Living and Comfort Conditions in Heritage Housing: The Inner Courtyard as a Uniting Element in the Cités of Santiago Poniente

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Abstract: Heritage buildings represent an essential housing stock that has been available in Santiago de Chile for over a century. However, most of these buildings show sustained deterioration due to lack of maintenance, which creates degrading living conditions for its residents caused by habitability problems. One of these cases is the "cité" typology, which was massively built at the end of the 19th century. The Cité is a group of houses with a continuous facade, with built areas of 50 to 80 m², connected through a common and private space that provides access to the residences. Currently, the reduced housing area in the city has forced users to occupy the existing courtyards to satisfy their needs. This situation affects interior lighting conditions, thermal control, and air quality. These interventions modify the architectural design into units with only one facade exposed to the exterior environment. Nevertheless, adaptation strategies have become more and more complex due to restrictions on heritage building regulations, which generally do not meet thermal performance or natural light availability.

Among the environmental conditions, indoor air quality is a relevant factor and could be related to the progressive deterioration of the residence’s interior conditions, and the health of its residents. The methodology considers data compilation on existing units and energy performance simulations of both original and existing units. Software such as DesignBuilder and a wind tunnel were used to simulate different habitability variables. Results confirm that in the majority of cases studied, indoor air quality is not bad due to air infiltrations as a product of modifications, spontaneous extensions, and building deterioration through the years. However, they show an inadequate thermal performance that does not meet the minimal comfort conditions. Nevertheless, the simulations on original units demonstrate a positive impact of courtyards for reaching ventilation and natural lighting standards. Measurements on-site have shown a beneficial effect from using vegetation in ventilated covered courtyards.

1. Introduction

Currently, cities face increasing housing demand thanks to population growth. According to data from INE Chile, Santiago inhabitants have grown from 6,094,118 in 2002 to 7,112,808 in 2017 with an estimated population of 7,500,000 for 2020 [1]. This situation is accentuated in central areas, with Pudahuel being one of the communes with the highest housing deficit in the country [2]. In many cases, existing houses are adapted by users to respond to family growth or for a simple lack of space. However, informal extensions and renovations run the risk of deteriorating habitability conditions, putting at risk their health and the lifespan of the building.
Housing habitability conditions include factors such as thermal, lighting, and acoustic comfort, humidity, and indoor air quality. These are closely linked to user behavior, building design, shape, orientation, materiality, and weather [3]. These factors are altered on buildings with spontaneous modifications by the emergence of new facades with no insulation, close enclosures, or deep ones. Insufficient sunlight and limited natural lighting translate into higher demand for lighting, heating, and poor indoor air quality.

In some old buildings (such as traditional houses, worker buildings, and cité housing), this subject is far more complicated due to potential regulative restrictions for safeguarding cultural and architectural heritage, which can limit the possibilities for interventions. The design of these houses includes interior courtyards whose function is to light and ventilate enclosures naturally. However, because of the reduced surface of the house, residents have occupied these courtyards, thus altering the quality of the indoor environment and, currently, they show poor maintenance and vulnerability due to deterioration.

Heritage houses represent an architectural value that needs to meet current habitability conditions for them to be sustainable in the face of city growth. Nonetheless, the impact of informal modifications has not been assessed in depth. For this reason, this study analyzes and evaluates indoor air quality conditions, natural lighting, and thermal comfort as a reference for intervening or rehabilitating houses of heritage value.

2. Cité houses and their habitability conditions
Among buildings with heritage value, the cité type represents the first expression of social housing in Chile that was built on a massive scale, and that has survived city transformations, such as earthquakes, pressure from the real estate sector, and resident relocation to different communes [4]. The Cité is a group of houses with a continuous facade, with one or two stories, and built areas of 50 to 80 m², grouped around a common and private alley that functions as the primary access to the houses. Ventilation and sunlight come through either the alley or inner courtyards present in some of the designs. However, because of the narrow space between buildings, it is common to find issues with sunlight. The cités were built at the end of the 19th century as an example of small surface "sanitary low-cost housing" [5] [6]. Typically bedrooms, kitchen, and bathroom are directly connected by an inner courtyard without interspaces as a transition between the exterior and interior. This courtyard has different uses, sizes, locations, and features in order to illuminate adjacent areas and improve natural ventilation inside the house.

178 homogeneously scattered cités have been identified in the Santiago commune, most of which have been cataloged as heritage real estate. The case study considers five residences in four cités of the Restoration of Cités and Alleys Program 2013 – 2016, as part of the heritage real estate built between 1910 and 1945 [6]: cité General Bulnes 1411, Escorial, Recreo and Riquelme 828. For these case studies, we have used the following denomination:

- Case A: L3 Housing - Cité Recreo
- Case B: N°13 Housing - Cité General Bulnes 1411
- Case C: N°8 Housing - Cité General Bulnes 1411
- Case D: N°13 Housing - Cité Villa el Escorial
- Case E: N°1 Housing - Cité Riquelme 828

The residences show different architectural configurations related to the location of the inner courtyard, but they have similarities in the number of stories, orientation, and materiality. Inner courtyards have a surface of 12m² approximately, and their location varies inside the houses, as can be seen in Figure 1. Currently, cases A, B, and C have a roofed inner courtyard, while cases D and E keep it open (figure 2).

In most of the cité housing, the inner courtyard distribution corresponds to one of the types of the studied cases. This configuration entails the methodological replicability of the study to residences with similar characteristics and a possible impact in the recovery of heritage neighborhoods.
3. Methodology

In order to identify habitability conditions, a land registry card was made from photographic and planimetric surveys, where pathologies and modifications to the building were registered. Next, to assess the degree of deterioration of the lighting and thermal comfort, and the quality of indoor air, a comparative analysis was made between the original scenario and the current scenario through measurements on-site and computer simulations. Then, the process of extraction of quantitative data is described for each factor for subsequent evaluation.

3.1 Thermal comfort analysis

A temperature and relative humidity registry was done through measurements every 10 minutes with hygrothermal measurement instruments (HOBO U10 Temp/RH), during the summer-fall transition, between March 15th and 31st. A comparison of the demand for annual heating and refrigeration was made between the original and current scenarios. The DesignBuilder software was used to identify the total hours of thermal comfort and relative humidity at the interior of the premises during the selected period. Transmittance requirements for the envelope, as described in the current Thermal Regulation for Santiago, were used for the thermal analysis [3].

3.2 Lighting comfort analysis

Lighting measurement was made using HOBO Pendant® Temp/Light, 64K, with a data registry every 10 minutes between March 15th and 31st. Two enclosures were considered. One directly connected to the inner courtyard, and the other located at the back of the house. The conditions of the original scenario of the house were simulated using the DesignBuilder software.

3.3 CO2 Measurements and wind tunnel

CO2 levels were registered on-site inside the residence with HOBO MX CO2 meters, with data obtained every 5 minutes between May 27th and June 2nd, a time when temperatures in Santiago start decreasing. Since ventilation is closely related to indoor air quality, an assessment of air circulation was made by simulations in a wind tunnel for physical models.
4. Results

4.1 Thermal comfort analysis
Thermal transmittance of the envelope’s constructive elements on the studied residences presents higher values than allowed by the current regulations (table 1), where the most significant differences are found on floors and roofs. The thermal transmittance of the walls studied (30 cm. thick adobe with $U=1.94 \text{ W/m}^2\text{K}$) is close to what the stipulation requires in the regulation. Nevertheless, residences that have a brick masonry envelope are the exception ($U=2.89 \text{ W/m}^2\text{K}$). The percentage of the glazed surface on the facade meets the regulations as adobe constructive systems require minimal openings according to their structural requirements [7]. For a better understanding, we have used the following denominations:

- Case A: L3 Housing - Cité Recreo
- Case B: N°13 Housing - Cité General Bulnes 1411
- Case C: N°8 Housing - Cité General Bulnes 1411
- Case D: N°13 Housing - Cité Villa el Escorial
- Case F: N°1 Housing - Cité Riquelme 828

Table 1. Thermal Transmittance Values for Envelope Elements on Case Studies and Regulation Requirements (Art. 4.4.10 General Construction and Urbanism Ordinance)

| Item    | Roofing | Walls | Floors | Windows (max. % of glazing in relation to the envelope) |
|---------|---------|-------|--------|-----------------------------------------------------|
| REGULATION | 0.47 W/m²K | 1.9 W/m²K | 0.7 W/m²K | 25% Monolithic Glass |
| CASE A  | 3.45  | 1.94 (adobe) | 1.68 | 22% |
|         |       | 2.89 (masonry) |    |    |
| CASE B  | 3.45  | 1.94 (adobe) | 1.85 | 14.23% |
| CASE C  | 3.45  | 1.94 (adobe) | 1.68 | 11.09 |
| CASE D  | 3.45  | 1.94 (adobe) | 1.68 | 12.5% |
| CASE E  | 3.45  | 1.94 (adobe) | 1.85 | 11.08% |

Own figures based on Art. 4.1.10 General Construction and Urbanism Ordinance

4.1.1 Digital simulations
An annual thermal performance simulation was conducted both for the original design of the house and its current situation. The comfort range was set between 20°C and 27°C [3]. Table 1 shows results for thermal comfort hours (%) in winter and summer, and design characteristics of the inner courtyard as well.

Simulations done for the winter period did not meet comfort levels. The zinc coats without insulation in the houses have a high thermal transmittance. In these cases, there is a significant loss of heat due to infiltrations resulting from bad roof installation, which shows openings of three to five centimeters wide.

Modifying the inner courtyard by covering it decreases heat loss through ventilation of the premises, but the translucent material of the roof also increases incident solar radiation. The indoor temperature in cases B and C with covered inner courtyards showed an increase of 0.2 and 1.5°C during winter, and between 0.5 and 1.5°C during summer. In these cases, renovating the inner courtyard by covering it improves the overall thermal comfort of the residence (figure 2).
In the summer, studied cases reach comfort levels as the mass of the walls prevents overheating, and the height from floor to ceiling is 3.20m. In cases with a covered inner courtyard, the roof's reduced level of transparency has a positive impact on the comfort conditions of the premises, since direct solar radiation becomes limited.

The original scenario in Case A shows overheating during summer when only 29% of the time, it stays at comfort level. Whereas, in the current scenario, it does not meet any thermal comfort at all. This result is due to the 100% translucent roof generating a greenhouse effect. Nonetheless, this condition differs from on-site observations due to the presence of vegetation in the courtyard, as shown in figure 2 and detailed in section 4.1.2 here below. We do not find the same phenomenon in simulations on Cases B and C with covered courtyards, as the roof transparency corresponds to 11% and 22%, respectively.

### 4.1.2 Measurements during the summer-fall transition period

On-site measurements of residences with covered inner courtyards (Cases A, B, and C) were made during the fall-winter transition (March 15th - March 31st). Table 2 shows results with comfort hours (%). A reduction of heat loss through the walls was confirmed when the inner courtyard was covered. As a result, thermal fluctuations are smaller than those of the original design. In the summer, direct solar radiation over the courtyard can be reduced if the roof is opaque, but if it is translucent, overheating of the house can occur. In Cases B and C, there is an identifiable connection between comfort hours and the level of transparency of the patio roofing. However, in Case A, the covered courtyard has 100% transparency but reaches higher thermal comfort levels. This condition is the result of vegetation present in the inner courtyard as it generates shade, thus avoiding direct solar radiation and decreasing temperature via plant evapotranspiration (fig. 3). It is a decisive factor since it represents a passive cooling strategy [8] [9]. These results differ from the simulation as the software only considers the shade provided by vegetation but not its evapotranspiration process.
Figure 3. Thermal comfort percentage of high usage enclosures in residences with courtyard expansions

a) Case A shows indoor vegetation b) Case B c) Case C

| CASE | Comfort Hours % | Translucent elements % in covered courtyards |
|------|-----------------|---------------------------------------------|
| A    | 50%             | 100%                                        |
| B    | 90%             | 11%                                         |
| C    | 60%             | 22%                                         |

Table 2. Comfort hours percentage in cases with covered inner courtyards

In order to identify the effect of vegetation on indoor temperature's performance, we analyzed the performance of covered courtyards of Cases A and B. Both courtyards lack southern orientation; the courtyard in Case A has vegetation (figure 4), but not the one in Case B. Vegetation in Case A consists of approximately twelve plant pots with foliage of 0.30 m. to 1.00 m. wide.
The analysis considered on-site measurements for the three days when the majority of thermal fluctuations were registered. Results demonstrate that Case A shows a more constant temperature in comfort ranges between 20°C and 25°C. When the outdoor temperature reaches 13.6°C at night, the registered indoor temperature is 20°C, whereas when the outdoor temperature reaches 29.4°C in the day, the indoor temperature is 24.1°C (figure 5).

Figure 5. Indoor temperature performance of covered courtyards with southern orientation CASE A vs. CASE B.

Figure 6 shows photos taken with a thermal RayCAm camera, on May 23rd at 13:00hrs. with clear skies. It is noticeable that vegetation in Case A is at 15.4°C, while the roof reached temperatures up to 39.27°C. Adjacent walls show a superficial indoor temperature of 12.4°C as a result of the shade when the outdoor temperature is 20°C. The vegetation of the case studied reflects 20% to 30% of solar radiation.
4.2 Lighting Comfort Analysis

Inner courtyards in the cités are located on places that allow for illuminating areas at the back of the residence or on the sides. Computer simulations of the original scenario show lighting levels within standard comfort for the summer (80 - 300 lux), but it does not reach lighting comfort levels in the winter when the sky is overcast.

Case A has better natural lighting as the inner courtyard is located in the central area of the residence, which allows for a more homogeneous distribution by having four facades with a glazed envelope. By contrast, the original scenario in case C shows lower rates of lighting comfort. The reduced dimensions of the inner courtyard with only two facades do not allow for natural light to come in.

Measurements of the current scenario of our case studies with covered courtyards do not meet recommended levels or exceed 40 lux. In most cases, enclosures adjacent to the courtyard are almost in complete darkness as a consequence of renovations and furniture displays that obstruct the windows facing the courtyard. Thus, residences depend on artificial lighting with and energy demand between 50 and 75 US$/month.

Simulations and measurements that were done on-site have demonstrated that expansions and renovations to the initial plan result in adverse habitability conditions concerning lighting.

4.3 Air quality analysis

Wind tunnel simulations show that the original scenario of the residence allows for cross ventilation through the inner courtyard, even by having only one facade with external ventilation. The current scenario presents air-tightness as a result of the modifications that were made. The stale air generated in kitchens and bathrooms concentrates at the interior of the house and is not expelled through unilateral ventilation (figure 7). As a result of condensation and lack of ventilation, there is humidity on walls and ceilings in bathrooms and bedrooms (figure 8).
Figure 8. Presence of humidity on residences with facades facing the outside environment

In renovations where the inner courtyard has been covered, there are openings between the residence and the deficient installation of the new structure (3 to 5 cm.). These openings affect the thermal performance of the residence negatively, but they have a positive effect on the quality of indoor air during the winter period, as air renovation is constant and ventilates the inner spaces of the residence. Indoor CO$_2$ measurements did not exceed 1000 ppm when the range of outside air was 300 to 470 ppm. However, there was a significant increase in CO$_2$ concentration in closed areas and when gas heating was used. In cases C and D, total comfort hours of air quality only reached 46% and 56%, respectively.

5. Conclusions
This study has implemented on-site measurements and computer simulations of habitability conditions, to assess the impact of informal renovations on residences in cités in Santiago.

It has been demonstrated that the design and location of the inner courtyard have relevance to the thermal comfort performance, lighting performance, and air quality in the residences. By roofing the inner courtyard, there is a slight improvement in the thermal performance of the residence, but there is also the risk of overheating in the summer. The main negative impact of the covered inner courtyard is unacceptable lighting levels, which make residences dependent on artificial lighting. The studied residences reach comfort levels regarding CO$_2$ since uncontrolled ventilation does not permanently renew indoor air. However, closed areas do not reach comfort levels regarding indoor air quality.

It was also established that the presence of plants in inner courtyards represents an asset to energy savings, through the obstruction of solar radiation and evaporative cooling. For future development, it is recommended to evaluate the impact of vegetation in other houses of similar characteristics to determine its impact with better accuracy.

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