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The Pavillon de l'Esprit Nouveau of Le Corbusier. From real scale replica to digital modelling and environmental analysis

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Abstract. The aim of this paper is to promote a discussion on the transmission of Le Corbusier's work over time and, more in general, on the technological performance of his buildings. The specific object of investigation is one of the earliest projects by Le Corbusier, the Pavillon de l'Esprit Nouveau, built in 1925 for the Exhibition of Decorative Arts in Paris. Being temporary, the building was demolished at the end of the exhibition, but an exact replica was erected in Bologna in 1977, to pay homage to the participation of France in the International Building Exhibition (SAIE) in the city. The initial review of some publications on technical aspects of Le Corbusier's work, in particular environmental issues, is followed by a description of the replica in Bologna and an investigation of its performances by means of digital models, in particular with regard to energy and illumination aspects. Through the performance analysis of the building, the paper aims to highlight the complex relationship between modern language and techniques and the fruition of the artwork in society, not only from an aesthetic and anthropological perspective but also from a functional and technological point of view.

Keywords: Le Corbusier, Esprit Nouveau, Reconstruction, Digital model, Prototype, Environmental analysis.

1 Introduction: the knowledge of Le Corbusier's work

Being Le Corbusier one of the masters of Modern Architecture, his projects have been widely published, photographed and represented [1] [2]. The Le Corbusier Foundation is the major source of documentation and information [3].

Studies on Le Corbusier are still highly popular in Schools of Architecture and redrawing his buildings is a common practice to understand the principles and the visual lexicon of Modern Architecture. In the best architectural tradition, using the original drawings from Le Corbusier Foundation's digital archives, the architect Steven Park has digitally redrawn 130 perspectival sections, as well as plans, sections, and elevations [4]. These new drawings «combine the conceptual clarity of the section with the spatial qualities of the perspective» and help students experience specific works spatially and learn to critically examine Le Corbusier's works. This is the only published book that features all the 26 self-sufficient and detached single and double-family houses since 1920, including the Pavillon de l'Esprit Nouveau.

A multitude of digital models of buildings are available over the internet in different formats. Many reworked and re-rendered images of Le Corbusier's built and unbuilt projects, or even some of his drawings, are stored in social networks or available in websites with copyleft license or free-to-use. More difficult is to find reproductions of Le Corbusier's construction details instead. The technological aspect of his work attracts less researchers, architects and students simply because this is not the core of his architectural message. To a certain extent, Le Corbusier was not interested in representing technology, despite the continuous in-depth exploration of the use of industrialized materials and new building elements [5]. Flora Samuel illustrates the ways in which Le Corbusier's details are expressive of his overall intentions and inform the overall architectural narrative of the buildings [6]. However, she is not delivering a book on drawn construction details in the usual sense.

There is no doubt that for Le Corbusier architecture goes beyond construction [7]: « […] but architecture is lowered to the level of its utilitarian purposes: boudoirs, W.C.'s, radiators, ferro-concrete, vaults or pointed arches, etc., etc. This is construction, this is not architecture. Architecture only exists where there is a poetic emotion. Architecture is a plastic thing. I mean by "plastic" what is seen and measured by the eyes. Obviously, if the roof were to fall in, if the central heating did not work, if the walls cracked, the joys of architecture would be greatly diminished [...]».

The case study presented here is unique in a way: the reconstruction of the Pavillon de l'Esprit Nouveau by Le Corbusier in Bologna is probably the only real scale permanent prototype – or model – of any of his buildings. A much simpler full-size model of Maison Dom-ino was built in engineered timber by the German architect Valentin Bontjes van Beek and some students from the Architectural Association in London for Venice Architecture Biennale 2014. According to Brett Steele, director of the Association, «As a project Dom-ino distils modern architecture to a set of guiding, abstract and idealized principles. This is a key reason why the 'afterlife' of Dom-ino can still be seen and felt today, a hundred years later on». The minimal design for Maison Dom-ino image has become one of the most recognizable images of XX century architecture. However, the Venice model, which was consisting of different materials after all, remains a non-functioning house. In the case of Bologna's replica, which is a fully functional building, it is possible to monitor the real behaviour over time, as the building was erected trying to follow the technological features of Le Corbusier's project of 1925. As a matter of fact, its parameters can be directly measured, using it as a sort of research lab, where the performances of the real building and those simulated in the digital models can be conveniently compared.

2 Environmental issues in Le Corbusier's work

Many digital models of Le Corbusier's buildings have been created in the past, but a limited number of them has been directed to the knowledge of building performances, in particular environmental quality and thermal and visual comfort. The main goal of this paper is to highlight some technological features of Le Corbusier's work, focusing on buildings, delving beyond the architectural lexicon.

During his career Le Corbusier proposed and invented new technological elements in his new and revolutionary approach to architecture, in response to environmental requirements. Many of these elements had – and still have – a relevant impact on user comfort: building components like the *fenêtre en longeur, pan de verre, mur neutralisant, brise soleil*, green roofs are clearly innovative elements of a new language of architecture that are shaped around human well-being and are still widely used in contemporary architecture. His attitude well reflected the typical modern approach to innovation. Yet, refusing tradition and consolidated functional and technical solutions, constructions had to face difficulties and failures over the years.

However, comfort and room temperature in modern architecture must be understood within the technical, cultural and sensory framework of that period. As Banham says, Le Corbusier's indisputable prestige and its prominent position among the architects of the Modern Movement make him too easy a target for the criticism on the environmental performances of his buildings [8]. It is clear that environmental issues, in the terms we see them now, were not always properly addressed by Le Corbusier and surely not completely resolved. Nevertheless, he was capable of bringing to light key issues related to environment and human well-being for his entire professional life, giving new answers through design.

Clearly after a first period of internationalism, during the years Le Corbusier's projects more and more reflected a regenerated attitude towards the local context and the local construction culture, especially in extra-European countries [9] [10]. It is also clear that during the first half of the XX century energy consumption was not a problem. In this perspective, environmental issues in Le Corbusier's works should be seen through the lens of achieved thermal and visual comfort for the user than energy efficiency; the centre of his attention was always the human being in relation to the spatiality of the building.

In the work of Le Corbusier some fundamental phases in relation to the environmental aspects, in particular ventilation and illumination, were identified by Sobin [11]. Each phase is characterized by an environmental component on which the Swiss architect concentrated his interest and efforts and by a "type-object", satisfying the corresponding needs. At the beginning there was a Purist or high tech period (1920-30), in which he focused on the theme of light and glass; then, a period of transition or reconsideration (1930-45), in which the theme of heat took over, and it was treated through the use of sunshades (*brise soleil*); finally, a primitivist or low tech period (1945-65), with a focus on ventilation and aerators.

During the 1920s Le Corbusier was mainly concentrated on strategies to address the issue of daylighting. As he wrote, the window was mostly made to illuminate, not to ventilate. Conditioned by the hygienic culture of the time, he did not hesitate to include gyms and solariums in his homes, where people could devote themselves to body care and enjoy the benefits of natural light, as in the Pavillon de l'Esprit Nouveau (1925) – the object of this paper – and in Villa Savoye (1928).

Le Corbusier was interrogating himself – rhetorically – about the usefulness of filling a space between the frame that was given empty to him. He mainly adopted casement windows with metallic frame, which usually appeared as vertical openings within larger portions of continuous glass walls (*pan de verre*). More than a solution to functional problems, glass was an opportunity offered by the use of reinforced concrete frames to organize the façades freely, since external walls had lost any structural function (Fig. 1).

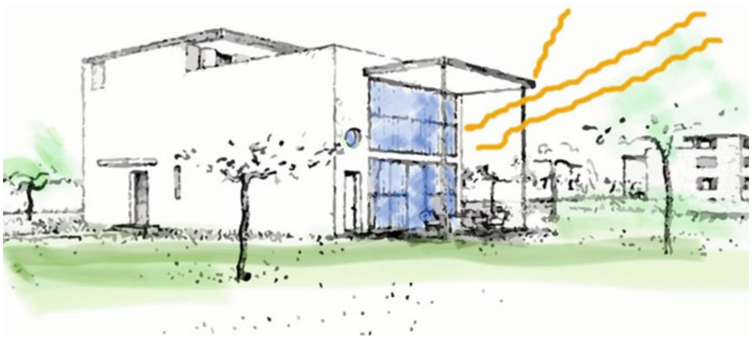

Fig. 1. Le Corbusier's mass-production villa, 1922. Framework of concrete. A large living-room 300 × 16 feet; kitchen, maids' room; bedroom, boudoir; two bedrooms and a "solarium". A very high portico is placed in front of the pan the verre. Coloured sketch of original black and white drawing [7] (L. Guardigli, C. Mazzoli, 2021)

The Corbuserian transparent walls were based on examples of fine industrial glass (*vitrage d'usine*) typically used in factories and greenhouses of the XIX century, which appeared in the form of curtain walls, marked by T-shaped metal uprights placed at narrow intervals. Sometimes the windows were presented as isolated square openings, generally in areas of the houses that required privacy and relatively little light, such as bathrooms, laundry rooms and stairwells. The other common version of windows was that of ribbon window (*fenêtre en longueur*), also made possible by the use of structural frames.

As Banham mentioned, Le Corbusier started using the glass walls for the studios of clients who were passionate about art or people who already had experienced this type of environment. They would therefore have been prepared, if not tolerant, for the corresponding heating costs, which in most cases were not too high, since the apartments usually formed part of compact urban complexes. The windows traditionally overlooked towards the north, to receive a constant light, which was the basis of the pictorial traditions of the Paris school. At that time "thin" must have been one of the most popular terms for Le Corbusier, and all other materials in his eyes might have appeared miserable alternatives to glass, which was his ideal of dematerialized building envelope, as the minimum membrane between internal and external. The inevitable consequence was the loss of the advantages provided by the mass and the volume of the walls: heat capacity, thermal insulation, sound insulation, visual intimacy, or also a place to hang a picture or hide a pipe.

Ultimately, in the 1920s Le Corbusier's activity was still strongly affected by the experiments in the architectural field of the late XIX century, characterized by the use of glass and metal carried on by the generation of Paxton and Horeau, and, even more significantly, by the enthusiasm linked to the age of the machine. Machines constituted the main model for the architectural organism (*machine à habiter*). His mechanistic view, however, was part of a broader thinking about the potential of industry and mass production, and, in particular, of its confidence in the possibility of making any place liveable through the new technologies achieved, thanks to industrial progresses. The house became an industrial object like a vehicle, a prototype to be mass-produced, characterized by light and glazed envelopes, whose climatic regulation did not rely on the external environment, but only on industrial systems, in particular on the first forms of air conditioning, already popular in the United States.

As early as 1926 Le Corbusier studied the use of two technically sophisticated mechanical systems for large-scale projects, probably conceived to function in a complementary way: the *mur neutralisant* (neutralizing wall) and the *air exact* (exact air), sometimes also called *respiration exacte* (exact breathing). The latter consisted of a mechanized ventilation system, capable of regulating temperature and humidity, basically an elementary form of air conditioning. It seems that this idea, which he defined "*aeration ponctuelle*" (punctual ventilation), derived from Gustave Lyon (1857-1936) and was intended to guarantee an internal room temperature of 18 °C in all seasons.

It was practically the first time that Le Corbusier publicly acknowledged the possibility of using an environmental technique that required energy consumption. But it was not the first time that such a concept had crossed his mind, because also the last building of his project activity in Switzerland, the Villa Schwob in La Chaux-le-Fonds, included a kind of neutralizing wall. For this single-family house from 1915, one of the first with a reinforced concrete frame, the space between the supporting elements was almost all filled with double walls, with the void between the two layers used for the routing of pipes and cables. The house had also double glazing on all main windows, some of them of notable size; one of these, two floors high, had heating pipes located in the lower part of the void between the two layers of glass, to prevent the formation of downward drafts during the winter season.

Until the 1930s, the study of the sun path and radiation were absent in Le Corbusier's projects. At first he adopted the heliothermic theory, on which the design theory behind the Unité d'Habitation (Fig. 2), also called Cité Radieuse, is based; then, he dealt with the problem of strong irradiation of the South facing *pan de verre* and introduced the *brise soleil*, of which he proclaimed himself the creator, to fight summer overheating (July 1945, lecture later published in the complete work) and reconcile winter sunshine through the windows. Summer protection is definitely a problem that

Le Corbusier explored only in the 1940s, clearly after the conception of the Pavillon de Esprit Nouveau, in 1925 [12] [13].

Fig. 2. Unité d'Habitation de Marseille, Le Corbusier. Main façade and detail of the sun path scheme drawn on a bench in concrete located in the external courtyard (C. Mazzoli, 2017)

3 The construction of Pavillon de l'Esprit Nouveau in Paris and its replica in Bologna

In 1925 Le Corbusier conceived the Pavillon de l'Ésprit Nouveau for the Exhibition of Decorative Arts in Paris as one of the units of the Immeuble Villas ("freehold maisonnettes"), with the strong will to promote his new vision of architecture. Inside the pavilion he placed the diorama of the Plan Voisin for the city of 3 million inhabitants, in a sort of "*musée imaginaire*" [14].

The Immeuble Villas is a knot in the chain that goes from the general to the particular and back, in the typical Le Corbusier's system of reasoning [15]. It is a large block made of cell-like individual apartments (villas) stacked on top of each other. With this project of 1922 he sought an efficient way to house large numbers of people in response to the urban housing crisis in France (Fig. 3).

Described as single freestanding building with 120 stacked maisonette dwellings, the block has a perimeter of 400x200 m, and contains 340 villas. The pavilion is a real scale prototype representing one of these units. The basic villa element is 11.5 m in length, and gives the whole dwelling a footprint of approximately 130 m^2. It contains a large shared bedroom for the children, one bedroom with attached boudoir for the parents, a study, a bathroom, a sports room and an open-plan dining-living-room. The plan of the block is organized in an L-shape, with a *terrasse-jardin* (hanging garden) in the remaining space. On its ground floor, the villa is connected to the rest of the building via a corridor of a width of 2.5 m. The Immeuble Villas encompasses a whole system of services for the inhabitants:

« A command service supplies all the necessities and provides the solution to the servant question (which is only just beginning and is an inevitable social fact). Modern achievement, applied to so important an enterprise, replaces human labour by the machine and by good organization; constant hot water, central-heating, refrigerators, vacuum cleaners, pure water, etc. […] The provision of food, whether cooked or not, is arranged by a special purchasing service, which makes for quality and economy».

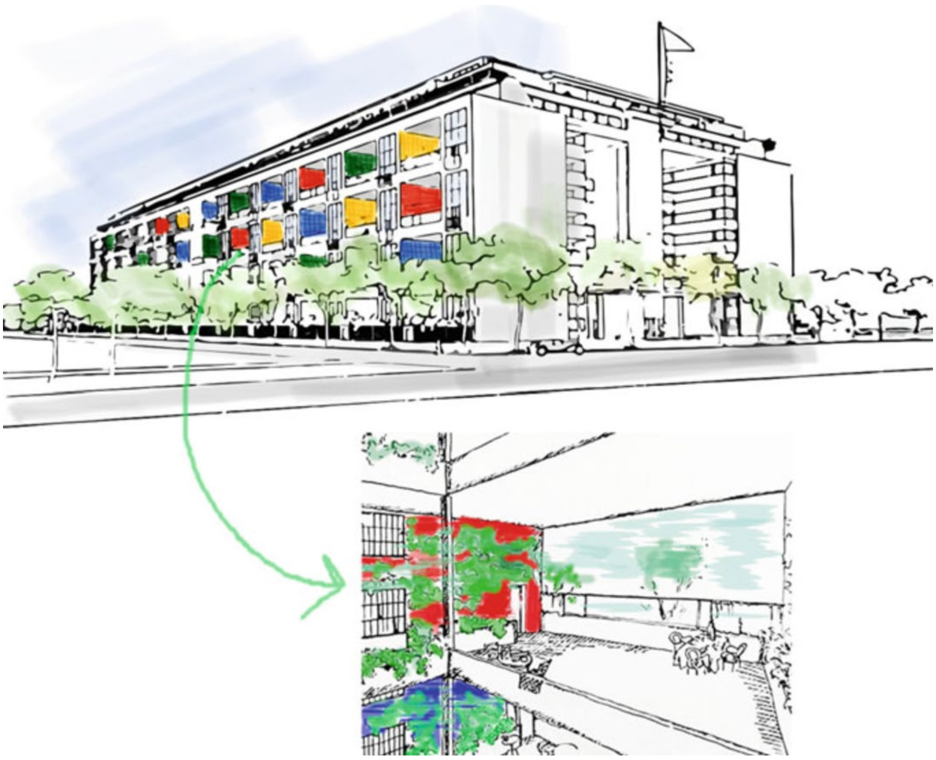

Fig. 3. "Freehold maisonettes", general viewof one block and the hanging gardens. Coloured sketch of original black and white drawing [7] (L. Guardigli, C. Mazzoli, 2021)

In this context the central issue of the design is the relation between the building and its units and the city, as evidenced later in the first volume of the Oeuvre complete, which deals with projects between 1910 and 1929 [16]:

« […] Thus the proportions of the huge scaffolding in front of the Bon Marché confirmed my theory of the scale that urban buildings ought to embody in the future. It seems clear that buildings should be set back further and further from the street, that the open spaces so created should be made larger and larger; and that we should build upwards to two or three times the existing height-limit. Were this the case the present height of rooms in ordinary flats, which architectural practice has fixed at 9-12 feet, could be sensibly increased. Future groundplans will postulate fresh architectural conditions which will lead to the adoption of a new norm of height; probable 18-22 feet».

In this period Le Corbusier's conception of architecture must be understood within the broader context of Purist aesthetic theory, which he developed with the artist Amédée Ozenfant following their initial meeting in 1918. He presented a model of standardization applied to mass production, where Modern architecture created pure forms and embraced every detail of household furnishing. He wanted to demonstrate the radical transformations derived from the use of reinforced concrete and steel and show that «these comfortable and elegant units of habitation, these practical machines for living in, could be agglomerated in long, lofty blocks of villa-flats». This Modern house prototype was originally designed to be reproduced in series and therefore built as a dry assembly/disassembly removable construction. Le Corbusier collected the story of the pavilion in the volume of the Almanach d'Architecture moderne published in spring 1925 [17]:

« Sans standardisation, il n'y a pas d'industrialisation possible; par conséquent, pas de chantier organisé et pas de solution financière au prix du bâtiment, pas de solution à la crise des loyers. [...] Notre bâtimens comportait un jeu de 37 puteaux de béton écartés de 5 ou de 2 mètres et demi dans un sens et de 3 mètres dans l'autre sens. Ainsi les poutrelles de ciment qui constituaient les trois planchers était elles toutes de 3 mètres, toutes fabriquées à pied d'œuvre en série».

For problems of time and money, however, he had to decline his original technical choices towards traditional materials and methods, creating an object that could be disassembled and recovered anyway, thus detaching himself from the original project. He also had to face a very small space for construction at the Exhibition, with the presence of trees (Fig. 4); therefore, he built the temporary building around a tree, opening a hole in the roof. The Pavillon de l'Esprit Nouveau was then demolished after the exhibition.

Fig. 4. Pavillon de l'Esprit Nouveau at the exhibition in Paris, 1925 (Unknown author, from Wikimedia Commons)

There is very little mention of environmental issues in relation to this project. Indeed, in the Almanach pages, Le Corbusier talks about the technological solutions for the glazed surfaces and the heating system:

« Les fenêtres étaient le résultat de plusieurs années d'expérimentation (toutes les reproductions de cet almanach montrent l'emploi des fenêtres en longueur et l'évolution de leurs dimensions entre des mesures qui peu à peu se précisent et semblent bien correspondre à la taille humaine). [...] Pour le chauffage a l'eau chaude, nous avons proposé comme solution éventuelle in certains cas, l'emploi de regimes de tuyaux verticaux, solution économique préconisée pour le chauffage del locaux industriels; nous pensons que le radiateur actuel est loin d'avoir attaint à sa forme definitive ».

This approach seems quite rigorous: in fact, he is interested in improving and eventually optimizing the innovative solutions through testing and experimentation.

The Immeuble Villas was never built according to the original project, but many buildings in the world have been inspired by this model. The Immeuble Villas contains the germ of the Unité d'Habitation for the concept of a multi-function building and the organization of the apartments in two storeys, although the plan and the shaping of the elevation are radically different. The house of Via dell'Annunciata in Milan by Figini and Pollini, called "overlapping villas" (*Casa a ville sovrapposte*, 1933-34), represents one of the first experiences of a "Modern condominium" in the city but it is more likely a tribute to Le Corbusier's imaginative lexicon than a new real building type. In 1987 la Régie Immobilière de la Ville de Paris organized a competition for the re-interpretation of the superimposed villa-buildings imagined by Le Corbusier in 1922, where each apartment was actually a house with garden, all overlooking a landscaped square. The façades of the duplex apartments for artists overlooking the Jardin J. Miro in the Ilot Gandon (J. Dubus & J- P. Lott, Arch., 1987-1991) have a close resemblance with the original. The building in Bologna is therefore a unique example.

In 1977 the idea of reconstructing a real scale replica of the Pavillon de L'Esprit Nouveau in Bologna arose from the editorial staff of the magazine Parametro, which resulted in the formation of an "initiative group" for the realization of the project. This group included the architects Giuliano Gresleri, Glauco Gresleri, Enea Manfredini, Giorgio Trebbi, and Enzo Zacchiroli [18] [19].

The intent was to revive the original spirit of Le Corbusier and obtain an object that would have been not only an icon or a tourist destination, but also a real piece of architecture for studying Modern Architecture and Le Corbusier's production. The enterprise was also a way to discuss about the process of scientific reconstruction and/or reinterpretation [19] [20] [21]. The reconstruction of the pavilion was based on a maniacal search for original documents and sources. In this perspective the initiative is particularly interesting and actual, if seen in the context of Modern Heritage preservation.

The Le Corbusier Foundation of Paris, then chaired by André Wogenscky, gave its consent and patronage and delegated the technical direction of the works to the architecs José Oubrerie and Roger Aujame from the former Le Corbusier atelier. Giuliano Gresleri was entrusted with the artistic direction of the work and the High Surveillance. The reconstruction was made possible by the intervention of the company

Grandi Lavori which, through its president, Mario Tamburini, provided for the financing and the realization of the project. A pool of public and private bodies (Autonomous Body for Bologna Fair District, University of Bologna, Regional Union of Chambers of Commerce of Emilia Romagna, Grandi Lavori, InArch, Faenza Editrice, National Association of Building Constructors, National Association of Labor Production Cooperatives, Confederation of Italian Cooperatives) supported the initiative. The Municipality of Bologna made available the land on which the pavilion was rebuilt between June and September 1977.

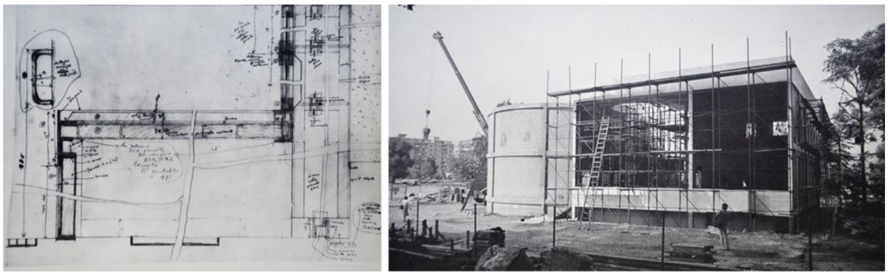

Fig. 5. Window detail and Pavillon in 1977 during construction (courtesy of G. Gresleri's Archive).

Working on drawings by Le Corbusier and Pierre Jeanneret, and comparing the graphic documentation with the photographic originals of the time, the design steps were reconstructed. The architectural drawings were translated by Grandi Lavori into construction documents, after having developed the program for the manufacture of the prefabricated parts (Fig. 5).

The experience in Bologna, although very accurate, was inevitably forced to use construction techniques and materials further different from those used in Paris, which would guarantee the creation of a product as faithful as possible to the original prototype: they opted for a mixed technique, partly prefabricated and partly on site, replacing the materials used by Le Corbusier no longer available on the market (i.e. thermal insulation panels in "solomite") with current ones. To a certain extent, the construction system used in Bologna ended up being more faithful to the original idea of prefabrication of the units than the technologies used for the prototype in Paris. According to Giuliano Gresleri, who was later commenting on the operation of 1977 [22]:

« […] One can almost say that, with respect to the project, the same pavilion of 1925 constituted a first "fake", paradoxically authenticated by the author, and that of Bologna a second "true" one, without pedigree, but implicitly authorized by Le Corbusier who had thought of the original to be reproduced in the immeubles in every place».

The example in Bologna was definitively an experiment of mass production.

4 The experience of space, digital representation and performance analysis of the Pavillon

The pavilion in Bologna is located near the entrance of the fair district, in a large green space. The main façade with the loggia is almost perfectly facing south, rotated by 4 degrees towards the south-west. Building plan and front elevation respect the Modulor, based on the Golden Section. The structural grid follows the same scheme (Fig. 6). The width of the unit is approximately 12.60 m, while the depth is 14.80 m. On the ground floor there are the living room and the dining room (together 5.00x11.90 m), a small kitchen (not furnished in the case of Bologna), one bathroom, the north corridor and the almost perfectly square loggia on the opposite side. The living room is a double volume space with the full height south facing window. The diorama is on the west side and it is directly connected to the unit through the corridor; its dimensions are 10.50x17.80 m; there are two separate staircases, one for the apartment and one serving the diorama. The first floor of the apartment is composed by one master bedroom, projecting over the living room, another bedroom, a solarium facing north, and two WCs.

The layout of the replica in Bologna follows the project of the Pavillon in Paris, which is not exactly what le Corbusier designed for the Immeuble Villas. This is partly explained by the needs of the exhibition. In particular, the bedroom on the first floor is not facing towards the living room downstairs, and it is divided in two parts, creating a studio room, with a horizontal window facing the loggia. The arrangement of the furniture is also different in most of the rooms. However, this different layout does not change the general concept behind Le Corbusier's scheme (Fig. 7).

After the last intervention in 2017, the internal walls were repainted using 11 colours of Le Corbusier's colour keyboards (Fig. 8). The combination of the colours recalls the ones selected in Maisons La-roche Jeanneret in Paris. Le Corbusier's colour palettes can be checked online [23]. Les Couleurs® Le Corbusier has the exclusive worldwide license.

Large windows with the same kind of frame are placed on the north and south sides of the building; on the north side we have the *fenêtre en longeur*, while the south side is characterized by the *pan de verre*. The south facing windows were provided with curtains. In the Ozenfant House (1922) two large windows facing north and east are used for the artist's studio.

The pavilion is functionally divided in two distinguished parts: the residential unit and the diorama. In the original version in Paris the diorama hosted the images of Plan Voisin; the same image was reproduced in Bologna's replica (Fig. 9).

The apartment is partially furnished and therefore it can be experienced as a prototype of a living space. On that regard, some other furniture should be provided, to complete the interiors in the bedrooms and in the kitchen. Cristian Chironi is a writer that experienced living in the house in the fall 2015. He lamented a very poor level of comfort for the insufficient heating system [24].

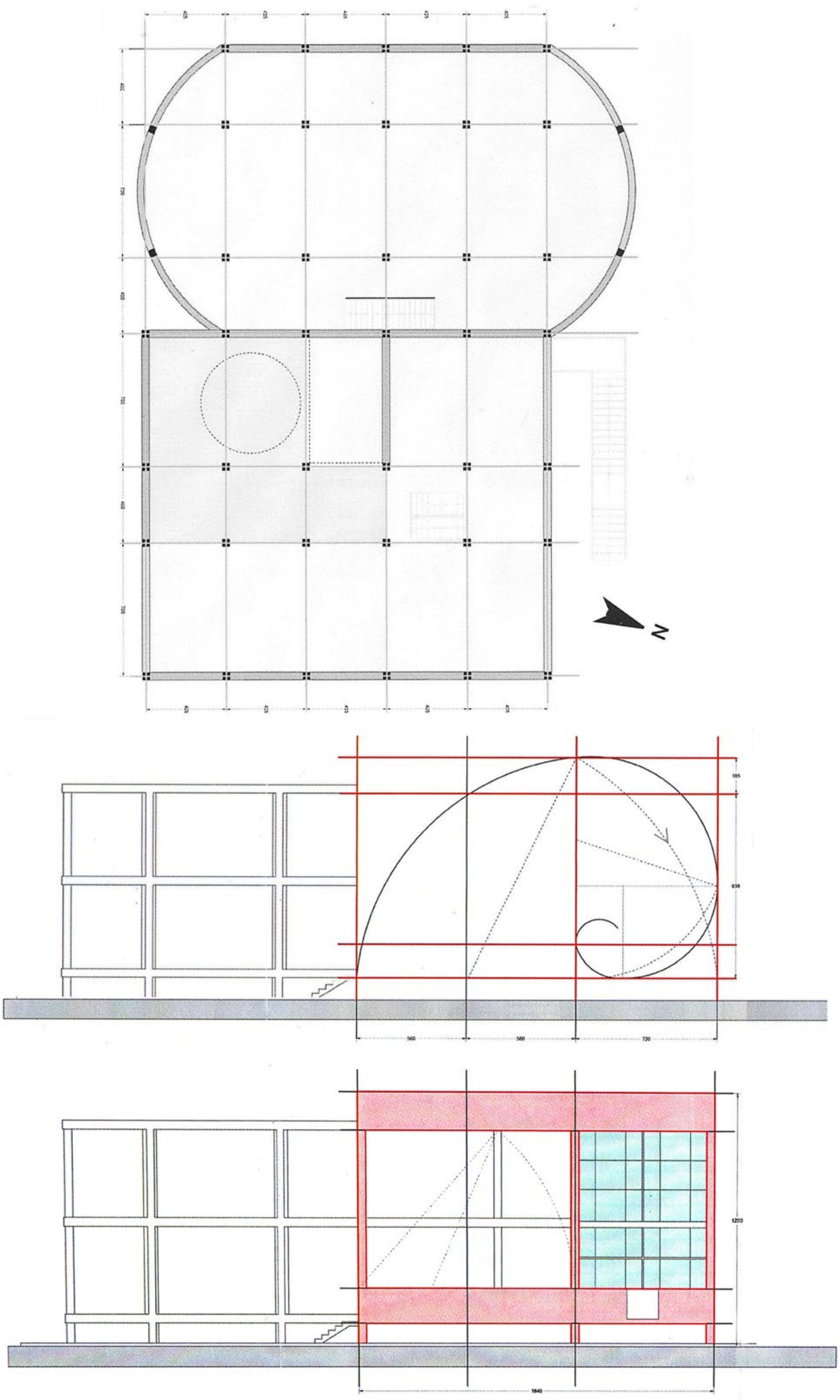

Fig. 6. Structural grid and proportions of south elevation (R. Bellinazzi, 2018)

Fig. 7. Pavillon de l'Esprit Nouveau in Bologna, after repainting and maintenance (L. Guardigli, 2018)

Fig. 8. Internal views of the pavilion and colours from KEIMFARBEN, Les Coleurs Le Corbusier – *Polychromie architecturale*: *terre d'ombre brûlée* 31 (32130, according to colour keyboards of 1931) and *outremere moyen* (32021) in the living room; *outremere moyen* (32021) and *vert clair* (32052) in the bedroom and solarium; *terre siene brûlée* 31 (32120) and *l'ocre rouge moyen* (32111) in the diorama. The original colour codes have been assigned by arch. Laura Biagi, as part of the maintenance intervention carried out on the occasion of the 40th anniversary of the reconstruction of the pavilion in 2017 (L. Guardigli, 2018)

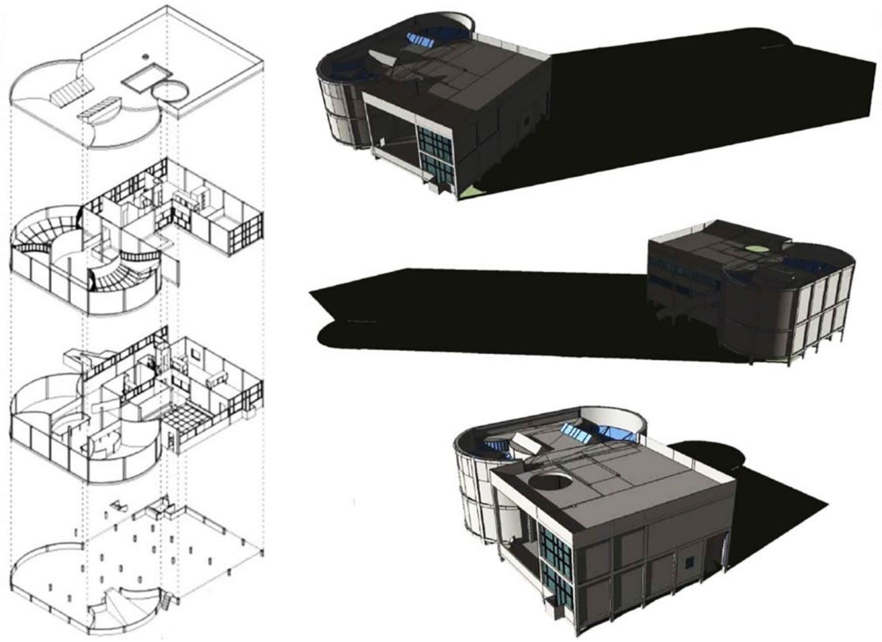

Fig. 9. (Left) Pavillon de l'Esprit Nouveau in Bologna, axonometric views of floors. (Right) Sun exposure in February from top: south side view, 4.00 pm; north side view, 4.00 pm; south side view, 12.00 am (R. Bellinazzi, 2018)

From the point of view of building's morphology, therefore of compactness and regularity, the choice certainly does not follow the principle of enclosure; the unit is characterized by a large loggia, which has as its reference the vegetable gardens of the Carthusian monasteries. Le Corbusier visited the Certosa of Ema al Galluzzo and identified the independent gardens associated with the individual units as a promising solution for aggregated housing units. With this invention he wanted to compensate the loss of relationship with the nature of the Immeuble inserted in an urban context and the scale of the block. In the Unité d'Habitation this open space will be lost while the *brise soleil* that are missing here will be inserted. The structure of the Unité will also acquire a defined unitary structure with the *pilotis*.

Digital models of the pavilion are downloadable from the Net, like many other Le Corbusier's projects, even if they are not always very accurate; in this case we adapted the model and corrected the main inaccuracies [25]. We analysed the orientation of the pavilion and the exposition to sun path, drawing the section of the building (Fig. 10). The main façade is facing south. The minimum inclination of the sun during the winter at noon is 23°; as there are no sunshades on top of the south facing window, the radiation penetrates all the way through the living room. In the summer the maximum exposition is 73° and the direct radiation enters for the first 3-4 m of the living room; some walls are painted with dark colours; indirect radiation is stronger in the afternoon, since the west wall of the living room is painted in white, while the east wall is painted in *terre de siene*.

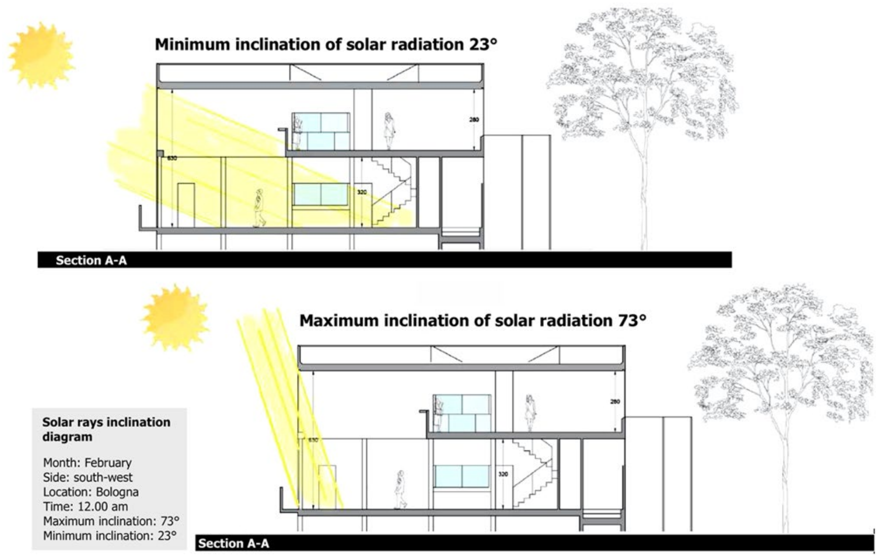

Fig. 10. Sections of the building (R. Bellinazzi, 2018)

The choice to have a south oriented glass façade was already taken by Le Corbusier for his building for the Deutscher Werbund exhibition in Stuttgart in 1927; according to Banham, this decision was probably made to enjoy the view of the valley; most likely a similar decision was taken for Bologna, to offer a view of the yard. Possibly, to orient the glass façade towards the street, therefore towards the north, would have been a more consistent solution with the idea of the unit being part of an urban block. In any case, these considerations on orientation make sense only in relation to the unit in Bologna. The Immeuble Villas was not planned for a specific location; we can assume that Le Corbusier would have preferably oriented the building along the heliothermic axis, in order to have the flats facing east and west. However, we know that the south orientation of the glass walls of the Maison Clarté in Geneva and the Cité de Refuge in Paris caused serious problems, that were later fixed with the renewal of the façades and the installation of sunshades. The light analysis of the real building in Bologna was performed manually with simplified formulas, with BRE geometric-analytical method and with Radiance software, using the same orientation and light conditions for the digital model. The investigated parameters were Daylight Factor (DF), illuminance (E) and luminance. Results with software were compared with on-site measurements in February 2018, in a day with cloudy sky (Table 1). Daylight Factor values of the living room and the master bedroom from software are evidenced below (Fig. 11).

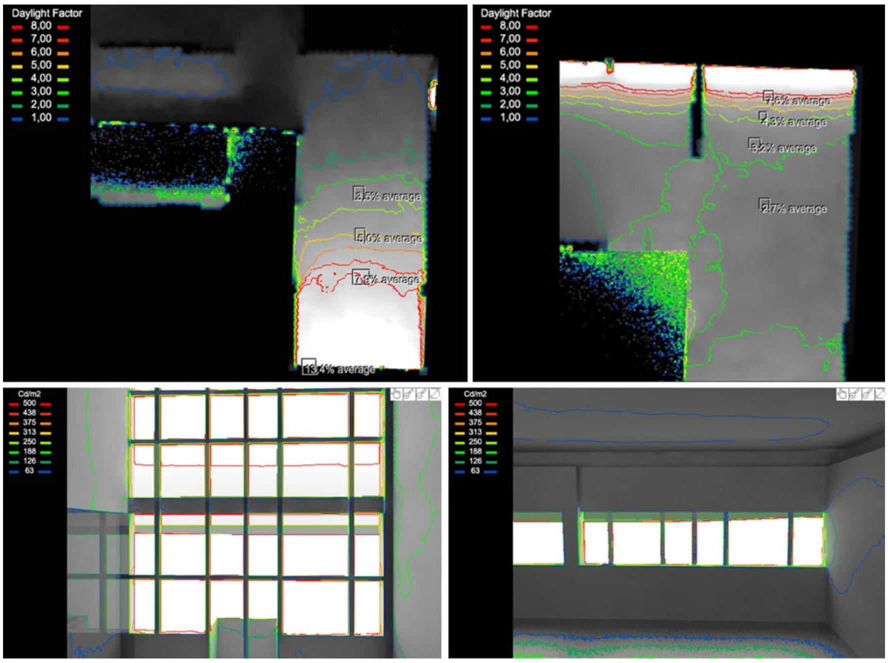

Fig. 11. Daylight factor and luminance in the living room and in the master bedroom (simulation in February) (R. Bellinazzi, 2018)

Table 1. FLD and E, mean values, different methods compared.

Method	Living room		Master bedroom	
	E_m (lux)	DF_m (%)	E_m (lux)	DF_m (%)
Geometric analytical (BRE)		9.98		4.91
Radiance software	479.3	7.33	244	3.73
On-site measurements	432.5	8.65	169	3.38

Mean values of DF are well over the 2% required by the actual standards for the whole surfaces, although the mean value does not have a great meaning in terms of visual comfort. Values over 8% are present 4 m away from the glass in the living room, and 1 m from the window of the bedroom. The images clearly show what was expected: values of DF change from more than 10% to less than 1% within the same room. In the same way illuminance range from 600 lux near the transparent surfaces to 60 lux in the darkest positions of the rooms. Levels of illuminance change also significantly depending on the month of the year (Table 2).

Output data from radiance method and BRE manual method using standard input data were compared with on-site measurements in order to be validated. The luxmeter was positioned in some checking points of the pavilion (Fig. 12); the distribution of measured values was compatible with methods, while the absolute values differed at least by 10%. The BRE method tends to overestimate the values.

Table 2. Mean E values in different months (4.00 pm); cloudy sky type 1.

Month	Living room E_m (lux)	Bedroom E_m (lux)
January	92.23	220
February	224	244
March	412.6	274
April	600	297
May	753	304
June	755	306.8
July	739	307.7
August	582	306.7
September	382.8	296.3
October	381	270
November	163.2	238.4
December	83.56	222

DF is constantly over 8% in the double space of the living room (5 m from the window), and illumination 2 m away from glass over 450 lux, which is what is required for a working activity (300-750 lux) and where Le Corbusier positioned the working table and the piano; visual requirements of precision start form 500 lux. That is conformed with the work an artist or an architect, who can draw with natural light in a cloudy day. The depth of the living room lowers the mean value of the luminance in winter, while in the bedroom the situation is more tolerable.

Discomfort is mainly caused by direct radiation during sunny days, which forces to use the curtains continuously, ending up with low illuminance levels and intolerable thermal conditions. The extensive study of luminance by Iommi on 7 houses by Le Corbusier confirms this evaluation [26].

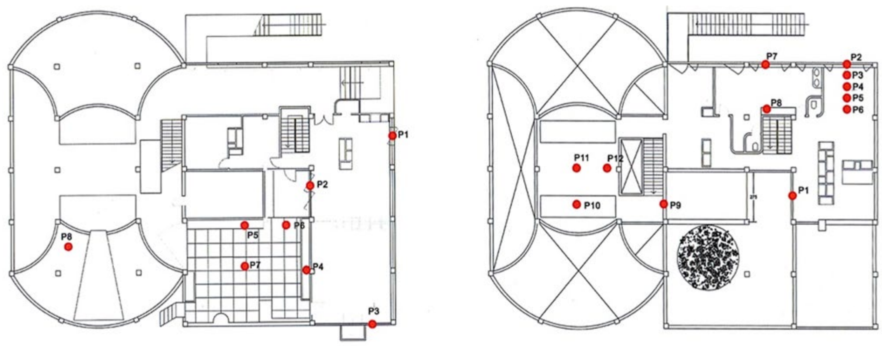

Fig. 12. Ground floor and first floor with measurement points (Bellinazzi, 2018

For the energy analysis another digital model was required, with the goal to understand the actual behaviour of the building and address its energy performances. In particular, the purpose of the energy analysis was to understand the internal comfort conditions, assessing the energy demand and eventually identifying energy retrofit strategies, since in the last 40 years its poor performances have been repeatedly highlighted. The characteristics of the building components were taken from the construction documents of 1977, kindly made available by the daughter of the author, the engineer C. Biagi. The reinforced concrete frame rests on continuous foundations and it is cast on site; it is made up of 21x21 cm pillars, placed at a variable distance on the east-west axis (5.2 and 2.7 m in the unit) and every 3 m on the north-south axis. The beams follow the north-south direction and have a span of 3 m too. The cladding walls, placed between the pillars, are made of prefabricated panels – straight for the house and curved for the diorama – , consisting of a 5 cm layer of polystyrene between two layers of reinforced concrete, each of the same thickness (Fig. 13). The floors, warped orthogonally to the beams, are made by a 4 cm prefabricated slab and by 15 cm high joists, which are cast on site between polystyrene blocks and an upper slab of 6 cm, accompanied by an electro-welded mesh of a 5 mm of diameter.

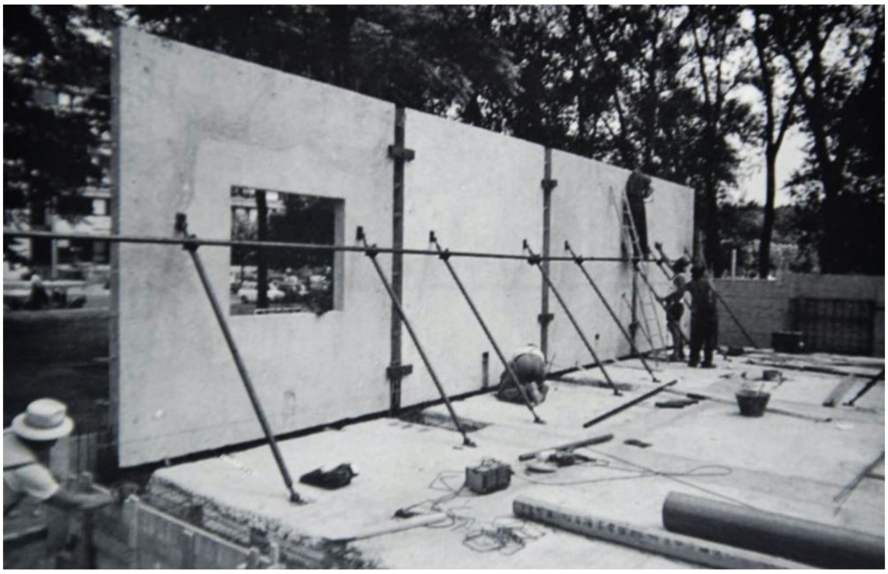

Fig. 13. Assembly of the prefabricated panels, 1977 (courtesy of G. Gresleri's Archive)

The building was modelled in Design Builder (Fig. 14), assuming an exhibition centre as a function [27]. The main parameters of the models are reported below. For location, geographical coordinates, and geomorphological details of the place (altitude on the sea level, exposure to the wind, characteristics of the land) the template and the climatic file of Bologna Borgo Panigale were chosen. It was assumed that the pavilion remained open in the morning for three days during the week and all Sunday during the hottest months. For the internal heat gains (computers, lighting, appliances, ...) the load was set to 5 W/m^2. Occupancy was set at 0.3 people/m^2, based on what is reported in the Standard UNI 10339 for exhibition halls and museums. An average value of 2.0 met was used for the metabolic rate, which refers to a situation where people are walking slowly. For hot water demand, considering an average turnout of 30 people per day and an area of 250 m^2, the average value was set at 0.24 l/m^2 per day.

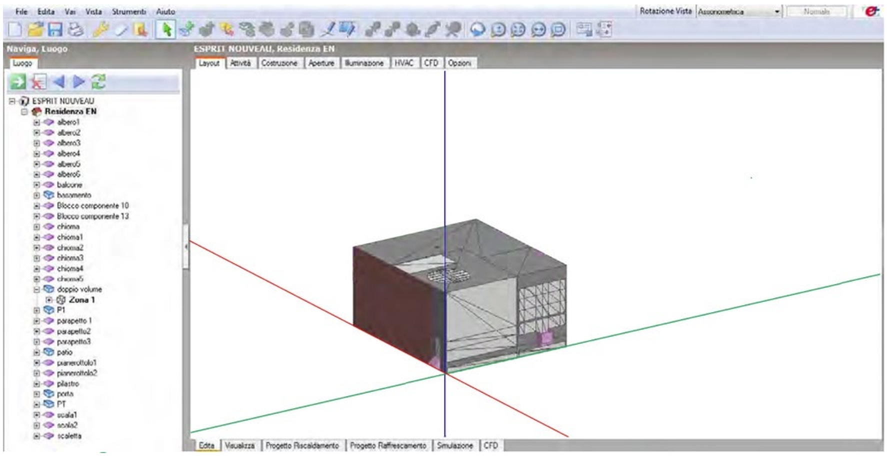

Fig. 14. Design Builder model (G. Abate, 2018)

The set point for winter heating was fixed at 20 °C and that for summer cooling at 26°C, equal to the natural ventilation setpoint. The ventilation air change rate was assumed to be 0.5 vol/h.

All the characteristics of the walls and windows were analysed. The calculated U-values of enclosures and partitions are the following: roof 0.747 [W/m^{2}K]; ground and first floors 0.731 [W/m^{2}K]; external prefabricated wall 1.617 [W/m^{2}K]. The diorama was excluded in the model, considering no heat exchange between the two parts. The Table 3 shows the results of the dynamic simulation, relative to the occupied periods (opening hours) during the winter season.

The difference between heat losses and energy gains are compensated by the heating system, considering that the system takes a certain amount of time to reach the required internal temperature. We can remark that although the windows are the main responsible for heat losses, their large extension on south direction gives high values of solar radiation, reducing the total energy needs for heating.

Studies on thermal comfort and air conditioning should be implemented in further research. In the figure below the trend of PMV and temperature is simply reported for a day in May, where it is evidenced that thermal comfort cannot be achieved without conditioning system even during the spring season (Fig. 15).

Table 3. Losses and gains of whole winter season for occupied periods.

components	losses	
	kWh	(%)
Glass surfaces	-14,980.74	39.35
Opaque vertical surfaces	-11,843.86	31.12
Ground floor	-4,985.83	13.11
Roof	-6,250.80	16.42
TOT (all season)	-38,061.23	100.00

components	gains	
	kWh	(%)
Solar (external glass surfaces)	+26,993.62	86.67
Solar (glass surfaces of the loggia)	+593.06	1.90
Occupation	+3,559.87	11.43
TOT (all season)	+31,146.55	100.00

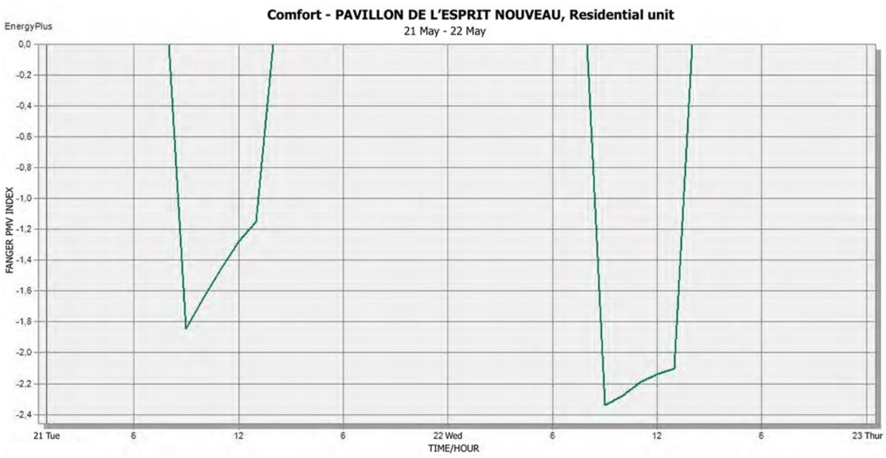

Fig. 15. Fanger PMV. Values set to zero during closing times; calculated only during opening hours, from 9.00 am to 3.00 pm. Month: May 21st and 22nd. Heating system not operating. Values show a slightly cool condition. (+3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold) (G. Abate, 2018)

Given the technological features of the replica of the original Pavillon de l'Esprit Nouveau, selecting passive solutions to improve the energy performances of the building becomes a challenging task. Considering the pureness of the building, any added element can easily cause a dramatic change in the visual impact. To make an example, since the windows are positioned flush with the outside, insulation should be placed only to the inside. This can be done using insulation with small thickness (20-40 mm); this thickness can be achieved with special materials like aerogel panels or similar (λ = 0.015 W/mK EN12667, μ = 5), aligning the insulation panels to the pillars. This will reduce the U-value of the wall to 0.3-0.4 W/m^{2}K, depending on the presence of thermal bridges. Windows frames can be retrofitted with double glass. A satisfactory insulation of the flat roof can be achieved more easily.

5 Discussion and final remarks

Today, performance analysis and, in general, digital representation facilitate the knowledge of Le Corbusier's projects. Quantitative analysis and digital representation offer a different perspective on Le Corbusier's work and help to better understand the functional characteristics of his buildings and the behaviour of the employed technologies, raising many questions on the quality of the projects.

With regard to the assessment of environmental quality in Le Corbusier's projects, it is necessary to focus on the concept of human comfort, because man – perhaps a new idea of man – was always placed at the centre of his research. The main goal of Le Corbusier's work was to satisfy human needs, rather than safeguard environmental resources, according to our contemporary approach. Although the effects on the environment of Le Corbusier's vision of modern city and planning can be reasonably opposed today, and the performances of his buildings are certainly not adequate, perhaps the focus should be shifted to the search for human well-being and his aspiration to live in functional spaces suitable for his modern life. Besides, the thermal comfort perceived by Le Corbusier has a very strong sensorial psychological component. His approach is definitively holistic – see Cristian Chironi experience – and not only quantitative. There are other Le Corbusier's projects that better represent the search for this comfort after the 1930s.

If the principles of Modernism privileged the north-south orientation for apartment buildings, in the Immeuble Villa these concepts were not accomplished yet, because orientation was not a specific matter of that project. The issue of orientation was developed later in Le Corbusier's work, when the concept of *brise soleil* was developed. Moreover, in the case of the pavilion in Bologna, orientation is not an issue, because it derives directly from the location of the building.

Furthermore, the shape of the openings in the pavilion does not allow the modulation of light. In fact, an excessive radiation was clearly detected. The difficult assessment of light does not favour an acceptable use of some rooms of the units, especially the living areas and curtains are necessary in summer days to avoid an excessive amount of natural light.

Finally, materials that have been used in the replica were not particularly performative. This aspect has an impact on the use of the building, that is today hardly adaptable to other uses, especially during the winter season. The architects of the replica in Bologna did not look at the low energy performances of the original. They just sought the most similar materials, in a sort of exact replica, without being interested in any technological improvement. In doing so they jeopardized the future use of the building. Today environmental quality and thermal comfort of the pavilion have become a complex problem of restoration. The question to be raised now is whether to pursue a strictly rigid policy of conservation, to faithfully preserve the integrity of the replica, or rather regenerate the building in order to use it more profitably.

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