engineering proceedings

MDPI

Proceeding Paper

Energy and Climatic Performances of Modern Architecture: A Complete Overview of Building Physics Implications †

Elena Lucchi

Department of Architecture, Built Environment and Construction Engineering (DABC), Politecnico di Milano, 20133 Milan, Italy; elena.lucchi@polimi.it

† Presented at the 1st International Online Conference on Buildings, 24–26 October 2023; Available online: https://iocbd2023.sciforum.net/.

Abstract: The architecture of the 20th century stands as an imperative realm of experimentation. Inside it, the architecture of the Modern Movement emerged from 1900 to 1940, with shapes, features, and materials completely different from pre-industrial buildings, rejecting traditional construction practices, techniques, and materials. Its key design concepts include (i) the "*Form Follows Function*" principle establishing a strict relationship between building aesthetics and function, favoring minimalism, balanced composition, and visible materials; (ii) the creation of comfortable and healthy buildings with natural light and ventilation through windows, biophilia, and spacious rooms; and (iii) advancements in engineering enabling novel design possibilities (e.g., metal-framed curtain walls, complex windows) and mass-produced materials (e.g., glass, steel, reinforced concrete, plywood, Masonite, and cast iron). These criteria directly influence energy efficiency and human comfort. Otherwise, technical problems have emerged due to inadequate comprehension of the long-time performance of these experimentations, leading to deterioration and aging. This research provides a complete overview of the energy and climatic performances of Modern Architecture, discussing the building physics implications of the key design principles through several case studies.

Keywords: energy performance; energy audit; energy simulation; energy retrofit; Modern Architecture; building materials

check for updates

Citation: Lucchi, E. Energy and Climatic Performances of Modern Architecture: A Complete Overview of Building Physics Implications. *Eng. Proc.* **2023**, *53*, 19. https://doi.org/10.3390/IOCBD2023-15203

Academic Editor: Alessandro Cannavale

Published: 24 October 2023

Copyright: © 2023 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Cultural heritage is universally recognized as a driver for sustainable development and energy transition, thanks to its role in transmitting cultural identity, creativity, and economic expansion [1]. This discussion has ignited deep-seated political and cultural discourses that have encompassed the improvements in energy and climatic performance of these buildings [2]. Nonetheless, an unregulated adoption of the current legislation could jeopardize the preservation of heritage. To safeguard architectural values, it becomes essential to evaluate the possible trade-offs between conservation, energy generation, and climatic comfort [3]. Numerous countries have formulated guidelines and policies for improving the energy and climatic performances of heritage buildings and towns. These documents primarily focus on historical buildings, often leaving 20th-century structures in the background. Inside them, three architectural styles can be identified [4]:

- *Post-industrial Architecture is* constructed using traditional shapes and materials.
- *Modern Architecture is* built using materials, styles, and forms in contrast with the past.
- *Post-war Architecture is* composed of diverse architectural styles that require tailored and not generalizable rules.

While energy and environmental performances of post-industrial and post-war architecture have garnered extensive attention in the literature, Modern Architecture remains relatively underexplored [4]. These studies primarily center on specific buildings, where a meticulous examination of their historical context and current state of conservation precedes the proposal of energy retrofit interventions [5]. Consequently, the investigation of such examples is particularly valuable for formulating a comprehensive theoretical framework for understanding the energy and climatic performance of Modern Architecture that considers specific needs and building physics implications associated with the key design principles of these buildings.

2. Energy and Climatic Performances of Modern Architecture

The term Modern Architecture delineates an architectural style that emerged within the socio-cultural and artistic context of Modernism. It was prominent from 1900 to 1940, emphasizing experimentation, the rejection of established norms, and liberation from traditional artistic and architectural conventions. Throughout time, it proliferated globally, adapting to regional variations aligned with local requirements and design sensibilities. Despite this, several key design principles can be recognized [5]:

- *Architectural geometry*, prioritizing a balance between aesthetics and utility, effective functionality, flexibility, modularity, and attention to detail. This concept aligns with minimalism, embracing compact shapes, simple geometries, clean lines, rational forms, and the absence of ornamentation. This philosophy contrasts with traditional buildings, which are characterized by complex shapes and rich decorations.
- *Transparency*, creating comfortable, healthy, and hygienic indoor environments through natural light and air ventilation. These differences are particularly evident when compared to post-industrial buildings, which often featured limited daylight, small windows, and cramped rooms.
- *Connection with nature*, establishing a profound correlation between buildings and natural environments through proper orientation, vegetation, water, and biophilia.
- *Industrial and mass-produced technologies*, hinging on the utilization innovative materials (e.g., glass, steel, reinforced concrete, cast iron, plywood, and Masonite) and building elements (e.g., curtain walls, horizontal ribbon windows).

3. Building Physic Implications of Key Design Principles of Modern Architecture

These design principles have a significant influence on the energy and climatic performance of such buildings, creating new challenges, particularly concerning energy efficiency and human comfort. Their building physics implications are discussed below to offer a comprehensive overview of the interconnected issues that may arise.

3.1. Architectural Geometry

Architectural geometries play a crucial role in shaping the energy efficiency of buildings. One advantage of the compact shape of Modern Architecture is the low surface-to-volume ratio (S/V) factor that minimizes heat losses [5]. Unfortunately, the presence of pure geometries has also given rise to a series of preservation issues related to the absence of protective components, such as shielding ridges and overhangs for safeguarding cladding and window frames. Their absence has resulted in inefficient drainage, water infiltration, and the corrosion of frames. These phenomena also impact the energy performance of the building, as the presence of interstitial moisture leads to a decrease in the thermal transmittance (U-value) of the walls. These factors have led to tensions between the panels and the supporting surface and, in some cases, the corrosion of metal strip anchors [6]. A similar effect occurs in the absence of projecting roofs, which expose the façade to surface wash-off effects, resulting in a decrease in energy performance [6] (Figure 1). Flexibility in layout design is closely linked to the reduction in wall and slab thickness compared to historical architecture. This reduction was possible thanks to the mechanical properties of new materials, especially concrete and metals [4]. As a result, thinner elements contribute to lower U-values compared to their traditional counterparts. On average, modern wall thickness ranges from 0.25 to 0.30 m, which is significantly less than the 0.35 to 1 m thickness of traditional architecture [7].

Figure 1. Conservation issues related to the metaphysical geometries of the Municipal Building of Corridonia designed by Pirro Francalancia and Giuseppe Marrani (1936), Italy (Source: Municipality of Corridonia).

Additionally, many industrial materials have a higher thermal conductivity (λ-value) compared to traditional materials (Section 3.4) [7]. The combination of these factors, along with the absence of thermal insulation, leads to substantial heat losses during colder seasons. Furthermore, the strategic placement of radiators beneath windows, while potentially beneficial for space utilization, can lead to higher heat losses associated with thin walls and ventilation losses through glass surfaces [4]. On the other hand, there is an improvement in thermal comfort due to the increasing average radiant temperature resulting from convective air currents generated by radiators positioned beneath windows. The building physics implications of architectural geometry are synthesized in Table 1.

Table 1. Building physics implications of architectural geometry in Modern Architecture for energy and climatic performance (Source: author's elaboration).

Principle	Description	Building Physics Implications for Energy and Climatic Performance	
		Positive Aspects	**Negative Aspects**
Form Follows Function	Design of simple and rational shapes to enhance the relationship between aesthetics and functionality.	Low S/V factor.	Reduction in the thermal performance of external walls due to leaching and internal moisture.
		Reduction in heat losses (cold seasons) and minimization of excessive heating and cooling (hot seasons).	Inefficient drainage, water infiltration, and corrosion of frames due to the absence of protective components
Modularity and flexibility	Adaptable spaces to support evolving needs.	Absence of material thermal bridges on the façades due to the separation of the structures from walls.	-
		Absence of heat losses with the ground due the presence of pilotis.	Thermal bridges between slabs and pilotis.
Absence of ornamentation	Emphasis on the inherent beauty of traditional construction materials.	High thermal inertia of traditional materials (e.g., brick or wood veneer façades).	Reduction in the thermal performance of new materials due to internal moisture or water (e.g., concrete and Masonite),
			Reduction in the thermal performance of walls due to the rising damp associated with the absence of building bases.
			Presence of thermal bridges (e.g., stone slab façades).
Attention to detail	Attention to building design and construction.	Attention to construction details (e.g., complex windows and vapor barriers).	-
		Attention to construction phases.	

3.2. Transparency

Transparency entails utilizing natural light and ventilation to create comfortable and hygienic indoor conditions. Achieving transparency was accomplished using various window types, glass blocks, and curtain walls. In the first case, modern windows utilize all available opening motions, including folding, pivoting, tilt, tilt-and-turn, up, down, or horizontal sliding [5]. Meticulous design attention is given to making these openings distinctive façade elements [8]. Casement and awning windows are also deployed to allow internal lighting while also minimizing air exchange. During this period, Le Corbusier introduced the horizontal ribbon windows, which featured long and narrow horizontal opening extending across the façade. This design choice was frequently employed to maximize natural light and provide panoramic views, establishing a direct connection with the surroundings (Section 3.3). All these windows typically featured single-panel glass with reduced thickness (0.004–0.005 m) and a U-value of 5.7–5.8 W/m^{2}K. Metal frames were commonly used to maximize the glass surface area and provide design flexibility (average U-value 5.8 W/m^{2}K) [7]. Wooden frames, occasionally paired with double windows, found use primarily in colder climates and residential buildings (average U-value of 2.0–2.5 W/m^{2}K) [7]. The limited thermal performance of both the glass and frames significantly impacts the energy efficiency of the glazing system and façades. It's worth noting that glass surfaces covered approximately 40–60% of the façade, which had clear implications for heat loss in the building envelope. Translucent glass block walls with a U-value of 1.8–2.0 W/m^{2}K present another option. Additionally, curtain walls were constructed using lightweight materials such as glass, aluminum, or steel [6]. They were primarily used in commercial or high-rise buildings to achieve transparency, leverage natural light, and establish a connection with nature. Calculating the average U-value in this context is indeed challenging, as it depends on the materials, proportions, and geometry involved. In all cases, various methods were employed to reduce heat gains, including solar shading systems, float glasses in combination with internal or external blinds, or curtains (Figure 2).

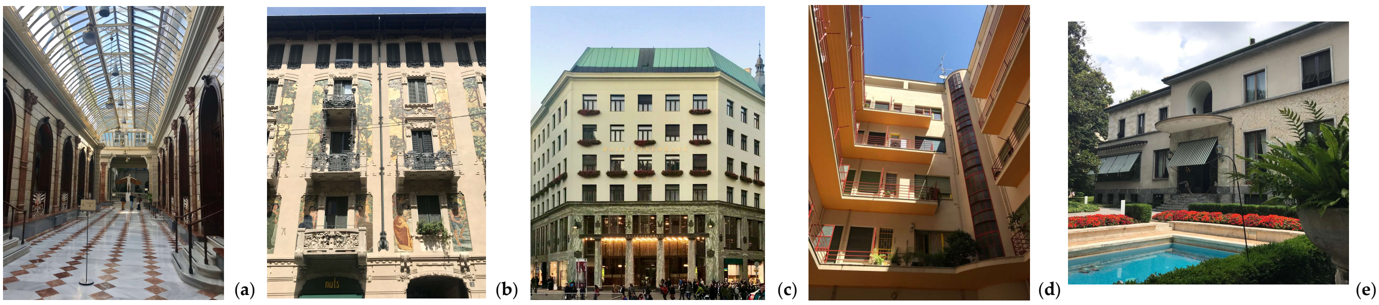

Figure 2. Different typologies of transparent envelope in modern buildings: (**a**) Real Casino de Murcia by Pedro Cerdan Martinez (1902); (**b**) Casa Galimberti in Milan by Giovan Battista Bossi (1906); (**c**) Looshaus in Vienna by Adolf loos (1912); (**d**) Novocomum in Como by Giuseppe Terragni (1928-29); (**e**) Villa Necchi Campiglio in Milan by Piero Portaluppi (1932), Italy (Sources: Elena Lucchi).

While this practice reduces energy consumption for artificial lighting and enhances visual comfort, the presence of numerous glazed surfaces also increases heat transmission losses through the building envelope. Furthermore, while transparency helps reduce cooling demands, it can contribute to ventilation losses. A related aspect is associated with the selection of artificial lighting systems, which aim to enhance the quality of natural light. This involves selecting light sources with a neutral color temperature and maximum color rendering. The building physics implications of transparency are synthesized in Table 2.

Table 2. Building physics implications of transparency in Modern Architecture for energy and climatic performance (Source: author's elaboration).

Principle	Description	Building Physics Implications for Energy and Climatic Performance	
		Positive Aspects	**Negative Aspects**
Transparency	Use of natural light and ventilation to create comfortable and healthy indoor conditions.	Reduction in energy consumption for artificial lighting.	Low thermal performance due to glazed surfaces.
		Daylighting and high quality of light (white light).	High transmission losses from the building envelope.
		Proper ventilation rates.	High ventilation losses from windows.
			Cooling loads during hot seasons.

3.3. Connection with Nature

A balance must be struck when incorporating natural elements. The presence of plants can mitigate overheating in hot seasons, also contributing to the thermal loads' reduction, thermal regulation, and air filtration [4]. This strategy might generate an excessive decrease in sunlight and heat gains during colder periods. Moreover, the introduction of additional thermal insulation via vegetation layers offers thermal advantages. Another benefit is the attenuation of indoor and outdoor thermal fluctuations through the heat absorption of water and green areas. Conversely, this strategy may lead to an excessive reduction in sunlight and heat gains during colder periods while also cutting the amount of natural light due to shading. Furthermore, vegetation-induced moisture retention could impact the thermal performance of building materials (Section 3.4). The building physics implications of biophilia are synthesized in Table 3.

Table 3. Building physics implications of connection to nature in Modern Architecture for energy and climatic performance (Source: author's elaboration).

Principle	Description	Building Physics Implications for Energy and Climatic Performance	
		Positive Aspects	**Negative Aspects**
Connection with nature	Connection with nature through correct orientation and biophilia to generate a profound relationship with buildings and their surroundings.	Thermal regulation through greenery.	Overcooling due to vegetation that can increase the need for heating.
		Reduction in summer thermal loads through shading (e.g., hot seasons).	Excessive reduction in sunlight and heat gains due to shading (e.g., cold seasons).
		Additional thermal insulation generated by vegetation layers.	Reduction in natural light due to vegetation.
		Reduction in indoor and outdoor thermal fluctuations through heat absorption of water and green areas.	Reduction in the thermal performances of building materials due to moisture retention generated by vegetation.
		Air filtration by greenery that improves indoor and outdoor air quality.	Aging and low durability of building materials due to moisture retention.

3.4. Industrial and Mass-Produced Technologies

The energy and climatic performance of modern materials significantly differ from traditional ones, particularly concerning aspects like thermal insulation, thermal phase shift, durability, and maintenance [4]. In many cases, industrial materials such as concrete, glass, iron, cast-iron, and plywood exhibit have lower thermal performance compared to traditional bricks and wood [7]. Additionally, they often have limited thermal inertia, which hinders the exploitation of potential benefits related to thermal phase shift and thermal attenuation found in traditional materials [7]. Conversely, enhancing the aesthetic features inherent in traditional materials can contribute to addressing these challenges. This can be observed, for example, when employing brick veneer walls. The limited understanding of the potential of these materials, especially during the early years of Modern Architecture, has led to widespread degradation, particularly when associated with aging and moisture [9]. This degradation affects both the thermal and hygrometric performance of these materials. Issues such as leaching from non-overhanging roofs, which can compromise the thermal performance of façades, underscore the importance of comprehensive design details. Major problems include the corrosion of metal frames (Section 3.2), the reduction in the U-value of concrete, Masonite, and plywood due to internal moisture, and the dissimilar thermal expansion between architraves and stone cladding due to rising damp. The building physics implications of biophilia are synthesized in Table 4.

Table 4. Building physics implications of the use of industrial and mass-produced technologies in Modern Architecture for energy and climatic performance (Source: author's elaboration).

Principle	Description	Building Physics Implications for Energy and Climatic Performance	
		Positive Aspects	**Negative Aspects**
Industrial and mass-produced technologies	Experimentation with industrial materials, techniques, and building elements.	High thermal phase shift of new (e.g., Masonite, cast iron) and traditional (e.g., brick, wood) materials.	Low thermal performance of new materials (e.g., concrete, glass, steel, and iron).
			Reduction in thermal performance of hygroscopic materials due to moisture (e.g., plywood and reinforced concrete).
			Thermal bridges in innovative systems (e.g., metal-framed curtain walls and reinforced concrete structures).
			Absence of thermal insulation.
			Different thermal expansion of architraves and stone cladding.
	Reduced thickness of the slab and walls.	Lightweight of the technical systems.	Reduction in thermal performance due to reduced thicknesses of walls and slabs.
			Increase in heat losses due to radiators beneath windows (linked also to the reduction in wall thickness).

4. Conclusions

The energy and climatic performances of Modern Architecture differ significantly from traditional architecture, introducing new conservation and environmental challenges. Despite the presence of several common key design principles, architectural experimentation necessitates specific diagnostic procedures and targeted interventions for each building. Therefore, this study aims to provide guidance to assist conservators and designers during the energy retrofit process, with the goal of balancing heritage preservation, energy savings, and human comfort. To this purpose, clear rules of building physics were proposed to address the evolving conservation and environmental challenges posed by Modern Architecture.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No data available.

Conflicts of Interest: The author declares no conflict of interest.

References

1. United Nations (UN). *Paris Climate Agreement*; UN: Paris, France, 2015.
2. Potts, A. Executive Summary. In *European Cultural Heritage Green Paper Executive Summary*; Europa Nostra: The Hague, The Netherlands; Brussels, Belgium, 2021.
3. Lucchi, E.; Baiani, S.; Altamura, P. Design criteria for the integration of active solar technologies in the historic built environment: Taxonomy of international recommendations. *Energy Build.* **2023**, *278*, 112651. [CrossRef]
4. Flaman, B.; McCoy, C. *Managing Energy Use in Modern Buildings: Case Studies in Conservation Practice*; Getty Conservation Instutute Publication: Los Angeles, CA, USA, 2021.
5. Barber, D.A. *Modern Architecture and Climate: Design before Air Conditioning*; Princeton University Press: Oxford, MS, USA, 2020.
6. Stazi, F.; Mugianesi, M.; Munafò, P. Recommendation for restoration of Modern buildings with stone cladding and steel windows: A multi-disciplinary approach on a significant case study. *Constr. Build. Mater.* **2012**, *37*, 728–737.
7. Nardi, I.; Lucchi, E. In situ thermal transmittance assessment of the building envelope: Practical advice and outlooks for standard and innovative procedures. *Energies* **2023**, *16*, 3319. [CrossRef]
8. Buda, A.; Mauri, S. Building survey and energy modelling: An innovative restoration project for Casa del Fascio in Como. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W11*, 331–338. [CrossRef]
9. Martín-Garín, A.; Rodríguez-Vidal, I.; Otaegi, J.; Rico-Martínez, J.M.; Millán-García, J.A.; Senderos Laka, M.; Lucchi, E. Hygrothermal Performance Analysis of Building Components and Materials. A Tool for Energy Refurbishments Assessments. In *Building Engineering Facing the Challenges of the 21st Century*; Bienvenido-Huertas, D., Durán-Álvarez, J., Eds.; Lecture Notes in Civil Engineering; Springer: Singapore, 2023; Volume 345.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.