Future technologies in Le Corbusier's environmental conditioning systems:
City of Refuge in Paris

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ABSTRACT: The City of Refuge in Paris (1929-30) is an experimental building where Le Corbusier wanted to apply his famous proposal of environmental conditioning systems of buildings through the combination of two technological advances that supported his concept of machine à habiter: the mur neutralisant and respiration exacte.
This paper presents a historical journey from the first attempts to carry out these two technological innovations to a complete informative documentation on the major decisions and changes made in the City of Refuge by collecting letters and reports of the main actors who intervened in it. The aim of this study is to investigate environmental conditioning through passive and active strategies in Le Corbusier's architecture, carrying this study out in the year 2013, which marks the 50th anniversary of his death. The results and findings have allowed us to complete the analysis that architectural critics have produced on the City of Refuge, through understanding the real behaviour of the building as originally built, as well as the success that the combination of the mur neutralisant and the respiration exacte, advanced technologies for their time, could have had. At present these are once again being used in the design of active façades which deal with existing concerns about sustainability and energy efficiency.

Keywords: Le Corbusier, mur neutralisant, respiration exacte, environmental conditioning systems, active façade systems.

INTRODUCTION

The current solutions for active façades have their most interesting precedent in the technological innovations introduced by Le Corbusier in the first third of the twentieth century with the *mur neutralisant*, combined with *respiration exacte*, planned in the City of Refuge in Paris [1]. These innovations were only partially executed [2], and may have failed because they were burdened from the initial design stage, economically, and by the lack of simulation tools allowing relatively reliable prediction of indoor temperature.

The lack of interest in the integration of active systems into façades contrasted with progress in air conditioning systems for building occurring in the USA at that stage, an indubitable milestone in the development of climatisation technologies for modern architecture during the twentieth century [3]. Le Corbusier gained first-hand knowledge of these advances on his trip to the USA in 1935 [4] and adopted them [5]. He shared the interest of American engineers in the creation of artificial indoor atmospheres, healthy and free from pollution (including acoustic pollution), in airtight buildings, regardless of outdoor climate conditions [6].

It was 50 years before another great architect, N. Foster, came back in the late 1980s to the idea of the *mur neutralisant* in Duisburg Microelectronic Park, one of the earliest and most representative examples of Eco-Architecture [7], sharing the search for a more holistic interpretation of architecture. This concept, incorporating the problems of environmental conditioning, led to modern active façade systems being proposed as solutions for environmental conditioning, leading to an increase in energy efficiency in buildings.

This paper has two main aims. The first is to offer a timeline of the events occurring in the City of Refuge in Paris, while the second is to compare the thermal behaviour of the City of Refuge, as it was constructed, with what it would have been had all the innovations introduced by Le Corbusier been executed. To do so, two energy models designed for the main dormitory of the City of Refuge (Fig. 1) have been defined, one corresponding to what was actually built and the other to what was planned, taking into account climate conditions, orientation, operational conditions, spatial characteristics and the material characteristics of the thermal envelope.

Fortunately, modern computer tools for energy and environmental simulation have enabled us to carry out this task. These have provided us with the conclusions which have expanded our knowledge of the design and development of modern active façade systems as well as of the system designed by Le Corbusier and the calculations obtained by physicist G. Lyon. These results were compared with those obtained from the solution that was finally used.

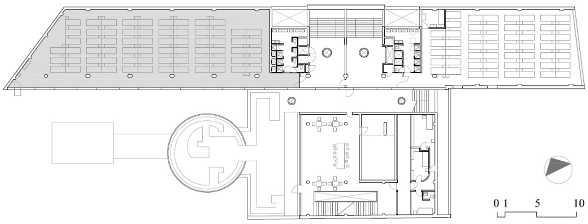

Figure 1: First floor of City of Refuge. Women's main dormitory with 289.5 m2 of surface, 67 beds and 37.2 m of glass façade.

THE *MUR NEUTRALISANT* AND THE *RESPIRATION EXACTE*: DESCRIPTION OF THE ACTIVE FAÇADE SYSTEM

In the Modern Movement, from 1910 to 1930, a new relationship was constructed between architecture and energy, based mainly on the formal analogy of the machine, a two-fold aesthetic: that of the functional machine and that of the symbolic machine [8]. The progressive speeding up of construction processes and the incorporation of large sheets of glazing, along with the abandonment of traditional solutions, generated an unknown energy behaviour which was hard to control and required new energy strategies. The result was an architectural form increasingly foreign to climate conditions and a search for thermal homogeneity relying upon the implementation of powerful new industrial technologies, which entailedthe mechanisation of the atmosphere and the creation of an artificial climate.

In this context, Le Corbusier represented the new and modern spirit of the 1920s, inventing new architectures and precedingfuture innovations and models, rehearsed in Le Corbusier's work from a perspective of contradiction and debate between scientific rigor and intuition [9]. In his architecture Le Corbusier adopted glass as a paradigm of modernity and attempted to satisfy the environmental demands of modern man through an architecture which aspired to be independent from climate, generating uniform thermal environments (*isothermiques*) through the sublimation of a technical and technological development which provided a universal architectural language.

Le Corbusier presented his proposals for technological innovations resulting from his mechanistic ideals, aiming for environmental control as defined in the Athens Charter in 1933. The development of Domino housing in 1914 allowed him to research new functions for building envelopes [10]. The solution of the *mur neutralisant* is based on an envelope with a double glass pane forming an inner chamber through which air, previously heated or cooled by the building's heating or cooling systems circulated. This was designed to reduce energy exchanges between indoors and outdoors through the glazed openings [11]. The temperature of the air circulating through the chamber depended on outdoor temperature conditions.

Le Corbusier defined the solution of *respiration exacte* using an organic analogy, that of an arterial system of conduits which use ventilation and diffusers to force clean air indoors, and a vein system of conduits which equally uses ventilation to return polluted air from this indoor atmosphere and regenerate it. Although this system had been used by G. Lyon in the Parisian Salle Pleyel in 1927 [12] it was not usually incorporated into residential buildings. This system made the building completely airtight without any need to incorporate windows with an opening system.

THE TECHNOLOGICAL INNOVATIONS: CHRONOLOGY OF THE CITY OF REFUGE IN PARIS

For the City of Refuge, Le Corbusier's 1929 proposal was an active façade system similar to that previously and unsuccessfully presented to the League of Nations in Geneva [13], but more developed and advanced, designed with the advice of G. Lyon. The building could accommodate approximately 600 people sleeping in dormitories. As it was designed to be more than a simple refuge for the night it required electric and mechanical installations that operated day and night, depending on the needs of its occupants [14].

For the envelope of the dormitories, Le Corbusier designed a *mur neutralisant*, a large surface of approximately 1000 m^2, with a chamber through which air previously heated in winter was to circulate, maintaining indoor room temperature at around 18ºC (Fig. 2). As well as helping to reach this temperature, the *respiration exacte* contributed to purifying indoor air in the dormitories, regenerating it and humidifying it when necessary. This clear forerunner of the active façade systems prompted numerous technical and financial concerns to its builders [15].

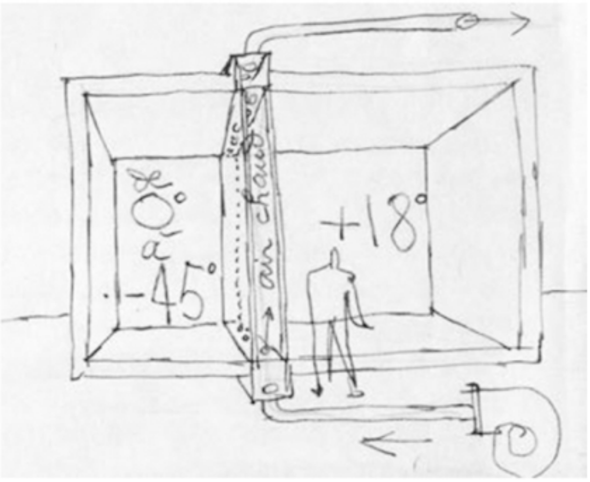

Figure 2: Description of the mur neutralisant by Le Corbusier.

In the end, the *mur neutralisant* was never built for mainly financial reasons, and was replaced by a *pan de verre* [16], a simple 7 mm sheet of toughened glass, manufactured using the Securit technique, developed by the company Saint Gobain at the request of the car manufacturing industry in 1929 (Fig. 3) [17]. The air chamber and the inner sheet of the glazing were eliminated, thus preventing airflow and making it impossible for the technological innovation proposed by Le Corbusier to be executed [18].

In November 1931 the contract was signed for the company "M.M.M" to be in charge of the production of this *pan de verre*, which was completed in December 1931, still pending the selection of the mechanical ventilation and thermal conditioning systems. Although Le Corbusier was unable to finally ensure the construction of a *mur neutralisant*, he hoped he would be able to convince of the suitability of its execution, and reserved space for its construction, as well as a location for the entry and exit of possible conduits [16]. In fact, in 1932 engineers from Saint Gobain carried out several trials to simulate the behaviour of the *mur neutralisant* using the calculations of G. Lyon [19]. These were mostly aimed at calculating heat transmission coefficients for different glazing thicknesses and airflow through the chamber.

The *pan de verre* manufactured had an indoor solar protection system of horizontally sliding panels that could be closed using floor guide rails, leaving an air chamber between these panels and the 2 m glazed modules (Fig. 3-4 (right)).

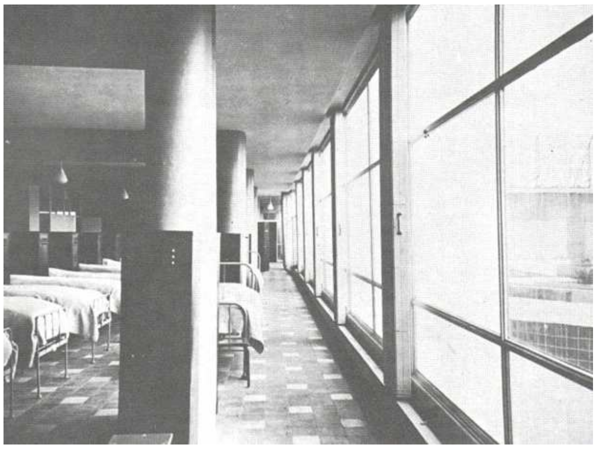

Figure 3: Interior view of the pan de verre with solar protection system. Brian Brace, T. (1987).

As regards *respiration exacte*, in May 1933 it was decided that the mechanical ventilation system should boost the previously filtered out door air to the corridors, and so, out to the roof. In winter, the operation provided 1 ACH (air change per hour) and between 2 and 3.5 ACH in summer [20]. In 1933, the Salvation Army attempted to placate the residents who felt suffocated by the heat in the summer, as they could not open the airtight windows and the ventilation system was not working. The doctor in charge of the City of Refuge admitted that the temperatures were extremely high, between 30-33ºC, and that the air needed to be changed [12].

In September 1934, the Salvation Army asked for 50 windows to be opened and the interior filtered and heated air circuit to be replaced by direct ventilation grilles to the exterior. Le Corbusier was obviously in disagreement given the potential for variation in indoor temperatures [15].

In January 1935, the Technical Services of the Prefecture of the Seine stated that in the children's dormitories high concentrations of CO_2 and temperatures of 27-28ºC were being reached. For empty rooms the CO_2 concentrations were normal, from 45-64 l/m³, with exterior values close to 40 l/m³. However, these concentrations increased in densely occupied rooms, reaching 272 l/m³. According to the Technical Services these concentrations were the result of the windows not opening, as this prevented the entry of clean air into the interior, and of the lack of a cooling system. Consequently, they requested that all the windows in the building be made functional [15].

Le Corbusier stated that all this was caused by the deficient operation of the ventilation system and added that the CO_2 concentrations and the increase in temperature would be resolved by increasing the air velocity (from 1 to 3 m/s) and the flow of exterior air. He made it clear that the windows not opening was a measure to control and prevent the entry of pollution and extremely hot or cold air into the building from outside [21]. Le Corbusier proposed the money earmarked for the creation of openings be used for a cooling system to reduce the temperature in the children's rooms [22].

In January 1936, Le Corbusier hired a tribunal of accredited experts to produce a report on the ventilation in the dormitories. The conclusions of this report stated that although operation in the wintertime was correct, in the summer a cooling system was needed. As an alternative they recommended the incorporation of a row of 60 openings of 4 x 1 cm, two thirds up the glazed façade. These openings would remain closed in winter and would allow air to circulate in the summer. As a result of these suggestions, Le Corbusier proposed that sliding windows 0.90 m wide be placed on the top third of the façade [23].

All these proposals were stopped by the Second World War. In August 1944 a German bomb outside the City of Refuge completely destroyed the façade [16]. Le Corbusier offered to repair the damage and was allowed to do so on the condition that the solution for each floor should be one third solid material, the next closed glazing and the last third functional glazing. Le Corbusier incorporated the brise-soleils (Fig. 4 (left)) made up of equally size overhangs on the side of the building [24]. The closed glazing was finally made operable and construction was completed in 1952. These new features have allowed it to still be habitable.

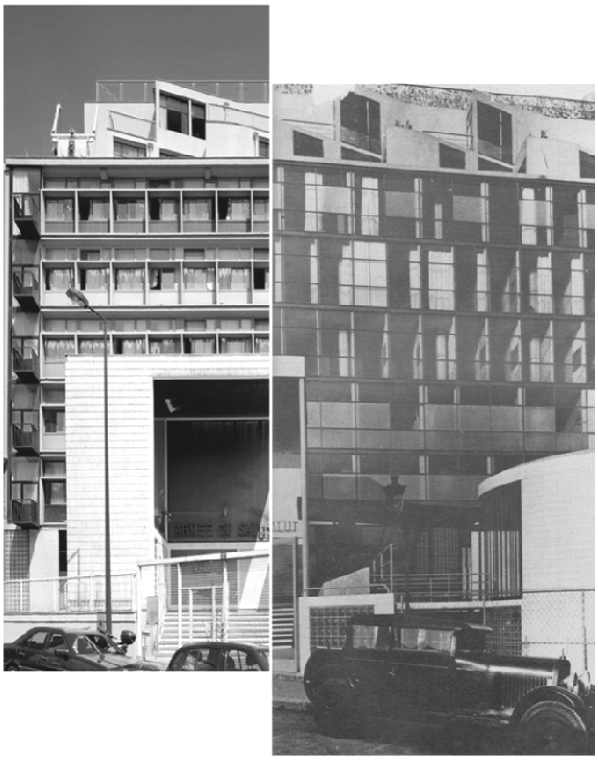

Figure 4: Exterior view before (right) and after (left) building the brise-soleils.

ENERGY SIMULATION: EXECUTED AND PROJECTED FAÇADE SYSTEMS

An analysis and evaluation of the energy exchanges between the exterior and the interior of the main dormitory of the City of Refuge in Paris, developed at the same time as the study of its history, has allowed us to verify the validity of Le Corbusier's proposals for this building, formulated jointly with G. Lyon. This has been made possible by the advances in knowledge and simulation tools currently at our disposal.

Assessments have been carried out on the thermal behaviour of the room under study in the building as it was when it was constructed, that is to say, with the combination of *pan de verre*and *respiration exacte*. Energy simulation program DesignBuilder [25] based on the module EnergyPlus [26], was used.In addition, assessments were carried out on the efficiency of the innovations that were initially planned but never incorporated: the combination of the *mur neutralisant* (Fig. 5) and *respiration exacte*. For this, the energy evaluation was executed with Computational Fluid Dynamics (CFD), using FreeFem++ [27], which required C++ programming of the algorithms to reproduce the physical phenomena which take place. The discussion of results in both these configurations is as follows:

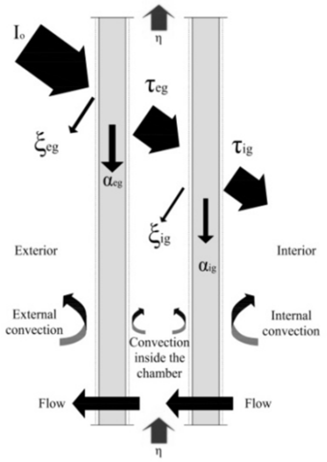

Figure 5: Physical phenomena in the mur neutralisant.

Simulation of the system executed: *pan de verre* and *respiration exacte*.

The presence of the large *pan de verre*generates an indoor space that is clearly dependent on exterior conditions, particularly the effect of solar radiation.This is favourable in winter as it provides thermal gains, but is clearly detrimental in summer as on a hot summer day the operative temperature increases to 33-34ºC, clearly higher than the comfort temperature for summer conditions. Its combination with the constantly operating ventilation system, *respiration exacte*, is mainly designed to influence indoor air quality, but also affects room temperature, causing significant improvement in winter and summer, and increasing and reducing the operative temperature, although this still does not fall within comfort conditions.

Finally, the incorporation of an indoor solar protection system provides a decrease in summer temperatures, when it reduces part of the direct solar radiation received during the hours with highest radiation. In winter it provides an increase as it prevents major heat losses due to the thermal resistance offered by the solar protection and the air chamber between this and the glass façade at night. The opening of the solar protection system contributes to heat accumulation during the day, achieving temperatures of up to 17ºC.

Simulation of the planned system: *mur neutralisant* and *respiration exacte*.

Despite the fact that they are two independent systems, the *mur neutralisant* and *respiration exacte* are interconnected and act together to make it possible to reach the desired temperature control:

G. Lyon calculated an impulse flow of 60 l/s for the active chamber and a thermal jump of 10ºCbetween the indoor room temperature andthe supply air temperature from the active chamber (30ºC in winter and 15ºC in summer).He also established a flow for the *respiration*exacte of 83.33 l/s and 291.66 l/s for winter and summer respectively. Considering that the supply air of the *respiration exacte* occurs in neutral conditions, that is to say,at 20ºC in winter and 25ºC in summer, the conditions obtained were within the recommended values for thermal comfort:around 21ºC in winter and 25ºC in summer (Fig. 6).

Figure 6: Energy simulation using CFD. Room with mur neutralisant and respiration exacte studied for a summer day.

CONCLUSION

The City of Refuge, a transition piece clearly inspired by the ocean liners Le Corbusier so admired, and his obsession with incorporating new techniques into architecture, did not manage to convince with the innovations which he had hoped would provide a solution to temperature control problems. This was mostly due to the obstacles encountered in the building, which prevented the execution of one of the most brilliant technological innovations proposed by Le Corbusier: the combination of the *mur neutralisant* and the *respiration exacte*.

The reconstruction of the timeline of the project and its execution has allowed us to establish the vicissitudes and difficulties affecting Le Corbusier's innovative project.In the end it was never executed in the original planned form due to financial constraints and mistrustof the technology. Le Corbusier, with the invaluable help of G. Lyon, proposed a solution that was ahead of its time, partially controlling the façade temperature, that of the *mur neutralisant* with an active chamber through which hot or cold air flowed, depending on the time of year. His system was a forerunner of what today are known as active façade systems.

This paper has attempted to provide a transversal reading of the knowledge of Le Corbusier's work, showcasing his architecture's links with environmental conditioning through an integral concept which incorporates environmental control systems into architecture, an innovative way of understanding architecture which fits into the framework of modern concerns for reducing energy demand.

As regards the system executed in the City of Refuge, a combination of *pan de verre*and respiration exacte, the complaintsof the users to those in charge of the building, who passed these on in letters to Le Corbusier, were completely justified. The values indicated for indoor temperatures in the summer, resulting from the measurements made by the technicians following these complaints, coincide approximately with those obtained in the simulations (between 29ºC and 31ºC in daylight).

As regards the simulations carried out and the subsequent analysis of the system as designed initially, these validate Le Corbusier's project combining the *mur neutralisant* and *respiration exacte* for the environmental conditioning of the City of Refuge, with winter temperatures of up to 21ºC and summer temperatures around 25ºC, which can be considered to fall within the comfort band. Therefore, G. Lyon's calculations for both systems and the trials executed in August 1932 by Saint Gobain, show the importance of this proposal which was over 50 years ahead of modern active façade systems, whose clearest forerunner is this project by Le Corbusier.

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