Impact of increasing the depth of urban street canyons on building heating and cooling loads in Tel Aviv, Israel

Evyatar Erell[1], Yannai Kalman[2]
[1,2] *Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Israel*
erell@bgu.ac.il

Abstract

Computer simulation was used to predict the effects on urban microclimate of increasing the height of existing buildings in Tel Aviv. The nocturnal urban heat island is expected to intensify and wind speed to be reduced, thus reducing the potential for free cooling in summer - but annual energy consumption is not increased in fully air conditioned buildings.

Keywords: Urban microclimate, computer simulation, CAT model, climate cooling potential

1. Introduction

Israel lies along the Dead Sea Transform, with earthquakes of magnitudes between 6 and 7.2 occurring in the region on average every 80-100 years. Many of the existing buildings in Tel Aviv's older neighbourhoods suffer from structural weaknesses and might collapse in the event of a major earthquake, of which there is a high probability. As an attempt to mitigate potential damage to buildings constructed or planned before introduction of a stringent seismic design code in 1980, the Israel Ministry of Interior created National Guideline Plan 38 - NGP 38 (IMI, 2005). The plan seeks to address this problem by facilitating the reinforcement of unsafe buildings by allowing construction of additional storeys to existing buildings undergoing reinforcement, thus providing a financial incentive and a suitable regulatory framework. The number of building renovations under NGP 38 has increased steadily with each successive revision of the plan, particularly in the densely populated centre of the country where land values are high. If plan implementation becomes widespread, it could mean substantially deeper street canyons in older parts of many cities in Israel. The increase in urban density, although desirable in many respects, may also be expected to exacerbate the urban heat island.

Canyon geometry affects the microclimate within, creating and defining the magnitude of urban heat islands (Oke, 1981; 1982). Some studies claim that as a consequence, UHIs lead to increased building energy demand (Hassid et al, 2000; Priyadarsini, 2009; Santamouris et al, 2011). Others show that mutual shadowing among adjacent buildings may lead to reduced energy consumption in hot climates, so that the same factors that lead to the creation of UHIs may also counteract their effects (Williamson et al, 2009). This study applies numerical modelling and computer simulation to examine the potential effect of widespread implementation of NGP 38 - which will lead to substantial increases in urban density - on building energy consumption for air conditioning and on the potential for night ventilation cooling.

2. Methodology

The study examines the potential effects of increasing building height by means of computer simulation. The Canyon Air Temperature model (Erell & Williamson, 2006) is used to generate site-specific weather data from time-series measured at a reference weather station, accounting for urban geometry, materials and surrounding land cover. These data are used as inputs for assessing:

a) The 'climatic cooling potential' (CCP), a metric that estimates the potential for cooling by ventilation in a non-air conditioned building whose temperature is assumed to oscillate harmonically in response to the diurnal cycle of external air temperature, with a time lag and decrement factor that are due to the presence of thermal mass.
b) Heating and cooling requirements in a fully air conditioned building, using the EnergyPlus building thermal simulation software.

Both indicators were calculated first for the reference weather station (at Bet Dagan, about 7.3km inland, 32°0'28"N, 34°48'52"E); then for conditions in typical existing streets in southern Tel Aviv; and finally for different scenarios of increased building height, up to a total of 8 floors. No other changes to street geometry or materials were modelled.

The standard '.epw' TMY weather file representing the Tel Aviv area is based on data from the Israel Meteorological Service station at Bet Dagan, which is located in a semi-rural area. The standard procedure uses these data as input for ENERGYui (Yezioro et al, 2011), an interface for the EnergyPlus building thermal simulation software (US DOE, 2011) which rates building energy efficiency according to Israeli standards. The EnergyPlus simulation engine simulates building energy requirements for acclimatization based on inputs including building materials, geometry and designated function, as well as solar angles and meteorological data.

The CAT model uses meteorological data from a nearby representative weather station to generate time series of local-scale meteorological parameters at an urban street canyon. Temperature, humidity and wind speed data from the weather station are modified by CAT to generate ‘urbanized’ inputs for the building energy simulation carried out by EnergyPlus. The transformation is based on a complete surface energy balance at the two sites: In addition to a 2.5-dimensional analysis of radiant exchange accounting for short and long-wave fluxes, it incorporates several elements of the LUMPS parameterization scheme (Grimmond and Oke, 2002), including moisture advection from nearby vegetation and bodies of water, as detailed in Erell et al (2010). The effect of turbulent mixing in different stability regimes is estimated by means of an empirical correlation established using site data from Adelaide and Goteborg.

2.2 Simulation parameters

The Tel Aviv study area (32° 4'N, 34°46'E) is about 350 m from the sea. The streets, which are about 15m wide and flanked by 2-3 storey buildings, form a grid parallel to the beach (approx. N-S) and perpendicular to it. The neighbourhood has little vegetation. The albedo of building walls is estimated at 0.4, and the road at 0.15.

Energy consumption was simulated for an H-shaped apartment building of a type commonly constructed in Israel pre-1980, before the enforcement of seismic building codes. In some areas, this building makes up the majority of the urban fabric, and it is therefore a candidate for renovation and expansion under NGP 38. Buildings typically comprise 4 apartments per floor, each of about 84 m^2 in floor area. Walls are constructed of hollow concrete block and the flat roofs comprise a concrete slab with minimal thermal insulation. Windows are small (window/wall ratio =0.11), single-glazed and display no preferred orientation. Although in reality any major retrofit may be expected to include a thermal upgrade, the study modelled energy consumption on the assumption that additional floors were identical to existing ones, so as to isolate the effects of modifications to microclimate.

A simulation of the building’s thermal loads was carried out for a variety of building heights, from one 3-meter storey to eight storeys, in order to simulate the effects of canyon aspect ratio on building efficiency. Additional floors were assumed to have the same thermal characteristics as the existing structure, to simplify the analysis and to isolate the effect of changes to the urban microclimate.

ENERGYui is capable of accounting for self-shading by building elements such as balconies, but it does not account for shading by adjacent buildings. To achieve a more realistic measure of the effects of solar radiation in a densely built urban neighbourhood, an unheated built space was added to the model, representing the volume of eight adjacent buildings surrounding the object of the simulation. The heights of these buildings were altered to match the height of the simulated building in each of the different scenarios. The impact of outdoor microclimate on building energy demands was defined as the difference between simulation results using the standard TMY weather data and results using a TMY file altered by the CAT model to represent the relevant urban scenario.

3. Results

3.1 Urban Microclimate

The CAT model simulation first reproduces differences between the Bet Dagan weather station, which is about 7km inland, and the Tel Aviv streets, which are affected by proximity to the sea: In Tel Aviv, daily minima are higher but maxima are typically slightly lower. CAT was then used to evaluate the effects of the addition of buildings, which generates a nocturnal heat island whose intensity increases, up to about 5^{o}C, as building height grows. Concurrently, wind speed is reduced with increasing canyon aspect ratio (H/W). Modelled daytime differences in air temperature are modest – less than 1 degree.

Temperatures for a typical summer day (July 6th), plotted in Fig.1, show the effect of increasing canyon depth on air temperature. As canyons become deeper the sky view factor (SVF) becomes smaller, allowing less long wave radiation to escape at night to the atmosphere and generating the expected night-time UHI.

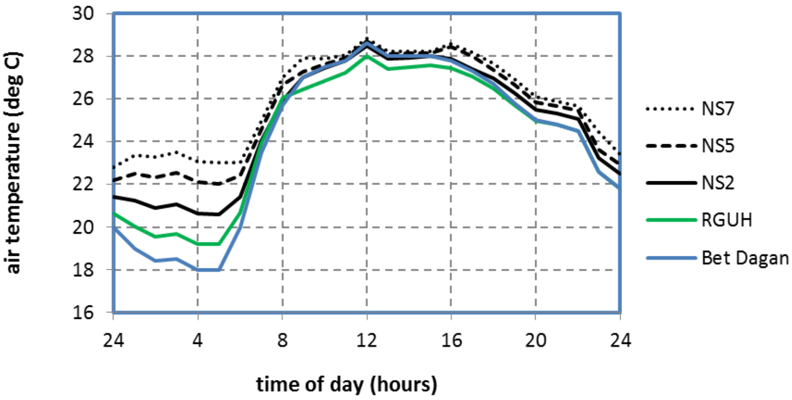

Fig. 1: Dry bulb temperature at the Bet Dagan weather station, simulated effects on air temperature of vegetation and water bodies (referred to here as ‘rural geometry-urban hydrology’, RGUH) and predicted temperatures for a N-S street canyon flanked by buildings of 2, 5 and 7 storeys.

Wind speed in the city of Tel Aviv, as in most urban areas, is reduced substantially due to the overall aerodynamic roughness of the urban surface, but there is a further, localized effect as deeper street canyons experience lower wind speed at street level. Fig. 2 shows the effect of aspect ratio on wind speed in the canyon. Concurrent wind speed at the reference (rural) meteorological station was minimal at night, increasing gradually to maximum values of as much as 6 m/s.

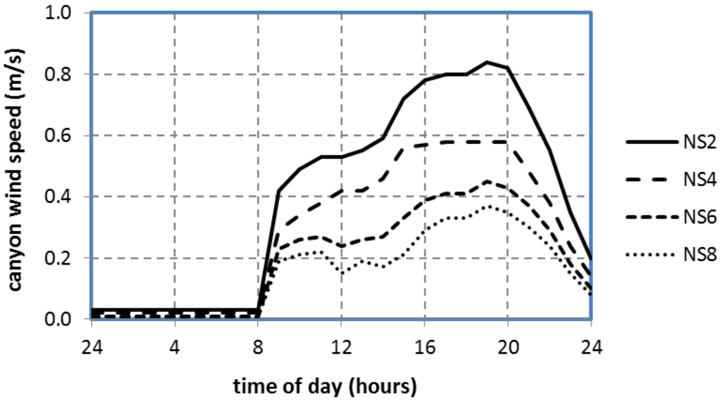

Fig. 2: Wind speed at pedestrian height (1.5m) in a N-S street canyon 15m wide flanked by buildings of different heights (2-8 storeys).

3.2 Climatic Cooling Potential

The ‘climatic cooling potential’ (CCP) proposed by Artmann et al (2007) estimates the potential for cooling by ventilation in a non-air conditioned building. Rather than prescribing a fixed reference temperature for cooling, as is done in the calculation of the Cooling Degree Days metric, this method assumes that internal building temperature is allowed to oscillate harmonically in response to the diurnal cycle of external air temperature, with a time lag and decrement factor that are due to the presence of thermal mass. For this analysis, the building temperature at time *h* is given by the expression:

$$T_{b,h} = 24.5 + 2.5\cos(2\pi \frac{h - h_i}{24})$$

and h_i is the time ventilation normally starts (for example – at 19:00). Ventilation is considered to be effective if there is a temperature difference of at least 2K between the building and the outdoor air. The CCP is the product of this temperature difference and the time step, typically hours, summed over the period of interest. The CCP is thus given in units of ‘degree-hours’.

Fig. 3 illustrates the effect of proposed modification to the urban fabric on the climate cooling potential for a typical day in July. The cooling potential is represented by the shaded area between the assumed indoor temperature, minus 2 degrees, shown by the blue line, and the actual air temperature at Bet Dagan. The increase in night-time air temperature predicted by the model, shown on the right, results in complete elimination of the potential for passive cooling by ventilation during this night.

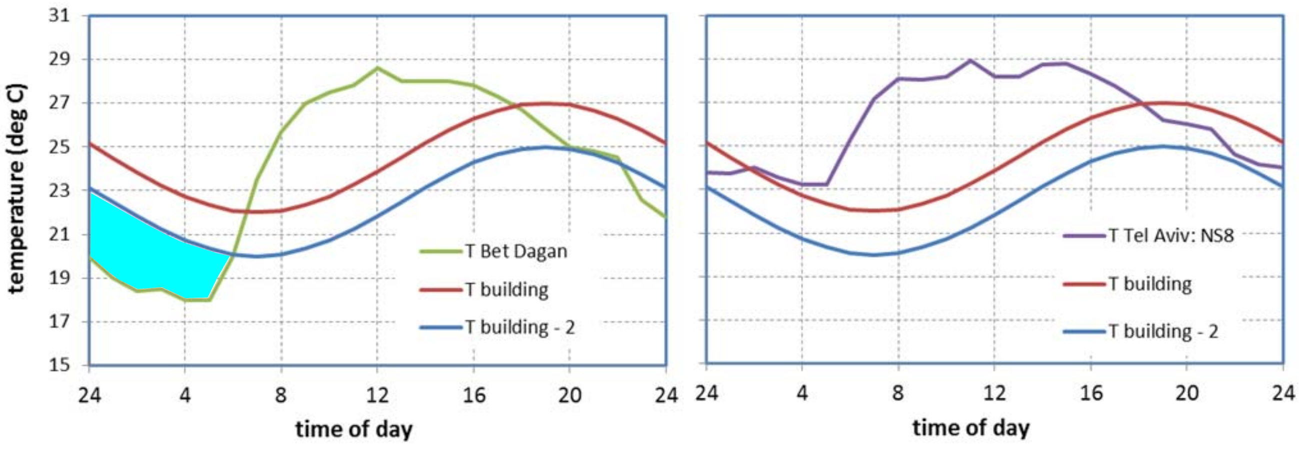

Fig. 3: Climate cooling potential on a typical day in July. On the left – CCP calculated for an exposed building at Bet Dagan. On the right – the CCP for a building in a street with 8-storey buildings, using air temperature generated by CAT.

The cumulative effect of changes to the CCP over an extended summer period is demonstrated for the month of July. In Bet Dagan the total climate cooling potential for the month is 947 degree-hours; the comparable value for an exposed area near the sea, with no buildings, is only 744 degree-hours, because night-time temperature minima are moderated by proximity to the sea. When the effect of existing 2-story buildings on air temperature is included, the cooling potential is reduced slightly to 696 degree-hours. Increasing building height to 4, 6 or 8 floors results in further reduction of the potential to 521, 374 and 178 degree-hours for the month of July, respectively.

3.3 Building Energy Consumption

Several factors affect the energy efficiency of the modelled buildings, including: variation in surface-to-volume ratio of buildings of different height; the relative effect of the top floor which is exposed to the sky; the proportion of glazed surface which is shaded by nearby buildings; and the outdoor microclimatic conditions which are altered by the surrounding building geometry.

Increasing building height reduces the simulated building energy consumption for space heating and cooling from about 34 kWh/m^2 per year for a 1-floor building to about 26 kWh/m^2 for a 7-floor building. This is firstly because the effect of elevated night-time air temperature in deeper streets, which may be expected to increase cooling loads in summer, is offset by mutual shading between adjacent buildings, which reduces the radiant load on the external walls and windows; and secondly, because increasing the number of intermediate stories reduces the relative effect of the exposed top floor, which requires more energy to heat in winter and to cool in summer.

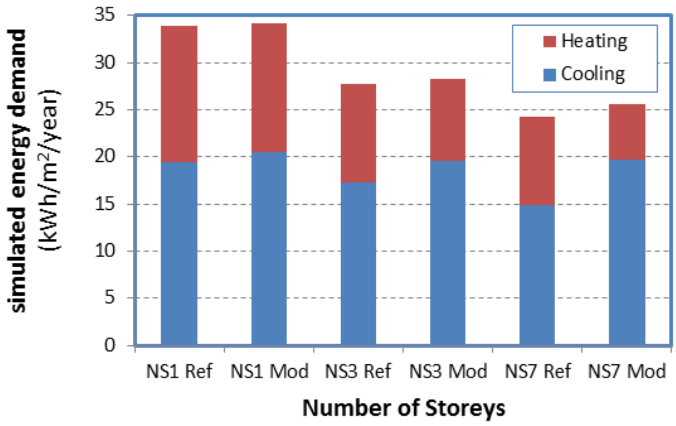

Fig. 4: Simulated energy demand for heating and cooling buildings on a N-S canyon, for building heights of 1, 3, and 7 storeys. Buildings simulated with TMY data from the reference site at Bet Dagan are referred to as 'ref' and those simulated with TMY modified to account for urban site conditions according to different density scenarios are referred to as 'mod'.

As Fig. 4 shows, the 7-storey building, as measured by its specific energy consumption (kW/m^2/year), is more energy-efficient than the shorter buildings. Additionally, we see that although CAT predicts the formation of substantial nocturnal heat islands, which grow in magnitude with greater building height, the increase in summer cooling loads is offset by a decrease in winter heating loads. Thus, the largest variation between simulations using reference and modified weather data is ~1.4 kWh/m^2 over the course of a year. Table 1 shows the breakdown of energy consumption for each level of a 5-storey building modelled using both climate inputs from the meteorological site and CAT-modified data for the urban canyon. The data shown for each floor are the average for 4 apartments, which display some variance among themselves due to different orientations. The smallest total loads can be seen for the ground floor, which is coupled to the thermal mass of the ground beneath it, keeping temperatures relatively stable. The greatest total loads are for the top floor, which is exposed to the sky above and to the air on four sides. The middle storeys all have very similar energy requirements.

Table 1: Heating, cooling and total loads for each floor of a 5 storey building on a N-S oriented canyon. Results show simulations using reference data from the Bet Dagan meteorological site (left) and modified data for the urban canyon (right).

	using Bet Dagan TMY			using modified TMY		
Storey	Cooling	Heating	Total	Cooling	Heating	Total
1	8.7	7.6	29.2	11.1	5.6	29.5
2	14.4	7.6	34.7	18.0	5.1	35.9
3	14.8	7.3	34.9	18.4	4.9	36.0
4	15.5	6.8	35.0	19.0	4.4	36.3
5	25.8	16.5	55.0	29.9	13.3	55.9
average	15.8	9.1	37.8	19.3	6.6	38.7

To summarize, the building energy modelling study shows that in the case of Tel Aviv, altered canyon microclimate plays less of a role in energy efficiency of fully air conditioned buildings than do other factors, such as the proportion of building envelope exposed to the sky and mutual shading by adjacent buildings. Thus, although increased summer cooling requirements are offset by a reduction in winter heating, taller buildings are, overall, slightly more economical under the conditions simulated.

4. DISCUSSION

The simulations carried out in this study were designed to assess the sensitivity of building energy consumption and the potential for night cooling to proposed changes in building height. The framing of the research question is necessarily narrow, and allows a focus on the effect of modifications to the urban microclimate. However, as experienced users of building energy simulation will acknowledge, the terms of reference may have great effect on the results of the exercise. Several of these limitations are listed below.

- The finding that taller buildings are more efficient in terms of indoor acclimatization than are lower buildings (up to 8 storeys) is attributed largely to differences in the number of floors not exposed to the sky: The roof suffers high radiant loads in summer and is most exposed to wind at winter, so it is a weak point in the building envelope, especially considering the current standard of thermal insulation: The energy consumption of the top floor is ~55 kWh/m^2/year, compared to ~35 for an intermediate level floor. Simply installing better roof insulation would reduce this effect.
- The effect of mutual shading by adjacent buildings, which reduces overheating in summer but also limits the potential for passive solar heating in winter, depends on the details of the fenestration and glazing design. These include, but are not limited to, the size of windows, glazing properties, shading elements installed and occupant controls.
- The simulated buildings have a fairly rudimentary thermal envelope, reflecting building practice at the time of their construction over 30 years ago. In particular, external walls and roofs are poorly insulated. Better construction during retrofit is likely to yield even smaller differences among buildings of different heights, especially if roof insulation is improved.
- Buildings were only modelled under conditions where all surrounding buildings were of the same height. Additional complexity resulting from varied building height, such as altered wind patterns and changes to the radiation balance of the street and to mutual shading from adjacent buildings, was not accounted for.
- The model accounts for the reduced solar gains in winter as well as in summer, but assigns a fixed lighting schedule. The effect of this simplification on the results of the simulation is marginal in our case: deeper street canyons are in fact going to allow less sunlight, but since Israel is a sunny country this may have a smaller effect compared to most other locations.

The study described here is limited to conditions in Tel Aviv, which has a Mediterranean climate. Potential effects of similar urban densification in other locations were not investigated. The effect on energy consumption of buildings in other climates/latitudes, with larger window/wall ratios, different window shading patterns or of different construction materials (i.e. lightweight timbre frames) requires further research. The consumption of office buildings is likewise unaccounted for in this study.

Increasing urban density also has other effects, in addition to modifying air temperature, wind speed and radiant exchange. Although as a general rule air pollution concentrations in the canyon increase with aspect ratio, this effect is a complex issue beyond the scope of this research. Also not addressed were the effects of density on energy consumption for other uses, such as transport, which tends to become smaller as cities become more compact.

Finally, all building thermal simulation requires assumptions regarding occupant behaviour and preferences, such as thermostat set points. Making such assumptions is unavoidable – but the poor correlation observed in several studies between modelled energy requirements and actual consumption suggests that care should be taken in drawing conclusions and proposing policy recommendations to mitigate the effect of urban heat islands.

5. CONCLUSIONS

This paper presented a series of computer simulations modelling hypothetical modifications to the built environment in a Mediterranean city, manifested in increasing urban density by addition of floors to existing buildings. The goals were to create a comprehensive image of thermal exchanges in a Tel Aviv street and to generate recommendations regarding the effects of changes to building geometry which are likely to take place in coming years.

The simulations confirm that deeper streets resulting from widespread implementation of NGP 38 are, in fact, likely to create more intense nocturnal heat islands. Consequently, as the reduction in the Climate Cooling Potential indicates, occupants of non-air conditioned buildings would suffer disproportionately from elevated nocturnal temperatures and reduced wind speed on warm summer nights – encouraging use of air conditioning that may otherwise have been avoided. The impact of this modification to microclimate may, however, be quite small in practice: most Tel Aviv residents already use air conditioning extensively, including at night and while sleeping. So, considering only the possible impact on energy consumption, it is likely that the impact on combined annual energy requirements for both cooling and heating is negligible. In Tel Aviv, the increase in summer cooling resulting from more intense urban heat islands is offset by the reduction in winter heating.

The findings of this case study are necessarily specific to Tel Aviv and to the building types investigated. However, they illustrate the importance of a comprehensive approach to computer modelling that accounts for all of the factors that affect building energy performance. Thus, although the properties of the building may be accounted for in conventional building thermal simulation, several potentially confounding factors are often ignored: a) local microclimatic characteristics are not accounted for because such data are not available, despite potentially significant differences, and b) the effect of shading by adjacent buildings is disregarded because the software does not explicitly require them to be included in the model. As demonstrated here, assessing the effect of elevated air temperature in isolation, disregarding the coincident effects of the very same factors that generate the UHI, such as mutual shading among buildings in a dense urban fabric, may lead to erroneous conclusions.

REFERENCES

Artmann N., Manz H. and Heiselberg P., 2007: Climatic potential for passive cooling of buildings by night-time ventilation in Europe. *Applied Energy* 84, 187-201.

Erell E. and Williamson T., 2006: Simulating Air Temperature in an Urban Street Canyon in All Weather Conditions Using Measured Data at a Reference Meteorological Station. *International Journal of Climatology*, 26, 1671-1694.

Erell E., Eliasson E., Grimmond S., Offerle B. and Williamson T., 2010: The effect of stability on estimated variations of advected moisture in the Canyon Air Temperature (CAT) model. The 9th AMS Symposium on the Urban Environment, Keystone, Co., Aug. 2-6 2010.

Grimmond S. and Oke T., 2002: Turbulent heat fluxes in urban areas: Observations and a Local-scale Urban Meteorological Parameterization Scheme (LUMPS). Journal of Applied Meteorology, 41: p. 792-810.

Hassid S., Santamouris M., Papanikolaou N., Linardi A., Klitsikas N., Georgakis C. and Assimakopoulos, D. 2000: The effect of the Athens heat island on air conditioning load. Energy and Buildings, 32: p. 131-141.

Israel Ministry of the Interior, 2005: National Guideline Plan for the Reinforcement of Existing Buildings against Earthquakes (NGP 38).

Oke T., 1981: Canyon Geometry and the Nocturnal Urban Heat Island: Comparison of Scale Model and Field Observations. Journal of Climatology, 1: p. 237-254.

Oke T., 1982: The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society, 108: p. 1-24.

Priyadarsini R., 2009: Urban Heat Island and its Impact on Building Energy Consumption. Advances in Building Energy Research, 3: p. 261-270.

Santamouris M., Papanikolaou N., Livada I., Koronakis I., Georgakis C., Argiriou A. and Assimakopoulos, D., 2001: On the Impact of Urban Climate on the Energy Consumption of Buildings. Solar Energy, 70: p. 201-216.

US Department of Energy, 2011: EnergyPlus. http://apps1.eere.energy.gov/buildings/energyplus/

Williamson T., Erell, E. and Soebarto V., 2009: Assessing the Error from Failure to Account for Urban Microclimate in Computer Simulation of Building Energy Performance. In Building Simulation 2009, Proceedings of the 11th International IBPSA Conference, Glasgow, Scotland, July 27-30 2009, p. 497-504.

Yezioro A., Shapir O. and Capeluto G., 2011: A simple user interface for energy rating of buildings. Proceedings of Building Simulation 2011, 12 IBPSA Conference, Sydney, 14-16 Nov. 2011, p. 1293-1298.