THE IMPACT OF BUILDING CLIMATOLOGY ON ARCHITECTURAL DESIGN: A SIMULATION-ASSISTED HISTORICAL CASE STUDY

Or Aleksandrowicz[1,2], Ardeshir Mahdavi[1]
[1]Department of Building Physics and Building Ecology, Vienna University of Technology, Vienna, Austria
[2]Faculty of Architecture and Town Planning, Technion - Israel Institute of Technology, Haifa, Israel

ABSTRACT

This study focuses on the design of a university building in Tel Aviv during the 1960's through a combination of building simulation and historical research. The combined methodology was used for tracing the way knowledge in building climatology was implemented by the building's architects during its design, and for assessing the effects of their proclaimed climatic intentions on the building's indoor conditions. The simulation helped to affirm that the main climatic features of the original design – especially the clever massing of the building and the design of its sun protections – had a positive effect on the building's indoor climate.

INTRODUCTION

Historical research of buildings usually confines itself to relatively conservative research methods, like on-site documentation, archival research, and personal interviews. Until now, not much attention has been given to the application of computational simulation tools in the writing of architectural history, even though such tools are capable of expanding our understanding of historic architecture. Building simulation can be applied for the thermal analysis of climatically-adapted traditional buildings (Aleksandrowicz and Mahdavi 2012), as well as in historical research of modern structures. Modern architecture is unique in the way it evolved in parts out of purported concern to the climatic aspects of construction, supported by an increasingly available scientific knowledge in building physics. Computational performance tools can thus be used also for evaluating the impact of building climatology research on architectural design and for assessing the congruence between manifested design intentions and actual performance; this also applies to cases in which the structures under investigation have been extensively modified or even demolished.

In this study, thermal building simulation was applied for exploring the relation between building climatology and the design of the Gilman Building, a modern university building located at the heart of Tel Aviv University campus (32.112 N, 34.805 E, 39 m above sea level). It was designed during 1963 and built between 1964 and 1965 by Werner Joseph Wittkower (1903-1997), a local pioneer of building climatology and the building's architect of record, and Israel Stein (b. 1934), who was the building's architect in charge. Their design employed several passive methods for maintaining agreeable indoor conditions and for preventing summer overheating. Using a dynamic building energy simulation tool, the climatic effects of the design and the way it integrated knowledge in building climatology were analysed. The results suggest that the Gilman Building can be regarded as a fine example of an intelligent design that successfully and systematically exploited passive cooling strategies and scientific knowledge. However, the results also reveal the limits of such passive design under the climatic conditions of Israel's Coastal Plain.

HISTORICAL BACKGROUND

Wittkower can be described as the unrecognized founder of building climatology research in Mandatory Palestine, and later in Israel. His analytical and practical works in the field during the 1940's and the first half of the 1950's had no precedent, as well as no contemporaneous equivalents. As an active architect, Wittkower was aware of the need of building climatology to provide scientifically sound design guidelines, focusing on a limited set of major questions like building orientation, building massing, window size and orientation, shading design, and wall and roof composition; among these issues, he found the question of building orientation the fundamental of all.

Wittkower was the first architect in Palestine to advocate a north-south orientation of buildings because of the much lesser insolation of northern and southern walls during summer. His hypothesis, which contrasted with the contemporary habit among local architects to orient the main building facade to the prevalent western winds, was that the protection of the building envelope from direct solar radiation is far more significant for maintaining indoor summer comfort than optimizing the rapid flow of air through the building. This hypothesis was tested by a team of experts gathered by Wittkower in 1946 (Feige et al. 1952). After monitoring identical unoccupied residential buildings of different orientations, they concluded that a north-south orientation (in contrast to east-west orientation) produces much lower indoor temperatures during summer in the country's Coastal Plain. This conclusion was eventually received as a prevalent norm in Israel's architecture of the 1950's and 1960's (Hashimshoni 1962). In spite of his own preference for a north-south orientation, Wittkower's own master plan for the Tel Aviv University campus (conceived in the late 1950's in cooperation with architects Dov Karmi, Arieh El-Hanani, and Nahum Salkind) dictated the climatically problematic east-west orientation for the Gilman Building (alongside three other buildings), probably in order to better define the campus' outdoor spaces.

Building massing

The Gilman Building was originally built with two main floors, each of about 3500 m^2, and a basement floor of about 3100 m^2. It consisted of two rectangular wings, northern and southern, connected through a single corridor (or a "bridge"); each wing was arranged around two non-identical rectangular courtyards. A third floor was designed in 1972 and built on top of the second floor in 1974-75, following the same layout of the original floors.

Three major climatic concerns, in descending order of importance, were given close attention during the design of the Gilman Building: the first and foremost was building orientation; the second was the ensuing need for sun protections; and the third and the relatively less discussed was the composition of the building envelope and its insulating properties.

Building orientation posed the first difficulty for the designers. It seems that the campus planners (among them Wittkower) were aware of the climatic weak point in their plan, and therefore suggested to arrange all the campus buildings that were oriented to east and west around courtyards or "patios" (Figure 1). This architectural feature, which was applied also to the Gilman Building, enabled to maximize the number of rooms that could face the preferable directions of north or south, while orienting spaces of lesser importance to east and west. The courtyards were thus used for transforming the generic rectangular slab into an articulated set of perpendicular "stripes", while securing a neat and unobstructed exterior.

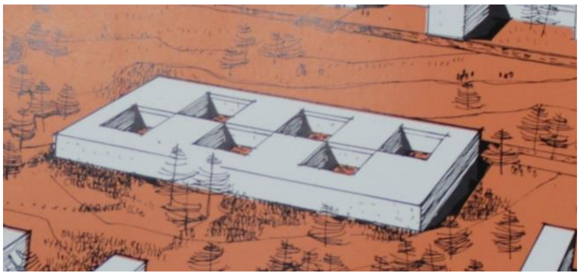

Figure 1: Gilman Building as it appeared in an artist rendition of the proposed Tel Aviv University campus (Tel Aviv University 1962)

Based on a similar principle, Wittkower and Stein further developed the idea of mass articulation and divided the Gilman Building into two detached wings, each one arranged around courtyards (Figure 2), in a way that further increased the number of rooms oriented to the north and south. The most important spaces of the building (the lecture halls and classrooms) were arranged only in north and south facing spaces, while service areas and smaller rooms (seminar rooms and offices) were distributed along the eastern and western facades (Figure 3).

Figure 2: Aerial view of the Gilman Building during construction of its northern wing, 1965, a detail of a larger photograph (Tel Aviv University Archive)

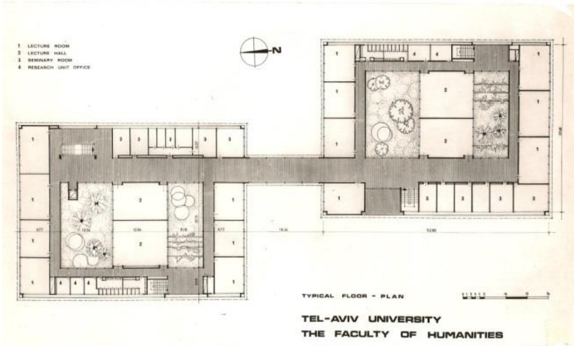

Figure 3: Typical floor plan of the Gilman building, a presentation plan, 1963 (courtesy of Israel Stein)

Although air conditioning was an integral part of the original design, the Tel Aviv University lacked at that time the resources for buying and installing the designed system. Wittkower and Stein were aware of this constraint and therefore paid close attention to naturally ventilating the building. The building's location was almost ideal for natural ventilation, at one of the highest points in northern Tel Aviv, with very little obstruction from adjacent buildings. Thus, the arrangement of spaces around courtyards was not only intended to mitigate the effects of solar exposure but also to enable the cross ventilation of classrooms. As described by Stein,

> On the side of the corridor there is the problem of noise coming from the corridor […] In the Gilman Building we tried to resolve this by using a recessed ceiling in the corridors, and shutters in the classrooms [Figure 4] were opened to the space above the corridor. The corridors themselves were closed, above and below [the recessed ceiling], by shutters [which enabled the free movement of air; see Figure 6]. (Stein 2012)

Figure 4: Rare original ventilation shutters, now unused, inside a classroom in the Gilman Building, leading to the air space above the adjacent corridor that connects to the facade to the courtyards, 2014 (photograph by the authors)

Sun protections

The Gilman Building was designed in an era in which a plethora of shading options and styles were regularly available to Israeli architects. Israel of the 1950's and 1960's was an effervescent field of experimentation and innovation in shading elements of different types and effects, and local architects were keen on exploiting the field of solar protections for developing a new local architectural idiom. At the same time, this richness of possibilities led at times to excessive use of shading elements for purely ornamental purposes, which had very little in common with the technical purpose of sun protection.

Although building massing and space allocation were intended to overcome the negative effects of the building's orientation, the designers of the Gilman Building still had to deal with the exposure of the smaller rooms to the eastern and western sun. In an article published in 1955, Wittkower referred to a similar situation, writing

> If one cannot escape the orientation of the main facades to the east and west, it is possible to well protect these facades using horizontal or vertical sun protectors – which are called Brise Soleil in our professional jargon. It is very much recommended that the sun protectors should protect the entire facade and not only the windows, in order to prevent the heating of the entire wall. Vertical sun protectors, which could be rotated and adjusted, are without doubt an ideal solution, since they assist in capturing the drafts and in directing it through the building. (Wittkower 1955)

Following a similar reasoning, fixed precast concrete elements, which formed an external shading screen, covered most of the eastern and western facades of the Gilman Building (Figure 5). The choice of fixed instead of rotatable elements was done, among other things, because of maintenance considerations (Stein 2012). Screening the facades from direct sunlight by an array of identical precast elements also enabled the designers to create a harmonized external image for the building even when the location of the openings in the walls behind the shading screens produced a visual composition which tended to be less than satisfactory.

In addition to the precast screens, two other types of sun protections were designed for the building: fixed horizontal louvered elements made out of aluminium which were installed on the northern and southern facades (Figure 5); and sliding PVC-aluminium shutters with rotatable slats which screened some of the facades to the courtyards (Figure 6). The latter devices proved to be too flimsy for the public areas of the building, and were eventually removed a few years after the building's completion (instead, light asbestos-cement walls combined with narrow windows were installed). As for the horizontal louvers, they were identical in both the northern and southern facades; the similarity allegedly stemmed from their similar function as glare protection, though in the southern facade they were also intended to block the penetration of direct solar radiation (Wittkower 1965). Above them, a narrow strip of about 80 cm below the ceiling was sealed using glass in the northern facades and fixed aluminium shutters in the southern facades, reflecting an intention to block the penetration of solar radiation only from the south.

Figure 5: Gilman Building, the south-western corner of the southern wing, showing the different sun protections applied to the southern (right) and western (left) facades (photograph by Isaac Berez, Tel Aviv University Archive)

Figure 6: Gilman Building, the smaller courtyard of the southern wing, looking east, ca. 1966 (courtesy of Israel Stein). The corridor facades, here facing north and west, were screened with sliding aluminium panels of rotatable PVC slats

Wall and Roof composition

While the wall composition of the Gilman Building was rudimentary in nature (plastered concrete blocks 20 cm thick), more attention was given to the components of the roof, acknowledging its significant thermal function. Wittkower dedicated a monitoring experiment, executed in Tel Aviv during 1950 and 1951, to the thermal properties of common local roofing technique. The results showed that for summer conditions in Tel Aviv,

> […] the best roof is the hollow-block roof [a ribbed slab] whitewashed, without the addition of insulating materials […] In cases where the house is solely used between the morning and afternoon hours, it is advantageous to add an insulating layer to the hollow-block roof […] and paint the roof white from above. Daytime temperatures will be relatively low under such a roof (Wittkower, Frenkiel and Neumann 1953).

The roof of the Gilman Building (as well as its indoor ceilings) was indeed constructed as a ribbed slab roof. Nevertheless, its inlay components were not hollow concrete blocks but solid Ytong blocks, which were being produced in Israel since 1953. By the beginning of the 1960's, Ytong blocks became a common component of ribbed slabs, mainly because of their much lower weight. On top of the ribbed slab roof of the Gilman Building a whitewashed layer of foam concrete was applied; Wittkower was aware of its insulative thermal properties and used it as the insulating layer for flat roofs in his 1950-51 experiment.

SIMULATION

The Gilman Building went through substantial transformations throughout the years, making it impossible to evaluate its original thermal performance by on-site monitoring. Computational thermal simulation is therefore the best and probably the only viable method for assessing the effects of the main climatic features of the original design on the thermal performance of the building. The building was simulated in its original state (Figure 7), i.e. without the third floor which was constructed in 1974-75 (Figure 8), including the original sliding shutters installed at the corridors' facades to the courtyards, which were replaced during the 1970's.

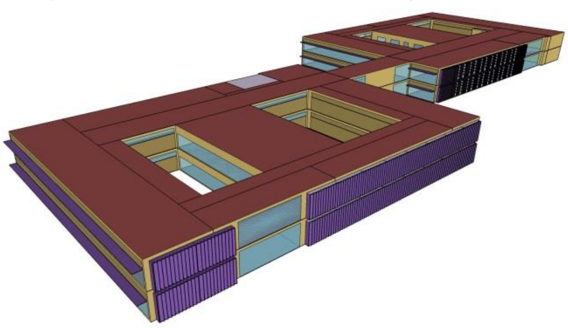

Figure 7: Rendering of the simulation model

Figure 8: Gilman Building, current state of the south-eastern corner of the southern wing with the additional third floor, 2014 (photograph by the authors)

Thermal simulation was conducted using version 8.1 of the EnergyPlus simulation engine (U.S. Department of Energy 2013). Physical properties (thermal conductivity, density, specific heat, and solar absorptance; see Table 1 and Table 2) of the building materials were extracted from existing literature. Physical properties of windows (U-value, solar heat gain, visible transmittance) were calculated using version 7.2 of the WINDOW software (Lawrence Berkeley National Laboratory 2014). Weather file of a sample year was created using Version 7.0 of the Meteonorm software (Meteotest 2012), based on monitored historic weather data (from the years 1961-1990) and solar radiation (1981-1990) data. Since the building was originally designed for natural ventilation, a constant rate of 3.0 ACH per hour for summer was calculated based on the value given in CIBSE Guide A: Environmental Design (CIBSE 2006).

Table 1: Thermal and physical properties of the main simulated materials

Material	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (J/kg·K)
Aluminium fixed shutters	45	7680	420
Cement floor tiles	1.1	2100	840
External cement-based plaster	0.72	1860	840
Foam concrete	0.07	320	920
Hollow concrete block	0.86	930	840
Indoor plaster	0.22	800	840
PVC shutters	0.16	1380	1000
Reinforced concrete	1.9	2300	840
Sand	1.74	2240	840
Ytong block	0.11	450	840

Table 2: Solar absorptance properties of simulated exterior materials

Material	Solar Absorptance
Aluminium fixed shutters	0.65
External cement-based plaster	0.73
PVC shutters	0.50
Reinforced concrete (exposed)	0.73
Whitewash	0.35

Simulation results: effect of building orientation

Shading devices vary in the Gilman Building from one facade to another (thus having a non-uniform impact on the building envelope); therefore, and in order to evaluate the effect of orientation alone on indoor temperatures, the building was simulated without its shading devices (scenario BSNS). Analysis was conducted by calculating "overheating rates" (defined as the percentage of hours with indoor temperatures above 27°C) for the differently-oriented rooms during daytime (07:00-19:00) only, since the building was not meant to be occupied during the night. Average results for the summer months (July-September) in both wings and floors are shown in Figure 9. In addition to the overheating rates, indoor temperatures of a typical summer day were calculated and compared with the outdoor temperature amplitude (Figure 10).

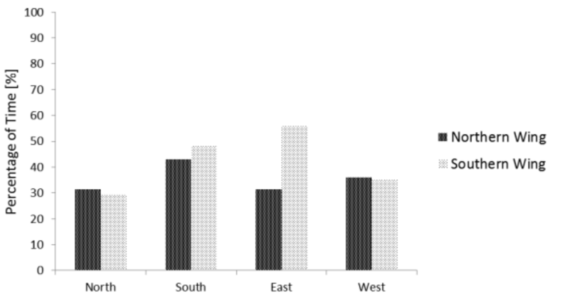

Figure 9: Summer overheating rates of rooms oriented differently (first floor) excluding the effect of sun protections (scenario BSNS)

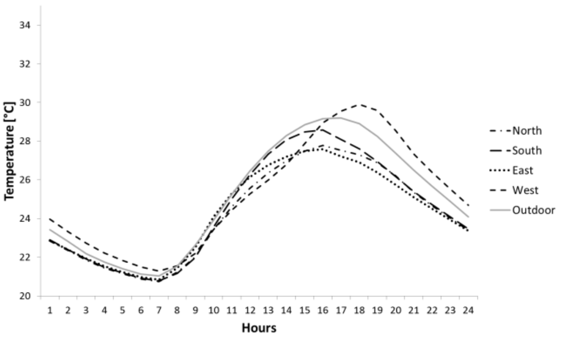

Figure 10: Simulated indoor temperatures for a typical summer day (July-September) of rooms oriented differently (northern wing, first floor) excluding the effect of sun protections (scenario BSNS)

Simulation results showed that in both floors and wings, overheating rates during daytime cannot be explained by reference to the rooms' orientation alone, though it can be argued that northern rooms were generally cooler than all other rooms. In other words, indoor temperatures, even without sun protections, depended on other factors than mere orientation, mainly the glazing to wall and glazing to floor ratios (indoor air temperatures increased as wall glazing to floor area ratios increased). This is best manifested in the results for the eastern rooms: the eastern rooms of the southern wing were the coolest of all, while the eastern rooms of the northern wing were the warmest of all. This result can be explained based on the much higher glazing to floor area ratio of the eastern rooms in the southern wing, compared to the similarly oriented rooms in the northern wing (Table 3).

Table 3: Wall glazing to floor area ratio for all rooms

	N. rooms	S. rooms	E. rooms	W. rooms
N. Wing	0.38	0.27	0.11	0.30
S. Wing	0.41	0.28	0.35	0.27

Simulation results: effect of sun protections

The efficacy of shading devices in the Gilman Building was evaluated by comparing two simulation scenarios: the original state of the building (BS) and the building stripped of its shading elements (BSNS). Overheating rates for daytime hours (07:00-19:00) were calculated for the summer months (July-September) and are shown in Figure 11; the cooling effect of the shading devices, expressed in temperature difference between the two scenarios (BSNS-BS) of the maximum daily temperature for a typical summer day, is shown in Table 4. The results showed that the precast concrete elements were responsible for a substantial lowering of indoor temperatures in the eastern and western rooms alike. The horizontal shading overhangs of the southern facades helped in lowering the indoor temperatures during daytime, though in a relatively moderate way. As expected, the horizontal shading overhangs of the northern facades had almost no effect on indoor temperatures.

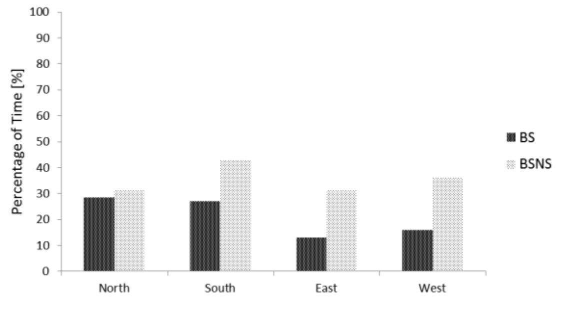

Figure 11: Summer overheating rates of rooms oriented differently, first floor of the northern wing (scenarios BS and BSNS)

Table 4: The cooling effect of shading devices for different room orientations, expressed as the difference [in K] between the maximum temperatures of scenarios BSNS and BS for a typical summer day

		N. rooms	S. rooms	E. rooms	W. rooms
1st Floor	N. Wing	0.1	1.0	0.8	3.1
	S. Wing	0.2	1.1	1.3	2.5
2nd Floor	N. Wing	0.2	1.4	1.3	5.1
	S. Wing	0.3	1.5	2.6	4.3

Notwithstanding their effective role during summer, it is interesting to examine whether the shading devices had a negative impact on indoor winter temperatures because of the blocking of solar radiation that could have been exploited for passive heating. To answer this question, "underheating rates" (defined as the percentage of hours with indoor temperatures below 20°C) were calculated for the different rooms during daytime (07:00-19:00); the results for the BS and BSNS scenarios were then compared (Figure 12). The cooling effect of the shading devices, expressed in temperature difference between the two scenarios (BSNS-BS) of maximum daily temperature for a typical winter day, is shown in Table 5.

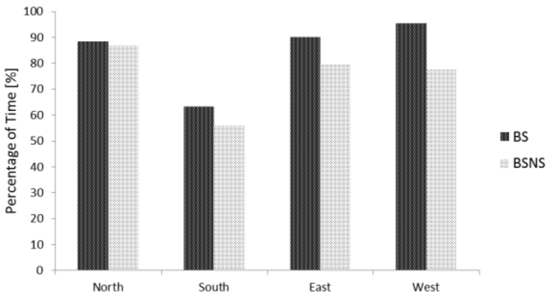

Figure 12: Winter underheating rates of rooms oriented differently, first floor of the northern wing (scenarios BS and BSNS)

Table 5: The cooling effect of shading devices for different room orientations, expressed as the difference [in K] between maximum temperatures of scenarios BSNS and BS for a typical winter day

		N. rooms	S. rooms	E. rooms	W. rooms
1st Floor	N. Wing	0.2	1.2	0.7	2.2
	S. Wing	0.3	1.3	1.1	1.9
2nd Floor	N. Wing	0.3	2.3	1.4	3.9
	S. Wing	0.4	2.3	2.1	3.8

The results showed that for the eastern and western rooms, the fixed precast shading elements prevented a proper exploitation of solar radiation for passive heating during winter. A somewhat more moderate effect was also simulated in the southern rooms, though even with the shading devices temperatures in these rooms were still relatively high, making them much less dependent on additional heating than rooms oriented to the north, east, or west. These results indicate that the design of shadings in the Gilman Building, while providing excellent summer solar protection, was not optimized for winter operation.

Simulation results: effect of roof construction

As can be seen in Figure 13, simulated indoor summer temperatures in the second (upper) floor were consistently higher than room temperatures in similarly-oriented rooms of the first floor (with a temperature difference of 2-3K). Since the first and second floors of the Gilman Building were originally identical in their layout and facade design, this difference must be attributed to the direct exposure of the second floor's ceiling (i.e. the building's roof) to solar radiation and outdoor air temperatures. Rooms directly below the roof were warmer than outdoor conditions, while the rooms below them were cooler.

The roof composition of the Gilman Building was almost optimal in terms of its thermal performance, with a total thickness of 40 cm and a U-value of 0.28 W/m^{2}K. It was also congruent with the climatic recommendations of Wittkower from his 1950-51 experiment. The only minor exception was the application of Ytong blocks instead of hollow concrete blocks, which, because of their much better thermal resistance (0.11 W/mK, in comparison to 0.86 W/mK of hollow concrete blocks), could have had a negative effect on the upper rooms' ability to cool down during nighttime.

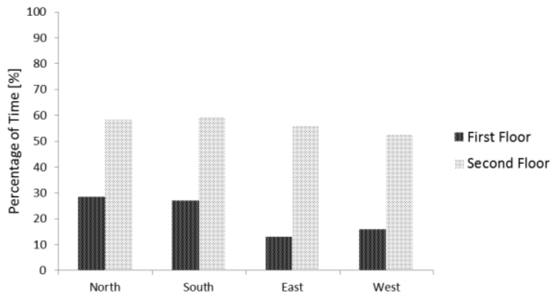

Figure 13: Summer overheating rates of rooms oriented differently, the northern wing (scenario BS)

In order to evaluate whether a substantial improvement in indoor temperatures could have resulted from the use of hollow concrete blocks, a comparison was made between the original roof composition and a scenario where hollow concrete blocks replaced the Ytong blocks in the roof construction (scenario BSCB; this resulted in a higher roof construction U-value of 0.65 W/m^{2}K). Calculation of summer overheating rates showed that the application of hollow concrete blocks could have produced a reduction of 3-5% of overheating rates. In terms of temperature reduction, hollow concrete blocks kept indoor temperatures cooler by about 0.5K in all orientations (see for example Figure 14). However, these results were obtained by applying the same ventilation rate assumption in both scenarios (3.0 ACH). A higher nighttime ventilation rate in scenario BS could have presumbly offset the temperature increase effect due to higher roof insulation.

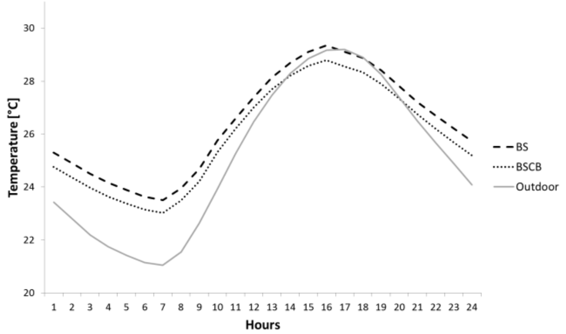

Figure 14: Simulated indoor temperatures for a typical summer day (July-September) of eastern rooms, the second floor of the northern wing (scenarios BS and BSCB)

During winter (Figure 15), assuming a constant ventilation rate of 1.0 ACH for the two scenarios, there was almost no difference in indoor temperatures between the two roof constructions (and thus no actual difference in heating loads), though rooms with roof consisting of Ytong blocks were slightly warmer in all orientations. This smaller difference in indoor temperatures (comapred to the higher summer temperature difference) should be attributed to the application of lower ventilation rates for winter simulation, following the recommended values given in CIBSE Guide A: Environmental Design (CIBSE 2006). The applied winter ventilation rate represented the constant closure of all windows in the building, which conforms to the typical assumed user behaviour.

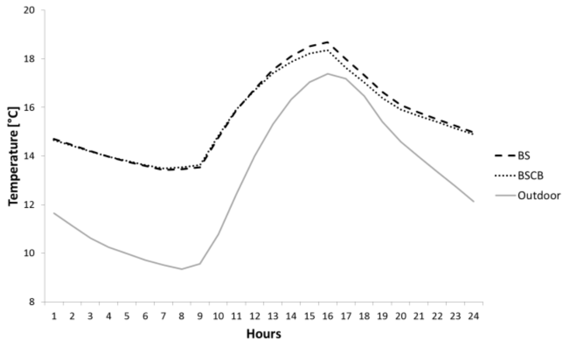

Figure 15: Simulated indoor temperatures for a typical winter day (December-February) of eastern rooms, the second floor of the northern wing (scenarios BS and BSCB)

DISCUSSION

The main climatic challenge of the Gilman Building was perceived by its designers as its undesirable orientation, with its longer facades facing east and west. From this perspective, the design proved to be climatically effective since it maximized the exposure of the building's main spaces to the north and south and secured agreeable summer indoor conditions in its first floor. This implicitly demonstrated that the prescriptive attitude to the question of orientation so common in Israel of that time was not fully justified: with intelligent building massing and sun protection, problems emanating from orientation could be resolved or at least ameliorated given the right design.

Besides the clever massing of the building, the application of shading devices had a major effect on the building's indoor climate. Shading design was the main reason behind the cooler indoor conditions of the eastern and western rooms during summer, and while the eastern and western facades were almost entirely masked from direct sun penetration, shading of the warmer southern rooms was less effective. This treatment of the facades, which gave much more emphasis to the protection of the eastern and western facades from direct solar radiation, corresponded to the climatic views expressed by Wittkower since the beginning of the 1940's.

The relatively agreeable summer indoor conditions were not an outcome of a special attention given to the composition of the external walls. Walls in the Gilman Building were constructed in the most conventional way for that time (plastered hollow concrete blocks). A non-conventional design might have resulted in higher thermal resistance and thermal capacity of the walls, but such an enhancement had little sense in a building that was designed for natural ventilation. Some improvement could have been achieved during wintertime, but since winter conditions were not seen by the architects, as well as their contemporaries, as a genuine climatic challenge, it is hard to criticize their final choice of wall composition.

In contrast to its walls, the roof of the Gilman Building was designed with much more care to its composition. The result was a roof with a relatively low U-value, as well as a relatively high albedo value. Nevertheless, the roof still represented a weak point in the thermal performance of the building during summer, with indoor temperatures in the upper floor being 2-3K higher than first floor temperatures. Not much could have been done to overcome this inherent deficiency, at least not in terms of the common practice of that time; and while natural ventilation might have helped to reduce discomfort during the height of summer, one could not but understand why air conditioning has been gradually installed in the building since the mid-1970's.

CONCLUSION

As the case of the Gilman Building may prove, conscious application of knowledge in building climatology can produce an architectural design which has an aesthetic appeal as well as satisfactory thermal performance. This achievement is highly dependent not only on the architects' professional expertise, but also on the design stage in which climatic knowledge is applied: in the case of the Gilman Building, the building's architects were aware of the climatic effects of their decisions from the very first stages of conceptual design up to the final stages of envelope detailing. Even though the applied knowledge was relatively rudimentary in today's terms, it still had a more than positive effect on the climatic performance of the final design.

Three major climatic concerns, in descending order of importance, were given close attention during the design of the Gilman Building: the first and foremost was building orientation and the ensuing facade insolation; the second was the need for sun protections, especially against the direct penetration of sunlight into indoor spaces; and the third was the composition of the building envelope and its insulating capacities. Building simulation showed that the design was able to overcome much of the negative effects of climate through clever massing of the building and extensive use of solar protections. At the same time, it also indicated that the design of shading for the southern facades, combined with the relatively high wall glazing to floor area ratios, produced summer indoor overheating that could be partly avoided. Nonetheless, as it turned out, the main climatic weak spot of the building was not its walls or windows but its roof. Since the roof's design was more than reasonable in terms of the contemporary design possibilities and habits, its eventual performance demonstrated that there may be times in which passive means alone cannot bring the thermal performance of a building to a desirable level.

Historical research was used in this study in order to follow the manifested design intentions of the architects, and especially the way the architects translated their knowledge in building climatology into specific design decisions. By combining these findings with thermal building simulation, it was possible not only to describe the assumed thermal performance of the building, but, moreover, to critically assess whether the design decisions were consistent with the proclaimed climatic intentions of the architects and whether they could have produced agreeable indoor conditions. Thermal building simulation was thus used here as a historical research tool that produced insights and appreciation of the original design which could not have resulted from more conventional methods of historical research.

REFERENCES

Aleksandrowicz, O., Mahdavi, A., 2012. Thermal Performance Analysis of Central Hall Houses in the Israeli Coastal Plain, Proceeding of BauSIM 2012: Fourth German-Austrian IBPSA Conference, Berlin, pp. 13-22.

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

Feige, R., Koch, W., Neumann, J., Wittkower, W. J., 1952. Report on the Indoor Climate of Two Apartments, Israel Meteorological Service, Jerusalem.

Hashimshoni, A., 1962. HaBe'ayot HaAqlimiyot MiNekudat HaRe'ut Shel HaArkhitekt (Climatic Problems from the Architect's Point of View), Hashpa'at HaAqlim 'al HaAdam BeIsrael (Climate and Man in Israel), National Council for Research and Development, Jerusalem, pp. 124–135.

Lawrence Berkeley National Laboratory, 2014. WINDOW 7.2, windows.lbl.gov/software/window.

Meteotest, 2012. Meteonorm 7.0, meteonorm.com/en/downloads.

Stein, I., 2012. Personal interview with Or Aleksandrowicz, 12.9.2012.

Tel Aviv University, 1962. Universitat Tel Aviv (Tel Aviv University) [Promotional Booklet], Tel Aviv Municipality Historical Archive, 362(48)/5-2-1962-1.

U.S. Department of Energy, 2013. EnergyPlus 8.1, apps1.eere.energy.gov/buildings/energyplus.

Wittkower, W. J., 1955. Ivrur UVidud (Ventilation and Insulation), Journal of the Association of Engineers and Architects in Israel 13(1), 26–27.

Wittkower, W. J., 1965. Tichnun Universitat Tel-Aviv (Plan for Tel Aviv University), Journal of the Association of Engineers and Architects in Israel 23(6), 37-45.

Wittkower, W. J., Frenkiel, J., Neumann, J., 1953. Effects of Some Types of Roof Construction upon Air Temperatures Close to the Ceiling in the Late Summer Months in Israel, Research Council of Israel, Jerusalem.