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Abstract. The Modern Movement in architecture was a key player in the post-war construction of many countries around the world, having diverse facets that can be seen from Chicago’s skyscrapers to Brazil with the construction of Brasilia. In a Spanish scenario, it is possible to find some unequal examples of preserved architectural heritage that present distinctive curtain walls. The Barcelona “Trade Buildings” (1966-1971) are a great example of those glazed volumes. Although many modern glazed façade buildings age relatively well, the current environmental requirements are far from the initial ones, configured during the 50’, 60s or 70s. It is thus undeniable that most of those buildings require energy refurbishment as soon as possible to keep operating in the sustainable environment we are trying to accomplish. In order to determine an analysis methodology for refurbishing the glazed buildings of the modern heritage, this study aims to evaluate a building through its energetic aspects and establish refurbishment strategies that contribute to more sustainable development, always respecting the historical and architectural value of the cities. By using the Barcelona “Trade Buildings” as a case study, this research surveys problems related to the lack of energy efficiency in the building. An intervention of this nature must identify the current conditions of the building, analyzing its energy and comfort requirements to finally propose energy-efficient and heritage-friendly solutions for the project. The three main responsible aspects that can influence in the energy consumption are, first of all, the users, who usually are responsible for energy wasting, the external building envelope, which is that factor that determines the energetic demand, and the mechanical systems, that must provide the appropriate habitability and comfort conditions. The analysis method has been carried out by developing an energetic survey through data of consumption and energy simulation programs. The results of the performance of the building materiality and systems obtained were used to propose improvement measures for the building based on Nearly Zero\(^1\) and circular economy concepts\(^1\), through the development of isolation strategies and shading mechanisms. Among the objectives of this research, we have imposed the preservation of the modern exterior image devised by Modernism, extending
and improving the building’s lifetime, implementing comfort conditions in accordance with current habitability requirements. In addition to this, in the long term, it is assumed that the building will have a sustainable character, by reducing the energy costs and carbon emissions originally generated.

1. Introduction

Built between 1965 and 1969, the Barcelona Trade Buildings are characterized by its four curvilinear towers, with the fully glazed grey colour envelope that determines the apparent materiality of the work. The architectural solution proposed by the architect José Antonio Coderch has great historical and architectural value and uses a particular curtain wall, an innovative solution for the period of construction of the building.

The initial project started from an ordination approved by the City Council that had a volume that, at first, was distributed in four prismatic towers of 20 m x 20 m, and with a height of ground floor + 10 floors, and a body of rectangular plant at the bottom that linked three of them.

When the project was commissioned to the architect Coderch, an initial form conditioned him to follow a compulsory composition, which did not correspond to his architecture. The little slenderness configured in this volume has oriented the architect to project buildings with sinuous shapes.

The volumetry is divided into four office towers of approximately 10 floors. A plinth connects three of these towers (west, east and north tower), and some interstitial gardens that accompany the organic drawing of the project are arranged on the rooftop of this base level to complement the architectural design. The distribution of each tower is developed around a concrete central nucleus so that all the offices occupy the glazed perimeter. The central nucleus gathers the reception and circulation area containing stairs, elevators and utilities. The complementary structure of steel pillars is arranged behind the perimeter of the tower to allow the free passage of the glazed enclosure, resolved in sawtooth to guarantee the perfect angulation of the volumetry.

According to Maria Lluïsa Borràs (1969), the architect José Antonio Coderch had the challenge of projecting office spaces with optimal working conditions in all offices, having natural light and exterior views in all directions. In this way, translucent sinuous facades were proposed that determine the architectural value of the complex, and are resolved with a particular curtain wall: to be able to adapt to the curvilinear perimeter, the windows divided into vertical strips, which configure the architectural rhythm of the facade, they are supported by asymmetric upright profiles forming a saw tooth shape. The base module of the curtain wall is 80 cm between upright profiles and is made up of an opaque sill and a fixed window. This curtain wall stands out at night when it contrasts with the internal artificial light from the towers, making the silhouette of the building even clearer and more objective (Figure 1). Surprisingly, the curtain wall covers a masonry layer, consisting of a double ceramic partition with a chamber filled with foam concrete. This parapet converts into a large interior shelf that houses the pillars of the structure, the air conditioning units and allows various combinations of work tables.
This great historical and architectural value achieved by the architecture of the Trade Buildings resulted in its cataloguing in the Barcelona City Council as assets with elements of architectural interest: maintenance of volumes, facades, type and use; maintenance and/or recovery of original textures, materials and colours. Despite the fact that the building has aged relatively well, the current environmental requirements are far from the initial ones, given that the building was inaugurated in 1968, so it seems interesting to propose an energy refurbishment of the building, in order to extend the useful life of this project that make up the history of Barcelona. Thus, this study aims to evaluate the building’s energy performance and present some energy improvement measures in order to enhance the curtain wall façade efficiency.

In order to achieve this, an intervention of this nature must identify the current conditions of the building, analyzing its energy and comfort requirements to finally propose energy-efficient and heritage-friendly solutions for the project. The methods to accomplish it are diverse: through case studies, simulations on digital platforms, development of isolation strategies, clean energy production and sunning according to the project. For this reason, based on in-depth studies on the building energy characteristics, this study intends to establish a diagnosis methodology for Modernism glazed buildings for the purpose of generating a more sustainable architecture, committed to the environment and to the energy needs of today’s society, contributing to the preservation of the built heritage in a respectful and durable way.

2. Methodology

The challenge in the Trade buildings of Barcelona is mainly related to the curtain wall envelope, a construction solution implemented by the architect José Antonio Coderch in order to lighten the volume proposed for the Barcelona office towers project.

The definitive construction method chosen for the project was the sawtooth curtain wall, adapting it to the sinuosity of the new drawing of the complex and lightening the initially proposed volumetry. The convex curve of the corners finds its counterpoint in the concave, generating different shadows and reflections in each section of the facade. Despite this, the four towers of the complex show similar shadow behaviours, when each tower is analysed in an independent way. Although, if we examine the influence of solar orientation, we notice that the highest exposure is in the West tower6.
In this way, the research methodology used in this work is based, in principle, on a pre-diagnosis of the current state of the buildings in order to propose measures to improve the envelope that are sustainable and respectful of the built architectural heritage.

We present the basic scheme of work development, organized in phases to clarify the starting point of the work:

- **Phase 1**: pre-diagnosis and data collection
  Explains the architecture and construction of the curtain wall of the Trade buildings, the facilities and the profile of use and activities.

- **Phase 2**: data analysis and evaluation
  Analyses architectural, construction, installation system, consumption, the intensity of use and comfort conditions data and evaluates from comparison or simulation programs.

- **Phase 3**: Diagnosis and lines of action
  Identify the weak points of the building and set outlines of action to improve it.

- **Phase 4**: Proposals for intervention
  It proposes the solutions considered most positive for the energy improvement of the building and the maintenance of the architectural heritage.

The method of analysis has been carried out in two main phases: first, based on energy consumption data collected through interviews; then, energy simulation programs available on digital platforms, such as the CE3X and DesignBuilder programs, were used and the results of the performance of the tower envelope construction systems were obtained from them. From the analysis of the data shown in the generated graphics and an in-depth study of evaluation of the results, it is intended to propose measures to improve the envelope.

Among the objectives of this research, we have set ourselves the preservation of the modern exterior image devised by Coderch, extending and improving the useful life of buildings representative of the history of the city, implementing comfort conditions in accordance with current habitability requirements. In addition to this, in the long term, it is assumed that the building will have a sustainable character, by reducing the energy costs and carbon emissions originally generated, thus making it possible to extend the useful life of the heritage built in a comfortable and durable way.

2.1. The three evaluation methods
As a way to identify problems related to the lack of energy efficiency in Trade buildings in Barcelona, a pre-diagnosis of the current state of the building was developed, specifying energy consumption by sector of the building. From this first study, the aim is to identify dysfunctions that can be improved.

Given that the Trade buildings are heritage listed, it is essential to maintain the historical aspect of the complex, being careful to keep the footprint that the buildings have in Barcelona’s skyline.

The first step of the methodology consisted of a deep study of the building by analyzing bibliographic reviews to know the project’s main characteristics that need to be respected to keep the architectonical essence of the work. The second point was designing an assessment methodology to exam the current
state of the building by checking up the pathologies related to the lack of energy efficiency. This part was divided into three methods:

1) analysis of energy consumption data, by getting real consumption data from the building’s administrator company.
2) simulations of the building’s comportment to check its energetic qualification by using the software CE3X.
3) simulation of building’s comportment by using the software Design Builder in order to get closer to a more accurate result, since this program allows to simulate 3D models.

The method number one was important to see which of the four towers was the one which had the less efficient scenario in terms of energetic demand. By comparing the four towers, the west tower was the one that showed the highest consumption. Since that, we analyzed the consumption of each office, since each floor of the building is divided into four quadrants (Figure 2). With this assessment, we were able to see if the orientation of the offices influenced its energetic consumption.

![Figure 2. Division of quadrants in West tower](image)

In Figure 3, it is possible to see that the quadrants 2 and 3 are the ones that demand the most. This means that the orientation southwest and northwest were those that suffered more climate influences.
By knowing that the west tower was the less energetically favourable, we have introduced its constructive façade systems and its installation systems in the certified energy efficiency in existing buildings program CE3X. This way we could evaluate if the building was functioning according to the current energetic necessities. The results obtained declared that the current state of the building had an efficiency qualified as E, with consumption of 184.8 kWh/m² per year, which are values that do not reach the results recommended for sustainable buildings (Figure 4).

Then, the third method consisted of modelling the whole building in Design Builder which analysed the energetic performance of it. As a result, we have obtained that the most responsible for the high heating demand was the building’s curtain wall system (Figure 5).
With those three methods, we could evaluate the weaknesses of the system being able to propose some improvement measures according to its necessities.

3. Results and discussions
Since the Barcelona Trade Buildings have a very particular curtain wall, the refurbishment solutions were inspired by a circular economy. Through the use of technology in conjunction with some quasi-craft work and the reuse of materials, a façade solution is proposed that increases the useful life of the built heritage in order to maintain our modern heritage in accordance with current conditions of sustainability.

Among the improvement measures, the study proposed 3 main changes in the buildings envelope:

1) Increasing the glazing system performance:
   The new glazing would consist of reconstructing the windows so that a double glass system can be implemented in it. This system is configured by a first layer that reuses the original 6mm gray Parsol glass, followed by a 12mm air chamber and 4mm + 4mm glass. The original glass remains on the exterior face of the building and all other layers are followed by it, inside the building. With this configuration we achieve a glass with thermal transmittance of 1.6W (m²·K), UV transmission of 1%, energy transmission of 28%, solar factor much lower than the original, being 36%, external reflection of 6%, just 1% larger than the original, and an exterior reflection colour rendering index of 97, which was previously 98, so it is pretty close to the original aesthetics characteristics.

2) Improving the carpentry system:
   It is intended to reuse the original upright profiles and crossbars, inserting expanded polyurethane foam inside it to improve its thermal performance. Furthermore, since the carpentry is all aluminum, there would not be a total improvement in the thermal behaviour of the upright since the heat would enter through conduction through the aluminum. That is why it is proposed to attach a 20mm cork-rubber layer, since it is a composite material in which cork, a natural and recyclable material, guarantees very low thermal conductivity (0.04 W / m · K), and the rubber provides excellent impermeability, excellent compressibility, high recovery degree and very good adaptability. This material prevents condensation and promotes energy savings in the building as well as working as an excellent acoustic insulator.

3) Improving parapets thermal performance:
   A new constructive solution is proposed for the interior sills, which have an air chamber. To improve the thermal performance of the parapet it is proposed to pump cellulose inside the air chamber. This material was chosen because it is a sustainable material, renewable, and often from recycling. According to the technical documentation of the Aislanat company, this material has very good thermal benefits, presenting Thermal Conductivity of 0.040 W / m · K. In addition, it has

Figure 5. Building’s thermal balance (kW)
a fire-retardant treatment acquiring the Bs2d0 classification, which corresponds to the definition of non-flammable. Boron salts are added in the cellulose wadding manufacturing process to prevent the fire from spreading and it also functions as an antifungal and rot-proof material, as it is a repellent against insects and mice and prevents the formation of fungi. Cellulose is also a material with good sound insulation capabilities.

To simulate the efficiency of the systems that have been proposed, the transmittance characteristics of the chosen materials have been incorporated into the CE3X program again, simulating three different scenario options, each with a set of improvement measures. In addition, all three scenarios feature the replacement of current lighting by linear LED tube lamps throughout the building.

These three scenarios simulate how we could gradually improve the envelope of the west tower. The idea is to have one of the towers as a pilot model that reduces energy consumption considerably and serves as a reference for the entire complex, being able to insert the rehabilitation model in all facades of the Trade buildings in the future.

The best scenario is the one that implements all the three improvement measures in the whole envelope of the west tower. In this study the energetic rating went up from E to C, reducing the annual non-renewable primary energy consumption by a value calculated by the CE3X of 184.8 kWh/m² in the original building, for annual consumption of 103.2 kWh/m² with improvement measures, obtaining a saving of 44.2 % in the energy demand of the building.

4. Conclusions
In order to generate more sustainable buildings in accordance with current regulations, current energy refurbishments can, many times, corrupt the existing urban landscape in favour of an extremely technological intervention that ignores the architectural concepts of the modern movement. In this work, the importance of spending time reflecting on what are the objectives to be achieved with an energy rehabilitation of protected heritage office buildings has been highlighted. Each building has its specificities, and it is necessary to study them very well when applying an intervention on its facades, guaranteeing the historical aspect that this building carries. Sometimes it is necessary to “sacrifice” some energy characteristics to maintain heritage values, but surely we will increase the lifecycle of this building by increasing its quality in terms of comfort and environmental impact. The energy rehabilitation, therefore, generates not only an improvement in terms of energy consumption and demand but also in the comfort of the users inside the spaces.

Therefore, it is clear that in facade interventions that improve the energy performance of buildings, there are risks and benefits. In the case of the Trade buildings and many other buildings of the Modern movement, the challenge is based on the curtain wall, which, at the time, has not been thought in accordance with current energy consumption parameters, both due to lack of material energy technology, as for the energy abundance of the time. The curtain wall is a key element for the buildings of this architecture, so it is necessary to be very cautious when proposing envelope solutions that help in the energy issue. In this work, an academic approach to feasible solutions for the maintenance of heritage has been achieved, improving its thermal and, consequently, energy performance.
As seen in the options for the improvement measures set, the renovated building with the chosen measures reaches the energy rating C. Considering that the initial rating of the building had the E grade with global emissions of 36.7 kgCO₂ / m², we realize that, with an adequate choice of materials and systems, we can have a reduction in carbon emissions and energy demand of up to 44.2%, through creative solutions of design adaptation, reasoning the use of technologies and combining it with the maintenance of the heritage value of a historic building. In this way, we are able to extend the useful life of modern buildings, trying as much as possible to carry out rehabilitation with a commitment to the environment.

With these solutions, we have seen that it is possible to maintain the historical character of the Modern Movement of the city of Barcelona, extending the lifetime of emblematic and historical buildings, and implementing comfort conditions in accordance with current regulations. In addition to this, in the long term, it is assumed that the building will have a sustainable character, by reducing the energy costs and carbon emissions originally generated, thus enabling use of the built heritage that is comfortable and durable. Bringing together the traditional and the innovative, through the use of technology together with sometimes artisan work and the reuse of materials, it is possible, therefore, to extend the useful life of the built heritage in order to keep our modern heritage in line with the current conditions of sustainability.

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