

On natural ventilation and thermal comfort in compact urban environments – the Old Havana case

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Abstract

The Historical Centre of Old Havana in Cuba is currently undergoing a comprehensive preservation and urban recovering program. Housing units are built in existing vacant plots of the old city. The design of the new buildings should be integrated in the compact urban structure that has developed throughout the past centuries. This compact morphology however obstructs the breezes that are an essential component to achieve thermal comfort by passive means in warm and humid climates. New courtyard buildings should be designed in such a way that natural ventilation and thermal comfort are enhanced. Research on natural ventilation and thermal comfort in compact urban environments however is scarce. This paper first presents an historical overview of the typological evolution of the residential architecture in this part of the city and its relation to natural ventilation and thermal comfort. Next, it provides a partial study of the morphological characteristics of the Historical Centre. From this study, appropriate locations have been selected for field measurements and a limited comfort survey, from which a tentative summer comfort zone for residential buildings in Old Havana is suggested. Finally, based on the historical overview, the measurements and the survey, some preliminary design recommendations for residential buildings in Old Havana are provided.

Keywords: Courtyard building; Warm humid climate; Compact morphology; Air flow; Residential architecture; Field measurements

1. Introduction

The Historical Centre of Old Havana in Cuba comprises the former intramural Colonial City and other surrounding areas¹. Because of the large amount of valuable buildings from a historical and architectonic point of view and the high-qualified urban environment, UNESCO declared the Fortress System and the Historical Centre of Old Havana a “World Cultural Heritage” in 1982. The Old Havana urban structure is very compact, which has a negative impact on the potential for natural ventilation and thermal comfort. Cuba, and Havana in particular, is located close to the Tropic of Cancer as illustrated in Figure 1. The climatic conditions are less extreme than in Continental Tropical regions thanks to the sea breezes, but nevertheless, as in other islands with Marine-Island Tropical climate, there is a combination of relatively high values of air temperature and high values of relative humidity that can produce uncomfortable conditions during long periods of the year. The

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¹ In this paper we will refer to the Historical Centre as the area that comprises only the former intramural city and not the surroundings due to their different morphology and historical evolution.

August daily mean maximum temperature is 31.4°C, the daily mean minimum is 23.8°C, the August daily mean maximum relative humidity is 91% while the daily mean minimum is 68%.

The very compact Old Havana urban structure has kept the same street network for centuries (Fig. 2). Most of the Cuban cities were founded during the process of colonisation after the arrival of Spaniards in 1492. Havana was founded in 1519 and it was built with climatic factors in mind, but those of the dry climate of Southern Spain and not those of the humid conditions of the Caribbean Islands. As a result, the urban scheme and architectonic patterns followed since the beginning (contiguity of houses, each with a courtyard) was that of the hot-dry lands and somehow with the influence of the Islamic tradition which gave the houses an introverted character. As time passed, the envelope of those introverted houses – walls, roofs and windows – was gradually adapted to the local climatic requirements, but the existing fabric and urban structure were never abandoned. During the 20th century, due partly to land speculation, a process of densification started in the Historical Centre. Nowadays, the urban blocks in Old Havana are formed by a compact layout in which the only open spaces are the inner courtyards of each building, most of which are very small (Fig. 3). The streets are very narrow allowing shade during the day hours but obstructing natural ventilation. Research has indeed shown that in narrow passages and streets between buildings, the so-called Venturi-effect is almost negligible, and that street ventilation can decrease rather than increase when the streets get narrower [2-4]. This is important because natural ventilation by wind is often the only available strategy to achieve thermal comfort or at least to diminish the hot sensation of occupants. The large majority of the population in Cuba and in many other tropical and humid regions can not afford the use of air-conditioning. In the present global energy crisis, sustainable solutions should be found to reduce energy use while increasing the quality of life of the people.

Due to lack of maintenance, the Centre of Old Havana currently comprises many vacant plots, buildings in ruins and houses declared uninhabitable and practically irrecoverable. On the other hand, there is a high demand for new dwellings inside the existing urban tissue. The Historian Office of Havana, which is the main institution that is in charge of the recovery of the Historical Centre [5,6], is leading the construction of new housing on the vacant plots. The new dwellings should be integrated in the compact urban structure. At the same time, their design should be directed towards providing better thermal comfort to the inhabitants. However, the present urban and building regulations do not contain specific thermal and natural ventilation requirements.

Most of the studies [7-9] recommending solutions to improve thermal comfort in cities in tropical and humid climates were made for “ideal” spread-out urban environments that are not really representative for the compact urban structure in several actual tropical cities like Old Havana. Some studies have been made concerning courtyard buildings and their climatic behaviour, but most of them focused on courtyard buildings located in hot and dry climates [10,11]. Other studies focused on isolated courtyard buildings [12] with apertures all around the building envelope, which is different from the situation in Old Havana. The most important study in Old Havana concerning climate and architecture is “The compact city, architecture and microclimate”, by Alfonso et al. [13], which focused on exterior measurements (streets and courtyards) of temperature and relative humidity in Old Havana and other compact urban areas like the “Centro Habana” municipality. This study however did neither include wind speed measurements, nor an analysis of thermal comfort conditions inside buildings.

New courtyard buildings should be designed in such a way that natural ventilation and thermal comfort are enhanced without an increase of energy use. At the same time, these new buildings should be integrated in the existing compact urban environment. Research on natural ventilation and thermal comfort in compact urban environments is scarce. In this framework, this paper first presents an overview of the typological evolution of the residential architecture in this part of the city and its relation to natural ventilation and thermal comfort. Next, it provides a partial study of the morphological characteristics of the Historical Centre, from which appropriate locations for field measurements and a comfort survey are selected. After that, a tentative summer comfort zone for residential buildings in Old Havana is suggested. Finally, based on the historical overview, the measurements and the survey, preliminary design recommendations for residential buildings in Old Havana are given. Note that, throughout this paper, the term natural ventilation is used to indicate ventilation by wind (forced convection) and/or local temperature differences (natural convection), as opposed to mechanical ventilation.

2. Evolution of residential architecture in Old Havana and its relation to climatic aspects

The evolutionary process of the residential architecture in the Historical Centre of Old Havana and its qualitative relation to climatic aspects, comfort and people’s way of life are presented. It provides the background and the basic context for future building design and interventions in the Centre. It is a selective representation of the evolution of Old Havana’s residential architecture rather than an exhaustive and complete study of its history. It is based on the concepts of the “Historical Reading” method [14] but its principles are adjusted to the specific aim of this study. The main objectives are (1) to present the typological evolution of the houses in Old Havana in a compressed form through previous studies [15-18] and field work; (2) to decompose each building type and to identify the creation and evolution (positive or not) of its typological elements along time; and (3) to analyse the relation of these typological elements with the climatic, functional and cultural

aspects in order to recognise those elements that should/could be kept in new buildings' design. The new temporal classification of the different building types made in this study is described below. It considers three main periods, taking into account the type of plots:

1st period: Along the 16th century

2nd period: *Type 1: Narrow plot:* From the end of the 16th century to the beginning of the 20th century
Type 2: Wide plot: From the 17th to the 19th century

3rd period: From the end of the 19th century to the end of the 20th century

Plot subdivision in a (compact) urban area will often be constant over a long period. So throughout the centuries, the type has been adapted on the same plot layout. In some cases adjacent plots were merged. In the following overview, the description is accompanied by a series of figures and drawings that were specifically made for this analysis.

2.1. First period: From rural "bohío" to urban courtyard house²

The first houses Spaniards built followed the aborigine "bohío" type. They were rectangular with a single space made of plank-like walls and palm-thatch roof [16] (Fig. 4). Due to the highly combustible properties of the "bohío" materials these houses were gradually replaced after fire and in 1576 the roofs made of thatch were forbidden in the intramural area. Still, even in 1622, many bohío-type houses existed in Havana. During the 16th century, an important process of house evolution took place (Fig. 4). The rectangular blocks, the plot size and its elongated shape somehow guided the house layout. The first isolated bohío-type (Fig. 4a) gradually evolved to a courtyard house (Fig. 4d). The first step was the occupation of the whole front line (Fig. 4b), by which the isolated house became a parting-wall house. Later, more important transformations occurred in the backyards where successive extensions, first as an open covered space for horses and house provisions (Fig. 4c) and later as an interior space (Fig. 4d), shaped the inner courtyard. This process of gradually filling in the plot and the evolution of a type or the creation of a new one have also been described in other contexts with the name of "property cycles" [19] and "burgage cycle"[20]. The two main reasons for the creation of the courtyard-house were (1) the process of filling up the plot area combined with the improvement of building materials and (2) the influence of the architecture from the South of Spain. Because most of the bricklayers and operators came from southern Spain, its architecture had a mayor influence in the first Cuban constructions. The Moorish courtyard house in Andalusia was considered as a sign of well-being, because the courtyards provided light and fresh air to the interior in contrast to the gloomy and badly ventilated houses of the majority of the population [15]. In addition, the courtyards provided a private and secure space for outdoor activities. For those reasons and due to the initial higher availability of land, the house scheme with courtyard was adopted in the Americas for every house, independent of the social condition of its inhabitants.. Overall, both the employment of the courtyard and the use of better and more durable materials in this period until the end of the 16th century, contributed to a more comfortable environment inside the houses from climatic, spatial and material point of view.

2.2. Second period - Type 1: One-family house on narrow plots

The narrow and elongated plots in the compact environment restricted the possibilities for architectural variations. This can be one of the reasons why the one-family house of one and two levels kept a similar layout, except for some changes of space use, from the end of the 16th century until the first decades of the 20th century (Fig. 5). The houses on narrow plots accommodated the lower and middle class and their development was strongly influenced by the evolution of the larger houses in the wider plots that will be discussed in section 2.3. The layout of the narrow-plot one-family house included a lateral courtyard. The house had one or two courtyards according to the depth of the plot. The second courtyard is called "traspatio" and it served for domestic activities while the first one had a more representative and thus ornamental character. The entrance hall or "zaguán" was first positioned in such a way that the views to the interior were blocked (Islamic tradition, not shown here). Then, the zaguán was displaced in the axis of the courtyard (Roman tradition) [18]. The existence of an axis street-courtyard-traspatio, through corridors on the ground floor, allowed cross-ventilation, potentially contributing to thermal comfort.. In the course of time, the ceiling heights changed from 3.00 to 5.50 m. The roofs changed both in material and shape. The first roofs, called "alfarges"³, were pitched and were made of

² The plans of the houses on figures 4 to 7 are mainly based on a typological classification made by Menendez [17], the plot drawings and the axonometric drawings were made by the authors and are an interpretation of the main features of the building types rather than a specific existing house. Some facade characteristics are also taken from Weiss [15], Menendez [17], and by direct observation. The pictures are all taken by the author except the picture of figure 4 and the last picture of figure 6 which are reproduced from Weiss [15] with permission. The first picture on figure 5 is taken from the Historian Office [6].

³ Name of the timber roof structure from Andalusia's Moorish and Mudejar Architecture that is present in simpler forms in the roofs of Havana's houses and churches. Due to the clear inspiration source, the origin of the carpenters and its similarities to that of Andalusia's alfarges, Prat Puig [16] continues calling the Cuban roofs with the same name.

timber covered by red tiles (Fig. 5a and 5b). Later, due to fashion changes and the lesser influence from Mudejar⁴ practices, flat roofs substituted the alfarges, but still using timber as main material (Fig. 5c and 5d). The facade design changed according to the style of the time and at the same time, the windows were subjected to a gradual transformation to be more permeable to the exterior environment: their size increased (higher ratio of window to facade dimensions), which permitted more light and higher ventilation rates, indoor air speed and a better airflow distribution inside the rooms [7-9, 21]. The window design became more complex with the addition of louvers or Venetian blinds (Fig. 5c) and later the “luceta” or stained glass in the upper part of doors and windows (Fig. 5d).

In conclusion, several of these changes can be considered as a sign of progress. The existence of more than one courtyard (allowing cross-ventilation) and the higher ceilings and the wider windows with louvers positively affected the ventilation and/or thermal comfort conditions inside the houses. Besides, the process of facade opening and permeability was in line with the emergent local lifestyle to have direct relation with the exterior. The covered courtyard circulation and the use of stained glass above openings favoured solar and rain protection. Other progress included the use of stronger wall materials that allowed lighter walls and wider interiors.

2.3. Second period –Type 2: One-family house on wide plots

The largest plots, shown in Fig. 6, accommodated the houses of the wealthiest families from the end of 17th century to the 19th century. The house plan was developed around one or two open courtyards, thanks to the wider shape of the plot. In the case of two courtyards the first one was always the most important and widest. Three or four galleries surrounding the patio served as a transitional space between the courtyard and the interior. The gallery was in its beginning a narrow covered space for circulation purpose (Fig. 6a). Later, it grew in depth and transformed into a wide continuous space (Fig. 6b). In the 19th century, some of the existing galleries were closed with large operable windows that allowed users to open them completely during the hottest hours or close them while having ventilation by the louvered windows (Fig. 6c). Most of this carpentry included stained glass.

The zaguán or entrance hall was another space inside the house that played an important role for the connection between the inside and outside space. The zaguán moved from a corner place on the facade to the central position in line with the courtyard. Because of this position and its wide dimensions, meant to allow access to horses and carriages, the zaguán permitted air circulation between the street and the courtyard, thus improving ventilation during the day hours.

The balconies in Havana evolved from being individual for each opening (Fig. 6a) to run along the whole facade (Fig. 6b and 6c). At the beginning, Havana’s balconies had a roof protection at a lower level than the main roof, and in the 19th century, due to the incorporation of neoclassical patterns, this protection was substituted by a kind of cornice over each opening (Fig. 6c). The balconies had a balustrade which allowed the breezes to pass into the rooms.

In the 18th century, the houses that had a facade facing a main square started adding open porticoes that were public at the ground floor and private at the upper floor (Fig. 6b). These porticoes are covered porches or walkways supported by regularly spaced columns at the building facade. Like the courtyard galleries, they created a transitional space from which the inhabitants could enter the house through the zaguán that was connected with the inner courtyard. They also provided shading and rain protection to pedestrians and a space where the inhabitants could benefit from higher air speed than inside the rooms.

Most of the architectural changes in this type of houses can be considered a sign of progress in terms of natural ventilation and thermal comfort. They show in their process of evolution a clear adaptation to the local climate and customs. However, concerning the solar protection over the openings, the removal of the balcony cover was a negative transformation. The larger dimensions of the courtyard provided less solar shading on the courtyard floor compared to the narrow courtyards that generally provided more solar shading.

The process of “adaptation” of Havana’s houses towards the climate and local customs stopped in Old Havana after the wealthiest families moved out to new urbanisations. This process of adaptation and cultural transformations continued in greener and less compact urban morphologies.

2.4. Third period: Multi-family and mixed buildings

The turn of the 19th to the 20th century marked crucial changes in the Cuban scenario. The two wars against Spanish colonisation (1868-1878 and 1895-1898) and later the American intervention (1898-1902) and the constitution of the Republic under strong influence of the United States, which lasted until the Revolution of 1959, provoked big architectural and urban changes in Havana. The construction of multi-family buildings in the

⁴ Mudejar is the name given to the art and architecture developed after the defeat of the Moorish in the south of Spain at the end of the 15th century. It is a mix between the Moorish and Spanish-Christian art.

intramural area was common from the end of the 19th century. Figure 7 illustrates the main features of the evolution of residential architecture during that period.

During these decades, after the abolition of slavery in 1886 and the demolition of the city walls, the richest families moved out of the intramural city and started building eclectic villas in the new “garden city” areas of “Cerro” and “Vedado”. The servants and former slaves occupied the Colonial houses and subdivided them. These transformed houses are called “Solares” or “Ciudadelas” and have subsisted till present times. A new typology “Cuartería” (Fig. 7a) also appeared for the worker class. These buildings of one or two floors have a lateral or central courtyard and accommodate several families each one in one or two rooms. The facades of these buildings followed the stylish norms of Neoclassicism and latter of Eclecticism. The exterior image did not differ very much from the other “higher class” houses. Besides, the cuarterías kept in their design the positive contributions of the previous house-types like the use of balconies along the facade, the operable windows with louvers and lucetas and the courtyard as an obligatory element for light and ventilation.

The evolution of the multi-family buildings brought negative consequences concerning thermal comfort. The process of densification by the construction of new apartment buildings affected the courtyard aspect ratio (width/height) and transformed the courtyard from a place of rest and transit to a narrow space with poor light and ventilation (Fig. 7c). In addition, the transfer of some principles of the Modern Movement which were mainly developed for open urban environments, like the simplification of window design, the transformation of the balustrade into a brick wall and the lower ceilings, negatively affected the ventilation inside the apartments.

2.5. Recognition of typological elements and their purposes

A main objective of the historical reading in this study is to distinguish essential elements of the past residential architecture that can be interpreted in new buildings and proposals for building regulations. Two parallel pattern systems; the “typological elements” and the “purposes”, have been elaborated⁵.

The typological elements are divided in three categories that correspond with different scales: house spatial layout, building elements and additional elements. Purposes and uses have also three categories according to the type of functions: house functional organization, climatic functions and customs and traditions.

From the distinguished elements and their relation with purposes, the most important links among them have been recognised. The element that responds to more purposes is the courtyard-gallery seconded by the courtyard, facade-galleries and balconies. The most repeated purpose is ventilation, as demonstrated by eg. by the use of courtyards, porticoes, louvers on windows, higher ceilings, etc. Other purposes are, solar protection, ornament and rain protection. Some climatic purposes linked to elements like louvers, remain constant during the analysed period. The protection from direct solar radiation and the control over the wind flow are good examples of the required permanence in time of certain functions in order to improve the thermal condition inside the houses independent of the historical period and the style of the building.

3. Morphological subdivision of the Historical Centre of Havana: selection of a study sector

The Historical Centre of Old Havana, which comprises the area inside the former city walls (intramural) and the monumental border area, extends over 2.14 km² [6]. Due to the morphological differences between the intramural and the bordering area, this study will focus on the compact intramural area. This area itself however is about 1.2 km² and has differences between the various neighbourhoods. In this section, the main morphological characteristics of the intramural area are briefly described. Based on this description, a subdivision of sectors is made from which one is selected to reduce the area of the study. As mentioned before, in this study the term Historical Centre will be used to refer to the intramural area only.

3.1. General morphological characteristics of the Historical Centre

The present street grid is almost orthogonal and runs from North-Northwest to South-Southeast and from West-Southwest to East-Northeast (Fig. 2). The streets are about 6 to 8 m wide and the sidewalks are 0.8 to 1.2 m giving a distance between the building facades of about 7 to 10 m. The majority of residential buildings have one (4-5 m) or two stories (8-10 m), while the apartment buildings have three (9-12 m) or four (12-15 m). The street canyons have width/height (W/H) aspect ratios from 1.2 to 0.5. Often, these aspect ratios are low and the canyons are quite deep.

The urban blocks vary somehow in size and shape. They are generally rectangular with an average area of 6400 m². The parcel system shown in the plan of Figure 3 is one of shared party walls, with no open space in between buildings. The facade of each building is generally narrow (6 to 12 m) which gives the plot an elongated

⁵ The relationship between physical elements of the building and their meanings and use is inspired by the studies of Alexander et al. [22].

shape. The urban blocks do not have a central common open space but instead small courtyards exist in each plot or house. On average, the land occupation inside the blocks is high with only 15 to 20% of open space.

3.2. Morphological subdivision

The Master Plan of the Historical Centre considers a subdivision into 12 environmental sectors [6]. This subdivision comprises all aspects of the territorial characteristics but it does not rely on morphological characteristics as the main point to distinguish between sectors. Moreover, the environmental subdivision of the Master Plan considers other areas of the Historical Centre that are outside of the intramural area, which is the zone of interest in this study. Therefore, in this paper, a new subdivision is elaborated. This morphological subdivision covers the area of the intramural city that is limited by the Port Avenue and the Avenues of Belgium (Egido), Monserrate and Misiones. This compact area, with a shape of an almond, is indicated with a dashed-dotted line in Figure 2.

For the morphological subdivision, the information provided by the Master Plan Office about each block and building was used and a mapping of all vacant plots in the intramural city was made. Due to the homogeneity of the street network, the regularity of the topography and the similarity of the street profiles, only three main aspects are considered in the morphological subdivision: (1) the average height of the buildings and the average size of the plots of each urban block, (2) the main functions and the most common typologies of the buildings in the blocks and (3) the geographical location of the blocks with respect to the harbour. The latter aspect is important because the blocks facing the harbour have different morphological characteristics, less wind obstruction by other buildings and less shading. As a result, these blocks are not really representative of the compact nature of Old Havana. Figure 8 illustrates the six main morphological sectors that were distinguished in the intramural area. They are 1: South; 2: Eclectic; 3: North; 4: Historical; 5: Financial; and 6: Coastal.

From these morphological sectors, sector 2 was selected for the measurements and field survey because – together with sector 1 – it contained the largest amount of vacant plots and buildings in ruins. It is also one of the largest sectors and it has a clearly residential character. Finally, in this area, the degree of deterioration is more advanced in comparison with other, more protected areas.

4. Field measurements

The field measurements⁶ were performed in the Belen neighbourhood of sector 2. Fig. 9 shows the plan of the Historical Centre, together with the selected area with the parcelling system and the location of the selected buildings for indoor measurements and comfort survey. This site is located at the west side of the harbour of Havana at 2-5 m above sea level and 1 km from the meteorological station which is on the east side of the harbour at 51 m above sea level. The geographical co-ordinates of the meteorological station are 23° 10' north latitude and 82° 20' west hemisphere. The hourly measurements of wind speed and air temperature at this station will serve as a reference for the measurements in the Historical Centre.

Outdoor and indoor measurements were performed as part of a two-week measurement campaign in summer (July 2003). These weeks are considered representative of typical summer conditions. Three different types of courtyard buildings in the Belen neighbourhood were selected for the interior and courtyard measurements. Figure 10 illustrates schematic plans and sections of each building together with a view of the courtyards. The apartments in which the measurements were made are hatched.

Building 1 is located in a corner of a block and has two facades with directions WSW and NNW. It was constructed in two main steps; the ground floor around the mid 18th century and the top floor at the beginning of the 19th century. Therefore, the original building classifies as “second period / one-family house on wide plots” according to the classification that was presented in section 2. At the beginning of the 20th century, the building was subdivided and transformed into a multi-family house, thus having also some characteristics of the 3rd period. It has two main floors with additional mezzanines on the top floor, a height of 14 m with an additional 1 m balustrade and a central main square courtyard of 10.2 x 10.5 m². There is also a smaller courtyard (traspatio) with 5.8 x 8.5 m². The two courtyards are open on top and the main courtyard has a wide entrance (zaguán) which allows a direct connection to the street. Most apartments have windows both facing the street and the main courtyard, thus allowing cross-ventilation. The building walls are thick compact soil walls with stone bands (0.4-0.6 m). The flat roof consists of wooden beams that support a wooden framework, which in turn supports a clay-filling material of around 0.1-0.2 m. It is covered by flat ceramic tiles. The windows are large (about 1.2 m width by 2 m high). Most windows have louvers and single glazing, which is opened most of the time. They are protected only by a narrow cornice of about 0.15-0.2 m. There are no additional elements that can provide solar shading. The two apartments in this building in which measurements were made are located between the main courtyard and the Luz street.

⁶ A more detailed description of the methodology and results of the micro-climatic measurements can be found in Tablada et al. [23].

Building 2 is located in the middle of a block. The street facade is oriented to ENE. This building was constructed around the fourth decade of the 20th century and belongs to the third period (“multi-family and mixed buildings”). It has four floors, a height of 18 m and a long and narrow courtyard of 2.5 x 18 m². The main axis of the courtyard is oriented ENE-WSW and it is only open on top, and thus has no direct connection to the surrounding streets. The brick walls have a thickness of 0.3-0.4 m and the flat roof is made of metallic beams spanned by “bovedilla” (pot floors or arch-shaped bricks), with clay-filling material on top, which is covered by flat ceramic tiles. The windows are narrower than in building 1 (about 0.9 m wide and 2 m high) and are equipped with louvers and single glazing. The courtyard is surrounded by a 1 m wide balcony that serves as a circulation path and provides access to the apartments. This balcony provides solar shading to the courtyard walls but it also reduces the width of the courtyard.

Building 3 also has only one street facade, facing SSE. It was built around the third decade of the 20th century and belongs to the same period in the historical classification as building 2. It has a warehouse on the ground floor. At this floor, there is no courtyard and no direct interaction with the apartments on top of it. Therefore, in the analysis, we only consider the floors above the warehouse, which do have a direct link with the central long and narrow courtyard of about 3 x 15 m². There are two floors on the WSW side and three on the ENE side. The lowest floor with apartments facing the courtyard will be called “ground floor” here while the intermediate floor will be termed “upper floor”. The height is 19.5 m plus 1 metre of roof balustrade on the street facade. The main axis of the courtyard is oriented NNW-SSE. The courtyard is only open on top, like the courtyard of building 2. Building 3 has brick walls (0.3 m) and the roof construction and window dimensions are similar to those of building 2. The courtyard has a balcony (circulation path) of 0.8 m on the side facing ENE with an iron balustrade, and the other side facing WSW a small cornice of 0.1 m. Both features can provide solar shading. Most apartments in building 2 and 3 only have single-side ventilation through openings facing the courtyard. The apartments of building 2 and 3 in which the measurements were made are such single-side ventilated apartments.

The measurements were conducted following the specifications of Class II field measurements⁷ [24] except for the fact that no hot-wire anemometer was used. Two sets of measurement instruments were placed simultaneously at the centre of the room and in the courtyard in the shade. Each set included the following instruments: a psychrometer (at a height of 1.60 m), a globe-temperature thermometer (at 1.20 m height) and two dry bulb thermometers (at 0.60 m and 0.10 m height). Apart from that, two axial anemometers were positioned inside, at 1.20 m, and two cup anemometers in the courtyard at 1.80 m above the ground and at 1.80 m above the roof, to measure air speed in a horizontal plane. Both long-term measurements (2 weeks) of air temperature and relative humidity and short-term measurements (15 minutes) of wind/air speed, air temperature, radiant temperature and relative humidity were performed. The long-term measurements consisted of all-day, 1-minute measurements that were subsequently averaged to obtain hourly values. The long-term measurements were performed at the roof of the selected buildings and in the living-rooms of the ground-floor apartment of building 1 and the upper-floor apartment of building 2. The short-term measurements were performed at the same time as the survey. This was done once every day, during the two weeks, in the courtyards and in the living-rooms facing the courtyards, of two apartments at ground and upper floor in each of the three buildings. Note that measurements at the meteorological station were needed as a reference because wind speed was not measured in all buildings simultaneously. The station was also considered as the reference location for air temperature. At the same time, a limited field survey with 101 answers (55 persons) was conducted in order to assess the thermal sensation of occupants in these three courtyard buildings [25]. The results of the measurements and of this survey are presented and discussed in section 5.3.

5. Thermal comfort: results of measurements and comfort sensation survey, comfort model and summer comfort zone

5.1. Adaptation in thermal comfort

In the last decades, the research about thermal comfort has shifted from finding a standard methodology to predict the thermal sensation inside buildings [26] towards testing these methodologies and indices in different kinds of environments [27-29]. The thermal comfort studies that started in climatic chambers and offices with HVAC systems nowadays focus on more diverse situations where other, less controllable factors, such as microclimatic conditions and personal expectations, play an important role in defining the thermal sensation of

⁷ According to [24], class II field measurements are defined as measurements in which all physical environmental variables (air temperature, radiant temperature, air speed, relative humidity, clothing, metabolic rate) necessary for the calculation of heat-balance indices SET* and PMV/PPD, were collected at the same time and place where the thermal questionnaire was administered. Humidity measurements should be taken by an aspirated psychrometer or by absorption relative humidity sensors. Air speeds should be measured by hot wire probes with thresholds above 0.1 m/s and/or directional sensing elements and/or time constants exceeding the threshold required for turbulence intensity assessments.

occupants. These situations, which are more common in countries with warm climates, are present in non-air-conditioned and in fully or partially naturally-ventilated buildings⁸ where occupants have some contact with the exterior environment and develop certain “adaptive” abilities in order to feel comfortable in a changing environment.

Several studies [24,30,31] have shown that there are some non-quantifiable elements of comfort that influence the thermal sensation. Aspects like culture and habits, mental states and expectations can vary the level of tolerance towards certain thermal conditions. Studies made by Fanger [32] and others [33,34] in climatic chambers have shown no difference in thermal preferences between people from different regions. Moreover, according to these studies, the factors of sex, age and daily or seasonal rhythms don't affect the preferred thermal environment. Therefore, the physiological adaptation of people to the environment has little influence on the preferred ambient temperature. However, in “uncomfortably” warm and cold environments or in a changing climatic condition, adaptation will often have an influence [35] because people have a natural tendency to adapt to changing conditions in their environment [30].

It is recognised that psychological adaptation actually plays an important role in people's perception of thermal conditions and could also explain the differences in observed and predicted thermal sensations in different environmental contexts like office vs. residential and air-conditioned (AC) vs. naturally-ventilated (NV) buildings. Nicol and Humphreys [30] state that three contextual variables (climate, building and time) influence the way in which people relate with their thermal environment and also influence the response and acceptability they have toward it. The building's provision of controls and the occupant's possibility of modifying the surrounding environment have been described both in terms of “adaptive opportunity” [36] and “adaptive constraints” [37]. The adaptive behaviour is then a combination of two types of action - “changing the conditions to accord with comfort and changing the comfort temperature to accord with prevailing conditions” [30].

Apart from the adaptive opportunity, other studies [27,29,30,38,39] have shown that when occupants are directly or indirectly related to the exterior conditions their thermal expectations are more closely linked to the external ambient temperature. This phenomenon is not only affected by the immediate external conditions but also by the accumulative registered thermal sensations over the previous days, and the expectation people have over certain seasonal conditions which have manifested similarly over their entire life. The adaptive approach is then based on the assumption that factors beyond fundamental physics and physiology play an important role in occupants' expectations and thermal preferences [29,40]. This leads to consider the prediction and evaluation of indoor thermal comfort in diverse contexts and situations with a different approach which is the case of the NV buildings in the warm-humid climate in this study.

5.2. *Comfort zone in the humid tropics*

A number of studies have been conducted in NV buildings in tropical-humid climates in order to investigate the thermal sensation of people and then to propose a comfort zone for the studied region. In a field study made in both AC and NV offices in Thailand, Busch [28] found that for AC offices the neutral effective temperature ET^{*9} was 24.7 °C while for NV offices it was 27.4 °C. As a function of SET^* , the neutral temperatures were lower: 24.4 °C for AC buildings and 22.8 °C for the NV buildings due to probably the lower value of reported clo. For the NV building sample, the upper boundary of the comfort zone was found to be approximately 31.0 °C which is significantly higher than the ASHRAE comfort standard 55-92 value of 26.1°C ET^* [41].

A more recent study made by Wong and Khoo [42] in NV classrooms in Singapore showed that the range of operative temperatures (T_o) in which people feel an acceptable thermal environment were from 27.1 to 29.3 °C. A neutral T_o of 28.8 °C was obtained. A slightly higher comfort temperature was found in a study in NV residential buildings in Jogjakarta, Indonesia ($T_o = 29.2$ °C, $ET^* = 29.9$ °C) [43] while it was lower in NV classrooms in Hawaii ($ET^* = 26.8$ °C) [44].

Apart from South-East Asia and the Pacific region, no other field studies have been found in the literature to confirm that those differences are also valid in other regions with similar warm-humid (marine) climates but with different culture and habits, such as in coastal areas of Africa, the Caribbean and Latin America. This was one of the reasons to organise a series of measurements and a limited thermal sensation survey in Old Havana for this study.

5.3. *Measurement results*

⁸ In this paper we refer to all types of buildings in which at the moment of thermal evaluation there is no air-conditioning (AC) or centralised HVAC system as naturally-ventilated (NV) buildings

⁹ The Effective Temperature ET^* is defined as “that temperature of an environment at 50% relative humidity, and with mean radiant temperature equal to air temperature, that would produce the same total heat loss from the skin and thermal sensation as in the actual environment” [35].

Figure 11 shows results of the measurements and the resulting Standard Effective Temperature SET^{*10} [45]. This parameter is selected because it takes into account the effect of the air speed, which is essential for this part of the analysis in this study, and the personal variables like clothing (clo) and the metabolic rate (met). The air temperature (t_a) and Effective Temperature (ET^*) do not fully take into account these environmental and personal parameters. Figure 11a shows the average wind speed measured in the buildings and the corresponding wind speed at the station. It indicates that building 1, with its wider courtyard that is connected to the street (and to a second courtyard), has considerably higher air speed values in its courtyard and in the rooms, due to cross-ventilation between the street and the courtyard. Figure 11b shows that, in spite of a higher SET^* in this courtyard, due to solar radiation, the favourable effect of natural ventilation and thus higher indoor air speed yields lower values in the adjacent apartments ($SET^* = 28.3\text{ }^\circ\text{C}$). In spite of better solar protection, the apartments of buildings 2 and 3, facing the most shaded and protected courtyard but with single-sided ventilation, had worse thermal conditions ($SET^* = 29.1$ to $29.4\text{ }^\circ\text{C}$). Note that the measurements in the different buildings were not made at the same time, and that this is also the reason why the corresponding data from the meteorological station are provided. But, the conclusions are reinforced by the fact that the average air temperature at the reference position (meteorological station) was higher during the measurements in building 1 than during the measurements in building 2 and 3. The error for the SET^* was calculated to be at maximum 0.4°C which is less than the differences of the obtained SET^* between building 1 and building 2 and 3. Figure 12 provides some more detailed information. It shows the measurements of temperature and relative humidity inside the ground-floor apartment of building 1 and the upper-floor apartment of building 2. While there is a clear correlation between the temperature and relative humidity in the apartment of building 1 and those at the meteorological station, this is not the case for the apartment in building 2, where the conditions are more stable but unfavourable. This different behaviour is attributed to the differences in ventilation rate.

The fact that the cross-ventilated rooms in building 1 have better conditions than the single-side ventilated rooms in buildings 2 and 3 indicates that indoor air speed may have a more important role in thermal comfort than the courtyard's protection from solar radiation in this specific context. Note that with solar protection in the courtyards, thermal conditions could be further improved. It should also be noted that the majority of the measurements were conducted at outside air temperatures below 33°C . As a result, no conclusions could be drawn concerning the influence of ventilation at temperatures above this threshold.

5.4. Thermal sensation survey and comfort model

The limited thermal sensation survey was performed to analyse possible differences between the predicted thermal sensation by the Predicted Mean Vote (PMV) model [26, 46] and the actual thermal sensation of people in the context of Havana. The extended Predicted Mean Vote (PMV_{ext}) model proposed by Fanger and Toftum [47] is used in this section for comparison with the actual thermal sensation votes on the ASHRAE scale and the comfort sensation votes on the Bedford scale. The extended model considers a reduction of the activity level (MET) when the PMV is higher than zero (warmer conditions than neutral). The reduction of the metabolic rate is based on the assumption that people when feeling warm unconsciously tend to slow down their activity. The corrected model reduces the metabolic rate by 6.7% for every scale unit of PMV above neutral. It also includes an “expectancy factor” e that takes into account the higher acceptability to warm conditions of people who live in regions with a long summer and also who are not used to AC buildings. The e factor is estimated to vary between 1 and 0.5. The higher extreme (1) is for AC buildings and the lowest value (0.5) for NV buildings placed in areas in which the weather is warm whole year round and there are few or no other AC buildings. This model was selected to conduct the comfort analysis for several reasons. First, the PMV_{ext} model takes into account both psychological adaptive factors and also the human factors such as the clothing and activity and the four classical thermal parameters (air temperature, mean radiant temperature, air relative humidity and air speed) that have according to [47] “a well-known impact on the human heat balance and therefore on the thermal sensation”. It is also argued that the accuracy of the adaptive models that only consider the neutral temperature in relation to the monthly average outdoor temperature is uncertain for predicting thermal comfort in new types of buildings in the future where the occupants may wear different clothing and change their activity pattern [47]. Second, the results could be compared with the values of the original PMV model [26] and with the results of previous studies in tropical-humid regions.

The overall reported votes from the questionnaire were 1.76 and 1.70 for the ASHRAE and Bedford scales respectively while the value of PMV was 2. But, although people accept warmer conditions than indicated by the ASHRAE standard, their preference was toward cooler conditions. Moreover, the reported votes (1.70) were more critical than the PMV values predicted by the extended PMV model ($PMV_{ext} = 1.33$) using an expectancy factor of 0.7. The value of 0.7 corresponds to the higher point in the scale proposed by Fanger and Toftum [47]

¹⁰ The Standard Effective Temperature SET^* is defined as “the equivalent air temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for the activity concerned, has the same heat stress (skin temperature T_{sk}) and thermoregulatory strain (skin wetness w) as in the actual environment” [35].

for a region with long warm periods and few AC buildings. One reason of the discrepancy between the questionnaire results and the PMV_{ext} model could be an improper choice of the e factor that largely influences the final PMV value and could easily counteract the accuracy of the original model. The second reason could be in the way people responded the questionnaire. This is shown in Figure 13 that compares the PMV, the votes and the SET* between the apartments where the measurements and the thermal sensation survey took place. It shows that some people from two single-side ventilated ground-floor apartments of building 2 and 3 responded hypercritically in comparison with the answer from the other apartments and with the PMV model values obtained for these two apartments. In the case of Old Havana, where there is a comprehensive recovering program that includes building and social conditions, some people automatically link any questionnaire with the possibility of posterior actions for improving their life conditions. Thus, hypercritical answers might be related to an expectation of an upgrade of housing conditions due to this answer. The average of votes without considering the hypercritical answers from ground-floor apartments of building 2 and 3 is 1.31 and 1.27 for the ASHRAE and Bedford scales respectively which are very similar to the PMV value of the extended model with $e = 0.7$ ($PMV_{ext} = 1.33$).

Another important result from the survey, as shown in Fig. 13, was the evident difference between the votes from the cross ventilated apartments in building 1 (1.11) and the votes from the single-side ventilated apartments of building 2 and 3 (1.38) which reflects the importance of the ventilation strategy on the thermal sensation of people. The preference for environments with higher air speed is confirmed by Fig. 14 that represents the average indoor air speed at the moment people responded the questionnaire, as a function of the Bedford scale votes. The results show that people who voted as comfortable in the scale of Bedford were in a situation with higher indoor air speed than people who voted as thermally uncomfortable. These differences are in line with the results from the field measurements (Fig. 11-12). The results of this survey are used in the next section to suggest a tentative summer comfort zone for residential buildings in Old Havana.

5.5. Summer comfort zone for Old Havana residential buildings

Based on the votes of the thermal survey (without the hypercritical votes) and on the thermal parameters, a summer comfort temperature and a comfort zone are proposed for residential buildings in Old Havana. Although neutral temperatures may not always reflect the thermal sensation people would like to have [40,43], in this study a comfort temperature based on the neutral rather than on preference votes was applied taking into account that the survey was only performed during summer with a small range of thermal conditions ($29 < ET^* < 34.7^{\circ}C$). Using the ET^* comfort temperature (T_{comf}) was preferred over air temperature because of two reasons: (1) including the influence of the relative humidity parameter which is, most of the time, higher than 50% in the context of Havana; and (2) to allow comparison with previous studies that also used the ET^* comfort temperature. Figure 15 shows the obtained T_{comf} by linear regression analysis between the reported thermal sensation votes on both the ASHRAE and Bedford scales and the measured ET^* .

The proposed summer comfort zone ranges from 24.7 to 30.7°C for 80% acceptability, with a T_{comf} of 27.7°C ET^* (average of ASHRAE and Bedford scale). This agrees with a previous study in a climatic chamber in Havana [48] (higher limit of comfort zone: 31.3°C ET^*) and it is similar to other studies in the tropics such as the one in Thailand ($ET^* = 27.4^{\circ}C$ for NV buildings) [28], and the studies mentioned in section 5.2 in which the T_{comf} are above 26°C ET^* . The T_{comf} obtained in this study using the ET^* can be compared then, with several adaptive models proposed in literature [29,30,38,39] based on thermal comfort surveys covering different climatic regions and thermal conditions. Some of these models use the mean monthly outdoor temperature for the calculation of the comfort temperature while other use the mean daily outdoor air temperature and ET^* ($T_{mmo} = 27.7^{\circ}C$, $T_{a\ out} = 29.2^{\circ}C$ and $ET^*_{out} = 29.7^{\circ}C$ respectively in this study). Table 1 shows the adaptive models and their corresponding neutral and comfort temperature for summer conditions in Old Havana. In the new version of ASHRAE comfort standard 55-2004 an adaptive model is incorporated based on an extensive database of field studies [29,39]. The model of de Dear and Brager [29] proposes a range of 5 to 7°C of the comfort zone for 90 and 80% acceptability respectively. Applying the 80% acceptability we obtain for Old Havana a comfort zone from 23.4 to 30.4°C and a comfort temperature of 26.8°C. Applying the equivalent model [39] for exterior ET^* and 80% acceptability results in a comfort zone from 23.7 to 30.7°C and a T_{comf} of 27.2°C. The results obtained from the adaptive model using the ET^* [39] are very similar to the results obtained from the thermal comfort survey in Old Havana. However, the lower limit of the comfort zone obtained in this study should be adjusted or corroborated by extending the survey to other seasons where thermal conditions are cooler than in summer.

6. Preliminary design recommendations for residential buildings in Old Havana

Based on the study of the evolution of residential architecture in Old Havana and on the results of the field measurements and the thermal sensation survey, a set of preliminary design recommendations can be proposed for residential buildings in the Historical Centre of Havana. These recommendations focus on the need for cross

ventilation and protection from solar radiation. While many other authors have proposed recommendations buildings in warm and humid climates [7-9] based on cross-ventilation and solar protection, these primarily focused on open urban schemes. The recommendations in this paper are different because they focus explicitly on the use of passive means in courtyard buildings in compact urban environments and, more specifically, to the specific context of Old Havana. The following general recommendations are provided:

- Combining a main wide courtyard with smaller secondary courtyards to provide cross ventilation in rooms that are not directly connected to the street.
- Providing a ratio of “open space” inside the plot that is higher than the 15% required by the present regulations [6], to provide larger possibility to design areas for courtyards.
- Establishing an interconnection between the street and the courtyards and among the courtyards through a circulation path on ground floor in order to promote ventilation inside the courtyards and the connected rooms.
- The wider courtyards (similar in shape and dimensions to the one of building 1) should have a proper solar protection both on the windows and on the courtyard walls by means of overhangs (permeable to the wind) or by pergolas. While the narrower courtyards are less exposed to solar radiation in general, solar protection should be considered for the top floor rooms.
- It is important to keep using louvers/Venetian blinds for the windows at every floor, with windows that can be opened completely.

7. Discussion and conclusions

In the framework of the design of new courtyard buildings as part of the comprehensive preservation and urban recovering program in the Historical Centre of Old Havana, this paper has presented an overview of the evolution of the residential architecture in the Historical Centre in relation with the local climatic conditions, a morphological subdivision of the Historical Centre and the results of micrometeorological measurements, of a limited comfort survey and a tentative summer comfort zone. Finally, some preliminary design recommendations have been given for new residential buildings in the Historical Centre of Havana.

The evolution of the residential architecture in Old Havana expresses a progressive adaptation of the courtyard house to provide – among others – a better thermal comfort. After the Colonial period however, the evolution of the multi-family buildings had negative repercussions on natural ventilation and thermal comfort. In many buildings, the courtyard was gradually transformed into a narrow space with poor light and ventilation.

A morphological subdivision of the Historical Centre was made from which sectors and residential buildings were carefully selected for further study. Sector 2 ‘Eclectic’ was selected, because it has the largest potential for new housing interventions due to its clear residential character and the large amount of vacant plots and building deterioration.

Measurements in sector 2 indicated that, for this particular urban environment and climate, indoor ventilation can have a more important role in thermal comfort than enclosing the courtyard to achieve better protection from solar radiation. The importance of cross-ventilation between the street and a wide courtyard, as opposed to single-sided ventilation through a narrow courtyard, was confirmed. In the context of Old Havana, the evident way of achieving cross ventilation is with courtyards that are permeable to the exterior environment both from the ground floor and from the top. This more open courtyard configuration allows higher indoor ventilation rates than the one achieved in buildings with a single narrow courtyard which are only open at the top. Notice that in cases of wide courtyards, additional solar protection should be provided. The measurement results give more evidence about the qualitative conclusions from the study of the evolution of the residential architecture in Old Havana.

Based on the comfort survey, the obtained comfort zone for summer conditions for Old Havana residential buildings ranges from 24.7 to 30.7°C ET*. This is in line with the results of previous studies in warm and humid regions in which the comfort zone is above the summer comfort zone recommended previously in the international standards (ASHRAE: 23.0 to 26.1°C). The main reasons are behavioural adaptation (different clothing) and psychological adaptation (lower expectation to cooler conditions). The results in this study also agree with the adaptive model accepted for the new version of the ASHRAE comfort standard 55-2004 [49] based on field studies worldwide.

Based on the results of this study, several preliminary design recommendations have been given for new residential buildings inserted in the Historical Centre of Havana. They focus on the need of cross ventilation and protection from solar radiation, but adapted to the specific urban context of Old Havana.

This study has provided the framework and the basis (historical context, building plots, expectancy factor for the comfort model and local comfort zone) to support further experimental and numerical analysis of natural ventilation and thermal conditions and the development of more specific courtyard-building design recommendations in the compact urban morphology of Old Havana.

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Fig. 1. Geographical location of the Island of Cuba near the Tropic of Cancer. (Havana: 23.1° north latitude, 82.3° west hemisphere) (from [1]).

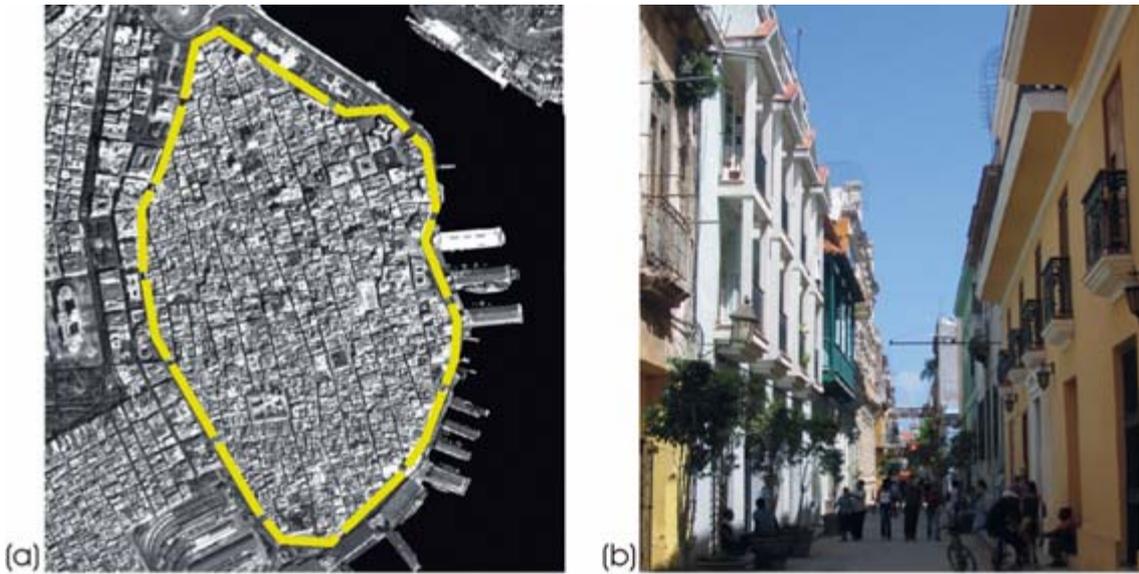


Fig. 2. (a) Satellite photo of the Historical Centre of Old Havana (source: Archive of the Historian Office of Havana). The dashed-dotted line indicates the limit of the intramural city. (b) View of a typical street in Old Havana.

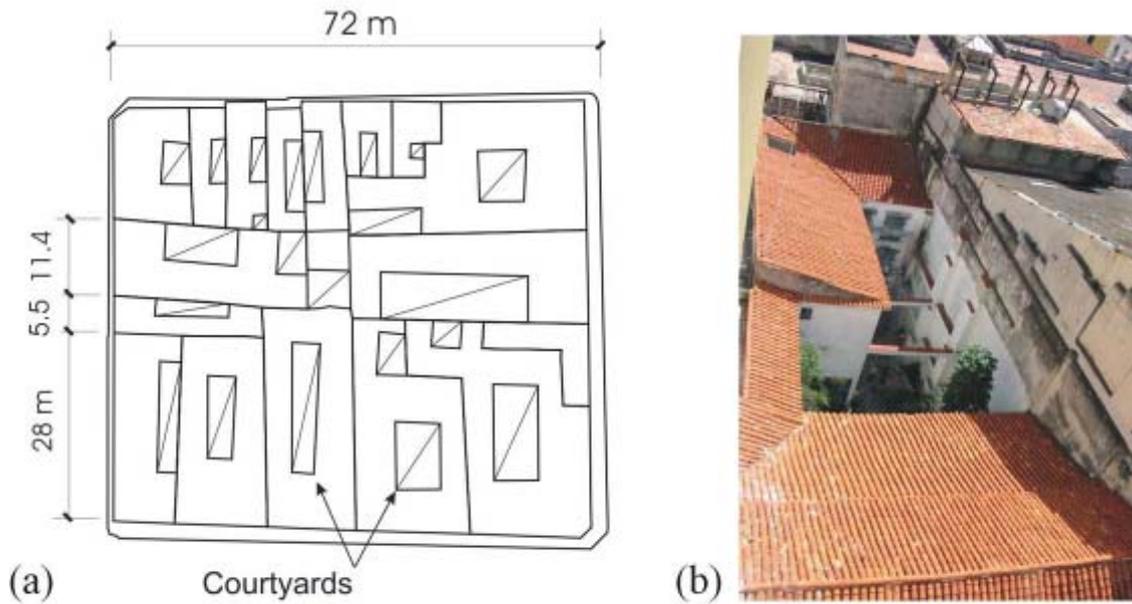


Fig. 3. (a) Typical urban block and the location of inner courtyards on each plot. (b) Bird-eye view of a courtyard house

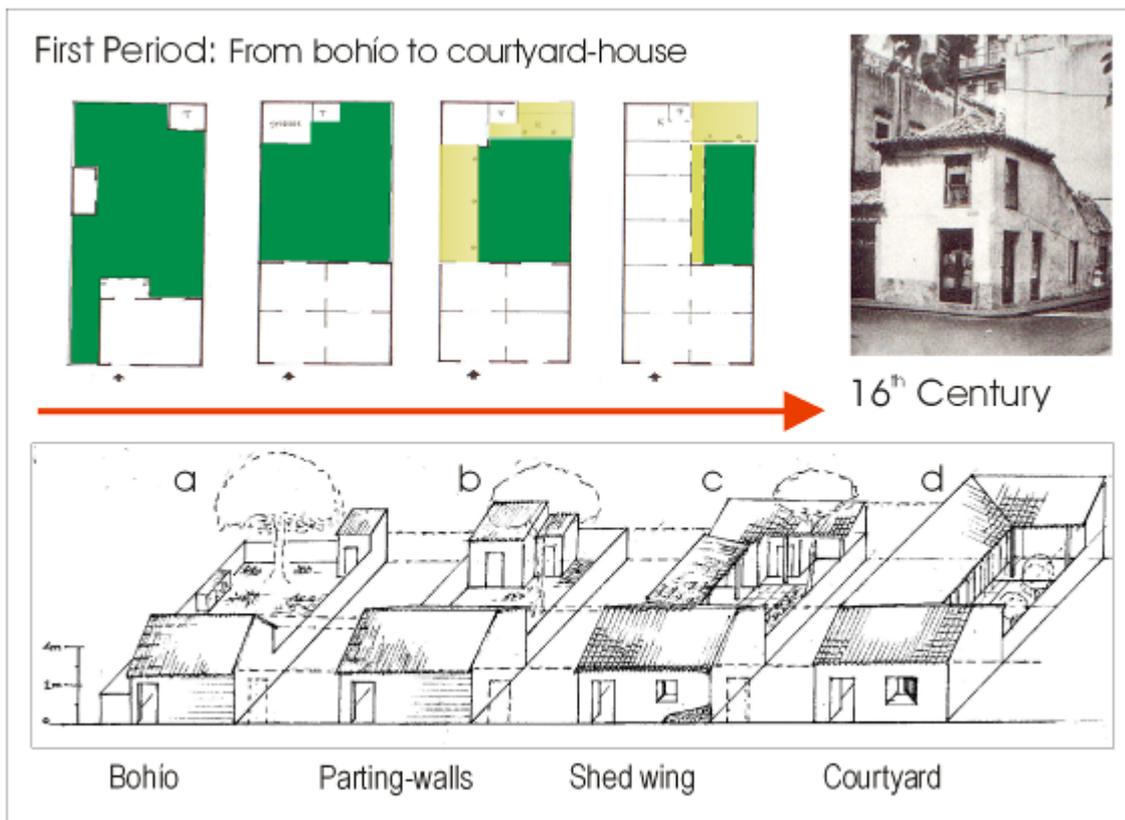


Fig. 4. First period of the evolution of residential architecture: from rural “bohío” (a) to the urban courtyard house (d). In green/dark grey: open courtyard; in yellow/light grey: semi-open areas like galleries and shed wing.

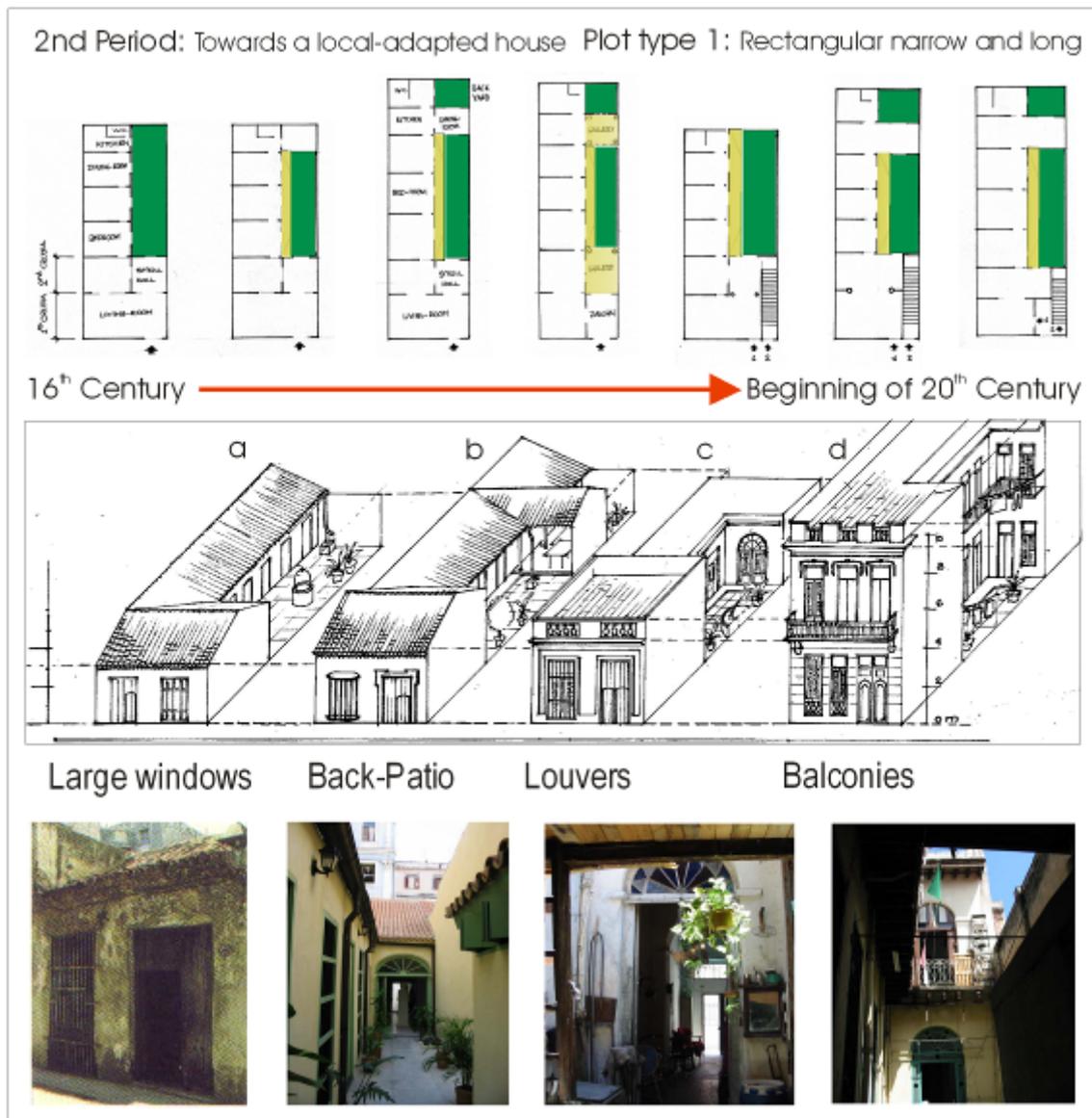


Fig. 5. Second period of the evolution of residential architecture: the one-family house in narrow and elongated plots. In green/dark grey: open courtyard; in yellow/light grey: semi-open areas or circulation areas protected by overhangs. Indication of (1) backyard; (2) gallery; (3) zaguan.

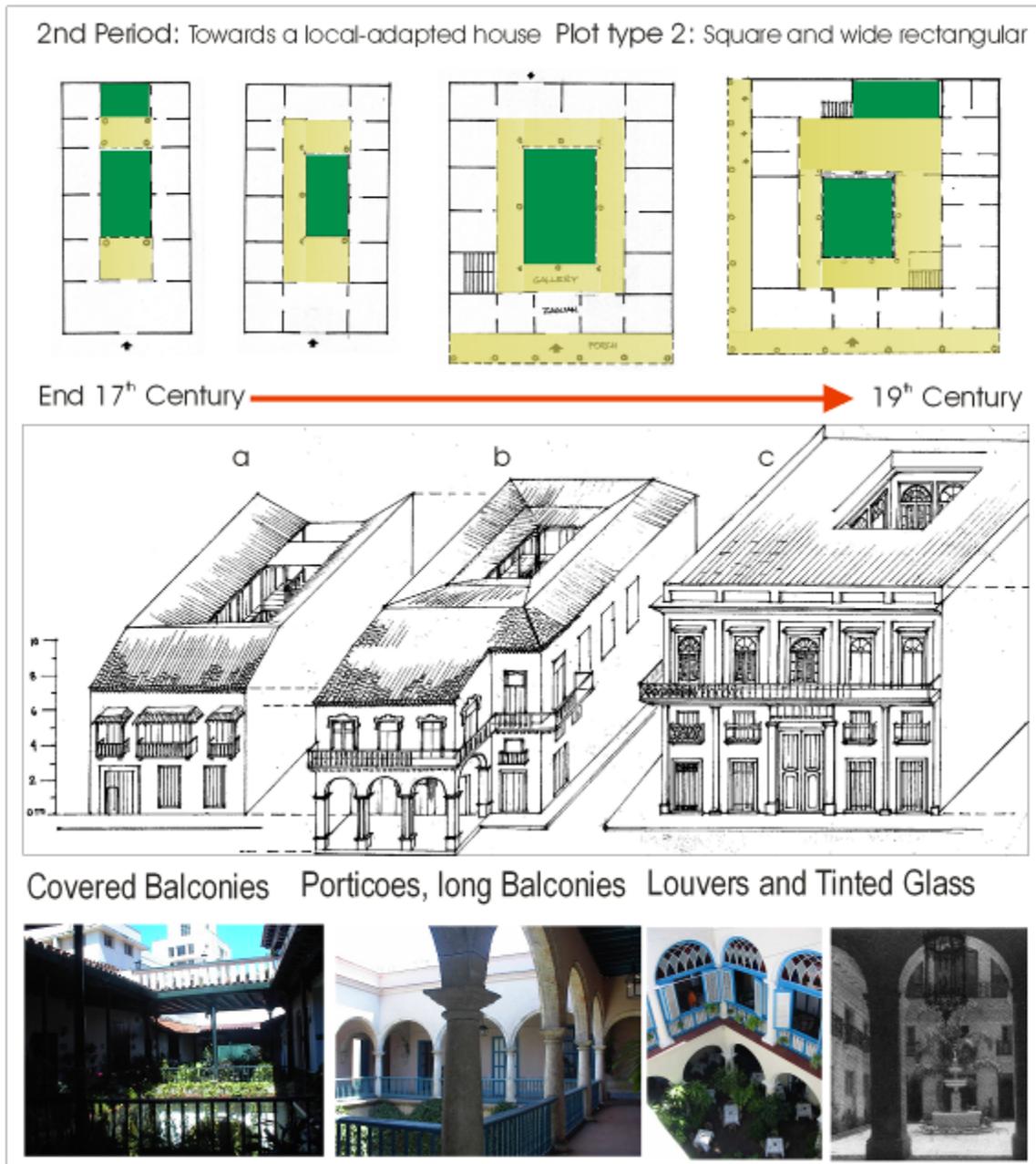


Fig. 6. Second period of the evolution of residential architecture: the one-family house in wide plots. In green/dark grey: open courtyard; in yellow/light grey: semi-open areas like galleries, porticoes or circulation areas protected by overhangs. Indication of (1) gallery; (2) zaguan; (3) porch.

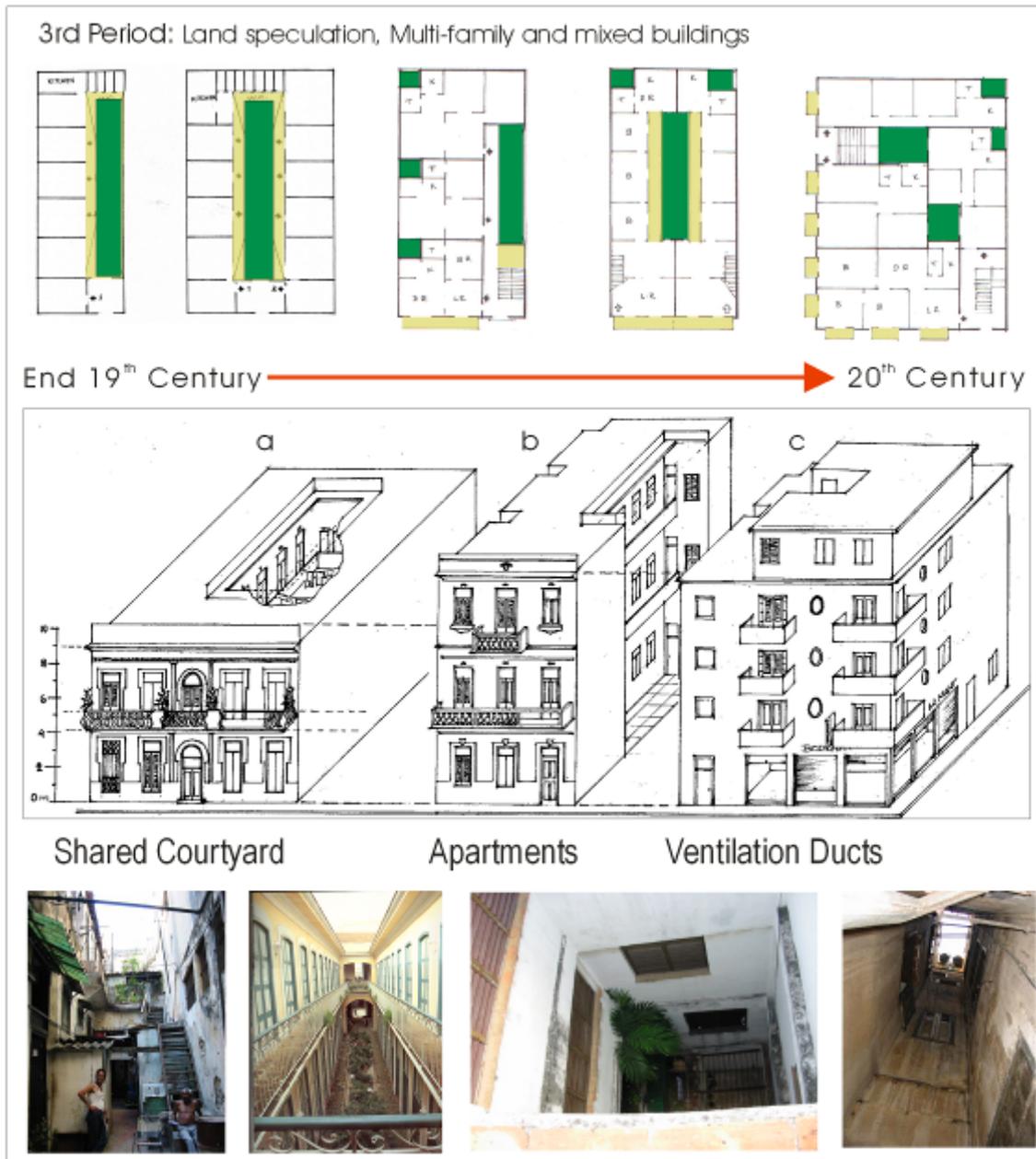


Fig. 7. Third period of the evolution of residential architecture: from “cuarterías” to apartments and mixed buildings. In green/dark grey: open courtyard; in yellow/light grey: semi-open areas, balconies or circulation areas protected by overhangs.

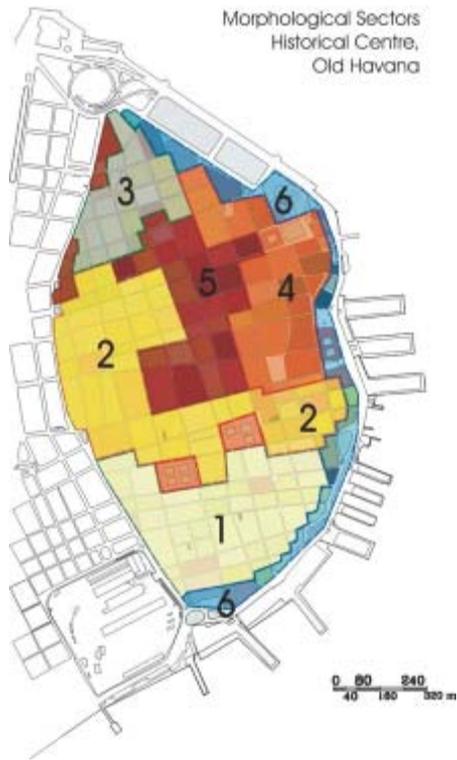
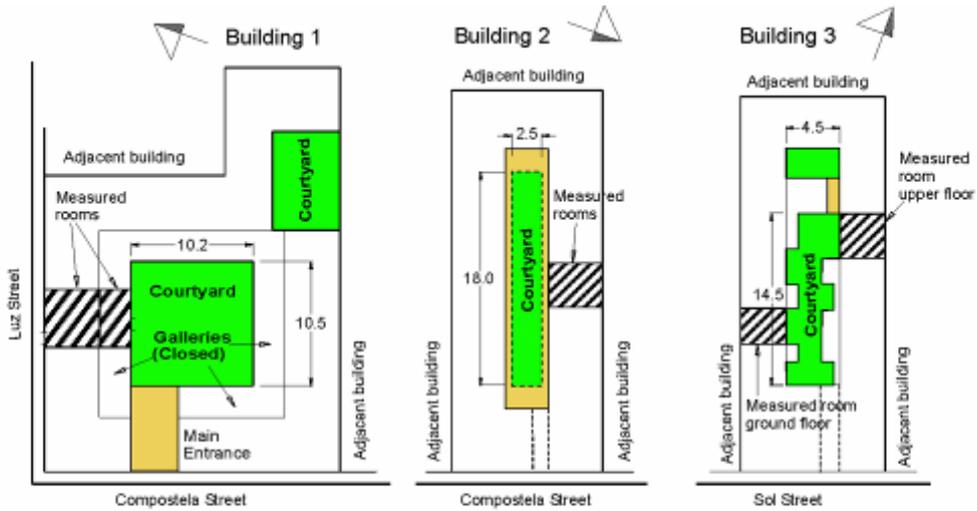


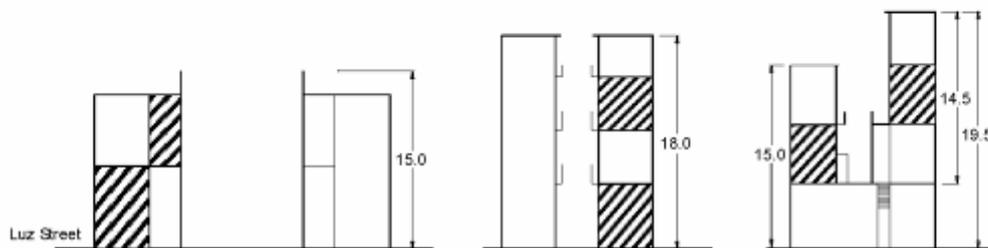
Fig. 8. Morphological sectors of the Historical Centre of Old Havana based on morphological characteristics and geographical situation of building blocks. 1: South; 2: Eclectic; 3: North; 4: Historical; 5: Financial; and 6: Coastal.



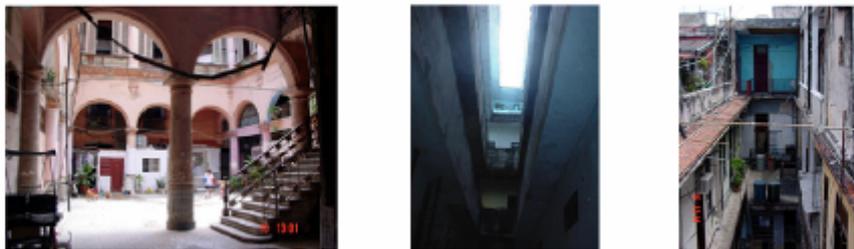
Fig. 9. Location of the selected buildings for indoor measurements and comfort survey. (a) Plan of the Historical Centre and the location of all empty plots and buildings in ruins in 2003. (b) Selected area with the parcelling system. (c) Location of the selected buildings.



Schematic Plans



Schematic Sections



View of Courtyards

Fig. 10. View of courtyards and schematic plans and sections of the selected buildings and the location of the measured rooms for building 1, 2 and 3. The rooms in which measurements were made are indicated (hatched).

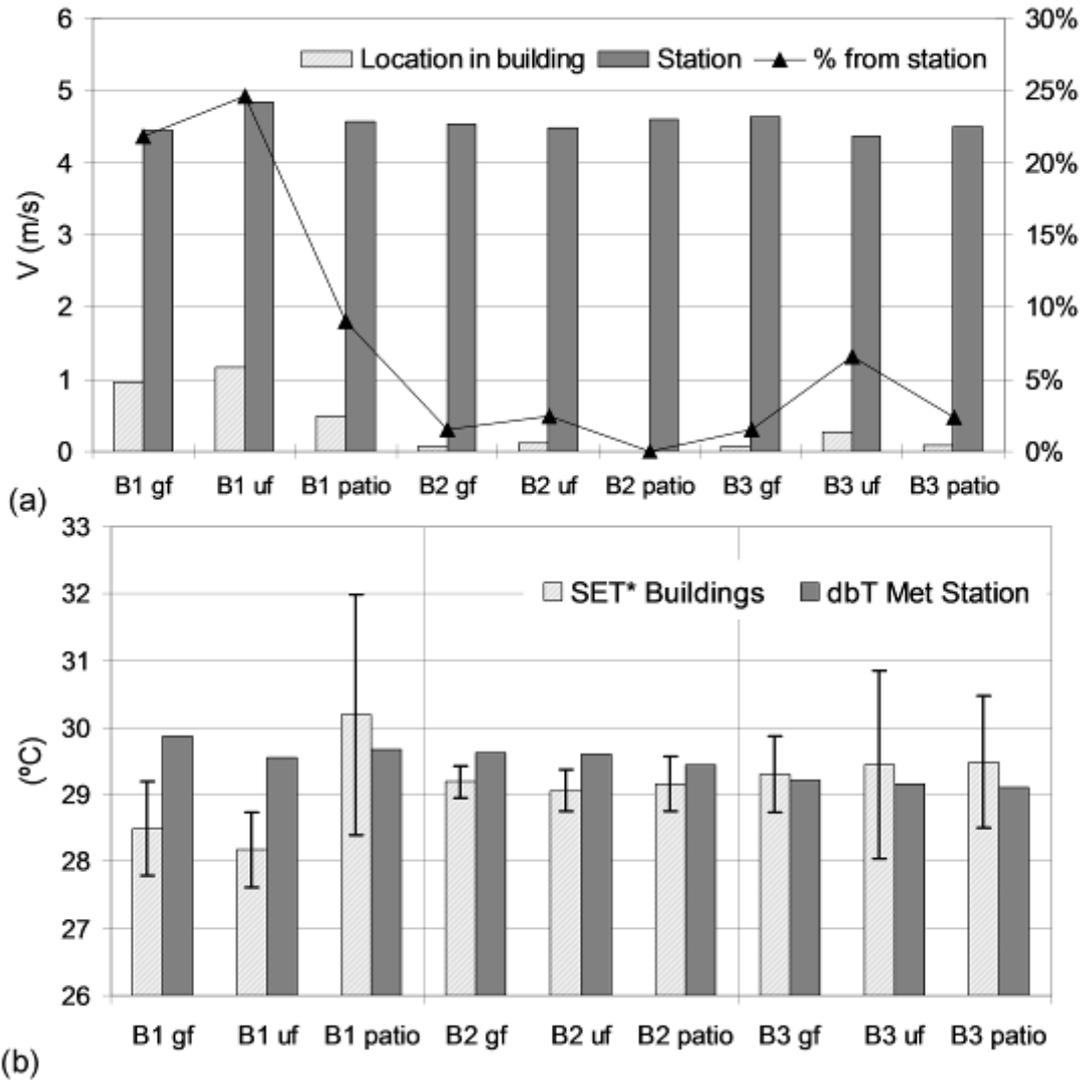


Fig. 11 (a) Average wind speed measured in the three buildings and the corresponding reference wind speed at the station. The percentage of the station data is also indicated (B=building, gf=ground floor, uf=upper floor, court=courtyard). (b) Standard effective temperature (SET*) in buildings 1, 2 and 3 and the corresponding average dry bulb temperature (dbT) at the meteorological station. Error bars represent the standard deviation.

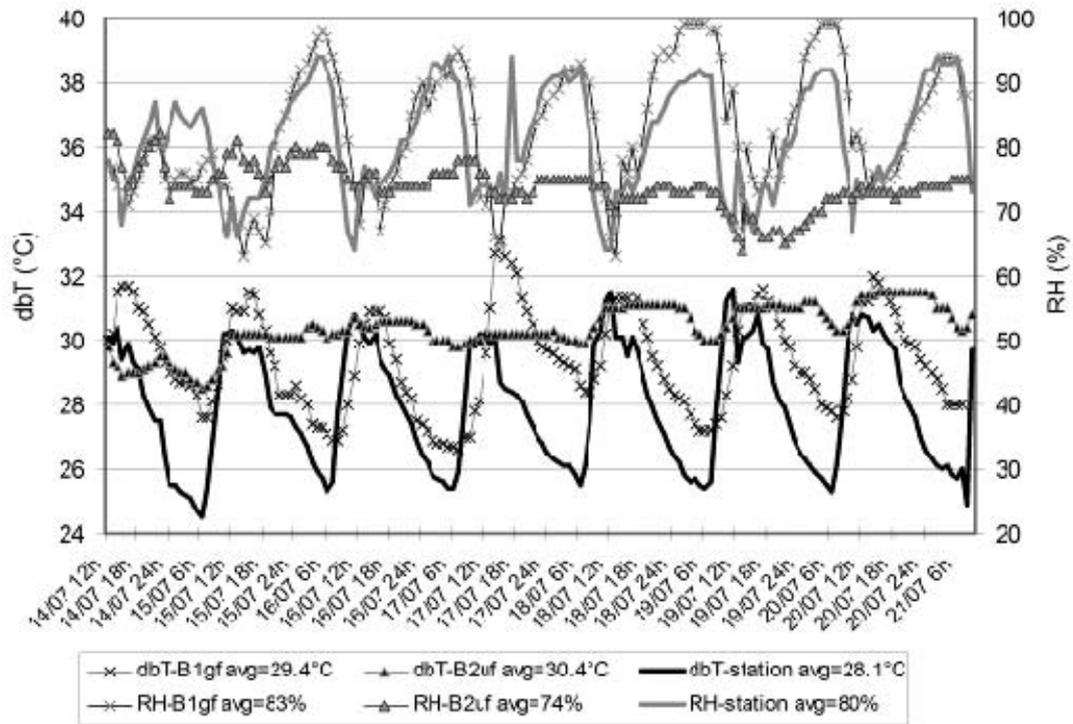


Fig. 12. Dry bulb temperature (dbT) and relative humidity (RH) during one week in July 2003 for the living rooms in the ground-floor apartment of building and the upper-floor apartment of building 2.

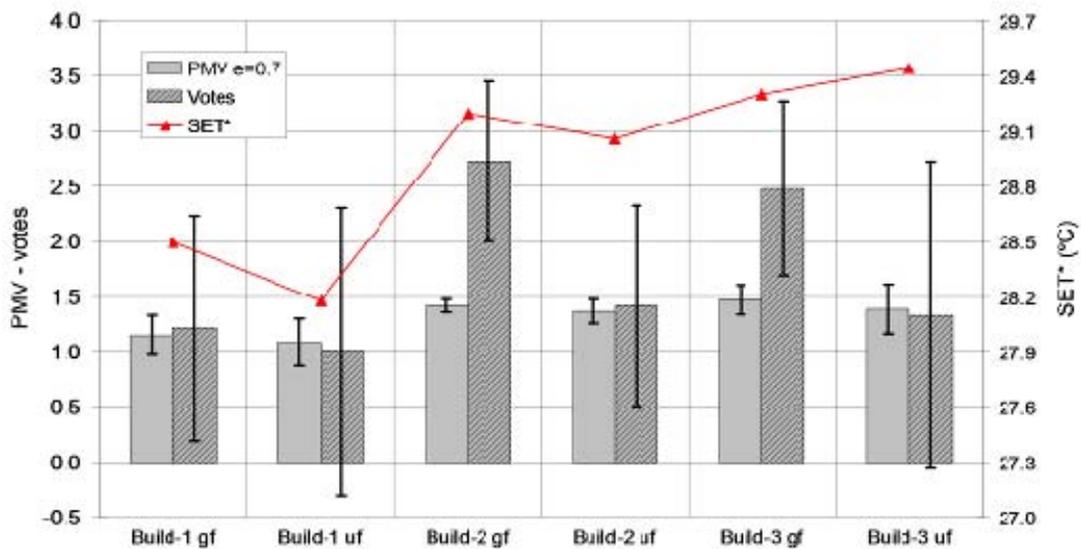


Fig. 13. Comparison of PMV, votes on the ASHRAE thermal scale and SET* between the different apartments where the measurements and thermal sensation survey took place. Error bars represent the standard deviation. (Build = building, gf = ground floor, uf = upper floor).

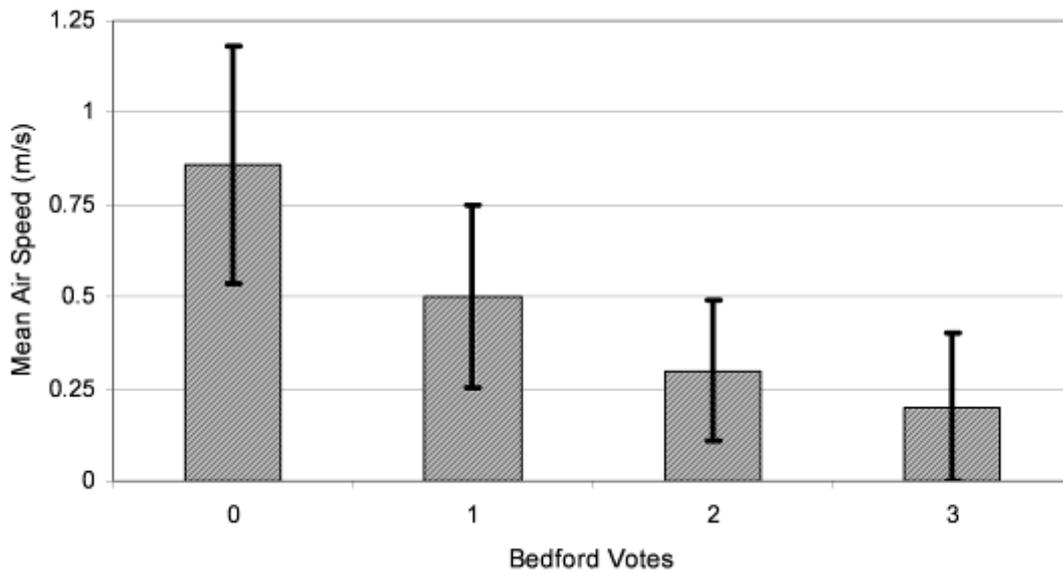


Fig. 14. Average indoor air speed at the moment people responded to the questionnaire as a function of the Bedford scale votes (0 = comfortable, 1 = comfortably warm, 2 = too warm, 3 = much too warm). Error bars represent the standard deviation.

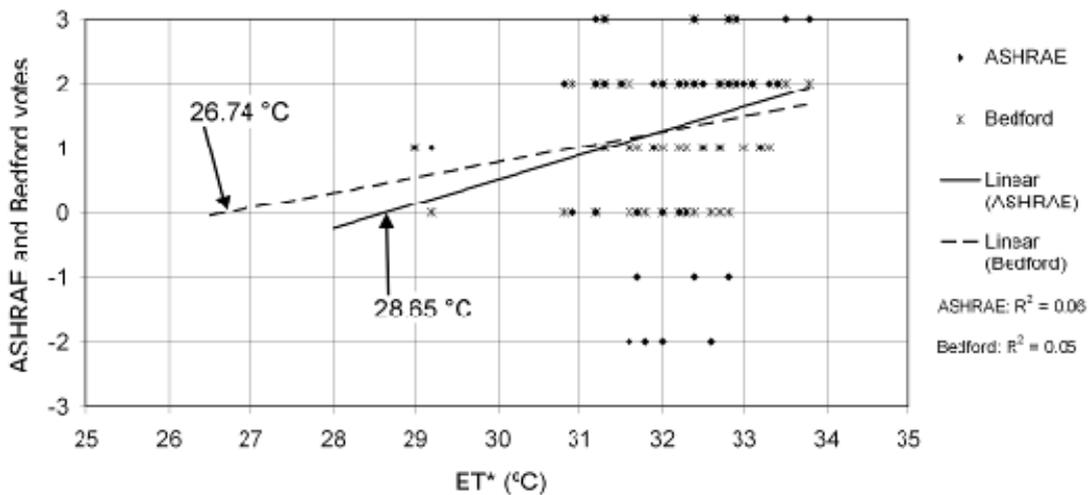


Fig. 15. Distribution of votes (not considering hypercritical votes) versus ET^* and the obtained comfort temperature (T_{comf}), for both the ASHRAE thermal and the Bedford comfort scale. (Bedford comfort scale: 0 = comfortable, 1 = comfortably warm, 2 = too warm, 3 = much too warm. ASHRAE thermal scale: 0 = neutral, 1 = slightly warm, 2 = warm, 3 = hot).