TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

MASTERARBEIT

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

ausgeführt zum Zwecke der Erlangung des akademischen Grades einer Diplom-Ingenieurs

unter der Leitung von
Univ. Prof. DI Dr. Ardeshir Mahdavi
E 259-3 Abteilung Bauphysik und Bauökologie
Institut für Architekturwissenschaften

eingerichtet an der
Technischen Universität Wien
Fakultät für Architektur

von
Arch. Or Aleksandrowicz
Matrikelnr. 0927381
Gußhausstraße 26/7, 1040 Wien

Wien, Februar 2012

ACKNOWLEDGEMENTS

This research owes more than a little to the help and support of others.

First and foremost, I would like to thank my advisor, Prof. Ardeshir Mahdavi, for his careful guidance. His numerous suggestions proved to be invaluable for the development and completion of this research.

I would also like to thank Dr. Kristina Orehounig and the rest of the scientific staff of the building physics and building ecology department at Vienna University of Technology for introducing me to the scientific tools and methods that were essential for performing this research.

I am grateful to Yael Alef, Arch. Amnon Bar-Or, Dr. Ron Fuchs, Arch. Waleed Karkabi, Arch. Naor Meimar, Prof. Isaac Meir and Eng. Yaacov Schaffer, who gladly shared with me their insights and knowledge of Central Hall houses.

Special thanks must be conveyed to my parents, Pasana and Sinai, my sister Nili and my brother Gadi, who were helpful and supportive in many aspects throughout the process of this research.

Last but not least, I would like to thank my wife, Miri Sharon, for her long and caring partnership.

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 House 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. The research proposes a method for performing an indicative assessment of the environmental features of the Central Hall House building type in the Israeli coastal plain through the integration of architectural and historical survey with computer-aided simulation techniques.

Contents

1 INTRODUCTION

1.1 The Central Hall House building type

Vernacular Architecture is a term used to describe built elements in the human environment that were constructed following common know-how and practice that resulted from a relatively long process of adaptation and perpetuation in a given culture. Because of the ongoing evolving process that is typical to vernacular building methods and because of the builders' need to make the best out of a limited range of resources, vernacular architecture is likely to consist of features that embody highly workable performance solutions even when the technology used is relatively unsophisticated. This claim, however, should not be generally accepted without further exploration (Meir et al 2004), since adhering to certain building habits may stem from totally different factors than the pure technical performance of the built product. On the other hand, if indeed certain built vernaculars contain applicable and practical solutions for certain performance features, understanding the mechanisms that lie behind them will enable their integration into current design, 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 southern Sanjaks (the highest administrative subunit) of the Ottoman empire (Acre, Nablus, Jerusalem and Gaza, later on British Palestine and today's Israel and the Palestinian territories). In a relatively short period of time, this building type was widely adopted by wealthy locals, who regarded it the most suitable building pattern for constructing their own houses and mansions. This situation persisted 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).

The historical phenomenon of the Central Hall House was usually researched in the past focusing on its cultural and typological aspects, while its more technical facets were almost entirely neglected and therefore still remain relatively unknown. Assuming this building type, as a salient example of Middle Eastern vernacular architecture, integrates intelligent design features, a closer look into its performance mechanisms is believed to produce insights that may have an impact also on the contemporary building techniques used in the region.

1.2 Research motivation

The climate of the Israeli coastal plain is known to be relatively hot and humid (Csa climate type according to the Köppen-Geiger climate classification). During the peak months of July and August the average high temperature is about 30˚C with a relative humidity rising above 80%. In the last two decades these conditions, alongside the substantial rise in the standard of living, have been responsible for the increasing use of air conditioning systems for both public and domestic purposes in Israel, mainly in the Tel Aviv-Jaffa metropolis (with a population of more than 3 millions). The growing numbers of air conditioning systems is said to be the main reason for the constant rise in electricity demand in Israel, which in the past few years reached a new peak every summer (Hirsch 2004, IV). Therefore, reduced use of conventional air conditioning systems, especially within the hot and humid Tel Aviv-Jaffa metropolis, will result in a substantial cut in electricity consumption (and thus in overall CO_2 emissions) in Israel.

Since we can assume that the climate of the Tel Aviv-Jaffa region (as well as of the Israeli coastal plain in general) was not essentially different 130 years ago,[1] one way of devising energy-efficient methods for maintaining thermal comfort in today's buildings is to tap into past experience, where electricity-based techniques for cooling and heating did not exist, thus making it necessary to rely on the sheer performance of the structure. The rapid expansion of the Central Hall House building type along the eastern shores of the Mediterranean and its extensive adoption from the 1880s until at least the 1920s (a period when only passive cooling methods were at hand) may imply that it proved to be highly suited for the region's climate. In other words, its popularity might have had something to do with the improved indoor conditions, compared with former building types.

[1] One of the earliest thorough scientific descriptions of the climate characteristics of Tel Aviv dates back to 1935. It is based on data that was systematically gathered and documented between 1923 and 1933. A concise summary of the findings was published a year later in a book dedicated to the history and geography of Tel Aviv and Jaffa. Among other issues, the author states there that "The average yearly relative humidity in Tel-Aviv is 73%. The most humid months are during summer, a time period when the effect of the sea winds is at its peak […] November is the month with the lowest relative humidity (70%) and July and August with the highest (76%). During these months the high humidity has a negative effect since the temperature is simultaneously high. Therefore, the excess human sweat cannot be evaporated properly and the body feels overstressed because of the excess heat and humidity: our air is then virtually tropical, though with no tropical rains." (Baruch 1936, 416)

1.3 Historic background

The term "Central Hall House" was coined four decades ago by the architecture scholar Friedrich Ragette. Ragette sought to describe a building type that emerged in Lebanon during the second half of the 19th century and had a typical floor plan of a rectangular central hall that leads to several rooms on both of its sides. Houses of this type consisted usually of a ground level used solely for storage, and an upper level accommodating the living spaces. 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, inaccessible and untreated. It is worth to mention that this kind of roof construction was new and unique in the region at that time.

The Central Hall House emerged in Lebanon at first as an urban mansion, mainly in the rapidly-developing urban center of Beirut; later on it was also adopted by wealthy residents of the rural areas, most of them returning to their home villages after gaining a small fortune abroad (Khater 2003, 371-372, 382-386). This wide distribution made the Central Hall House a Lebanese national symbol and encouraged researchers to refer to it as a genuine Lebanese phenomenon (Ragette 1974, 92). The historical facts, however, may imply otherwise, since the same building type emerged at about the same time in the urban centers of Palestine, gaining there a status of a common building convention (Fuchs 1998, 63-65).

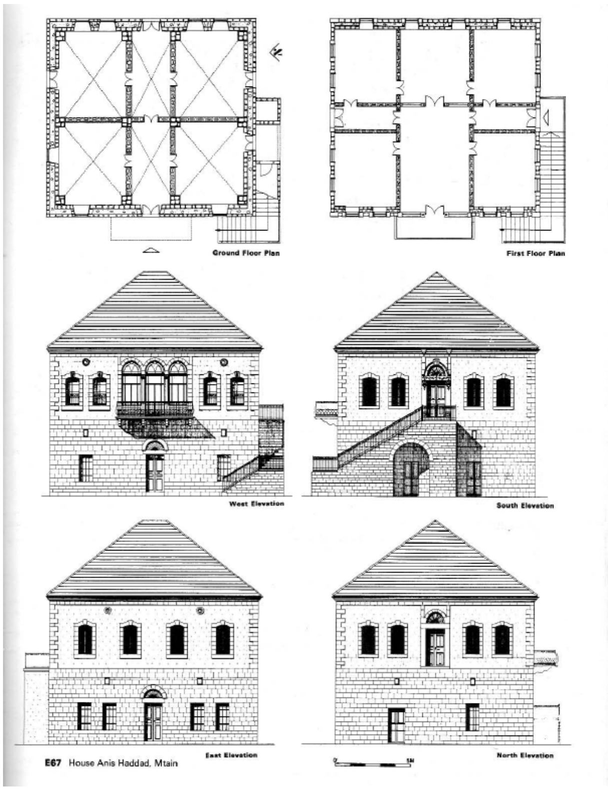


Figure 1.3.1: A "typical" Lebanese Central Hall house (Ragette 1974, 99)

Central Hall houses differed in their sizes (the area of the living floor ranged from 100 to 500 square meters) while retaining a similar internal division of space. Rooms – two or three to each side – were laid parallel to the larger rectangular central hall. The side rooms could only be approached from the hall, making it the main and most significant living space. On both ends of the central hall there were usually three arched windows; in some variants a central window on one side was replaced by a door leading to an external balcony. Internal arched openings were sometimes used to subdivide the central hall into two or three separate sitting areas. These were left open to enable free movement between spaces.

Apart from the three arched windows that were opened on both sides of the central hall, other rectangular windows were located in every room, usually two on each room's external wall. In many cases, small round apertures were built into the external walls relatively close to the room ceiling. While the rectangular windows were glazed and closed with external wooden shutters, these round apertures were sometimes left unglazed, enabling an undisturbed flow of air into and out of the room during summertime: during winter, an inner wooden plate was used for sealing them.

The building materials of Central Hall houses incorporated usually local construction traditions with contemporary industrialized products. The walls were built out of local stone that was sometimes left unplastered. The ceiling of the ground level consisted usually of a plastered ribbed vault construction made of stone and rubble; in times a different construction was used, consisting of steel I-shaped beams with clay tubes or bricks (or sometimes even plain stone), arranged in an arched form, filling the gaps between them. Floor tiles made of stone, clay or cement were laid above the floor's structural elements. The roof tiles were made out of clay, with a horizontal surface of gypsum-covered wooden stripes, attached to structural wooden beams, separating the upper level from the unused roof space. The window frames were made out of wood. Since the stone used for construction was quarried locally, it differed from one area to another.

Surveying the existing body of research about the Central Hall House, it is interesting to note that almost all of it is dedicated to its typologies and historical aspects, without a deep and systematic analysis of its technical features and environmental performance, making this research almost the first of its kind. It is also worth mentioning that the attention that was given to the proliferation of use of this building type in Palestine is relatively marginal compared with the body of research dedicated to the Lebanese case. Therefore, further research into the Palestinian exemplars of the pattern is believed to enrich not only the understanding of the functional aspects of this building type but also its history.

1.4 Research methodology

Central Hall houses found in the Israeli coastal plain are the main target of this research. Detailed description of the selected houses was based on architectural documentation done by others (private conservation architects or architects working for governmental conservation bodies). Their documentation consists of a full survey of the building's dimensions as well as the original construction materials, technologies and structural elements. 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.

Figure 1.4.1: Historic Central Hall houses in today's Jaffa (photos taken by the author, 2009)

The sample set of houses used in this research consists of three structures (two in Tel-Aviv-Jaffa and one in Haifa), as described in detail in chapter 2. A computer-based simulation tool was used for evaluation of the thermal performance of the selected structures. Digital models of the houses were constructed following the existing documentation while using registered or estimated thermal conductivity values of the original building materials. Contemporary local weather conditions data was used for simulation, assuming that any shift in local climate conditions during the last century was not substantial. The research limited itself to the six warmest months of the year (May-October), since these are regarded today as the major climatic challenge in maintaining indoor thermal comfort in Israel's coastal plain.

The simulation results were analyzed using four different thermal comfort models, which represent several current approaches to the concept of thermal comfort and its evaluation strategies. This enabled not only the understanding of the performance mechanisms of the houses but also the deeper exploration of the sheer concept of thermal comfort under the specific climate conditions of the region.

1.5 Results

This research originated from the assumption that the historical phenomenon of the Central Hall House in Palestine may embody practical strategies and features that were conceived for tackling the climatic needs of their builders. The historic circumstances of the emergence of the Central Hall House, its quasi-modern character and its prevailing dominant status for several decades may imply that this type had integrated better mechanisms for environmental control compared with its predecessors, even though its remarkable prominence may have resulted from entirely different factors, such as common cultural aesthetic conventions or local living habits.

Although decisive conclusions could only be drawn from on-site monitoring results, the simulation process used here produced enough data for initial testing of the underlying research hypothesis. The simulation results helped in drawing a clear overall description of the thermal conditions inside the simulated houses and thus enabled the understanding of the environmental mechanisms behind the resultant performance. Special attention was given to the role natural ventilation may have in maintaining indoor comfort conditions during summer.[2]

Since Bernard Rudofsky's seminal exhibition and book on vernacular architecture (*Architecture without Architects*, 1964) common interest in the "ancient wisdom" that led allegedly to the creation of human habitats by

[2]Natural ventilation is believed to be the only effective way of cooling the examined houses without any mechanical means. Here it is interesting to quote the words of a local Jewish reporter who described in 1900 the new buildings of Jaffa: "The new houses of Jaffa are generally spacious, their rooms broaden one's mind, and their big and wide windows, which also lack iron gratings, are an evidence to the strong and immense love that the sons of the sandy land have for the fresh and cool wind that blows here so rarely." (Yelin 1900)

anonymous builders have grown rapidly, partly as a counter reaction to the failures of Modernism in architecture. Rudofsky made a strong argument for structures shaped by the marriage of local climate, resources, traditions and skills, while assuming these structures exhibit intelligent ongoing adaptation to local conditions. In Rudofsky's words,

> The beauty of this architecture has long been dismissed as accidental, but today we should be able to recognize it as a result of rare good sense in the handling of practical problems. The shapes of the houses, sometimes transmitted through a hundred generations […] seem eternally valid, like those of their tools. (Rudofsky 1964, 4)

Yet, although the belief in the validity of the environmental solutions embodied in vernacular architecture is not far-fetched, it should not, on the other hand, be widely accepted without further and deeper exploration. The architecture historian Reyner Banham, who was less impressed by the degree of environmental control achieved while using pre-modern means, claimed that vernacular building conventions may perpetuate not only good practical solution but also a kind of petrifying grip on cultures. In his words,

> Vernaculars (of architecture, language or whatever else) are bodies of culturally transmitted habits which can hold unquestioned sway over the lives of the communities that practice them, even when they have no survival value for those communities […] Any vernacular […] can be counter-productive when confronted with extreme aberrant conditions. (Banham 1984, 304)

This research, in its humble scope, aims also at asking whether the specific building type under discussion here embodies some kind of "lost wisdom" in handling the problematic summer climate of the Israeli coastal plain and whether its environmental solutions were satisfactory enough for the original users. In a way, this research also questions the ability of vernacular building techniques of the past to produce acceptable environmental control solutions for our present way of living, under the specific local conditions of the Israeli coastal plain.

Last but not least, the methodology employed here may also demonstrate the potential use of computer-based simulation tools for research purposes by architecture historians and not only as means for contemporary performance evaluation of existing or proposed buildings. Analysis of building performance, in its physical sense, is, generally speaking, almost absent from the writing about architectural history, and even when existing, it is based on vague impressions or questionable arguments made by the original designers, rather than on consistent and critical scientific research. The computer-based simulation tools, which are relatively new in the field of architectural research, can be employed in order to better understand the way buildings of the past performed and to better assess the relations between the intentions of their creators and the actual results, functionally speaking, even when the historic building no longer exists or has been substantially modified. This new perspective on historic buildings may thus serve for enhancing the assessment of historic transformations in architecture, vernacular or other.

2 RESEARCH METHODOLOGY

2.1 Overview

The simulation procedure that was used for this research relied on existing documentation of historic buildings in order to reconstruct their digital models and analyze their thermal performance under the conditions prevailing during the warmer part of the year. The simulation results enabled the assessment of the indoor conditions of the sample buildings according to several widely accepted thermal comfort models. Special attention was given to simulating a range of operational scenarios, focusing on the way natural ventilation affects the indoor conditions and comfort sensation. Natural ventilation is believed to be the main tool that historically helped to maintain indoor thermal comfort during the hot months in the region, when no mechanical means of cooling existed.

The simulation limited itself to the domain of thermal performance, excluding other possible aspects of environmental control such as lighting and acoustics. This was mainly done since it is believed that the thermal performance of the examined structures was given a much higher degree of importance in their original design than other environmental factors.

2.2 The sample buildings

2.2.1 House at 30 Chelouche Street, Tel-Aviv-Jaffa

This single story house consists of a gross floor area of 190m^2. It is located about 600m away from the sea side, in the historic neighborhood of Neveh-Tzedeq (32.060456 N, 34.765258 E, 15m 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 with five rooms in the living level (one central hall with two rooms on each of its sides). Later on, a northern wing was added, blocking the northern windows of the north-eastern room and adding some basement space. Some other changes in the inner partitioning of the house and in the basement deformed its original layout, although not severely. The house was documented in 2008 by architect Naor Meimar, who included in his report a suggested reconstruction of its original state. This research is based on his reconstruction.

Figure 2.2.1: The eastern façade of the house at 30 Chelouche Street (photo taken by the author, 2010)

The architectural documentation file indicates the main building materials that were used for the construction of the house (table 2.2.1). The house was built from typical local sandstone (eolianite calcareous sandstone named "Kurkar"), with a pitched roof built from a wooden frame construction upon which clay tiles were laid. External walls are about 50cm thick and internal walls are about 35cm thick – each 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 – a typical technique of the time of the original construction.

Table 2.2.1: Building Materials of the House at 30 Chelouche Street, Tel-Aviv-Jaffa

Building Element	Construction
External walls	Kurkar stone (eolianite calcareous sandstone) covered with lime-based plaster from both sides
Internal walls	Kurkar stone covered with lime-based plaster from both sides
Basement floor	Cement floor tiles on tightened soil (assumed)
Basement ceiling	I–shaped steel beams with rubble Kurkar stones laid between the beams and an upper layer of crushed stones, soil and lime mixture. The ceiling is covered with lime-based plaster
Ground level floor	Cement floor tiles on sand
Ground level ceiling	Wooden (pine?) stripes covered with gypsum plastering
Roof	Marseilles clay roof tiles (exact manufacturer unknown) laid on (cedar?) wooden beam construction
Windows	Wooden (pine?) frame with a single glass sheet pane (thickness unknown)
External shutters	Wooden "French" shutters
External door	Wooden
Internal doors	Wooden
External staircase	Precast concrete stairs

This house represents an almost "ideal" realization of the Central Hall House building type, consisting of all main characteristics of the type (lower storage level, living level of a symmetrical layout where the central hall lead to all side rooms, high unusable roof space below a tiled pitched roof) with one minor exception: the northern rooms have one more window than the southern rooms. The room height is 485cm. The geometry of the living floor is shown in figure 2.2.2, as well as the naming convention used for each room in the simulation (CH for central hall, SW for south-western room, etc.). As can be seen in the plan, the central hall is divided into two connected spaces. The openings between the two spaces were never closed. This division is typical of the building type and was done presumably to create a somewhat secluded sitting area at the rear end of the central hall. Since the two spaces cannot be separated "climatically", they are referred to in this research as one space.

Each room of the house has windows facing two directions. All windows have lower vertical glazed wings and an upper horizontal glazed frame that could be opened only to a certain extent (tilt window). All windows are opened indoors. External wooden "French" shutters with non-adjustable louvers were installed next to each window. Iron bars were located between the glazed windows and the shutters for security reasons. In the central hall three decorative arched windows are located on both facades, above the operable windows and doors.

These windows were permanently glazed and could not be opened. To the west, the central hall is leading to a small balcony made out of concrete. In the side rooms, higher round apertures are located at the upper part of each wall, high above the glazed windows (marked here with a dashed line and a special rhombus sign at its end). Originally, these apertures had no glazing, which enabled the free flow of air through them during all year, except in the cooler winter months, where they were blocked from inside using a round wooden board. It is interesting to note that in the decades following the original construction these apertures were glazed in a fixed manner, thus eliminating entirely their ventilative potential.

The house had one external door, leading to the central hall, with doors leading from the central hall to each of the side rooms, and doors connecting two adjacent side rooms.

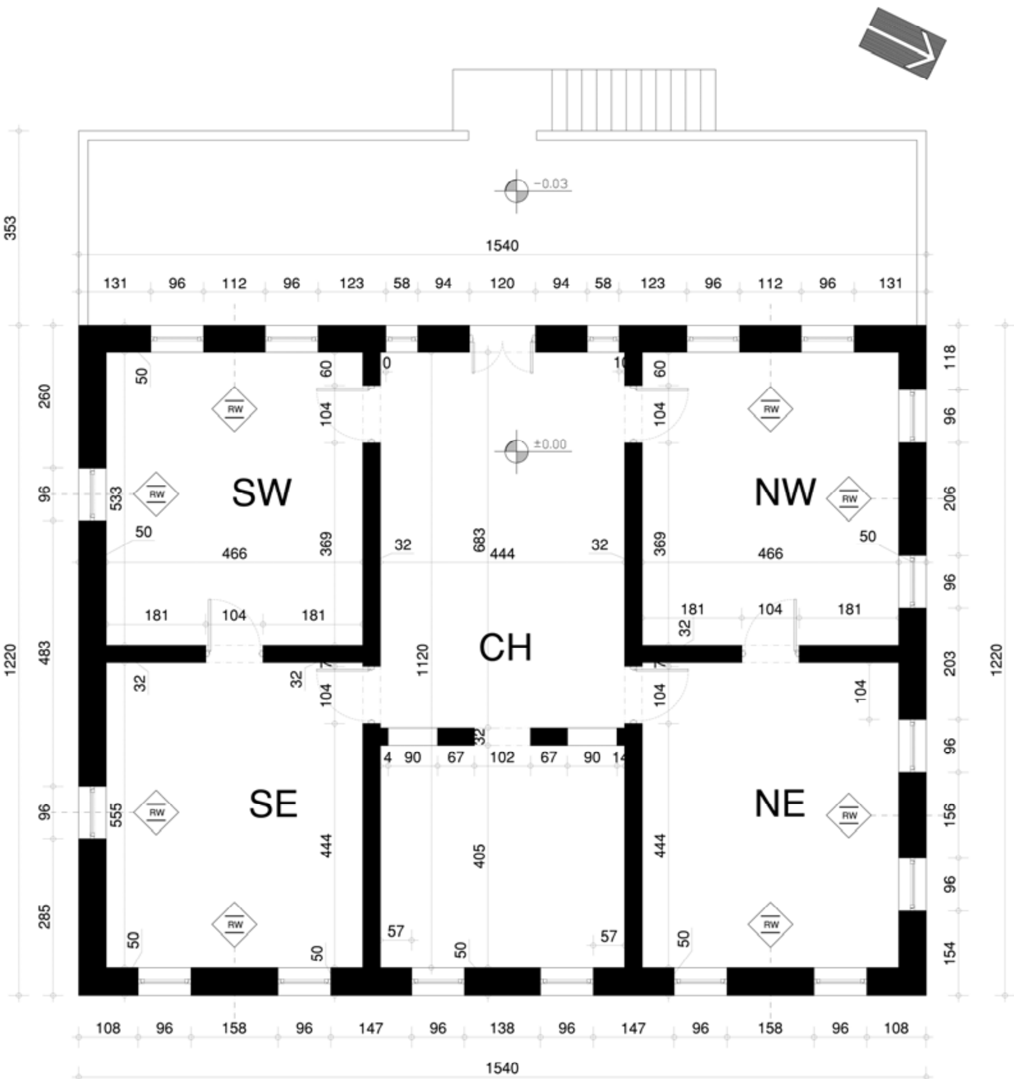


Figure 2.2.2: living floor plan of the house at 30 Chelouche Street, Tel-Aviv-Jaffa (redrawn by the author based on existing documentation)

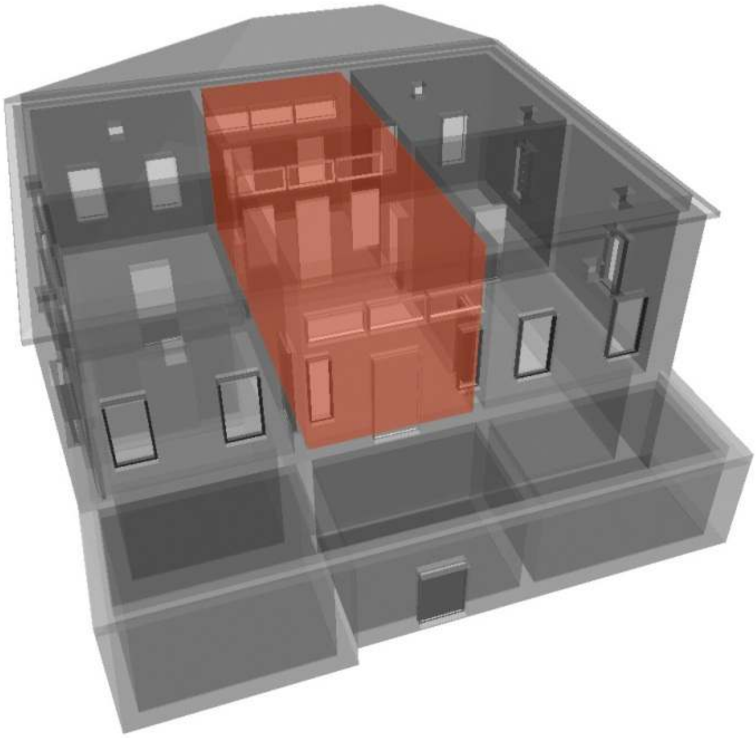


Figure 2.2.3: a 3D model of the house at 30 Chelouche Street, used for the simulation, with the central hall highlighted in red (looking from west to east)

Average monthly values of outdoor dry-bulb temperatures and relative humidity levels for the six warmest months of the year are listed below (table 2.2.2).

Table 2.2.2: Average Monthly Outdoor Dry-Bulb Temperatures and Relative Humidity Levels for the House at 30 Chelouche Street, Tel-Aviv-Jaffa (based on the Meteonorm database)

	May	**June**	**July**	**August**	**September**	**October**
DB Temperature [°C]	19.8	22.2	24.9	25.6	24.4	22.2
Relative Humidity [%]	68	74	73	72	70	67

2.2.2 House at 35 Israel Me-Salant Street, Tel-Aviv-Jaffa

This two-story house consists of a lower ground floor used for storage (gross floor area of 300m^2) and an upper living floor (gross floor area of 170m^2). It is located about 2.5km away 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 the Shapira neighborhood, 32.051350 N, 34.781636 E, 30m above sea level). The ground floor of the house was built before the 1870s as an agricultural facility which consisted of an irrigation pool and a closed storage area for an adjacent orange grove. The additional living floor was constructed by the owners of the orange grove during the 1920s and consisted of a central hall with two side rooms at each side and additional side rooms that were located next to the south-western room and could only be entered directly from an external terrace. Throughout the years some inner partitions were added to the central hall without deforming its original layout. The house was documented in 2007 by architect Amnon Bar-Or, who included in his report a suggested reconstruction of the original state of the house. This research is based on his reconstruction.

Figure 2.2.4: The western façade of the house at 35 Israel Me-Salant Street (photo taken by the author, 2005)

The architectural documentation file indicates the main building materials that were used for the construction of the house (table 2.2.3). 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 35cm thick, built from one layer of cut stone, covered with lime-based plaster. The reinforced concrete roof slab above it is 24cm thick. It is surrounded by an 85cm high reinforced concrete parapet.

Table 2.2.3: Building Materials of the House at 35 Israel Me-Salant Street, Tel-Aviv-Jaffa

Building Element	Construction
External walls	Kurkar stone (eolianite calcareous sandstone) covered with lime-based plaster from both sides. Some precast concrete decorative columns are used for dividing the openings of the two central hall facades. External reinforced concrete columns are used for supporting the overhang roof slab above the upper level's terrace
Internal walls	Kurkar stone covered with lime-based plaster from both sides
Ground level floor	Clay floor tiles on tightened soil (assumed)
Ground level ceiling	Kurkar stone vaulted construction with rubble of Kurkar stones (crushed stones, soil and lime mixture) used as an upper "leveling" material. The ceiling is covered with lime-based plaster
Upper level floor	Cement floor tiles on sand
Upper level ceiling	Reinforced concrete slab
Roof	Reinforced concrete slab
Windows	Wooden (pine?) frame with a single glass sheet pane (thickness unknown)
External shutters	Wooden "French" shutters
External doors	Wooden
Internal doors	Wooden
External staircase	Precast concrete stairs

This house represents a late transformation of the "ideal" Central Hall House building type. Although the basic plan of the living (upper) floor conforms to the typical characteristics of the building type, it consists of some substantial additional elements, namely three small rooms that are totally detached from the main living rooms and a wide, L-shaped, terrace which is partially covered by an overhang. Moreover – instead of the traditional pitched tiled roof, the roof here is more "modern" in nature, consisting of a relatively slim reinforced concrete slab that directly covers the rooms. The room height in the upper floor is 417cm. The geometry of the living floor is shown in figure 2.2.5, as well as the naming convention used for each room in the simulation (CH for central hall, SW for south-western room, etc.). As can be seen in the plan, the south-western room that opens to the central hall is attached to another southern room (named S1), which can be accessed only from the outside. One can assume that the two other adjacent smaller spaces (S2 and S3) might have been used, because of their dimensions, for service purposes only. Therefore, following the simulation procedure, results for rooms S2 and S3 were not analyzed.

Each room of the house, except for room SW and the S2 and S3 service spaces, has windows facing two directions. All windows have lower vertical glazed wings and an upper horizontal glazed frame that could be opened only to a certain extent (tilt window). All windows are opened indoors. External wooden "French" shutters with non-adjustable louvers were installed next to each window. Iron railings were located between the glazed windows and the shutters to prevent falling over. In the central hall three decorative arched windows are located on both facades, above the operable windows. These windows are permanently glazed and could not be opened. Unlike many other Central Hall houses, no high round apertures were built into any of the external walls, making the rectangular windows the sole mean for natural ventilation.

The house has one main external door leading to the central hall, with doors leading from the central hall to each of the side room and doors connecting two adjacent side rooms. In addition, rooms NE, SE, S1, S2 and S3 have external doors which also lead to the adjacent terrace. Another door leads from room NE to a northern balcony with a side staircase leading to the lower level. The number of external doors is unusual for the Central Hall House building type.

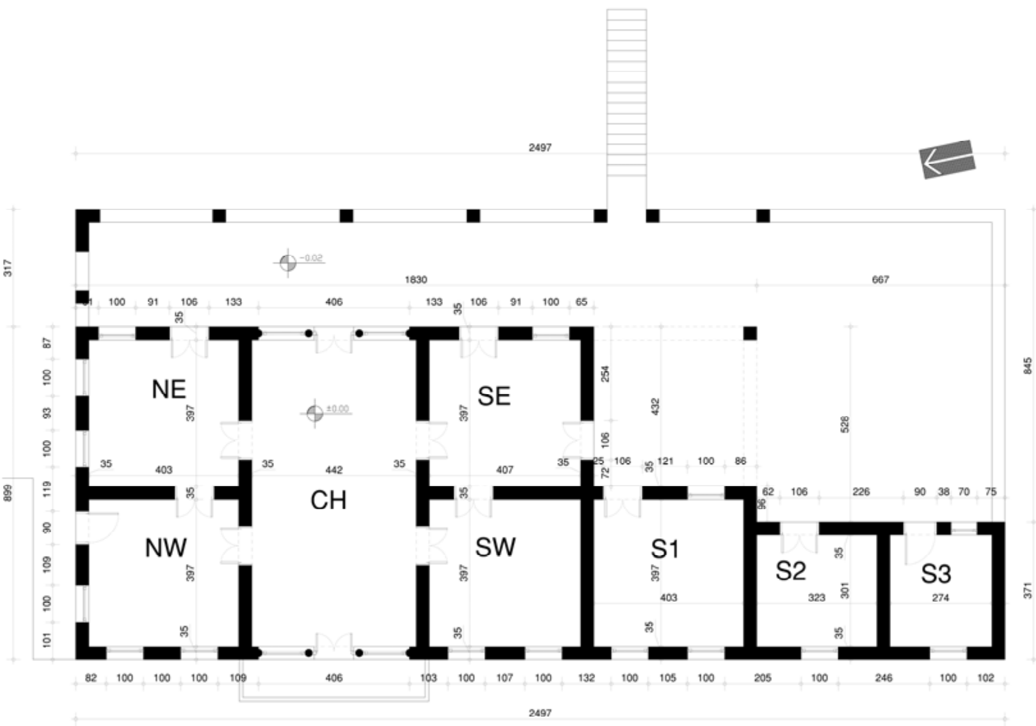


Figure 2.2.5: living floor plan of the house at 35 Israel Me-Salant Street, Tel-Aviv-Jaffa (redrawn by the author based on existing documentation)

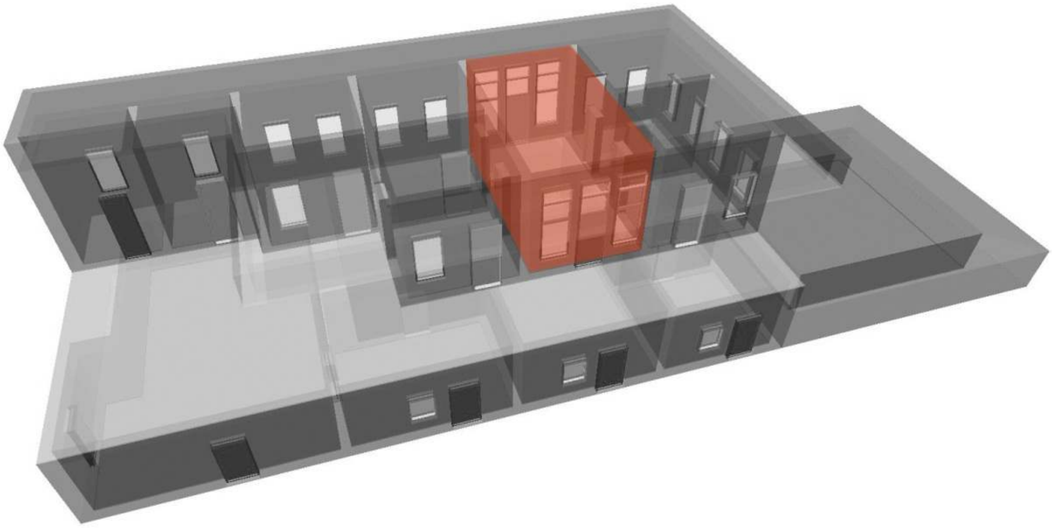


Figure 2.2.6: a 3D model of the house at 35 Israel Me-Salant Street, used for the simulation, with the central hall highlighted in red (looking from east to west). To the right is an open irrigation pool adjacent to the lower storage level.

Average monthly values of outdoor dry-bulb temperatures and relative humidity levels for the six warmest months of the year are listed below (table 2.2.4).

Table 2.2.4: Average Monthly Outdoor Dry-Bulb Temperatures and Relative Humidity Levels for the House at 35 Israel Me-Salant Street, Tel-Aviv-Jaffa (based on the Meteonorm database)

	May	**June**	**July**	**August**	**September**	**October**
DB Temperature [°C]	20.4	22.9	25.3	25.7	24.0	21.6
Relative Humidity [%]	66	71	72	72	71	69

2.2.3 House at 19 Ma’ale Ha-Shihrur Street, Haifa

This lavish two-story house consists of a lower ground floor used for storage (gross floor area of 340m^2) and an upper living floor (gross floor area of 570m^2). It is located in the city of Haifa, about 500m away from the sea side (32.812947 N, 35.001047 E, 51m above sea level). The house was built between 1870 and 1874 by a wealthy local family on a hilly slope, with one side of its lower floor attached to the rocky hill. Today, after numerous changes and deformations, it has lost much of its past grandeur. Nevertheless, its original exceptional character is still evident. The house was documented in 1995 by interior architect Yael Alef and engineer Edward Kulik from Israel Antiquities Authority, who included in the report a reconstruction suggestion. This research is based on their reconstruction.

Figure 2.2.7: The eastern façade of the house at 19 Ma’ale Ha-Shihrur Street (photo taken by the author, 2011)

The architectural documentation file indicates the main building materials that were used for the construction of the house (table 2.2.5). 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 67cm thick, except the arcade and service section walls which are 35cm thick. Internal walls are also about 35cm 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 – a typical technique at the time of the original construction.

Table 2.2.5: Building Materials of the House 19 Ma'ale Ha-Shihrur Street, Haifa

Building Element	Construction
External walls	Local limestone covered with lime-based plaster from both sides. In the building corner ashlar Kurkar stone (eolianite calcareous sandstone) was used, as well as in top lintel of windows
Internal walls	Limestone covered with lime-based plaster from both sides
Basement floor	Cement tiles on sand above rock foundation
Basement ceiling	Limestone barrel vaults (cut stone, rubble stone, soil and lime) covered with lime-based plaster
Ground level floor	Limestone tiles, marble tiles with slate borders and clay tiles (Fabrique La Plata Marseilles) on sand
Ground level ceiling	Wooden (spruce) stripes covered in some rooms with gypsum plastering and with lime-based plastering in other rooms
Roof	Marseilles clay roof tiles (exact manufacturer unknown) laid on cedar, spruce and Turkish pine wooden beam construction
Arcade floor	Limestone tiles and white marble tiles on sand
Arcade columns	Undefined sandstone and white marble
Windows	Wooden (cedar) frame with a single glass sheet pane (thickness unknown)
External shutters	Wooden (cedar) "French" shutters
External doors	Wooden (assumed)
Internal doors	Wooden (assumed)
External staircase	Limestone stairs (assumed)

This house represents an extravagant version of the Central Hall House building type, consisting of all of its main characteristics (lower storage level, living level with a quasi-symmetrical layout where all side rooms open to the central hall, high unusable roof space below a tiled pitched roof). Nevertheless, it also consists of the rare spatial element of a Riwaq (رِواق, the Arabic word used to describe an arcade or a loggia) which surrounds the main living spaces of the upper floor. Room height in this level is 539cm. The geometry of the living floor is shown in figure 2.2.8, as well as the naming convention used for each room in the simulation. The central hall (CH) leads to a rectangular hallway (HW) that connects to the surrounding Riwaq. Living spaces (N1, N2 and S1) are arranged along both sides of the central hall.[3] Three rooms are located at the back (N3, CH2 and S2); unlike the other rooms, they are not a part of the central scheme of rooms surrounded by a Riwaq. Three small and low service rooms (S3) protrude from part of the southern wing of the house. Because of their marginal use as living spaces, results for rooms N3, CH2, HW, S2 and S3 and the surrounding Riwaq were not analyzed. Therefore, the

[3] The gross area of the central hall and the adjacent living spaces is 265m^2.

"side rooms", which are referred to below, are only those that can be accessed directly from the central hall, namely N1, N2 and S1.

It is interesting to note that the Riwaq was originally designed as a closed space, in which each arched opening is closed by an elaborate window structure (upper fixed windows, middle tilt windows and lower wing windows). Nevertheless, it was perceived as an external layer added to the traditional central hall structure. This is why external wooden "French" shutters were fixed to windows of the rooms facing the arcade, though technically being inside a closed space. The same kind of shutters was used also for all external windows except those of the Riwaq. All windows have lower vertical glazed wings and an upper horizontal glazed frame that could be opened only to a certain extent (tilt window). In the central hall three decorative arched windows were located on both facades. These were glazed permanently and could not be opened. In the side rooms higher round apertures were located at the upper part of each wall, high above the glazed windows (marked here with a dashed line and a special rhombus sign at its end).

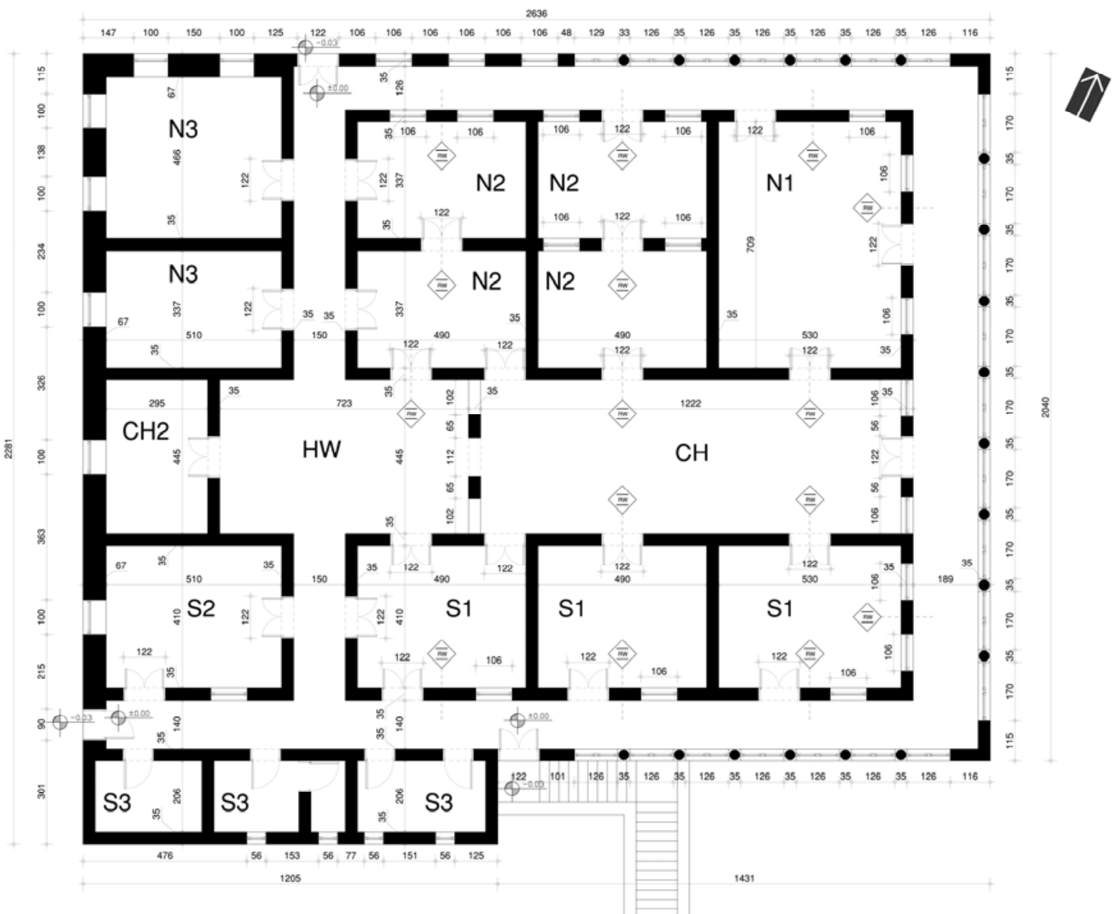


Figure 2.2.8: living floor plan of the house at 19 Ma'ale Ha-Shihrur Street, Tel-Aviv-Jaffa (redrawn by the author based on existing documentation)

The house had three external doors which led to the surrounding Riwaq. All rooms had internal doors leading to the Riwaq. Rooms adjacent to the central hall had another set of doors leading to the central hall as well.

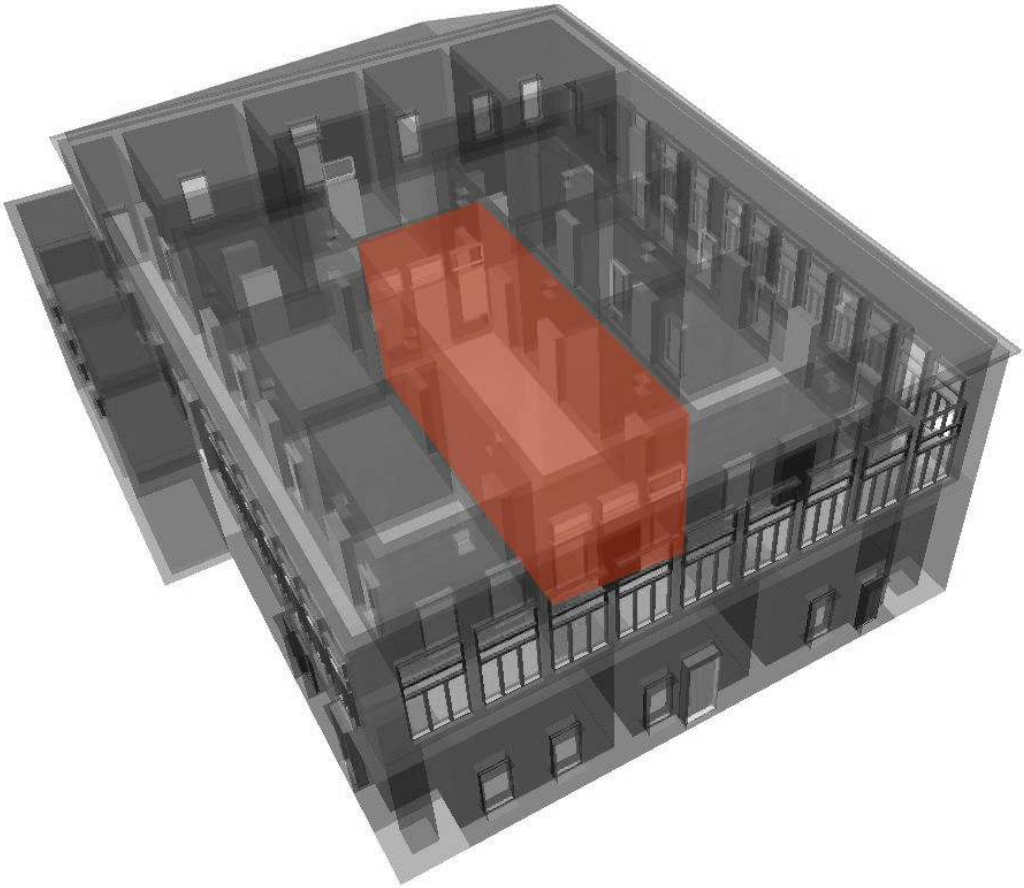


Figure 2.2.9: a 3D model of the house at 19 Ma'ale Ha-Shihrur Street, used for the simulation, with the central hall highlighted in red (looking from east to west)

Average monthly values of outdoor dry-bulb temperatures and relative humidity levels for the six warmest months of the year are listed below (table 2.2.6).

Table 2.2.6: Average Monthly Outdoor Dry-Bulb Temperatures and Relative Humidity Levels for the House at 19 Ma'ale Ha-Shihrur Street, Haifa (based on the Meteonorm database)

	May	**June**	**July**	**August**	**September**	**October**
DB Temperature [°C]	20.1	22.4	25.0	25.8	24.7	22.4
Relative Humidity [%]	66	71	71	70	68	65

2.3 Simulation procedure overview and description

2.3.1 Selection of simulation tool

In order to simulate the internal thermal conditions of the sample houses it was decided to apply an hourly-based dynamic simulation technique using the EDSL Tas software package, version 9.1.4.2 (EDSL 2010). The Tas simulation was conducted in the following way:

- An approximate 3D model of the building was digitally reconstructed.
- Building materials with predefined or user-defined properties were assigned to the different building elements of the 3D model (walls, floors, ceilings, windows, doors, etc.).
- Operational scenarios were set, determining internal gains levels, window and shutter positions and opening times and air infiltration rates.
- Weather data, which contains dry-bulb (DB) outdoor temperatures, outdoor relative humidity levels and wind speeds with matching wind directions, was integrated into the model database.
- The simulation produced a wide array of hourly values for different internal climatic indicators (temperature, relative humidity, air change rate, heating or cooling loads, local gains, etc.). All simulation data was retrieved on an hourly basis, and was indicative to a certain zone or zones of the building (namely, rooms of the living floor).

2.3.2 Weather data

The weather data used for the simulation was propagated using the Meteonorm 6.0 Software tool (Meteotest 2010), based on the exact geographic location and altitude of the building site. The weather file generated by the software is based on actual weather measurements, interpolated to overcome the differences between the location of the weather station and the location of the building.

2.3.3 Building materials properties

Building materials thermal properties were retrieved from several databases. A comprehensive list of the used values and their origins can be found in table 2.3.1.

Table 2.3.1: Physical Properties of Simulated Materials

Material	Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)	Specific Heat ($J \cdot kg^{-1} \cdot K^{-1}$)	Source
Cement floor tiles	1.46	2100	1000	CIBSE 2006 (precast concrete, dense, protected)
Clay floor tiles	1.3	2000	840	CIBSE 2006 (clay tile, burnt)
Concrete slab, reinforced	1.9	2300	840	CIBSE 2006 (concrete – dense, reinforced)
Glass	1.05	2500	840	CIBSE 2006 (glass – solid, soda-lime)
Gypsum-based plaster	0.81	1680	840	CIBSE 2006 (gypsum plaster, sand aggregate)
Kurkar stone (eolianite calcareous sandstone) [4]	1.30	2150	840	CIBSE 2006 (sandstone)
	2.26	-	-	Eckstein and Simmons 1977
	-	2004	-	Wasserman 2002
Lime-based plaster[5]	0.80	1600	1000	CIBSE 2006 (external render – lime, sand)
Limestone	1.50	2180	720	CIBSE 2006 (limestone)
Marseilles clay roof tiles	0.81	1700	840	CIBSE 2006 (roofing materials, - tile, terracotta)
Pine wood	0.12	510	1380	CIBSE 2006 (fir, pine)

[4]Recorded thermal properties values for Kurkar stone (unlike generic sandstone) are hard to find. For the simulations, the thermal conductivity value that was used (2.26W/mK) was found only in one source. Because of the lack of data, it was decided to generate a "worst case scenario" for the sake of simulation by integrating the values that will produce the lowest thermal insulation capacity. Therefore, density and specific heat values were taken from the CIBSE guide values for generic sandstone, although a lower density was recorded by another research that examined local Kurkar stones taken from the northern city of Acre.

[5] Solar reflectance for the lime-based plaster was set to 0.6, which represents a light-colored plaster.

2.3.4 Wind obstruction profile

The simulated effect of wind on the structure is calculated in Tas using one of two optional methods: either by a user-defined wind pressure coefficients for each of the structure's openings, or following a generic wind coefficient data that is based on wind tunnel experiments. Since the wind data in the weather data file is based on values measured at the standard altitude of 10m in an unobstructed environment, Tas uses an adjustment formula that takes the recorded wind speeds and adjusts them to fit the opening altitude as well as the surrounding obstructions. According to Tas Theory Manual, this is done based on the formula that appears in British Standard BS5925:1991, in which one of four terrain types (Open Flat Country, Country with Scattered Windbreaks, Urban, City) is used to simulate the estimated effect of the surrounding obstructions on the wind speed. For the three sample buildings it was decided to use the Tas "Town" terrain type, which corresponds to the "Urban" terrain type of the British standard. This was done while taking in mind the surrounding settings of the original structures, which consisted of low-rise houses in a relatively low density urban fabric. The same definition was applied to all simulation scenarios.

2.3.5 Average indoor air speeds

Tas simulation cannot produce average internal air speed data, which is needed for using the PMV-PPD thermal comfort index (see discussion of the index in section 2.6). In order to use the index some extra calculations or simulations were therefore needed. Some optional methods were considered, as follows:

- Tas provides data for air change rate at every envelope inlet and outlet (i.e. open window or "aperture" in Tas terminology). This type of data, which is given in ach or in kg/s values, describes the rate in which air flows through a given opening into or out of the room. A basic but inaccurate way to calculate the average indoor air speed is by dividing the volume flow rate through the room (ach) by a section plane area of the room which is normal to the flow direction. This applies mainly to rectangular spaces with cross ventilation, where the flow is directed from one side of the room to its opposite side (a configuration which is typical to the central hall of the sample buildings). Thus

  $$V_{avg} = \frac{ACH \cdot Vol}{3600 \cdot A_{sct}}$$

  where V_{avg} is the average indoor wind speed [m/s], ACH is the air change rate in the room, Vol is the room's volume [m^3] and A_{sct} is the area of the room's section which is perpendicular to the flow direction [m^2].

However, this method can be highly inaccurate, since it neglects totally the flow patterns of the air inside the room (based on its geometrical properties as well as the location and size of the windows). Using this method it is also impossible to calculate the average air speed at the effective height of 120-150cm, which relates to the human body upper part and therefore can have a direct influence on the sensible thermal comfort.

- In a research that was conducted in 2004, Claus Pröglhöf found a certain correlation between measured air change rate and average indoor air speeds in a given room (Pröglhöf 2004, 77). His monitoring results enabled him to formulate the following mathematical correlation between the air change rate and indoor air speed

  $$V = \frac{ACH + 3.43}{63.1}$$

  where V is the average indoor air speed [m/s] and ACH is the air change rate in the room.

  However, Pröglhöf's formula was not based on cross-ventilation monitoring results, a ventilation type that is highly-relevant to the examined building type, and is based on a relatively small sample taken in one specific location.

- In a recent study, Wang and Wong examined the concept of "coupled simulations" for naturally ventilated rooms, i.e. the integration between conventional building simulation (BS) tools (as EDSL Tas) and computational fluid dynamics (CFD) simulation software (Wang and Wong 2009) in order to "improve indoor thermal environment prediction for natural ventilation taking wind as the major force". Since full 3D CFD simulation for a large building requires substantial amount of time and computational resources, the writers suggested to use BS software to determine the boundary conditions for a certain space (surface temperatures and air pressure or speed at the space openings), and then to perform a full indoor CFD simulation for the same space based on the calculated boundary conditions, thus achieving a much better accuracy in predicting air speeds and movement patterns within the space. According to Wang and Wong, the CFD tool can be used in a limited way and for relatively simple geometric setting while producing results that are close enough to those generated by the much complex procedure of full 3D CDF simulation. In this way, the time needed to compute the average indoor air speed for a certain space is reduced dramatically without compromising the accuracy of the air speed calculation results. It is also worth noting that Wang and Wong's conclusion is based on a model of a rectangular room with cross-ventilation, in a setting similar to the central hall of the sample buildings.

After considering these three options, it was decided to rely on the Pröglhöf formula, which is based on on-site monitoring results, gives average air speed values and does not require the use of an extra simulation tool (a CFD tool), although its accuracy may be put in doubt. The main reason for not using a CFD tool, which certainly would have produced more accurate results for each particular setting, is because of the nature of this research. The main goal was to assess the building's thermal performance based on a statistical analysis of large data sets, in which the simulation result database should contain internal air speed data for a whole year on an hourly basis. In the current available CFD tools the production of such data consumes overwhelming amount of time (even with the "concise" version suggested by Wang and Wong), and therefore cannot be considered a feasible option, practically speaking, for our own purposes.

2.4 Tas simulation scenarios

The strength of dynamic simulation method lies, among other things, in its ability to apply different operational scenarios to the same building in order to shed light on the operational mechanism of the structure. In our research this functionality was mainly used for exploring the effect of natural ventilation on the structure, since natural ventilation was originally the only mean for relieving the thermal discomfort which was caused by the combination of high relative humidity levels and relatively high dry-bulb temperatures.

The operational scenarios that were simulated try to mimic the way the structures in their *original* state were operated and used (or meant to be used) around the time of their construction. Therefore, the following assumptions were made:

- The building was used for domestic purposes, which meant it was occupied during the whole day, with most of the communal daytime activities taking place in the central hall. During nighttime activity in the central hall was scarce and was transferred to the side rooms (which were used and regarded as the private section of the house).
- The building was not connected to any sort of electric power (which was introduced in Palestine only during the 1920s, in a gradual and limited scope at first), rendering any form of electric ventilation or lighting impossible.
- When opened, the main rectangular windows were put in a full opening position, in order to take the maximal advantage of the flow of air from the outside.
- The upper round apertures (if existed), which were originally unglazed, were left constantly open during all seasons except winter. Blocking these apertures cannot be done easily, owing to their location (far above the reach of an unaided human hand), thus making it a "once in a season" type of act, not a daily habit.
- The external "French" shutters were put in either fully opened or fully closed position, since this kind of shutters is not capable of gradual positioning or differential adjustment. In order to prevent unnecessary complication of the simulation procedure, the shutters were always simulated as open when the windows behind them were also open. It is worth mentioning that although real historic evidence of the customary use of the shutters is hard to find, one can conclude from examining

historic photos from the first decades of the 20th century that no consistent pattern of using the shutters during daytime was kept, at least not one that followed systematically the time of day or the position of the sun; that means, opening or closing the shutters was the result of strictly private circumstances and preferences, and should therefore be overlooked in this context.

- Internal doors between the central hall and the side rooms were kept constantly closed.
- Internal doors between adjacent side rooms were kept constantly closed.
- The air infiltration rate of the building envelope was set to 0.3ACH, while the air infiltration rate of the roof area was set to 2.0ACH.
- Internal occupancy sensible gain was set to a constant value of $1.0W/m^2$.

In the original state of the buildings, only two building elements could have been used to control the internal thermal conditions, namely the rectangular windows and the external shutters. In order to facilitate the simulation procedures and following a well-documented operational logic (see the discussion in the introduction to chapter 4), it was decided to schedule the operation of these elements in 12-hours 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, mimicking different natural ventilation strategies (table 2.4.1): Daytime Ventilation (scenario DV); Nighttime Ventilation with shutters opened also during daytime (while the windows remain closed, scenario NV-DSO); Nighttime Ventilation with closed shutters during daytime (assuming enough light penetrated the rooms through upper apertures or fixed windows; scenario NV-DSC); and a limited ventilation scenario in which both the rectangular windows and the shutters are constantly closed, leaving the round apertures, which were kept open throughout the warmer months, as the only mean of natural ventilation (scenario CC).

Table 2.4.1: Simulation Scenarios Definition

	DV	**NV-DSO**	**NV-DSC**	**CC**
Rectangular windows	Opened fully during **daytime** only (07:00-19:00), nighttime closed	Opened fully during **nighttime** only (19:00-07:00), daytime closed	Opened fully during **nighttime** only (19:00-07:00), daytime closed	**Constantly** closed
External Shades	Opened fully during **daytime** only (07:00-19:00), nighttime closed	**Constantly** open	Opened fully during **nighttime** only (19:00-07:00), daytime closed	**Constantly** closed
Round Apertures (when existing)	**Constantly** open	**Constantly** open	**Constantly** open	**Constantly** open

2.5 Simulation results reliability

The selected methodology for the research, i.e. the exclusive use of a single simulation tool for the analysis of the indoor thermal conditions, marks also its limits. A simulation tool, good as it may be, is only reliable to a certain extent and the results produced by it should not be blindly accepted as portraying some reality without further inspection. This research is of no exception.

A common way of checking and adjusting the simulation results is to validate them against data acquired from on-site monitoring of the simulated structure (even for relatively short periods of time), using the same weather data if possible. In this way, the simulation results are closely compared to the on-site monitoring results and when found inconsistent, adjustments in the basic assumptions is made in order to "calibrate" the simulated model in reference to the on-site results.

Although the above method enhances substantially the accuracy of the simulation results and its predictive properties, it was not used in this research, mainly because of the limited resources that prevented the author from conducting on-site monitoring in the comprehensive way needed for a reliable calibration outcome. Moreover, since this research focuses on the *original* state of historic buildings that went through a series of alterations throughout the years, on-site monitoring was believed to have a lesser potential to be used as a reference data. Therefore, the accuracy of the simulation results needed to be examined in another way.

One issue received more attention – that of the simulated internal air change rates. This issue is of high importance because of the nature of the sample buildings, which relied heavily on natural ventilation for maintaining internal thermal comfort conditions. The air change rate results from the simulations were compared with results produced by using the Orifice Flow Equation in the method described in CIBSE Guide A for rough calculations of natural ventilation rates for simple structures (CIBSE 2006, 4-16-4-19).[6] The comparison was applied for cross ventilation scenario, which is the dominant scenario in the sample buildings.

[6] The equation used is:

$$Q_w = C_d \cdot A_w \cdot V_r \cdot (\Delta C_p)^{0.5}$$

where Q_w is the indoor air change rate [ach], C_d is the discharge coefficient, A_w is Equivalent area for ventilation by wind only [m^2], V_r is the mean wind speed at building roof height [m/s] and ΔC_p is the wind pressure coefficient difference between inlet and outlet.

The comparison consisted of air change rate values that relate to wind direction that is perfectly normal to the central hall windows on one side of the structure (with assumed window opening of 100%). Matching pressure coefficient values were taken from table 4.6 in CIBSE Guide A (the calculated pressure coefficient difference was 0.45), discharge coefficient was set to 0.61 based on the CIBSE guidelines. Wind speed was taken from the TAS weather file.[7] This comparison procedure revealed an almost perfect correlation between the Tas air change rate results and the values produced by using the "manual" method suggested by the CIBSE Guide A, as is shown in figure 2.5.1. Tas values were consistently lower than the equation values by about 22% in the examined structure (the consistent discrepancy is believed to result from the special characteristics of the structure). This led to the conclusion that the air change rate results produced by Tas are reliable in a sense that they conform to the contemporary accepted building physics theory.

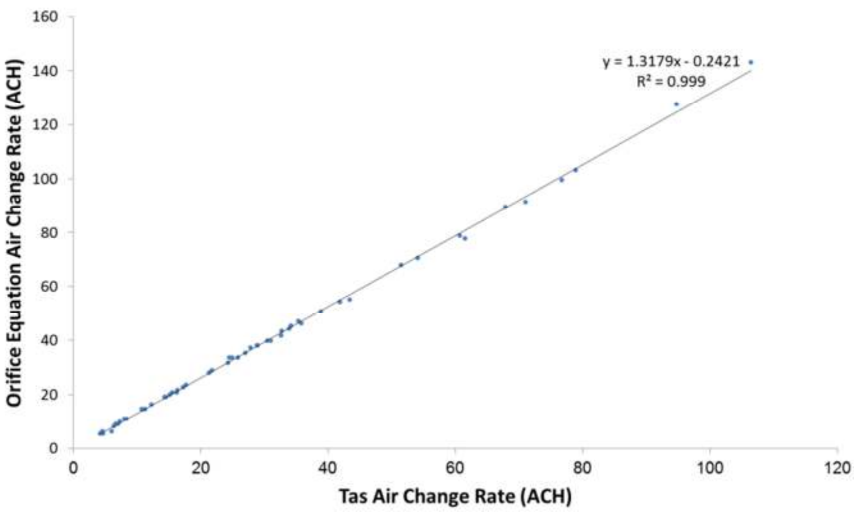


Figure 2.5.1: Air change rates for wind direction normal to central hall windows - orifice equation to Tas results

[7] Since Tas does not provide mean wind speed values at the top of the building, the wind speeds taken from the weather file were used instead, taking into account the possibility that this may produce a deviation from the Tas results. Anyway, for the sake of this comparison procedure, it was important that there is a linear correlation between the Tas results and the results produced by the orifice flow equation, not to check whether the same results are produced by the two methods.

2.6 Tas results analysis

2.6.1 The concept of thermal comfort

This research aims at determining whether thermal comfort conditions could have been maintained in the sample buildings during the warmer months of the year (May-October, with special care given to the period between July and September) without the use of any HVAC or other mechanical systems. In order to answer this question, one must first clearly define the concept of thermal comfort.

Both ISO 7730 and ASHRAE Standard 55 define thermal comfort as the "condition of mind that expresses satisfaction with the thermal environment." To that ASHRAE Standard 55 adds that thermal comfort is also "assessed by subjective evaluation". This short definition encompasses the complexity of the concept of comfort, which is based on a correlation drawn between objective evidence (as, for instance, air temperature and humidity) and subjective human psychological perception. This is also the main reason why even today there is not one single thermal comfort model that has been accepted as valid for all locations and settings.

The most widely accepted and used thermal comfort model was conceived and developed about four decades ago by PO Fanger (Fanger 1970). Based on laboratory and climate chamber studies, Fanger created a 7-steps scale (ranging from "cool" to "hot") that describes the subjective human reaction to surrounding thermal conditions, and then formulated a correlation between the Predicted Mean Vote (PMV) of a large group of people that use the 7-steps scale and an index that takes into account four climatic variables (air temperature, mean radiant temperature, relative humidity, air speed) and two personal variables (clothing insulation factor and activity level). Using the PMV value, it is possible to determine whether certain conditions would yield a certain degree of thermal discomfort (referred to as Predicted Percentage of Dissatisfied [PPD] in Fanger's theory) or not. Fanger's work is the basis for ASHRAE Standard 55 and ISO 7730 standard for thermal comfort calculations and is therefore used extensively also as a design tool for indoor environment climates.

The wide acceptance of Fanger's model for thermal comfort does not mean it proves to be perfectly suitable for any given setting. Fanger's claim that his theory is valid for all human beings, regardless of geographical location or climate, has been put since its formulation into substantial doubt by numerous field studies that indicate otherwise (Auliciems and Szokolay 2007, 42). For the purpose of our research it is interesting to examine criticism that focuses on climate conditions similar to summer conditions in the Israeli coastline plain – i.e., hot and humid climate, with a relatively minor diurnal change of temperatures. Auliciems and Szokolay cite a study by Williamson, Coldicutt and Riordan that argues that "the PMV strongly overestimates warm discomfort, especially in warm climates." Moreover, in an extensive report to ASHRAE focusing on the need to integrate the concept of adaptability into thermal indices, de Dear, Brager and Cooper stated that

> The *PMV/PPD* model is inapplicable to naturally ventilated premises because it only partially accounts for processes of thermal adaptation to indoor climate. The prescription of summer and winter comfort zones is inappropriate for this standard because the steep gradient on the naturally ventilated adaptive model would render climatological definitions of universal "summer" and "winter" conditions misleading. (de Dear, Brager and Cooper 1997, 168)

It should also be noted that due to the criticism on the PMV-PPD model, the concept of adaptation was introduced into the current version of ISO 7730, though without a clear definition that would have enabled the calculation of an "adaptation factor", as follows

> Extended acceptable environments may be applied for occupant-controlled, naturally conditioned, spaces in warm climate regions or during warm periods, where the thermal conditions of the space are regulated primarily by the occupants through the opening and closing of windows. Field experiments have shown that occupants of such buildings could accept higher temperatures than those predicted by the PMV. In such cases, the thermal conditions may be designed for higher PMV values than those given in Clause 6 and Annex A. (ISO 2005, 12)

Baruch Givoni, who has a long and documented record of researching the human reaction to hot climates, accepts the need to take into account the possible "adaptation" or "acclimatization" factor of people in different locations, but adds that Fanger's equation fails to properly describe the human reaction to hot and humid conditions also because it does not take into account the effect of air speed on sweat evaporation, thus making the PMV value almost the same under different air speeds in hot and humid conditions. Therefore

> This point limits greatly the ability of the Fanger formulae to evaluate the psychological and sensory effect of airspeed, which is a very significant factor in hot-humid climates. (Givoni 1998, 33)

According to Givoni (Givoni 1998, 18-45), the role of indoor air speed in achieving indoor thermal comfort during the summer is crucial in hot-humid conditions. Based on research evidence, Givoni claims that under relatively low air speeds of up to 2m/s thermal comfort may still exist even when the outdoor temperatures and relative humidity are at high levels.[8] This happens not as a result from of the cooling of the building envelope or the lowering of indoor temperature (which is kept, because of the constant penetration of outdoor air, at about the same levels as the outdoor ambient temperature), but by enhancing skin evaporation and cooling sensation of the occupants. Nocturnal ventilative cooling strategy is not effective, according to Givoni, in such settings because the outdoor diurnal range during summer is kept relatively low (less than 10°K), making the direct cross-ventilation during daytime the only way to improve the cooling sensation of the occupants (Givoni 1998, 35-39, 189).

It is far beyond the scope of this research to answer the question which of the many thermal comfort models devised through years of research is more accurate or more applicable to the weather conditions in Israel. Nevertheless, one way of tackling this question is to evaluate the simulation results using several thermal comfort models which will reflect different attitudes to the question.

2.6.2 The concept of comfort zone

ASHRAE Standard 55 states that a comfort zone "is defined in terms of a range of operative temperatures that provide acceptable thermal environmental conditions or in terms of the combinations of air temperature and mean radiant temperature that people find thermally acceptable" (ASHRAE 2004, 4). In other words, the comfort zone is a range of climatic conditions that produce a subjective sense of thermal comfort. Therefore, the way the boundaries of such a zone are defined is crucial for the assessment of the thermal effect of a certain environment.

For our own purposes, it was decided to use several separate definitions of comfort zones for the assessment of the indoor thermal conditions of the sample buildings. Their selection reflects a wide range of attitudes towards the concept of comfort in hot and humid climates, enabling not only the assessment

---

[8] For still air conditions, Givoni claims that the upper limit of the comfort zone ranges between 23.5°C at 80% RH and 27°C at 50% RH (in developing countries the upper limit temperature can rise by another 2°K for each of the same humidity levels). For indoor air speed of 2m/s the upper limit of **external** conditions ranges between 25.5°C at 80% RH and 30°C at 50% RH (with a similar 2°K upper correction for developing countries).

of the simulated indoor conditions but also the comparison and discussion of their suitability to the specific climate of the Israeli coastal plain.

Each simulation scenario produces an hourly-based dataset of environmental indicators for each room (for one whole year). This dataset was analyzed on a seasonal basis (spring-autumn vs. summer periods; see more on section 2.6.4) in order to find what is the percentage of hours in which thermal comfort conditions – following the different definition of the concept by each of the selected comfort models – prevailed in a certain room during a certain period of time. It was believed that because of the expected differences in results produced by the multiple comfort models this method would also reveal the inherent problems of the scientific assessment of human comfort in the particular climate under discussion.

2.6.3 Thermal comfort indices and comfort zone definitions used for assessment

Following is a description of each environmental model that was used for the assessment of the thermal conditions inside the sample buildings:

- Fanger's PMV-PPD model, as accepted and defined by ISO 7730, is the most widely accepted and used comfort index. ISO 7730 described five methods for comfort evaluation (Annex H of the Standard). This research will use method A, assuming the buildings are occupied constantly.[9] This method uses only the PMV values as an indicator of thermal comfort. ISO 7730 defines three comfort categories, which conform to an ascending scale of predicted percentage of dissatisfied: category A ($-0.2<\text{PMV}<+0.2$, $\text{PPD}<6$), category B ($-0.5<\text{PMV}<+0.5$, $\text{PPD}<10$) and category C ($-0.7<\text{PMV}<+0.7$, $\text{PPD}<15$).

- Szokolay's definition of "adaptive comfort zone", based on the concept of the standard effective temperature (SET), integrates the concept of thermal adaptability into a thermal comfort model that is based on the combined effect of dry-bulb temperature and relative humidity. Szokolay's definition uses a standard psychrometric chart for the demarcation of the comfort zone by four boundary lines: lower and upper boundaries of absolute moisture content (4 and 12g/kg dry air respectively) and two side boundaries based on SET isolines representing lower and upper temperature limits that are specific to the examined month and are based on the mean monthly outdoor

[9] Method A is described as follows: "Calculate the number or percentage of hours during the hours the building is occupied, the PMV or the operative temperature is outside a specified range" (ISO 2005, 47).

temperature of the site (Szokolay 2008, 21-22).[10] Any combination of air temperature and relative humidity that is found inside this comfort polygon (see figure 2.6.1) is regarded as representing thermal comfort conditions.

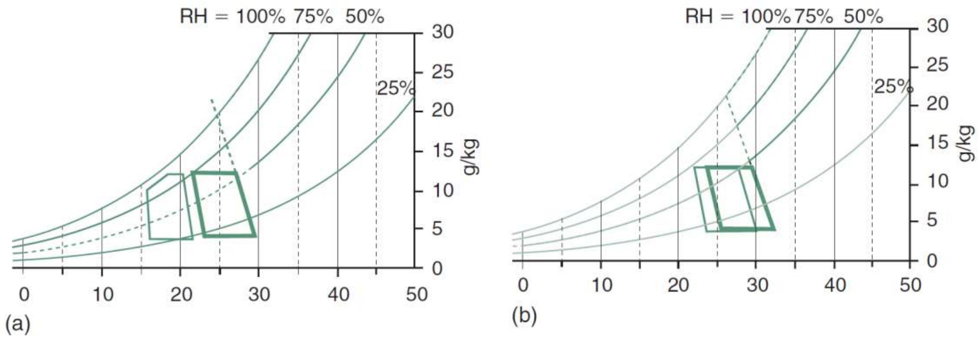


Figure 2.6.1: Szokolay's adaptive comfort zone exemplary demarcation on a psychrometric chart for two separate locations, indicating a winter (light outline) and a summer (bold outline) comfort zone for each location (Szokolay 2008, 22)

- Like Szokolay's method, Givoni's "building bio-climatic chart" (BBCC) contains a definition for a thermal comfort zone using a standard psychrometric chart (Givoni 1998, 37-38). Givoni's interpretation for the concept of adaptability is not location-dependent. He claims that in buildings with no mechanical air conditioning occupants are more tolerant to higher temperature and humidity levels, resulting from a combination of ongoing adaptation and a certain expectation level. The comfort zone is demarcated as follows: lower and upper boundaries of absolute moisture content (4 and 15g/kg dry air respectively) and side boundaries of 20°C and 27°C. One additional boundary is drawn along the 80% relative humidity isoline between the values of 20°C and 15g/kg moisture content, and another one connects 25°C temperature at 15g/kg moisture content with 27°C temperature at 12g/kg moisture content. The result is a polygon-like shape with six vertices (see figure 2.6.2). Any combination of air temperature and relative humidity that is located inside this comfort demarcation is regarded as representing thermal comfort conditions.

[10] For each month, a Thermal Neutrality Temperature is calculated using the following formula:

$$T_n = 17.8 + 0.31 \cdot T_m$$

where T_n is the thermal neutrality temperature and T_m is the mean monthly temperature. Comfort limits are defined as $T_n \pm 2.5$, after translated into SET values (which combine dry-bulb temperature values with values of air's moisture content in order to reflect the sensible effect of higher relative humidity values in warm temperatures).

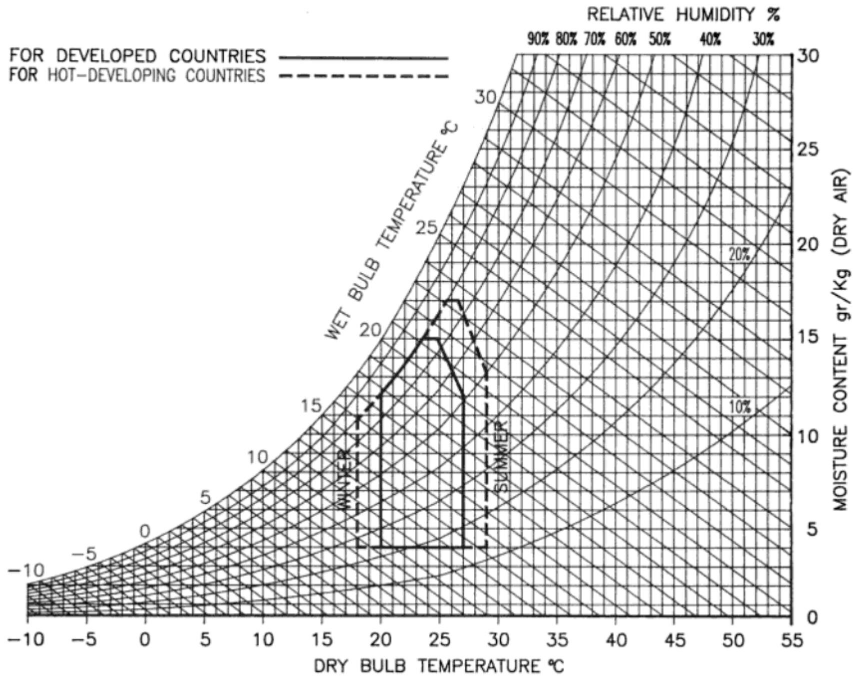


Figure 2.6.2: Givoni's building bio-climatic chart with a demarcation of his version of the thermal comfort zone (for still air), with suggested extension for developing countries with hot climate (Givoni 1998, 38)

Givoni's comfort zone relies on research conducted in the United States, Europe and Israel, which are regarded as developed countries. Following the claim that users' comfort sensation may rely also on their expectations, Givoni adds that his comfort zone can be extended upwards by 2.0°K for people living in developing countries and acclimatized to hot-humid conditions, though this extension is not based on his own scientific research but on studies by others. Since his comfort zone is applicable for indoor conditions under still air, additional ventilation (natural or mechanical) is believed to widen the comfort zone even farther, though Givoni does not clearly define what are the limits of the extended comfort zone produced by additional ventilation.

- The fourth thermal comfort assessment model used here is drawn from the relatively new European Standard EN 15251. This standard, while following ISO 7730 in the adoption of the PMV-PPD model, suggests an alternative method for thermal comfort evaluation to be used in buildings without mechanical cooling system and with operable windows for natural ventilation (Annex A2 to the standard). This method, which is based on a large empiric dataset from researches conducted in European countries, correlates the relation between indoor and outdoor temperatures to the concept of comfort in a way that is believed to integrate the concept of adaptability.

In EN 15251 Annex A2, a comfort temperature is calculated in relation to an indoor "operative temperature" and a daily "running mean outdoor temperature". Operative temperature is calculated based mainly on the combined effect of air temperature and mean radiant temperature, with a minor effect of the indoor air speed (the value is valid for sedentary activities and dwelling). A daily running mean temperature is an exponentially weighted value combining the mean daily temperature and the running mean temperature, both for the day before the calculated day. A comfort temperature is calculated using a formula based on a running mean temperature for a certain day, assuming that the running mean temperature is lower than 30°C (CEN 2007 and also Nicol and Humphreys 2010).[11] Although this method has some similarities to the optional method described in section 2.5.3 of ASHRAE Standard 55 (ASHRAE 2004, 9-11), it differs from it in the definition of the comfort zones and temperatures, while using a running mean daily temperature instead of the less accurate value of mean monthly temperature that is used in the ASHRAE standard.

EN 15251 defines three comfort categories that demarcate the comfort boundaries in relation to a certain comfort temperature (figure 2.6.3). These categories represent the concept of "user expectations", where the lower are the expectations for a "perfect" comfort sensation the wider is the comfort zone.[12] The reasoning behind the method is explained as follows

> Several field experiments have shown that occupants' thermal responses in such spaces depends in part on the outdoor climate, and differ from the thermal responses of occupants in buildings with HVAC systems, mainly because of differences in thermal experience, availability of control and shifts in occupants' expectations.

---

[11] The formula for comfort temperature is

$$T_i = 0.33 \cdot T_{rm} + 18.8$$

where T_i is the comfort temperature and T_{rm} is the daily running mean outdoor temperature.

[12] Category I (Ti ±2°K) is defined as representing a "high level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons", category II (Ti±3°K) represents a "normal level of expectation and should be used for new buildings and renovations" while category III (Ti±4°K) should be used for "an acceptable, moderate level of expectation and may be used for existing buildings".

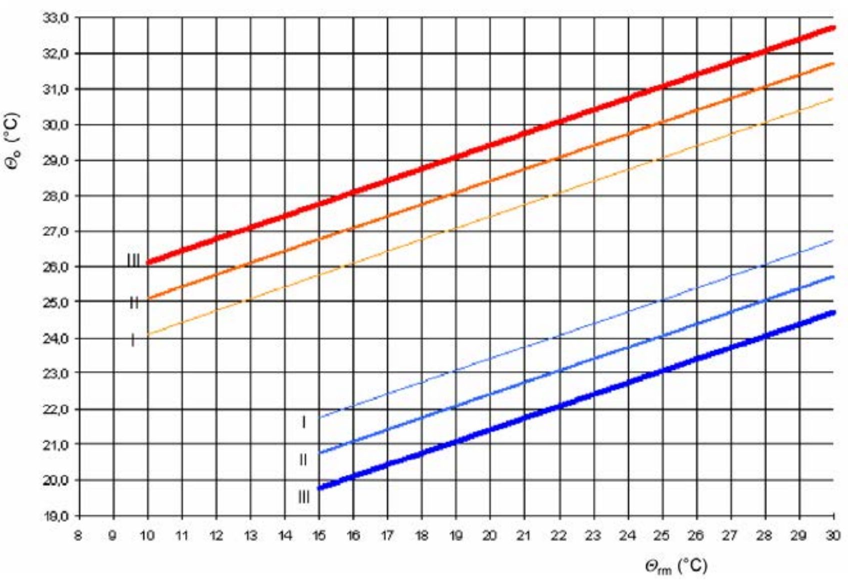


Figure 2.6.3: EN 15251 design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the external temperature (CEN 2007, 27)

It is interesting to note that the effect of relative humidity on thermal comfort is neglected altogether in the EN 15251 method for thermal evaluation of naturally ventilated spaces because "humidity has only a small effect on thermal sensation and perceived air quality in the rooms of sedentary occupancy" (CEN 2007, 16). Although this conclusion relates to conditions prevalent in countries of the European Union, the resemblance of the climate in the Israeli coastline to certain areas in Europe with high humidity levels (especially along the coasts of the Mediterranean Sea) makes the suggested method applicable also to our own study.

The above four thermal comfort models were selected because each one of them represents a substantially exclusive approach. Fanger's PMV-PPD model, while being the most widely accepted and used model, does not consist of any reference to the effect of adaptability nor to user expectations which are regarded today as important factors in the evaluation of the subjective thermal sensations in different parts of the world. In the core of Szokolay's method lies the concept of adaptability, but user expectations are totally neglected. Szokolay also uses a strict upper humidity level that may be put into question in climates where people are accustomed to higher relative humidities. In contrast to Szokolay, Givoni uses a more flexible definition for a comfort zone, allowing higher humidity levels (depending on dry-bulb temperatures). Also contrary to Szokolay, the effect of adaptability in Givoni's model is reflected in his boundary definition for dry-bulb temperatures, which is wider but independent from the mean monthly outdoor temperature. Givoni also recognizes implicitly the concept of user expectations when allowing a wider comfort zone for developing countries. The EN 15251 Annex A2 method is different from all other three in neglecting the effect of relative humidity altogether while integrating the concepts of adaptability and user expectations. Like Givoni's model, it was meant to be used exclusively for the assessment of naturally ventilated buildings (both Fanger's and Szokolay's models are independent of the way occupants cool the space). It may also be regarded as the most up-to-date and widely researched method for buildings of that kind.

2.6.4 Analysis procedure

In order to analyze the large datasets of the simulation results in reference to the four comfort definitions that were described above there was a need to employ a programed analysis procedure. This was done using scripts and functions written by the author to run under the MATLAB numerical computing environment (MathWorks 2011), as follows:

- The PMV values were calculated on the basis of the mathematical formulation of the calculation method that appears in ISO 7730. Dry-bulb air temperature, mean radiant temperature and relative humidity values were extracted from the Tas simulation results. Air speed was calculated based on simulated air change rate values using the Pröglhöf formula mentioned earlier (see section 2.3.5). Metabolic rate was constantly set to 1.2met (conforms to sedentary activity) and clothing value to 0.6clo (conforms to traditional Middle Eastern clothing for summer).[13]

- Szokolay's comfort zone was calculated on a monthly basis, using the mean outdoor monthly temperature drawn from the weather file. Dry-bulb air temperature and relative humidity (thus moisture content) values were extracted from the Tas simulation results.

- Givoni's comfort zone was calculated using dry-bulb air temperature and relative humidity (thus moisture content) values from the Tas simulation results.

- EN 15251 operative temperatures were calculated by using dry-bulb air temperature and mean radiant temperature values that were extracted from the Tas simulation results. The needed air speed values were calculated based on simulated air change rate values using the Pröglhöf

[13] See Al-ajmi et al 2008, 413.

formula. The running mean temperatures were calculated based on the Meteonorm weather file values.

The main analysis indicator for all four comfort definitions can be described as a periodical "percentage inside the range", meaning the percentage of occupied hours when the comfort indicator value (PMV, dry-bulb temperature to moisture content, operative temperature to running mean daily temperature) is within the specific comfort range. This value was calculated for each room under each scenario for each season (spring-autumn: May, June and October; summer: July-September).

Since three of the four comfort models consist of more than a single comfort zone category (the three categories of the PMV-PPD and the EN 15251 Annex A2 models and the two comfort zones of Givoni), choosing a single category from each model was necessary as a comparison base. In the case of the PMV-PPD and the EN 15251 Annex A2 models, it was decided to use category II as the reference comfort range. According to EN 15251, this category represents "normal level of expectation and should be used for new buildings and renovations" for both PMV-PPD evaluation method as well as the method described in Annex A2 for naturally ventilated buildings (CEN 2007, 12). This corresponds to category B of the PMV-PPD model as defined by ISO 7730 (ISO 2005, 13). Category II was selected because it stands for "normal expectations" level, a level that presumably existed among the builders of the houses upon their occupation, especially when dealing with buildings without mechanical ventilation (fans, air-conditioning) as in Annex A2. The selected Givoni comfort zone was the extended comfort zone for the "developing" countries, which can also correspond to a "normal" level of expectations of users who cannot use mechanical ventilation means. Although the original builders of the sample houses were regarded as belonging to the "developed" upper class of their time, it can still be argued that they had lower expectation level for thermal comfort than is customary today because of the somewhat limited, non-modern cooling methods that were available for them; therefore, Givoni's comfort zone for developing countries represents their assumed thermal sensation better than the one for developed countries.

3 SIMULATION RESULTS

The simulation results were analyzed in a way that could answer the following questions:

- What are the main structural elements that determine the thermal performance of the structures?
- How does natural ventilation affect the thermal performance of the structures?
- Is there a recurring pattern that distinguishes the thermal performance of the central hall from the thermal performance of the side rooms?
- What is the role of natural ventilation in maintaining thermal comfort conditions inside each structure?
- What is the best strategy for using the windows and shutters in each structure in order to achieve the highest thermal comfort rates?
- Does the selection of a specific thermal comfort model have a substantial impact on the results, thus on our understanding of the structures' performance?

In order to answer these questions:

- The results were analyzed for two separate periods: the spring-autumn period (May, June and October) and the summer period (July-September). The results for the central hall were analyzed separately from those of the side rooms.[14]
- The indoor thermal performance was analyzed by calculating indoor mean hourly dry-bulb temperatures under the different natural ventilation scenarios, while comparing these with the outdoor mean hourly temperatures. Overheating rates (percentage of hours with indoor temperatures above 27°C) and cumulative frequency of indoor temperatures were also calculated for the same purpose.

[14] It is important to note that the decision to analyze all the side rooms as a whole and not separately was made after reviewing the results for each of the rooms. It can be said that although there are minor differences in the thermal performance of each of the side rooms, they all show a similar overall response to the outdoor conditions independent of their orientation and size, and therefore, and for the sake of clarity, their results were averaged into one single value for each period and simulation scenario.

- Indoor comfort rates were calculated for each of the four thermal comfort models which were selected for analysis. A comparison between the "best operational scenarios" according to each of the comfort models was used in order to determine the optimal operational scenario of the structures' windows and shutters. This also enabled to explore the sensitivities of each of the comfort models to changes in the natural ventilation scenarios under the simulated hot and humid weather conditions. Comparing comfort rates produced under different comfort models also enabled to understand the general limitations of preferring one model over the other.

- The effect of indoor thermal conditions and natural ventilation scenarios on thermal comfort rates was mainly analyzed in reference to Givoni's extended comfort zone definition, since it is the only of the four models which takes into account the combined effect of dry-bulb temperatures and relative humidity levels while acknowledging the impact of both thermal adaptability of the body and user expectation on the subjective sensation of comfort. This model was selected for in-depth analysis also because it proved to produce the most plausible results of all four models.

- Psychrometric charts with an outlined "comfort zone" (using Givoni's definition) were used for graphical depiction of the correlation between indoor temperatures, relative humidity levels, thermal comfort rates and the effect natural ventilation has on them.

3.1 30 Chelouche Street – results analysis

3.1.1 30 Chelouche Street – indoor mean hourly dry-bulb temperatures

Looking at the mean hourly indoor temperatures during summer (figures 3.1.1, 3.1.5 and 3.1.6), it is quite evident that nocturnal ventilation, rather than daytime ventilation or limited aperture ventilation, results in lowering indoor temperatures (both during daytime and nighttime). In addition, a substantial difference in indoor temperatures between the central hall and the side rooms (under the same outdoor conditions and ventilation scenario) was also recorded. Overall, the side rooms maintained lower temperatures under all scenarios during almost all hours with only one negligible exception - the peak hours under scenarios NV-DSO and NV-DSC. Comparison of overheating rates (percentage of hours with indoor temperatures above 27°C, figure 3.1.2) and cumulative frequency charts of indoor temperatures (figures 3.1.3 and 3.1.4) show the same general tendencies.

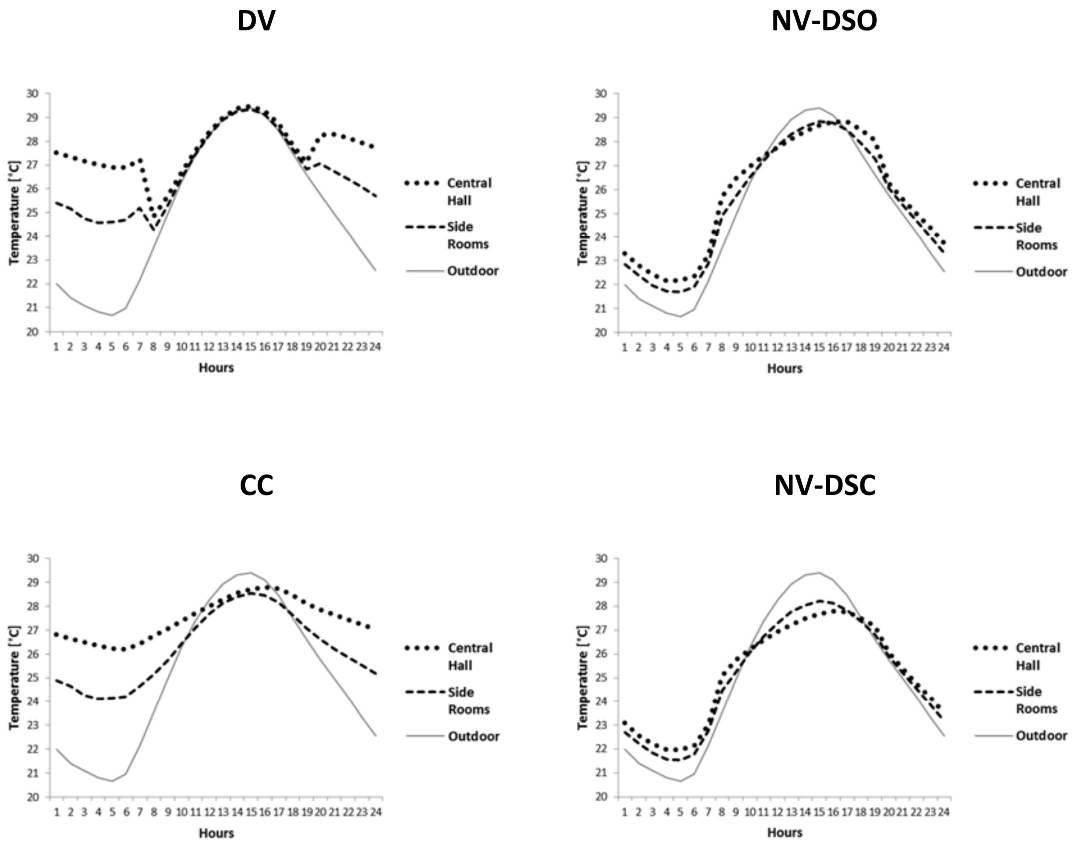


Figure 3.1.1: 30 Chelouche Street, mean hourly dry-bulb temperatures for July-September under several ventilation scenarios

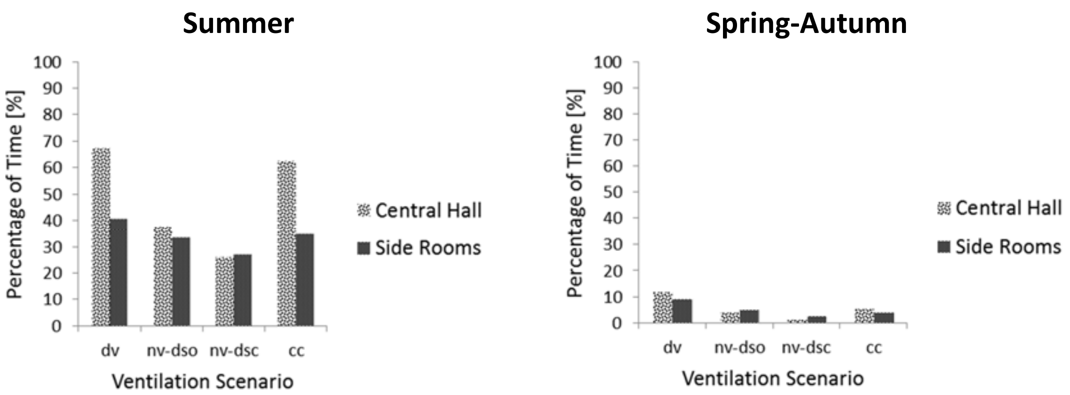


Figure 3.1.2: 30 Chelouche Street, overheating rates

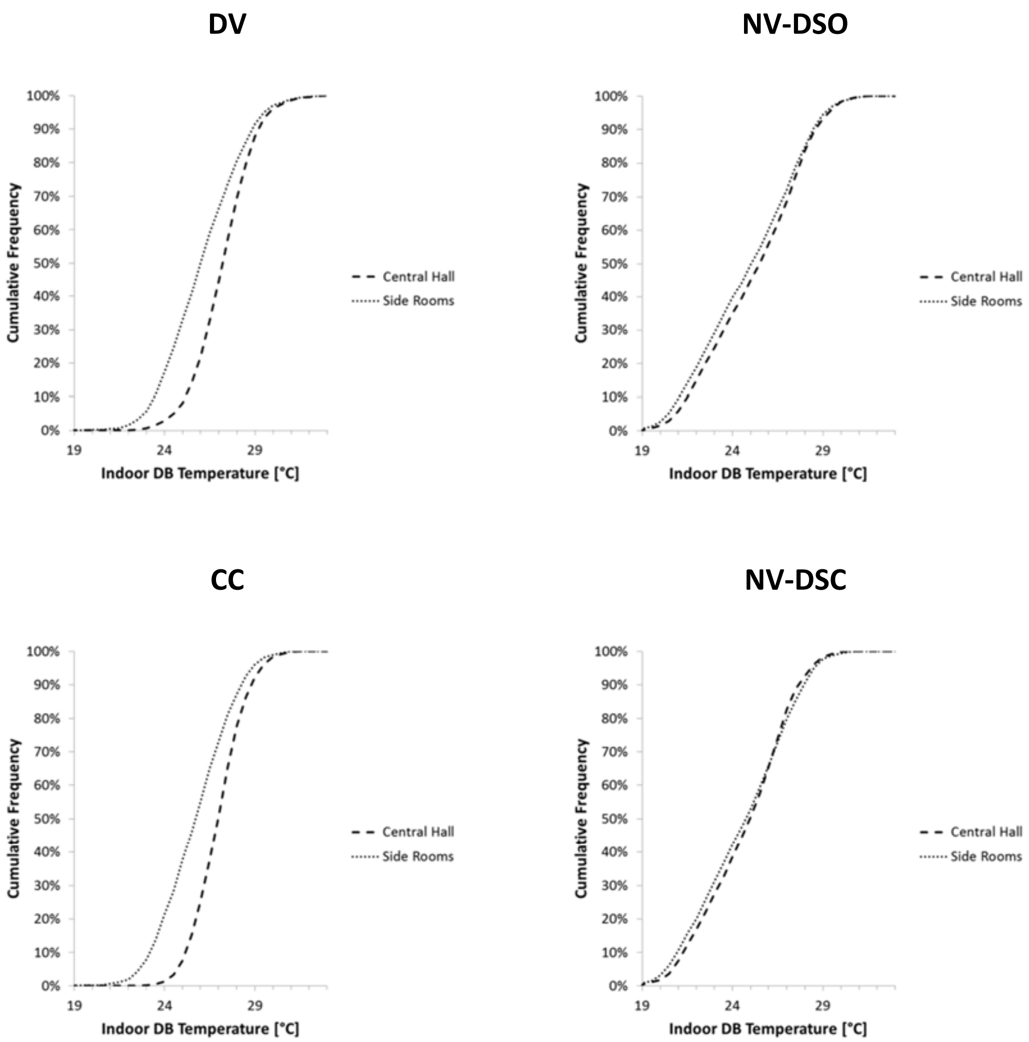
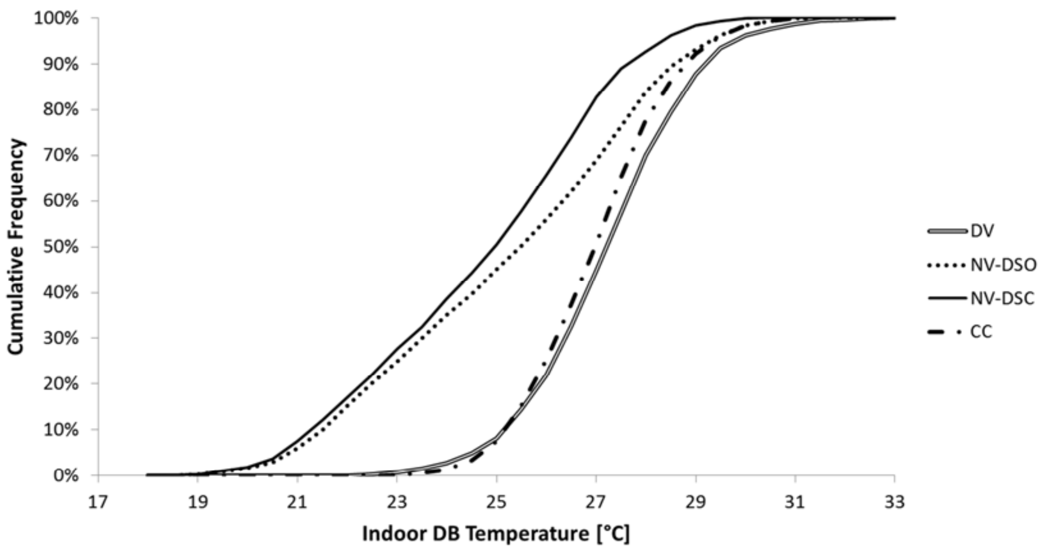
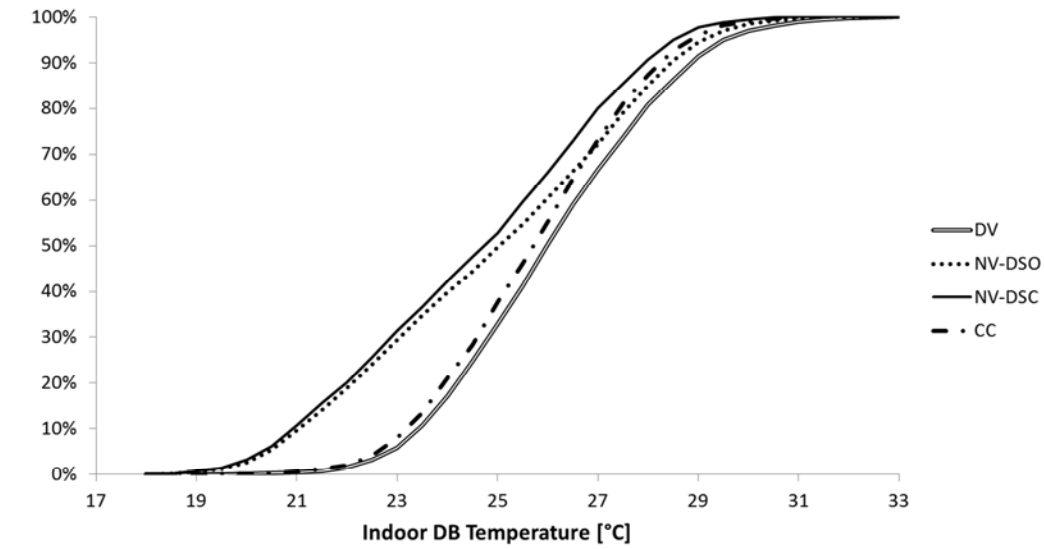


Figure 3.1.3: 30 Chelouche Street, cumulative frequency of indoor temperatures under several ventilation scenarios for the months July-September, central hall vs. side rooms



(a)



(b)

Figure 3.1.4: 30 Chelouche Street, cumulative frequency of indoor temperatures for the months July-September for all four ventilation scenarios: central hall (a), side rooms (b)

A more detailed list of findings for the summer period is summarized below:

- In all rooms, the lowest daily peak temperatures were recorded under scenario NV-DSC and the highest peak values under scenario DV.
- In all rooms, highest nighttime temperatures were recorded under scenario DV.
- In all rooms, smallest diurnal range was recorded under scenario CC. It is important to note that the side rooms values under this scenario were

consistently lower than those of the central hall, where no round apertures exist (with a difference ranging between 0.5-2.0°K).

- Scenarios DV and CC produced much higher night temperatures in the central hall than in the side rooms (up to a difference of 2.0°K), while maintaining almost identical values in all rooms during daytime's peak hours.
- Scenarios NV-DSO and NV-DSC produced almost similar temperatures in both the central hall and the side rooms, with slightly lower temperatures in the side rooms during most of the time.
- All Scenarios produced average nighttime temperatures higher than the outdoor temperatures. During peak hours, all scenarios except scenario DV produced lower average daily temperatures, compared with the outdoor temperatures.

It is important to note that these tendencies, which are based on the summer results, were almost identical when analyzing the spring-autumn period (May, June and October), although the average temperature values were naturally lower.[15]

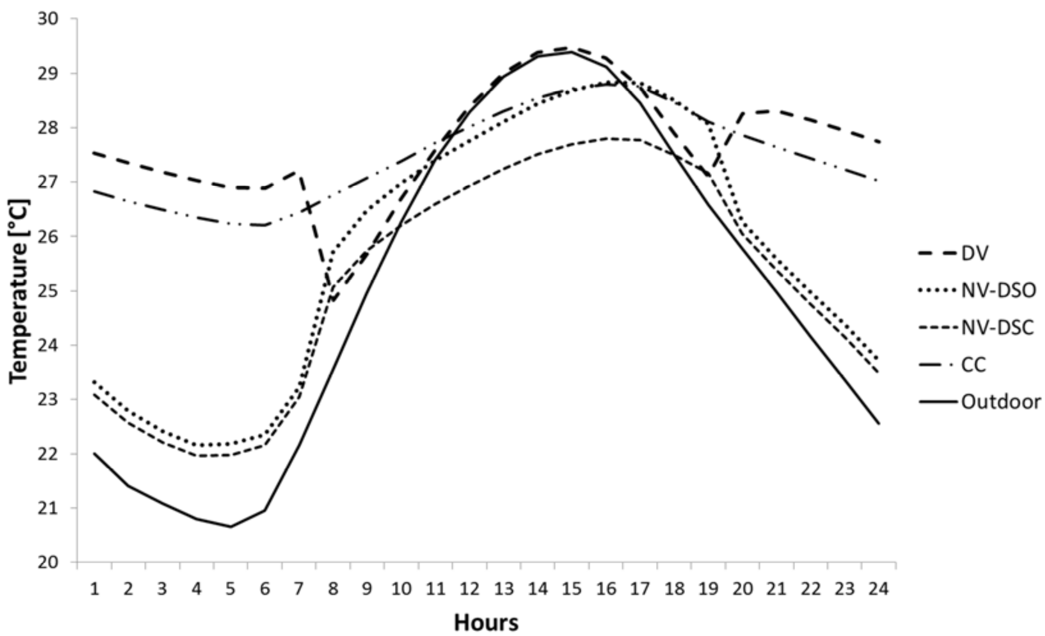


Figure 3.1.5: 30 Chelouche Street, central hall mean hourly dry-bulb temperatures for July-September under different ventilation scenarios

[15] The only exception is that during the spring-autumn period, temperatures in the central hall were lower than those in the side rooms during peak hours also under scenario CC.

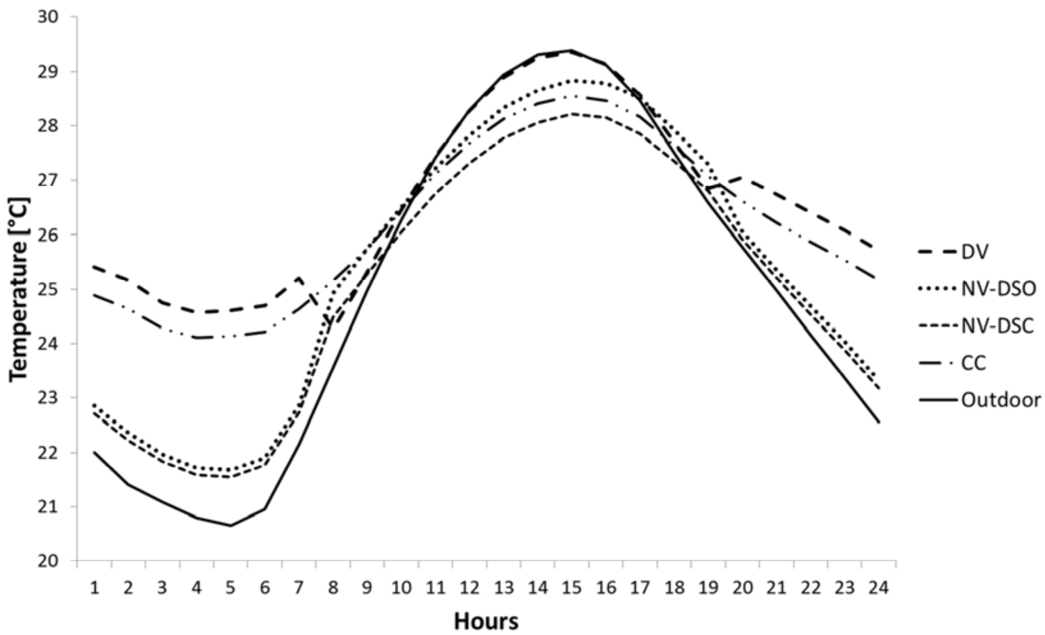
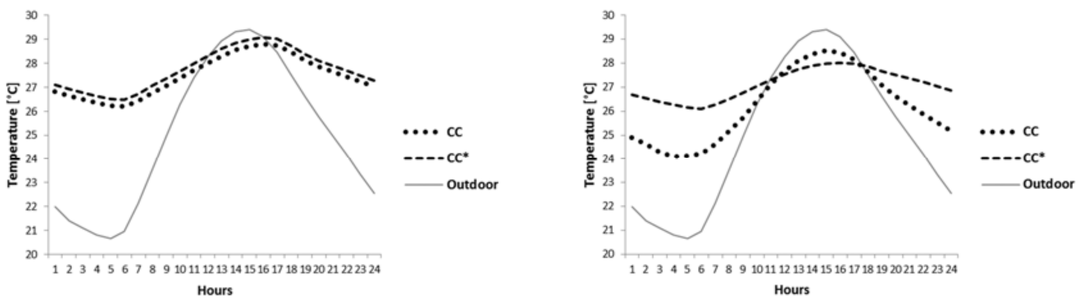


Figure 3.1.6: 30 Chelouche Street, side rooms mean hourly dry-bulb temperatures for July-September under different ventilation scenarios

In order to isolate the effect of the round apertures on indoor temperatures, an alternative scenario (CC*, figure 3.1.7) was used, in which all windows, shutters and apertures were defined as constantly closed (though this mode of use has a weak operational logic). In the side rooms, it can be argued that the apertures are responsible for a substantial lowering of temperatures during nighttime (up to 2.0°K), while during daytime's warmest hours the round apertures were responsible for elevating indoor temperatures (up to 0.5°K). In the central hall, where no apertures exist, opened apertures in the side rooms result in constant temperature lowering of 0.2°K.



(a) (b)

Figure 3.1.7: 30 Chelouche Street, mean hourly dry-bulb temperatures for July-September under two ventilation scenarios, CC (a) and CC*: central hall (a) and side rooms (b). Scenario CC* is identical to scenario CC with one exception: the round apertures are defined as constantly closed, like the rectangular windows.

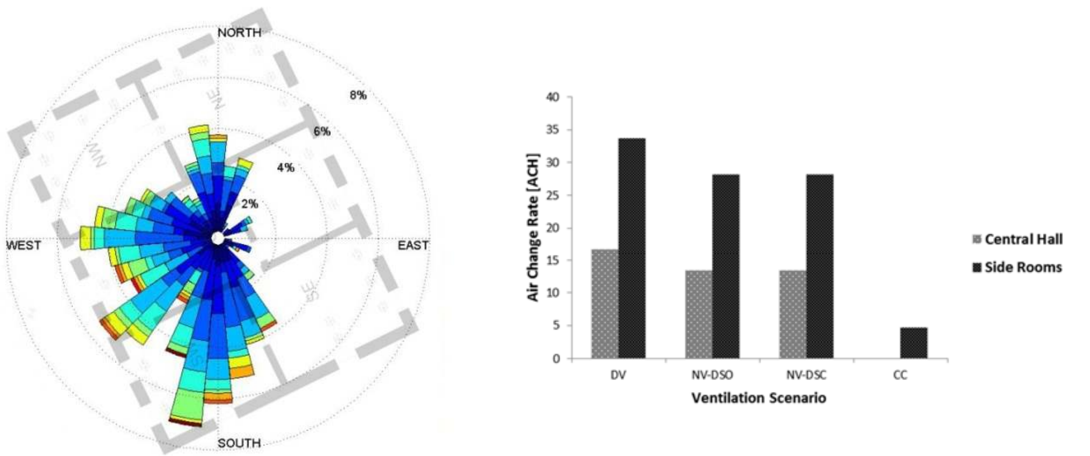
3.1.2 30 Chelouche Street – indoor air change rates

Typical wind directions for the site are southern to western winds (figure 3.1.8 (a)). Therefore, it is not surprising that the western rooms (NW, SW) have double the higher air change rates in comparison with the eastern rooms (NE, SE). Nevertheless, for the sake of analysis, air change rates for all four side rooms were averaged, since their differentiation in values had little to do with differences in indoor air temperatures or comfort rates, probably because of the relatively high air change rates that were recorded even in the eastern rooms.

As can be seen from figure 3.1.8 (b), substantial lower air change rates were calculated for the central hall compared with the side rooms, independent of the ventilation scenario that was applied. This may be attributed to several factors:

- The structure's layout, which makes the central hall relatively long and narrow, in comparison to the side rooms.
- Windows in the central hall are directed in two opposite directions and not in two perpendicular directions, making it more sensitive to alteration in wind direction.
- Window area per volume in the central hall was much lower than in the side rooms.

In ventilation scenario CC, natural ventilation did not exist in the central hall since its walls are missing any round apertures. This scenario also resulted in much lower air change rates in the side rooms, with an average of less than 5ACH per hour.



(a) (b)

Figure 3.1.8: Superposition of 30 Chelouche Street living floor plan on a typical monthly wind rose for the month of August (a), average hourly air change rates for July-September (b). Average air change rates for the spring-autumn period (May, June and October) were almost identical.

3.1.3 30 Chelouche Street – indoor thermal comfort according to different comfort models

All results showed clear and substantial differences between the comfort rates that were produced by analyzing the simulation results according to the four selected comfort models. These differences appear to be more significant during summer (July-September).

An overview of the results reveals the following tendencies (figure 3.1.9):

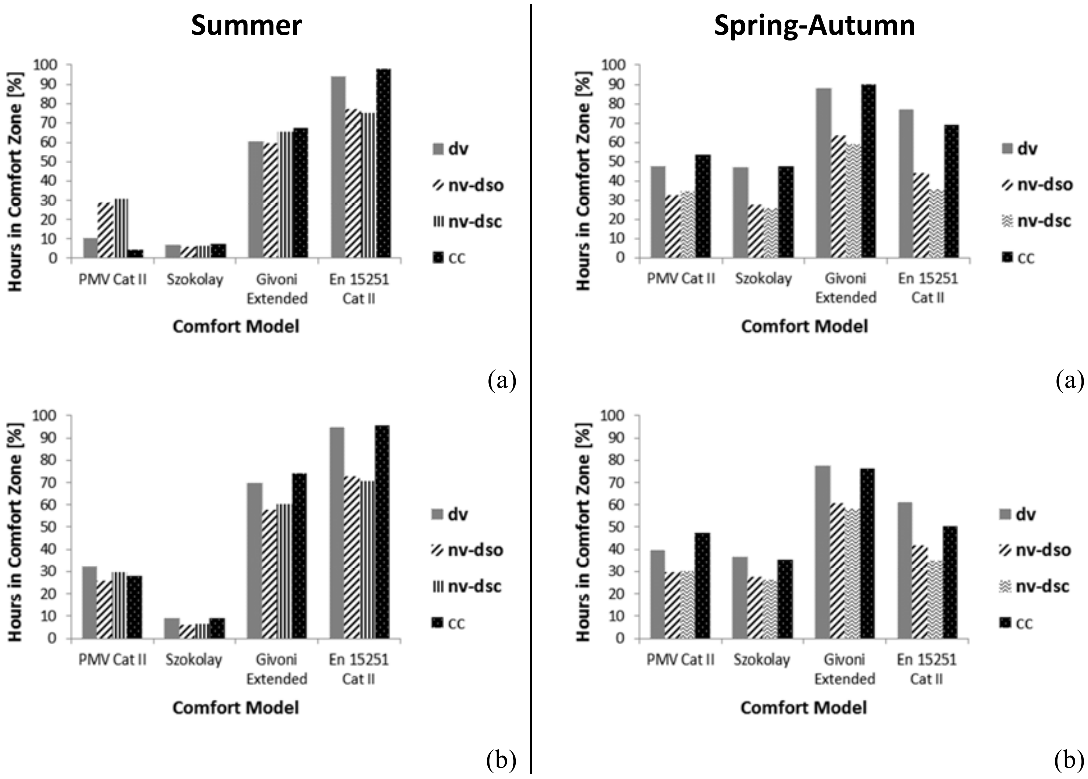


Figure 3.1.9: 30 Chelouche Street, comfort rates according to four comfort models: central hall (a) and side rooms (b)

- During summer, highest comfort rates were recorded using the EN 15251 model. During spring and autumn Givoni's extended model produced the highest comfort rates.
- During summer, analysis according to Szokolay's model produced substantially lower comfort rates than those produced by using all other three models.
- During summer, while the EN 15251 and Szokolay's model showed that the different ventilation scenarios had almost the same effect on comfort rates in both the central hall and the side rooms, analysis according to Givoni's and the PMV model produced a quite different

picture, in which the effect of the chosen ventilation strategy was far from being similar in the central hall and the side rooms.

- During spring-autumn, when comparing the results produced under the different ventilation scenarios, the overall "hierarchy" of results (which scenarios performed better than others and to what extent) was relatively the same in all comfort models. In contrast, during the summer period a much weaker "hierarchal" similarity was found.
- Although the spring-autumn period analysis produced narrower result range compared with the summer period, the highest comfort rates (using Givoni's extended model) were still more than twice higher than the lower rates (Szokolay's model).

Searching for a "best" ventilation scenario for each period and space under each comfort model may prove to be a misleading analysis tool, since it neglects cases in which the first and second best comfort rates are relatively similar. Therefore, a "second-best" scenario is indicated when difference between the best two results is less than 10% (tables 3.1.1 and 3.1.2).

Table 3.1.1: Summer, Best Scenario According to Different Comfort Models (second-best result appears when it differs from the best result in less than 10%)

	PMV-PPD Cat II	**Szokolay**	**Givoni Extended**	**EN 15251 Cat II**
Central Hall	NV-DSC/NV-DSO	CC/DV	CC/NV-DSC	CC/DV
Side Rooms	DV/NV-DSC	CC/DV	CC/DV	CC/DV

Table 3.1.2: Spring-Autumn, Best Scenario According to Different Comfort Models (second-best result appears when it differs from the best result in less than 10%)

	PMV-PPD Cat II	**Szokolay**	**Givoni Extended**	**EN 15251 Cat II**
Central Hall	CC	CC/DV	CC/DV	DV
Side Rooms	CC	DV/CC	DV/CC	DV

This type of analysis shows clearly that different models provide different answer to the initial question, a tendency which proves to be far more evident for the summer results. Nevertheless, it is also clear that during the spring-autumn period all four models may lead to a similar conclusion: that nocturnal ventilation results in substantially lower comfort rates, compared with the two other ventilation scenarios.

3.1.4 30 Chelouche Street – indoor thermal comfort according to Givoni's extended comfort zone

The relation between indoor dry-bulb temperatures, relative humidities and thermal comfort definition reveals two distinctive general tendencies:

- During the summer months (July-September, figure 3.1.10), substantial lowering of comfort rates was mainly a result of lower indoor temperatures during nighttime. Since air moisture content is kept the same under all ventilation scenarios, lowering of indoor dry-bulb temperature (which, during nighttime, is the direct result of natural ventilation, see section 3.1.1) leads to higher relative humidity values (for each specific air moisture content level). Based on the comfort model selected for analysis, higher relative humidities lead to lower comfort rates, since temperature levels are kept relatively high even after being decreased by natural ventilation.

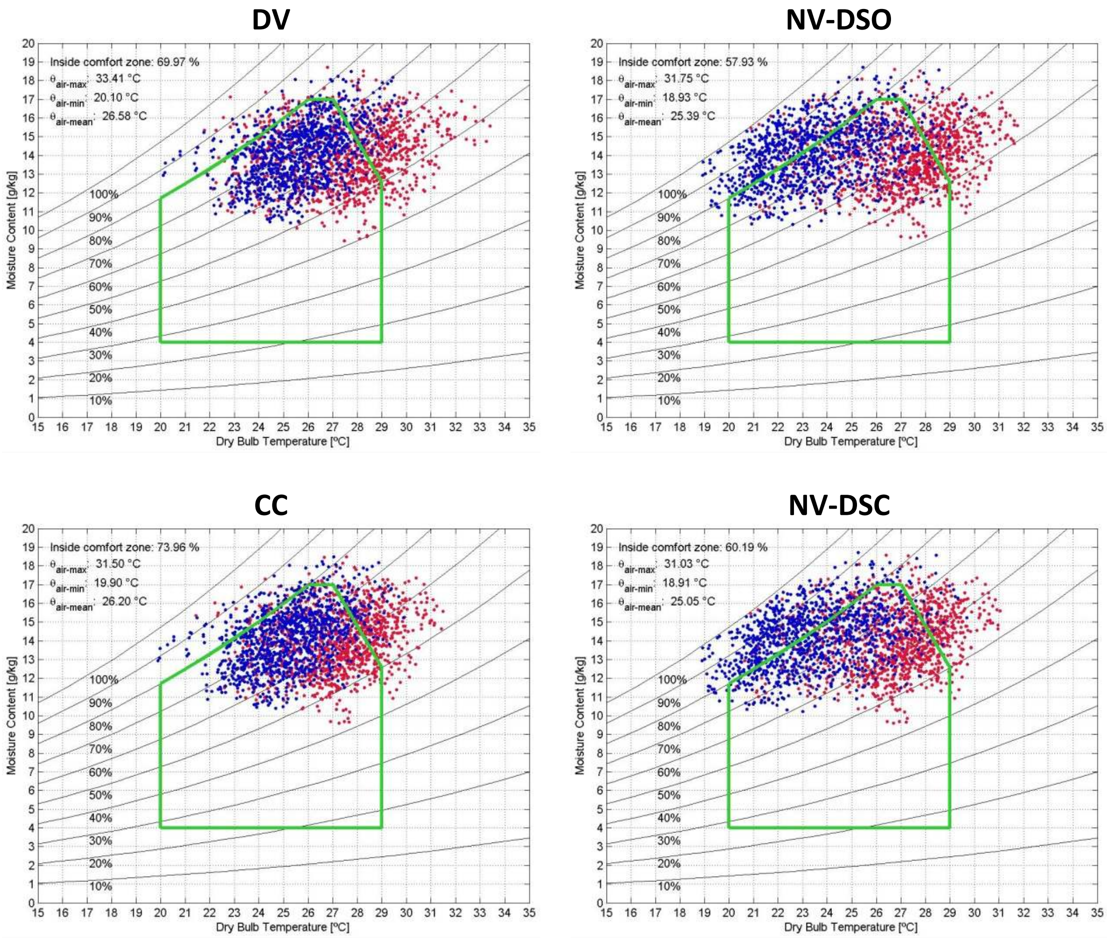


Figure 3.1.10: 30 Chelouche Street, psychrometric charts with Givoni's extended comfort zone for July-September (side rooms) under several ventilation scenarios. Red dots represent daytime values, blue ones – nighttime values

- During the spring and autumn months (May, June and October, figure 3.1.11) substantial lowering of comfort rates was mainly a result of lower indoor temperatures during nighttime, this time mainly because of substantial decrease of the indoor temperature levels. During this period, higher relative humidity levels have only a minor impact on stepping outside the thermal "comfort zone".

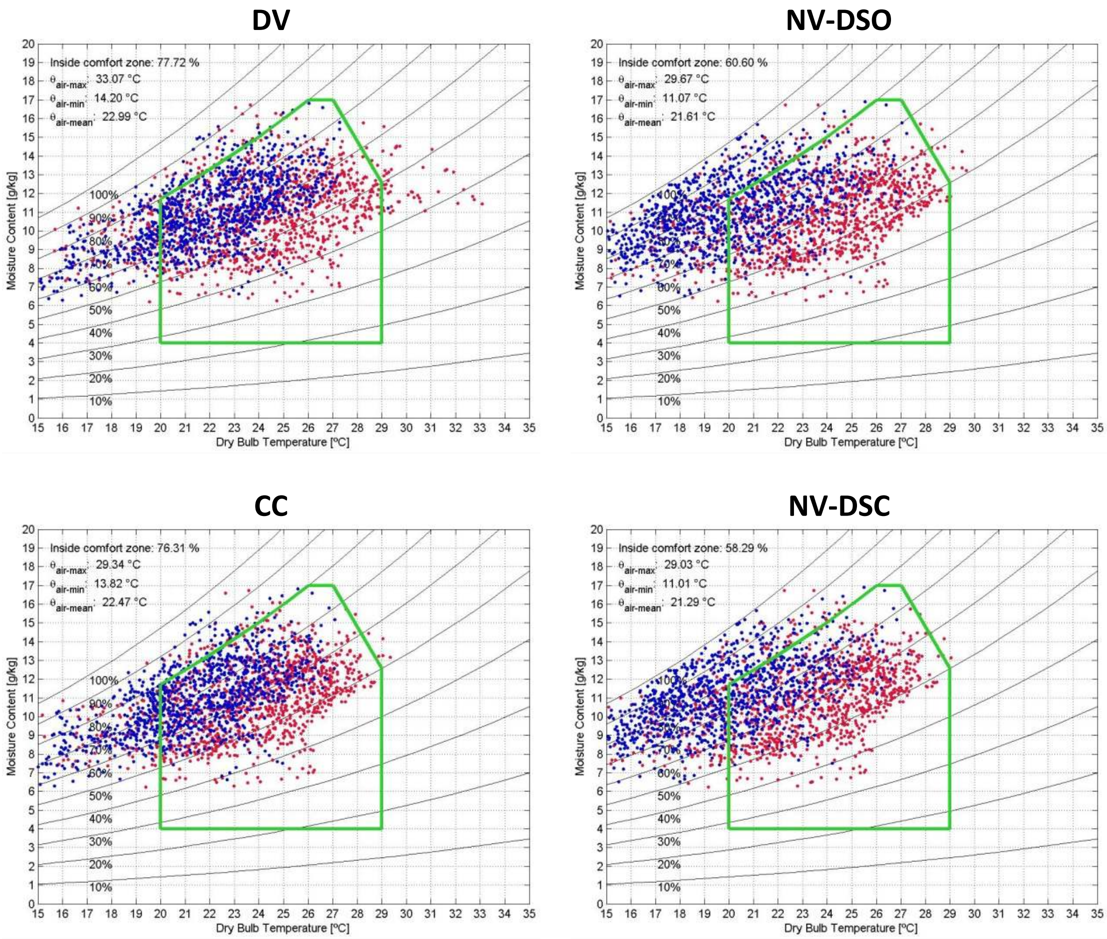


Figure 3.1.11: 30 Chelouche Street, psychrometric charts with Givoni's extended comfort zone for May, June and October (side rooms) under several ventilation scenarios. Red dots represent daytime values, blue ones – nighttime values

While the same overall tendencies can be traced in both the central hall and the side rooms under all scenarios, it is important to address some substantial differences in their thermal performance:

- During summer, daytime ventilation (figure 3.1.12) results in much higher nighttime temperatures in the central hall than in the side rooms, thus leading to lower comfort rates, although relative humidities in the central hall are simultaneously lower (**in contrast to the overall opposite correlation as was described above**). This results from the nighttime temperature range prevalent in the central hall, which is relatively higher than in the side rooms.

- A similar tendency was also recorded during the spring-autumn months, but, because of the different temperature range, it had an opposite impact on comfort rates, basically because indoor temperatures in the side rooms did not reach the lower temperature boundary of the "comfort zone". Thus, during this period comfort rates in the side rooms were substantially lower than in the central hall.

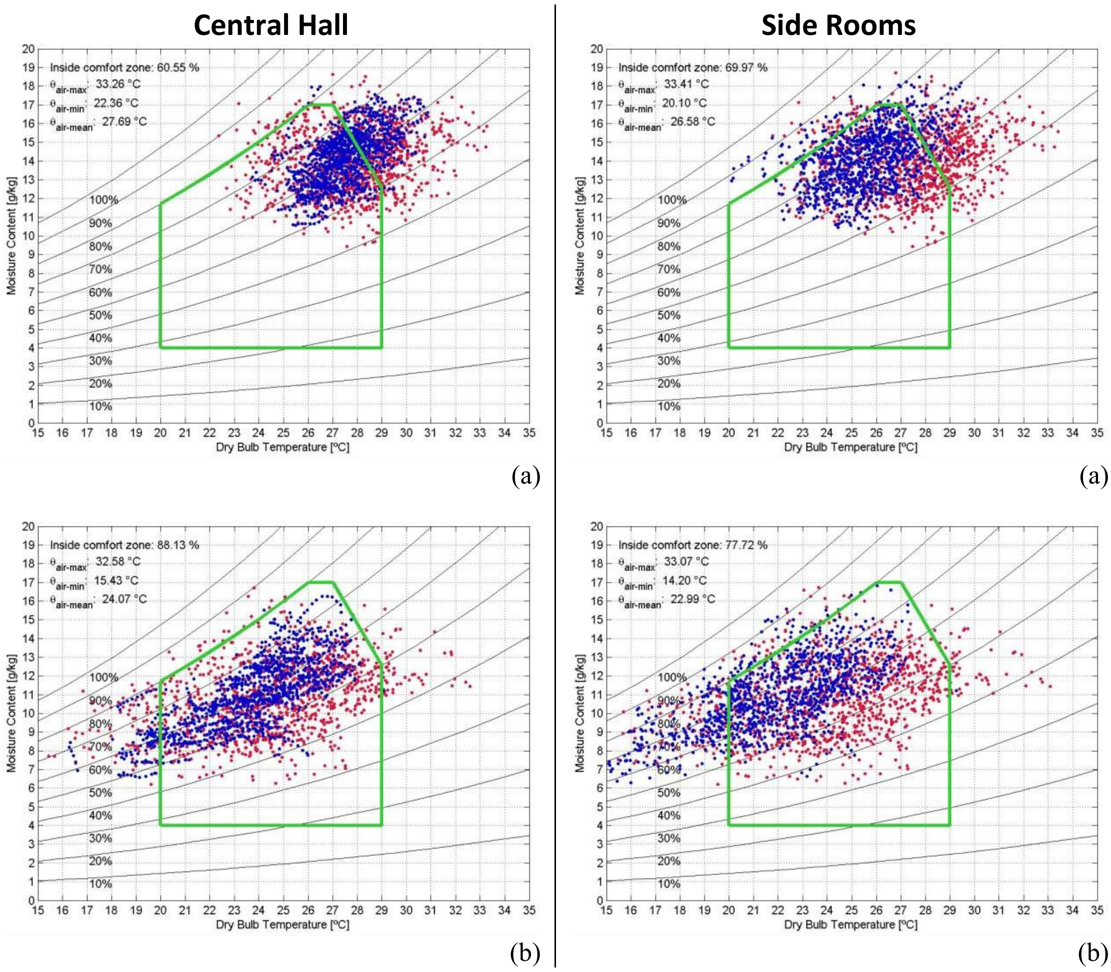


Figure 3.1.12: 30 Chelouche Street, psychrometric charts with Givoni's extended comfort zone for ventilation scenario DV: July-September (a) and May, June and October (b). Red dots represent daytime values, blue ones – nighttime values

- During summer, natural ventilation affects differently the central hall and the side rooms. While the side rooms show clearly higher comfort rates under the limited aperture ventilation or daytime ventilation scenarios (figure 3.1.10), comfort rates in the central hall are almost similar **under all scenarios** (figure 3.1.13). A careful look reveals that major differences between the scenarios exist in nighttime temperatures, but these differences have almost no effect on differences in comfort rates because of the specific properties of the comfort model used here. Thus, while the indoor conditions in the central hall during summer are qualitatively different under each ventilation scenario, Givoni's extended model renders them as relatively similar in relation to the resultant comfort rates.

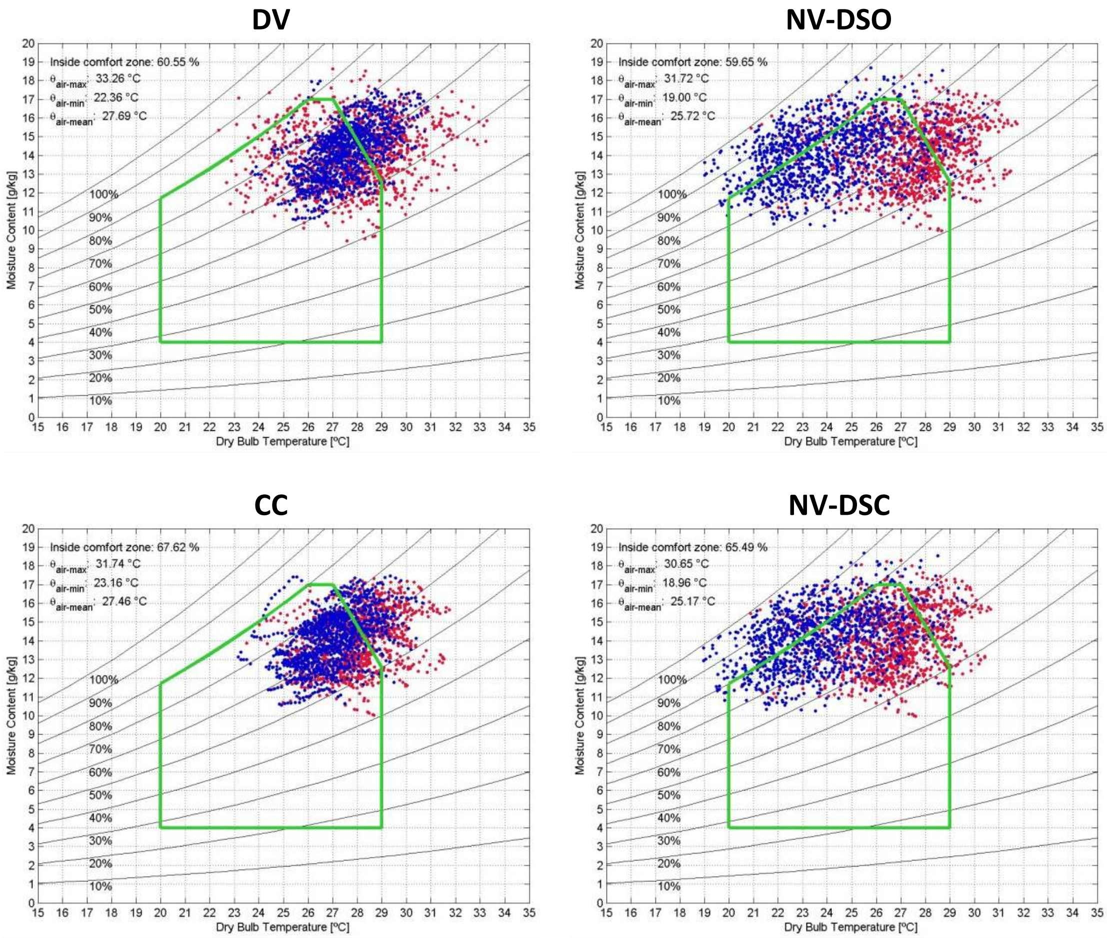


Figure 3.1.13: 30 Chelouche Street, psychrometric charts with Givoni's extended comfort zone for July-September (central hall) under several ventilation scenarios. Red dots represent daytime values, blue ones – nighttime values

As a last remark, it should be added that opening or closing of the shutters during daytime proved to have a negligible effect on temperature levels, thus on comfort rates, when nocturnal ventilation was applied. The relatively marginal effect of the penetrating solar radiation on comfort rates can also be traced by comparing comfort rates from scenarios DV and CC, which produce almost the same values while reflecting an opposite operation mode of the shutters (opened against closed) during daytime.

3.2 35 Israel Me-Salant Street - Results Analysis

3.2.1 35 Israel Me-Salant Street – indoor mean hourly dry-bulb temperatures

Looking at the mean hourly indoor temperatures during summer (figures 3.2.1, 3.2.5 and 3.2.6), it is quite evident that nocturnal ventilation is the best method for lowering indoor temperatures (both during daytime and nighttime). In addition, a consistent difference in indoor temperatures between the central hall and the side rooms was recorded. Overall, the side rooms maintained lower temperatures under all scenarios. Comparison of overheating rates (percentage of hours with indoor temperature above 27°C, figure 3.2.2) and cumulative frequency charts of indoor temperatures (figures 3.2.3 and 3.2.4) show the same general tendencies.

It is important to note that since this building has no round wall-apertures, scenario CC (unlike the two other sample buildings) represents a "zero natural ventilation" scenario in both the central hall and the side rooms.

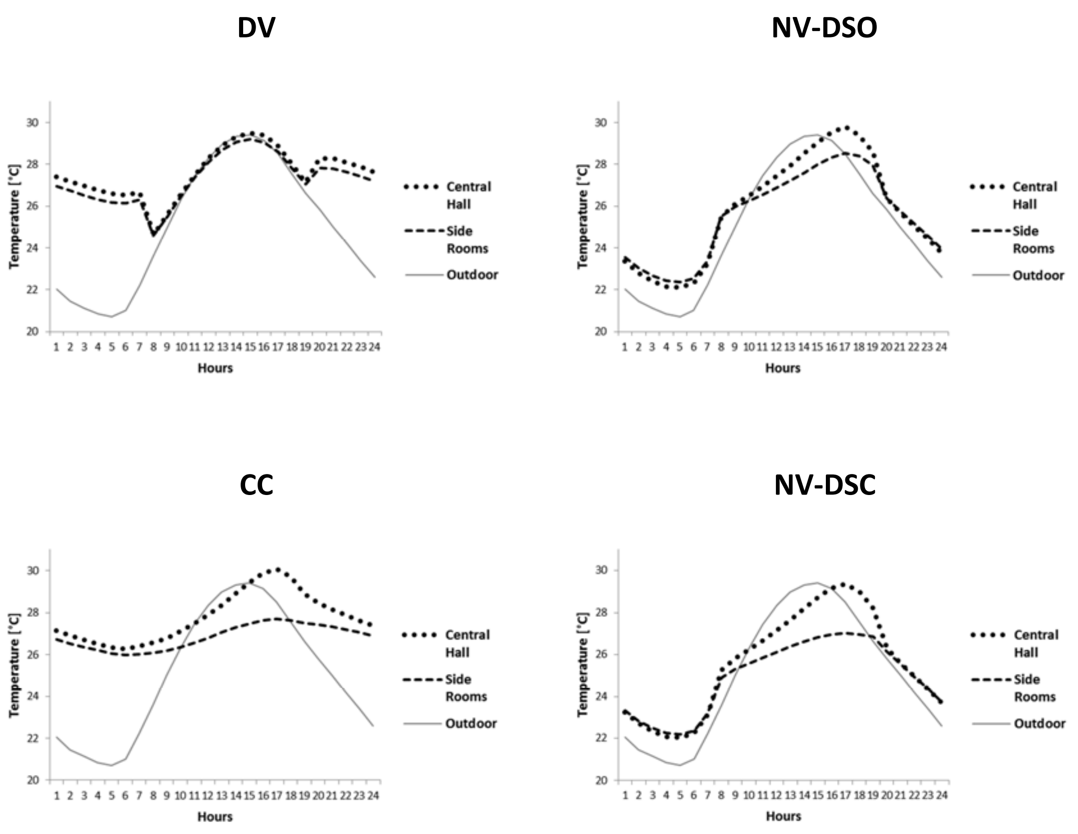


Figure 3.2.1: 35 Israel Me-Salant Street, mean hourly dry-bulb temperatures for July-September under several ventilation scenarios

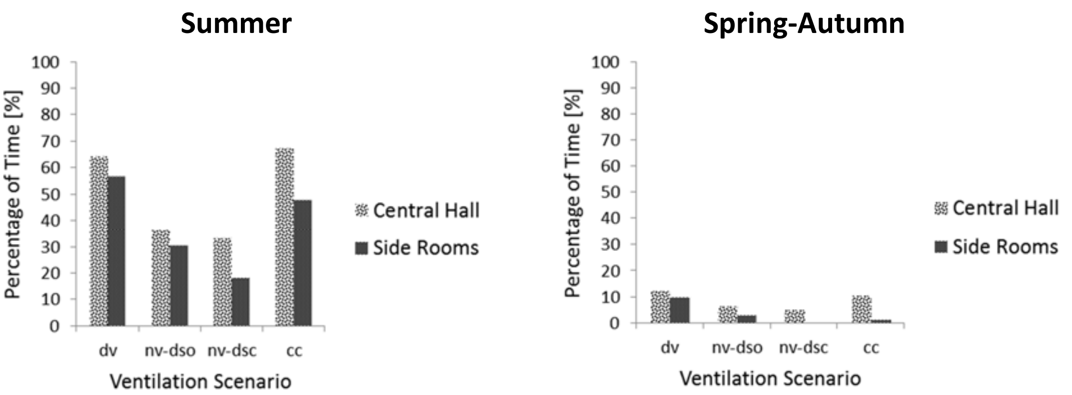


Figure 3.2.2: 35 Israel Me-Salant Street, overheating rates

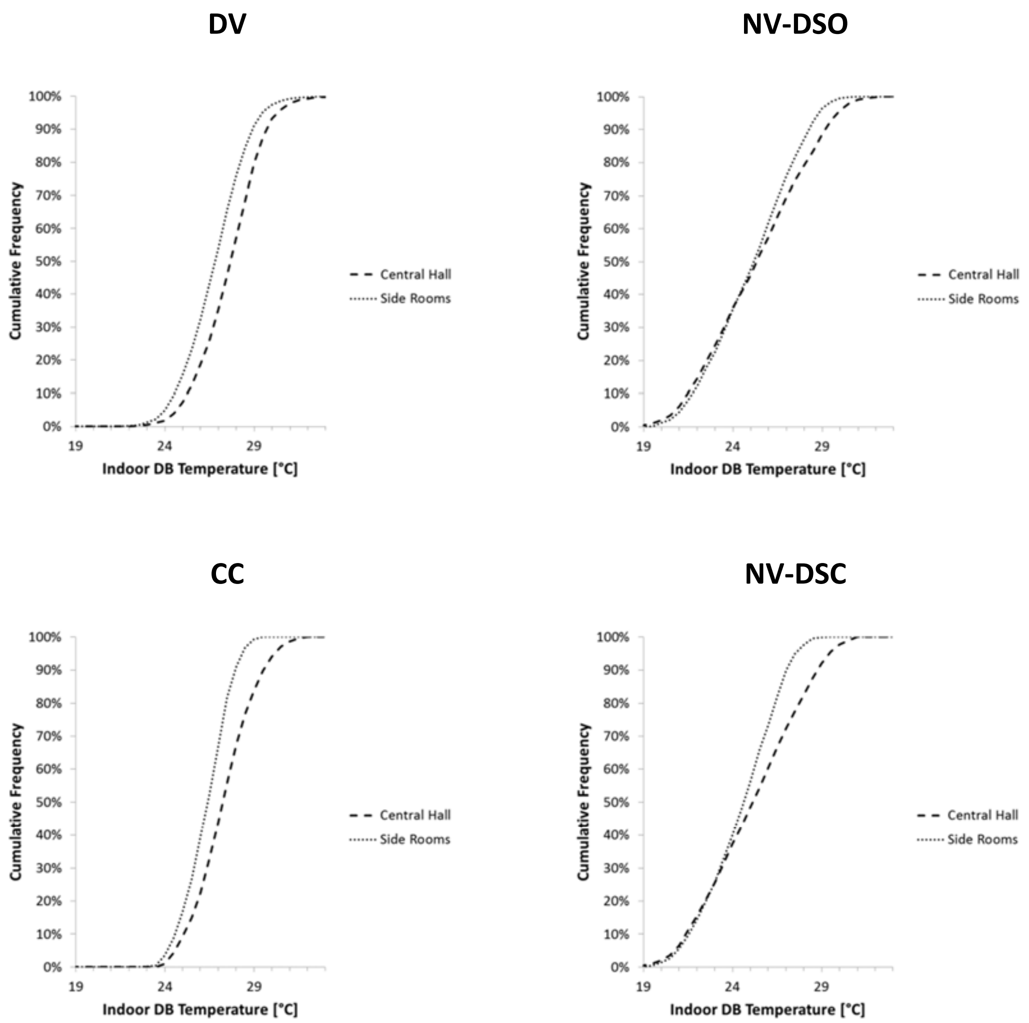
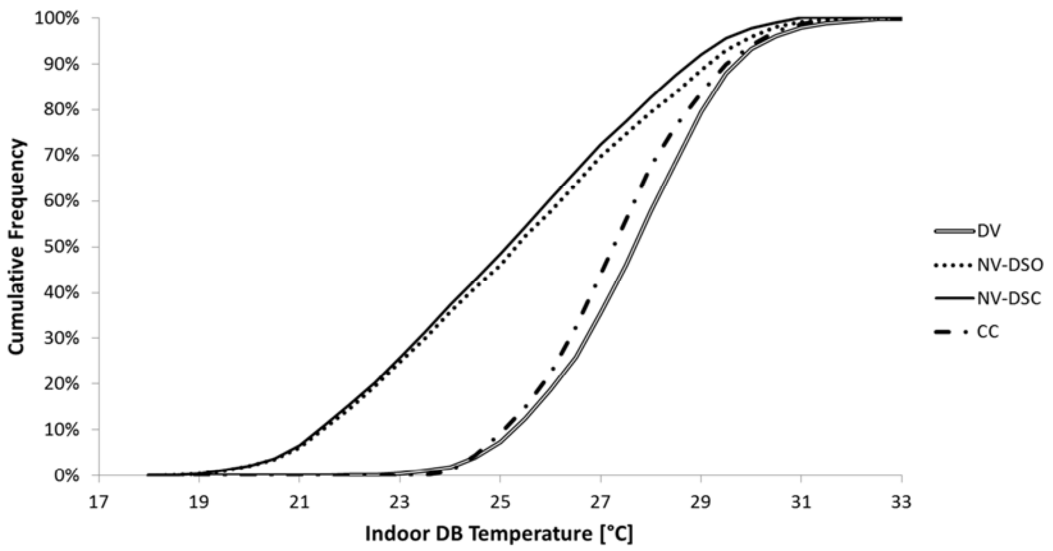
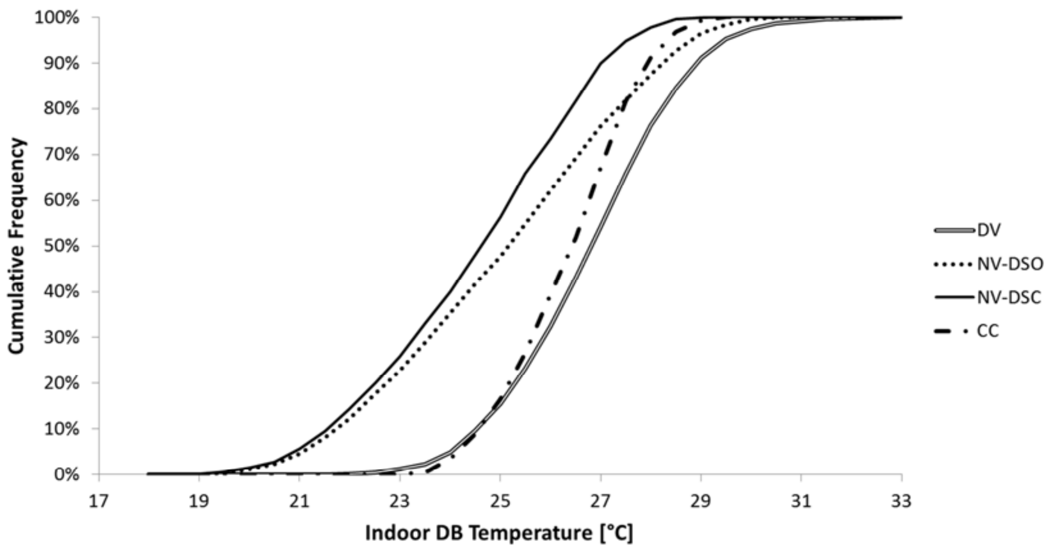


Figure 3.2.3: 35 Israel Me-Salant Street, cumulative frequency of indoor temperatures under several ventilation scenarios for the months July-September, central hall vs. side rooms



(a)



(b)

Figure 3.2.4: 35 Israel Me-Salant Street, cumulative frequency of indoor temperatures for the months July-September for all four ventilation scenarios: central hall (a), side rooms (b)

A more detailed list of findings for the summer period is summarized below:

- In all rooms, the lowest daily peak temperatures were recorded under scenario NV-DSC.
- Highest daytime temperatures for the central hall were recorded under scenario CC; for the side rooms, highest daytime temperatures were recorded under scenario DV.
- In all rooms, highest nighttime temperatures were recorded under scenario DV.

- In all rooms, smallest diurnal range was recorded under scenario CC.
- Scenarios NV-DSO, NV-DSC and CC produced much higher daily peak temperatures in the central hall than in the side rooms. In these scenarios a two-hour shift of the daily peak indoor temperature, compared with the outdoor peak temperature, was also recorded.
- Nighttime temperatures were almost identical in the central hall and the side rooms.
- Unlike the overall tendency, central hall temperatures during nighttime were lower than those of the side rooms under scenarios NV-DSO and NV-DSC.
- All Scenarios produced average nighttime temperatures higher than the outdoor temperatures.

It is important to note that these tendencies, which are based on the summer results, were almost identical when analyzing the spring-autumn period (May, June and October), though the average temperature values were naturally lower.

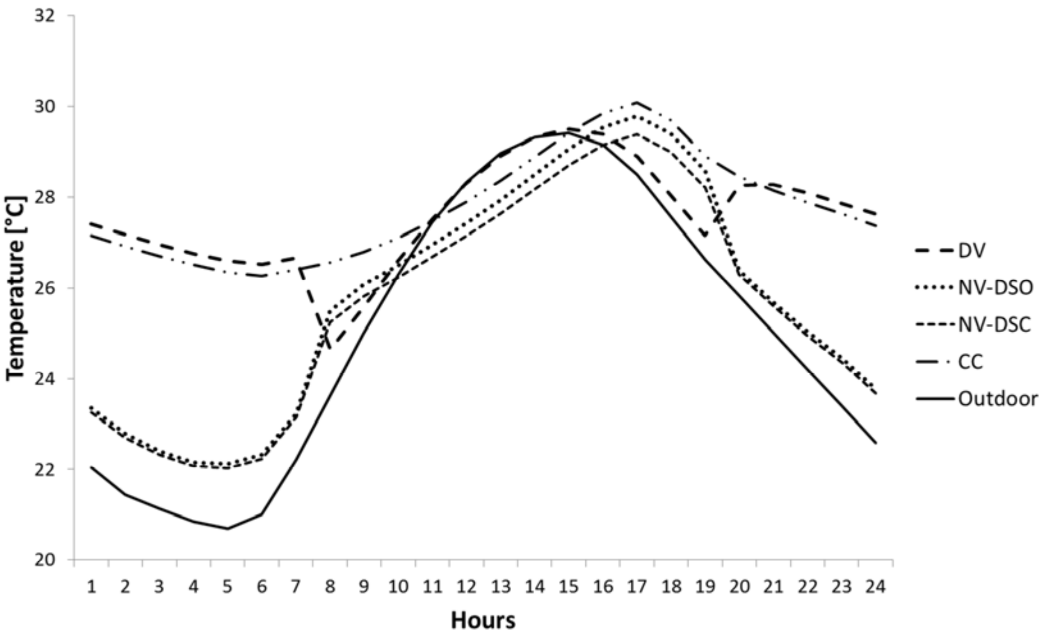


Figure 3.2.5: 35 Israel Me-Salant Street, central hall mean hourly dry-bulb temperatures for July-September under different ventilation scenarios

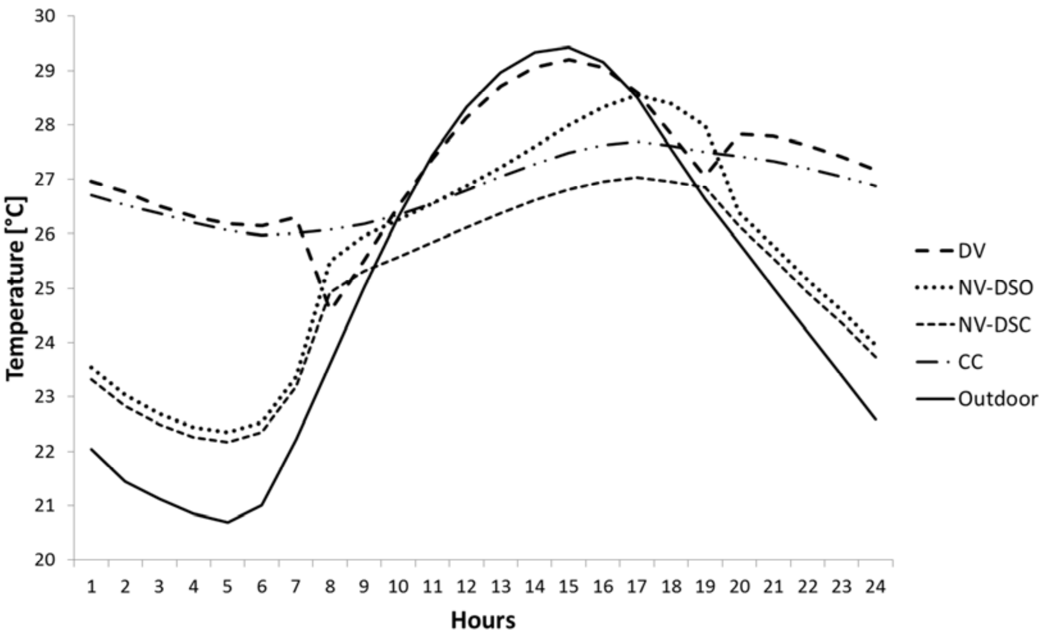


Figure 3.2.6: 35 Israel Me-Salant Street, side rooms mean hourly dry-bulb temperatures for July-September under different ventilation scenarios

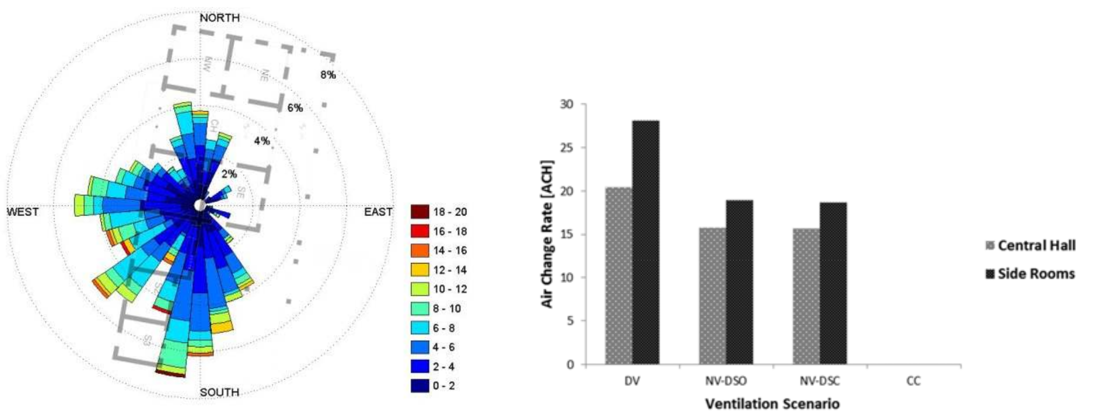
3.2.2 35 Israel Me-Salant Street – indoor air change rates

Typical wind directions for the site are southern to western winds (figure 3.2.7 (a)). Therefore, it is not surprising that the western rooms (NW, SW and S1) have more than double the higher air change rates in comparison to the adjacent eastern rooms (NE and SE). Nevertheless, for the sake of analysis, air change rates for all four side rooms were averaged, since their differentiation in values had little to do with differences in indoor air temperatures or comfort rates, probably because of the relatively high air change rates that were recorded even in the eastern rooms.

As can be seen from figure 3.2.7 (b), substantial lower air change rates were calculated for the central hall compared with the side rooms, independent of the ventilation scenario that was applied. This may be attributed to several factors:

- The structure's layout, which makes the central hall relatively long and narrow, in comparison to the side rooms.
- Windows in the central hall are directed in two opposite directions and not in two perpendicular directions, making it more sensitive to alternation in wind direction.
- Window area per volume in the central hall was much lower than in the side rooms.

As was explained above, in ventilation scenario CC natural ventilation did not exist in all rooms.



(a) (b)

Figure 3.2.7: Superposition of 35 Israel Me-Salant Street living floor plan on a typical monthly wind rose for the month of August (a), average hourly air change rates for July-September (b). Average air change rates for the spring-autumn period (May, June and October) were almost identical.

3.2.3 35 Israel Me-Salant Street – indoor thermal comfort according to different comfort models

All results showed clear and substantial differences between the comfort rates that were produced by analyzing the simulation results according to the four selected comfort models. These differences appear to be more significant during summer (July-September).

An overview of the results reveals the following tendencies (figure 3.2.8):

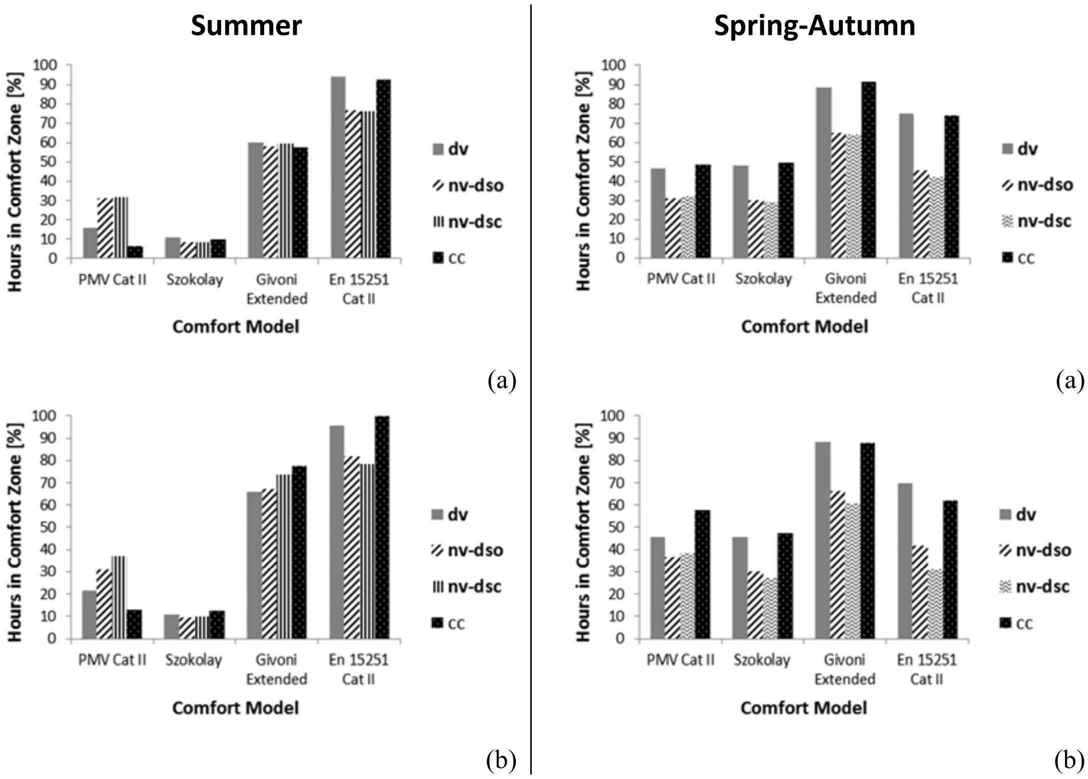


Figure 3.2.8: 35 Israel Me-Salant Street, comfort rates according to four comfort models: central hall (a) and side rooms (b)

- During summer, highest comfort rates were recorded using the EN 15251 model. During spring and autumn Givoni's extended model produced the highest rates.
- During summer, analysis according to Szokolay's model produced substantially lower comfort rates, mainly in comparison to Givoni's model and the EN 15251 model.
- During both the summer and the spring-autumn periods all models showed that the different ventilation scenarios had relatively similar effect on both the central hall and the side rooms. The only exception is Givoni's model during summer, which showed a slightly higher

differentiation in results in the side rooms, compared with the central hall.

- Though the spring-autumn period analysis produced narrower result range compared with the summer period, the highest rates (using Givoni's extended model) were still more than twice higher than the lower rates (Szokolay's model).

"Best" ventilation analysis (tables 3.2.1 and 3.2.2) shows clearly that different models provide different "best" results, a tendency which proves to be far more evident for the summer results. Nevertheless, it is also clear that during the spring-autumn period all four models may lead to a similar conclusion: that nocturnal ventilation results in substantially lower comfort rates, compared with the two other ventilation scenarios.

Table 3.2.1: Summer, Best Scenario According to Different Comfort Models (second-best result appears when it differs from the best result in less than 10%)

	PMV-PPD Cat II	**Szokolay**	**Givoni Extended**	**EN 15251 Cat II**
Central Hall	NV-DSC/NV-DSO	DV/CC	DV/NV-DSC	DV/CC
Side Rooms	NV-DSC	CC	CC/ NV-DSC	CC/DV

Table 3.2.2: Spring-Autumn, Best Scenario According to Different Comfort Models (second-best result appears when it differs from the best result in less than 10%)

	PMV-PPD Cat II	**Szokolay**	**Givoni Extended**	**EN 15251 Cat II**
Central Hall	CC/DV	CC/DV	CC/DV	DV/CC
Side Rooms	CC	CC/DV	DV/CC	DV

3.2.4 35 Israel Me-Salant Street – indoor thermal comfort according to Givoni's extended comfort zone

The relation between indoor dry-bulb temperatures, relative humidities and thermal comfort definition reveals two distinctive general tendencies:

- During the summer months (July-September, figures 3.2.9 and 3.2.10), there are two main reasons for discomfort: high dry-bulb temperatures (scenarios DV and CC) and high nighttime relative humidities (scenarios NV-DSO and NV-DSC). Although these are two distinctively different thermal phenomena, their impact on the comfort rates is almost similar.

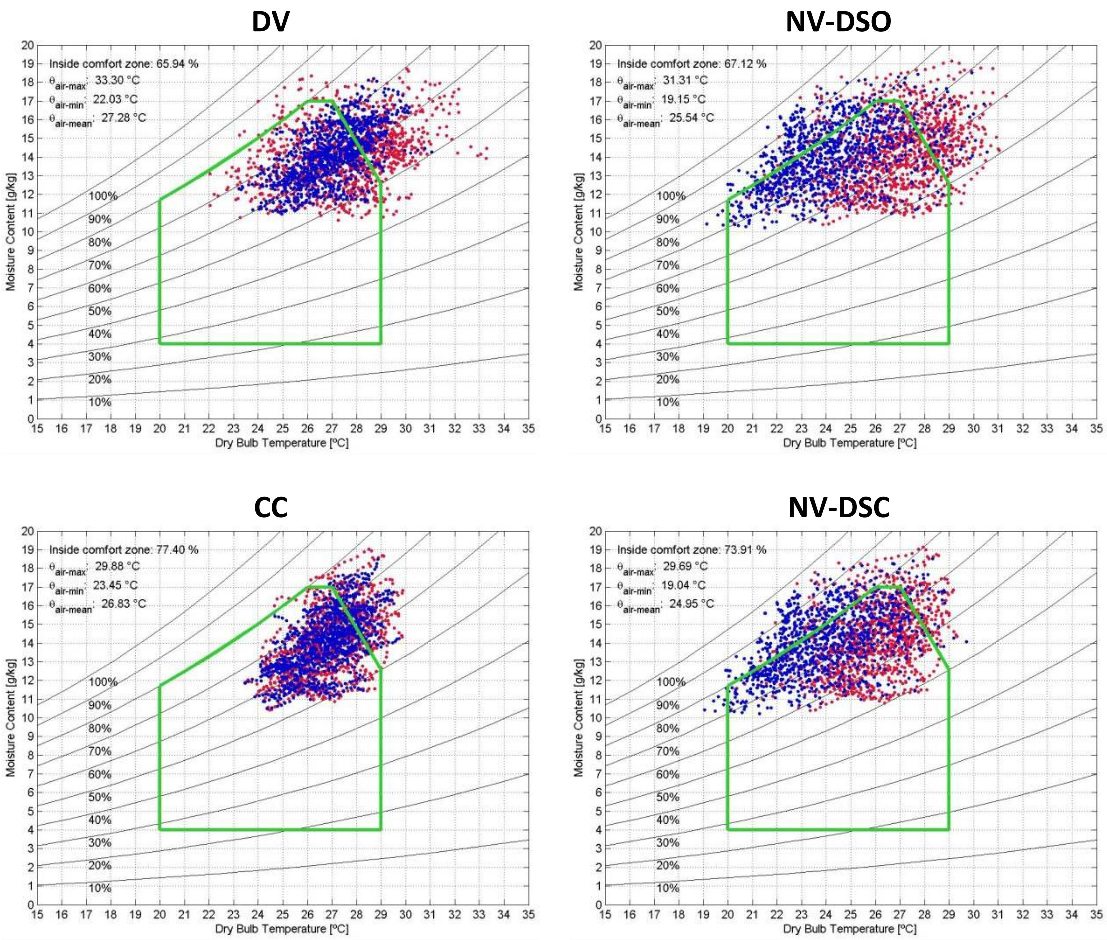


Figure 3.2.9: 35 Israel Me-Salant Street, psychrometric charts with Givoni's extended comfort zone for July-September (side rooms) under several ventilation scenarios. Red dots represent daytime values, blue ones – nighttime values

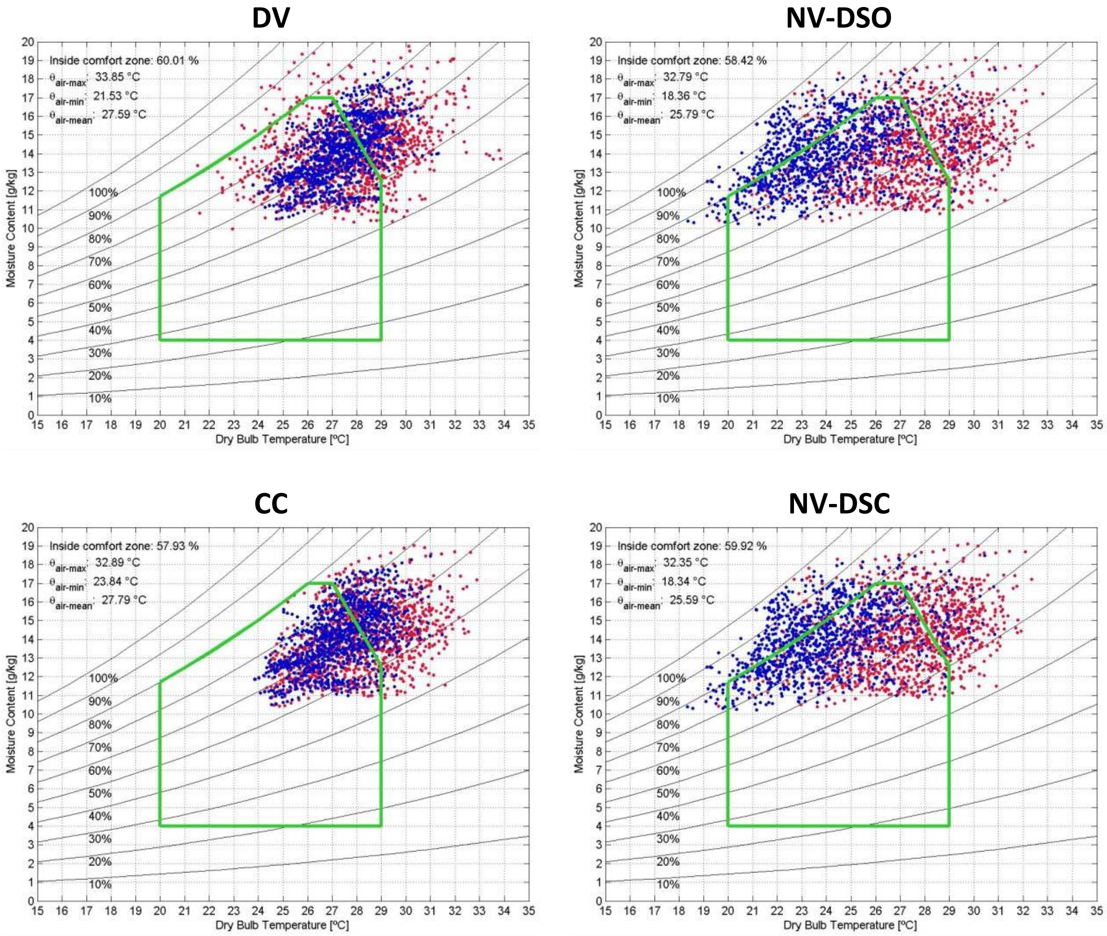


Figure 3.2.10: 35 Israel Me-Salant Street, psychrometric charts with Givoni's extended comfort zone for July-September (central hall) under several ventilation scenarios. Red dots represent daytime values, blue ones – nighttime values

It is interesting to note that direct solar radiation that penetrates the rooms may have a substantial negative impact, in terms of thermal comfort, though only in the side rooms. This can be seen from the lower comfort rates recorded under scenarios with opened shutters (DV, NV-DSO), which seems to be a direct result from higher indoor temperatures (for example, the mean daily indoor temperature under scenario NV-DSC is about 0.6°K below the mean daily temperature under scenario NV-DSO. The operational difference between these two scenarios is only the shutters position).

- During the spring and autumn months (May, June and October, figure 3.2.11) substantial lowering of comfort rates was mainly a result of lower indoor temperatures during nighttime because of substantial decrease in indoor temperature levels. During this period, higher relative humidity levels have only a minor impact on stepping outside the thermal "comfort zone".

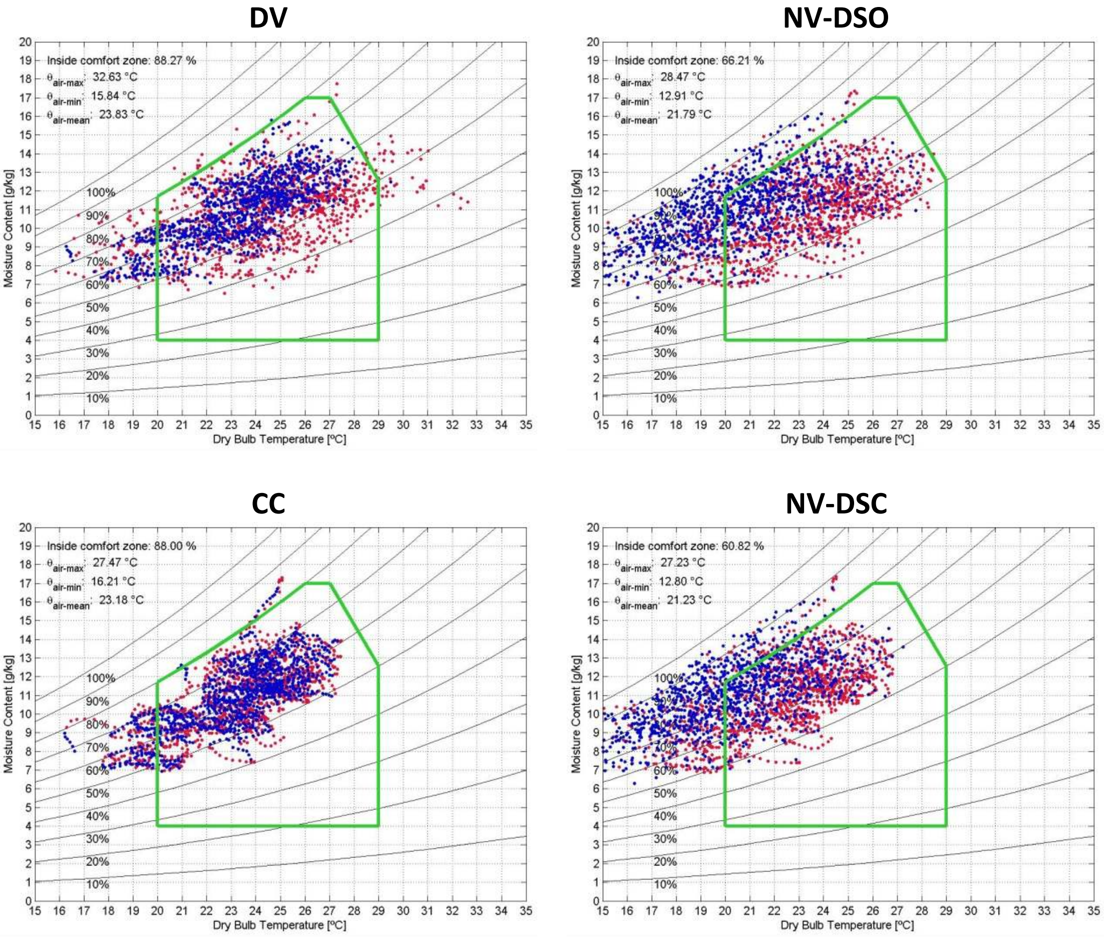


Figure 3.2.11: 35 Israel Me-Salant Street, psychrometric charts with Givoni's extended comfort zone for May, June and October (side rooms) under several ventilation scenarios. Red dots represent daytime values, blue ones – nighttime values

3.3 19 Ma'ale Ha-Shihrur Street - Results Analysis

3.3.1 19 Ma'ale Ha-Shihrur Street – indoor mean hourly dry-bulb temperatures

Looking at the mean hourly indoor temperatures during summer (figures 3.3.1, 3.3.5 and 3.3.6), it is quite evident that nocturnal ventilation, rather than daytime ventilation or limited aperture ventilation, results in lowering indoor temperatures. Limited aperture ventilation produces exceptionally higher indoor temperatures, with a difference of about 1.5°K between the indoor and outdoor average daily peak temperatures during summer and of about 0.5°K during spring-autumn. In addition, no substantial difference in indoor temperatures between the central hall and the side rooms (under the same outdoor conditions and ventilation scenario) was recorded, though the side rooms were slightly cooler during daytime and slightly warmer during nighttime. Comparison of overheating rates (percentage of hours with indoor temperature above 27°C, figure 3.3.2) and cumulative frequency charts of indoor temperatures (figures 3.3.3 and 3.3.4) show the same general tendencies.

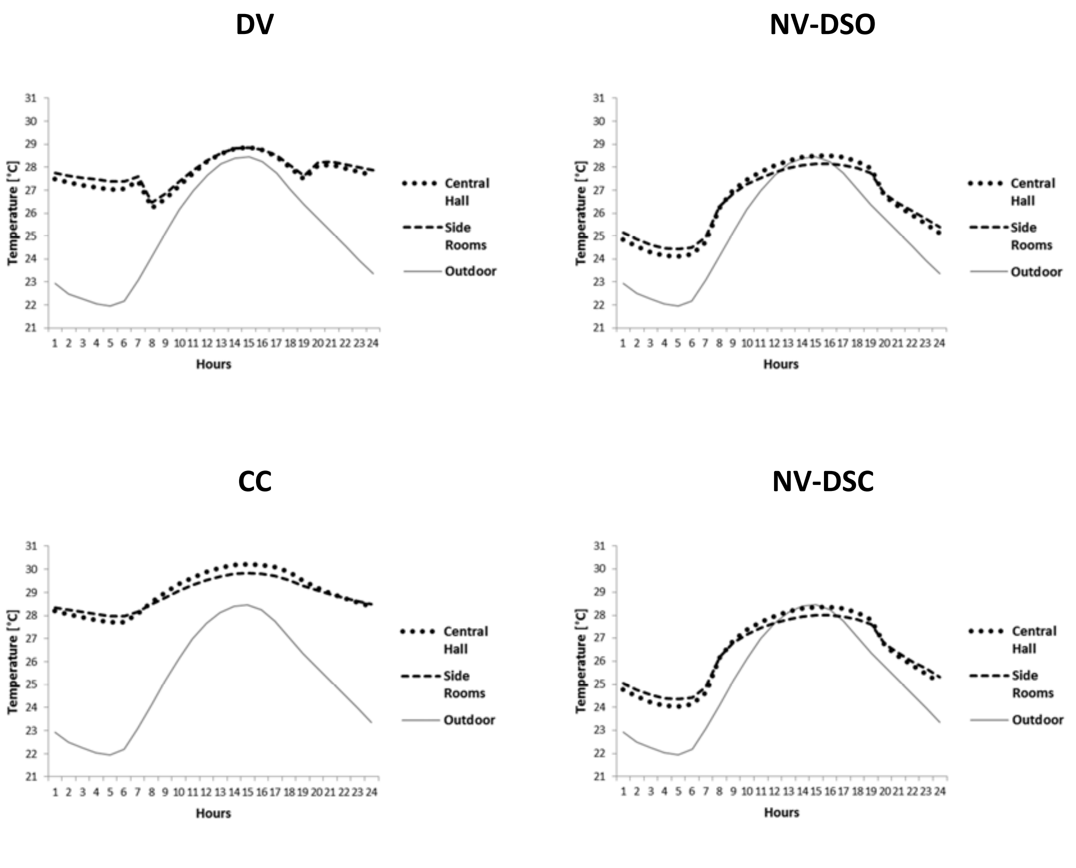


Figure 3.3.1: 19 Ma'ale Ha-Shihrur Street, mean hourly dry-bulb temperatures for July-September under several ventilation scenarios

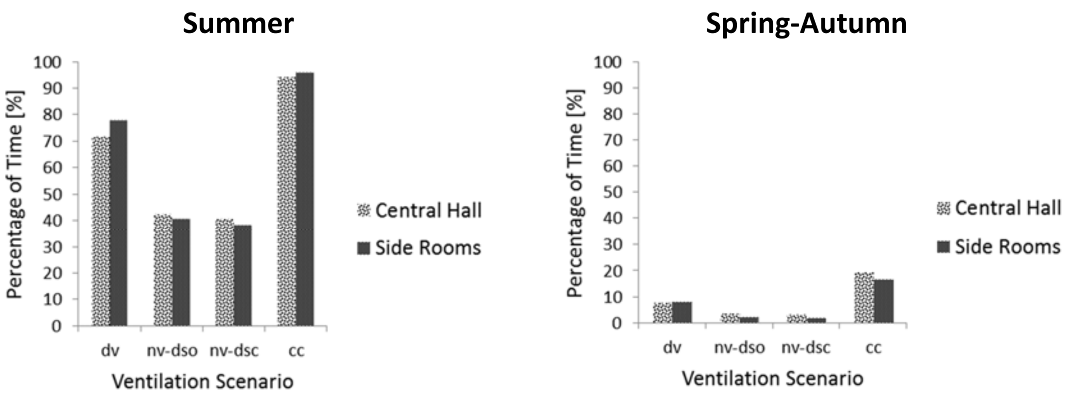
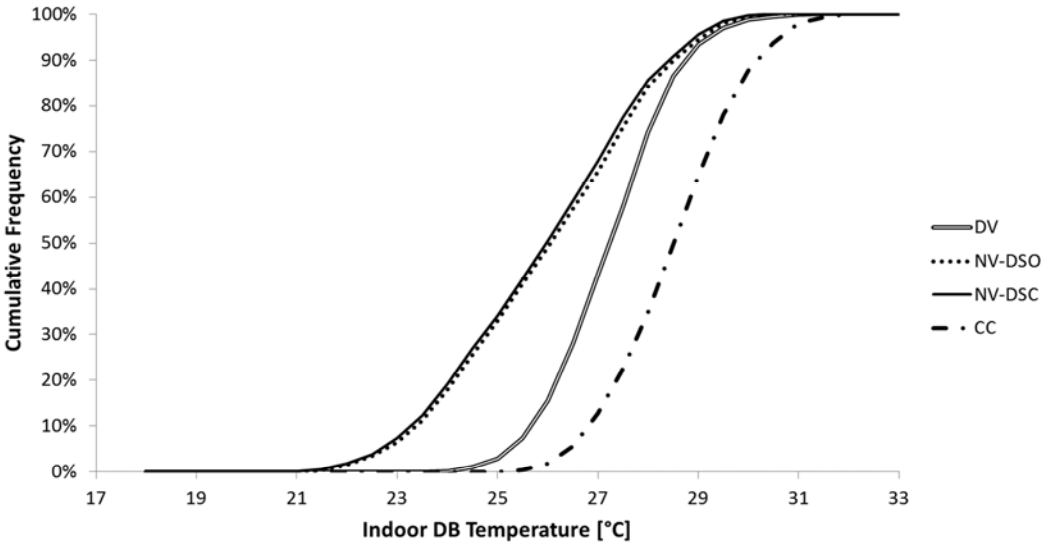
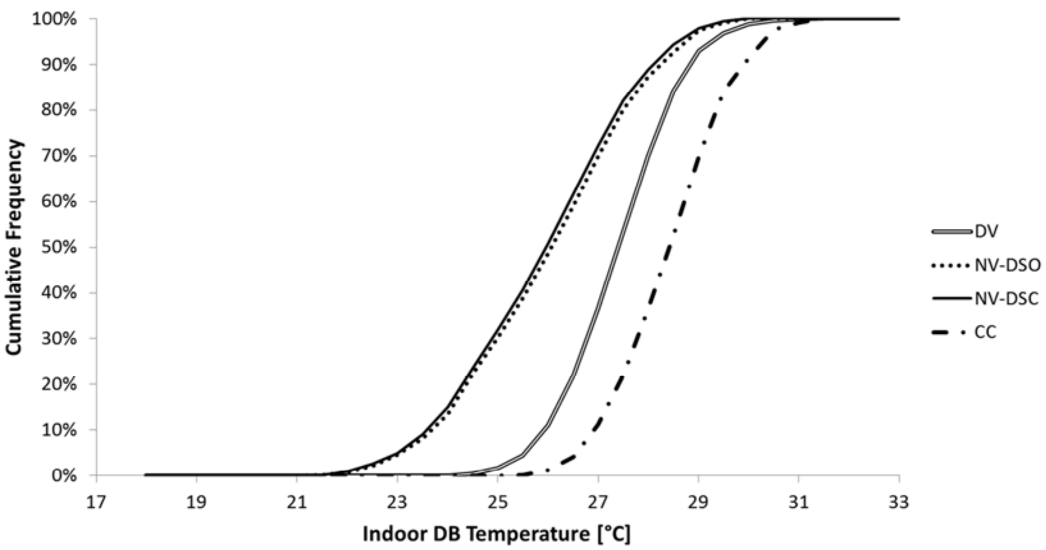


Figure 3.3.2: 19 Ma’ale Ha-Shihrur Street, overheating rates



(a)



(b)

Figure 3.3.3: 19 Ma’ale Ha-Shihrur Street, cumulative frequency of indoor temperatures for the months July-September for all four ventilation scenarios: central hall (a), side rooms (b)

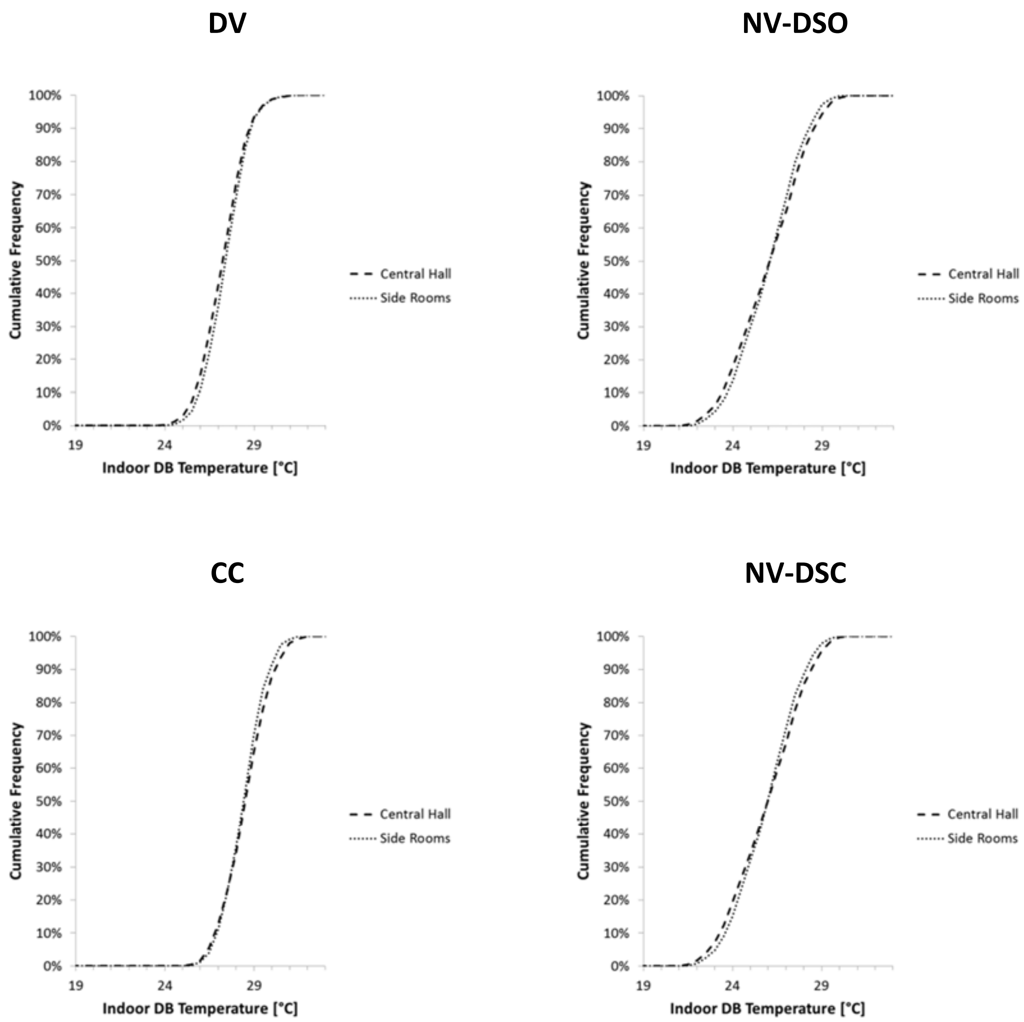


Figure 3.3.4: 19 Ma’ale Ha-Shihrur Street, cumulative frequency of indoor temperatures under several ventilation scenarios for the months July-September, central hall vs. side rooms

A more detailed list of findings is summarized below:

- In all rooms, the lowest daytime and nighttime peak temperatures were recorded under scenario NV-DSC and the highest under scenario CC.
- Temperatures under scenario CC were exceptionally higher than those recorded under all three other scenarios.
- Scenarios CC and DV produced daytime peak temperatures higher than the corresponding outdoor values. Nocturnal ventilation produced daytime peak temperatures almost similar to the outdoor values.
- All Scenarios produced average nighttime temperatures higher than the outdoor temperatures.
- In all rooms, smallest diurnal range was recorded under scenario CC.

It is important to note that these tendencies, which are based on summer results, were almost identical when analyzing the spring-autumn period (May, June and October), although the average temperature values were naturally lower. The only exception is that nocturnal ventilation produced daytime peak temperatures lower than the corresponding outdoor values during spring-autumn.

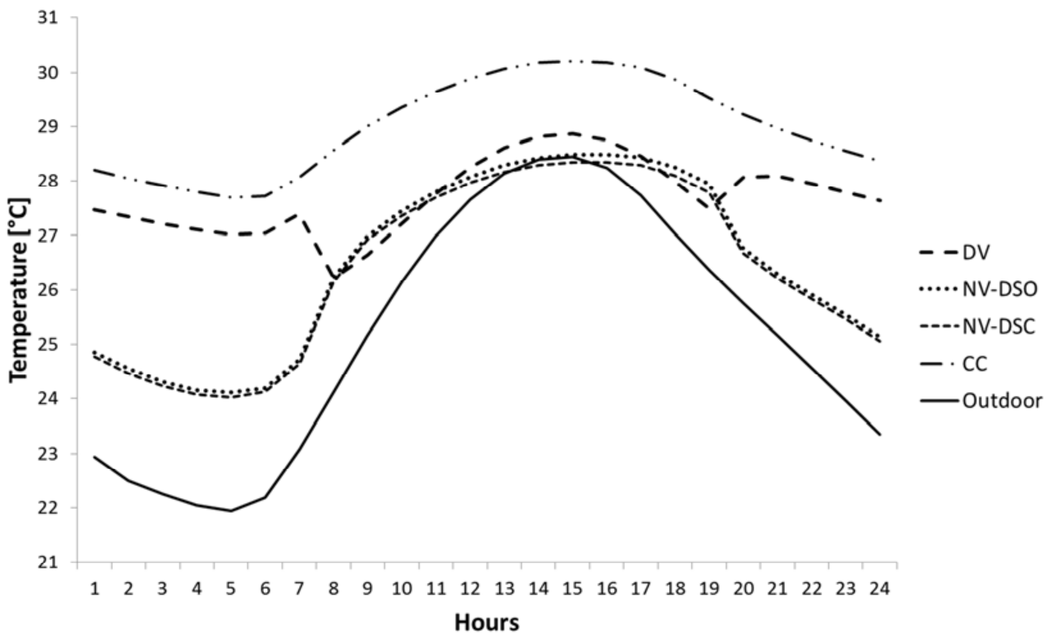


Figure 3.3.5: 19 Ma'ale Ha-Shihrur Street, central hall mean hourly dry-bulb temperatures for July-September under different ventilation scenarios

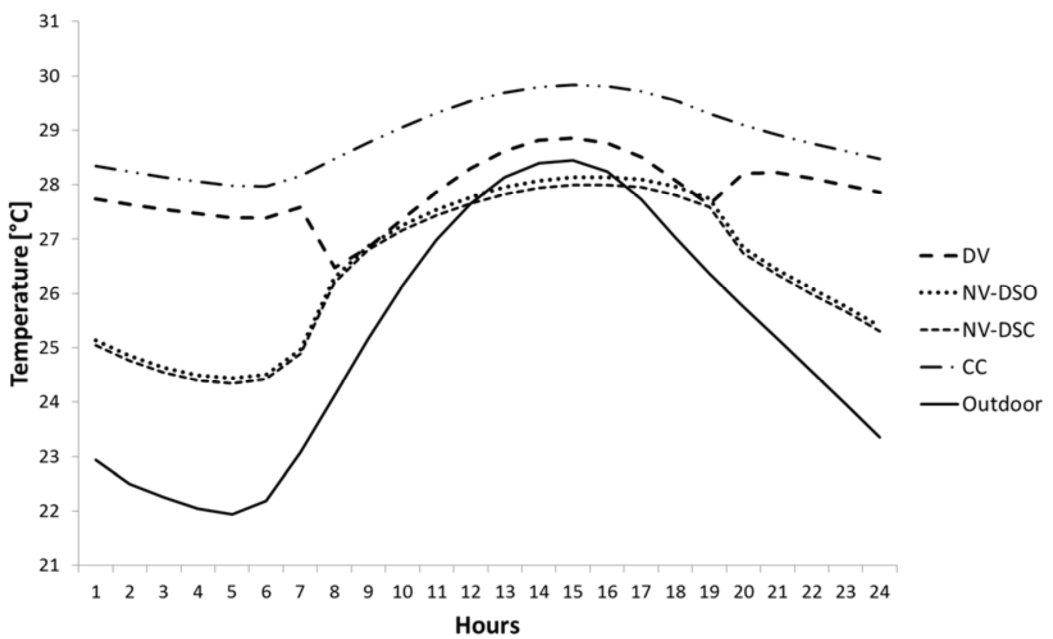
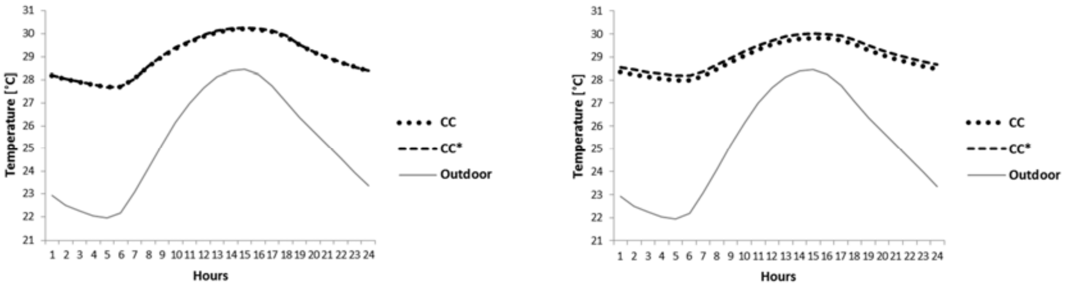


Figure 3.3.6: 19 Ma'ale Ha-Shihrur Street, side rooms mean hourly dry-bulb temperatures for July-September under different ventilation scenarios

In order to isolate the effect of the round apertures on indoor temperatures, an alternative scenario (CC*, figure 3.3.7) was used, in which all windows, shutters and apertures were defined as constantly closed (though this mode of use has a weak operational logic). The results show virtually no difference in indoor temperatures under these two scenarios, both in the side rooms and in the central hall. This result is a direct outcome of the special spatial feature of the surrounding Riwaq, which blocks, when its windows are closed, any air movement into or out of the living level.



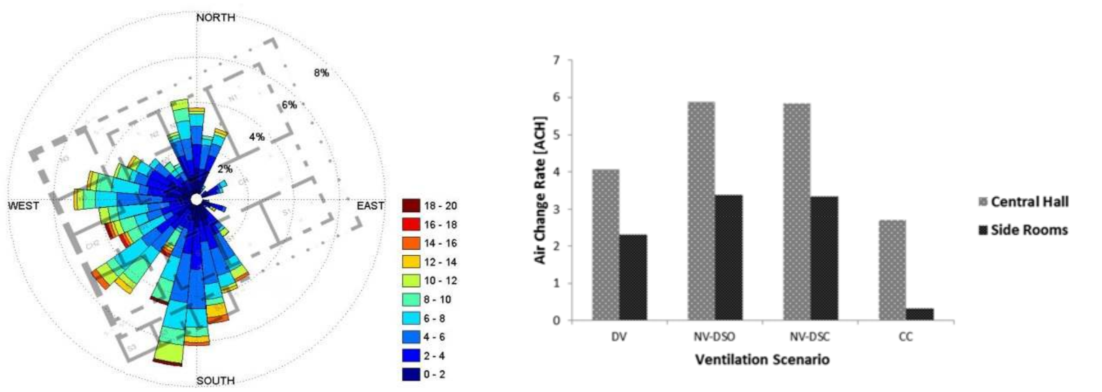
(a) (b)

Figure 3.3.7: 19 Ma'ale Ha-Shihrur Street, mean hourly dry-bulb temperatures for July-September under two ventilation scenarios, CC (a) and CC*: central hall (a) and side rooms (b). Scenario CC* is identical to scenario CC with one exception: the round apertures are defined as constantly closed, like the rectangular windows.

3.3.2 19 Ma'ale Ha-Shihrur Street – indoor air change rates

Typical wind directions for the site are southern to western winds (figure 3.3.8 (a)). Thus, the orientation of the building is not optimal in regard to exploiting the natural winds, since direct wind flow from the west is virtually blocked from entering the main spaces (CH, N1, N2 and S1) by the three rear rooms. The surrounding Riwaq helps in improving the wind flow through the floor since it faces three directions, but here again, an alternative orientation may have produced much higher air change rate values. The overall outcome is relatively low air change rates in all of the building's main spaces.

As can be seen from figure 3.3.8 (b), the central hall enjoyed higher air change rates compared with the side rooms, independent of the ventilation scenario that was applied. This may be primarily attributed to its relative "openness" to the Riwaq, compared with the side rooms. It should be added that because of this special configuration, in all side rooms almost similar – and low – air change rates were calculated.



(a) (b)

Figure 3.3.8: Superposition of 19 Ma'ale Ha-Shihrur Street living floor plan on a typical monthly wind rose for the month of August (a), average hourly air change rates for July-September (b). Average air change rates for the spring-autumn period (May, June and October) were almost identical.

3.3.3 19 Ma’ale Ha-Shihrur Street – indoor thermal comfort according to different comfort models

All results showed clear and substantial differences between the comfort rates that were produced by analyzing the simulation results according to the four selected comfort models. These differences appear to be more significant during summer (July-September).

An overview of the results reveals the following tendencies (figure 3.3.9):

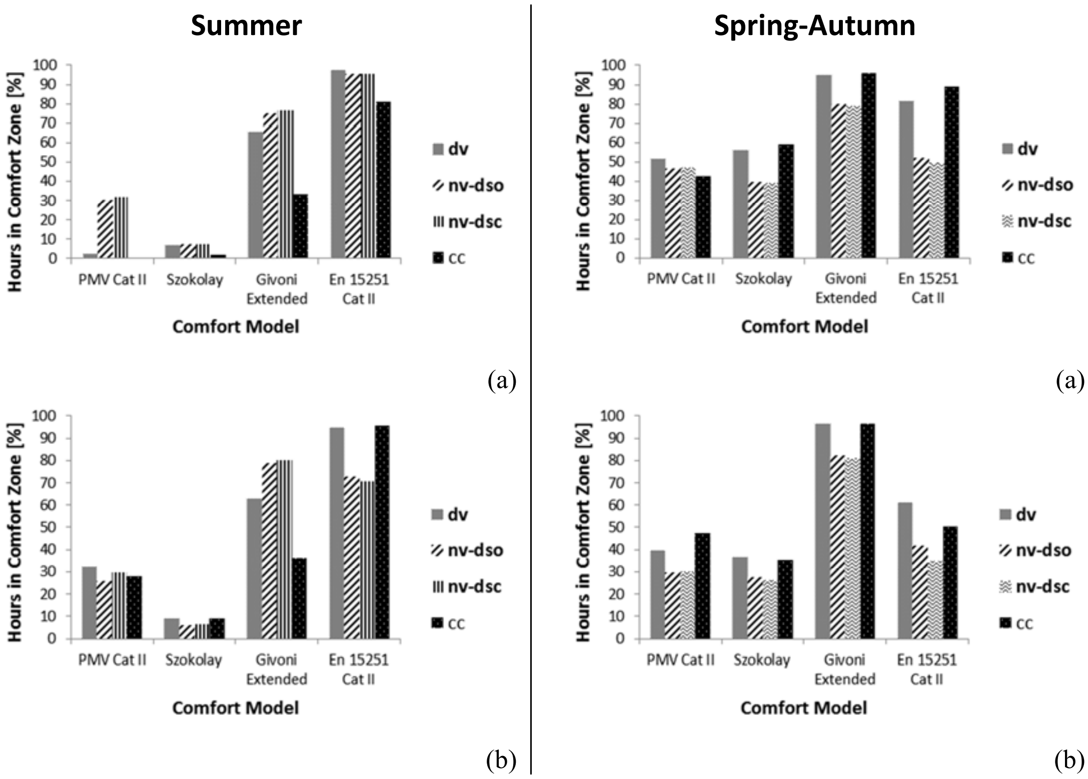


Figure 3.3.9: 19 Ma’ale Ha-Shihrur Street, comfort rates according to four comfort models: central hall (a) and side rooms (b)

- During summer, highest comfort rates were recorded using the EN 15251 model. During spring and autumn Givoni's extended model produced the highest rates.
- During summer, analysis according to Szokolay's model produced substantially lower comfort rates, mainly in comparison to Givoni's model and the EN 15251 model.
- During summer, Givoni's model showed that the different ventilation scenarios had almost the same effect on comfort rates in both the central hall and the side rooms, while analysis according to all other three models produced a quite different picture, in which the effect of the

chosen ventilation strategy was far from being similar in the central hall and the side rooms.

- During spring-autumn, when comparing the results produced under the different ventilation scenarios, the overall "hierarchy" of results (which scenarios performed better than others and to what extent) was relatively the same in all comfort models. In contrast, during the summer period a much weaker "hierarchal" similarity was found.
- Though the spring-autumn period analysis produced narrower result range compared with the summer period, the highest rates (using Givoni's extended models) were still more than twice higher than the lower rates (Szokolay's model).

"Best" ventilation analysis (tables 3.3.1 and 3.3.2) shows clearly that different models provide different "best" results, a tendency which proves to be far more evident in the summer results. Nevertheless, it is also clear that during the spring-autumn period all four models may lead to almost similar conclusion: that nocturnal ventilation results in substantially lower comfort rates, compared with the two other ventilation scenarios.

Table 3.3.1: Summer, Best Scenario According to Different Comfort Models (second-best result appears when it differs from the best result in less than 10%)

	PMV-PPD Cat II	**Szokolay**	**Givoni Extended**	**EN 15251 Cat II**
Central Hall	NV-DSC/NV-DSO	NV-DSO/NV-DSC	NV-DSC/NV-DSO	DV/NV-DSO
Side Rooms	DV/NV-DSC	CC/DV	NV-DSC/NV-DSO	CC/DV

Table 3.3.2: Spring-Autumn, Best Scenario According to Different Comfort Models (second-best result appears when it differs from the best result in less than 10%)

	PMV-PPD Cat II	**Szokolay**	**Givoni Extended**	**EN 15251 Cat II**
Central Hall	DV/NS-DSC	CC/DV	CC/DV	CC/DV
Side Rooms	CC	DV/CC	CC/DV	DV

3.3.4 19 Ma'ale Ha-Shihrur Street – indoor thermal comfort according to Givoni's extended comfort zone

The relation between indoor dry-bulb temperatures, relative humidities and thermal comfort definition reveals two distinctive general tendencies:

- During the summer months (July-September, figures 3.3.10 and 3.3.11), the main reason for discomfort is high dry-bulb temperatures in all ventilation scenarios. The differences in comfort rates are attributed primarily to differences in indoor temperatures, where lower indoor temperatures lead to higher comfort rates. This tendency was recorded in both the central hall and the side rooms.

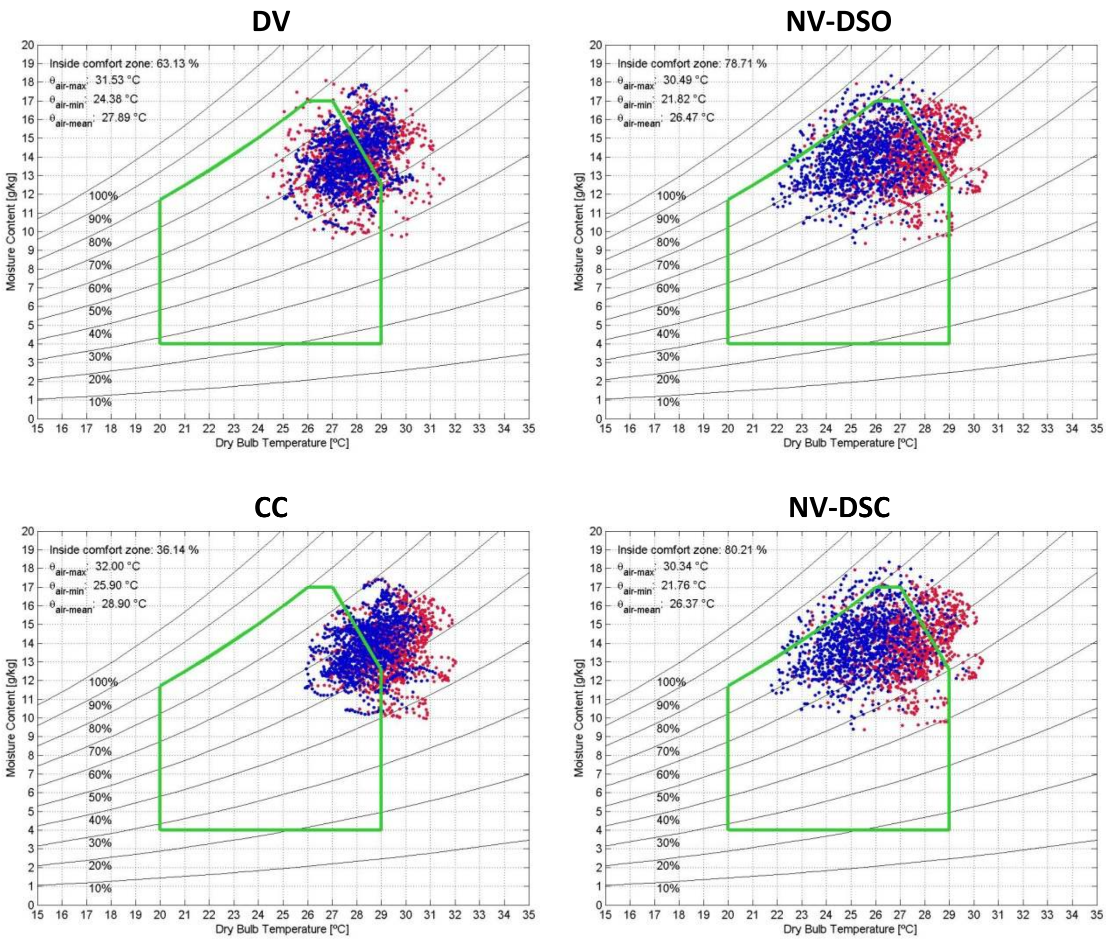


Figure 3.3.10: 19 Ma'ale Ha-Shihrur Street, psychrometric charts with Givoni's extended comfort zone for July-September (side rooms) under several ventilation scenarios. Red dots represent daytime values, blue ones – nighttime values

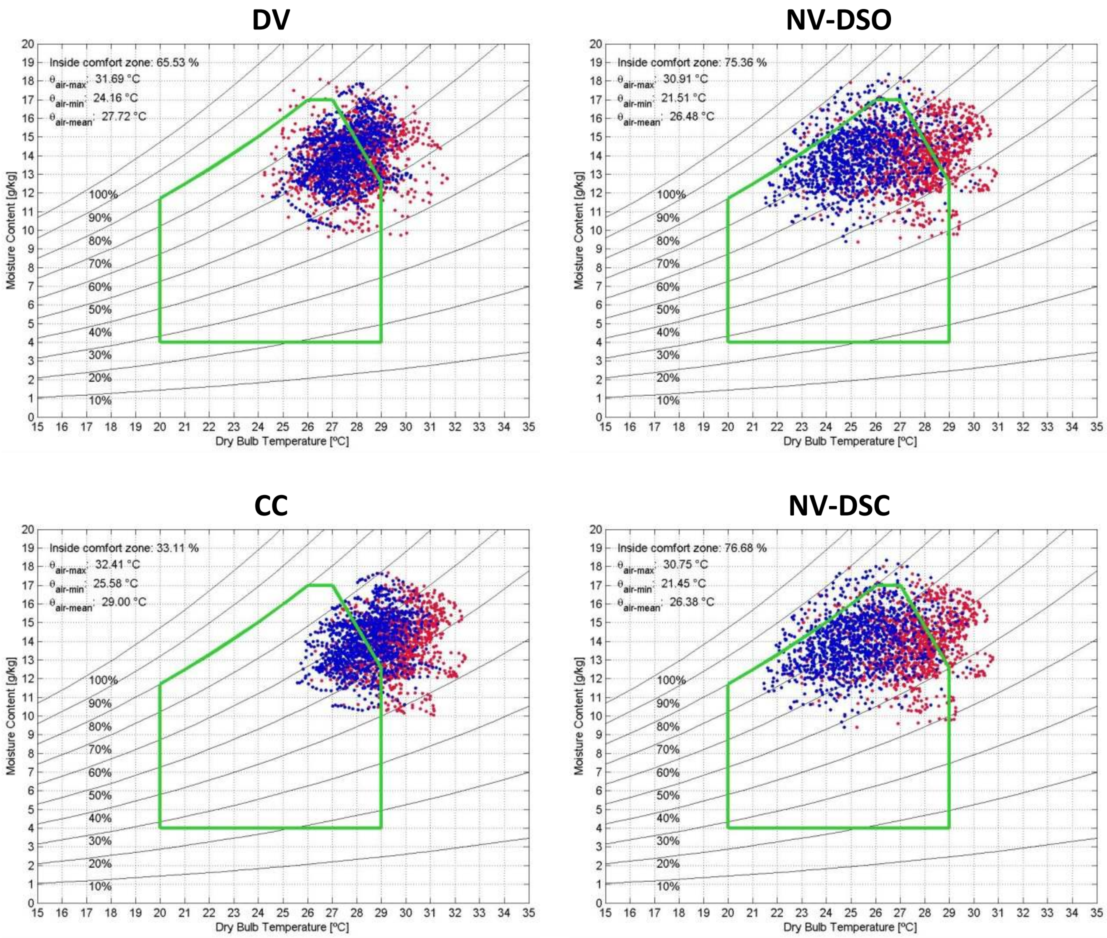


Figure 3.3.11: 19 Ma'ale Ha-Shihrur Street, psychrometric charts with Givoni's extended comfort zone for July-September (central hall) under several ventilation scenarios. Red dots represent daytime values, blue ones – nighttime values

- During the spring and autumn months (May, June and October, figure 3.3.12) substantial lowering of comfort rates was mainly a result of lower indoor temperatures during nighttime, this time mainly because of substantial decrease of the indoor temperature levels. During this period, higher relative humidity levels have only a minor impact on stepping outside of the thermal "comfort zone". This tendency was recorded in both the central hall and the side rooms.

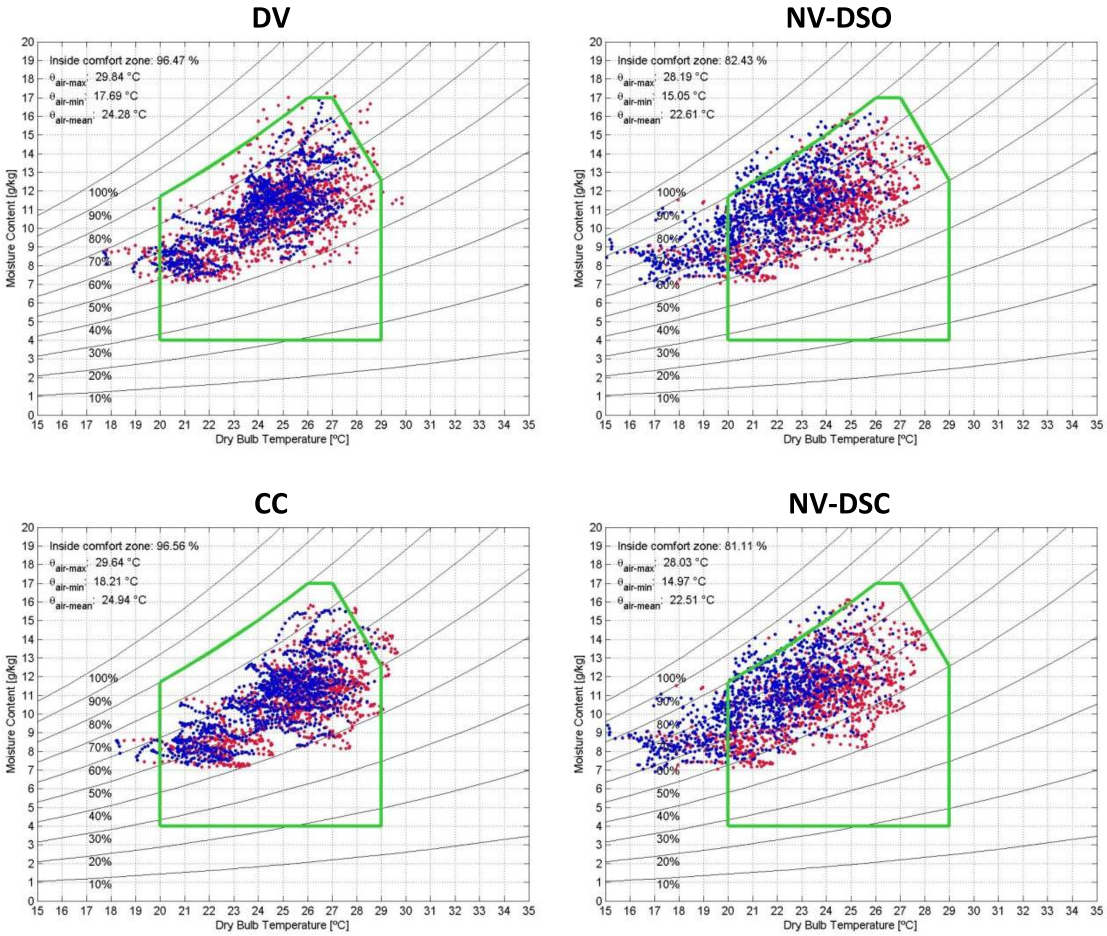


Figure 3.3.12: 19 Ma'ale Ha-Shihrur Street, psychrometric charts with Givoni's extended comfort zone for May, June and October (side rooms) under several ventilation scenarios. Red dots represent daytime values, blue ones – nighttime values

It should be added that the comfort rates that were produced using Givoni's model for both the central hall and the side rooms were almost similar, with slightly lower rates (between 1% to 3%) recorded in the central hall.

Another much anticipated finding is the negligible effect of shutter operation on comfort rates. Since the amount of direct sunlight that penetrates the rooms is marginal because of the surrounding Riwaq, it has almost no effect both on temperature levels and on comfort rates. This tendency is most evident when comparing the results of scenarios NV-DSO and NV-DSC. While scenario NV-DSC produces the lowest temperatures and thus the highest comfort rates during summer, scenario NV-DSO (in which the shutters are opened during daytime) produced only slightly higher temperatures and lower comfort rates.

4 DISCUSSION

In his book, *Climate Considerations in Building and Urban Design*, Baruch Givoni describes two main natural ventilation strategies that he finds applicable under hot weather conditions. The first, termed "Comfort Ventilation", refers to ventilation that is aimed at enhancing the comfort of the users through the introduction of flowing air into the room, thus cooling primarily the occupants, not necessarily the structure itself. The other, termed "Nocturnal Ventilative Cooling", is used during night in order to empty the space from hot air by the introduction of the relatively colder night air from the outside, resulting primarily in cooling of the structure (Givoni 1998, 185-191). Givoni describes this mechanism in the following way:

> When an insulated high-mass building is ventilated at night its structural mass is cooled by convection from the inside, bypassing the thermal resistance of the envelope. During the daytime, the cooled mass can serve as a heat sink, if the mass is of sufficient amount and surface area and is adequately insulated from the outdoors. It absorbs the heat penetrating into and generated inside the building, by radiation and natural convection, and thus reduces the rate of indoor temperature rise. To this effect, the building should be closed (unventilated) during the daytime to prevent the hotter outdoor air from heating the interior. As a result, the indoor maximum temperature in such buildings can be appreciably lower than either the outdoor maximum or the indoor maximum temperature of a similar building not ventilated at night. (Givoni 1998, 189)

In addition,

> From the climatic aspect nocturnal ventilative cooling would be preferable to comfort ventilation in regions where the daytime temperatures in summer are above the upper limit of the comfort zone – with indoor airspeed of about 1.5 m/s (300 fpm). This strategy is applicable mainly in regions with a diurnal temperature swing of more than 15°C (27°F), especially arid regions where the daytime temperatures are between 32 and 36°C (89.6-96.8°F) and the night temperatures are about or below 20°C (68°F) (to enable sufficient nocturnal cold storage). (Givoni 1998, 190-191)

Alongside, Givoni claims that

> Assuming that an indoor airspeed of 1-1.5 m/s (200-300 fpm) can be achieved […] comfort ventilation is applicable mainly in regions/seasons when the outdoor *maximum* air temperature does not

> exceed 28-32°C (82.4-89.6°F) even on "hot" days, depending on the acclimatization of the population. It is particularly applicable in regions where the diurnal temperature range is less than about 10°C (18°F). (Givoni 1998, 189)

Givoni's statements can be put into closer examination in this research. The hot-humid summer conditions in the coastal region of Israel (hot – but not "too hot" – outdoor temperatures, a relatively small diurnal range) can fit into the description given above for regions that are more suitable for comfort (i.e. daytime) ventilation strategy than nocturnal ventilative cooling strategy. At the same time, when reviewing Steven Szokolay's description of thermal comfort prospects in hot-humid climates, especially in view of his own thermal comfort model, one can arrive to a clearly different conclusion. Szokolay is more skeptic than Givoni regarding the possibility of maintaining thermal comfort under summer conditions, claiming that

> **Warm-humid climates** are the most difficult ones to design for. The temperature maxima may not be as high as in the hot-dry climates, but the diurnal variation is very small (often less than 5K), thus the 'mass effect' cannot be relied on. As the humidity is high, evaporation from the skin is restricted and evaporative cooling will be neither effective, nor desirable, as it would increase the humidity. Indirect evaporative cooling may be used, as it does not add moisture to the supply air and produces some sensible cooling […] The best the designer can do is to ensure that the interior does not become (much) warmer than the outside (it cannot be any cooler), which can be achieved by adequate ventilation removing any excess heat input. (Szokolay 2008, 69)

Due to our research methodology it is hard to determine accurately and reliably the mean indoor air speed in each room (see discussion in section 2.3.5). Nevertheless, by following Givoni's comfort zone definition (which is based on still air indoor conditions), it is yet possible to put into question the validity of his assertion (meaning, is comfort daytime ventilation the best ventilation strategy for the sample buildings). At the same time, it is also possible to try to explore to what extent the sample buildings could have maintained thermal comfort conditions under the best ventilation strategy, challenging Szokolay's pessimism. A third and last question that should be addressed in this respect, particularly in regard to Szokolay's predictions, is the applicability of Givoni's comfort model, compared with the other comfort models discussed earlier, to the specific subjects of our research.

4.1 30 Chelouche Street, Tel-Aviv-Jaffa

4.1.1 30 Chelouche Street - thermal performance of the structure

The pure thermal performance of the structure, which is independent of the way natural ventilation is used, could be discerned in this building by tracing recurring similarities in the average daily indoor temperature amplitude under the different ventilation scenarios (see section 3.1.1). The performance mechanism of the structure can be described in the following way:

- The Kurkar stones used for the walls' construction, while producing a relatively poor thermal insulation (assumed conductivity of 1.3W/mK), have high density and heat capacity values which are responsible for a slow heat flow from the outside, thus resulting in a relatively low difference between the daily highest and lowest temperatures.
- This property of the stone walls is also responsible for keeping indoor temperatures lower than the outdoor temperatures during daytime peak hours (11:00-17:00) when no daytime ventilation is applied. On the other hand, the same property results in nighttime temperatures which are substantially higher than the outdoor ones.
- The unoccupied space of the high pitched roof, separated from the rooms in the living floor, is functioning as a kind of thermal insulator, thus supporting the lowering of the daytime temperatures below the outdoor levels.

As seen in sections 3.1.1 and 3.1.2, it is clear that natural ventilation has a substantial effect on indoor temperatures (and thus on relative humidities and comfort levels). The overall recorded tendency was that during the examined months nocturnal ventilation resulted in much lower indoor temperatures compared with daytime ventilation and that the central hall was consistently warmer than the side rooms. This can be explained in the following way:

- Daytime ventilation causes hot air to enter the structure, resulting in indoor temperatures which are almost identical to outdoor conditions. The best way to release the added heat is by enabling air flow to the outside during the cooler nighttime hours. Therefore, blocking natural ventilation during daytime leads not only to cooler air temperatures during daytime but also during nighttime, assuming some sort of nighttime ventilation exists.

- Heat release through the building envelope (walls, roof) is limited here, though it exists during nighttime and has a traceable contribution to lowering the indoor temperatures. Since the nighttime air is usually cooler than the walls that absorb heat during daytime, it has a cooling effect on the building envelope (and thus on indoor conditions). Rooms with more exterior wall area per volume are therefore expected to be cooler than others. In the examined structure, this can be seen in the lower temperatures of the side rooms, compared with the central hall. Thus it can be argued that the central hall is more dependent on natural ventilation as a cooling mechanism than the side rooms (which enjoy higher rate of heat release through the building envelope), although in both cases natural ventilation (and especially nocturnal ventilation) is the basic and the more effective cooling method.

Here it is important to note that no direct correlation between lower indoor temperatures and higher comfort rates was found. On the contrary, under the specific characteristics of the site and the prevailing weather conditions it can be argued that in most cases lower indoor temperatures lead to lower comfort rates, as described in the next section.

4.1.2 30 Chelouche Street – applicability of different comfort models

Comparison between comfort rates, as produced by using each of the four comfort models, reveals the following:

- Substantial differences in comfort rates for similar periods, spaces and ventilation scenarios. These differences are more significant during summer, but exist also during the spring-autumn period.
- A non-consistent hierarchy of results from different ventilation scenarios during summer.
- Recurring hierarchy of results from different ventilation scenarios during spring-autumn.

Givoni's extended model, which was assumed to be the "best fitting" model for the specific location and setting, proves to produce the most plausible results, in comparison with all other models. This conclusion is based on the following findings:

- Szokolay's model produces unreasonably low comfort rates for the summer period (summer comfort rates do not rise above 9%), which are about ten times lower than the highest rates produced by another model (EN 15251). These relatively low rates are a direct result of Szokolay's definition for the upper air moisture content comfort limit (12g/kg), which produces over-sensitivity to high levels of relative humidity.
- The EN 15251 model produces higher comfort rates for the summer period compared to the spring-autumn period, while the other three models show the opposite tendency. Taken the prevailing outdoor conditions, it is highly unreasonable that the summer period would produce the best indoor comfort rates, which, according to the EN 15251 model and under certain ventilation scenarios, reach above 95%. It seems that the way this model overlooks high relative humidity levels as a source of discomfort renders it less suitable for hot and humid climates. Another problematic outcome of the EN 15251 definition is the somewhat surprising lower comfort rates of the nocturnal ventilation scenarios during summer. One would expect that under a comfort model, which entirely neglects relative humidity levels, these cooler scenarios will also score the highest summer comfort rates. The opposite outcome is a result of the lower temperature limit of the model, which, at least here, seems to be too high.

- The PMV and Givoni's models show some interesting similarities in their results. They both show a clear difference in the way the central hall and the side rooms are affected by the different ventilation scenarios, they both produce clearly higher comfort rates for the spring-autumn period and they both produce comfort rates which are reasonable. Nevertheless, it seems that the comfort rates range produced by the PMV model may be too low, especially during summer (4%-32%, in comparison with 58%-74% of Givoni's model).

Although it is hard to determine whether Givoni's results may convey a "real" representation of the expected human reaction to the specific settings under analysis, it is still reasonable to conclude, based on the results that were produced by all four models, that it is the most suitable comfort model for this type of analysis since it produces the most plausible result range. It is simultaneously important to remember, though, that since the comfort perception of the original users in the original building was never documented, Givoni's model may not describe it in full accuracy.

4.1.3 30 Chelouche Street – natural ventilation effect on thermal comfort

Generally speaking, the effect of nocturnal ventilation on indoor thermal comfort rates proves to be a negative one during the spring-autumn months, while daytime ventilation and limited aperture ventilation result in similar comfort rates. During the summer months, the results show that daytime ventilation leads to higher comfort rates than those produced by nocturnal ventilation, although, surprisingly enough, limited aperture ventilation (in which ventilation is not applied through the main windows) creates comfort rates which are similar or even higher than those recorded in all other ventilation scenarios. This tendency should be partly attributed to the specific definition of the comfort model that was chosen for closer analysis (Givoni's extended model).

The described correlation between natural ventilation and comfort rates could be explained in the following way:

- During the spring and autumn months, higher indoor temperatures, under the given outdoor conditions, do not cause trouble but comfort. Therefore, nocturnal ventilation, which constantly lowers indoor temperatures, leads directly to lower indoor comfort rates.
- During the summer months, limited aperture ventilation and daytime ventilation lead to higher indoor temperatures when compared with nocturnal ventilation. These higher indoor temperatures, especially during nighttime, do not produce decline in comfort rates because they are simultaneously responsible for the lowering of the relative humidity levels (since the air moisture content does not change). Under the specific conditions of the site, higher relative humidities had a stronger negative impact on comfort rates than higher temperatures, and therefore higher indoor temperatures do not lower comfort rate up to a certain degree.

While these findings describe the general tendencies found in all rooms, the performance of the central hall during summer should be examined more closely. Here a more complex relation between higher temperatures and relative humidity levels unfolds: contrary to the side rooms, the central hall shows a much lower difference in comfort values under different ventilation scenarios (8% in the central hall, 16% in the side rooms), with nocturnal ventilation producing almost similar comfort rates as the two other scenarios. Reasons for this finding should be attributed to the unique properties of the central hall:

- The central hall has a limited wall area facing the outside, which lowers its heat release during night when no or less ventilation exists.
- The central hall is affected by much lower air change rates, which makes the differences in the thermal conditions between the several ventilation scenarios more moderate.
- The central hall has relatively smaller window area, thus limiting the overheating caused by solar radiation. In other words, the central hall's overheating is more a result of its wall's heat capacity.

The above properties create two distinctly different nighttime indoor conditions scenarios – one relatively cool but humid, the other relatively hot but dry – which produce virtually equivalent comfort levels. Within this space only, nocturnal ventilation could be chosen as a preferable ventilation strategy.

4.2 35 Israel Me-Salant Street, Tel-Aviv-Jaffa

4.2.1 35 Israel Me-Salant Street - thermal performance of the structure

The pure thermal performance of the structure, which is independent of the way natural ventilation is used, could be discerned in this building by looking at the average daily indoor temperature amplitude under scenario CC, in which no natural ventilation exists (see section 3.2.1). The performance mechanism of the structure can be described in the following way:

- The Kurkar stones used for the walls' construction, while producing a relatively poor thermal insulation (assumed conductivity of 1.3W/mK), have high density and heat capacity values which are responsible for a slow heat flow from the outside, thus resulting in a relatively low difference between the daily highest and lowest temperatures.
- Unlike Central Hall houses with a tiled pitched roof, this building's roof is made out of a flat reinforced concrete slab which is relatively thin, thus has a relatively lower heat capacity with very poor thermal insulation properties. This makes the living floor's ceiling a weak spot during summer, especially during daytime, when direct sunbeams strike the roof surface. Its impact on indoor temperatures is evident much more in the central hall than in the side rooms because of the different geometric properties of the spaces: while the relation between external wall area and ceiling area is 1.88 in the side rooms, the same value in the central hall is 1.01. This makes the ceiling's role in affecting the indoor temperature more substantial in the central hall, thus leading to the exceptionally higher temperatures recorded in it during daytime. For the same reasons, temperatures in the central hall and the side rooms are almost the same during nighttime, when the impact of the direct sunbeams is non-existent.

As seen in sections 3.2.1 and 3.2.2, it is clear that natural ventilation has a substantial effect on indoor temperatures. The overall recorded tendency was that during the examined months nocturnal ventilation resulted in much lower indoor temperatures compared with daytime ventilation and that the central hall was consistently warmer than the side rooms. This can be explained in the following way:

- Daytime ventilation causes hot air to enter the structure, resulting in indoor temperatures which are almost identical to outdoor conditions. The best way to release the added heat is by enabling air flow to the outside during the cooler nighttime hours. Therefore, blocking natural ventilation during daytime leads not only to cooler air temperatures during daytime but also during nighttime, assuming some sort of nighttime ventilation exists.

- Heat release through the building envelope (walls, roof) is limited here, though it exists during nighttime and has a traceable contribution to lowering the indoor temperatures. Since the nighttime air is usually cooler than the walls and roof that absorb heat during daytime, it has a cooling effect on the building envelope (and thus on indoor conditions). Rooms with more exterior walls and roof area per volume are therefore expected to be cooler than others. In the examined structure, this can be seen in the lower temperatures of the side rooms, compared with the central hall.

4.2.2 35 Israel Me-Salant Street – applicability of different comfort models

Comparison between comfort rates, as produced by using each of the four comfort models, reveals the following:

- Substantial differences in comfort rates for similar periods, spaces and ventilation scenarios. These differences are more significant during summer, but exist also during the spring-autumn period.
- A non-consistent hierarchy of results from different ventilation scenarios during summer.
- Recurring hierarchy of results from different ventilation scenarios during spring-autumn.

Givoni's extended model proves to produce the most plausible results, in comparison with all other models. This conclusion is based on the following findings:

- Szokolay's model produces unreasonably low comfort rates for the summer period (summer comfort rates do not rise above 12.5%), which are about eight times lower than the highest rates produced by another model (EN 15251). These relatively low rates are a direct result of Szokolay's definition for the upper air moisture content comfort limit (12g/kg), which produces over-sensitivity to high levels of relative humidity.
- The EN 15251 model produces higher comfort rates for the summer period compared to the spring-autumn period, while the other three models show the opposite tendency. Taken the prevailing outdoor conditions, it is highly unreasonable that the summer period would produce the best indoor comfort rates, which, according to the EN 15251 model and under certain ventilation scenarios, reach even up to 99.97%. It seems that the way this model overlooks high relative humidity levels as a source of discomfort renders it less suitable for hot and humid climates. Another problematic outcome of the EN 15251 definition is the somewhat surprising lower comfort rates of the nocturnal ventilation scenarios during summer. One would expect that under a comfort model, which entirely neglects relative humidity levels, these cooler scenarios will also score the highest summer comfort rates. The opposite outcome is a result of the lower temperature limit of the model, which, at least here, seems to be too high.

- The PMV model shows a clear similarity in comfort rates pattern between the central hall and the side rooms. During summer, the nocturnal ventilation scenarios produce substantially higher comfort rates compared with the other two scenarios, while the daytime ventilation produces higher rates than the "no-ventilation" scenario. Thus, the PMV model shows a direct correlation between indoor temperatures and comfort rates, where lower indoor temperatures lead to higher comfort rates during summer (during the spring-autumn period the correlation is almost the complete opposite). Its weak spot may lie in the low comfort rates it produces (between 6% and 37% during summer), which seems a bit too low when compared with Givoni's model (between 58% and 77% during summer). This may be attributed to the model's sensitivity to higher relative humidity levels.

Again, it is hard to determine whether Givoni's results may convey a "real" representation of the expected human reaction to the specific settings under analysis. Nevertheless, it is still reasonable to conclude, based on the results that were produced by all four models, that it is the most suitable comfort model for this type of analysis since it produces the most plausible result range.

4.2.3 35 Israel Me-Salant Street – natural ventilation effect on thermal comfort

Generally speaking, the effect of nocturnal ventilation on indoor thermal comfort rates proves to be a negative one during the spring-autumn months, while daytime ventilation and no ventilation result in similar comfort rates. During the summer months, the results show that almost the same comfort rates are maintained under all ventilation scenarios – including the "no-ventilation" option. This surprising tendency should be partly attributed to the specific definition of the comfort model that was chosen for closer analysis (Givoni's extended model).

The described correlation between natural ventilation and comfort rates could be explained in the following way:

- During the spring and autumn months, higher indoor temperatures, under the given outdoor conditions, do not cause trouble but comfort. Therefore, nocturnal ventilation, which constantly lowers indoor temperatures, leads directly to lower indoor comfort rates.
- During the summer months, two distinctively different thermal scenarios lead to almost similar comfort rates. As can be seen in the corresponding psychrometric charts (section 3.3.4 above), under ventilation scenarios DV and CC nighttime indoor conditions are relatively hot and dry when compared to the nocturnal ventilation scenarios. The combination of higher indoor temperatures and lower relative humidities which results from scenarios DV and CC creates comfort rates equivalent to the opposite combination resulting from nocturnal ventilation. The reason for that is that higher indoor temperatures result in lowering the relative humidities below the upper relative humidity comfort limit of Givoni's model.

These findings describe the general tendencies found in all rooms. Nevertheless, it is important to note that during summer the comfort rates in the central hall are consistently lower than those of the side rooms under all ventilation scenarios. The highest difference was recorded under scenarios NV-DSC and CC, which are the two scenarios in which the external shutters are simulated as closed. This may lead to another conclusion, that comfort rates in the central hall are less affected by penetration of direct sun light into the space and more by the thermal properties of its structural envelope.

4.3 19 Ma’ale Ha-Shihrur Street, Haifa

4.3.1 19 Ma’ale Ha-Shihrur Street - thermal performance of the structure

The pure thermal performance of the structure, which is independent of the way natural ventilation is used, could be discerned in this building by looking at the average daily indoor temperature amplitude under scenario CC, in which natural ventilation levels are relatively negligible (see sections 3.3.1 and 3.3.2). The performance mechanism of the structure can be described in the following way:

- The limestone used for the walls' construction, while producing a relatively poor thermal insulation (assumed conductivity of 1.5W/mK), have high density and heat capacity values which are responsible for a slow heat flow from the outside, thus resulting in a relatively low difference between the daily highest and lowest temperatures.
- The limited diurnal temperature range when no ventilation is applied can be partly attributed to the closed indoor arcade (Riwaq), which surrounds the central hall and the side rooms. When its windows are closed, the Riwaq prevents the releasing of absorbed heat from the main rooms' walls to the cooler outdoor air, which results in substantially higher indoor temperatures when no natural ventilation is applied.
- Although the unoccupied space of the high pitched roof is functioning as a kind of thermal insulator, it seems that its contribution to the lowering of the indoor temperatures has only a minor effect on temperature levels compared with the Riwaq's impact, since indoor temperatures are still much higher than outdoor temperatures when no natural ventilation is applied.

Natural ventilation – even with relatively low air change rates – has a substantial effect on indoor temperatures (and thus on comfort levels) in this building. The overall recorded tendency was that during the examined months nocturnal ventilation resulted in much lower indoor temperatures compared with daytime ventilation. The reason is the warmer air that enters the building by applying daytime ventilation.

No substantial differences were recorded, though, between temperatures of the central hall and the side rooms, even when natural ventilation was applied. The main reason for that is the surrounding Riwaq, which performs as a thermal "buffer" for both the central hall and the side rooms, making the temperature range next to these rooms less "fluctuational" and differential.

4.3.2 19 Ma'ale Ha-Shihrur Street – applicability of different comfort models

Comparison between comfort rates, as produced by using each of the four comfort models, reveals the following:

- Substantial differences in comfort rates for similar periods, spaces and ventilation scenarios. These differences are more significant during summer, but exist also during the spring-autumn period.
- A non-consistent hierarchy of results from different ventilation scenarios during summer.
- Recurring hierarchy of results from different ventilation scenarios during spring-autumn.

Givoni's extended model proves to produce the most plausible results, in comparison with all other models. This conclusion is based on the following findings:

- Szokolay's model produces unreasonably low comfort rates for the summer period (summer comfort rates do not rise above 9%), which are about ten times lower than the highest rates produced by another model (EN 15251). These relatively low rates are a direct result of Szokolay's definition for the upper air moisture content comfort limit (12g/kg), which produces over-sensitivity to high levels of relative humidity.
- The EN 15251 model produces higher comfort rates for the summer period compared with the spring-autumn period (especially for the side rooms), while the other three models show the opposite tendency. Taken the prevailing outdoor conditions, it is highly unreasonable that the summer period would produce the best indoor comfort rates, which, according to the EN 15251 model and under certain ventilation scenarios, reach above 97%. It seems that the way this model overlooks high relative humidity levels as a source of discomfort renders it less suitable for hot and humid climates. Another problematic outcome of the EN 15251 definition is the somewhat surprising lower comfort rates of the nocturnal ventilation scenarios during summer. One would expect that under a comfort model which entirely neglects relative humidity levels, these cooler scenarios will also score the highest summer comfort rates. The opposite outcome is a result of the lower temperature limit of the model, which, at least here, seems to be too high.

- The PMV model shows a surprising dissimilarity in comfort rates pattern between the central hall and the side rooms, taken the almost similar temperature levels in these rooms. During summer, a substantial difference in comfort rates between the different ventilation scenarios exists in the central hall (nocturnal ventilation produces comfort rates between 30%-31%, daytime ventilation – 2%, and limited aperture ventilation – 0%), while in the side rooms all scenarios produce comfort rates between 26% and 32%. Though this tendency is more evident during summer, it exists also during spring-autumn. Another weak spot of this comfort model may lie in the low comfort rates it produces (between 0% and 32% during summer), which seems a bit too low when compared to Givoni's model (between 33% and 80% during summer). This may be attributed to this model's sensitivity to higher relative humidity levels.

Once more, it is hard to determine whether Givoni's results may convey a "real" representation of the expected human reaction to the specific settings under analysis. Nevertheless, it is still reasonable to conclude, based on the results that were produced by all four models, that it is the most suitable comfort model for this type of analysis since it produces the most plausible result range.

4.3.3 19 Ma'ale Ha-Shihrur Street – natural ventilation effect on thermal comfort

Generally speaking, the effect of nocturnal ventilation on indoor thermal comfort rates proves to be a negative one during the spring-autumn months, while daytime ventilation and limited aperture ventilation result in almost similar comfort rates. During the summer months, the results show clearly that nocturnal ventilation leads to higher comfort rates than those produced by daytime ventilation, and that limited aperture ventilation produced much lower comfort rates than the other two ventilation strategies.

The described correlation between natural ventilation and comfort rates could be explained in the following way:

- During the spring and autumn months, higher indoor temperatures, under the given outdoor conditions, do not cause trouble but comfort. Therefore, nocturnal ventilation, which constantly lowers indoor temperatures, leads directly to lower indoor comfort rates.
- During the summer months, higher temperatures lead to lower comfort rates. In this building, the negative effect of high relative humidity is marginal because relative humidity levels are kept most of the time under the upper comfort limit that was suggested by Givoni.

These findings describe the general tendencies found in all rooms. It is important to note that comfort rates in the central hall and in the side rooms were almost similar under all scenarios (during both summer and spring-autumn), a direct result of their similarity in indoor temperatures.

4.4 The Central Hall House building type

The three sample buildings that were analyzed above can all be described, in spite of their special individual characteristics, as Central Hall houses, since all of them consist of a similar layout in which a main central hall is linked to smaller living rooms which are located along both of its longer walls. It is therefore interesting to explore whether any similarities in the thermal performance of these buildings exist, including the effect natural ventilation has on them. In order to answer the question, two kinds of cross comparisons were used: comparison of indoor temperatures (in relation to the outdoor temperatures) and comparison of thermal comfort rates (according to Givoni's model).

4.4.1 Central Hall House building type - thermal performance of the structure

Since the outdoor thermal conditions in each of the three sample buildings were similar but not identical, comparing their indoor temperatures should take into account the dissimilarities in outdoor conditions. This is done by calculating the average hourly temperature difference between the examined space and the outdoor space for the summer and the spring-autumn periods. Summer results for the central hall appear in figure 4.4.1 and for the side rooms in figure 4.4.2. Since spring-autumn results show the same tendencies, they are not shown here.

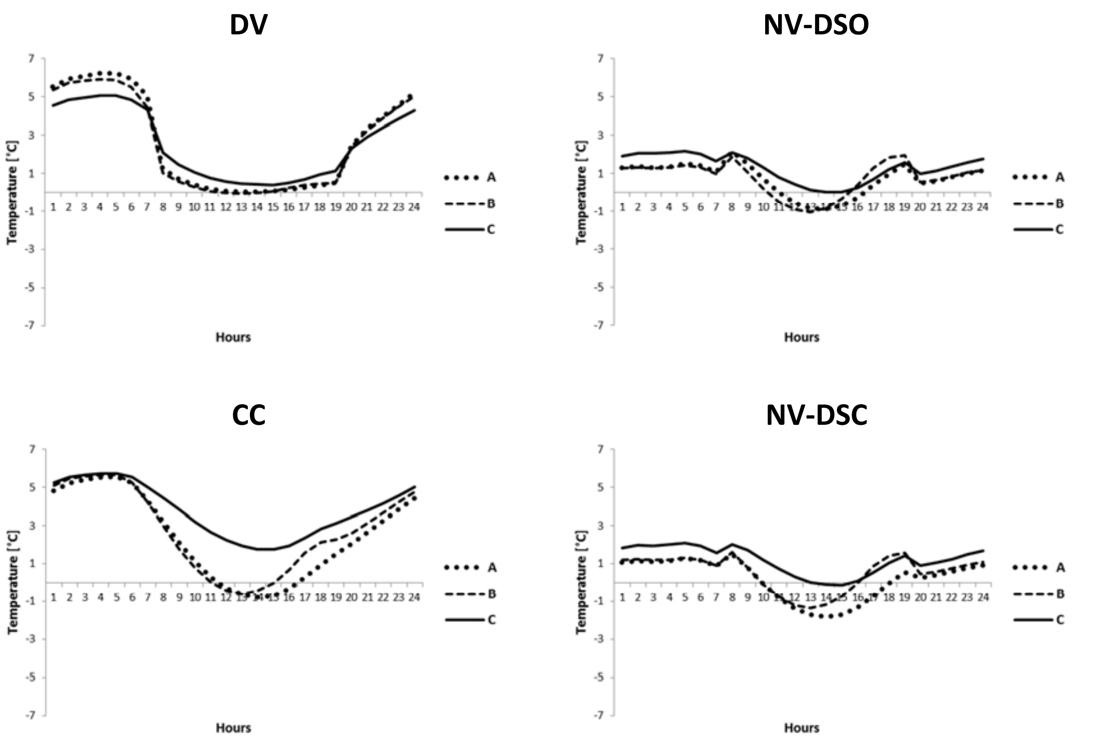


Figure 4.4.1: Average hourly temperature difference between indoor and outdoor temperatures during summer, central hall of the three sample buildings, under different ventilation scenarios. Building A is 30 Chelouche Street, B – 35 Israel Me-Salant Street, and C – 19 Ma'ale Ha-Shihrur Street

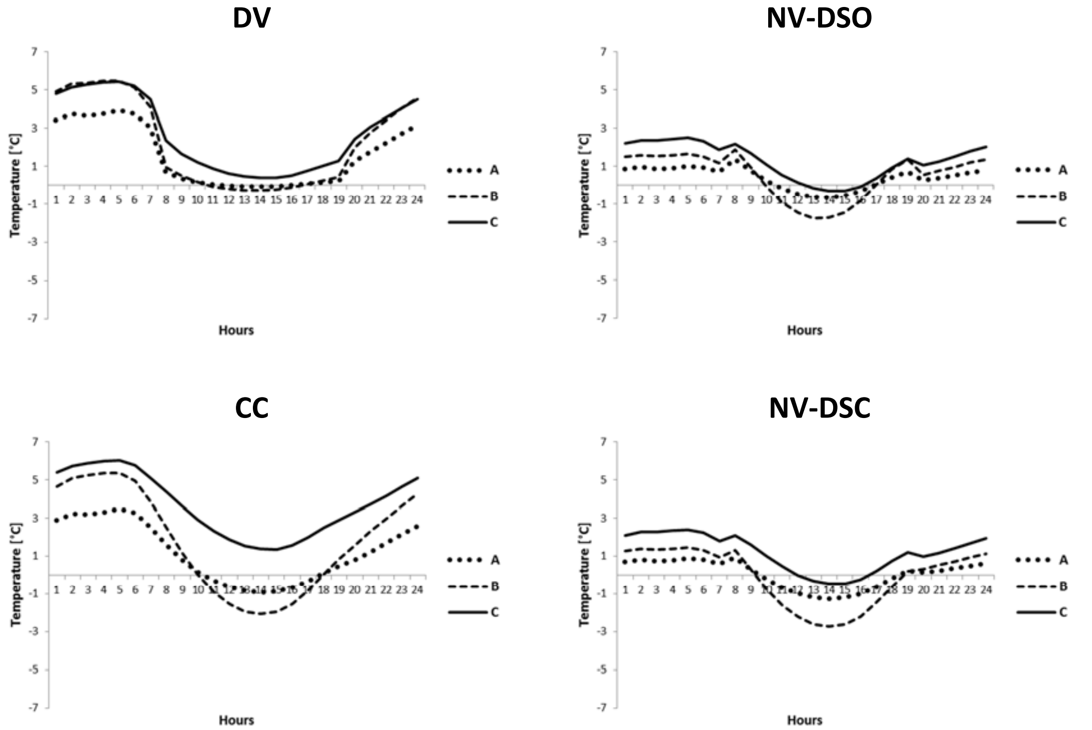


Figure 4.4.2: Average hourly temperature difference between indoor and outdoor temperatures during summer, side rooms of the three sample buildings, under different ventilation scenarios. Building A is 30 Chelouche Street, B – 35 Israel Me-Salant Street, and C – 19 Ma'ale Ha-Shihrur Street

It is quite clear that under daytime and nocturnal ventilation, both the central hall and the side rooms show a 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. It is therefore possible to conclude the following:

- Under daytime ventilation, daytime indoor temperatures and outdoor temperatures are almost similar in both the central hall and the side rooms, while during nighttime their indoor temperatures are substantially higher than outside.
- Under nocturnal ventilation, daytime indoor temperatures are generally lower than outdoor temperatures in both the central hall and the side rooms. Nighttime indoor temperatures are slightly higher than outside in all rooms.
- Without natural ventilation, indoor temperatures are usually at their highest peak during both daytime and nighttime.

4.4.2 Central Hall House building type - indoor thermal comfort according to Givoni's extended comfort zone

Comparing the comfort rates produced for each of the sample buildings according to Givoni's comfort model (figure 4.4.3) 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 model truthfully describes the comfort perception of the original users, this may lead to the conclusion 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.

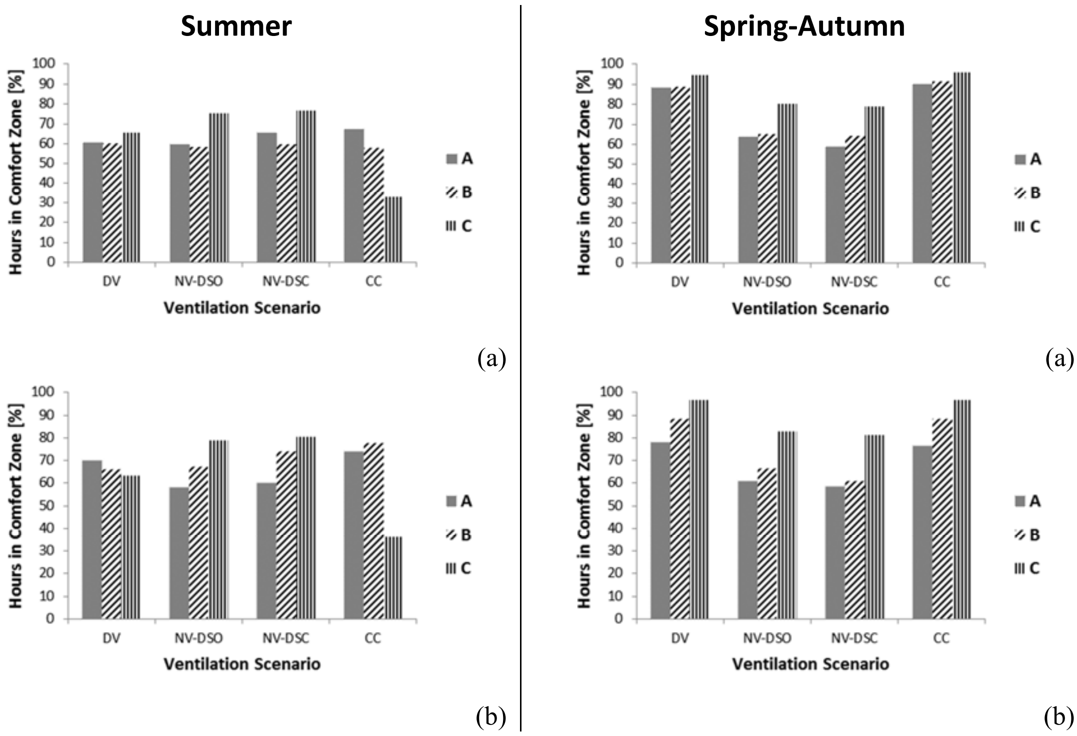


Figure 4.4.3: Thermal comfort rate comparison according to Givoni's extended comfort zone under different ventilation scenarios: central hall (a) and side rooms (b). Building A is 30 Chelouche Street, B – 35 Israel Me-Salant Street, and C – 19 Ma'ale Ha-Shihrur Street

A more detailed list of findings is summarized below:

- Daytime ventilation had almost similar effect on comfort rates in all three buildings in both the central hall and side rooms. One exception is the side rooms during the spring-autumn period, a possible outcome of the substantial differences in indoor nighttime temperatures between the three buildings.

- Under nocturnal ventilation, building C (19 Ma'ale Ha-Shihrur Street) enjoys much higher comfort rates than the corresponding rates in the two other buildings. Since Givoni's model uses an upper comfort limit of 80% relative humidity, reviewing the percentage of time in which indoor conditions were under this limit (figure 4.4.4) may produce a partial explanation for differences in discomfort rates (mainly during summer nights, when discomfort is highly increased by higher relative humidity levels because of the already relatively high indoor temperatures). Here it seems that the difference in summer comfort rates between the three sample buildings may be directly attributed to the substantially lower relative humidity levels that were recorded in building C (during spring-autumn the difference lies in the substantially higher night temperatures in building C). This may lead to the conclusion that discomfort sensation in the Central Hall building type – under summer nocturnal ventilation – may be highly sensitive to relatively narrow variations in indoor relative humidity levels.

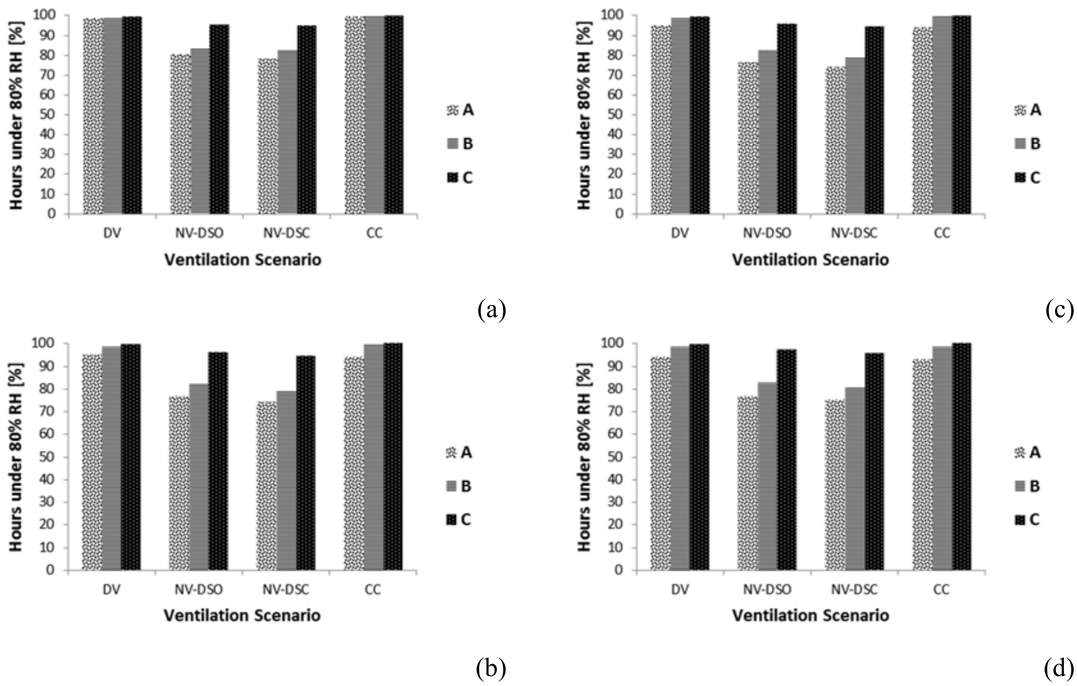


Figure 4.4.4: Percentage of time with relative humidity under 80% under different ventilation scenarios: central hall, July-September (a), side rooms, July-September (b), central hall, May, June and October (c) and side rooms, May, June and October (d). Building A is 30 Chelouche Street, B – 35 Israel Me-Salant Street, and C – 19 Ma'ale Ha-Shihrur Street

- No ventilation (or limited aperture ventilation) produced the most varying results in all three buildings, especially during summer. It is therefore hard to draw any general conclusions about the Central Hall building type based on these results.

5 CONCLUSION

The Central Hall building type is a quasi-modern vernacular phenomenon that had an exceptional lasting prominence along the east coast of the Mediterranean Sea since the 1870s. This research was aimed at understanding the thermal performance characteristics of this building type during the six warmest months of the year by simulating indoor conditions in three existing structures in Tel Aviv-Jaffa and Haifa. Summer months were of the highest interest since it is believed that under the prevailing weather conditions of this yearly period it is hard to provide indoor thermal comfort conditions without an excessive use of mechanical aids.

Regarding the thermal performance of the structures, it can be argued that:

- The high thermal mass of the stone walls had a positive role in maintaining relatively low indoor temperatures during the summer's warmest hours. This tendency was enhanced by the role of the enclosed space under the high pitched roof, which functioned as an insulating buffer.
- Nocturnal ventilation had a clear positive effect on substantially reducing daytime indoor temperatures during summer, while keeping nighttime temperatures at a relatively low level.
- Daytime ventilation resulted in temperature levels similar to outdoor conditions during daytime, with substantially higher temperatures during nighttime. Nevertheless, even this ventilation strategy produced lower temperature levels compared with no ventilation or limited aperture ventilation.
- The central hall was 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 faced substantially lower air change rates than the side rooms when no surrounding arcade (a rare feature in Central Hall houses) exists.
- The open round apertures help in cooling the indoor space during nighttime, although their role as a ventilation tool is limited compared with the rectangular windows.

Regarding the thermal comfort conditions, based on Givoni's extended comfort definition, it can be argued that:

- Natural ventilation (both daytime and nocturnal) helped in maintaining relatively reasonable comfort rates during summer (around 60%-70%). Nocturnal ventilation had a negative effect on comfort rates during the spring-autumn period.
- 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 hard to determine 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.
- It is hard to determine whether the central hall consistently produced better or worse comfort rates than the side rooms.
- Since Givoni's model, which was used here for closer assessment, does not take into account the positive effect that higher wind speeds might have on comfort sensation, it is believed that comfort rates during summer could actually be higher than suggested here, mainly when daytime ventilation is applied.
- Using Givoni's model, no consistent relation between low indoor temperatures and high summer comfort rates was found. This should be attributed to the high relative humidity levels of the Israeli coastal plain, which have a significant effect on discomfort levels, especially during nighttime.

While the above findings address the direct underlying research questions, this research can provide some more general insights into the notions of thermal comfort, vernacular architecture and their interrelations:

- Although there are some good reasons to believe that the Central Hall building type proved to provide more than reasonable indoor conditions for its original builders and users (conditions that could be easily enhanced today with relatively minimal efforts), it seems that the main driving force behind its formal development was not its thermal properties. The central hall was regarded as the most important space of the house and was the mostly occupied space of the house throughout the day. Nevertheless, our findings show that the thermal performance of the central hall was not better – and usually worse – than that of the side rooms during summer. This may lead to the conclusion that the spatial scheme behind it had much more to do with formal and cultural conventions than with its sheer thermal performance.

- Under the prevailing weather conditions of the Israeli coastal plain, it is quite clear that the selection of a certain comfort model can have a substantial impact on the analyzed comfort rates and thus on any conclusions drawn from them. It is also evident that widely used comfort models that may be suitable for other climates are hardly fitting to the conditions under question here. This may lead to the conclusion that at least for the hot and humid climate that was examined in this research some kind of further research is needed in order to determine more precisely which thermal comfort model is the most suitable.

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 regarding the Central Hall building type and its performance under hot and humid climate. Nevertheless, the simulation tool that was used here demonstrates the potential of applying similar techniques, which can shed more light on the physical performance of past structures, in historic architectural research in general.

6 REFERENCES

Al-ajmi, FF, Loveday, DL, Bedwell, KH, and Havenith, G: 2008, Thermal insulation and clothing area factors of typical Arabian Gulf clothing ensembles for males and females: Measurements using thermal manikins, *Applied Ergonomics* **39**: 407-414.

Alef, Y: 1995, *Documentation File of the House in 19 Ma'ale Ha-Shihrur Street, Haifa*, Israel Antiquities Authority and Haifa Municipality, Haifa.

Aleksandrowicz, O: 2010, Kurkar, cement, Arabs, Jews: How to construct a Hebrew city [in Hebrew], *Teorya ve-Bikoret* (Theory and Criticism) **36**: 61-87.

ASHRAE: 2004, *ASHRAE Standard 55-2004: Thermal Environmental Conditions for Human Occupancy*, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc, Atlanta.

Ausliciems, A and Szokolay, SV: 2007, *Thermal Comfort (PLEA Note 3)*, PLEA, Cambridge.

Banham, R: 1984, *The Architecture of the Well-tempered Environment* (second edition), Steensen Varming, Australia.

Bar-Or, A: 2007, *Documentation File of the House in 35 Israel Me-Salant Street, Tel Aviv-Jaffa*, Documentation file produced for Tel Aviv-Jaffa's Conservation of Buildings and Sites Department, Tel Aviv.

Baruch, A: 1936, The Climate of Tel Aviv [in Hebrew], in A Druyanov (ed), *Tel-Aviv Book: First Volume*, Tel-Aviv Book Committee, Tel Aviv, pp. 411-434.

CEN: 2007, *European Standard EN 15251:2007*: *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*, European Committee for Standardization, Brussels.

CIBSE: 2006, *CIBSE Guide A: Environmental Design*, The Chartered Institution of Building Services Engineers, London.

de Dear, RJ, Brager, G and Cooper, D: 1997, *Developing an Adaptive Model of Thermal Comfort and Preference*, *Final report*, *ASHRAE RP-884*, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc, Atlanta.

Dow, M: 1996, *The Islamic Baths of Palestine*, Oxford University Press, Jerusalem.

Eckstein, Y and Simmons, G: 1977, Measurements and Interpretation of Terrestrial Heat Flow in Israel, *Geothermics* **3-4**(6): 117-142.

EDSL: 2010, *EDSL Tas v. 9.1.4.2*, www.edsl.net [retrieved October 2010].

Fanger, OP: 1970, *Thermal Comfort: Analysis and Applications in Environmental Engineering*, Danish Technical Press, Copenhagen.

Fuchs, R: 1998 (1), The Palestinian Arab House Reconsidered, Part B: The Changes of the 19th Century [in Hebrew], *Cathedra* **90**: 53-86.

Fuchs, R: 1998 (2), The Palestinian Arab House and the Islamic Primitive Hut, *Muqarnas - an Annual for Islamic Art & Architecture* **15**: 157-177.

Givoni, B: 1998, *Climate Considerations in Building and Urban Design*, Van Nostrand Reinhold, New York.

Hirsch, M et al.: 2004, *Air Conditioning Survey in Israel: Potential for Economization and Implementation Policy* [in Hebrew], Technion - Israel Institute of Technology, Haifa.

ISO: 2005, *ISO 7730: Ergonomics of The Thermal Environment −Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*, International Organization for Standardization, Geneva.

Khater, A: 2003, Building Class: Emigration, the Central Hall House and the Construction of a Rural Middle Class in Lebanon, 1890-1914, in MF Davie (ed), *La Maison Beyrouthine aux Trois Arcs. Une architecture bourgeoise du Levant*, ALBA, Beirut, pp. 371-393.

Koranteng, C and Mahdavi, A: 2011, An Investigation into the Thermal Performance of Office Buildings in Ghana, *Energy and Buildings* **43** (2011): 555-563.

Mahdavi A et al.: 2007, Analyzing Traditional Buildings via Empirically Calibrated Building Performance Models, *Proceedings: Building Simulation 2007*, Beijing, pp. 71-78.

Mahdavi, A and Orehounig, K: 2008, An Inquiry into the Thermal, Acoustical, and Visual Aspects of Indoor Environment in Traditional Hammāms, *International Journal of Architectural Research* **3**(2): 136-149.

MathWorks: 2011, *MATLAB v. 7.11.0.584 (R2010b)*, www.mathworks.com [retrieved June 2011].

Meimar, N: 2008, *Documentation File of the House in 30 Chelouche Street, Tel Aviv-Jaffa*, Documentation file produced for Tel Aviv-Jaffa's Conservation of Buildings and Sites Department, Tel Aviv.

Meir, IA et al.: 2004, The Vernacular and the Environment: Towards a Comprehensive Research Methodology, paper presented in *The 21th Conference on Passive and Low Energy Architecture*, Eindhoven.

Meteotest: 2010, *Meteonorm v. 6.0*, www.meteotest.ch [retrieved October 2010].

Meyer-Brodnitz, M and Fuchs, R: 1989, The Emergence of the Central Hall House Type in the Context of 19th Century Palestine, *in* JP Bourdier and N. AlSayyad (eds), *Dwellings, Settlements & Tradition*, University Press of America, Lanham, pp. 403-424.

Nicol, F and Humphreys, M: 2010, Derivation of the adaptive equations for thermal comfort in free-running buildings in European Standard EN15251, *Building and Environment* **45**(2010): 11-17.

Pataki, MHA: 1935, Yafo – Tel-Aviv [in Hebrew], *Ha-Binyan Ba-Mizrah Ha-Karov* (The Building in the Near East) **2**: 5-9.

Pröglhöf, C: 2004, *Aspekte der natürlichen Fensterlüftung – eine Fallstudie*, Diploma thesis, Vienna University of Technology.

Ragette, F: 1974, *Architecture in Lebanon: The Lebanese House during the 18th and 19th Centuries*, American University of Beirut, Beirut.

Rudofsky, B: 1964, *Architecture without Architects: A Short Introduction to Non-Pedigreed Architecture*, Doubleday & Company, New York.

Saliba, R: 2004, The Genesis of Modern Architecture in Beirut, *in* Jamal Abed (ed), *Architecture Re-introduced: New Projects in Societies in Change*, The Aga Khan Award for Architecture, Geneva, pp. 23–34.

Schaffer, Y: 1991, *Technologies-Construction Techniques in Tel-Aviv-Jaffa during the 19th and 20th centuries* [in Hebrew], private survey conducted for Tel Aviv Institute of Research.

Steadman, RG: 1994, Norms of Apparent Temperature in Australia, *Australian Meteorological Magazine* **43** (1994): 1-16.

Szokolay, SV: 2008, *Introduction to Architectural Science: The Basis of Sustainable Design* (second edition), Architectural Press, Oxford.

Yelin, D: 1900, City of Orange Groves [in Hebrew], *Ha-Melitz* **235**: 3.

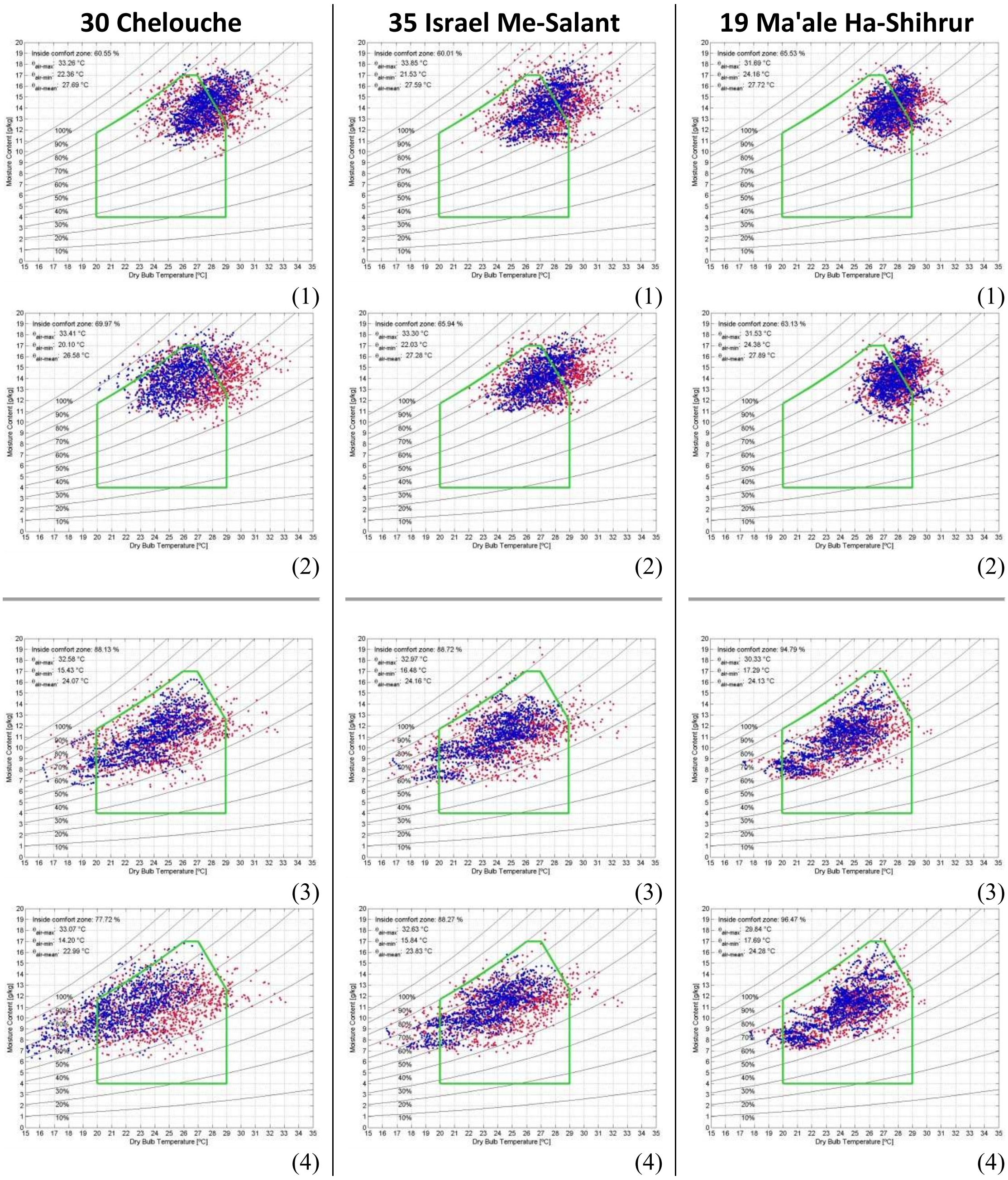
Wasserman, I: 2002(?), *Assessment of The Durability of Two Natural Stones Intended for the Conservation of The Historical Masonry Sea Wall in The Old Town of Acre***,** www.arcchip.cz/w10/w10_wasserman.pdf [retrieved December 2010]

Wang, L and Wong, NH: 2009, Coupled Simulations for Naturally Ventilated Rooms Between Building Simulation (BS) and Computational Fluid Dynamics (CFD) for Better Prediction of Indoor Thermal Environment, *Building and Environment* **44** (2009): 95-112.

Wang, L: 2006, *The Conflation of Building Simulation (BS) and Computational Fluid Dynamics (CFD) for the Prediction of Thermal Performance of Façade for Naturally Ventilated Residential Buildings in Singapore*, PhD diss., National University of Singapore.

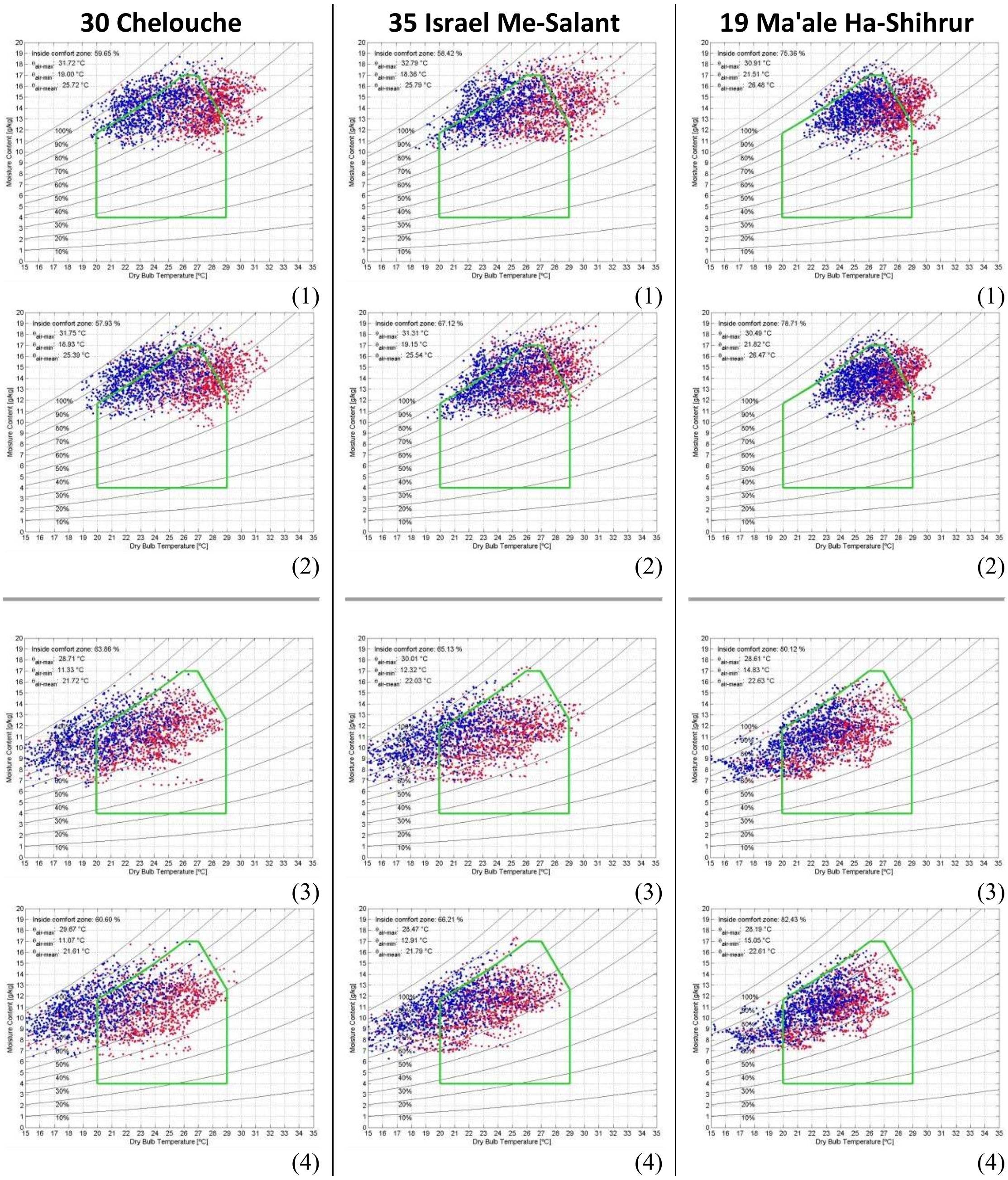
7 APPENDICES

7.1 Cross comparison of psychrometric charts, scenario DV



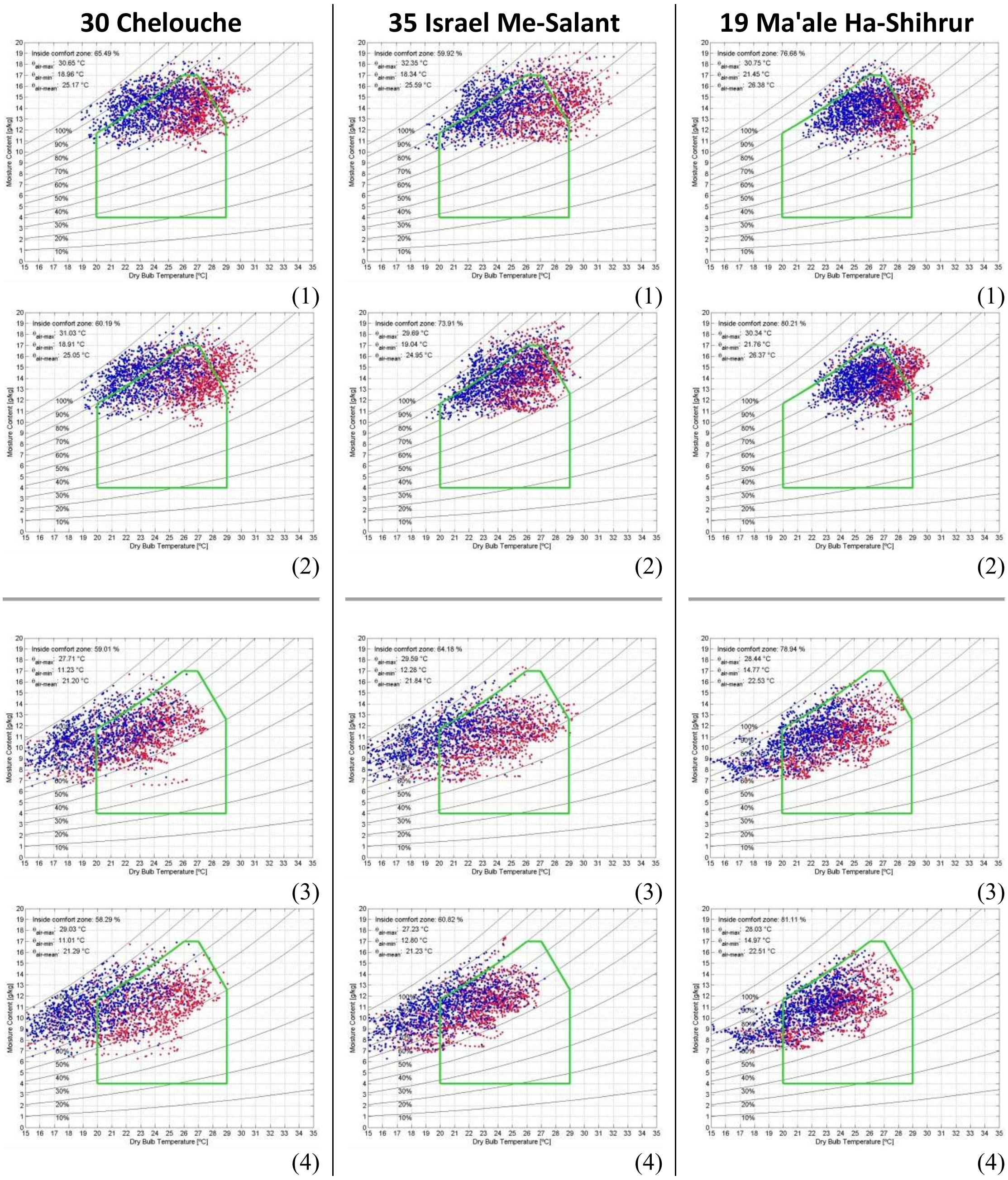
Psychrometric charts with Givoni's extended comfort zone definition under ventilation scenario DV: central hall, July-September (1), side rooms, July-September (2), central hall, May, June and October (3) and side rooms, May, June and October (4)

7.2 Cross comparison of psychrometric charts, scenario NV-DSO



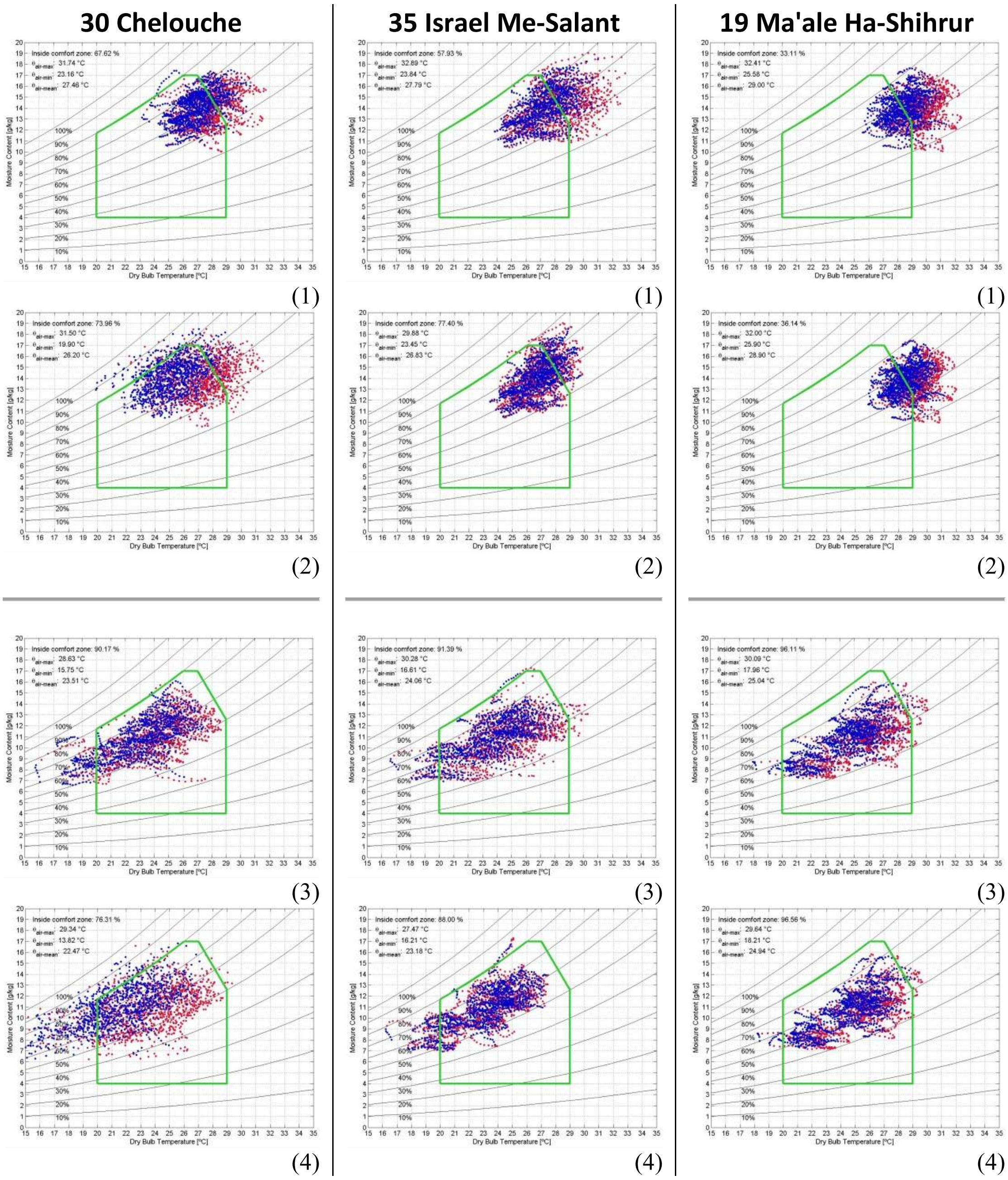
Psychrometric charts with Givoni's extended comfort zone definition under ventilation scenario NV-DSO: central hall, July-September (1), side rooms, July-September (2), central hall, May, June and October (3) and side rooms, May, June and October (4)

7.3 Cross comparison of psychrometric charts, scenario NV-DSC



Psychrometric charts with Givoni's extended comfort zone definition under ventilation scenario NV-DSC: central hall, July-September (1), side rooms, July-September (2), central hall, May, June and October (3) and side rooms, May, June and October (4)

7.4 Cross comparison of psychrometric charts, scenario CC



Psychrometric charts with Givoni's extended comfort zone definition under ventilation scenario CC: central hall, July-September (1), side rooms, July-September (2), central hall, May, June and October (3) and side rooms, May, June and October (4)