

AKADÉMIAI KIADÓ

Performance trade-off in high-rise office building envelope design

Basma Naili^{1,4*} , István Háber^{2,4} and István Kistelegdi^{3,4}

Pollack Periodica •
An International Journal
for Engineering and
Information Sciences

17 (2022) 2, 121-126

DOI:

[10.1556/606.2022.00503](https://doi.org/10.1556/606.2022.00503)

© 2022 The Author(s)

¹ Marcel Breuer Doctoral School, Faculty of Engineering and Information Technology, Institute of Architecture, University of Pécs, Boszorkány u. 2, H-7624 Pécs, Hungary

² Department of Mechanical Engineering, Faculty of Engineering and Information Technology, Institute of Smart Technology and Engineering, University of Pécs, Boszorkány u. 2, H-7624 Pécs, Hungary

³ Department of Building Structures and Energy Design, Faculty of Engineering and Information Technology, Institute of Architecture, University of Pécs, Boszorkány u. 2, H-7624 Pécs, Hungary

⁴ Energia Design Building Technology Research Group, Szentágotthai Research Centre, University of Pécs, Ifjúság útja 20, H-7624 Pécs, Hungary

Received: October 22, 2021 • Revised manuscript received: January 20, 2022 • Accepted: February 4, 2022

Published online: May 4, 2022

ORIGINAL RESEARCH PAPER



ABSTRACT

The optimization of high-rise office buildings' envelope and the application of energy-efficient measures have become a priority nowadays. Therefore, this investigation aims to assess the role of the façade's geometry design factors, e.g., folded façade perforation, window orientation, and window-to-wall ratio on building comfort and energy performance. The energy simulations were performed using IDA ICE 4.8 thermal simulation program to evaluate the thermal and visual comfort and the energy consumption of various façade test models. The optimization resulted in a façade model with a great level of thermal and visual comfort as well as a total energy reduction of 14%, representing a good compromise solution in the trade-off between thermal and visual comfort as well as energy efficiency.

KEYWORDS

high-rise office building, façade morphology optimization, energy efficiency, thermal comfort, visual comfort, thermal simulation

1. INTRODUCTION

The design and the construction of high-rise office buildings are increasing in response to the several needs and challenges of today's modern society. New implementation plans are found all over the world. However, there are only a few well-performing examples. A poorly designed high-rise building envelope can considerably increase the building's appetite for energy. Therefore, high-rise building façade optimization is a major stake to consider during the design process [1, 2]. For this reason, study [3] attempts to promote skyscraper energy efficiency by investigating climate responsive design strategies, for example orientation, thermal properties of the building envelope, and the effect of altitude on high-rises. The subject of the investigation was two reference models, a residential and an office one located in a hot humid climate. Initial thermal simulations were performed on a 100 m high structure, to gradually upgrade the building envelope and to examine its relationship with the changing microclimate between the ground and the upper levels. Then the advanced envelope was simulated again at higher altitudes up to 400 m height, to gain a better understanding of the wind acceleration effects, and the air temperature drops on energy consumption. Therefore, comparisons of the heating and the cooling loads of different building heights and building types were made. The results showed that the microclimate changing with height affects the energy performance: the cooling energy decreases, while the

*Corresponding author.

E-mail: basma.naili.m@gmail.com



heating energy increases. Findings also indicated that the use of shading devices reduces the cooling energy consumption by around 30% for both office and residential towers.

A further study [4], investigated a high-rise building envelope applying passive design strategies to reduce the building energy loads. Thermal simulation-based initial analysis was carried out on three single-skin and a ventilated double-skin envelopes located in the Mediterranean climate. The analysis evaluated the heating and cooling loads as well as their relationship with the changing environmental variables and building height. Thereafter, the focus was shifted to increase the energy efficiency of the double-skin façade. A comparison was made between four double-skin façade scenarios, with different glazing types and orientations. The findings were in favor of the double skin façade options. As a result, the study supports that considerable energy saving can be achieved by adapting the building envelope design to the specific location and climate conditions, and by taking advantage of passive strategies, such as natural ventilation of a double skin façade cavity. Drawing from the conclusions of this investigation, a next double-skin façade study [5] aimed at the reduction of the high cooling loads relevant to the Mediterranean climate. The energy efficiency of different double-skin façade cavities was tested by calculations of thermal models. Results revealed that increasing the width of the cavity from 0.2 to 0.5 m can considerably decrease the cooling load, and also great reductions can be achieved with 1.0 and 2.0 m double-skin façade cavity width solutions.

Although, there have been several studies on envelope parameters of offices buildings [6], and tall office buildings such as window thermal properties, shading systems [7, 8], as well as double-skin façade strategies [9], the effects of building envelope geometry factors for instance comfort and energy consequences of the perforation and morphological structure of the façade, have been only partially covered in a few studies. These projects focused mainly on the integration of active systems Photo Voltaic (PV) panels for example [10–12], or studies dealing with low-rise buildings [13–15].

This paper is the extension of a façade morphology optimization research, presented previously [16]. A case study task has been set to optimize the envelope and the shading systems for a design competition entry. This design optimization task represents generic dimensions, appropriately suitable for typical high-rise office building optimization in a temperate climate zone. A large fully glazed façade of a bank tower project in Budapest, Hungary had to be optimized to avoid summer overheating and glare effect. Multiple façade variants were tested by assessing the thermal and visual comfort, as well as the energy demand with thermal simulations. Results revealed the best-performing, optimized façade configuration in terms of comfort and energy efficiency. The present paper draws from the findings of the previous study to investigate the fenestration geometry parameters of the building (window to wall ratio, and window orientation) together with the grade of the façade perforation, and to define the morphological parameters with the highest impact and potential in thermal and visual comfort as well as in heating and cooling energy efficiency.

2. METHODOLOGY

In a previous study, the envelope parameters of a high-rise office building in the temperate climate zone were investigated: the building's two large fully glazed façades facing East and West had to be optimized based on energy simulations. The best performing façade configuration in terms of comfort and energy efficiency was represented by the 'zig-zag' double-skin façade, a horizontally folded surface that saved up to 47% heating and cooling energy in comparison with a simple curtain wall or the simple double-skin façade. This version serves as the reference case for comparison purposes. The typical floor level of the reference zig-zag façade design and the orientation are shown in Fig. 1.

The high-rise office building reference model is 88.0 m high, including 22 floors, oriented along the North-South axis. Simulations were conducted at two intermediate floors (13 and 14), approximately 57.0 m above ground level. The building model was developed in the IDA ICE 4.8 dynamic building indoor climate and energy simulation program to assess:

- Thermal comfort (No. of hours with operative temperatures, $T_{op} \geq 26$ °C);
- Visual comfort (average daylight factor) and (average daylight level);
- Heating and cooling energy demand (delivered energy, kWh/m²a).

The methodological scheme that shows the concept of this study is illustrated in Fig. 2. The focus of the research was the modification of the reference double-skin façade zig-zag configuration, which consists of two different horizontally

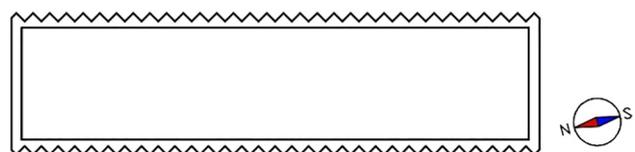


Fig. 1. Reference case – the zig-zag double-skin façade with the orientation

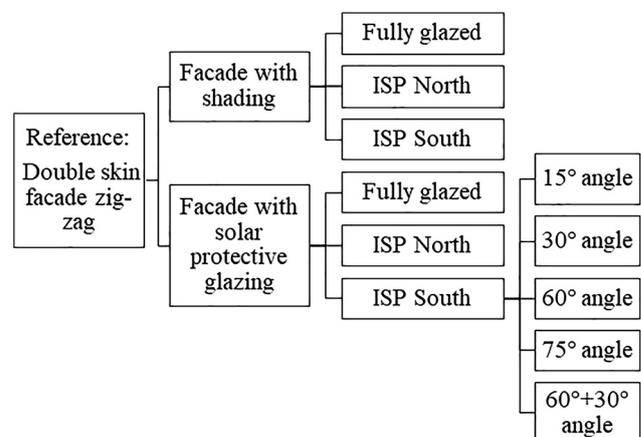


Fig. 2. Methodological scheme of the façade investigation cases

tilted façade faces (45°) to provide effective shading to the low-elevation angle solar radiation from East and West. The methodology comprises two basic steps:

First step: Based on the previous research result data, the two best-performing models, the 45° zig-zag double-skin façades with solar protective glazing and with integrated shading were selected. By changing the glazing of each second façade face to an Insulated Sandwich Panel (ISP), the shading (and hence cooling) efficiency should be increased. The ISPs were added to each second North-oriented face, then to the South sides of the zig-zag façade surfaces.

Second step: As the South facing ISP performed the best results, the tilt angle of the façade folding was changed several times from 45° to 15° , 30° , 60° , and 75° , as well as the Window-to-Wall Ratio (WWR) from 90% (fully glazed reference version) to 81%, 67%, 55%, 44%, and 32% (Figs 3 and 4 and Table 1).

The different façade configurations implemented in the study and the simulation input data and operation details are presented in the following Tables 1 and 2. Façade Scenarios (FS) 01, FS02, and FS03 represent the zig-zag double-skin façade with integrated shading cases group. FS01, the reference model, is fully glazed, FS02 has ISP to the North, and FS03 is equipped with ISP on the South-oriented surface. The variations of (FS04-FS10) represent the zig-zag double-skin façade group with solar protective glazing cases. FS04 is fully glazed, FS05 has ISP to the North, and all other

cases have ISP to the South with different tilt angles, and different window-to-wall ratios (Table 1). Besides the 45° folded façade geometry, four tilting steps are considered as 15° , 30° , 60° , and 75° to test different grades of South-oriented structural shading solutions. Finally, the last model FS11 which includes the two best performing configurations, FS08 and FS09, each on a floor, whereas alternating 30° and 60° tilted and folded façade perforation should provide eventually optimal results among the investigated cases.

The ISP consists of a double-sided aluminum sandwich structure with Expanded PolyStyrene (EPS) foam core. The thermal properties are shown in (Table 2). In all façade scenarios, the inner glazing is composed of two-panes of thermal insulation glazing (4–12–4 mm). As outer glazing, two different configurations have been applied; the first one involves FS01, FS02, and FS03 containing one 4 mm thermal insulation glazing pane with integrated shading (blinds) and automated solar radiation control (blinds are drawn when radiation is above 100 W/m^2 at the outer pane). The other glazing consists of one external solar protective glazing pane, for the following cases: FS04 – FS11.

3. RESULTS AND DISCUSSION

3.1. Thermal comfort

As it is presented in Fig. 5, the simulation results show the performance result for the Indoor Air Quality (IAQ), which represents the CO_2 level in the interior office spaces. The results vary between 648 and 650 ppm in all the cases, which is considered a high IAQ performance. For the average thermal comfort assessment (No. of hours with $T_{op} \geq 26^\circ\text{C}$) see Fig. 5. The general trend of the results indicates a gradual decrease of thermal discomfort hours by the integration of the ISP-s. Adding the ISP-s to the North side of the façade improved the results by 58%, then with South-oriented ISP-s, thermal comfort was further improved by 92%. The solar protective glazing cases generated better results in general. In FS04 and FS07, the number of discomfort hours was slightly higher due to the high window-to-wall ratio (FS04 with 90% and FS07 with 81%). In the rest of the models, the results were the best, with almost no discomfort hours. Summing up, the thermal comfort performance was highest by implementing the ISP in South orientation.

3.2. Visual comfort

Regarding the average Daylight Factor (DF_{AVE}) results, indicating the visual comfort values, see Fig. 6. The best performing models were FS04 and FS01 with DF_{AVE} 9.9 and 7.2 respectively, due to the fully glazed façades. By integrating the ISP-s the DF_{AVE} value decreased between 4.4 and 2.2 depending on the variation of the window-to-wall ratio. Being above the 1.7 threshold [17], for all façade scenarios, these performances are still acceptable. However, due to the very low window-to-wall ratio of FS09 and FS10 cases, the results here were not suitable (1.5–0.9).

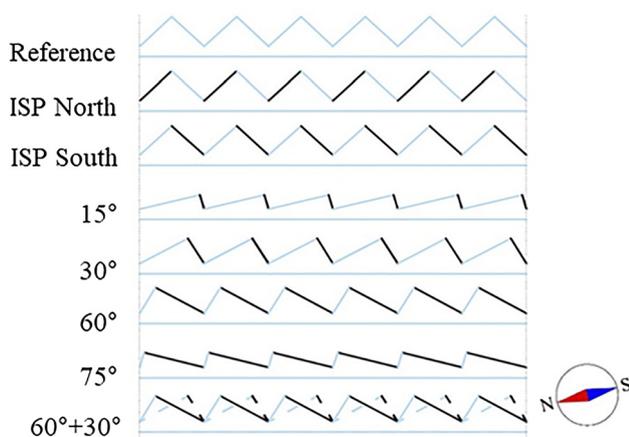


Fig. 3. Folding versions and the orientation of the zig-zag façade – eight base façade units' detail

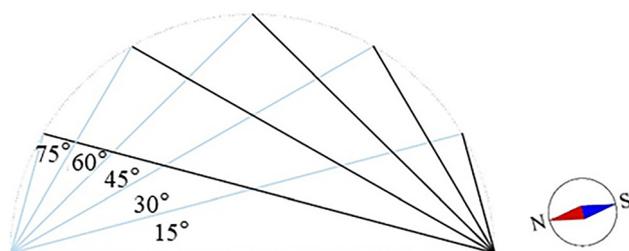


Fig. 4. Folding versions and the orientation of the zig-zag façade – one base façade unit detail

Table 1. Façade optimization scenarios

Façade scenarios	Folding angle	WWR	Zig-zag double skin façade configuration		
FS01		45°	90%	Fully glazed – reference case	Integrated shading
FS02		45°	55%	ISP North	
FS03		45°	55%	ISP South	
FS04		45°	90%	Fully glazed – reference case	Solar protective glazing
FS05		45°	55%	ISP North	
FS06		45°	55%	ISP South	
FS07		15°	81%	ISP South	
FS08		30°	67%	ISP South	
FS09		60°	44%	ISP South	
FS10		75°	32%	ISP South	
FS11		60°+30°	53%	ISP South	

Table 2. Simulation input data and operation details

		FS01	FS (02–03)	FS04	FS (05–11)
Sandwich panel 100 mm	Thermal conductivity [W/(m K)]	–	0.0225	–	0.0225
	Density [kg/m ³]	–	20	–	20
	Specific heat [J/(kgK)]	–	1,400	–	1,400
Inner Glazing	Solar Heat Gain Coefficient	0.76	0.76	0.76	0.76
	T _{vis} , Visible transmittance	0.81	0.81	0.81	0.81
	Glazing U-value [W/m ² K]	1.1	1.1	1.1	1.1
Outer Glazing	Pane	2 pane thermal insulation glazing, 4–12–4 mm	2 pane thermal insulation glazing, 4–12–4 mm	2 pane thermal insulation glazing, 4–12–4 mm	2 pane thermal insulation glazing, 4–12–4 mm
	Solar Heat Gain Coefficient	0.85	0.85	0.26	0.26
	T _{vis} , Visible transmittance	0.9	0.9	0.54	0.54
Integrated Window Shading Auto control	Glazing U-value [W/m ² K]	5.8	5.8	5.8	5.8
	Pane	1 pane thermal insulation glazing, 4 mm	1 pane thermal insulation glazing, 4 mm	1 pane solar protective glazing, 4 mm	1 pane solar protective glazing, 4 mm
	Blinds	Blinds	Blinds	–	–
		≥100 [W/m ²] solar radiation at outer pane draws shading	≥100 [W/m ²] solar radiation at outer pane draws shading	–	–



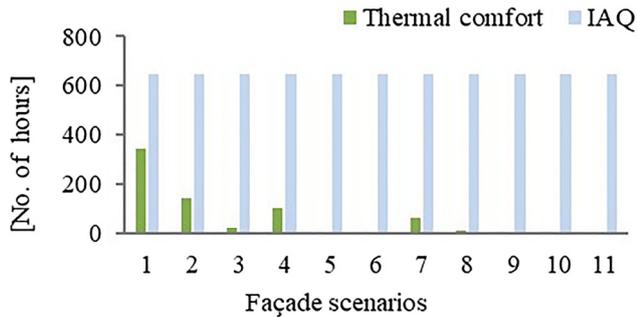


Fig. 5. Results: indoor air quality No. of hours with CO₂ concentration ≤1,000 ppm and thermal comfort No. of hours with Top ≥ 26 °C

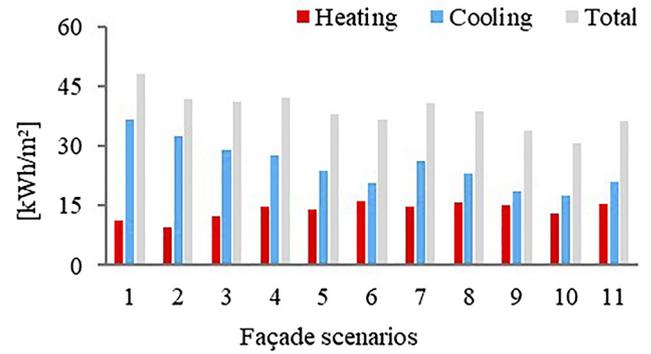


Fig. 8. Results: energy (cooling, heating, and total)

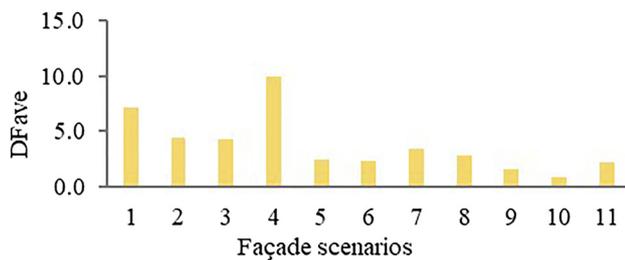


Fig. 6. Results: visual comfort (average daylight factor)

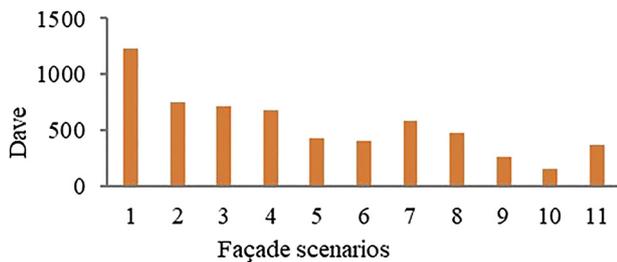


Fig. 7. Results: visual comfort (average Daylight level)

Assessing the average Daylight level (D_{AVE}), the general character of the results is very similar to the average daylight factor results, progressively decreasing, depending on the window-to-wall ratio changes and the presence of the ISP-s and their orientation (Fig. 7).

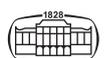
3.3. Energy: cooling and heating

The heating and cooling energy results (Fig. 8) produced trend results similar to the thermal comfort performance distribution but unlike the visual comfort characteristics. The integration of the ISP-s, particularly in the South, reduced energy consumption in general. The group of zig-zag façades with integrated shading (louvers) cases was the least efficient (FS01-03 models). The FS01 model had the highest energy consumption overall. In the FS02 case with ISP-s in the North sides, the consumption decreased by 12.5%, and with the ISP-s in the South (FS03), it decreased further by 14%. However, the group of zig-zag façades with solar protective glazing cases (FS04-FS10) performed better

results: with the ISP-s in the North sides of the folded façades (FS05) 10% saving was made, then with the ISP-s in the South the savings results improved as follows: FS06 13%, FS07 3%, FS08 8%, FS09 20%, and FS10 27% (and 35% compared to the reference FS01). The FS10 had the greatest energy savings due to the very low WWR (32%). The last model version FS11, containing both the 60° and 30° tilted and folded façade represents relevant advantages in terms of energy savings (14%), since its façade morphology allows relatively great solar gains during the heating period (WWR 53%), yet it provides sufficient shading during the cooling operation season.

4. CONCLUSION

In the present paper, a series of thermal simulations was performed using the IDA ICE 4.8 indoor energy and climate simulation software to find the optimal façade configuration of a high-rise office building, located in the temperate climate zone. The results obtained from the simulations have shown that the optimization of the building façade geometry morphology such as folding the glazed external surface of the double skin climate façade in a way that gradually modifies solar radiation penetration due to variations of transparent, shaded transparent (blinds or solar protective glazing) as well as opaque (ISP-s) façade surface sections towards South and North orientation could significantly improve the building energy performance. The folding of the outer façade surface evidently changed the window-to-wall ratio and window orientation as well. The façade folding development could decrease energy consumption up to 35% (FS10, 75° folding) compared to the reference FS01 and up to 27% compared to the reference FS04. Thermal comfort performance is in accordance with the energy result characteristic. However, the visual (daylight provision) comfort is the lowest in FS10, because the WWR is extremely lowered (32%). On the other hand, the best daylight-performing models FS01 and FS04 delivered the worst energy results due to high WWR. The energy consumption decreases, and the thermal comfort gets improved each time the window-to-wall ratio was reduced, and the windows were gradually oriented more intensively towards the North. In terms of



visual comfort, the exact opposite effect is the case. Among the test cases, FS06 and FS11 were the two models, which could achieve the best performance in energy consumption while maintaining good thermal and visual comfort for office workers: the tradeoff between energy efficiency (savings of 13% and 14%, respectively), thermal comfort (savings of 96% and 94% respectively), and visual comfort (savings of 47% and 29.4% respectively) is solved because in FS06 the WWR is specified in a good middle range of 55%, and the opaque ISP-s provide effective shading from the South. The combination of the 30° and 60° folded façade morphology in FS11 provides similar WWR and shading properties. The results could be of assistance to make decisions for future similarly oriented tall office buildings.

Properly sized and designed climate façades with folded outer layer geometry, containing solar protective glazing as well as transparent windows and opaque insulation panels not only significantly improve energy efficiency in high-rise office buildings under moderate climate, but also deliver a good compromise solution for a good trade-off between the contradictory energy, thermal and visual comfort performance results.

REFERENCES

- [1] E. D. Giouri, M. Tenpierik, and M. Turrin, "Zero energy potential of a high-rise office building in a Mediterranean climate: using multi-objective optimization to understand the impact of design decisions towards zero-energy high-rise buildings," *Energy Build.*, vol. 209, 2020.
- [2] F. Bano and V. Sehgal, "Evaluation of energy-efficient design strategies: comparison of the thermal performance of energy-efficient office buildings in composite climate, India," *Sol. Energy*, vol. 176, pp. 506–519, 2018.
- [3] T. Saroglou, I. A. Meir, T. Theodosiou, and B. Givoni, "Towards energy efficient skyscrapers," *Energy Build.*, vol. 149, pp. 437–449, 2017.
- [4] T. Saroglou, T. Theodosiou, B. Givoni, and I. A. Meir, "A study of different envelope scenarios towards low carbon high-rise buildings in the Mediterranean climate – Can DSF be part of the solution?" *Renew. Sustain. Energy Rev.*, vol. 113, 2019.
- [5] T. Saroglou, T. Theodosiou, B. Givoni, and I. A. Meir, "Studies on the optimum double-skin curtain wall design for high-rise buildings in the Mediterranean climate," *Energy Build.*, vol. 208, 2020, Paper no. 109641.
- [6] E. Mozsonics and I. Kistelegdi, "Typological investigation of climate systems and design of multifunctional shading structures for the façade of the Szentágotthai Research Center," *Pollack Period.*, vol. 10, no. 1, pp. 61–70, 2015.
- [7] K. K. Lau, E. Salleh, C. H. Lim, and M. Y. Sulaiman, "Potential of shading devices and glazing configurations on cooling energy savings for high-rise office buildings in hot-humid climates: the case of Malaysia," *Int. J. Sustain. Built Environ.*, vol. 5, no. 2, pp. 387–399, 2016.
- [8] J. Zhao and Y. Du, "Multi-objective optimization design for windows and shading configuration considering energy consumption and thermal comfort: a case study for office building in different climatic regions of China," *Sol. Energy*, vol. 206, pp. 997–1017, 2020.
- [9] N. Hashemi, R. Fayaz, and M. Sarshar, "Thermal behavior of a ventilated double skin façade in hot arid climate," *Energy Build.*, vol. 42, no. 10, pp. 1823–1832, 2010.
- [10] S. Giostra, G. Masera, M. Pesenti, and P. Pavesi, "Use of 3D tessellation in curtain wall façades to improve visual comfort and energy production in buildings," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 296, no. 1, 2019, Paper no. 012044.
- [11] T. Mendis, Z. Huang, S. Xu, and W. Zhang, "Economic potential analysis of photovoltaic integrated shading strategies on commercial building façades in urban blocks: a case study of Colombo, Sri Lanka," *Energy*, vol. 194, 2020, Paper no. 116908.
- [12] Q. T. Nguyen, D. L. Luong, A. D. Pham, and Q. C. Truong, "Developing an optimization model of solar cell installation on building façades in high-rise buildings – A case study in Viet Nam," *GMSARN Int. J.*, vol. 15, no. 1, pp. 44–49, 2021.
- [13] M. Ornetzeder, M. Wicher, and J. Suschek-Berger, "User satisfaction and well-being in energy efficient office buildings: Evidence from cutting-edge projects in Austria," *Energy Build.*, vol. 118, pp. 18–26, 2016.
- [14] Y. Luo, L. Zhang, X. Wang, L. X. Z. Liu, J. Wu, Y. Zhang, and X. He, "A comparative study on thermal performance evaluation of a new double skin façade system integrated with photovoltaic blinds," *Appl. Energy*, vol. 199, pp. 281–293, 2017.
- [15] N. Skandalos and J. Tywoniak, "Influence of PV façade configuration on the energy demand and visual comfort in office buildings," *J. Phys. Conf. Ser.*, vol. 1343, no. 1, 2019, Paper no. 012094.
- [16] B. Naili, I. Haber, and I. Kistelegdi, "Simulation-supported design of high-rise office building envelope", *Pollack Period.*, vol. 17, no. 1, pp. 139–144, 2022.
- [17] J. Mardaljevic and J. Christoffersen, "Climate connectivity' in the daylight factor basis of building standards," *Building Environ.*, vol. 113, pp. 200–209, 2017.

