.

The research by Lops et al. [30] is aimed at assessing the vulnerability to climate change of a building located in central Italy, estimating its energy needs and comfort rates in future weather conditions, and considering possible energy improvement solutions. The retrofit solutions studied take into account the installation of DSF on the main facades of the building, analyzing the most effective configurations depending on the specific climate area. The innovative aspect of the work lies in considering the installation of the DSF on multiple facades of the building, differently oriented. Generally, in fact, DSF systems are installed on the north facade, the coldest one for the Mediterranean area. However, it could be convenient and functional to install the DSF system also on the other facades, for example, in the case of renovation and structural interventions on the facade, installation of anti-seismic devices, etc., with a view to a holistic renovation of the building.

Mahmoudi et al. [31] highlight that another important aspect of double-skin facades is their esthetic value due to the impact that the facade of a building has from an urban point of view, a topic that has always been stimulating for urban planners and architects. The use of DSF technology contributes to improving the esthetic and architectural characteristics of the building. The use of the double-skin facade in the Qazvin Engineering Organization building has allowed for the combination of technological requirements and esthetic principles. In fact, a key element of the DSF system is the possibility of using the esthetics of transparency of the facade as a representation of the idea of high-tech architecture. In the DSF system, architects and engineers work closely together to experiment with hybrid facade solutions, capable of merging the needs of energy comfort with those of esthetic appearance. Gaffarianhoseini et al. [32] highlight how glass DSFs are widely used, especially for commercial buildings, for their esthetics, lightness, and potential for natural light. The study investigates the multiple benefits of DSF, including the improvement of visual and esthetic quality. The esthetic aspect is, after all, a determining factor for the increase of the social and economic value of real estate assets.

3. System requirements

From the literature analysis, some recurring requirements emerged, which a DSF system should satisfy, thanks to the adoption of appropriate design choices. These requirements can be summarized as follows:

Thermal performance to ensure the improvement of living comfort and energy efficiency, both operational and built-in.

Fire resistance/resilience: DSF systems, being non-structural and lightweight systems, are very vulnerable to fire risk; the spread of a potential fire, in fact, is favored by the presence of a natural ventilation channel, of greater or lesser depth, placed between the two skins of the system.

Design flexibility: The structural and energy retrofit intervention of a building represents the opportunity to improve its esthetics and also to achieve an economic return, in terms of increased real estate value, in the face of the still high costs of the system.

Durability: The technological system (DSF) is characterized by particular lightness and consequent vulnerability; during the life cycle: wind, seismic, vibration-induced stresses, thermal expansion, thermo-hygrometric behavior, etc., require that the system be designed in compliance with high durability standards. In this regard, the Italian standard UNI 11018–1:2023 imposes requirements in terms of safety in the event of a fire, seismic action, impact resistance, energy saving, and maintenance plans.

Acoustics: The retrofit of existing buildings, using DSF, represents an opportunity to ensure the acoustic insulation of internal environments, an aspect particularly felt also for non-residential uses, such as schools, hospitals, hotels, professional offices, etc.

Circularity: The eco-sustainability of the technological system represents one of the current and most carefully considered requirements in terms of improving the performance of the envelope, with particular reference to the reduction of the carbon footprint in all phases of the life cycle.

4. The technical solution: The ventilated facade

Double-skin facade systems allow to achieve, simultaneously, multiple benefits, both in terms of improved thermal and acoustic performance and in terms of esthetic requalification of the building envelope. As regards thermal improvement, ventilation of the cavity, appropriately regulated according to the seasons and the climatic context, guarantees a notable contribution in terms of periodic thermal transmittance and thermal phase shift of the envelope. As regards esthetic requalification, the industry today can provide designers with a notable variety and assortment of surface materials in order to obtain the desired texture in relation to the design objectives. The ventilated cavity guarantees advantages in terms of durability and energy efficiency (compared, for example, to the traditional plastered “coat” system). In fact, the air movements, which are triggered by convection inside the ventilation chamber, allow the expulsion of water vapor generated inside the homes, reducing condensation phenomena that could lead to more rapid degradation of the materials. Furthermore, as a second skin, it guarantees further protection from the entry of rainwater.

The seasonal behavior of the ventilated facade can be summarized as follows (as schematically represented in **Figure 4**):

- in summer: part of the heat caused by solar radiation is reflected outside; another part penetrates the cavity, activating the chimney effect, and can be expelled outside. Only the residual part is absorbed by the building;
- in winter: the ventilation of the cavity involves a limited penalization of the insulating effects of the insulation, since the chimney effect, in the cold season, is reduced; due to the absence of strong heat incident on the external wall, the air inside the cavity and the external air are approximately at the same temperature and density. The system also contributes to the control of energy losses, flows, and rates of water vapor and to the formation of frost in the cavity and on the facade plane.

In summary, the main advantages of ventilated DSFs are:

- speed of construction processes: preparation of the load-bearing wall is not required, and all components have a high degree of prefabrication;
- absence of “wet” installation procedures;
- simple installation, although it requires qualification and training of workers;
- customized elements, even directly on site;
- estimated useful life: 50–100 years;
- limited operating costs;
- wide choice of thermal insulation materials;
- wide choice of outer skin materials;
- esthetically relevant, as it allows the formal appearance of the building to be modified;
- flexibility, the system is able to adapt to the needs of new and existing buildings, both from the point of view of structural choice and characterization of the stratigraphy;
- energy efficient, as it is able to guarantee good continuity of the insulating layer to protect the primary structure and at the same time a ventilation layer to reduce external surface temperatures in the summer;
- sustainability of the technological system since it is entirely made “dry” and therefore particularly suitable for disassembly, dismantling, and recovery of the components at the end of their life.

5. The case study: The “ventilated facade” system in rock wool

When we talk about a ventilated façade, we mean an opaque wall with an external cladding made up of elements of various make, size, and material consistency, installed dry using mechanical or chemical suspension and fastening devices, which allow them to be separated from the rear infill wall, suitably insulated, so as to create a thin cavity that allows the circulation of external air. It is important that this cavity has a thickness that interrupts the physical continuity between the cladding and the infill wall so as to allow suitable air circulation within the system. The creation of a ventilated facade also allows the installation of continuous insulation, even in correspondence with the structural elements, with a consequent correction of thermal bridges. With this solution, it is therefore possible to significantly improve the configuration of the opaque vertical envelope of buildings, both from a technological and performance perspective and from an architectural one.

For these reasons, ventilated facade systems have become one of the most technologically advanced solutions over time.

The product of the REDAir research [33] combines the thermal insulation of the facade, represented by ROCKWOOL rock wool panels, with Rockpanel cladding panels, with notable esthetic possibilities, versatility, and high technical performance. The ventilated facade system has also been designed to function with specific horizontal and vertical fire compartments. The system therefore combines, in a single technical solution, advantages in terms of living comfort, fire protection, durability, speed of installation, esthetic possibilities, and sustainability.

Today, ventilated wall cladding, combined with a high-performance insulation layer, represents one of the main external finishing options for opaque closures and is used in particular for high-rise and large-sized buildings, as well as in all cases where the primary objective is to obtain functionality, esthetic effect, high performance, efficiency, and sustainability of the building envelope.

In the current commercial offering of materials and products for ventilated facade systems, ROCKWOOL stands out for its proposal of products specifically designed and optimized to guarantee ideal performance and installation methods on site.

REDAir is, in fact, suitable for different types of support and is suitable for both new constructions and renovations, especially for all those buildings that require high performance and esthetic appeal, such as hotels, commercial buildings, multi-family buildings, healthcare facilities, and schools.

These are the main performance characteristics of the system:

5.1 Thermal performance

The continuity of insulation guarantees an increase in living comfort. Energy efficiency is further guaranteed by the presence of the air cavity that allows heat to be dissipated, resulting in a reduction in the summer heat load and protecting the rear wall facing from solar radiation. Even during the winter months, the air cavity allows for better control of internal temperatures with consequent advantages in terms of energy savings. ROCKWOOL insulating panels, within the REDAir façade solutions, thanks to their conductivity, mass, and specific heat parameters, further contribute to achieving high performance.

5.2 Fire resistance/resilience

In ventilated facade technological systems, it is known that fire phenomena, triggered by possible internal or external sources to the building, can propagate very quickly due to the materials that make up the facade and the chimney effect that the ventilation air currents generate. To ensure safety in the event of a fire, limiting the spread of fire and smoke, and avoiding the detachment of facade components, the Fire Prevention regulatory framework suggests certain fire resistance requirements for the entire construction system and specific fire reaction performance for the insulating materials used. In this sense, REDAir offers a concrete response for different construction typologies. This is thanks to the high performance of ROCKWOOL insulating panels, fire compartmentalization partitions, and Rockpanel cladding.

5.3 Design flexibility

With REDAir, you can give each building the desired charm. Rockpanel external cladding offers endless esthetic possibilities and countless configurations: the available finishing ranges can be worked in various formats, decorated or with a rusticated effect, with the possibility of visible or hidden fixings and flat or curved assembly. From wood or metal effects to material variants, with REDAir, every design idea becomes a reality. The possible presence of a mineral veil coating on the ROCKWOOL insulation panels behind it further enhances the esthetic impact of the building.

5.4 Durability

Ventilated facades are characterized by high standards of durability and require little maintenance over time. The wall facing behind is protected by the presence of the facade cladding from the combined action of rain and wind. Rockpanel cladding also guarantees high durability of the color of the finishes over time, while ROCKWOOL insulating panels, thanks to their dimensional stability when humidity conditions vary, reduce the risk of deterioration. If created using dry installation, ventilated facades guarantee a high speed of installation, which is also a little dependent on the variables of external climatic conditions. Rockpanel panels can be easily laid and allow for further cutting and finishing work during installation. Furthermore, the characteristic optical effect of the cladding remains regardless of the direction in which the individual panels are mounted, which allows for quick and efficient processing, as well as a reduction in waste and costs.

5.5 Acoustics

The combination of rock wool insulation panels with Rockpanel ventilated facade cladding also brings significant advantages from an acoustic point of view. Thanks to their open-cell fibrous nature, rock wool panels act as a sound-absorbing element capable of limiting the propagation of noise and ensuring high levels of internal comfort.

5.6 Circularity

REDAir is made up of two products created from basalt rock, a natural, recyclable, and virtually inexhaustible element in nature. At ROCKWOOL factories, waste from internal production processes and other industries is transformed and reused as raw materials, with the aim of reducing resources and emissions, including CO₂. This reduces the impacts of raw material sourcing and the production process and allows for additional benefits throughout the entire lifecycle of the products.

6. Installation techniques

The system provides four possible technical solutions depending on specific design needs and the type of support:

1. On-brick support with visible fixing
2. On-brick support with hidden fixing

3. On wooden support (CLT) with visible fixing
4. On wooden support (timber frame) with visible fixing

6.1 On-brick support with visible fixing

The ventilated wall cladding system, analyzed below, is composed of Ventirock Duo insulating panels and Rockpanel compressed rock wool cladding panels with a thickness of 8 mm or 9 mm on a wall support made of 300 mm thick honeycomb brick block infills.

The proposed cladding solution is characterized by lightness, high durability, sustainability, and high esthetic and architectural appearance. The represented construction solution also helps to prevent the spread of fire (**Figures 6 and 7**).

6.2 On-brick support with hidden fixing

The ventilated wall cladding system, which is analyzed below, is composed of Fixrock 33 VF-type insulating panels and cladding panels in compressed Rockpanel rock wool with a thickness of 11 mm on a wall support consisting of 300 mm thick honeycomb brick block infills. The proposed cladding solution is characterized by easy and safe installation with concealed fixings that give the facade a clean, elegant, and linear design. The construction solution represented also helps prevent the spread of fire (**Figures 8 and 9**).

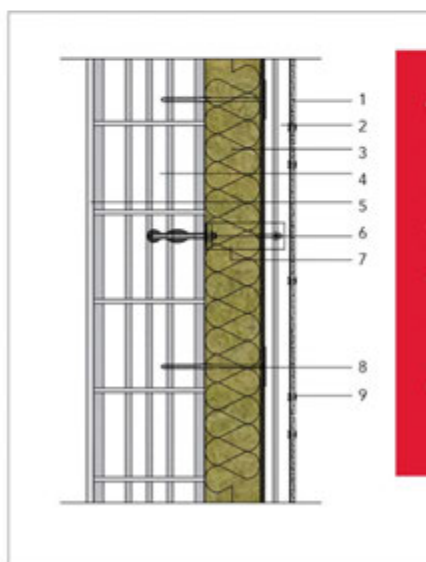


Figure 6.
Three-dimensional exploded view of solution 1.

CASO 1: REDAir su supporto in laterizio con fissaggio a vista



Il sistema di rivestimento a parete ventilata, di seguito analizzato, è composto da pannelli isolanti del tipo Ventirock Duo e pannelli di rivestimento in lana di roccia compressa Rockpanel dello spessore pari a 8 mm oppure 9 mm su supporto murario costituito da tamponamenti in blocchi di laterizio alveolati dello spessore di 300 mm. La soluzione di rivestimento proposta si contraddistingue per leggerezza, elevata durabilità, sostenibilità ed elevato aspetto estetico e architettonico. La soluzione costruttiva rappresentata aiuta inoltre a prevenire la propagazione del fuoco.



Si riporta di seguito la stratigrafia considerata ai fini delle valutazioni analitiche:

1. Pannello Rockpanel sp. 8 oppure 9 mm
2. Intercapedine d'aria sp. 60 mm*
3. Pannello ROCKWOOL Ventirock Duo (cfr. tabella pag. 19)
4. Muratura di tamponamento in blocchi alveolari sp. 300 mm
5. Intonaco di base sp. 15 mm
6. Ancoraggio di tipo chimico per murature in blocchi alveolari
7. Staffa in lega di alluminio pressofusa per controvento sottostruttura
8. Tassello per fissaggio pannello isolante
9. Rivetto di fissaggio in foro calibrato

* L'intercapedine d'aria può avere uno spessore variabile a seconda delle caratteristiche di progetto.

Nota: per maggiori dettagli sull'applicazione si prega di far riferimento all'ETA specifica in funzione del prodotto Rockpanel prescelto.

ROCKWOOL Firesafe Insulation

4

Figure 7.

Detail constructive solution 1. Characteristics of the stratigraphy (1): 1. Rockpanel panel thickness 8 or 9 mm, 2. Air gap 60 mm thick, 3. ROCKWOOL Ventirock Duo Panel (Table 1), 4. Infill masonry in 300 mm thick honeycomb blocks, 5. Base plaster 15 mm thick, 6. Chemical anchoring for honeycomb block walls, 7. Die-cast aluminum alloy bracket for substructure bracing, 8. Dowel for fixing insulation panel, 9. Fixing rivet in calibrated hole.

λD [W/mK]	Insulation thickness (mm)	Type of panel	U [W/m ² K]	Yield [W/m ² K]
0.035	80	Twenty Rock Duo	0.29	0.05
0.035	100		0.25	0.04
0.035	120		0.22	0.03
0.035	140		0.20	0.03

Table 1.
Case 1—REDAir on-brick support with visible fixing.



Figure 8.
Three-dimensional exploded view of solution 2.

6.3 On wooden support (CLT) with visible fixing

The ventilated wall cladding system analyzed below is composed of Fixrock 33 VF insulating panels and Rockpanel compressed rock wool cladding panels with a thickness of 8 mm or 9 mm on a wooden support made of 100 mm thick CLT panels. The proposed cladding solution is characterized by lightness, high durability, sustainability, and a high esthetic and architectural appearance. The construction solution represented also helps prevent the spread of fire. The internal counter wall is made with a metal frame structure in galvanized steel and “C” uprights filled with Acoustic 225 Plus panel, 40 mm thick, and closed with two sheets, the innermost one in gypsum fiber and the outermost one in plasterboard, 12.5 mm thick each (**Figures 10 and 11**).

6.4 On wooden support (timber frame) with visible fixing

The ventilated wall cladding system, analyzed below, is composed of Fixrock 33 VF-type insulating panels and Rockpanel compressed rock wool cladding panels

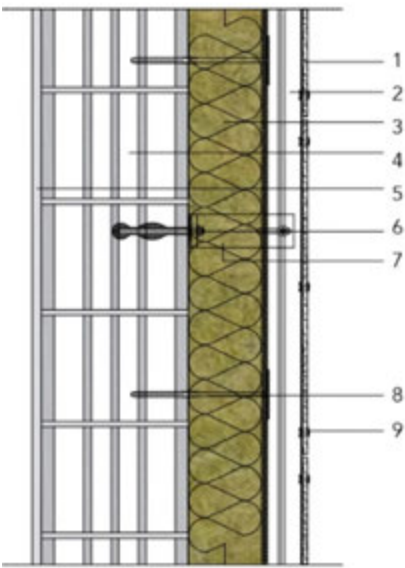


Figure 9.
Detail constructive solution 2. Characteristics of the stratigraphy (2): 1. Rockpanel Premium sp. 11 mm, 2. Air gap 60 mm thick, 3. ROCKWOOL Fixrock 33 VF panel (Table 2), 4. 300 mm thick brick support, 5. Horizontal aluminum substructure and clip, 6. TU-S Rivet, 7. Vertical aluminum substructure, 8. Bracket, 9. Suitable anchoring for brick support.

λD [W/mK]	Insulation thickness (mm)	Type of panel	U [W/m ² K]	Yield [W/m ² K]
0.033	80	Fixrock 33 VF	0.28	0.03
0.033	100		0.24	0.02
0.033	120		0.21	0.02
0.033	140		0.19	0.02

Table 2.
Case 2—REDAir on-brick support with hidden fixing.

with a thickness of 8 mm or 9 mm on a wooden support (Timber frame type). The proposed cladding solution is characterized by lightness, high durability, sustainability, and high esthetic and architectural appearance. The construction solution represented also helps prevent the spread of fire. The internal counter wall is instead made with a metal structure with plasterboard guides between which the 40 mm thick Panel 211 N is laid and closed by two sheets, in coated plaster, each 12.5 mm thick (Figures 12 and 13).

7. Fire resistance of the system

7.1 Fire-resistant insulation panel

Rigid panel in medium-density rock wool, coated on one side with black mineral veil, with an esthetic function, for thermal and acoustic insulation and safety in the



Figure 10.
Three-dimensional exploded view of solution 3.

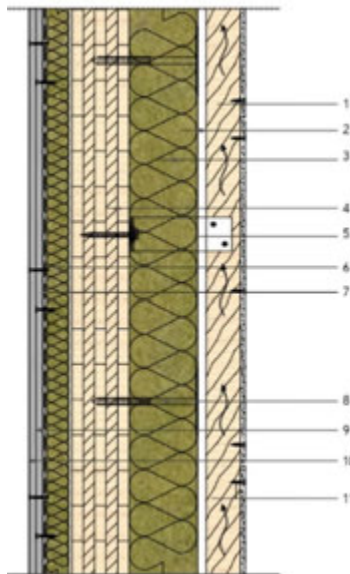


Figure 11.
Detail constructive solution 3. Characteristics of the stratigraphy (3): 1. Rockpanel panel thickness 8 or 9 mm, 2. Air gap 75 mm thick, 3. ROCKWOOL Fixrock 33 VF panel (Table 3), 4. Structure in CLT wood panels (X-Lam type) 100 mm thick, 5. Steel bracket for substructure bracing, 6. ROCKWOOL Acoustic 225 Plus panel thickness 40 mm (Table 3), 7. Air and steam sealing element, 8. Dowel for fixing insulation panel, 9. Gypsum fiber board, 12.5 mm thick, 10. 12.5 mm thick coated plasterboard, 11. Stainless steel fixing screw.



Figure 12.
 Three-dimensional exploded view of solution 4.

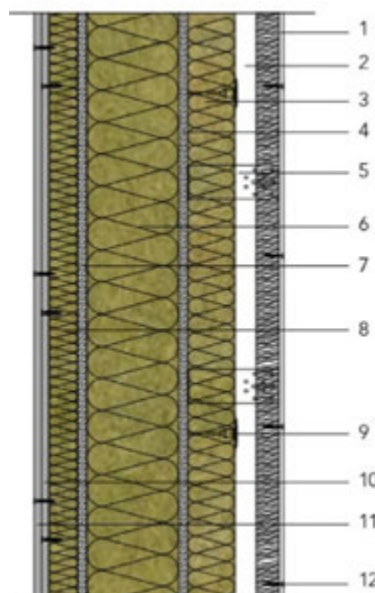


Figure 13.
 Detail constructive solution 4. Characteristics of the stratigraphy (4): 1. Rockpanel panel thickness 8 or 9 mm, 2. Air gap 80 mm thick, 3. ROCKWOOL Fixrock 33 VF panel (Table 4), 4. OSB thickness 18 mm, 5. Steel bracket for substructure bracing, 6. ROCKWOOL Acoustic 225 Plus panel thickness 160 mm (Table 4), 7. OSB thickness 18 mm, 8. ROCKWOOL 211 N panel, thickness 40 mm (Table 4), 9. Dowel for fixing insulation panel, 10. 12.5 mm thick coated plasterboard, 11. Coated plasterboard, thickness 12.5 mm, 12. Stainless steel fixing screw.

λD [W/mK]	Insulation thickness (mm)	Type of panel	U [W/m ² K]	Yield [W/m ² K]
0.033/0.033	80 + 40	Fixrock 33 VF + Acoustic 225 Plus	0.21	0.03
0.033/0.033	100 + 40		0.18	0.03
0.033/0.033	120 + 40		0.17	0.02
0.033/0.033	140 + 40		0.15	0.02

Table 3.
Case 3—REDAir on wooden support (CLT) with visible fixing.

λD [W/mK]	Insulation thickness (mm)	Type of panel	U [W/m ² K]	Yield [W/m ² K]
0.033/0.033/0.035	80 + 160 + 40	Fixrock 33 VF + Acoustic 225 Plus + Panel 211 N	0.12	0.02
0.033/0.033/0.035	100 + 160 + 40		0.11	0.01
0.033/0.033/0.035	120 + 160 + 40		0.10	0.007
0.033/0.033/0.035	140 + 160 + 40		0,0,95	0.006

Table 4.
Case 4—REDAir on a wooden support (timber frame) with visible fixing.

event of fire of ventilated facades. The panel, non-combustible, does not contribute to the fire and, if exposed to open flames, does not generate smoke or drops; it helps prevent the spread of fire, an essential aspect in the presence of a ventilated cavity.

7.2 Horizontal compartmentalization section

This is an element for the horizontal compartmentalization of the ventilated facade, with fire performance EI 120 to be combined with ROCKWOOL panels for the insulation of the ventilated facade. These are the main characteristics for installation (**Figure 14**):



Figure 14.
SP Firestop OSCB system.



Figure 15.
 SP FireStop EN system. Characteristics: SP FireStop EN 60. Format: 1200 × 1000 mm, thickness 75 mm, fire resistance up to 60 min SP FireStop EN 120. Format: 1200 × 1000 mm, thickness 90 mm, fire resistance up to 120 min.

- *Fixing brackets* in galvanized steel of variable length to fix the partition to the wall support. Incidence: 2 units per linear meter.
- *Spring screws* of spacing positioned between the partition and the cladding of the ventilated facade. Incidence: 3 units per linear meter.

Characteristics: Format 1000 mm × 90 mm (length × thickness), variable width.

- Air gap at the compartmentalization partition of maximum 25 mm
- Interspace with depth from 100 mm up to 600 mm

7.3 Vertical compartmentalization septum

This is a vertical compartmentalization element of the ventilated facade with fire resistance for up to 60 min or up to 120 min to be combined with ROCKWOOL panels for the insulation of the ventilated facade. Covered with a black aluminum sheet on two sides, to be cut on site to size based on the dimensions of the cavity of the ventilated facade. These are the main characteristics for installation (**Figure 15**):

- *Fixing brackets* in galvanized steel of variable length to fix the partition to the wall support. Incidence: 2 units per linear meter.
- *Adhesive tape* in black aluminum for sealing the joints of the vertical compartmentalization partition.

8. The esthetic-formal solutions: The facade panels

The facade cladding systems, designed for the stratigraphy of the REDAir system, are made of pre-compressed fibers (ROCKPANEL [34]). They respond to different esthetic needs: from the finish that changes appearance thanks to the action of atmospheric agents to the shades of wood and the stone effect with a



Figure 16.
Possible textures obtainable with the REDAir system.

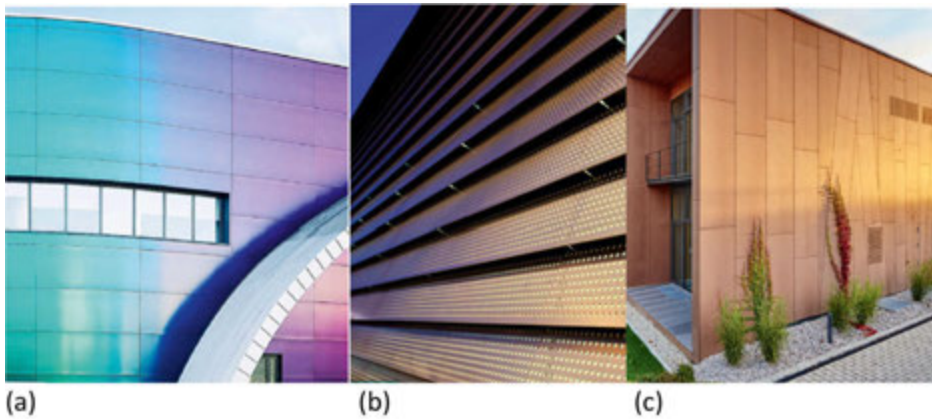


Figure 17.
Esthetic-formal potential of the REDAir system: (a) curved surface with iridescent shades; (b) perforated metal surface; (c) wood-effect surface.

smooth finish or material texture. The panels can also be applied on curved facade surfaces (**Figures 16 and 17**).

8.1 Compressed basalt cladding panel

Rockpanel Stones boards are made of compressed natural basalt, a sustainable and naturally available volcanic rock, held together with an organic binder, which gives the boards their unique properties. The products combine the benefits of stone with the workability of wood (**Figure 18**).

The solution was a ventilated facade made of Rockpanel Colors panels. Three different shades of green and the irregular structure with inclined joints.

The decision to use Rockpanel boards is the result of a thorough selection process. Numerous options were considered for the façades. The architects' original plan was to clad the building with wooden panels. As the contractor was concerned that this would lead to high maintenance costs in the long term, alternative solutions were considered. In addition, the contractor felt it was important to create a lively, child-friendly design for the building. Rockpanel boards were chosen because of their wide range of colors, ease of use, and sustainability.

The solution also provides optimum fire protection: Rockpanel Standard boards meet the requirements of Euroclass B-s2, d0 (in accordance with EN 13501-1).



Figure 18.
Case study: Extension of a special school located in Pfarrkirchen, Bavaria (Germany).

Furthermore, compared to other façade cladding materials, they offer a particularly environmentally friendly solution. The BRE Global Institute, which belongs to the British research and certification centre (Building Research Establishment BRE), has confirmed the sustainability characteristics of Rockpanel façade boards, awarding them an A+/A rating.

9. Conclusions

The double skin façade (DSF) has proven to be very effective in current building developments in terms of energy and environmental efficiency. One of the critical issues of the system is still its high cost, compared to the traditional façade. However, many experts agree that the double skin façade (DSF) is more convenient in the long term and that the initial cost can be amortized thanks to both energy savings and the greater durability of the system. Furthermore, the double-skin façade, thanks to the cavity ventilation system, helps to purify the incoming air, improving indoor well-being. The author hopes for future work and studies on the reduction of direct and indirect costs of this technological system in order to make this system overall convenient for addressing climate change and environmental risks.

In particular, the ventilated facade system, of which this work presents a case study, is the result of advanced research in the sector of this technological system. The technological system is, in fact, able to combine the following instances:

- The thermo-hygrometric benefits of rock wool insulation
- The fire resistance characteristics of the DSF
- The esthetic needs related to the need for formal and functional retrofitting of the building.

Acknowledgements

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Conflict of interest

The author declares no conflict of interest. The chapter is the result of scientific collaboration with Rockwool, a leading company in facade systems.

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Perspective Chapter: Coupled Analysis Based on Thermal Skin Heat Transfer Simulations

Tatsuhiko Yamamoto

Abstract

This chapter focuses on coupled analysis methods. Specifically, it considers the key issues for the complex building envelope calculation. Firstly, the building envelope has structural complexity, and secondly, the building envelope has thermal complexity. These two patterns are, at first sight, contradictory, and in a few cases, they coexist. This chapter describes the concept of a thermal environment analysis methodology for buildings with thermally complex envelopes but with design features. It suggests that a sophisticated methodology could facilitate heat transfer calculations in various building envelopes. In addition, the book explains the methodological approach to calculation models and analysis conditions, providing a valuable technical resource. In conclusion, it is suggested that a comprehensive coupled analysis technique, including both the external and internal sides, is essential for the calculation of heat transfer in the building envelope. On the other hand, if the computational load is negligible, it is considered advisable to calculate the three-dimensional heat flow inside the wall, considering the radial heat flow, instead of the two-dimensional heat flow calculation utilizing a coupled analysis based on a Computational Fluid Dynamics (CFD) splitting method. If the computational load cannot be ignored, solving the 2D heat flow is recommended. Consider dividing the number of slices per orientation. After considering solar heat gain on the wall, exploring this option could be beneficial. In other words, since the accuracy of the calculation is linked to solar heat gain, it is also regarded as desirable to study the microclimate around the building outdoors.

Keywords: heat transfer simulation, convective heat transfer coefficient, transfer flow, coupled simulation, building physics

1. Introduction

This chapter focuses on cases where the building envelope is thermally complex and where the calculation of sophisticated transient heat flows is desired for distinctively designed buildings. It also describes how the theory is conceived and captured. By focusing on the methodology of “coupled analysis,” which is expected to have a revolutionary impact on modern thermal calculations, it is hoped that the book will

tickle the fancy of many readers and become a designer's bible. As described below, the arguments for the Bible will be written up.

The history of thermal fluid calculations related to heat transfer theory is long. It has been built up from the definition of the Reynolds number [1], based on experimental equations, using the profile method as shown in Refs. [2, 3]. The Reynolds number is unclear in some areas, such as the representative length [4], depending on the object of analysis. Still, nowadays, when the SI unit system [5] is used, it is desirable to review the definition of this unit system. The basic theory of numerical fluid dynamics is based on the Navier-Stokes eqs. [6], but since it is an unsolved problem, it consists of a series of equations, equations of motion and energy equations, and turbulence models (typically the k-epsilon model [7]) are used to define the vortex. On the other hand, there is a large part that is governed by obscure parameters, such as turbulence intensity, which, although investigated in various studies [8, 9], is often given common values [10] and classified as an adjustment factor, since it is one of the input conditions. In addition, the heat transfer theory is slightly different from the theoretical system of thermal fluids, which is a discipline that also deals with heat transport inside walls [11]. Furthermore, it is a credible theory within certain limits, as it has a solid theoretical background in steady-state calculations and is also used in practice for verification on the safe side.

However, steady-state calculations excel at macroscopic heat transport, so while it is important to define the heat transport due to convection on the outdoor and indoor sides, on the other hand, it is more desirable to incorporate the ideas of numerical fluid dynamics because of the macroscopic nature of heat transport. There are few existing studies on the effects of microclimate on the exterior of buildings, and it is desirable to create a database, so it can be organized [12], and it should be added that microclimate weather data should be included in the heat transfer simulation [13]. Although near-future weather data have been developed [14], they are not statistically reliable compared to standard year weather data [15], which is a combination of representative weather data for a decade, and therefore, it is not desirable to use near-future weather data in the present situation. In other words, it is desirable to build an analytical model with high computational accuracy, especially for the calculation of the wall body, where outdoor weather data and solar radiation heat collection are important external parameters, and for the calculation of the wall body to be modeled in a precise manner. It should be noted that heat transfer theory is an old discipline, and its technical progress seems to have lost the opportunity for essential discussions due to a preoccupation with interfaces rather than cattle prods (e.g., ANSYS Fluent [16] and STAR-CCM+ [17]). As evidence of this, even in recent research, the definition of the Nusselt number has been tied to the Nusselt number [18], which is only a semi-experimental expression for flow in a pipe, and although there are, for example, calculations of heat flux from the longitudinal curvature of a tire [19], its derivation is questionable and has been used in structural form. The coupled structural-fluid analysis [20, 21], for example, is a study in name only and is not essential beyond the development of mathematical formulae. In other words, when macroscopic calculations are performed using Nusselt numbers to calculate convective heat transfer, the accuracy of the calculations is questionable. The history of coupled analysis is represented by Jhon Zhai's PhD thesis at MIT [22], conceived as an analysis method with an extremely high degree of difficulty in execution [23–25], and its application to design practice was not considered. However, analytical methods are being proposed for application to the design phase, and applicable theories are being developed in response to changing times.

There is not much literature on coupled analysis, and it is treated as a blue ocean due to its high level of difficulty. On the other hand, it is not easy for reviewers to understand the theory, and, due to the unreasonableness of not passing peer review if the calculation accuracy does not match, some papers question the results of analyses that do not publish adjustment factors by convention, although this is true from a professional point of view [26]. Despite this reality, in the coming era of technological innovation, it is desirable to follow the concept of coupled analysis; for example, although numerical analyses have been carried out using radiant panels [27], it is preferable to carry out coupled analysis based on integration with heat transfer theory. Although there are many studies of heat transfer simulation using radiant panels based on macroscopic heat transfer theory, most of them are calculated based on arbitrary adjustment of convective heat transfer, which is a complicated adjustment factor, and most of them do not disclose the parameters of the convective heat transfer coefficient. The calculation results are therefore highly questionable. In recent years, radiative panel calculations have often been performed using CFD, with analytical models ranging from macroscopic to sophisticated [28, 29]. Although elaborate analyses of radiative calculations using Gebherat absorption coefficients have been carried out [30], the theoretical background has not progressed significantly, and if calculation accuracy is required, it needs to be unraveled from the underlying fundamental theory. On the other hand, since it is also an important task to claim the foundations of coupled analysis using current theoretical systems, it is considered that this chapter will outline the theory of coupled analysis, which is linked to the existing basic theory, as it cannot be ignored.

Energy simulation has a long history, and with the development of heat transfer theory and improvements in computational capability, several analysis software packages have been developed, and in recent years, highly versatile GUIs such as TRNSYS [31] and Energy Plus [32] have made calculations possible. On the other hand, although annual calculations are also carried out using ES, most of them take a macroscopic view of physical phenomena and, based on macroscopic calculation results, perform several physical operations, such as energy calculations, to support the appearance of the building design field. However, the ES is built on theories that are tied to old academic models, and the reality is that major problems have arisen; for example, the definition of convective heat transfer coefficient uses the Nusselt number [33]. The definition of energy consumption is also based on power consumption [34], but the conversion is also considered to be crude and not very practical to use.

It should be added that the energy consumption calculation is tied to the insulation performance of the wall, that is, the through-flow heat flow. The through-flow heat flow within walls is generally provided to be considered at the nodes and does not lead to the expression of the distribution characteristics of the reference temperature, especially in the height direction. It shall be added that, in practice, variations in the through-flow heat flow inside the wall should occur and that no examples exist in the latest research to organically link the degree of maldistribution. Therefore, it should be added that to consider the through-flow heat flow inside the wall, it is preferable to use calculation tools that represent the distribution characteristics in three dimensions, such as CFD, as well as relying on tools such as ES. In other words, it is preferable to carry out a coupled analysis of ES and CFD, and in this chapter, since the subject of heat transfer is treated as heat transfer, it should be noted that this is linked to Heat Transfer Simulation, which is defined as an elaborate modeling of heat transport in ES.

Finally, this chapter focuses on coupled analysis, one of the most effective tools available today for dealing with thermal and designing complex building envelopes. It

describes the main points in detail, from the development of the theory to the computational considerations.

2. Coupling method

Eq. (1) expresses the heat balance equation for the room. As can be seen from the equation, it appears to be dominated by the convective heat transfer coefficient. The convective heat transfer coefficient is expressed by eqs. (2), (3), but it is important to define the heat flow and the reference temperature of the turbulent region.

$$V_{ol}\overline{c\gamma}\frac{dT_i}{dt} = \sum_{j=1}^J S_{i,j}h_{i,j}(T_{i,j} - T_i) + V_o c\gamma(T_o - T_i) \quad (1)$$

$$q_{wall} = \frac{\rho_f(y_c)C_{Pf}(y_c)u_\tau}{T^+(y^+_{fluid})}(t_{wall} - t_{fluid}) \quad (2)$$

$$h_{wall} = \frac{q_{wall}}{(t_{wall} - t_{fluid})} \quad (3)$$

The two-dimensional unsteady heat flow in the thermal envelope of the building is expressed by eq. (4) and in the steady state case by eq. (5).

$$\rho_{Cp} \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + q_{solar} \quad (4)$$

$$\lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + q_{solar} = 0 \quad (5)$$

Here, the ambient temperature T is decomposed and expressed by Eq. (7) in the steady-state calculation of the heat flow in the wall. The macroscopic ambient temperature is better expressed as the ratio of the contact area of each cell. Eq. (6) is commonly used for the steady-state heat flow expression. Conversely, when calculating ambient temperature, Eq. (7) is used as a variant of Eq. (6).

$$Q_{total} = U_{Area}(T - T_r) \quad (6)$$

$$T_r = T + \frac{Q_{total}}{U_{Area}} \quad (7)$$

Here, the ambient temperature T is decomposed and expressed using Eq. (8) to calculate the steady state heat flow through the wall. Macroscopic ambient temperature should be expressed as a ratio of the area exposed to each of its cells.

$$T = T_o \left(\frac{A_{To}}{A_{total}} \right) + Gt \left(\frac{A_{Gt}}{A_{total}} \right) \quad (8)$$

The theoretical background of the thermal envelope is shown in **Figure 1**. In the present study, the calculation of the thermal envelope is performed in a non-stationary manner. On the other hand, convergence calculations are required to

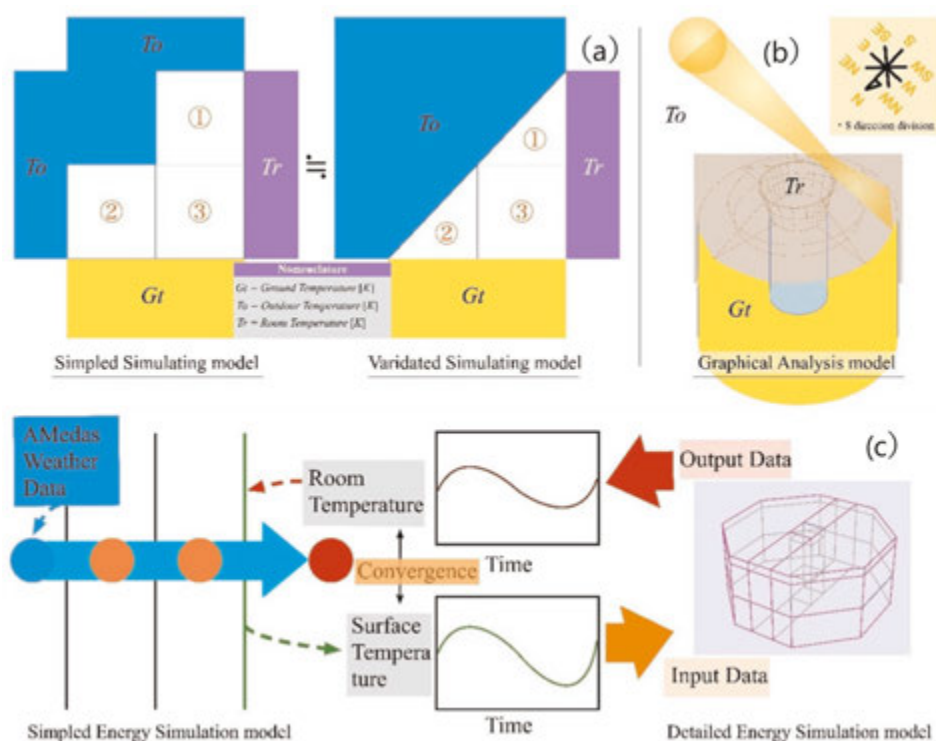


Figure 1. Thermal skin analysis method with theoretical flow. Source: Ref. [35], Figure 2 (Partially extended and ingenious).

perform more sophisticated calculations using extended AMeDAS weather data for outside air temperature as input conditions. As can be seen from **Figure 1(a)**, the layer-wall partitioning within the fill of the simplified model does not cause any variation in the exchange between the nodes compared to the detailed partitioning. Here, some errors occur when multiple outside air temperatures are obtained, but this is not an issue as the ES is a macroscopic theoretical model. As shown in **Figure 1(b)**, the analytical model is partitioned into eight orientations so that the interior surface temperature can be calculated by non-stationary two-dimensional heat transfer calculations. As shown in **Figure 1(c)**, the initial room temperature is obtained by calculating the room temperature using the simplified model with outdoor air as the input condition. Next, a two-dimensional unsteady heat transfer calculation is performed with the initial room temperature and outdoor air temperature as input conditions to obtain the indoor surface temperature. Finally, the transient heat transfer and ES calculations are performed until the room temperature and the indoor surface temperature converge, which is the input condition for CFD. It should be noted that in this study the actual measured values are used as input conditions for the outdoor and indoor surface temperatures, so there is no description of the convergence decision.

Figure 2 shows an example of a coupled analysis. Ideally, it would be preferable to consider three-dimensional (3D) heat flow rather than eight-directional partitioning, but to offer design practitioners a reduction in the computational burden, it is in some

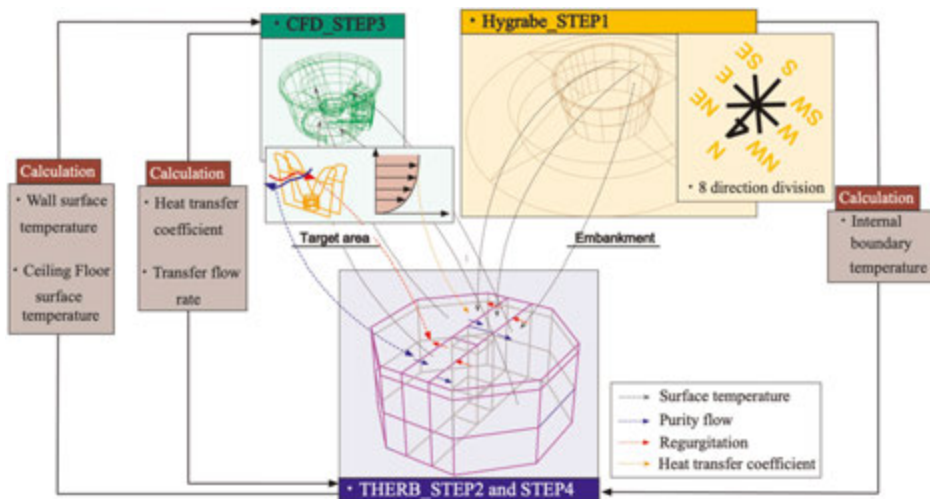


Figure 2.
Method of triple coupling analysis technics (for example). Source: Ref. [35], Figure 2 (not modified).

cases preferable to express the envelope heat flow calculations in two-dimensional (2D) heat flow. On the other hand, when expressed in 2D heat flow, the representation of heat transport on the horizontal axis, such as fin efficiency, is not complete, so it is assumed that it is desirable to consider 3D heat flow when performing calculations for a building envelope of a particular design. I want to add that if the building envelope falls within the scope of a typical building envelope, it may be desirable to achieve a coupled analysis of one-dimensional, two-dimensional, and three-dimensional heat flow to reduce the computational burden significantly.

The theoretical concept of a heat transfer analysis is shown in **Figure 3**: In STEP 1, it is advisable to perform a CFD analysis of an urban block to calculate the convective heat transfer coefficient of the external surface as well as the external air temperature. The rationale is that outdoor spaces have a microclimate and the ES and CFD should take the microclimate into account when setting the outdoor air temperature. However, due to the current computational load issues, it is desirable to separate the outdoor and indoor calculations. When performing outdoor CFD, it is desirable to set up the analysis model as accurately as possible, in addition to using experimental data for inflow profiles. Outdoor CFD is subject to many factors of divergence, and it is rare to prepare a city block model in which elaborate calculations are performed but to increase calculation accuracy as much as possible, it is possible to obtain data for generic input conditions by preparing an outdoor analysis model for each area and running it to accuracy verification.

In STEP 2, two models are prepared for the calculation of heat flow through walls. If a simplified model is used, it is difficult to represent the actual heat flow and it is preferable to use a detailed model; in STEP3, the detailed model captures the characteristics of heat transport by convection on the interior side.

Solar heat gain is an important factor when considering heat penetration through external walls. Solar heat gain is different in summer and winter due to the difference in sun elevation; a 2D plane cannot capture heat transport in the depth direction, so a detailed analysis is not possible, but 2D heat flow can be considered if certain

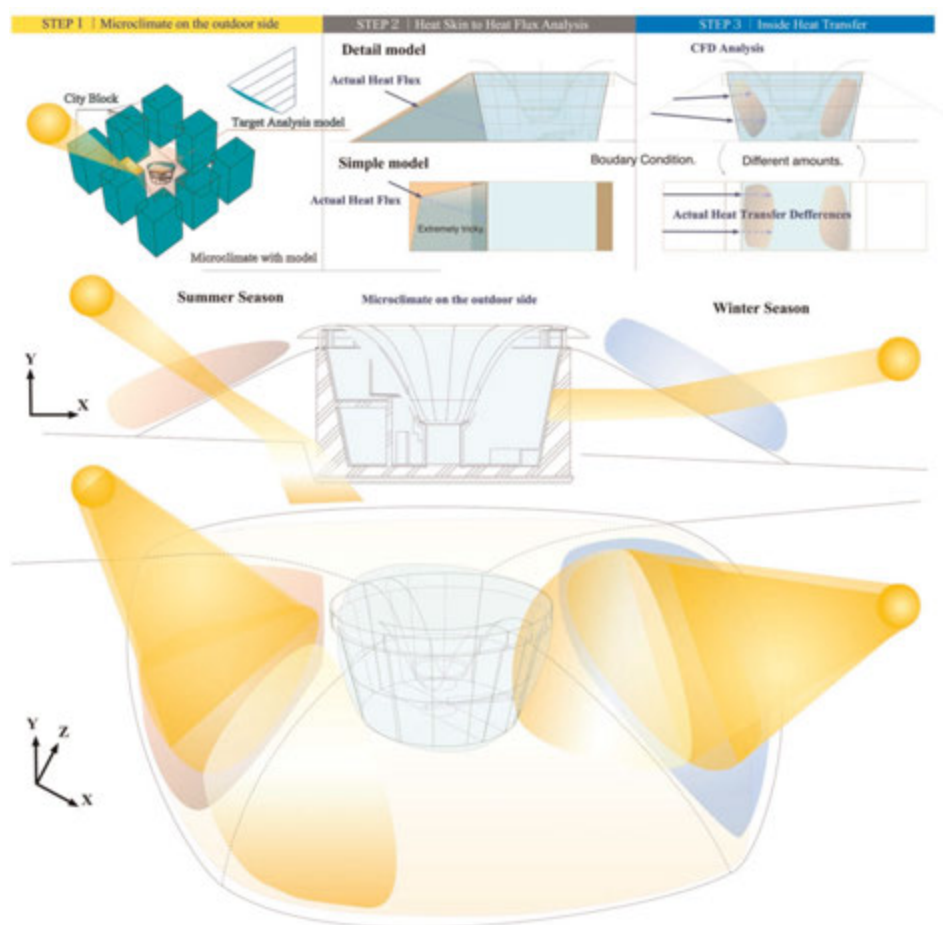


Figure 3.
 Theoretical analysis method. Source: Ref. [35], Figure 3 (Partially extended), Figure 6 (Partially extended and ingenious).

conditions are met, for example, if the external wall receives stable solar heat gain and if there are no buildings outside. However, if the outdoor microclimate is complex, 3D heat flow should be considered. In addition, 3D heat flow is more complex than the senses suggest because it is captured in planes, as shown in the figure. Fortunately, in the analysis model shown in the figure, the embankment is used as the outer wall, so the two-dimensional heat flow is sufficient to achieve sufficient analysis accuracy.

A flow: It should be noted that it is necessary to start the calculation with a heat transfer simulation. First, transient calculations are performed using the occasional outside air temperature and solar radiation as input conditions. If there is no convergence, a 2D heat flow calculation is performed with the room temperature calculated by the heat transfer simulation as input condition. On the other hand, after the second convergence calculation, the building information is not updated, and it is checked whether the residual difference between the room temperature and the indoor surface temperature has decreased sufficiently compared to the previous convergence calculation. If the residuals have decreased sufficiently, the calculation can be stopped.

The calculations should be performed according to the number of divisions in the wall section, and the final residuals should be performed for each division area.

Note that the interior surface temperature is used as an input condition for the heat transfer simulation as it is generally not converged in the first convergence decision. Note that in the initial calculation of the heat transfer simulation, the accuracy of the calculation cannot be expected as only convective heat transfer coefficient values can be used, for example, common values. Although there are mathematical formulae for flow in pipes, such as the profile method, the integral formulae are not generic and can only be used in specific flow fields, so the mathematical formula for convective heat transfer coefficient currently implemented in energy simulation does not ensure the accuracy of the calculation. If the convective heat transfer coefficient value is arbitrarily changed instead of a fixed value, it is easy to generate validation data, and only software that allows modification of the source code, such as open-source software, is considered undesirable for the construction of new computational theory models. Empirically, it is assumed that correct calculation results are more likely to be obtained if values around 4 to 6 are given as initial conditions for all wall bodies. Many existing calculation models have tuning parameters, and without disclosure of these parameters and rigorous double-checking of the back data, the uncertainty of any innovative calculation model for solving the heat transport within the wall cannot be ruled out, even if it emerges. It is not an exaggeration to say that in macro-models the treatment of convective heat transfer coefficients is everything, so it is advisable to use CFD and other methods for more sophisticated calculations.

Finally, although it is preferable to use CFD only for convergence calculations, there is a need to selectively use 2D or 3D depending on the computational load and, as can be seen in **Figure 4**, it is preferable to calculate 3D heat flow with CFD if circumferential heat transfer is considered important. The calculation procedure is not significantly different as the basic approach is to separate the exterior and interior wall and interior sides of the building. Here, the definition of the convective heat transfer coefficient is more important than the accuracy of the calculated convective heat transfer coefficient, but the definition from the SI unit system is ambiguous and a review of the definition is awaited. For example, a unit time resolution of 1 second for heat quantities makes it difficult to capture fine heat flows. In particular, the conversion formulae for calories and joules and their origins are unclear in many areas and it is felt that new definitions will enable truly sophisticated in-wall heat flow calculations.

3. Analytical modeling approach

For example, the zoning in ES should be divided by application, as shown in **Figure 5**. This is because although it accurately reflects temperature irregularities, it is not good at representing temperature stratification, as it is transmitted as a macroscopic heat transfer model. The use of CFD is desirable to represent temperature stratification and convective heat transfer coefficients can be obtained in post-processing depending on the definition, which is important when analyzing buildings with a thermally complex envelope shape with design features that can be completed by supplementing the ES input conditions. When performing a thermal analysis of the building envelope, the modeling of the internal side is an extremely important element, so the adequacy of the zoning is an organic link, considering the internal volume and the shape of the external walls comprehensively.

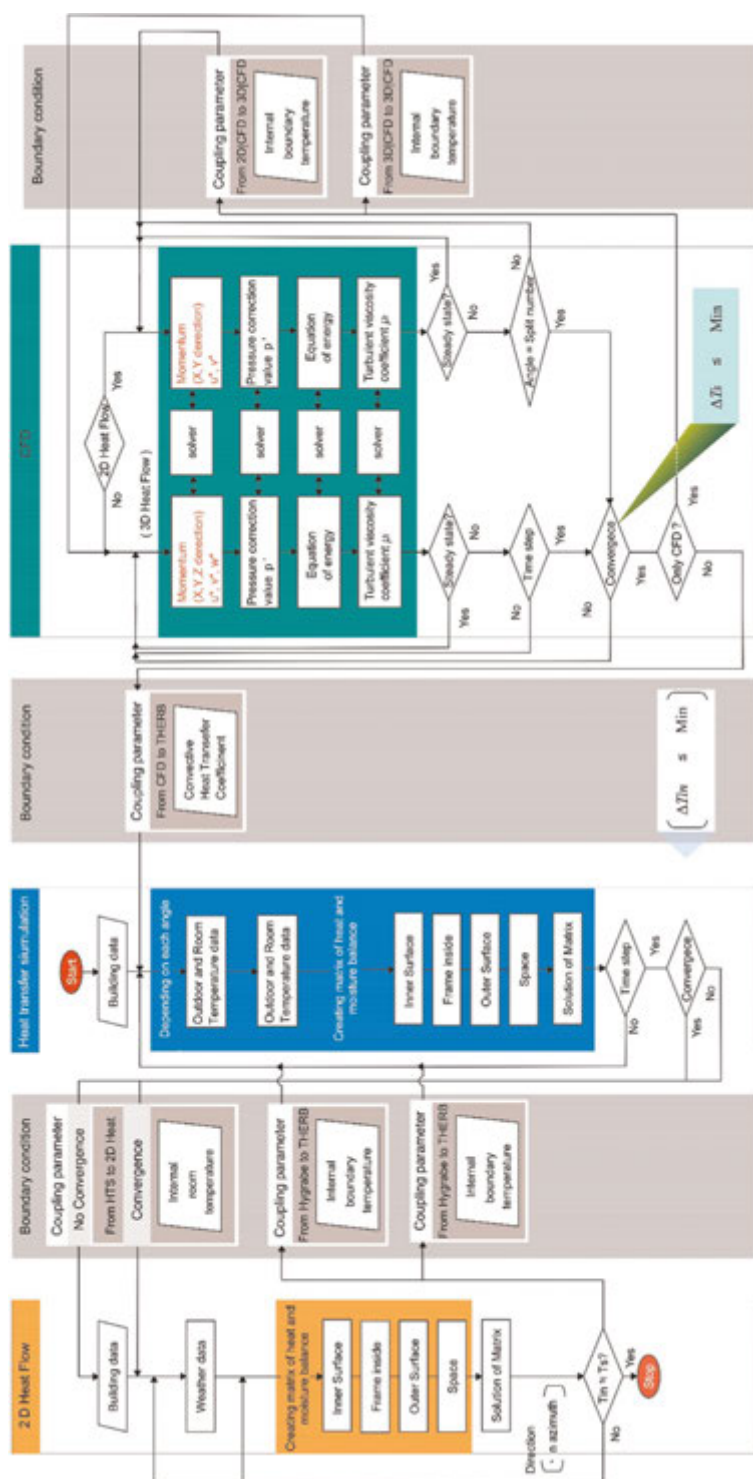


Figure 4.
Theoretical analysis flowchart. Source: Ref. [35], Figure 1 (Partially extended and ingenious).

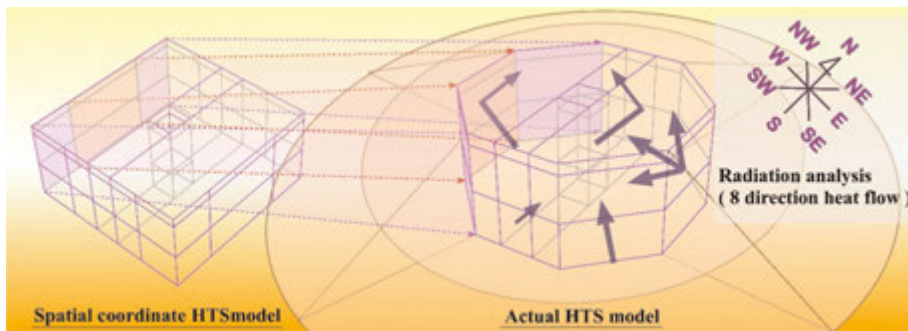


Figure 5.
Heat transfer simulation of zone split (validated radiation analysis). Source: Ref. [35], Figure 2 (Partially extended and ingenious).

For the elaboration of morphological coefficients based on radiometric calculations, attention should be paid to the way the coordinates are taken. The volume of the space should also be set according to the real scale. If the outer walls are conical trapezoidal, as shown in **Figure 5**, the area of the walls should be adjusted, and no errors should be introduced into the analysis. Although this is a more advanced use of heat transfer simulation than the general use of heat transfer simulation, it is recommended that it can be expected to improve the accuracy of the calculations with just a few steps.

The amount of advection between zones is discussed when the space under analysis is divided into zones, as shown in **Figure 6**. However, although the modeling is complex, it is possible to model the macroscopic advection exchange by cutting out the interfaces between zones, applying area integration and obtaining positive and negative flow directions. As far as the influence on the calculation results is concerned, some aspects cannot be ignored, as they are related to the way the supplied heat is transported. Therefore, it would be desirable to also calculate the advection between zones using CFD, but since it is easily output in post-processing, this chapter focuses on convective heat transfer coefficients and advection between zones is not discussed.

For wall heat flow calculations, it is important to have a comprehensive approach that includes external environmental information, and especially how to capture and verify accuracy. We describe how to construct the minimum process, analogous to the verification flow of the theory, as shown in **Figure 7**. In principle, the concept of convergence calculations exists in the field of coupled analysis. In fact, for many new theories, especially in the thermal field, convergence calculations are often required to the extent that they can be considered essential. The choice of initial conditions in many cases does not affect the accuracy of the final analysis obtained, although it is related to the computational load. In practice, a separate convergence decision may be necessary if the interior of the wall is too specialized, but in modern times macroscopic theories are universally used and the use of CFD, for example, is limited to analyses of interior spaces. Convergence of the boundary conditions is considered important. Finally, it should be noted that the minimum process required depends on the measurement points of the actual measurements. In **Figure 7**, the measurement points of the actual measurements were made on the indoor side, so the measurement points were used to study the zonal division of the ES and to construct a reasonable process.

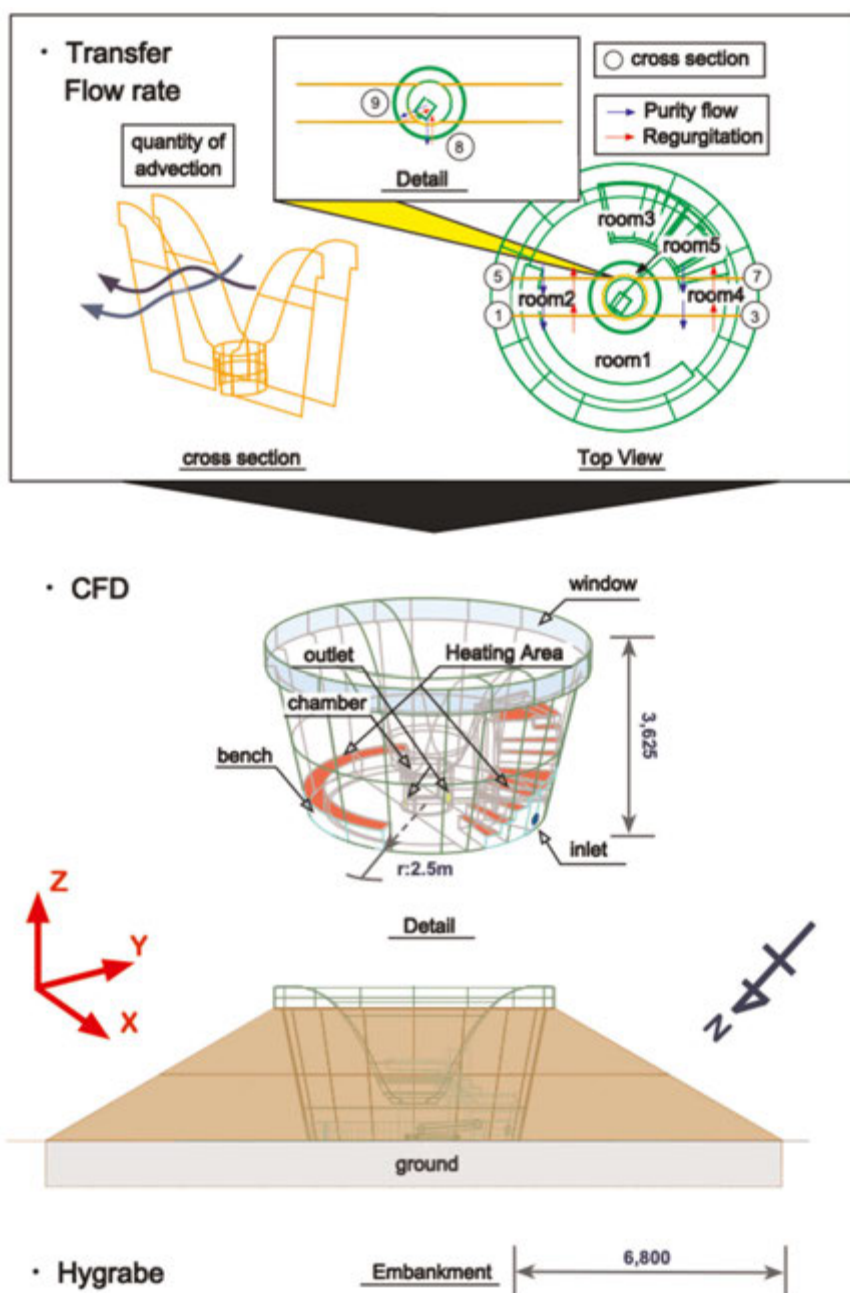


Figure 6.
 Analysis model in detail. Source: Ref. [35], Figure 6 (not modified).

4. Accuracy verification

Based on previous studies [35], this book chapter presents the concept of the various tables and other information corresponding to a thermally complex envelope. First, although it may be assumed that only the heat flow within the wall can be

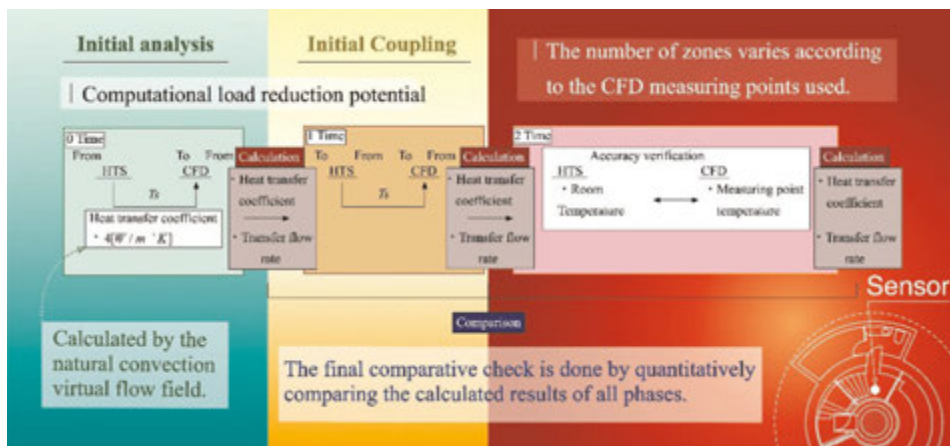


Figure 7.
Coupled flow analysis method with multiple considerations (Based on Ref. [35] modified). Source: Ref. [35].
Figure 7 (Modified and extended).

calculated, this chapter describes a comprehensive analytical approach that includes both the exterior and interior sides.

About the analysis conditions of the ES, the settings are made as shown in **Table 1**, following common practice. On the other hand, the calculation of the building envelope is performed separately, depending on the analysis conditions of the ES, which requires a special twist. Basically, in a typical ES, a standard year (10 years of representative weather data combined into 1 year, e.g., extended AMeDAS weather data) is used for normal walls. The proposed method divides the data into eight directions, but to take account of sunlit and shaded surfaces, the Gebherat absorption coefficients are used.

In principle, there is less needed to consider the external air temperature when the internal side is considered macroscopically, as it also corresponds to the zonal division

Item	Condition (for example)
Date and time of calculation	Year. Month. Day
Calculation area	Any place
Weather prediction	Meteorological Data 10 years (standard year) or Measured values
Air conditioning settings	Natural state or forced
Preliminary calculation days	30 d
Calculated time interval	1 minute or 1 hour or 1 second
Inter-zone advection	Not coupling $n \text{ m}^3\text{h}^{-1}$ Coupling: Enter a CFD value
Internal heat generation	Floor heating

Source: Ref. [35], Table 2 (something case).

Table 1.
Heat transfer simulation computation conditions (Based on Ref. [35] modified).

Item	Condition (for example)	
Turbulence model	k-ε model or something	
Number of meshes	Standard size: n mm $y_+ > 1$ or $y_+ > 5$ (Based on Prandtl's law of wall)	
Boundary condition	Walls and heat sources	THERB surface temperature of the calculated value [K] Velocity: No-slip, $k _{\text{wall}}$: No-slip $\varepsilon_{\text{wall}} = \frac{k^{3/2}}{l_e}$ l_e : length scale function [m]
	Air supply port	Flow rate: $n \text{ m}^3\text{h}^{-1}$, Temperature: n K $k = \frac{3}{2}(Iv)^2$ $\varepsilon = \frac{\rho C_\mu k^2}{(\mu_t/\mu)\mu}$ $I = n$ (calculation or common values) v : wind speed [m/s] C_μ : model coefficient [–] k : kinetic energy [m^2/s^2] I : turbulence intensity [–] ε : Turbulence dispersion rate [m^2/s^3] (μ_t/μ) : vortex viscosity ratio [–]
	Exhaust port	Pressure outlet: n Pa
Analysis software	STAR-CCM+ or ANSYS Fluent (measure software) or something	

Source: Ref. [35], Table 2 (something case).

Table 2.
CFD analysis conditions (Based on Ref. [35] modified).

of the internal side and requires mutual convergence calculations. For example, in the case of a building envelope with a wall as the envelope, due to the thermostatic properties of the wall, the influence of solar radiation on the heat transfer within the wall is more important than the external air temperature, so there is no need for a detailed understanding of the external air temperature. However, as the outside air temperature is strongly influenced by the outside of the block, it is desirable to use meteorological data that reflects the influence of the urban block and include it in the coupled analysis.

There are many physical models available for CFD, and the handling of turbulence models is important. On the other hand, although turbulence models are implemented in many generic tools, STARCCM+ and ANSYS Fluent are the two recommended choices for use in terms of versatility (Table 2). Accepted by many top journals and supported by representative vendors, they should be well-validated by the development team to ensure the quality of the solution. When targeting thermal envelopes with thermally complex design geometries, it is not possible to perform calculations that can withstand the complex geometry of the envelope without separating the interior and exterior sides. This methodology is similar even when using a supercomputer, so it is preferable to calculate the thermal fluid on the interior side using the boundary conditions of the interior surface, as has been done in the past. Ideally, the influence of the outdoor microclimate should be captured in the urban block fluid analysis, the 3D heat flow should be solved by CFD, and finally, the indoor thermal fluid should be analyzed. The mesh sizes required for the exterior and interior walls and interior spaces are different, and if they are not separated and calculated

separately, discussions will diverge, and it will be difficult to perform a high-quality analysis.

5. Conclusions

This chapter is an academic contribution to the calculation of heat flow in walls. Heat flow calculations are now carried out in many fields, such as architecture, mechanics, and medicine, and have a wide range of applications. To carry out truly sophisticated calculations, this study details the points to be considered when carrying out heat flow calculations within the walls of buildings and their significance. The main points are outlined below:

5.1 Coupled analysis significance

When performing coupled analysis, it is important to remember that due to the size of the analysis scale, divergence during the calculation is common. On the other hand, it is generally necessary to divide the analysis scale to avoid divergence during calculations. In this respect, coupled analysis is superior, as it can move back and forth between different macro- and micro-scales, thus addressing many analytical issues.

5.2 Computational load of coupled analysis

A coupled analysis is expected to improve accuracy rather than computational load. On the other hand, a dense-coupled flow also has the potential to reduce the computational load. Therefore, when performing a coupled analysis, efforts should first be made not to reduce the computational load, and priority should be given to computational accuracy. Then, it is desirable to reduce the computational load step by step. However, in non-theoretical phases, there are no major problems in using means to reduce the computational load.

5.3 Adjustment factors in heat flow calculations

In heat flow calculations, heat transport by convection is the most important and the most difficult: When calculating 2D heat flow, it is necessary to carefully consider whether the radial heat flow calculations need to be refined, considering the treatment of solar radiation loads. On the other hand, solving heat transport by convection requires careful consideration of the treatment of turbulence, and although reasonable experience and sensitivity are important, there are cases where the calculations do not need to be as rigorous. However, as databases for design applications are not yet available, decisions should be made with caution.

5.4 Concept of calculation conditions in heat flow calculations

The concept of calculation conditions should be determined based on the theoretical background of the physical model, and experience in research activities is essential for this decision. Although the development of designer-friendly tools is flourishing, it is very difficult to judge the pros and cons of the analysis results without an understanding of the physical model and experience in using the appropriate tools. Therefore, the knowledge and experience required for heat flow

calculations should be supplemented by academic conformity from mastering the subject during postgraduate studies. Attending classes and other courses can be a great help, but they are only an introduction and to learn you need to read the papers and books carefully.

5.5 Scientific questions about a particular calculation theory

Computation theory is a mysterious academic system that can be constructed naturally by unraveling the concept of coupled analysis. Although this chapter deals with coupled analysis as a subject, it is a robust and versatile academic theoretical system, so it would be better to learn it to become familiar with all physical phenomena and anticipate innovative technological developments.

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Declaration of interests

Declarations of interest: none.

Nomenclature

C_p	specific heat of air [J/kg·K]
γ	specific gravity [kg/m ³]
$T_{i,j}$	room temperature of the object element j [K]
$\bar{c}\gamma$	apparent heat-to-volume ratio of a room, including furniture [J/m ³ ·K]
$S_{i,j}$	room area of the object element j [m ²]
$h_{i,j}$	room convective heat transfer coefficient of the object element J [W/m ² ·K]
V_o	amount of ventilation with outside air [m ³ /s]
$c\gamma$	specific heat of air volume [J/m ³ ·K]
q_{wall}	heat flux on the wall [W/m ²]
ρ_f	fluid density [kg/m ³]
$C_{p,f}$	specific heat capacity of the fluid [J/kg·K]
y_c	normal distance of cells near the wall [–]
u_τ	velocity scale based on wall shear stress [m/s]
T^+	dimensionless temperature [–]
y^+_{fluid}	dimensionless distance to the turbulent layer [–]
h_{wall}	convective heat transfer coefficient of the wall surface [W/(m ² ·K)]
q_{wall}	heat flux on the wall [W/m ²]
t_{wall}	temperature of the wall surface [K]
t_{fluid}	fluid temperature [K]
T	temperature inside the wall [K]
q_{solar}	solar heat gain work on the exterior skin [W]

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Perspective Chapter: Expert Opinions on Data-Driven LCA-Based Frameworks for Modular Façade Systems

Luca Morganti

Abstract

This study explores the potential, challenges, and perspectives of data-driven frameworks to enhance environmental impact assessment and promote circular economy practices across the life cycle of modular façade systems. Building on prior research and innovation efforts in the field, semi-structured interviews were conducted with stakeholders representing diverse backgrounds to ensure a wide range of perspectives, including health, safety, and environment (HSE) managers, façade engineers, and software developers. The methodology was organised into three main phases. It began with a preparation phase, followed by the conduct of interviews. During these interviews, previous research findings were presented, leading to a discussion centred on the perceived potential, challenges, and perspectives related to these technologies. Finally, a thematic analysis was conducted to identify the common insights that emerged. The findings emphasise the importance of standardised data models, interoperability between systems, and the role of value chain networking and collaboration in advancing circular economy practices. While not exhaustive, the study provides valuable insights into the evolving landscape of sustainable façade construction and offers recommendations for future developments in LCA-based Frameworks for circular economy integration.

Keywords: expert interviews, eco-design tool, modular façade system, semantic data framework, circular economy, life cycle assessment (LCA)

1. Introduction

The increasing demand for digital tools to support decision-making towards sustainable practices underscores their role in the construction industry's circular and environmentally friendly transition [1–4]. These tools can significantly contribute to guiding stakeholders through complex considerations, including environmental performance assessments, resource optimisation, and lifecycle management [5–7].

On the other hand, modular façade systems (**Figure 1**) have emerged as a promising solution for circular design practices [8–10]. These systems can integrate low-impact materials [11, 12] and energy production technologies [13, 14], can be

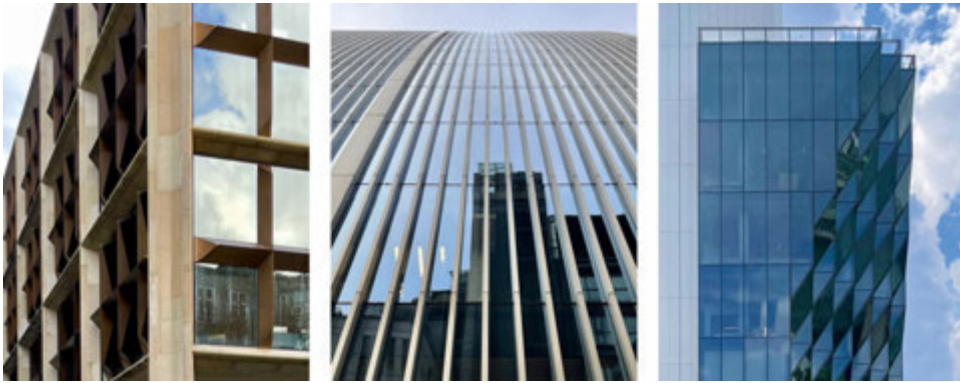


Figure 1.

Different types of custom modular façade systems (Pictures by the Author). From left to right: Bloomberg Headquarters in London (UK), glass and metal modular curtain wall system featured by Permasteelisa Group; 70 ST. Mary Axe in London (UK), fully glazed modular curtain wall with curved glass and external fins by Focchi Group; 40 Tenth Avenue “Solar Carve” Tower in New York (USA), five-panel tridimensional curtain wall modules by Focchi Group.

conceived through design from and for disassembly approaches [15, 16], and are effective for deep retrofitting existing buildings [17, 18]. However, assessing their environmental impact becomes increasingly challenging when such systems are customised due to their inherent complexity and the variability of data inputs.

To address these challenges, data-driven digital tools, models, and frameworks for life cycle assessment (LCA) and circularity assessment of façades are being developed [19–21]. Particularly, concerning custom prefabricated architectural façade modules, frameworks employ digital tools to optimise supply chain data, incorporating primary data from production facilities and other stakeholders that have been designed [22, 23]. Their aim is to enhance resource efficiency, monitor consumption and emissions, and facilitate data-driven decision-making. **Figure 2** represents a

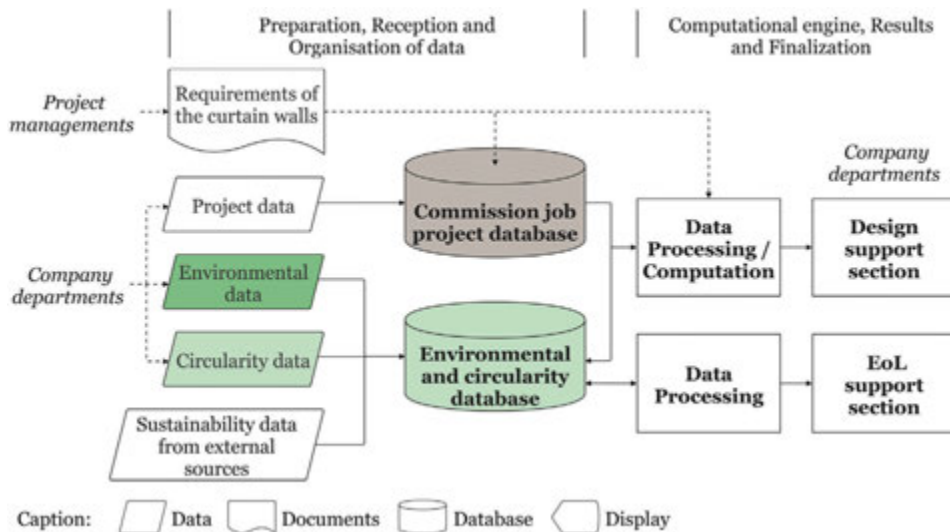


Figure 2.

Flowchart summarising the façade data optimisation processes according to semantic data-driven frameworks – Revised from [22]; EoL section added according to [23].

simplified flowchart of these framework's operations. A notable application is support in creating a Digital Product Passport, which provides essential information for the end-of-life (EOL) management of modular façade systems. Such innovations not only streamline the assessment process but also contribute to process innovation in the construction manufacturing sector.

This article presents the findings from a series of interviews conducted to evaluate the outcomes of two research initiatives within the domain of data-driven frameworks. The first initiative involves an assessment framework developed to support the design stage of custom façade models [22], while the second explores a lifecycle optimisation tool designed to promote circular economy principles [23]. These frameworks incorporate key data collection, processing, and analysis principles to support decision-making in designing and manufacturing prefabricated façade systems.

Central to the framework are three primary data repositories:

- Circularity database, which captures information related to façade components reuse, recyclability, and recovery rates, including data on the composition, modularity, and end-of-life pathways of façade components.
- Environmental database, which focuses on material-specific and process-specific environmental impacts, including embodied carbon, energy use, and emissions throughout the lifecycle stages.
- Project database, which integrates façade design-specific details, such as components, materials quantity, manufacturing, construction, use, and maintenance, enabling contextualisation of environmental and circular data.

Data acquisition is supported by company software systems integration, which provides primary data from manufacturing operations, logistics, and maintenance activities. These datasets are organised and standardised using semantic data models and ontologies, establishing a common framework for data integration and improving consistency and interoperability. Semantic models simplify data collection and analysis while maintaining the accuracy and quality of the results.

The framework also accommodates external service integration to enhance its functionality. For instance, “snag-listing” functions¹ can be employed to comply with regulatory standards and blockchain technology can be utilised to ensure the transparency and traceability of data across the supply chain [23].

Conducting interviews with experts in the field serves to validate the research findings and enhance the framework's relevance to industry practices. By engaging experienced professionals, the research ensures that its methodologies and results are critically evaluated for accuracy and reliability. Experts provide valuable insights into potential limitations, contextual factors such as regulatory or regional considerations, and socio-economic implications associated with adopting circular and environmental data-driven technologies. Lastly, these discussions also foster stakeholder engagement by strengthening the credibility and acceptance of the outcomes within the industry, while uncovering opportunities for practical applications [24].

¹ A snagging list is a document created by the contract administrator during the inspection to confirm the practical completion of the façade installation. This list includes items that require attention but are not significant enough to postpone practical completion.

2. Methodology

The methodology employed for this study consisted of three interconnected phases: the preparation of interviews, the conduct of semi-structured interviews, and the qualitative analysis of the reported content. These phases, depicted in a schema in **Figure 3**, were designed to ensure a thorough and comprehensive evaluation of the frameworks under investigation.

- Preparation of interviews

The preparatory phase began with defining the profiles of participants whose expertise was deemed essential for evaluating the frameworks. These included managers responsible for quality and sustainability, and for health, safety, and environment (HSE) issues in façade manufacturing companies, façade tendering engineers, software engineers and digital product developers, and experts from dismantling and demolition companies. Additionally, industrial R&D and academic professionals engaged in related fields were included to provide a balance of perspectives. Once the profiles were established, experts representing diverse stakeholder groups were contacted.

A presentation outlining prior research results was prepared to facilitate informed discussions. This material highlighted key aspects of the frameworks and was designed to focus the interviews on evaluating their practical applications and limitations.

- Conduction of semi-structured interviews

The interviews were conducted either face-to-face or through video conferencing, employing a semi-structured format that balanced flexibility with focused inquiry. Each session began with a presentation of the research

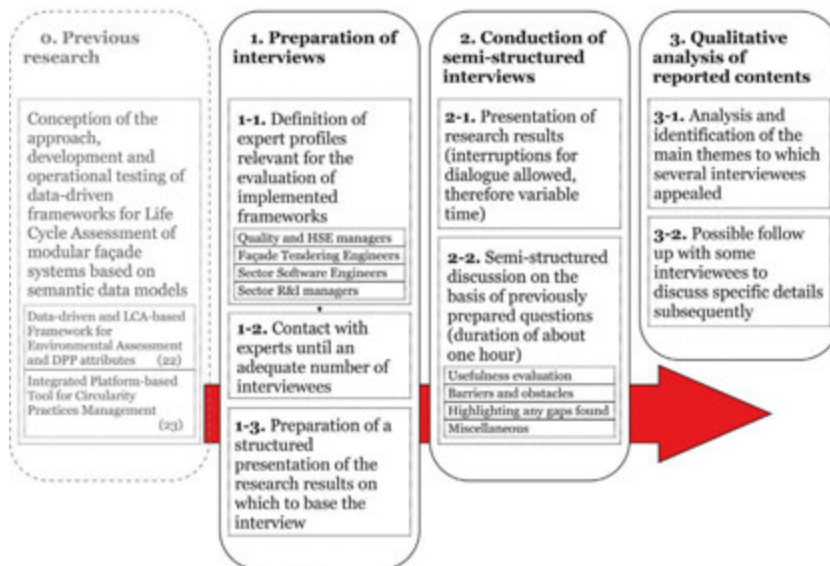


Figure 3.
Methodological schema representing the organised phases.

outcomes, setting the stage for an in-depth discussion. Lasting approximately 1 hour, the conversations explored four main areas: the perceived usefulness of the frameworks, barriers and obstacles to their implementation, gaps in their current design, and additional insights that could enhance their utility. This approach ensured a holistic assessment of the frameworks while allowing participants the freedom to share their expertise and observations.

- Qualitative analysis of reported content

The final phase centred on analysing the qualitative data collected during the interviews. A thematic analysis was executed to associate recurring patterns and themes across the responses. Particular emphasis was placed on commonalities that pointed to systemic issues or opportunities for improvement. Where clarification was required, follow-up discussions with the interviewees were conducted, using detailed notes and observations from the initial interviews to refine and validate the findings. This iterative process ensured the reliability and depth of the analysis.

2.1 Preparation of interviews

A series of semi-structured interviews, each lasting approximately 1 hour, were conducted to explore the advantages and disadvantages of the developed digital tools and to gather feedback from professionals with expertise in the design, manufacturing, and environmental and circular assessment of custom curtain wall façade systems. The digitalisation of supply chain processes for façade systems, particularly from an environmental and circular economy perspective, represents a complex and evolving field. A select group of stakeholders with specialised knowledge in sustainable construction practices were engaged to provide insights into the potential and limitations of the frameworks developed (**Table 1**).

Once the categories of interviewees were established, the subsequent step involved determining what may be a sufficient number of respondents required to ensure meaningful results and, therefore, contacting professionals from each group. Consequently, it is important to elucidate the rationale underlying the definition of the sample size.

While the sample size for interviews may be smaller, prioritising senior expertise over a larger group with less authority or experience is often more effective [25]. Careful selection was made to ensure a diverse range of perspectives, including private sector clients, public sector clients, academics, civil servants, consultants, and researchers. However, there remains some debate about what constitutes an adequate sample size for qualitative research. Many rely on anecdotal evidence or the opinions of experienced researchers, which can be insufficient [26]. According to Dams et al. [25], a smaller sample size is suitable for in-depth interviews and analysis, especially if repeated contact allows for more comprehensive data collection. Additionally, studies show that 94% of key themes can be identified within the first six to eight interviews [27, 28].

Thus, efforts were made to select at least two interviewees per category, ensuring that the total number of respondents reached a meaningful level. However, the Sector R&I Manager category was not adequately represented, as no suitable interviewees were available, and thus, it was excluded from the study's results. HSE and Sustainability Managers from dismantling and demolition companies have not been achieved either.

Position of interviewee profile	Environmental and circularity perspective and experience
Quality and HSE manager	Quality, HSE, and Sustainability Manager in one or more façade manufacturing companies with globally realised projects, and Quality, HSE, and Sustainability Manager from dismantling and demolition companies. They oversee regulatory compliance, lead sustainability strategies, and coordinate projects focused on environmental impact and greenhouse gas (GHG) emissions. They also collaborate with purchasing to ensure sustainability requirements within the supply chain. Minimum of 5 years' experience.
Façade engineer with tendering experience	Studying or having experience as a façade consultant or engineer in international engineering companies, architects, or integrated consultancy firms. Currently working as a tender engineer, involved in checking sustainability requirements at the tender stage, including recycled material percentages and Global Warming Potential (GWP) calculations. Minimum of 5 years' experience.
Sector software engineer and digital product developer	Employed in companies specialising in the development of software tools for sustainable and/or circular supply chains in the built environment. Experience in applied research on decentralised systems for the data economy within the manufacturing industry and in creating trustworthy collaborations across value supply chains. Experience in the construction sector is sufficient, though experience in the façade sector is not necessary. Minimum of 5 years' experience.
Sector R&I managers, professors, or heads of innovation	Qualified researchers specialised in energy efficiency, sustainability, circularity, façade design, and construction. They have experience in coordinating research projects that integrate approaches to decarbonising the built environment and digital processes for analysing façade circularity. Minimum of 5 years' experience.

Table 1.
Categories of professionals likely to provide significant feedback on the results obtained.

Once the interviewees were selected, the preparation of the two research project presentations began. These presentations highlighted the systemic approach aiming to optimise supply chain data for sustainability goals, the operational tools tested and validated within the projects, and the results obtained during the research.

Subsequently, semi-structured interview questions were developed [29] to address various aspects of the frameworks under investigation. The three main questions included in the discussions were:

- *Do you believe tools like these could improve your work or the sector in a more circular and sustainable direction?*
- *What obstacles do you foresee in implementing these systems?*
- *Are there aspects that you think could be useful for future developments but were not considered in the results presented?*

The interviews proceeded with a more open-ended discussion based on these prompts. No recordings were made during the interviews for privacy reasons; only notes and annotations were taken. Unstructured segments were also included, as they were considered valuable for eliciting expert opinions on the theoretical framework. These unstructured elements, characterised by their flexibility and exploratory nature, allowed for deeper insights into the subject [30].



Figure 4.
 Summary diagrams of the interviews. Only the geographical areas of origin are highlighted (states are not indicative).

2.2 Conduction of semi-structured interviews

The research focused on a diverse group of interviewees, all of whom were either based in or possessed relevant work experience within the contexts of Western and Southern Europe or the United Kingdom. Interviews were executed through two primary modalities: face-to-face interactions held in Italy and the United Kingdom and virtual meetings facilitated *via* video conferencing platforms. To safeguard the privacy and confidentiality of the participants, no audio or visual recordings were made during these sessions. However, provisions were established to allow for follow-up communications with interviewees should additional clarifications or insights be required (**Figure 4**).

Interviewees for this study encompassed professionals occupying roles in the context field, including Quality and Health, Safety, and Environment (HSE) managers employed in façade manufacturing companies, Façade Engineers possessing expertise in tendering processes, and Sector Software Engineers. The timeframe for conducting these interviews extended from the autumn of 2023 to early 2024.

2.3 Qualitative analysis of reported contents

Analysis arising from interactions during the project's presentation, responses to questions, and miscellaneous discussions extending from the core questions are presented. Questions progressed in a flexible manner to elicit wider views concerning the current frame within the construction industry and thoughts on furthering the agenda of circular construction. The presentation of results is divided into core sections derived from the discussed topics.

3. Results of the interviews

This chapter presents a discursive synthesis of the key points that emerged from the interviews. The findings are organised based on a reworking of the discussions generated by the three primary questions and subsequent miscellaneous

considerations. As outlined in Section 2.1, the questions aimed to explore the potentials, barriers, and future developments of the systems under investigation. These themes, and the reasoning derived from them, are reflected in the following five sections of this chapter:

- *Potential and Relevance of the Framework*
- *Barriers to LCA and Circular Economy Integration*
- *Practical Requirements for Digital Tools*
- *Critical Issues Arising from Actor Error or Superficiality*
- *Stakeholder Perspectives and Collaboration*

3.1 Potential and relevance of the framework

All interviewees recognised the utility of the proposed digital tools in alignment with the objectives for which they were conceived. The interviewees stated that such tools would have been valuable in addressing work-related challenges they faced in recent years. Moreover, they indicated that similar challenges are expected to become increasingly frequent in the future.

For instance, some interviewees noted that former clients had asked their company to retrieve components and materials from façade modules built in the past, enabling them to assess optimal disassembly and recycling operations. As one HSE manager explained, tools supporting end-of-life processes based on original primary supply chain data would have been useful in such scenarios, especially through the creation of an environmental and circularity database (Interviewee: HSE Manager). These databases, according to the reference research, collect quantitative and qualitative information about the environmental impacts of materials, products, and processes across their lifecycle stages. They also provide data on the design, use, and recovery of materials and components from custom prefabricated façade modules, facilitating reuse, recycling, or repurposing.

Such information is essential for many supply chain stakeholders. The fact that the framework was designed to be viewable by all actors involved in the façade production process garnered approval. This is because not only do design teams in the early and advanced stages need access to such data, but so do procurement and tendering teams. One interviewee noted the potential of expanding this integration so that data within a façade production company's framework could also be accessible by other on-site actors outside the façade company. An example of this potential is the “snag-listing” function, which could be useful not only for façade workers but also for reporting and addressing defects on the façade (Interviewee: HSE Manager).

Additionally, early design actors expressed interest in the tools. One interviewee highlighted how some two-stage tender processes may include a Pre-Construction Services Agreement (PCSA), which outlines contractor responsibilities during the pre-construction phase. This could resemble a consultancy agreement, clarifying whether the contractor will perform design work, assume design liability, and understand the implications if they are not selected for the construction stage. Tools such as those discussed in this study could be useful in predicting supply chain requirements while managing contractual targets and margins (Interviewee: TF Engineer).

Furthermore, having a historical database of environmental impact analyses from previous projects could greatly enhance the efficiency and precision of new bids, particularly during the early design stages (Interviewee: TF Engineer).

To implement circular practices, a shift in perspective is needed to design processes before products. The systemic approach being developed through this framework aims to optimise supply chain data for sustainability objectives, aligning with the right direction for circular construction (Interviewee: Software Engineer).

As environmental certifiers responsible for project reporting, two interviewees emphasised the potential to integrate these tools with broader environmental impact assessments at both the project and company levels. Collecting data on individual façade modules within the framework would be useful for obtaining certifications like LEED, BREEAM, and WELL, which overlap with LCA-measured impacts. Moreover, as companies are increasingly required to report their environmental impact (e.g. ISO standards and GHG protocols), incorporating these elements into LCA data could streamline reporting, especially concerning Scope 1, 2, and 3 emissions [31, 32] (Interviewee: HSE Manager).

The time saved by using these tools is a key economic factor, especially given the time-consuming nature of current practices. Moreover, being able to perform complex environmental analyses may benefit companies during tenders, particularly when dealing with clients who prioritise sustainability certifications (Interviewee: HSE Manager & TF Engineer).

3.2 Barriers to LCA and circular economy integration

Responses to questions about the obstacles to this approach varied, leading to the identification of two key insights: one concerning barriers to LCA and Circular Economy integration and the other regarding the practical requirements that digital tools must fulfil.

Some interviewees expressed concerns that a framework designed specifically for façades might struggle to integrate with frameworks used for other construction systems. While different systems may use distinct keys, their structure should be compatible with other systems to ensure broader applicability (Interviewee: HSE Manager). The importance of using widely accepted standards for data models was emphasised. Adopting standards like OPC UA and semantic web technologies would enable seamless integration across diverse systems, supporting interoperability and data consistency (Interviewee: Software Engineer).

Another issue raised was the challenge of managing data across multiple jurisdictions, particularly for companies operating in several countries with varying regulations and measurement units. For example, environmental data related to transportation might refer to Euro 5–6 trucks in Europe but use the FORS system in the UK (Interviewee: HSE Manager).

3.3 Practical requirements for digital tools

Interviewees suggested several useful features for digital tools that were not initially considered in the development phase. For example, tools could optimise material supply management across multiple projects, improving efficiency and minimising transport-related environmental impacts (Interviewee: HSE Manager & TF Engineer).

Within the environmental database, interviewees recommended expanding the tool to allow for the selection of different functional units for the Embodied Carbon

Factor, for example, kgCO₂eq/UM1 and kgCO₂eq/UM2 available (Interviewee: HSE Manager). This flexibility could replace the manual entry of conversion factors, although it would complicate the dataset and reduce the efficiency of the ontology.

At the end of the design phase, reports should be generated to summarise the environmental aspects of the entire project, which would assist environmental analysts (Interviewee: HSE Manager). Integrating AI interfaces capable of reading and standardising data from multiple formats could enhance this process (Interviewee: Software Engineer).

Additionally, integrating data from snagging lists, non-conformity reports, and site damage reports could help identify critical issues in construction and facilitate their resolution (Interviewee: HSE Manager). It was also noted that training on the new tools would incur costs, which should be carefully considered (Interviewee: HSE Manager).

Finally, there was a concern regarding the limited use of foreground data during on-site operations. For example, collecting accurate data on façade module installation remains challenging. Automating data collection is ideal, but it is not always possible to capture precise data, such as electricity usage at a job site, typically recorded by the general contractor (Interviewee: HSE Manager).

Looking ahead, it is unlikely that building owners or general contractors will manage multiple licences for each construction stakeholder (e.g. façade workers and structural engineers). Therefore, it is essential to consider a system that enables data exchange with centralisers used by owners and contractors (Interviewee: HSE Manager). The standardisation of APIs could facilitate this integration (Interviewee: TF Engineer).

Some interviewees also expressed concerns about the long-term effectiveness of certain data carriers (e.g. barcodes and RFID), suggesting that an integrated digital building logbook within a BIM model would offer greater longevity and reliability (Interviewee: Façade Engineer). Additionally, integrating a Digital Twin of the building with the system could allow for predictive maintenance and specify the quantity of recyclable materials in the building (Interviewee: HSE Manager).

3.4 Critical issues caused by possible actor error or superficiality

It has been highlighted that incoherent actions with the system's logic at crucial points in the framework could threaten the entire structure of the tool. Therefore, it is essential to limit the potential for operators to manage the necessary information to make errors that are incompatible with the semantic logic. For example, to function adequately (and, when possible, automatically), it is critical that manual inputs within PLM, ERP, and BIM systems strictly conform to the defined ontology. For instance, entering data under a different functional unit could compromise the reliability of the results, and failing to include a data point deemed fundamental by the ontology might block the system. Moreover, errors involving different magnitudes could be difficult to identify later, even by an experienced user (Interviewee: HSE manager).

One interviewee, observing the presence of a descriptive entity for façade components labelled as "Other", expressed dissatisfaction with the use of "Others" as a category. From their experience, this encourages external personnel tasked with selecting a category for the reference ontology to select "Others" too frequently, undermining the system's utility (Interviewee: HSE manager).

3.5 Stakeholder perspectives and collaboration

All interviewees highlighted the importance of collaboration within the supply chain to enhance ecological practices throughout the life cycle of façade systems. Sharing the development and use of such systems externally within different companies could, in some cases, prompt clients and lawmakers to update their standards. This could encourage more sustainable production practices and force even more reluctant companies to improve their practices (Interviewee: HSE manager).

It is difficult for a company to push the boundaries of these topics as a promoter without support from norms or explicit market demands. This is also due to the cost and time involved in analyses (Interviewee: HSE manager).

Finally, it was suggested that to enhance the credibility of the results, a third-party accredited and reliable organisation should be responsible for validating the results of the assessments conducted using the framework or for verifying the environmental data collected in the environmental database. This is similar to the case of EPDs (Environmental Product Declarations), which must always undergo verification by an independent third party before being published (Interviewee: TF Engineer) (Table 2).

Theme	Key findings	Insights	Implications
Framework potential	Recognised as valuable for optimising data management, supporting circularity, and enhancing end-of-life processes and early design stages.	Useful for disassembly, recycling, tendering, and sustainability certifications.	Facilitates efficient data sharing, sustainability alignment, and broader applicability across the supply chain.
Barriers to integration	Challenges include interoperability, regional variations, and data consistency across diverse regulatory contexts.	Standardisation through semantic models like OPC UA is necessary. Regional differences in key metrics pose challenges.	Requires standardised data models and adaptability. Integration across stakeholders is critical.
Digital tool requirements	Tools should automate data collection and integrate with BIM or digital building logbooks for predictive maintenance.	Automated reporting and AI-assisted standardisation is a possibility for improvement.	Enhances tool usability, efficiency, and integration with existing construction systems.
Actor errors	Possible data input errors and overuse of generic categories compromise reliability.	Adherence to ontology definitions is fundamental to maintaining system accuracy.	Emphasises the need for training and strict data governance.
Stakeholder collaboration	Collaboration and external validation are essential for the credibility and adoption of circular practices.	Third-party validation ensures trustworthiness. External promotion can influence market and regulatory standards.	Can support systemic adoption and credibility through collective industry action and accredited validation.

Table 2.
Summary of key findings and insights from expert interviews.

4. Conclusion

The interviewees selected for this study were chosen for their relevant expertise and roles within the construction industry, specifically within the domain of modular facade systems design and manufacturing and the integration of circular economy

principles in building practices. The group included professionals with diverse backgrounds, such as HSE managers, façade engineers with tendering experience, and software developers. Their participation provided a comprehensive and multifaceted perspective on the potential, challenges, and future directions of LCA and circular economy digital framework adoption in the façade construction industry.

The discussions revealed significant themes, which provide valuable insights for advancing practices within the industry. A primary point that emerged was the widespread recognition of the value of data-driven tools for improving the environmental and circularity performance of façade systems. Interviewees expressed support for systems that can assist in tracking the lifecycle impacts of materials, optimising procurement strategies, and supporting end-of-life disassembly and recycling. For example, the ability to access environmental and circularity data stored in a central database, which can be used by different stakeholders throughout the supply chain, was highlighted as a critical opportunity for enhancing collaboration and improving decision-making.

Another key finding was the recognition of the importance of collaboration across the supply chain to promote ecological practices throughout the entire lifecycle of façades. Interviewees emphasised that the integration of data and processes between design, procurement, construction, and post-construction phases is essential for advancing the circular economy agenda. They also pointed out that while tools can support sustainability efforts, collaboration amongst all actors in the value chain, including clients, designers, manufacturers, and contractors, is fundamental for realising the potential of these tools.

The interviews also underscored the need for greater standardisation in data models and frameworks to ensure compatibility across different construction systems. Several interviewees raised concerns about the difficulty of integrating LCA tools with other frameworks used in different stages of construction, pointing out the importance of adhering to emerging standards and adopting widely recognised data models, such as OPC UA and semantic web technologies. This is seen to facilitate interoperability and seamless data exchange between various systems used across the construction lifecycle. Furthermore, the need for tools to address different regulatory frameworks and units of measurement across geographical regions was highlighted, stressing the complexity of managing and harmonising data in international projects.

Despite the positive outlook on the potential of data-driven tools, several barriers were identified. Amongst these was the potential for operator error, which could undermine the reliability of the system if the data input is inconsistent or misaligned with the ontological framework. Interviewees noted that ensuring data accuracy and proper alignment with the defined system ontology maintains the tool's integrity.

In terms of practical implementation, the study also highlighted specific requirements for digital tools to be effective. For instance, the ability to manage and optimise the supply chain across multiple projects was identified as a key function that would enhance the utility of these tools. Another significant requirement was the integration of AI capabilities for generating reports and processing diverse data formats, which would help streamline environmental analyses and improve accuracy during the design and construction phases. The inclusion of advanced reporting features, such as visualisations of environmental impacts and operational data from on-site reports, was also emphasised, particularly for identifying potential risks and improving future planning.

The interviews also revealed the importance of training and educating personnel in the construction industry to use these new tools effectively. Given the time-intensive nature of many of the current processes, respondents stressed the economic

and operational advantages of automating data collection and analysis, and the need to invest in training to reduce the potential for error and inefficiency.

Lastly, while many of the interviewees acknowledged the potential benefits of LCA and circular economy integration, there was also recognition that industry-wide adoption will require more than just the development of tools. The alignment of market demands, regulatory pressures, and industry standards will play a significant role in advancing these practices. Several interviewees noted that clients, lawmakers, and certification bodies must update their standards to encourage the widespread adoption of these systems. A recurring theme was that companies, particularly smaller or less proactive ones, are unlikely to adopt these practices unless there is clear market or regulatory pressure to do so.

The study's findings underscore the importance of third-party validation in ensuring the credibility and accuracy of environmental assessments and data. Similar to the process used for Environmental Product Declarations (EPD), which are verified by independent entities before publication, it was suggested that a similar approach could be applied to the data collected in the environmental database of façade systems, enhancing confidence in the results and facilitating broader acceptance.

It is essential to note that the scope of this study was not intended to be fully exhaustive on the topics of LCA and circular economy integration within façade construction. Rather, the goal was to offer meaningful insights and reflections based on the perspectives shared by the interviewees. These reflections point to key opportunities and challenges for further developing tools and frameworks that support sustainable practices, and they highlight the need for ongoing collaboration, standardisation, and innovation in the field. The insights from this study contribute to the ongoing dialogue on the integration of LCA and circular economy principles in the construction industry, and they can help inform future research and development efforts in this area.

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Conflict of interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Informed consent statement

Informed consent was obtained from all participants in this study.

According to the interviewees, detailed information about them is not provided. This is because their working sector and professional profiles have been considered too specific to ensure their anonymity.

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Facade engineering and design is a challenging task that requires the optimal consideration and addressing of multidisciplinary issues and aspects. Over the past 15 years, Facades have become increasingly complex, with dynamic and smart Facades able to adapt to changing temperature and lighting conditions. Newly developed materials and technologies have broadened the scope of Facade functions. This book presents a selection of research contributions to provide a comprehensive overview of Facade design, focusing on material analysis, strategies, and approaches for energy-efficient Facades based on scientific sustainable principles, as well as high-performance requirements such as fire risk and heat transfer, and environmental design and process methodologies. Contributions focus on the development of new strategies for maintaining and designing traditional Facades, as well as the optimal application of new technologies for modern adaptive Facades and building envelopes.

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