Energy and comfort. The historical evolution of the façade in Western Architecture

Energía y confort. La evolución histórica de la fachada en la arquitectura occidental

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Abstract: The envelope is considered to be the boundary between the outside and the inside of a building. The aim of this study is to analyze both the process that led the concept of the façade to evolve in Western architecture and the repercussions of such evolution, focusing on energy consumption and comfort. The entire evolution of the façade has been closely related to the evolution of materials and construction technologies. The comfort and energy characteristics of architecture have always been determined by the materials and construction technologies employed in façades. Architecture has improved in technical aspects, especially in terms of lighting and thermal comfort. Nevertheless, thermal comfort is usually linked to energy consumption, which is the parameter that has increased the most in this development, with the only exception being sustainable architecture.

Keywords: Envelopes; development of façades; history of construction; technical advances in façades; review of façades.

Resumen: La envolvente se considera el límite entre el exterior y el interior de un edificio. El objetivo de este estudio es analizar el proceso que llevó a la evolución del concepto de fachada en la arquitectura occidental y las repercusiones de dicha evolución, centrándose en el consumo energético y el confort. Toda la evolución de la fachada ha estado estrechamente relacionada con la evolución de los materiales y las tecnologías de la construcción. El confort y las características energéticas de la arquitectura siempre han estado determinados por los materiales y tecnologías de construcción empleadas en las fachadas. La arquitectura ha mejorado en aspectos técnicos, especialmente en términos de iluminación y confort térmico. Sin embargo, el confort térmico suele estar ligado al consumo de energía, que es el parámetro que más ha aumentado en esta evolución, con la única excepción de la arquitectura sostenible.

Palabras clave: Envolvente; desarrollo de la fachada; historia de la construcción; avances técnicos en fachadas; revisión de fachadas.

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INTRODUCTION

The envelope is considered to be the boundary between the outside and the inside of a building. The components that define the envelope are classified into façade systems, roof systems, and underground systems. However, there are examples of contemporary architecture whose structure is complex and the division between the elements of the envelope is blurred, making it impossible to distinguish them clearly.

The envelope is a membrane that influences the relationship of a building with the environment and thus has two essential functions. The first is a performance function, which is understood from a technical point of view. Architecture arises with the technical function of protecting us from severe weather and the dangers of nature, with there even being architecture that adapts to climatic conditions.[1] The envelope is the face that people see, which is why the façade in architecture also has a great component of symbolism;[2] noted through different typologies that boast the status of the inhabitants within and the façade, thus being fundamental for the construction of the city.[3]

The envelope has additional inherent functions (such as light and energy exchange, indoor comfort,[4] and, more recently, sustainability criteria,[5] among others), which could be integrated into the performance function. Human needs, to which architecture must adapt, require an exchange with the outside environment. The envelope, being the boundary between these two worlds, must combine both conditions of refuge and exchange, which will sometimes contradict each other.

Therefore, construction materials are decisive when understanding the envelope. The evolution of materials implies an evolution of envelopes and their development goes hand in hand. Consequently, the typologies of buildings are linked to the technological advances of their time. Moreover, the symbolic character of the envelope, but mostly the façade, is expressed through the use of the most updated technical advances available at each historical moment.[6] These advances are at the forefront of all different architectural styles and have always been associated with advances in constructive possibilities.[7]

The goal of this work is to analyze both the process that led the concept of the façade to evolve into an envelope and the repercussions of this paradigm shift, with a focus on energy consumption and comfort. There are no scientific studies that fully dedicate to analyzing the chronological evolution of the façade by considering factors such as materiality, energy consumption, and comfort. However, a study carried out by Heidari Matin and Eydgahi,[8] have developed historical research on responsive façades. It is essential to understand the evolution of history in order to visualize the present with an adequate view of the past.[9] The evolution of these factors is not the same throughout the world, although they develop in parallel in diverse cultures.[10] In this work, due to the extent of the topic and the difficulty of discussing it, we will focus on Western architecture, highlighting the case of Europe.

METHODOLOGY

For this study, we used a systematic bibliographic review in which we prioritized impact journals and drew on documents in the field of architecture.[11] As there is also an historical element to this research, we have also resorted to old manuals on construction techniques.

For the subsequent analysis of the evolution of energy consumption and comfort,[12] the following aspects were evaluated:

- Energy consumption in manufacturing
    - Distance of the material to the construction site
    - Quantity of the material used in construction
    - Generation of construction materials

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- Energy consumption in usage
  - Average temperature difference between indoors and outdoors
  - Permeability of the enclosure
  - Thermal characteristics of the construction systems
  - Systems used for heat generation
  - Frequency of use of air conditioning systems (only in modern times)

- Thermal comfort
  - Average temperature difference between indoors and outdoors
  - Permeability of the enclosure
  - Frequency of use of air conditioning systems (only in modern times)
  - Comfort expectations
  - Textiles

- Lighting Comfort
  - Ratio of the surface of the openings to the surface of the façade

A timeline and a summary table are presented with the characteristics of the architecture from each historical period. In these tables, the buildings that could be considered typical of each historical period have been included and exceptional buildings have been excluded.

With regard to terminology, we use the term *façade* to refer only to the exterior vertical walls and the term *envelope* when referring to the set of all exterior surfaces or in the case of buildings where there is no clear division between the façade and roof. We will also use the term *vertical envelope* as a synonym for façade.

OPAQUE MATERIALS AS A SKELETON AND FAÇADE

Centuries ago, the scarcity or availability of a particular resource determined the architecture that was possible since the distance from the site where material was extracted would not exceed a few kilometers. In a semi-desert culture, such as in the Mesopotamian region,[13] where there was a severe lack of wood,[14] the main material used was earth-like soil, due to its ubiquity, with this material becoming one of the most widespread materials in the history of mankind.[15] There is evidence that this material was already being used in the 10th century BC, however, its use can be assumed to be even older (Figure 1). Stone and wood were also widely used in the areas where they were abundant, with wood being used on the slabs of small residential buildings.

It must be noted that sedentary cultures drew on wall-based architecture to build structures and enclosures and had thermal protection through the use of the façade. However, nomadic societies could not use this technique as construction took too long and nomads needed a system that would allow them to assemble and disassemble their buildings easily and in a reasonable time. As such, structures and enclosures had to be as light as possible and, as a result, these societies chose to separate all structures from their enclosures.[16] Although these types of solutions (the use of textile elements) have been used since the advent of humanity, the separation between structure and enclosure did not influence permanent architecture until much later. However, mass construction was quite efficient with respect to inclement weather. Moreover, the climate was also decisive in determining the shape of the envelope,[17] marking, for instance, the quantity and shape of the openings or slopes of the roofs.

Popular architecture in fluvial civilizations is considered very simple since it depended on the resources and technology of the peasant class. This is because the cost and distance to available materials were limited to the immediate surroundings, which differs from monumental and religious architecture, which were able to use all the resources of the state for their constructions (the importation of stone and ashlars, planning,

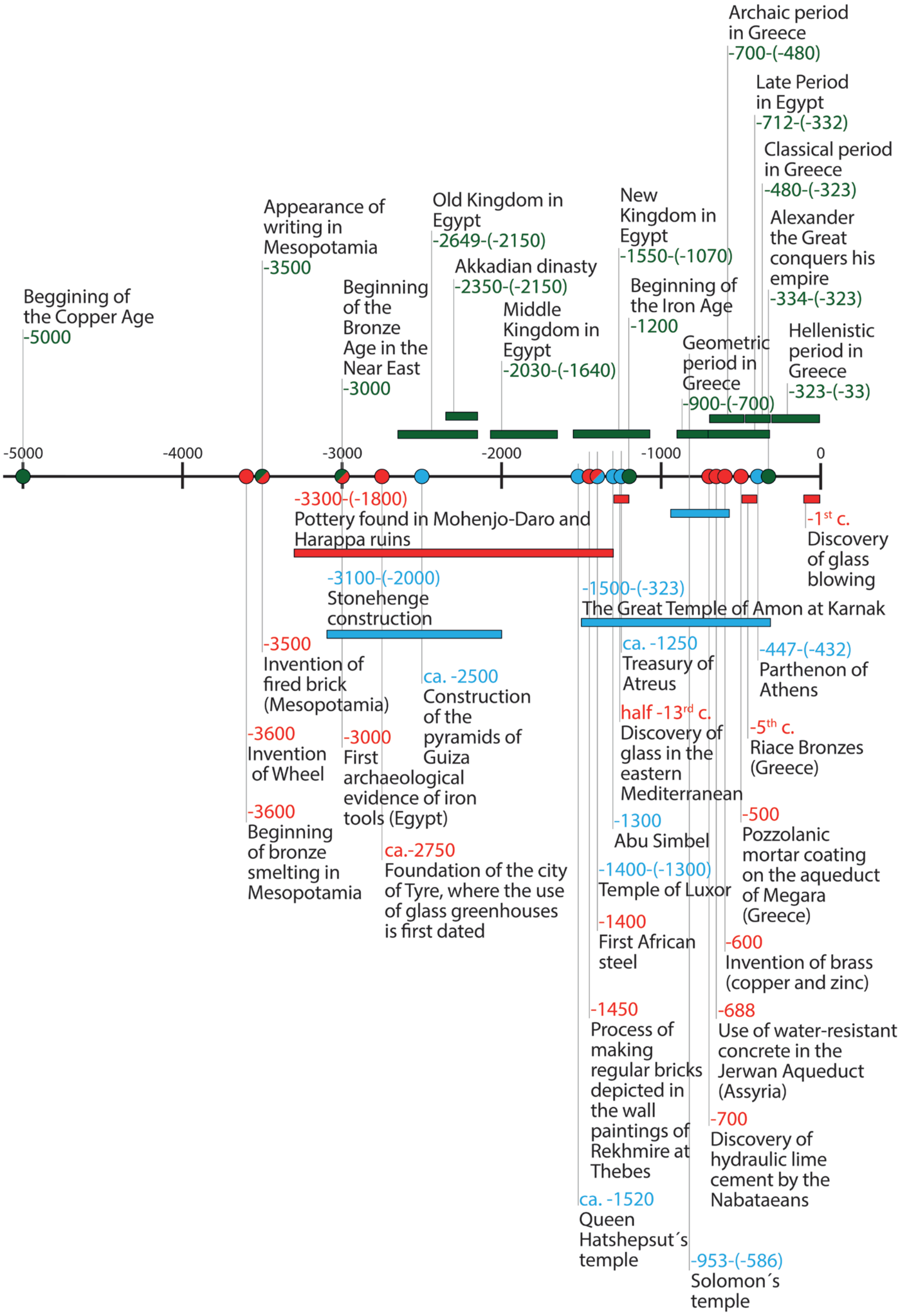

Figure 1. Between 5000 BCE and the year 0, there was a development in metallurgical technology and great ancient civilizations arose. Important architectural works, which have survived until the present day, were beginning to be built.

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		RIVER VALLEY CIVILIZATIONS	
		5,000 BC - 750 BC	
		POPULAR	MONUMENTAL
TECHNOLOGY	MATERIAL	ADOBE	STONE
	MAX. HEIGHT	up to 5 m	5-30 m
	DISTANCE RANGE	up to 5 km	50-100 km
	EXECUTION TIME	up to 1 year	> 20 years
	ECONOMIC COST	scarce	huge
COMFORT	THERMAL	poor	medium
	LIGHTING	very poor	very poor
ENERGY CONSUMPTION	MANUFACTURING	scarce	medium
	USAGE	low	scarce

scarce low medium significant huge
very poor poor medium good very good

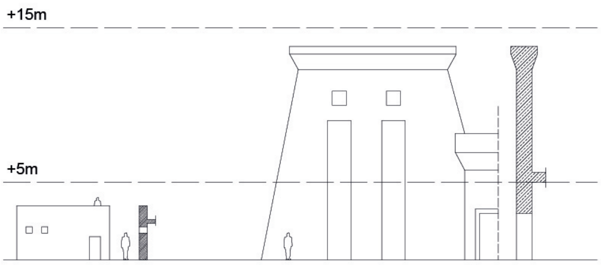

Figure 2. Characteristics of the Architecture from the River Valley civilizations. The illustrations correspond to an interpretation of models for Egyptian dwellings found in archaeological sites and the Luxor Temple.

etc.), resulting in elevated planning and construction (Figure 2). Although thermal comfort was not a real issue at the time, we can assume that it was high since the buildings were small and had large wall thicknesses that made use of the thermal inertia of the material. The lack of openings made for insufficient lighting. As a result of the evolution and innovation of the materials used in construction, the use of glass in greenhouses is mentioned for the first time in the Phoenician city of Tyre, founded around 2750 BC.[18]

Later, Greco-Latin architecture introduced arches and lintels to enlarge openings and ensure structural safety.[19] Moreover, the introduction of glass in classical architecture took place in the Roman Empire around 40 AD. The first examples of glasswork can be found during the Augustan era in the Atrium Vestae, which consisted of wooden or metal frames onto which glass panels were mounted to cover holes. The openings were not only enlarged but also covered, which partly impeded air circulation. The expansion of glass also contributed to the development of new typologies, such as baths.[20] In addition, during the Roman Imperial period there was a great advance in construction technology,

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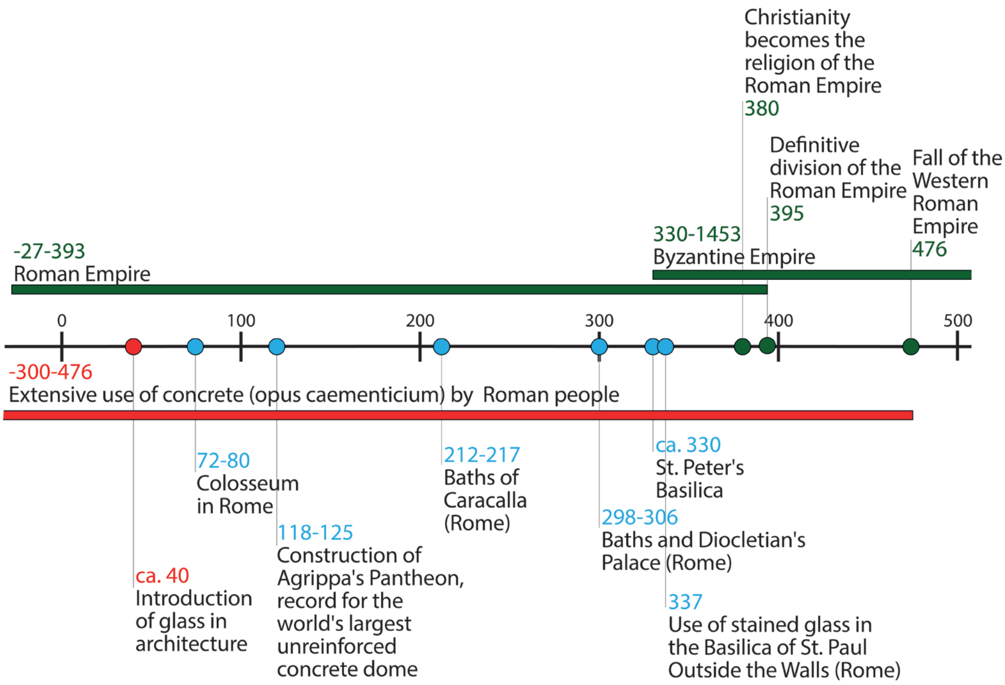

Figure 3. The rise and fall of the Roman Empire occurred between 0 and 500 AD. During this period, there was extensive use of *opus caementicium* and the appearance of glass in architecture.

during which we can highlight the use of concrete (opus caementicium) (Figure 3).

In the case of the Greco-Latin culture, a more efficient division of labor reduced execution times and increased costs. In terms of the popular Roman insulate, buildings were still modest and the costs were never excessive (Figure 4). Similarly, the possible radius of material importation also increased as trade proliferated and materials became cheaper. In relation to monumental architecture, it can be asserted again that the state had more resources than the commoners. Shorter execution times meant thinner walls in popular architecture, resulting in less thermal comfort compared to previous times; however, larger windows could be opened, which meant increased lighting.

FAÇADE'S FREEDOM

Until the Early Middle Ages, the façade was given this structural function, which led to the need to create wall-based and massive architecture, with the exception of a few examples concerning wooden textiles or textile architecture that was typical of nomadic societies,[21] or even Asian paper-based architecture such as the Japanese Shōji, which originated in the 600s AD. This function also caused a limitation in the choice of possible materials for the façades, as they needed to be strong enough.

The breaking point in this concept came with the arrival of the Gothic style. During this period, the massive walls typical of the Romanesque style were reduced to the minimum needed to ensure

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		GRECO-ROMAN WORLD	
		750 BC - 500 AD	
		POPULAR	MONUMENTAL
TECHNOLOGY	MATERIAL	BRICK	STONE/BRICK
	MAX. HEIGHT	5-30 m	30-50 m
	DISTANCE RANGE	5-15 km	> 100 km
	EXECUTION TIME	1-3 years	10-20 years
	ECONOMIC COST	medium	huge
COMFORT	THERMAL	poor	medium
	LIGHTING	poor	poor
ENERGY CONSUMPTION	MANUFACTURING	low	medium
	USAGE	scarce	medium

scarce | low | medium | significant | huge

very poor | poor | medium | good | very good

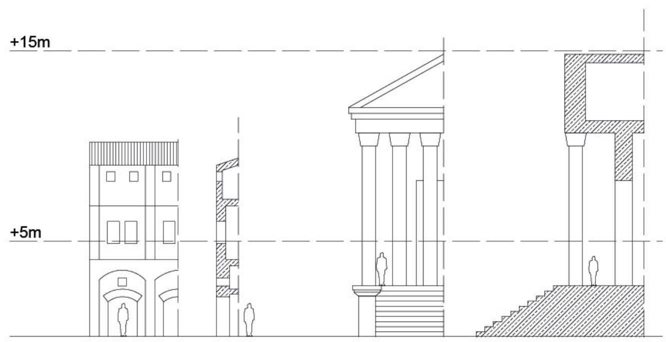

Figure 4. Characteristics of the Architecture from the Greco-Roman World. The illustrations correspond to an interpretation of a Roman house in Ostia and various other illustrations as well as the Temple of Jupiter Optimus Maximus.

the sustainability of the structure. As such, many more interstices were free to be filled by large stained glass. Moreover, the use of lintels to cover the window spans gradually became inefficient and these were subsequently replaced by arches that, in Gothic architecture, became more and more pointed, since this shape allowed for a better distribution of weight.[22] This was also because freeing the façade from structural loads was desirable as it would allow a maximum flow of light. It also led to the creation of large external auxiliary structures that have remained as a vestige of the pretension of light from this time. Due to these exterior structures, the vertical loads were transferred to the foundation of the building without being stuck on the façade.

The Gothic period was a revolution not only in a structural sense, but also in the spatial sense.[23] In addition to the exterior structures formed by buttresses and flying buttresses, the side aisles of the churches also assumed the function of structural reinforcement, changing the perception of space. All these structural advances allowed buildings to

		MIDDLE AGES/EARLY MODERN PERIOD		
		500 AD - 1700 AD		
		CIVIL	RELIGIOUS	MILITAR
TECHNOLOGY	MATERIAL	ADOBE/WOOD/GLASS	STONE/GLASS	STONE
	MAX. HEIGHT	5-30 m	> 10 m	30-50 m
	DISTANCE RANGE	15-50 km	15-50 km	5-15 km
	EXECUTION TIME	1-3 years	> 20 years	3-10 years
	ECONOMIC COST	medium	huge	significant
COMFORT	THERMAL	poor	medium	medium
	LIGHTING	poor	very good	very poor
ENERGY CONSUMPTION	MANUFACTURING	medium	significant	medium
	USAGE	low	low	low

scarce — low — medium — significant — huge

very poor — poor — medium — good — very good

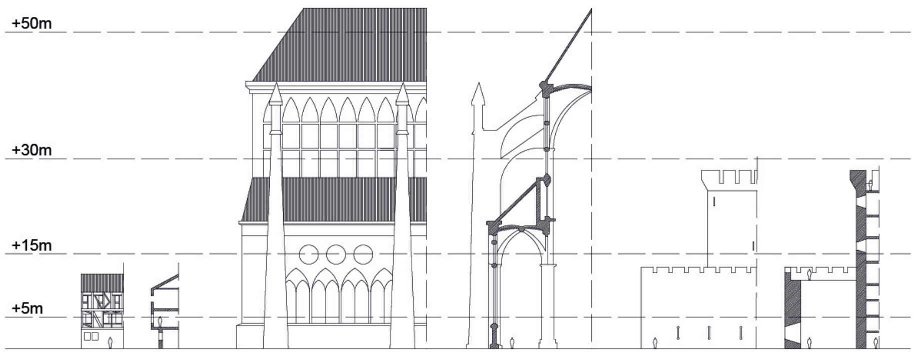

Figure 5. Characteristics of the Architecture from the Middle Ages and early modern period. The illustrations correspond to houses in Vannes, the Reims Cathedral, and an interpretation of Castillo de la Mota (Spain), as well as other castles in Castile (Spain).

achieve unprecedented heights,[24] becoming some of the tallest buildings worldwide for centuries. When analyzing the characteristics of the architecture of this period, it is important to distinguish between public, religious, civil, and military architecture (Figure 5). When Cathedrals were erected, they required a huge number of resources, in terms of both economy (masons, builders, artists) and energy (lime kilns, lifting of pieces...) for an extraordinarily long execution time. The need to reduce the thickness of the walls of the cathedrals to a minimum, the large volume of the cathedrals, and the large number of windows all increased lightning comfort but reduced thermal comfort to low levels. However, cathedrals and churches were crowded places, which, together with the typical thick wool dressing, improved thermal comfort.

In contrast, in medieval cities, popular architecture grew vertically and horizontally due to urban pressure. The technology accessible to the people had not changed and trade was less secure due to political instability, therefore resulting in the distance range being reduced.

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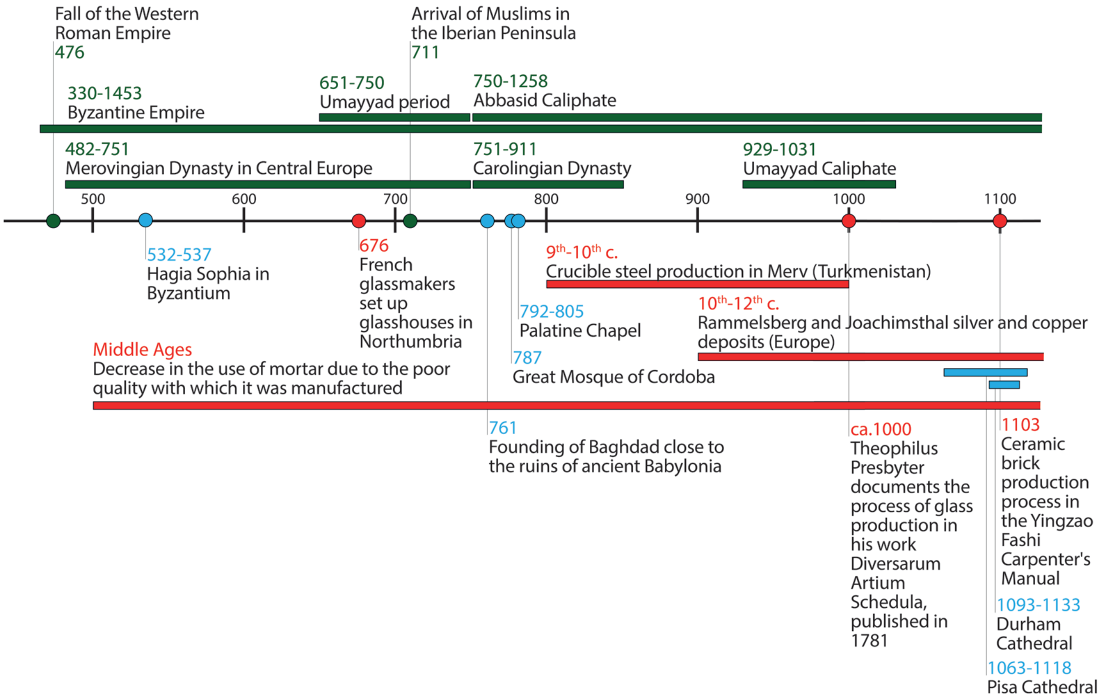

Figure 6. After the fall of the Roman Empire, the quality of mortar declined and, consequently, so did its use. During this period, the production techniques of metals and glass were slowly improving, which would have a great influence on the following centuries.

In the Middle Ages (Figure 6) in Europe, half-timbered systems were commonly used in the construction of buildings. This evolution happened due to a pressing need for major openings, combined with the concept of separating structures and enclosures, which came from nomadic tents.[25] In this latticing system, load-bearing timber was used as a skeleton for the façade, and its holes were filled with different materials. This separation happened only in terms of materials since both systems still made a single wall and, as such, we cannot talk about its structural separation yet.

Military architecture deserves a separate mention since its development and execution respond only to military defense purposes. The time available and the radius for obtaining materials, as well as the execution of the work, were limited since they were buildings that were constructed in unstable territories. Comfort was not a requirement and the principal function of the façade was protection against enemy attacks.

Regarding materials, stone continued to predominate in monumental buildings and adobe in popular ones; however, in areas where stone was scarce, such as in the plains of northern Europe, ceramics took on importance in the so-called Brick Gothic style. The quality of concrete during this period fell to very low levels and its use practically disappeared. The glass manufacturing process evolved, allowing for the creation of high-quality stained glass.

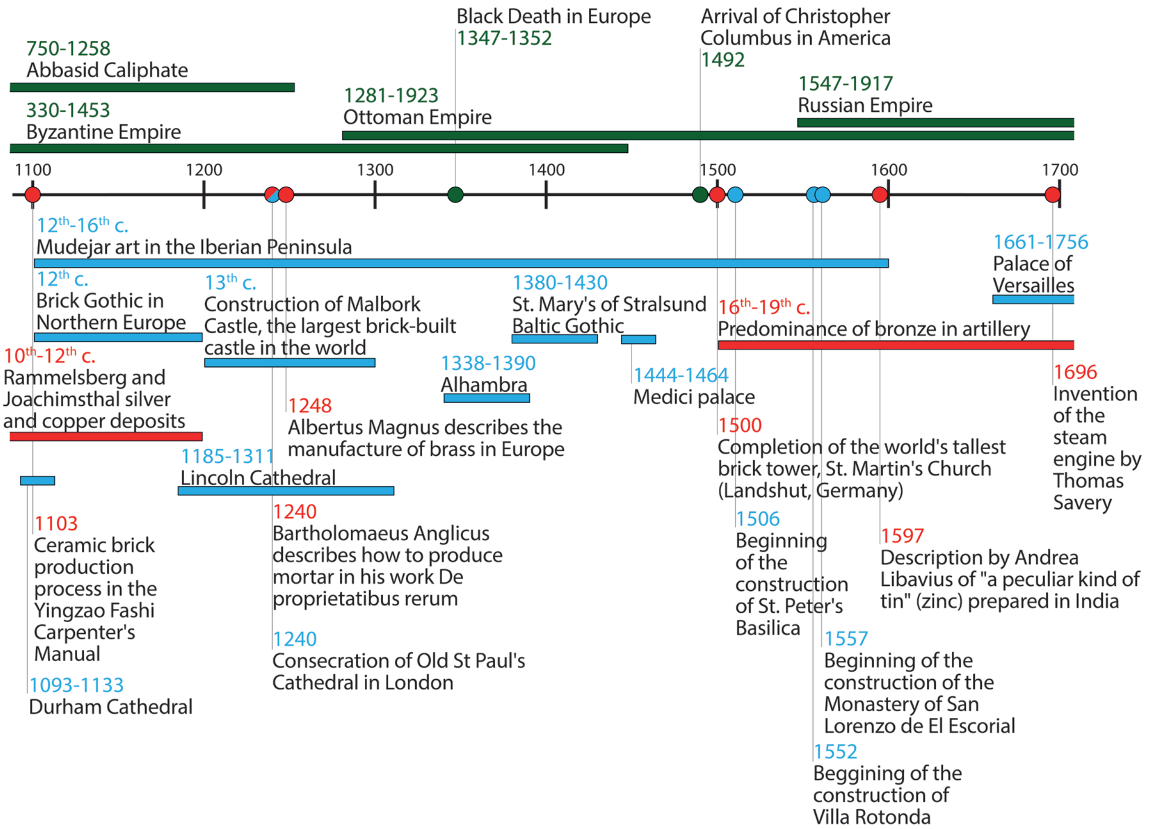

Figure 7. In the late Middle Ages, brick had a great influence both in the regions of southern Europe, with the Mudejar style being typical, as well as in northern Europe, with the Brick Gothic style. The great Gothic constructions appeared, which constituted a great spatial, structural, and technological advance that continued into Renaissance constructions.

The trend to increase heights that appeared in this period continued over the following centuries (Figure 7). However, it was not until the 18th and 19th centuries that there was the complete dissolution of the visual border between the interior and exterior. To achieve this, two advances in material research were needed.

In the early 18th century (Figure 8), cast iron began to be used as a structural element. It was first used as an architectural element in 1714 in the House of Commons in London.[26] The introduction of this material into factory buildings quickly became widespread. As a result, the structural system of iron-based pillars and beams had a greater development, going as far as to replace wooden constructions since they allowed for the creation of a skeleton with greater spans. The use of steel in architecture made large factories possible in a short time as it involved a low economic cost compared to other periods. As buildings were designed to house machines and not people, thermal comfort was very poor, although lighting comfort improved since glass panels became larger. Energy

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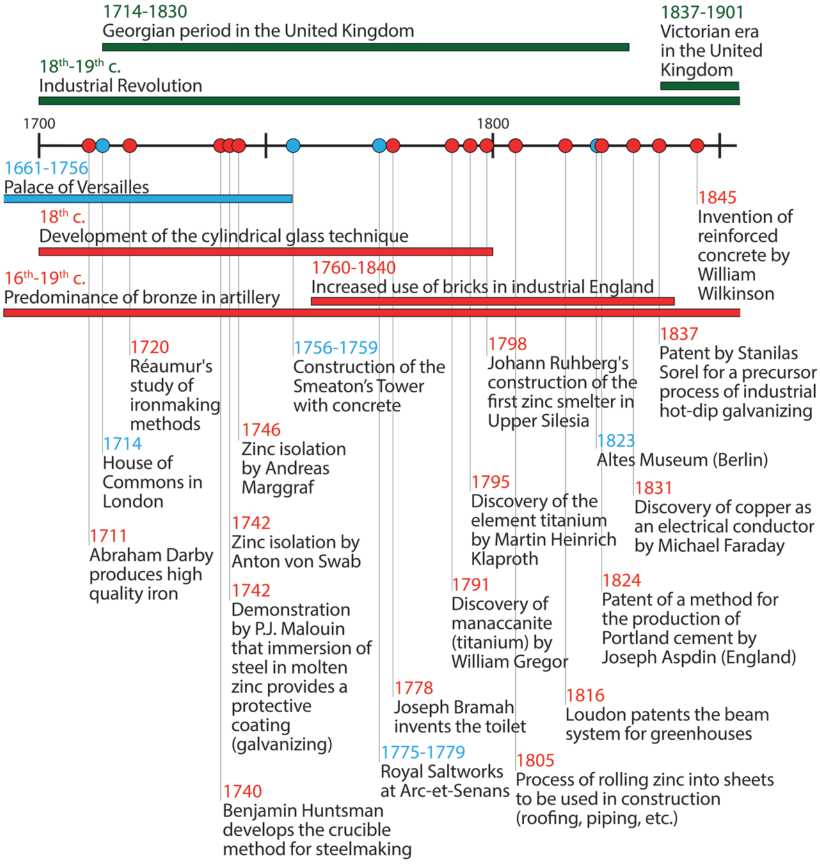

Figure 8. The Industrial Revolution began in the 18th century and with it the speed at which scientific and technological advances took place increased. The technique of cylindrical glass and the use of metallic structures began to develop. Discoveries of new materials and patents followed one after the other.

consumption in terms of manufacturing and usage rose to unprecedented levels (Figure 9).

Large masses of homeless flooded the cities to provide labor. To house them, low-quality dwellings were erected in a very short time and with a low economic cost due to a lack of interest in the quality of life of the tenants. As a result, thermal and lighting comfort were equally poor.

Considerable advances were also achieved in the development of glass manufacturing processes. In the 18th and 19th centuries, the cylindrical method for making flat glass produced an improved glass innovation within architecture. The cylindrical technique was widely used and, as such, was developed in the 18th century on the European continent, which explains why, in the 19th century, large sheets of glass could be obtained.[27] In parallel to this technique, crown glass was also developed,

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		INDUSTRIAL REVOLUTION		
		1700 AD - 1900AD		
		POPULAR	PUBLIC	INDUSTRIAL
TECHNOLOGY	MATERIAL	BRICK/GLASS	BRICK/GLASS	BRICK/GLASS
	MAX. HEIGHT	5-30 m	30-50 m	30-50 m
	DISTANCE RANGE	50-100 km	> 100 km	50-100 km
	EXECUTION TIME	1-3 years	3-10 years	up to 1 year
	ECONOMIC COST	scarce	medium	low
COMFORT	THERMAL	poor	good	medium
	LIGHTING	medium	good	good
ENERGY CONSUMPTION	MANUFACTURING	medium	significant	significant
	USAGE	low	medium	medium

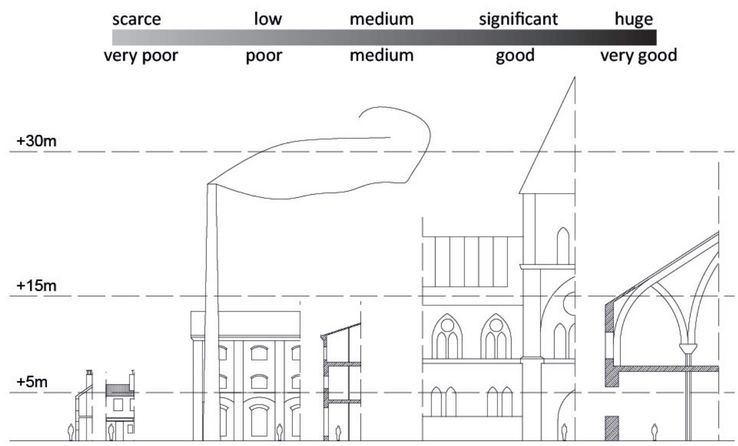

Figure 9. Characteristics of the Architecture from the Industrial Revolution. The illustrations correspond to a series of Victorian row houses on an East London street, an interpretation of Harrington Mills' lace factory in Long Eaton, and the Museum of Natural Sciences in London (Own contribution).

being widespread in Britain and commonly used in Western Europe until the 19th century.[28]

During the Georgian and Victorian eras in the United Kingdom, there was the rise of greenhouses, which came as a result of the fashionable hobby of growing exotic species in an unfavorable climate. These first greenhouses were built using wood, brick, and stone and their façades' large stained-glass windows were open, letting the light, and even more importantly, the energy necessary for plants to flood in. These buildings had the advantage of not strictly being subject to the aesthetic considerations of architecture, and, as such, they became an exceptional typology in research with regard to new materials to be developed.[29] In the late 18th century, among the many new discoveries about materials, horticulturist John Claudius Loudon began experimenting with these two materials in his constructions. By developing flexible wrought iron beams that allowed for the creation of curvilinear glazing without weakening their resistance, Loudon achieved that these beams reached only 13 millimeters wide.[30] Based on these advances, the Horticultural

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Society stimulated the development of more designs for these new greenhouses. This movement featured the figure of Joseph Paxton, Chief Gardener at Chatsworth Garden in the service of William George Cavendish. In 1833, Paxton refined Loudon's models of sloping glass roofs for greenhouse constructions in Chatsworth.

Paxton's masterpiece creation of the Crystal Palace in 1851 with 300,000 glass panels was a historical event in architecture.[31] This building was required to be a pavilion important enough to host the Great Exhibition taking place the same year. The meeting in which Paxton agreed to design the structure was held at short notice, with the structure being built in just eight days. Therefore, the Crystal Palace was not designed with the building's shape and function in mind but with a focus on the construction process instead. Its shape boasts a new construction system that focused only on the construction process from the very beginning, which involved thinking of all the phases a building must go through, including even the final dismantling of it.[32] The building was met with great admiration at the time and, thanks to its design, it was able to be moved to Sydenham, London, where the Crystal Palace remained until a fire destroyed it in 1937.

From this moment onward, it was possible to find a series of buildings in which the concept of structures and enclosures being made of glass panels could be seen. Examples of this include the Harper Bros Warehouse in New York in 1854 and the Gardner's Warehouse in Glasgow in 1856. This latter building by John Baird stands out for the sincere and logical use of its materials as well as for the visible structure, which, added to the glazing of its façade, causes a great feeling of lightness.[33] Constructive solutions for greenhouses began to be applied to the largest buildings,[34] and were often seen in many typologies such as railway stations or shopping arcades, which flourished throughout the 19th century, with the Vittorio Emanuele II gallery in Milan standing out as an example.

These advances led to a strong debate, which allows us to see the profound impact that industrialization had on construction and architecture. In response to this industrialization, a consolidation of moral architectural thinking took place at this historic moment and was included in this debate with figures such as Ruskin, Morris or Semper.[35]

THE INFLUENCE OF MATERIALS AND CONSTRUCTIVE SYSTEMS ON THE NEW FAÇADE PARADIGMS

Evolution around this issue might be one of the causes of the divergence of architecture into two different approaches in the 20th century. On the one hand, there was the use of multipurpose materials that guaranteed the requirements of the building with fewer materials and an appropriately homogeneous and continuous image in which glass was used only when needed. Examples of this trend are buildings such as the National Museum of Roman Art in Merida by Rafael Moneo and the chapel of Notre Dame du Haut by Le Corbusier.[36]

On the other hand, the option of High-Tech Architecture appeared. This kind of architecture emphasizes the industrial aesthetic and is based on the use of steel structures combined with glass. Richard Rogers' Pompidou Centre is considered a prototypical example of High-Tech Architecture. Over time, this trend gradually evolved into a more sustainable architecture type called Eco-Tech.

Regardless of the path in which façades were used, the development of building materials and systems has dramatically evolved since the last century (Figure 10). Glass has gone from being an overwhelmingly expensive material to being almost ubiquitous in today's cities. In addition to its inalterability[37] and flatness, glass has the advantage of transparency.[38] Transparency has made glass desirable and has contributed to its development.

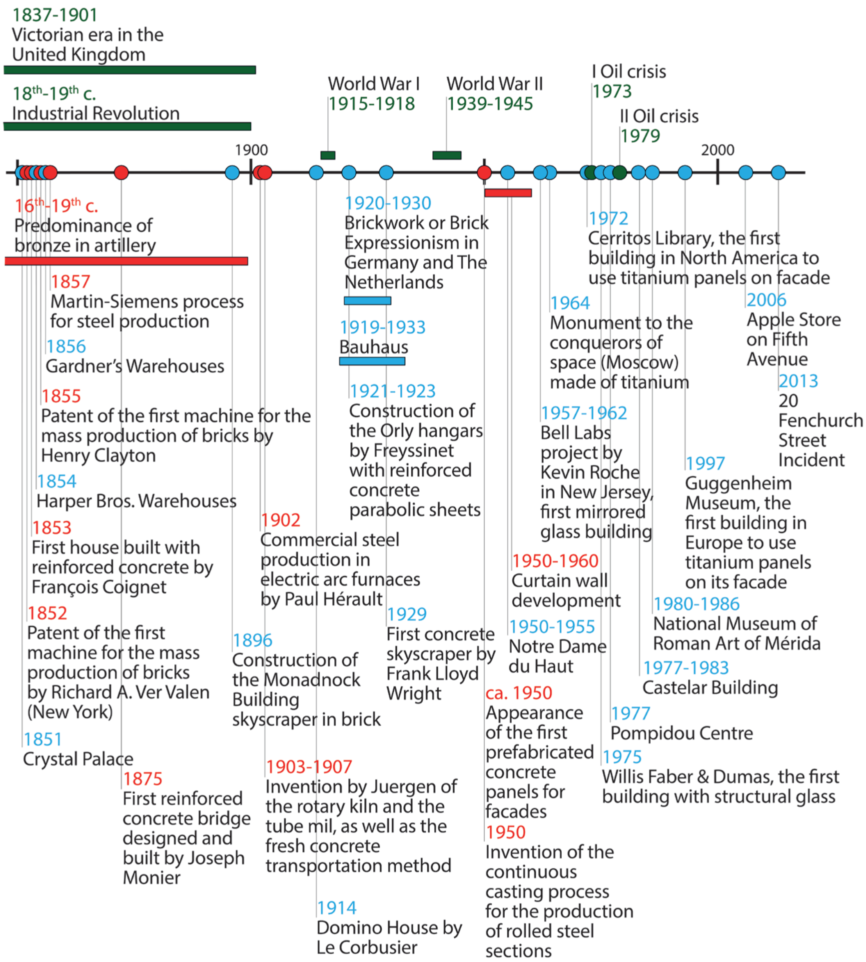

Figure 10. During the second half of the 19th century and into the 20th century, technological advances continued with the same intensity. The social revolutions that took place throughout the twentieth century would change the understanding of the needs and therefore the typologies of buildings, giving great importance to the corporate image. The concept of the envelope remained the same at this time thanks to the structural and functional freedom that was given to the façade, with solutions such as curtain walls and structural glass appearing.

Structurally speaking, the development of curtain walls supposed a great step forward since this system is independent of the main structure of the building.[39] However, this façade system has been strongly linked to a specific typology, that is, office buildings. This is why curtain walls are associated with working environments, that is, buildings with a reticular structure and a clear plan.[40]

Following the development of the curtain wall, the concept of the double façade or double-skin façade also emerged, which allowed further possibilities to be integrated inside the façade such

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as airflow and temperature control. An example of this is Rafael de la Hoz's Castelar building in Madrid, which manages to control the flow of sunlight beams entering the building thanks to the double skin covering it.[41]

The last breakthrough in this area is the appearance of structural glass, with the first architectural reference to this system being the Willis Faber & Dumas building by Foster + Partners in Ipswich, England, in 1975. This building incorporates structure-like ribs made of glass that support the façade and, because of this, with the exception of a few small metallic joints between the glass plates, we do not find any frame or auxiliary structure.[42] This system continued to develop, obtaining extraordinary results with the Apple Store on Fifth Avenue in New York and the Bohlin Cywinski Jackson studio, whose structure is entirely made of glass.

Another main protagonist of 20th-century architecture was reinforced concrete. During the 19th century, this material created controversy due to its controversy because of its color. The debate surrounding it focused on its aesthetics rather than the possibilities to create new forms.[43] Time has since shown its enormous potential and consequently concrete has become an essential material in today's world for both structures and surface finishes, such as in the BNP Paribas Fortis building in Brussels.

The arrival of light façade frames led to the use of new materials or those that were not traditionally considered, which evolved into their use on façades. Metals have become another common element, as well as plastics, which are also almost ubiquitous in construction, even though we are not aware of their massive application.[44] The current development in the science of materials leads to a world of multiple possibilities. Nevertheless, as is usually the case, these possibilities also involve an increase in the problems created by them.[45] Currently, one of the biggest problems we face in society and particularly in construction is energy consumption. Together with the new paradigm of envelopes, we have also abandoned both the use of local materials and traditional solutions in favor of the lightening of the façade. Although new systems have undeniably brought us advantages, the loss of traditional strategies has led us to a scenario where energy consumption has needed to be higher to ensure adequate parameters of welfare, which is usually supported by mechanical systems.[46]

However, the energy consumption of buildings lies not only in their use, but also in the energy consumed in their construction processes, such as the manufacturing of materials and systems, their transport, and their commissioning.[47] Current energy certification systems such as *Passivhaus* look to reduce this consumption by prioritizing the use of closely located materials and more efficient manufacturing processes.

However, limiting energy consumption by focusing on the quality of the materials and the manufacturing will not lead to efficient energy behavior. It is important that this attitude is transferred to the essence of design. The analysis of the shape factor, for example, can lead to significant energy savings. Controlling the shape of a building will also mean controlling heat gains by radiation, which, coupled with the choice of materials, can result in a significant improvement in the energy input of a building. This can be seen through the creation of a solar oven with a greenhouse-like space or achieving the opposite effect with a mass enclosure with great volume.[48]

Despite this, solar control glazing, or low-E glass has made exceptional lighting comfort possible (Figure 11) and has also improved thermal comfort.[49] New insulating materials have increased thermal comfort despite the thickness of walls having been reduced thanks to the façade being freed from having a structural function. The computerization and automation of the manufacturing, planning, and calculation processes related to construction, as well as the extreme division of labor, have achieved short execution times. This

		20th / 21st CENTURIES		
		1900 AD - NOWADAYS		
		RESIDENTIAL	PUBLIC	CORPORATIVE
TECHNOLOGY	MATERIAL	BRICK/CONCRETE	STEEL/GLASS	STEEL/GLASS
	MAX. HEIGHT	50-100 m	> 10 m	> 10 m
	DISTANCE RANGE	> 100 km	> 100 km	> 100 km
	EXECUTION TIME	1-3 years	3-10 years	1-3 years
	ECONOMIC COST	low	significant	huge
COMFORT	THERMAL	good	good	good
	LIGHTING	very good	very good	good
ENERGY CONSUMPTION	MANUFACTURING	huge	huge	huge
	USAGE	medium	medium	significant

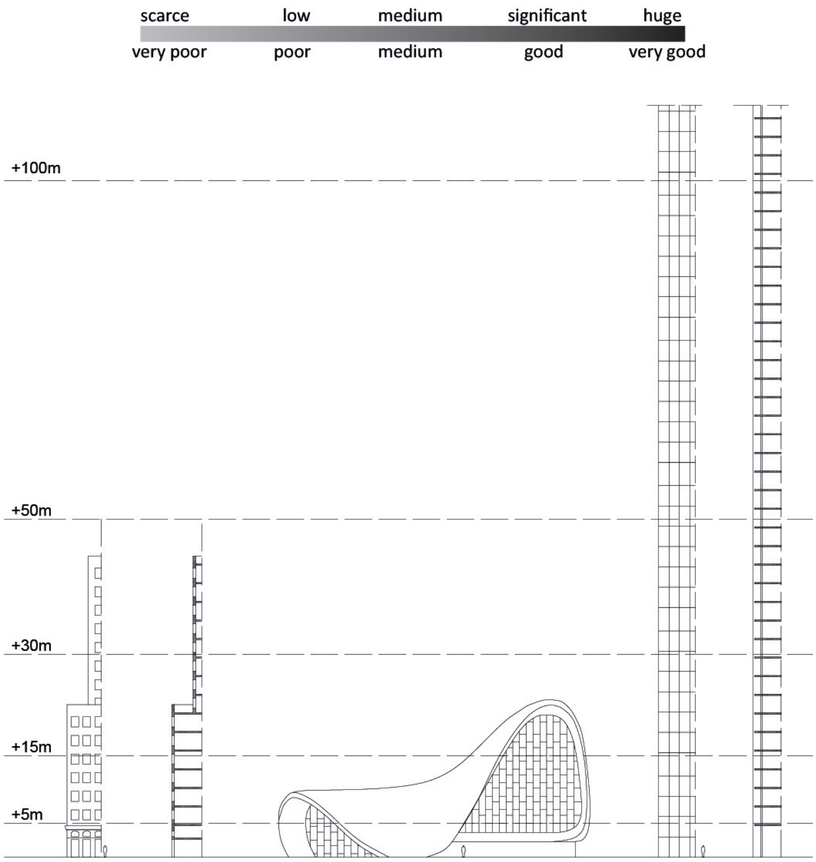

Figure 11. Characteristics of the Architecture of the 20th and 21st centuries. The illustrations correspond to an interpretation of actual residential buildings in New York, the Heydar Aliyev Center in Baku by Zaha Hadid, and the Twin Towers in New York (Own elaboration).

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is possible due to the enormous number of systems with which construction is carried out today compared to previous periods.

DISCUSSION

Façades have undergone significant changes. The façade has been abandoning functions, such as providing structure, but acquiring others, such as the commitment to energy sustainability and adaptability. Current regulations impose important requirements in terms of thermal performance and comfort. Therefore, during the evolution of the envelope, there has been a change in its criteria, which can be clearly observed. Several research papers points in this direction,[50] that discuss new functions of envelopes.

The technical evolution has allowed for a greater variety in the use of materials and morphologies of buildings, which can be interpreted as greater compositional freedom. As discussed, the greater demand for comfort has sometimes been fulfilled thanks to greater energy consumption by mechanical thermal conditioning systems. In addition, studies exist that highlight this point.[51]

However, traditional architectures presented knowledge that allowed them to have higher levels of thermal comfort without the need for energy input than some of the architectures built in the 20th century. In this regard, Paunović et al. comment on the damage that these modern architectures have produced by obviating the environment in which they are located,[52] causing knowledge to be lost and condemning their inhabitants to live in dwellings that do not meet good insulation and comfort characteristics. For this reason, architects such as Francis Keré advocate for the study of vernacular architecture.

In this paper, we see how the evolution of architecture has led to a separation between structure and the façade. This is in line with the findings of other authors.[53] However, it should be clarified that although the technical situation allows for the separation of both systems for a building, this does not necessarily always happen. We can highlight the case of other architectures that advocate for the union of both systems without losing morphological freedom, just as Molina[54] presents, thanks to technological advances and materials.

Therefore, during the evolution of the façade to the current concept of the envelope, we have improved in technical aspects, especially in terms of lighting and thermal comfort, reaching unprecedented levels. Thermal comfort is also greater than in previous times, although in most cases it is subject to energy consumption. Several façade design strategies, such as those presented by Thalfeldt et al. can contribute to the decrease of energy consumption to near-zero levels.[55]

Energy consumption is precisely the parameter that has increased the most in the development of the façade, with the concept of energy consumption not only including the use of the building to maintain comfort standards but also the construction process. Among other things, this is due to the greater distance range of the materials used, as well as all the manufacturing processes involved in the construction elements.[56] Thanks to prefabrication processes, the execution time of the different architectures has decreased and continues to do so as the efficiency of prefabrication advances.

As a summary of the results obtained on this issue, we present Figure 12, which shows a comparative summary of the evolution of technological capabilities, as well as comfort and energy consumption. This comparison shows that we currently have the most advanced technology and the widest range of new materials. Interior comfort has reached unprecedented levels never seen before. However, this has greatly increased energy consumption.

The replacement of traditional techniques with modern systems such as curtain walls, for example, brings advantages such as virtual connection

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		TECHNOLOGY					COMFORT		ENERGY CONSUMPTION	
		MATERIAL	MAX. HEIGHT	DISTANCE RANGE	EXECUTION TIME	ECONOMIC COST	THERMAL	LIGHTING	MANUFACTURING	USAGE
RIVER VALLEY CIVILIZATIONS 5,000 BC - 750 BC	POPULAR	ADOBE	*	*	*	*	**	*	*	**
	MONUMENTAL	STONE	***	****	*****	*****	***	*	***	*
GRECO-ROMAN WORLD 750 BC - 500 AD	POPULAR	BRICK	**	**	**	***	**	**	**	*
	MONUMENTAL	STONE BRICK	***	*****	****	*****	***	**	***	***
MIDDLE AGES/ EARLY MODERN PERIOD 500 AD - 1700 AD	CIVIL	ADOBE WOOD GLASS	**	***	**	***	**	***	***	**
	RELIGIOUS	STONE GLASS	*****	***	*****	*****	***	*****	****	**
	MILITAR	STONE	***	**	***	****	***	*	***	**
INDUSTRIAL REVOLUTION 1700 AD - 1900AD	POPULAR	BRICK GLASS	**	****	**	*	**	***	***	**
	PUBLIC	BRICK GLASS	***	*****	***	****	****	****	****	***
	INDUSTRIAL	BRICK GLASS	****	****	*	**	***	****	****	***
20th / 21st CENTURIES 1900 AD - NOWADAYS	RESIDENTIAL	BRICK CONCRETE	****	*****	**	**	****	*****	*****	***
	PUBLIC	STEEL GLASS	*****	*****	***	****	****	*****	*****	***
	CORPORATIVE	STEEL GLASS	*****	*****	**	*****	****	****	*****	****

Figure 12. Comparative table of the evolution of technological capabilities, as well as comfort and energy consumption.

with the exterior. However, there are several disadvantages to the current systems. The issue of energy increase can be considered one of the main problems today, but it is not the only one. Glass façade systems often impede natural ventilation, limiting it to mechanical systems that can generate air quality problems if they are not properly maintained. Noise is also one of the problems that increase with these façade systems.[57]

Therefore, the choice of shapes or materials should be based on substantial criteria and should avoid banality. The use of metal in façades can be very compromising due to the high energy level needed to obtain it in the first casting processes, consuming large amounts of energy and generating abundant waste. In addition, metals such as copper, zinc, and tin are in short supply and therefore non-renewable materials.[58]

Overall, there needs to be awareness about shape and materials not only for the inside of the building but also regarding that which people see on the outside. In the last five years, several authors such

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as Montes-Amoros (2015);[59] Suk, Schiler, & Kensek (2017);[60] Takebayashi (2016);[61] and Zhu, Jahn, & Rein (2019),[62] have studied the effect of cladding and the shape of buildings in their surrounding environment.

Therefore, we can confirm with our research that the evolution of the envelope has gone through certain stages that have allowed us to choose different materials and morphologies, giving us more tools for architectural design. For this reason, it is very important to make decisions in the design of façades with a methodology focused on the analysis of its functions.[63] Therefore, the choice of maintaining some functions in the envelope or separating them is a question of design rather than a necessity.

CONCLUSIONS

In this paper, we have analyzed both the process that made the concept of façade evolve into the envelope and the subsequent repercussions of this paradigm shift, without overlooking that this evolution is linked to the evolution of architecture itself. The façade model has undergone a momentous change throughout the history of architecture to become what we know today as envelopes. This evolution has been closely related to the evolution of materials and construction technologies, forming the long path of the liberation of the façade from having a structural function.

Analyzing comfort in ancient times is not easy due to comfort being a modern concept. Nevertheless, we have shown that architecture has improved in technical aspects, especially in terms of lighting comfort, reaching levels never achieved before. Thermal comfort is also greater than in previous times, although in this case, it is subject to energy consumption. This energy consumption also affects prefabrication processes, however, thanks to these processes, the execution time has decreased and continues to do so as the efficiency of prefabrication advances.

Energy consumption is precisely the parameter that has increased the most in the development of the façade. As research into materials and techniques progresses, the possibilities of solving the energy problem will increase. As this issue will be of special relevance in the coming decades, we must be aware of the most appropriate constructive solutions to solve it, resorting, among other things, to the study of architectures of the past.

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