THERMAL PERFORMANCE ANALYSIS OF CENTRAL HALL HOUSES IN THE ISRAELI COASTAL PLAIN

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ABSTRACT
Vernacular architecture is believed to integrate certain building features that were developed in a long process of adaptation and adjustment and therefore may embody valuable solutions for maintaining desirable indoor conditions. This claim, however, should not be taken for granted and must be critically examined in different contexts and settings. The Central Hall building type, which can be found in Lebanon, Israel, Syria and the Palestinian territories, is an example of an architectural vernacular that may prove to contain applicable design strategies in confronting the hot and humid climate of the region's coastal plain. This paper focuses on describing and understanding the thermal performance of Central Hall houses in the Israeli coastal plain through the integration of architectural and historical survey with computer-aided simulation methods.

INTRODUCTION
Vernacular Architecture is a term used to describe built elements in the human environment that were constructed following common know-how and practice and which resulted from a relatively long process of adaptation and perpetuation in a given culture. Because of the slow-evolving nature of vernacular building methods and the builders' need to make the best out of a limited range of resources, vernacular architecture is believed to embody highly workable performance solutions (Rudofsky 1964). This claim, however, should not be accepted without further exploration, since adhering to certain building habits may at times stem from totally different factors than pure technical performance (Banham 1984; Foruzanmehr and Vellinga 2011). On the other hand, if certain built vernaculars contain applicable and practical solutions for certain performance features, understanding the mechanisms that lie behind them may contribute to current design practices, even without the use of old and sometimes outdated construction methods and materials. This is especially important in cultural contexts where ultra-sophisticated (and thus expensive) building techniques or materials are not readily available.

During the 1870s a new building type, usually referred to as the Central Hall House, emerged in Lebanon and spread southwards, to most of the major towns of four of the southern Sanjaks (the highest administrative subunit) of the Ottoman empire (later to become British Palestine and today's Israel and the Palestinian territories), mainly along the Mediterranean shores (Meyer-Brodnitz and Fuchs 1989; Ragette 1974). This building type was widely and commonly adopted by wealthy locals at least until the 1920s, when new cultural ideas and building techniques started to gain dominance in the region.

The Central Hall House was quasi-modern in nature and combined local construction materials (mainly local stone blocks) with newly imported industrial products of European origin (steel beams, clay roof tiles, glass sheets for window panes). Central Hall houses differed in their sizes (the area of the living floor ranged from about 100 to 500 $m^2$) while retaining a similar division of space. They usually consisted of a ground level used solely for storage, and an upper level where the main gathering space of the central hall, stretching between the front and back façades, was flanked by two or three rooms to each side. Access to the side rooms was possible only from the central space. One of the most distinct characteristics of the building type was a high pitched tiled roof; though relatively high, the roof space was left empty and was practically inaccessible.

In the past, the historical phenomenon of the Central Hall House was usually researched focusing on its cultural and typological aspects, while its more technical facets were almost entirely neglected and therefore still remain relatively unknown. One interesting question is to what extent it provided thermal comfort conditions during summer, which is regarded in its region as the most "challenging" yearly period. Along the Mediterranean shores summers tend to be relatively hot and humid (Csa climate type by Köppen-Geiger climate classification, with an average peak high temperature of about 30 °C and relative humidity rising above 80%). The wide acceptance of the building type and its long-lasting dominance among wealthy locals may imply that it
consisted of good practical solutions for confronting the summer heat load, even in a world without mechanical cooling aids.

Until recently it was almost impossible to draw any scientifically-based conclusions about the *original* performance of historic buildings without laborious on-site monitoring, which in many times could not accurately mimic past conditions because of structural alternations made throughout the years. The recent introduction of powerful thermal simulation software enables us today to digitally recreate indoor thermal conditions of historic buildings *at their original state* and thus to open a new field of exploration in the history of architecture using tools that are rarely used today for historical research (Balocco and Grazzini 2009; Meir et al. 2004). Following this course, this research attempts to exploit a computer-based thermal simulation tool for the analysis of the thermal performance of Central Hall houses located in the Israeli coastline. Alongside, it puts into question the common belief that vernacular architecture embodies clever and sometimes sophisticated design solutions for handling the prevailing weather conditions.

**RESEARCH METHODOLOGY**

**The Sample Buildings**

Three historic buildings – which represent "classic", modernized and "extravagant" instances of the building type – were chosen for analysis. The simulation relied on existing architectural documentation of the buildings, including a suggested reconstruction of the structure's *original* state. A complementary research was conducted in order to survey the common building techniques and the customary use of the buildings at the time of construction. All three buildings are exposed mainly to southern and western winds during summer. It is important to note that since the orientation of Central Hall houses was usually based on the local position of the building lot in reference to the closest road (i.e., its main façade positioned usually parallel to the main road), Central Hall houses can be found in a wide variety of orientations. This tendency is also reflected in the selection of the sample structures. A general description of the three structures is given below.

**Building A (House at 30 Chelouche Street, Tel-Aviv-Jaffa)**

This building is a single story house with a gross floor area of 190 m$^2$. It is located about 600 m from the sea side, in the historic neighborhood of Neveh-Tzedeq (32.06 N, 34.77 E, 15 m above sea level), which consists mainly of low-rise houses of one, two or three levels. The house was built in the beginning of the 20th century and originally consisted of five rooms in the living floor (one central hall with two rooms on each of its sides, figure 1). The house was documented in 2008 by architect Naor Mimar (Mimar 2008). It can be regarded as a Central Hall house in its "classic" form.

![Figure 1 Floor plan of Building A](image)

**Building B (House at 35 Israel Me-Salant Street, Tel-Aviv-Jaffa)**

This building is a two-story house consisting of a lower ground floor used for storage (gross floor area of 300 m$^2$) and an upper living floor (gross floor area of 170 m$^2$, figure 2). It is located about 2.5 km from the sea side, in an area that was originally a part of the agricultural hinterland of the city of Jaffa (today a part of Shapira neighborhood, 32.05 N, 34.78 E, 30 m above sea level). The ground floor of the house was built before the 1870s as an agricultural facility. The additional living floor was constructed during the 1920s and consisted of a central hall flanked on both sides by two side rooms and additional side rooms that were located next to the south-western room and could be accessed directly only from an external terrace. The house was documented in 2007 by
architect Amnon Bar-Or (Bar-Or 2007). This house can be regarded as a "modernized" version of the classic type, integrating a less strict spatial arrangement while replacing the traditional pitched roof with a flat reinforced concrete slab.

The house was built from typical local sandstone ("Kurkar"). It is interesting to note the unusual mix of local stone walls and reinforced concrete elements (roof slab, supporting columns for the roof slab's overhang above the upper floor terrace, balconies). Its rarity implies a transitional phase in which modern construction techniques were gradually integrated into local building habits. Both the external and the internal walls of the upper floor are about 35 cm thick, built from one layer of cut stone, covered with lime-based plaster. The reinforced concrete roof slab above it is 24 cm thick. It is surrounded by an 85 cm high reinforced concrete parapet.

Building C (House at 19 Ma'ale Ha-Shihur Street, Haifa)

This building is a lavish two-story house consisting of a lower ground floor used for storage (gross floor area of 340 m²) and an upper living floor (gross floor area of 570 m², figure 3). It is located in the city of Haifa, about 500 m from the sea side (32.81 N, 35.00 E, 51 m above sea level). The house was built between 1870 and 1874 by a wealthy local family on a rocky hill. It was documented in 1995 by interior architect Yael Alef and engineer Edward Kulik from Israel Antiquities Authority (Alef 1995). This house represents an extravagant version of the Central Hall House type, consisting of all of its main characteristics with an additional rare spatial element of a riwaq (the Arabic word used to describe an arcade or a loggia), which surrounds the main living spaces of the upper floor.

The house was built from local limestone, typical of the Haifa region, with a pitched roof built from a wooden frame construction upon which clay tiles were laid. External walls are all 67 cm thick, except the arcade and the service section walls which are 35 cm thick. Internal walls are also about 35 cm thick. All of the walls were built from one layer of cut stone, covered with lime-based plaster. The roof space is left empty and unusable. The ceiling between the living floor and the roof space is made out of thin wooden stripes covered with gypsum plastering.

Simulation procedure

The internal thermal conditions of the sample houses were simulated using the EDSL Tas software package, version 9.1.4.2 (EDSL 2010). The simulation was conducted in the following way:

- An approximate 3D model of the building was digitally reconstructed (figure 4).
- "Building materials" with physical values based on existing scientifically-measured data were assigned to all building elements of the 3D model (walls, floors, ceilings, windows, doors, etc., see table 1).
- Operational scenarios were set, determining internal gains levels, air infiltration rates as well as windows and shutters opening schedules.
- Weather data was generated using the Meteonorm 6.0 Software tool (Meteotest 2010), based on the exact geographic location and altitude of the building site, including dry-bulb outdoor temperature, outdoor relative humidity level, and wind speed/direction. The effective wind speed at the building site was calculated by the
simulation software following the "Town" terrain type, which corresponds to the "Urban" terrain type of the British Standard BS 5925:1991 (British Standards Institution 1991).

- The dynamic simulation produced hourly values for different internal climatic indicators (temperatures, relative humidity levels, air change rates, heating or cooling loads, local gains, etc.).
- The deployed simulation tool cannot produce internal air speed data, which was needed for the PMV-PPD thermal comfort model (see below). While auxiliary CFD (Computational Fluid Dynamics) software could have been used for highly-accurate simulation of indoor air flow speeds, generation of such data is time-consuming even for a single set of environmental variables, and therefore could not have been considered as a feasible simulation option, practically speaking, for our own purposes (producing values on an hourly-basis for the six warmest months of the year would have resulted in 4416 separate CFD simulation sessions). Therefore, it was decided to follow a different methodology (Koranteng and Mahdavi 2011) and to roughly estimate indoor air flow speed using an empirically-based formula, which was derived from on-site monitoring results and correlates air change rate to internal wind speed (Pröglhöf 2004):

\[ v = \frac{(ACH+3.43)}{63.1} \]

Herein, \( v \) is the internal air speed in m/s and \( ACH \) is the hourly air change rate.

*Figure 4 Current photos of the sample buildings (left) and the digital 3D reconstruction of the buildings in their original state (right, the central hall is marked in red)*
Table 1 Simulation assumptions regarding the physical properties of the main construction materials

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>THERMAL CONDUCTIVITY (W m⁻¹ K⁻¹)</th>
<th>DENSITY (kg m⁻³)</th>
<th>SPECIFIC HEAT (J kg⁻¹ K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement floor tiles</td>
<td>1.46</td>
<td>2100</td>
<td>1000</td>
</tr>
<tr>
<td>Clay floor tiles</td>
<td>1.3</td>
<td>2000</td>
<td>840</td>
</tr>
<tr>
<td>Concrete slab, reinforced</td>
<td>1.9</td>
<td>2300</td>
<td>840</td>
</tr>
<tr>
<td>Glass</td>
<td>1.05</td>
<td>2500</td>
<td>840</td>
</tr>
<tr>
<td>Gypsum-based plaster</td>
<td>0.81</td>
<td>1680</td>
<td>840</td>
</tr>
<tr>
<td>Kurkar stone (eolianite calcareous sandstone)</td>
<td>2.26</td>
<td>2150</td>
<td>840</td>
</tr>
<tr>
<td>Lime-based plaster</td>
<td>0.80</td>
<td>1600</td>
<td>1000</td>
</tr>
<tr>
<td>Limestone</td>
<td>1.50</td>
<td>2180</td>
<td>720</td>
</tr>
<tr>
<td>Marseilles clay roof tiles</td>
<td>0.81</td>
<td>1700</td>
<td>840</td>
</tr>
<tr>
<td>Pine wood</td>
<td>0.12</td>
<td>510</td>
<td>1380</td>
</tr>
</tbody>
</table>

Simulation scenarios

Since natural ventilation was originally the only mean for relieving the thermal discomfort caused by the combination of high relative humidity levels and high dry-bulb temperatures, one of the main issues that had to be given a closer look was the effect of different natural ventilation scenarios on indoor conditions and thus on comfort levels. Toward this end, four operational scenarios were simulated, mimicking the way the structures at their original state were supposedly operated and used (or meant to be used) around the time of their construction.

Originally, two building elements were meant to control the internal thermal conditions, namely the windows and the external shutters. Upper round apertures, which existed at times, were rarely accessed because of their height and therefore were modeled as constantly open during summer. It was decided to schedule the operation of the adjustable elements in 12-hour periods, with each element type defined as constantly open or closed during daytime (07:00-19:00 daily) or nighttime (19:00-07:00 daily) only. Thus, the following four operational scenarios were applied, representing different natural ventilation strategies (table 2): Daytime Ventilation (scenario DV); Nighttime Ventilation with shutters opened during daytime (scenario NV-DSO); Nighttime Ventilation with closed shutters during daytime (scenario NV-DSC); and a limited ventilation scenario in which both the rectangular windows and the shutters were constantly closed, enabling penetration of air only through the round apertures, when existing (scenario CC). The air infiltration rate of the building envelope was set to 0.3 h⁻¹, while the air infiltration rate of the pitched roof area was set to 2.0 h⁻¹. Internal occupancy sensible gain was set to a constant value of 1.0 W/m².

Table 2 summarizes the applied ventilation scenarios.

Table 2 Simulation scenarios definitions

<table>
<thead>
<tr>
<th></th>
<th>DV</th>
<th>NV-DSO</th>
<th>NV-DSC</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular windows</td>
<td>Opened fully during <strong>daytime</strong> only (07:00-19:00), nighttime closed</td>
<td>Opened fully during <strong>nighttime</strong> only (19:00-07:00), daytime closed</td>
<td>Opened fully during <strong>nighttime</strong> only (19:00-07:00), daytime closed</td>
<td><strong>Constantly closed</strong></td>
</tr>
<tr>
<td>External Shades</td>
<td>Opened fully during <strong>daytime</strong> only (07:00-19:00), nighttime closed</td>
<td><strong>Constantly open</strong></td>
<td>Opened fully during <strong>nighttime</strong> only (19:00-07:00), daytime closed</td>
<td><strong>Constantly closed</strong></td>
</tr>
<tr>
<td>Round Apertures (when existing)</td>
<td><strong>Constantly open</strong></td>
<td><strong>Constantly open</strong></td>
<td><strong>Constantly open</strong></td>
<td><strong>Constantly open</strong></td>
</tr>
</tbody>
</table>
Thermal comfort indices and comfort zone definitions used for assessment

The main definition used here for comfort analysis is the extended comfort zone for developing countries of Baruch Givoni’s building bio-climatic chart (BBCC) (Givoni 1998). In order to assess the plausibility of the results produced by Givoni’s definition, these were compared with values produced by three other widely accepted comfort definitions: Fanger’s PMV-PPD model, as formulated in category B of the ISO 7730 standard (ISO 2005); Szokolay’s “adaptive comfort zone” (Szokolay 2008); and category II in Annex 2 to the relatively new European Standard EN 15251 (CEN 2007). Givoni’s definition was chosen as the primary definition for assessment since it is the only of the four definitions that takes into account the combined effect of dry-bulb temperatures and relative humidity levels while acknowledging the impact that thermal adaptability of the body and user expectations have on the subjective sensation of comfort. It is also exclusively devised for assessing indoor conditions of naturally ventilated buildings.

The main analysis indicator for all four comfort definitions can be described as the percentage of time when the comfort indicator value is within the comfort range. These values were calculated on a seasonal basis (spring-autumn: May, June and October; summer: July-September).

SIMULATION RESULTS

The following detailed results relate mainly to one of the three sample buildings (Building A, 30 Chelouche Street), although the overall tendencies were essentially similar in the other two buildings. The results can be divided into two types: results that help understand the basic thermal performance of the structures independent of the effect on human sensation (based only on indoor dry-bulb temperatures), and results that describe the structures’ assumed ability to provide indoor comfort conditions (using the thermal comfort rates). The central hall and the side rooms were analyzed separately. All side rooms were analyzed as a whole because they all show a similar overall reaction to the outdoor conditions, independent of their orientation and size.

Cumulative frequency charts of indoor temperatures in the central hall and side rooms (figures 5 and 6) reveal the effect of the different natural ventilation scenarios on indoor temperatures during summer. Figure 7 shows the effect of the various ventilation scenarios on mean hourly indoor temperatures during summer, compared with the corresponding outdoor temperatures.

Figures 8 and 9 show a cross-comparison of mean hourly indoor summer temperatures of the three sample buildings for the central hall and the side rooms. Since the outdoor conditions of the sample buildings are not identical, this was done by comparing the temperature difference between indoor and outdoor temperatures.
Figures 10 and 11 show the relation between indoor dry-bulb temperatures, relative humidity level and Givoni’s extended comfort zone in both summer and spring-autumn (side rooms of Building A only). These figures also help to understand the effect natural ventilation has on thermal comfort. The corresponding psychrometric charts for the central hall are not included here because they show essentially similar tendencies.

Figure 12 shows a cross-comparison of thermal comfort rates using Givoni’s definition for all three sample buildings under all ventilation scenarios. A comparison with thermal comfort rates produced by other comfort definitions is given in figure 13. It shows clear differences in rates that were produced by different comfort definitions using exactly the same dataset of thermal indicators.

Figure 12 Thermal comfort rates comparison for the three buildings under different ventilation scenarios and according to Givoni’s extended comfort zone: central hall (a) and side rooms (b)
Figure 13 Building A, comfort rates according to four comfort definitions: central hall (a) and side rooms (b)

Because of the important role natural ventilation has as a cooling aid in all three buildings, it is also important to note that the simulated average air change rates in Buildings A and B were much higher than in Building C (figure 14). Average summer air change rates were almost similar in all buildings and rooms to the corresponding spring-autumn values.

Discussion

Thermal Performance

It is quite clear that under daytime and nocturnal ventilation, both the central hall and the side rooms show a similar recurrent pattern of temperature change in all three buildings. Differences do exist, but they are relatively marginal. Under scenario CC, in which natural ventilation almost does not exist, differences are more evident and more crucial. These differences are mainly the outcome of differences in architectural features: Building B, in which a roof of flat concrete slab replaces the traditional high pitched tile roof, shows a tendency of quicker heating and cooling of the side rooms, compared with Building A; this may be attributed directly to the poor thermal insulation properties of the concrete slab. Building C shows under scenario CC much higher summer temperature levels than the other two sample buildings; this can be explained by the presence of the surrounding arcade, which prevents the direct release of heat from the central hall and side rooms to the outside through the envelope. Therefore, regarding the thermal performance of the building type as a whole, it can be argued that:

- The high thermal mass of the stone walls has a positive role in maintaining relatively low indoor temperatures during the summer's warmest hours. This tendency is enhanced by the role of the enclosed space under the high pitched roof, which functions as a thermal buffer.
- Nocturnal ventilation has a clear positive effect as it substantially reduces daytime indoor temperatures during summer, while keeping nighttime temperatures at a relatively low level.
- Daytime ventilation results in temperature levels similar to outdoor conditions during daytime, with substantially higher temperatures during nighttime. Nevertheless, even this ventilation strategy produces lower temperature levels compared with no ventilation or limited aperture ventilation.
- The central hall is usually warmer than the side rooms during daytime, independent of the applied ventilation scenario. This can be partially attributed to the fact that it has less external wall surface per volume compared with the side rooms (thus limiting its ability to release heat during nighttime) and that it has substantially lower air change rates than the side rooms when no surrounding arcade (a rare feature in Central Hall houses) exists.
- The high open round apertures, when existing, help in cooling the indoor space during nighttime, although their role as a ventilation tool is quite limited when compared with ventilation through the main rectangular windows.

Thermal Comfort

Comparison of the comfort rates produced for each of the sample buildings according to Givoni's extended comfort definition shows some similarities along some fundamental differences. Generally speaking, comfort rates ranged between 58-80% during summer and 58-96% during spring-autumn when daytime or nocturnal ventilation were applied, with no essential difference in results between the central hall and the side rooms. Assuming that Givoni's definition truthfully describes the comfort perception of the
original users, this may suggest that the Central Hall building type was well adapted to the local thermal conditions and enabled its users to enjoy relatively reasonable indoor conditions even during the warmest months of the year. Moreover, it can be argued that:

- Natural ventilation (both daytime and nocturnal) helped in maintaining relatively reasonable comfort rates during summer (around 60 to 70%). Nocturnal ventilation had a negative effect on comfort rates during the spring-autumn period mainly because of low nighttime dry-bulb temperatures.
- Under certain conditions, limited aperture ventilation resulted in virtually the same level of comfort rates as the other ventilation strategies because of a unique combination of high – but not too high – temperatures with lower relative humidity levels.
- Even low rates of indoor air change can result in reasonable comfort rates during summer.
- It is not clear which ventilation strategy produces the best comfort rates, since each of the three sample buildings showed a different hierarchy of results for each of the ventilation scenarios. Likewise, it is not clear whether the central hall consistently produced better or worse comfort rates than the side rooms.
- Givoni’s definition does not take into account the potentially positive effect of higher air flow speed on comfort sensation. It is thus possible that summer-time comfort rates could be higher than suggested here, when daytime ventilation is applied.
- Givoni’s definition shows no consistent relation between low indoor temperatures and high summer comfort rates. This should be attributed to the high relative humidity levels of the Israeli coastal plain, which have a dominant effect on discomfort levels, especially during nighttime.

A comparison between comfort rates that were produced by all four comfort definitions using the same data set of thermal indicators reveals major differences. For the present discussion, Givoni’s definition appears to produce the most plausible values: Szokolay’s definition produces unreasonably low values (not exceeding 10%); the EN 15251 definition produces summer rates which are consistently and substantially higher than the spring-autumn rates, in contrast to the opposite tendency produced by the other three models; and the PMV-PPD model, in contrast to the other three definitions, shows surprising internal inconsistencies in the correlation between indoor temperature, relative humidity and the comfort rates in each of the three buildings, while producing unreasonably low rates at times. While it is beyond the scope of this paper to analyze in depth the reasons for the major differences between the results, it can at least be argued that under the prevailing hot-humid weather conditions of the Israeli coastal plain, the selection of a certain comfort definition can substantially influence the evaluation’s outcome with respect to the thermal performance of the examined buildings. This suggests that further research is needed to more reliably identify the most suitable thermal comfort definition for hot and humid climatic regions.

CONCLUSION

The simulation results seem to suggest that the Central Hall building type could have yielded fairly reasonable indoor conditions for its original builders and users during summer, relying only on natural ventilation. Yet, at the same time, it seems as if the main driving force behind its formal development was not its thermal properties, since the performance of the central hall, which was regarded by the original users as the most important and most heavily used space of the house, was not better – and usually worse – than that of the side rooms during summer. This may indicate that the spatial scheme of a central hall flanked by two rows of side rooms had more to do with formal and cultural conventions than with the thermal conditions resulting from it.

Since this research is based solely on computer simulations that were not calibrated using on-site monitoring, further on-site research is needed in order to obtain more decisive conclusions about the Central Hall building type and its performance under hot and humid climate. It must be noted, though, that even on-site monitoring might not clarify the remaining questions exhaustively since most of the existing instances of this building type went through many structural modifications and refurbishments that substantially changed their original state.

In general terms, the research methodology applied here demonstrates the potential of using building simulation tools to shed more light on the physical performance of historic structures. In this, computational simulation can substantially enrich our understanding of historical phenomena, even when the buildings under question no longer exist.

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