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

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Abstract: 20th Century architecture 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; and (ii) 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 long-time performances of these experimentations, leading deterioration, and aging. This research provides a complete overview of energy and climatic performances of the Modern Architecture, discussing 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.

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1. Introduction

Cultural heritage is universally recognized as 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 has encompassed the improvement of 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* constructed using traditional shapes and materials.
- *Modern Architecture* built using materials, styles, and forms in contrast with the past.
- *Post-war Architecture* composed by diverse architectural styles, which require tailored and not generalizable rules.

While energy and environmental performances of post-industrial and post-war architecture have garnered extensive attention in 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, 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 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 trough 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 compared particularly concerning energy efficiency and human comfort. Their building physics implications are discussed below, to offer a comprehensive overview 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 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). The 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 of concrete and metals [4]. As a result, thinner elements contribute to lower the U-values compared to their traditional counterparts. On average, modern wall thickness ranges from 0.25 to 0.30 m, 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 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. Building physics implications of architectural geometry are synthesized in Table 1.

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

Principle	Description	Building physic 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 of thermal performance of external walls due to leaching, and internal moisture
		Reduction of 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 slab 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 of thermal performances of new materials due to internal moisture or water (e.g., concrete, Masonite)
			Reduction of thermal performance of walls due the rising damp associated to 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, 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, 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^2K. Metal frames were commonly used to maximize the glass surface area and provide design flexibility (average U-value 5,8 W/m^2K) [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^2K) [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^2K 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 aimed to enhance the quality of natural light. This involves selecting light sources with a neutral color temperature and maximum color rendering. Building physics implications of transparency are synthesized in Table 2.

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

Principle	**Description**	**Building physic implications for energy and climatic performance**	
		Positive aspects	**Negative aspects**
Transparency	Use of natural light and	Reduction of energy consumption for artificial lighting	Low thermal performance due to glazed surfaces

	ventilation to create comfortable and healthy indoor conditions	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 excessive decrease of 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 of sunlight and heat gains during colder periods while also cutting the amount of natural light due to shading. Furthermore, vegetation-induced moisture retention that could impact on the thermal performance of building materials (section 3.4). Building physics implications of biophilia are synthesized in Table 3.

Table 3. Building physics implications of key design principles of Modern Architecture for energy and climatic performance (Source: Author's elaboration)

Principle	**Description**	**Building physic 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 surrounding	Thermal regulation through greenery	Overcooling due to vegetation that can increased need for heating
		Reduction of summer thermal loads through shading (e.g., hot seasons)	Excessive reduction of sunlight and heat gains due to shading (e.g., cold seasons)
		Additional thermal insulation generated by vegetation layers	Reduction of natural light due to vegetation
		Reduction of indoor and outdoor thermal fluctuations through heat absorption of water and green areas	Reduction of 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 differs 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 of 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. Building physics implications of biophilia are synthesized in Table 4.

Table 4. Building physics implications of key design principles of Modern Architecture for energy and climatic performance (Source: Author's elaboration)

Principle	Description	Building physic implications for energy and climatic performance	
		Positive aspects	**Negative aspects**
Industrial and mass-produced technologies	Experimentation of 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, iron)
			Reduction of thermal performance of hygroscopic materials due to moisture (e.g., plywood, reinforced concrete)
			Thermal bridges in innovative systems (e.g., metal-framed curtain walls, reinforced concrete structures)
			Absence of thermal insulation
			Different thermal expansion of architraves and stone cladding
	Reduced thickness of slab and walls	Lightweight of the technical systems	Reduction of thermal performance due to reduced thicknesses of walls and slabs
			Increase of heat losses due to radiators beneath windows (linked also to the reduction of 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.

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