Title: **Improving the Energy Efficiency Of a Mediterranean High-Rise Envelope**

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Subjects: Façade Design
Sustainability/Green/Energy

Keywords: Energy Efficiency
Façade
Sustainability

Publication Date: 2020

Original Publication: CTBUH Journal 2020 Issue II

Paper Type:
1. Book chapter/Part chapter
2. **Journal paper**
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Improving the Energy Efficiency Of a Mediterranean High-Rise Envelope

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Abstract

This study focuses on the building envelope as the mediator between interior and exterior climatic conditions, examining its influence on energy loads. The parameters are: climatic conditions of the building's location (Mediterranean climate), the thermal properties of the building envelope, and the effect of building height, on a high-rise office building with increased internal heat gains. The proposed envelope under study is a glazed curtain wall design, reflecting current high-rise architectural tendencies. Simulation results are in favour of a double-skin envelope design, with double low-e glazing as the exterior layer, and single-layer clear glazing on the interior, with two exterior windows that open and close in relation to building height, exterior environmental conditions and interior thermal comfort. The outcome is a dynamic building envelope that adapts and performs in relation to the above parameters.

Keywords: Climatic Response, Envelope, High-Rise, Mediterranean Climate, Thermal Performance

Introduction

Although the potential of tall buildings to improve the overall sustainability of urban life is strong, further research and experimentation is needed, in order for this typology to comply with current and near-future regulations on embodied carbon and carbon emissions (EU 2010; Voss, Musall & Lichtme 2011; NYC 2015). Additionally, there is a significant gap between the practice of high-rise development worldwide, and the expertise gained on how to make these buildings more sustainable and energy-efficient (Donnolo, Galatro & Janes 2014; Simmonds 2015).

Tel Aviv, Israel, the focus of this study, has experienced vibrant high-rise activity. In 2011, the city's Planning and Construction Committee issued the 2025 City Master Plan, setting new guidelines allowing further skyrise development (Fox 2011) (see Figure 1). This study considers high-rise buildings as an urban phenomenon closely related to city living, and studies design strategies for advancing their energy efficiency.

An important consideration of high-rise buildings is their vast scale, which is also translated into increased energy loads, in comparison with low-rise construction (Cook, Browning & Garvin 2013; Leung & Ray 2013). As a result, their impact on the urban scale is much more energy-intensive than all other construction. According to the United Nations Environmental Program - Sustainable Buildings and Climate Initiative (UNEP-SBCI), the emissions produced from the operational energy (OE) of buildings, mainly used for heating, cooling and lighting, form the largest source of building-related greenhouse gas (GHG) emissions (approximately 80–90 percent), in relation to the emissions produced by the embodied energy (EE), used in the process of raw material extraction and processing (La Roche 2012). In addition, the building sector today is the most energy-intensive sector, accounting for almost 50 percent of GHG emissions. So, in order to reduce these, it becomes crucial to enhance the energy efficiency of buildings by reducing the OE.

This study looks at improving the energy efficiency of high-rise buildings, by focusing on the initial concept design stages, and more specifically on the design of the building envelope, considered as a passive design strategy that has the potential of reducing energy loads, by acting as a mediator between indoor and outdoor conditions (Cheung, Fuller & Luther 2005; Saroglou et al. 2017). A vital consideration in this relationship is the climatic conditions of the building's location. So, by designing a climatically responsive building envelope that interacts appropriately with the ambient climatic conditions, it is possible to take advantage of passive heating and cooling techniques, and reduce the operational energy, i.e., heating and cooling (Yik 2005; Choi, Cho & Kim 2012).

However, current architectural tendencies, initiated from the mid-20th century onwards, especially prominent in high-rise buildings, portray an increased transparency of the envelope, and lightness of the structure, resulting in high cooling and heating energy loads (Allard & Santamouris 1998). On the other hand, during the last few years, double-skin façades (DSFs) have gained popularity over single-skin curtain walls, as a more advanced envelope scenario that leads to improvements of the building's energy performance (Wood & Salib 2013). But, despite the number of built DSF built projects, and the numbers of DSF studies conducted, design guidelines on DSF energy performance are lacking, especially in relation to local climate (Joe et al. 2014; Ahmed et al. 2015; Ghaffarianhoseini et al. 2016).

This paper studies the performance of a building envelope for a high-rise reference model at different heights, in the hot and humid climate of Tel Aviv. The Tel Aviv climate (in terms of dry-bulb temperature, relative humidity, wind speed, and wind direction) is shown in Figure 2. Heating and cooling load comparisons are made by gradually upgrading the thermal properties of the building envelope for improving energy efficiency. Studies in hot climates are of special importance, due to the increased solar gains entering a glass façade, intensifying the cooling requirements. In addition, most research on double-skin envelopes, the focus of this study, has predominantly been undertaken in cold and temperate climates, with limited research taking place in hot ones (Hamza 2008; Pomponi et al. 2016; Halawa et al. 2018).

Figure 1. Tel Aviv skyline. © Antony Wood

Design Considerations for High-Rise Energy Efficiency

The effect of height on high-rise energy loads

A building interacts with the outdoors through the envelope (walls, roof, windows) generally, and specifically with the thermal properties of the materials that make up the building envelope. When estimating the energy loads of a high-rise building, it becomes important to take into consideration the changing microclimate with height, and how this affects the materials of the building envelope, through heat exchange with the ambient air by

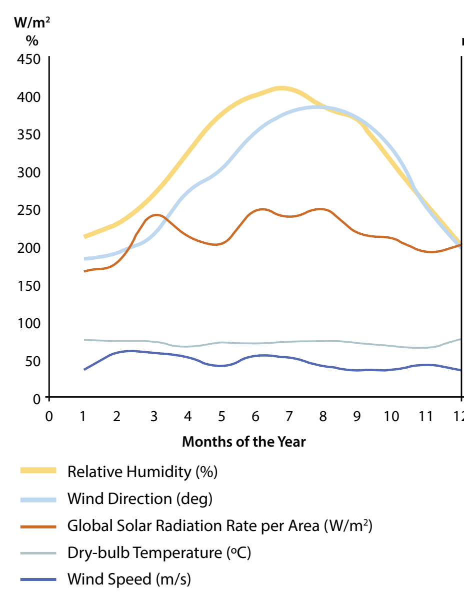

Figure 2. Tel Aviv annual climatic data. Source: EnergyPlus

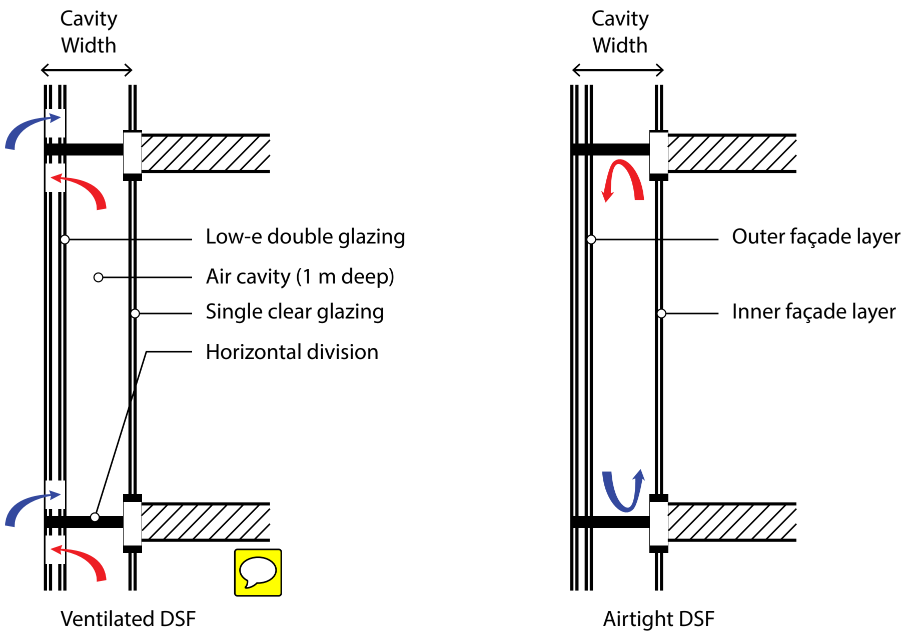

Figure 3. DSF configurations. left: ventilated/external air curtain DSF, right: airtight/air buffer DSF.

conduction, convection, and radiation (Ellis & Torcellini 2005; Lotfabadi 2014).

More specifically, wind speed increases with height above ground, while dry-bulb temperature drops. As the typical height of a meteorological station anemometer is 10 meters above ground, wind speed at higher altitudes is calculated to ASHRAE standards (ASHRAE 2009). On the other hand, dry-bulb temperature decreases with height at an almost linear rate, of approximately 1°C per 150 meters (NOAA 1976). The results in this study portray the changes in energy loads (heating and cooling) between the different heights of a simulated high-rise reference model, thus presenting information on the relationship between the building envelope and its microclimate, in relation to height above ground.

Natural ventilation in high-rise buildings

When considering the energy efficiency of a building, the implementation of passive design strategies becomes vital. Natural ventilation has the potential of considerably reducing cooling loads, especially prominent in a hot climate, but its implementation in high-rise buildings can be challenging. The effectiveness of natural ventilation is relevant to the climate and microclimate conditions, e.g., dry bulb temperature, humidity, wind intensity and wind direction, as well as the building's location, e.g., open plane, or dense/semi-dense city environment (Capeluto & Ochoa 2013; Zhou et al. 2014).

In the case of high-rise buildings, the potential of natural ventilation is also relevant to the changing microclimate with height: dry-bulb temperature decreasing, and wind speed increasing.

A study on the natural ventilation (NV) potential of high-rise structures located in cities with different climatic conditions in the United States found that the presence of high humidity levels created minimal variations in NV from ground to top, while in cities with low humidity, NV hours were reduced. On the other hand, cities with seasonal variations, like New York and Chicago, presented no NV potential during winter, while during summer the NV hours suggested considerable reductions of cooling energy (Tong, Chen & Malkawi 2017). An effective way to introduce natural ventilation into a high-rise structure is through a double-skin envelope. The exterior façade layer acts as a buffer zone to the higher wind speed intensities at higher altitudes while, depending on the climatic conditions and seasonal variations, the introduction of openings can allow for natural ventilation to take place within the cavity, and passively cool the building. Further design strategies, like segmentation of the DSF, i.e., per floor height, can minimize the wind intensities that may be created through buoyancy forces within the cavity, generating a higher level of wind control (Etheridge & Ford 2008).

The Double-Skin Façade (DSF) Envelope

The double-skin envelope is essentially comprised of three layers: the internal façade (layer 1), the intermediate air cavity (layer 2), and the external façade (layer 3). DSF typologies are classified according to their ventilation strategies (natural, mechanical, or hybrid), and according to the type of air-exchange strategies with the ambient atmosphere: exhaust air, supply air, static air buffer, external air curtain, and internal air curtain (Haase, Da Silva & Amato 2009). A third set of classifications relates to the design of the DSF: box window, shaft-box façade, corridor façade, and multi-story façade (Pomponi et al. 2016). These classifications refer to the design and construction of the DSF, while there are no specifications to date on the optimum design for energy efficiency according to climate (Wood & Salib 2013).

Studies around the world on the performance of DSFs stress the difficulties of accurately simulating the airflow that takes place in the cavity (Høseggen, Wachenfeldt, & Hanssen 2008; Chan et al. 2009; Halil & Mesut 2011; Kim & Park 2011). The studies are based on both simulations and experimentation, where the experimental results validate the simulation results, and vice-versa. Although there are still no official specifications on DSF optimum design, especially in relation to climatic conditions, results show a good agreement between the experimental and simulation results (Quesada et al. 2012; De Gracia et al. 2013). Studies on DSF performance are still taking place, albeit with a higher level of certainty on thermal simulations as a valid research tool.

The proposed DSF under study is a corridor DSF, where the DSF is segmented per floor level, and has two windows on the exterior layer (top and bottom) for allowing natural ventilation to passively cool the structure (see Figure 3). The introduction of natural ventilation will essentially reduce high cooling loads that are prominent in the Mediterranean climate of Tel Aviv, where this study takes place. Studies on DSF energy

Internal Heat Gains for a Typical Office (460 m² per floor)	
People	45 per floor
Ventilation	0.1125 m³/s
Infiltration	0.6 ACH
Lights	7.2 W/m²
Equipment	11 W/m²
Mass Wall (S)	U-value: 1.02 [W/m²-K]
Mass Wall (N/E/W)	U-value: 0.54 [W/m²-K]
Clear Glazing 6 mm	U-value: 5.778 [W/m²-K]
Double Glazing Low-e 6 mm/13 mm Air	U-value: 1.626 [W/m²-K]

Operational Schedule	
Heating	**Cooling**
until 07:00, 15°C	until 07:00, off
until 20:00, 20°C	until 20:00, 26°C
until 24:00, 15°C	until 24:00, off

Table 1. Simulation data for office reference model; internal heat gains, natural ventilation, and envelope characteristics. Heating operates when temperature drops below 15°C, and cooling operates when temperature rises above 26°C. Building envelope in accordance with Israel's Green Building Standards.

> "The authors' double-skin façade (DSF) design is a deviation from the typical DSF arrangement seen predominately in temperate climates, where the double low-e glazing is positioned as the interior layer of the double skin."

efficiency in hot and humid climates are of special importance, due to the high levels of solar radiation entering a glass envelope, resulting in high cooling loads. In this paper, the energy efficiency of a naturally ventilated double-skin envelope is studied in relation to the energy efficiency of the high-rise building typology in general, with a focus on reducing the high cooling loads prevalent in this and other humid climates. The methodology draws on the conclusions from two previous publications (Saroglou et al. 2019 & 2020), and investigates further an optimum DSF design for energy efficiency according to climatic conditions, building height, and interior thermal comfort.

Methodology

Simulations are conducted using EnergyPlus that include a variable in its calculations, estimating wind acceleration with height according to ASHRAE (2009), and air temperature drop by elevation, while energy loads are calculated in relation to indoor thermal comfort standards: 20°C for winter, and 26°C for the summer (Fanger 1970; Givoni 1981). The simulated reference model is an office building with high loads, to accentuate even further the requirement of reducing high cooling loads. The envelope specifications, wall U-values and window-to-floor ratio (WFR), meet the voluntary Energy Rating of Buildings Standard (SI 5282), which is one of the basic requirements in the Sustainable Construction Standard (SI 5281) (SII 2011) (see Table 1).

Simulations are conducted at five floor levels: 9 meters (ground level), 82, 167, 235, and 340 meters, for the first phase, and at three floor levels: 9, 167, and 339 meters for the second and third phases. The specific floor heights are taken from CTBUH database on typical tall building characteristics for office buildings (2.7 meters for occupiable space with a 1.2-meter plenum) (CTBUH 2015). Every floor level of 3.9 meters' height has a total of eight corridor DSFs, covering all orientations: 1: SE-E, 2: SE-S, 3: SW-S, 4: SW-W, 5: NE-E, 6: NE-N, 7: NW-N, 8: NW-W.

In Phase 1, a comparison is made between three envelope scenarios; one is with low-e glazing and external shading; another with a DSF envelope with low-e glazing as layer 1 and single-clear as layer 3; and a third with a DSF with low-e glazing as layer 3, and single-clear as layer 1. Results of this study are based on a previous publication on best energy performance of glazing configurations in the Mediterranean climate (Saroglou et al. 2019), and are in favor of a DSF design with: low-e double-glazing as the exterior layer 3; a 1-meter air cavity for layer 2; and single glazing as the interior layer 1. This is a deviation from the typical DSF arrangement seen predominately in temperate climates, where the double low-e glazing is positioned as the interior layer of the double skin.

In Phase 2 the focus is on the optimum DSF width, according to Tel Aviv climatic conditions. The simulated DSF cavity widths are: 0.2, 0.5, 1.0, and 2.0 meters deep, at 9, 167, and 339 meters' height. An initial analysis of the results of this study was published (Saroglou et al. 2020). Energy load reductions, both for heating and cooling, are recorded when increasing the cavity width, with a focus on cooling, as heating loads are very low to begin with. In order to best adjust the DSF design throughout the year, two windows are considered on the exterior glazing layer of the double skin, an air inlet at the bottom, and an air outlet at the top, each at a floor level of 3.9 meters high. These close during the cold season, from 1 November to 31 March (air buffer DSF), and open during the hot season from 1 April–31 October (external air curtain DSF). Airflow Network

(AFN) in EnergyPlus calculates the airflow between the three zones (stack effect and buoyancy), and the heat transfer to and from the thermal zone of the building. However, an hourly analysis of the DSF behavior for a summer day, 21 June, and for a winter day, 21 December, showed that cooling requirements are also present during winter and are relevant to the: exterior environmental conditions, interior thermal comfort standards, time of the day, width of the cavity, and building height.

In Phase 3, further simulations are conducted, with a focus on reducing the cooling loads present during winter, for all DSF widths. Four more days are simulated, and an hourly analysis of the heating and cooling loads is made for 10 and 20 January, and for 10 and 20 February. Conclusions are drawn on the heating and cooling requirements between the different DSFs for the different dates, while the hourly analysis provides an in-depth understanding between heating versus cooling requirements throughout the course of a winter day. Further simulations are then performed for reducing the high cooling requirements by taking the example of the "worst" DSF scenario.

Simulation Results and Discusion

Phase 1

Figure 4 shows the heating and cooling loads between three envelope scenarios: a single-skin envelope with low-e glazing and exterior shading devices; a double-skin envelope with low-e-glazing as layer 1 and single-clear glazing as Layer 3; and a third option where the low-e-glazing is layer 3 and a single-clear layer 1. For all scenarios, the thermal properties of the envelope materials are designed according to Table 1. From Figure 4, it is obvious that with height, cooling energy drops, while heating increases for all scenarios. However, the cooling requirements are much more intense in relation to heating. In addition, the cooling versus heating loads work in a reverse manner, meaning that at ground level (9 meters high) are found the lowest heating and highest cooling loads; while at 339 meters, are found the highest heating and lowest cooling loads, with the cooling-load differential still being much more intense between the two.

Further comparisons between the different scenarios shows that the building envelope with external shading performs better in relation to the DSF design with the low-e glazing as layer 1, with the DSF having higher heating loads at ground level, while with height, their differences are diminished. However, the implementation of shading devices is not popular, especially in high-rise buildings, on account of potentially blocking valuable views, reducing natural light and therefore increasing the need for artificial lighting, while a DSF envelope is suitable for maintaining a desired level of transparency as well as energy reductions. In addition, further issues, like maintenance and cleaning of the building's windows, also come into play when comparing the two options. Continuing the simulations on the energy efficiency of DSFs for the climatic conditions of Tel Aviv, results show that positioning the low-e glazing as the exterior layer of the DSF (3), and the single-clear glazing as the interior façade layer (1), cooling loads drop considerably from the first DSF option, and reduce even further from the scenario of low-e glazing and shading. By placing the low-e coatings on the exterior façade layer, the insulating performance of the glass is increased, as the ultraviolet part of the spectrum is reflected before entering the DSF zone, while the single clear glazing on the façade layer of the thermal zone allows exhausting heat gains, ideal for the hot and humid Mediterranean climate of Tel Aviv.

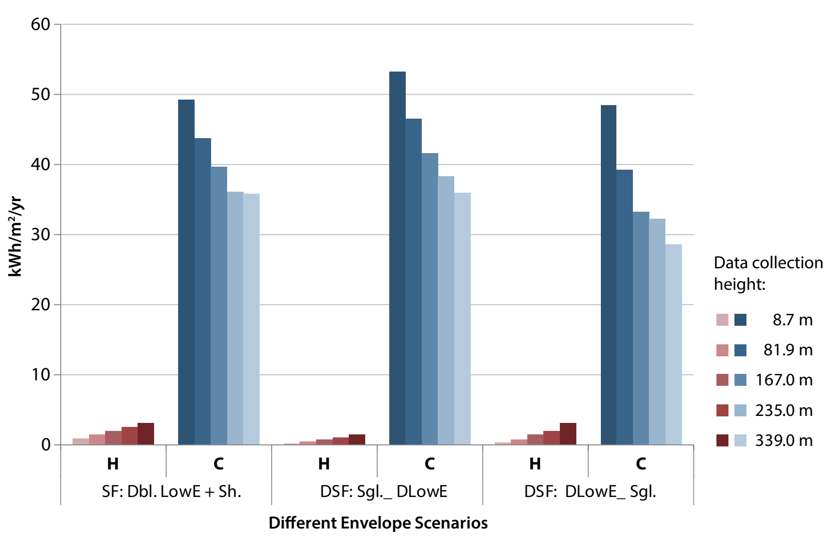

Figure 4. Heating (H) and cooling (C) loads of three envelope scenarios: (1) SF (single façade): Double-low-e and shading (Sh.); (2) DSF: double-skin façade consisting of single (outer) plus double-low-e (inner), and (3) DSF: double-skin façade consisting of double-low-e (outer) + single (inner). U-values of wall-to-window ratios are set according to Israel's GBS.

Phase 2

Figures 5 and 6 show the heating and cooling loads of four DSF width scenarios: 0.2, 0.5, 1.0, and 2.0 meters, at three height levels, L1: 8, L2: 167, and L3: 339 meters. Figure 5 depicts cooling loads for 21 June. From the graph, it is obvious that the highest cooling loads occur between 12:00 and 16:00; likewise, within the lines of the results of Phase 1, is that heating loads increase with height, while cooling loads drop. In addition, the increase of the cavity width has a positive effect on cooling loads by decreasing them, with the 2.0-meter DSF presenting the lowest values, especially at 339 meters' height.

Figure 6 depicts 21 December. It shows that heating loads are present during the

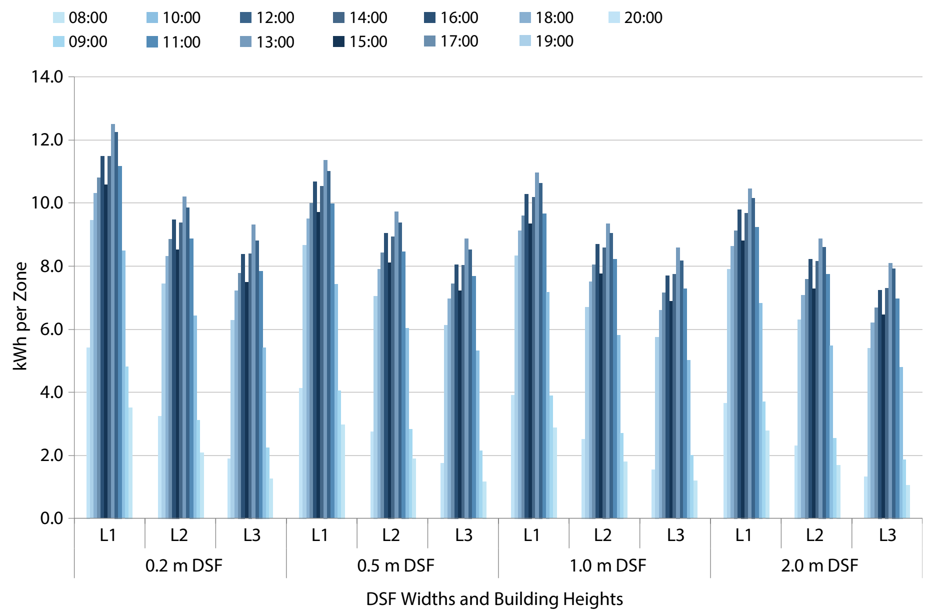

Figure 5. Hourly data of cooling (C) loads of four DSF width scenarios: 0.2 m, 0.5 m, 1.0 m, and 2.0 m, between 08:00 and 20:00 for the 21 June (no cooling occurring between these hours). L1: 8.7 m, L2: 167 m, and L3: 339 m.

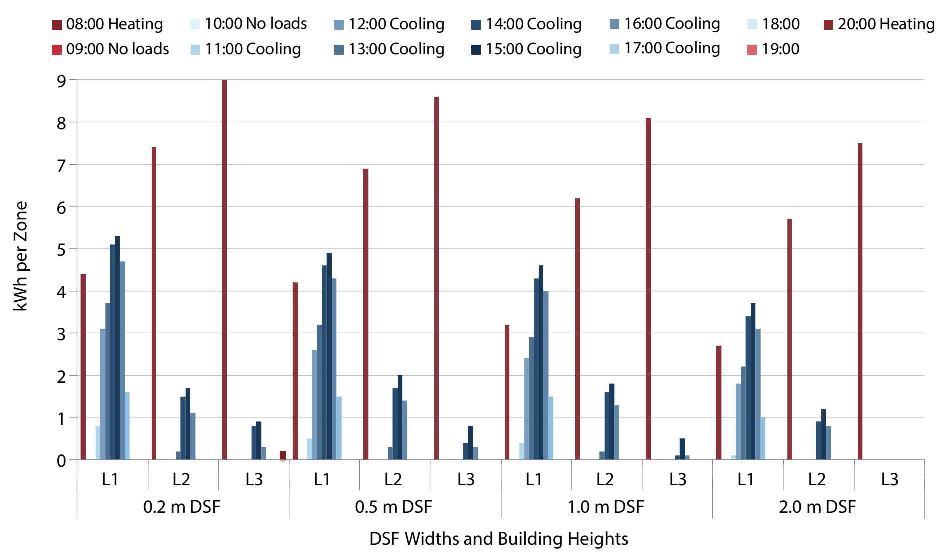

Figure 6. Hourly data of heating (H) and cooling (C) loads of four DSF width scenarios: 0.2 m, 0.5 m, 1.0 m, and 2.0 m, between 08:00 and 20:00 for the 21 December. L1: 8.7 m, L2: 167 m, and L3: 339 m.

morning and evening hours, while after 11:00 and until about 17:00, cooling loads are also present, even during this winter day. The highest cooling loads are observed at ground level (9 meters high) for the 0.2-meter DSF, while by increasing the DSF width, both heating and cooling loads are reduced. These results prompted further studies on the behavior of the DSF on a winter day, which take place in Phase 3.

Phase 3

Figure 7 depicts four more winter dates: 10 and 20 January, and 10 and 20 February, for the different DSF widths: 0.2, 0.5, 1.0, and 2.0 meters. Expanding the winter day's simulations, we see similar patterns in terms of heating requirements, with heating loads being present during the early hours of 08:00–09:00, and 19:00-20:00 in the evening. On the other hand, cooling is only present during 20 January and 20 February, and it's relevant to the higher ambient temperatures that occur during these dates. The pattern of cooling loads during these two dates is similar with the previous results of 21 December, with cooling requirements taking place between 11:00 and 17:00, and peak times between 13:00–15:00.

The highest cooling loads are observed for the 0.2-meter DSF at ground level of 9 meters high, on 20 February. As a next step towards advancing the energy efficiency of the structure, this case scenario is simulated with the DSF alternating between an airtight (air-buffer DSF) and an open (external air-curtain DSF), depending on the temperatures that are created within the cavity. Figure 8 depicts a comparison on the energy loads, heating and cooling, between scenario A and B for 20 February. In scenario A, the DSF is airtight, and in scenario B, it is alternating between an airtight and an open space, from 08:00-20:00. Results show that scenario B achieves cooling load reductions of up to 50 percent less.

Conclusions

The increasing number of high-rise buildings around the world directs the spotlight towards their energy performance and efficiency. This paper focused on the initial design strategies of the building envelope, by taking into consideration the specific climatic conditions of its location, i.e., Tel Aviv. Energy efficiency comparisons are made between different curtain-wall envelopes, and their relationship with the changing environmental variables with height. The intention of the simulated curtain wall designs was to depict current architectural practices, especially evident in high-rise construction, and propose strategies towards improving their energy performance, through appropriate detailing.

Results showed increased energy savings, with a focus on cooling, between single-skin and double-skin envelopes (with an average of 50 percent less energy expended in the double-skin scenario), while further adjustment of the DSF design to fit the specific climatic conditions reduced energy loads even further. An average reduction of 15 percent was observed in the DSF scenario with low-e glazing as the exterior layer. Further reductions occurred when increasing the DSF width, while an hourly analysis during a winter day revealed the presence of both heating and cooling loads, with a focus again on cooling. By considering a dynamic

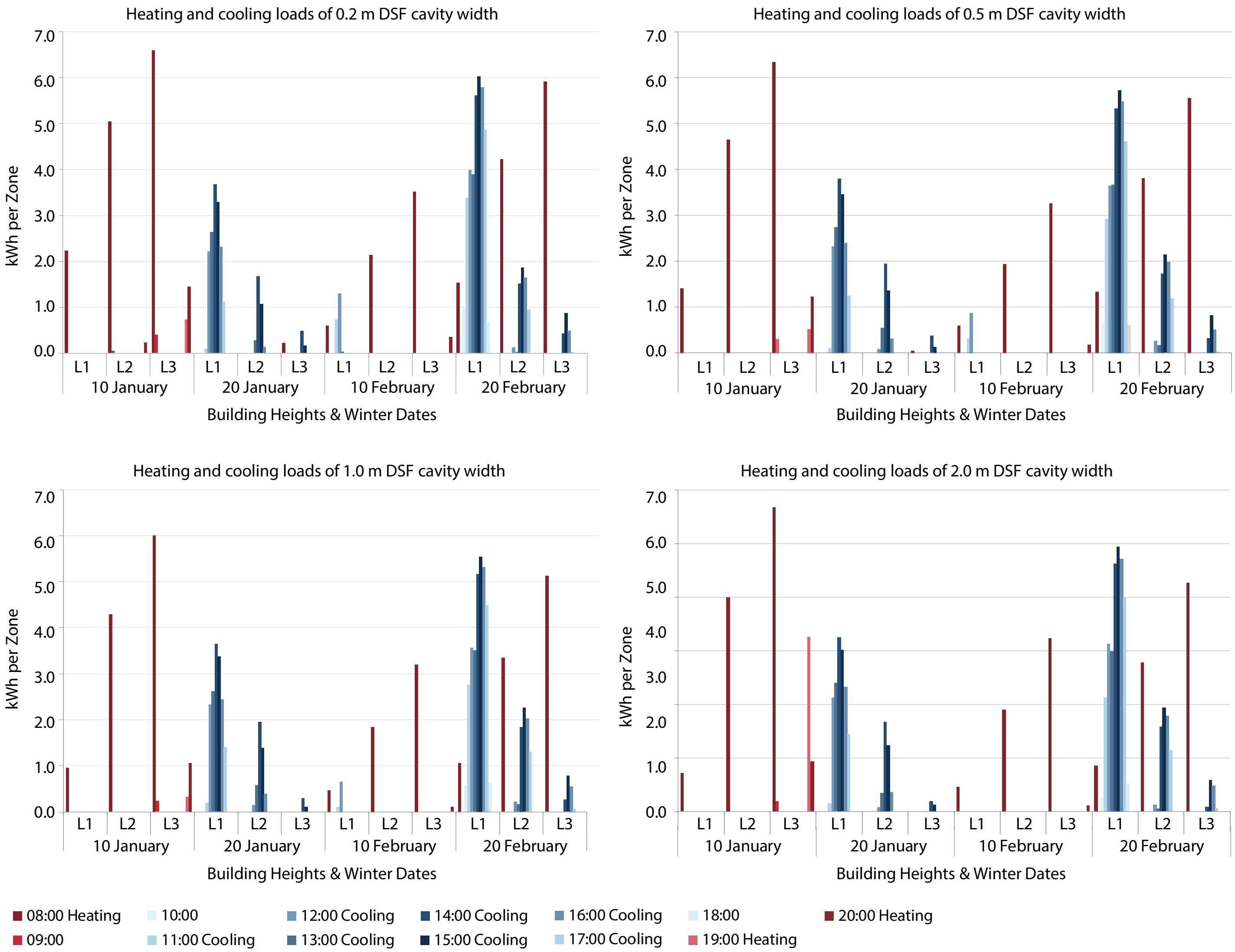

Figure 7. Hourly data of heating (H) and cooling (C) loads of four DSF width scenarios: 0.2 m, 0.5 m, 1.0 m, and 2.0 m, between 08:00 and 20:00 for the 10 January, 20 January, 10 February, and 20 February. L1: 8.7 m, L2: 167 m, and L3: 339 m high.

DSF envelope design that alternates between airtight and open-air, according to the temperatures that are created with the cavity, winter cooling loads dropped by 50 percent (in Phase 3).

The main design parameters of this study are: the thermal properties of the double-skin envelope, the width of the double-skin cavity, and the natural ventilation potential of the cavity (airtight / open DSF); the researchers examined how these can be used in an optimal way for reducing the energy loads of a high-rise structure located in Tel Aviv. The above findings point out the importance of carefully detailing the building envelope during the initial design stages in order to improve the energy efficiency of the structure, based on the specific climatic conditions of its location. ■

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References

Ahmed, M. M. S., Abel-Rahman, A. K., Ali, A. H. H. & Suzuki, M. 2015. "Double Skin Façade: The State of Art on Building Energy Efficiency." ***Journal of Clean Energy Technologies*** 4(1): 84–89. doi: 10.7763/JOCET.2016.V4.258.

Allard, F. & Santamouris, M. (eds.) 1998. ***Natural Ventilation in Buildings: A Design Handbook.*** New York: Routledge.

American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE). 2009. "Airflow Around Buildings." In ***ASHRAE Fundamentals.*** Altanta: ASHRAE.

Capeluto, G. & Ochoa, C. E. 2013. "On the Determination of Climate Strategies for A Multifunctional Energy Retrofit Façade System." In ***CISBAT 2013 Proceedings*** Volume 1, edited by: Jean-Louis Scartezzini, pp. 49–54. doi: 10.1017/CBO9781107415324.004.

Chan, A. L. S., Chow, T. T., Fong, K. F. & Lin, Z. 2009. "Investigation on Energy Performance of Double Skin Façade in Hong Kong." ***Energy and Buildings*** 41(11): 1135–42. doi: 10.1016/j.enbuild.2009.05.012.

Cheung, C. K., Fuller, R. J. & Luther, M. B. 2005. "Energy-Efficient Envelope Design for High-Rise Apartments." ***Energy and Buildings*** 37(1): 37–48. doi: 10.1016/j.enbuild.2004.05.002.

Choi, I. Y., Cho, S. H. & Kim, J. T. 2012. "Energy Consumption Characteristics of High-Rise Apartment Buildings According to Building Shape and Mixed-Use Development." ***Energy and Buildings*** 46: 123–31. doi: 10.1016/j.enbuild.2011.10.038.

Cook, R., Browning, B. & Garvin, C. 2013. "Sustainability and Energy Considerations." In ***The Tall Buildings Reference Book,*** edited by: David Parker & Antony Wood. New York: Routledge, pp.145–55.

CTBUH. 2015. "CTBUH Height Criteria." Accessed on 15 June 2016. https://www.ctbuh.org/resource/height

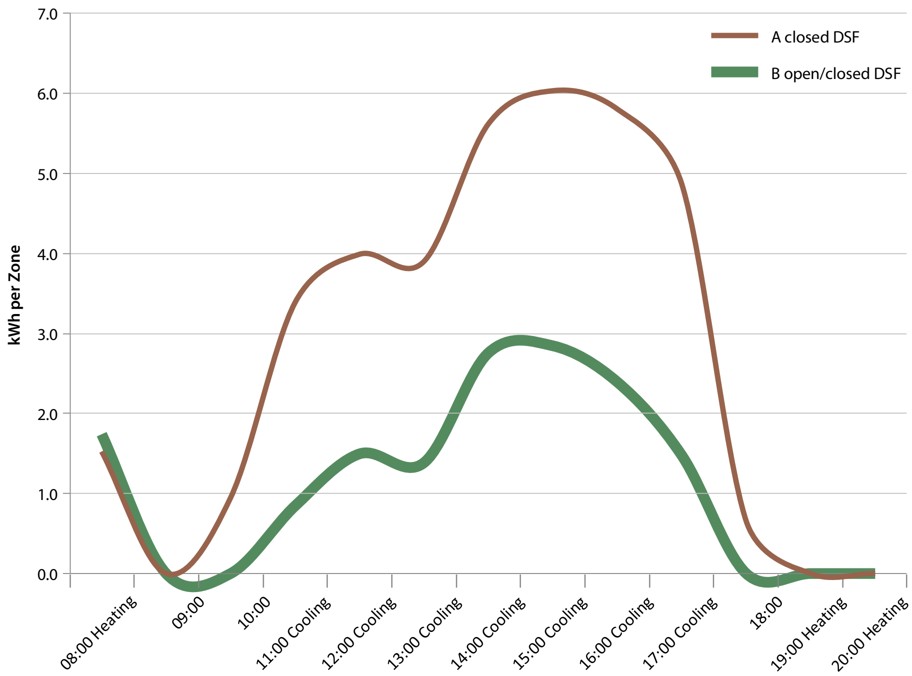

Figure 8. Comparisons of hourly data of heating (H) and cooling (C) loads of the 0.2-meter-width DSF at 8.7 meters high, between 08:00 and 20:00 for 20 February, in scenario A: closed DSF, and scenario B: open/closed DSF, according to temperature highs within the cavity.

De Gracia, A., Castell, A., Navarro, L., Oró, E. & Cabeza, L. F. 2013. "Numerical Modelling of Ventilated Façades : A Review." ***Renewable and Sustainable Energy Reviews*** 22: 539–9. doi: 10.1016/j.rser.2013.02.029.

Donnolo, M., Galatro, V. & Janes, L. 2014. "Bank of America Tower at One Bryant Park: New York City, NY." ***High Performing Buildings:*** 51–58.

Ellis, P. G. & Torcellini, P. A. 2005. "Simulating Tall Buildings Using Energyplus." In ***Proceedings of Building Simulation Conference 2005***, Montreal, August 15–8, pp. 279–86.

Etheridge, D. & Ford, B. 2008. "Natural Ventilation of Tall Buildings-Options and Limitations." In ***Tall & Green: Typology for a Sustainable Urban Future,*** edited by: Antony Wood, pp. 226–32.

European Union (EU). 2010. "Directive 2010/31/EU of The European Parliament and of The Council of 19 May 2010 on the Energy Performance of Buildings." ***Official Journal of the European Union*** 53: 13–35.

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

Fox, J. 2011. "Tel Aviv's Skyline in 2025." Accessed on 28 January 2016. https://www.smartcitiesdive.com/ex/sustainablecitiescollective/tel-aviv-s-skyline-2025/22464/

Ghaffarianhoseini, A., Ghaffarianhoseini, A., Berardi, U., Tookey, J., Li, D. H. W. & Kariminia, S. 2016. "Exploring the Advantages and Challenges of Double-Skin Façades (DSFs). ***Renewable and Sustainable Energy Reviews*** 60: 1052–65. doi: 10.1016/j.rser.2016.01.130.

Givoni, B. 1981. ***Man, Climate and Architecture.*** New York: Van Nostrand Reinhold.

Haase, M., da Silva, F. M. & Amato, A. 2009. "Simulation of Ventilated Façades in Hot and Humid Climates." ***Energy and Buildings*** 41(4): 361–73. doi: 10.1016/j.enbuild.2008.11.008.

Halawa, E., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Trombley, J., Hassan, N., Baig, M., Yusoff, S. Y. & Ismail, M. A. 2018. "A Review on Energy Conscious Designs of Building Façades in Hot and Humid Climates : Lessons For (And From) Kuala Lumpur and Darwin. ***Renewable and Sustainable Energy Reviews*** 82, Part 3: 2147–61. doi: 10.1016/j.rser.2017.08.061.

Halil, Z. A. & Mesut, B. O. 2011. "Thermal Comfort of Multiple-Skin Façades in Warm-Climate Offices." ***Scientific Research and Essays*** 6(19): 4065–78. doi: 10.5897/SRE11.319.

Hamza, N. 2008. "Double Versus Single Skin Façades in Hot Arid Areas." ***Energy and Buildings*** 40(3): 240–8. doi: 10.1016/j.enbuild.2007.02.025.

Høseggen, R., Wachenfeldt, B. J. & Hanssen, S. O. 2008. "Building Simulation as an Assisting Tool in Decision Making. Case Study: With or Without a Double-Skin Façade?" ***Energy and Buildings*** 40(5): 821–7. doi: 10.1016/j.enbuild.2007.05.015.

Joe, J., Choi, W., Kwak, Y. & Huh, J. 2014. "Optimal Design of A Multi-Story Double Skin Façade." ***Energy and Buildings*** 76: 143–50. doi: 10.1016/j.enbuild.2014.03.002.

Kim, D. W. & Park, C. S. 2011. "Difficulties and Limitations in Performance Simulation of a Double Skin Façade with Energyplus." ***Energy and Buildings*** 43(12): 3635–45. doi: 10.1016/j.enbuild.2011.09.038.

La Roche, P. 2012. "Buildings and Greenhouse Gas Emissions." In ***Carbon-Neutral Architectural Design.*** New York: Taylor & Francis Group: 1–15.

Leung, L. & Ray, S. D. 2013. "Low-energy Tall Buildings? Room for Improvement as Demonstrated by New York City Energy Benchmarking Data." ***International Journal of High-Rise Buildings*** 2(4): 285–91.

Lotfabadi, P. 2014. "High-Rise Buildings and Environmental Factors." ***Renewable and Sustainable Energy Reviews*** 38: 285–95. doi: doi:10.1016/j.rser.2014.05.024.

National Oceanic and Atmospheric Administration (NOAA). 1976. ***U.S. Standard Atmosphere 1976.*** Washington, D.C.: NOAA. doi: 10.1017/CBO9781107415324.004.

Pomponi, F., Piroozfar, P. A. E., Southall, R., Ashton, P. & Farr, E. R. P. 2016. "Energy Performance of Double-Skin Façades in Temperate Climates: A Systematic Review and Meta-Analysis." ***Renewable and Sustainable Energy Reviews*** 54: 1525–36. doi: 10.1016/j.rser.2015.10.075.

Quesada, G., Rousse, D., Dutil, Y., Badache, M. & Hallé, S. 2012. "A Comprehensive Review of Solar Façades. Transparent and Translucent Solar Façades." ***Renewable and Sustainable Energy Reviews*** 16(5): 2643–51. doi: 10.1016/j.rser.2012.02.059.

Saroglou, T., Meir, I. A., Theodosiou, T. & Givoni, B. 2017. "Towards Energy Efficient Skyscrapers." ***Energy and Buildings*** 149: 437–49. doi.org/10.1016/j.enbuild.2017.05.057.

Saroglou, T., Theodosiou, T., Givoni, B. & Meir, I. A. 2019. "A Study of Different Envelope Scenarios Towards Low Carbon High-Rise Buildings in The Mediterranean Climate–Can DSF Be Part of the Solution?" ***Renewable and Sustainable Energy Reviews*** 113: 109237. doi: 10.1016/j.rser.2019.06.044.

Saroglou, T., Theodosiou, T., Givoni, B. & Meir, I. A. 2020. "Studies on the Optimum Double-Skin Curtain Wall Design for High-Rise Buildings in the Mediterranean Climate." ***Energy And Buildings*** 208: 109641. doi: 10.1016/j.enbuild.2019.109641.

Simmonds, P. 2015. ***ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems.*** Atlanta: ASHRAE/CTBUH.

Standards Institution of Israel (SII). 2011. ***SI 5281 Sustainable Building. Part 3: Requirements for Office*** Buildings. Tel Aviv: Standards Institute of Israel.

The City of New York (NYC). 2015. "About OneNYC Green Buildings & Energy Efficiency." Accessed on 15 January 2015. http://home2.nyc.gov/html/gbee/html/about/about.shtml

Tong, Z., Chen, Y. & Malkawi, A. 2017. "Estimating Natural Ventilation Potential for High-Rise Buildings Considering Boundary Layer Meteorology." ***Applied Energy*** 193: 276–86. doi: 10.1016/j.apenergy.2017.02.041.

Voss, K., Musall, E. & Lichtme, M. 2011. "From Low-Energy to Net Zero-Energy Buildings: Status and Perspectives." ***Journal of Green Building*** 6(1): 46–57. doi: https://doi.org/10.3992/jgb.6.1.46.

Wood, A. & Salib, R. 2013. ***Natural Ventilation in High-Rise Office Buildings.*** Chicago: CTBUH / Routledge.

YIK, F. 2005. "Cooling Energy Evaluation for High-Rise Residential Buildings in Hong Kong." ***Energy and Buildings*** 37: 345–51. doi: 10.1016/j.enbuild.2004.07.003.

Zhou, C., Wang, Z., Chen, Q., Jiang, Y. & Pei, J. 2014. "Design Optimization And Field Demonstration of Natural Ventilation for High-Rise Residential Buildings." ***Energy and Buildings*** 82: 457–65. doi: 10.1016/j.enbuild.2014.06.036.