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OPTIMIZATION OF DOUBLE SKIN FAÇADES WITH INTEGRATED RENEWABLE ENERGY SOURCE IN COLD CLIMATES

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ABSTRACT

Façade technology has been undergoing continuous evolution with various systems suited for enhancing energy performance and occupancy comfort in new and retrofit buildings. In cold climates, Double Skin Façades (DSF) can provide a solution to low ambient temperatures and a potential for façade-integrated energy production, thus responding with a great extent to such measures. This study presents a new workflow to optimize DSF through balancing the façade's geometric form with relevant thermal loads, daylighting availability, and energy efficiency potentials in buildings. Brute-force parametric simulation was applied with a combination of visual scripting and sensitivity analysis to understand the behaviour of the outer and inner skin layers of DSF in cold climates. Thermal transmittance was calculated and modeled for radiative and conductive heat flow. The optimization was performed for five geometric parameters: Tilt angle within the façade (τ), Window to Wall Ratio (WWR), Vision-Spandrel Ratio (VSR), Floor Height (h), and Cavity Depth (d). Results indicate that, among the effect of a multitude of variables, a DSF system with an integrated renewable energy source can achieve nearly 38.7% to 45.2% energy improvement. In terms of daylighting availability and visual comfort, a τ of 50° was the most adequate in balancing Annual Daylight Exposure (ASE) and Spatial Daylight Autonomy (sDA) ranges with an h of 3 m to 3.5 m. Higher values of h yielded moderate energy improvement with best visual comfort conditions. If d is held constant at 1.2 m, energy performance was found to be optimum with reduced floor heights.

INTRODUCTION

Achieving energy efficiency in buildings is highly emerging as a main concern in the world. Today's buildings are responsible for around 40% of the energy use and around 38% of CO_2 emissions, which influences the necessity of adopting effective solutions to contribute to carbon-neutral goals and tackle net-zero energy aspects (Chang & Shen-Guan 2015; Amasyali & El-Gohary 2018). The urgent need to adapt to such approach has had researchers and building professionals focus on optimizing the role of façades in energy efficiency, thermal and visual comfort, and the possible integration of energy harnessing systems in buildings.

Façades have the primary role in controlling the indoor spaces and maintaining the relationship between the internal and external environments (Gelesz & Reith 2015; Ghaffarianhoseini et al. 2016; Araji & Shahid; 2017). The objective of façade glazing in buildings is not confined to aesthetics only. It has a dual function of minimizing heating loads in cold climates through solar radiation exposure. However, this brings a risk of increasing cooling loads in summer. Seeking a balance between these constraints is required (Grynning et al. 2014).

Several studies have examined heat transfer through façades, as losses and gains, for understanding the net energy demand of buildings. In Norway, a study reported that despite the heating dominating typology of the cold climate, cooling demands have high records in the energy consumption of office buildings in such conditions (Grynning et al. 2014). Few cities in Canada confirm these results due to a high variation between summer and winter temperatures, with a variance of -40°C to +35°C or higher.

Recent research studied the development of façade technologies that can improve insulation and solar shading in addition to thermal and visual comfort in interior spaces. The utilization of adaptive façades led to energy savings of 18.8% - 29% in summer and 14.9% - 22.7% in winter (Bui et al. 2020). Through multiobjective optimization, a 24% - 28% in energy reduction was correlated with an increase of 15% - 63% in daylight availability in cold climate regions (Jalali et al. 2019).

Double Skin Façade (DSF) is one of the technologies used to influence not only the energy consumption in a building but also the method and capacity of the mechanical system for optimized overall performance. The scientific term of DSF has a large variation of façades typologies that can be simplified to a composition of a pair of glass layers separated by an air space cavity with air inlets and outlets. Such façade system involves a second shield for the building to diminish the effects of the external environment on interior spaces and uses its geometry and shape in effectively adapting to the energy behavior and building performance. Generally, the integration between a DSF system and photovoltaics-façade technologies was reported to reduce net building-energy by 50% compared to that of conventional façade systems in Mediterranean cold climates (Gelesz & Reith 2015; Ghaffarianhoseini et al. 2016; Peng et al. 2016). The various components of DSF give the opportunity for more investigations that can encounter different parameters, such as external geometry, glazing ratios, and cavity depth. Determining the effective constraints in the performance of the façade is crucial to tackling design optimization. For instance, the cavity and airflow in DSF can be highly responsible for the adaptability of the system to the surrounding climatic conditions. This is possible through controlling solar radiation for heat gain and dissipating the heat outside the building when needed.

Some studies investigated the variations in the building form and its relation in achieving minimum energy consumption during the design phase of the building. In this context, the efficiency of freeform façades in cold climates was tested, with 100 different generations, to demonstrate the best and worst in terms of the optimization objectives, space efficiency, shape coefficient, and total radiation (Zhang et al., 2016). Genetic algorithms were utilized to propose different design iterations that develop the optimal solution without having an economic impact on the building construction feasibility (Gerber et al., 2017). Other studies examined the relationship between freeform building geometries and the thermal performance of interior spaces using genetic algorithms (Jin & Jeong 2014). Using three different types of parameters (namely: static, dynamic and dependent), this study revealed that the dependency of the building thermal load could be rapidly predicted and optimized in the early design phase using the proposed building form optimization process. One of the main categorization criteria for DSF systems is the cavity ventilation method, which involves naturally ventilated systems and mechanically ventilated systems. The latter has proven to be suitable for severe climates and provides constant thermal performance for the cavity. Several studies reported that mechanically ventilated DSF systems can achieve 21% - 26% energy savings in summer and 41% - 59% in winter (Poirazis 2008; Ghaffarianhoseini et al. 2016; Fallahi et al. 2010).

This paper developed a new approach in testing DSF systems. The potential value in the current approach is in solving complex façade design challenges, maximizing energy efficiency, improving parametric building information, and leveraging cold climate variability through the building façade system.

THEORETICAL APPROACH

The form of a DSF system can be simplified and geometrically introduced through four air cavity classifications, which can be vertically continuous across the entire façade (shaft-box façade), divided by floor (box window façade), connected horizontally (corridor façade) and fully connected (multistory façade). In general, such variations allow for improved airflow and other environmental barrier benefits. The corridor façade is known for reducing over-heating on upper floors, construction simplicity of a repeating unit in addition to noise, fire, and smoke transmission due to floor-by-floor divisions. This paper investigates the corridor façade category of DSF. The possible prototypes may vary, but for the purpose of this study, the focus will be on investigating the potential of prototype B (Fig. 1).

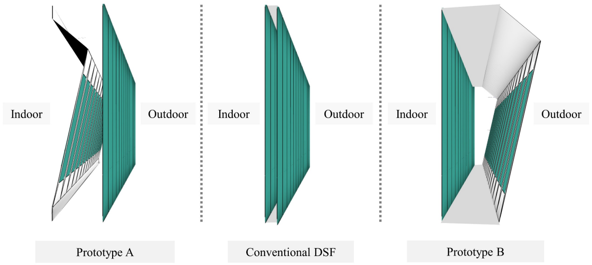

Figure 1 Prototypes of the DSF system.

The examined form has an unconventional external layer that involves a vision panel angled toward the ground, to minimize the amount of direct sun radiation and glare, with a spandrel panel oriented toward the sun for maximum collection of energy by its integrated renewable source. The end result is both purposeful and visually distinctive façade with balanced access to external views, energy efficiency strategies, and renewable energy generation technologies. The optimization of the panels became a driving factor in developing this research using the yearly incident solar irradiation on these surfaces.

For this study, an office space has been sought as a building typology with a south-facing orientation in a typical building floor (Table 1 and Fig. 2). The study is conducted under the extreme climate conditions of the city of Winnipeg, Canada (with a latitude 49.8951° N, longitude 97.1384° W) and no specific context has been applied in order to generalize the results. Instead, the effect of shading coming from the surrounding environment has been introduced as a reduction factor in the results. The cavity in the studied DSF was assumed to be mechanically ventilated due to the positive correlation between this application and thermal insulation in cold climates (Poirazis 2008). The ventilation rate was constant at 0.6 ACH with a setpoint of 18º Celsius threshold. Both, the office space and the cavity space were treated as two separate thermal zones with no air exchange. The two thermal zones were modeled without simplifications to achieve the highest level of accuracy in adapting to the change of the surrounding climatic conditions (Fig. 2). In terms of optical properties of glass, the vision panel is made of a double-glazed Insulating Glass Unit (IGU) applied to the external layer of DSF and composed of two 6mm clear glazing layers with a 3 mm air gap, 78% transmittance, 2.6 W/m^2-K U-value and 0.703 SHGC. The internal layer is composed of a 6 mm single-pane clear glazing with 88% transmittance, 5.8 W/m^2-K U-value, and 0.81 SHGC.

Table 1 Building and system properties of the studied space.

OFFICE DIMENSIONS (m)	*w* 20 x *l* 15 x *h* (3 – 4)	
OFFICE AREA (m^2)	300 m^2	
ORIENTATION	South	
SURFACE REFLECTIVITY	FLOOR	20%
	WALLS	50%
	CEILING	80%
OCCUPANCY	8:00 to 17:00	
RENEWABLE ENERGY SOURCE	TYPE	Monocrystalline
	EFFICIENCY	15%
	EFFECTIVE AREA	85%

Figure 3 presents the five parameters used in the simulations, including: 1) Tilt angle of the spandrel panel (τ), 2) Window to Wall Ratio (WWR), 3) Vision-Spandrel Ratio (VSR), 4) Floor Height (h), and 5) Cavity Depth (d). The resultant configurations from these simulations generated 1,800 different design combinations. By applying the proposed algorithm, the study first determines the τ of the spandrel panel that varied from 0º (vertical) to 90º (horizontal) with a step of 10º. Optimizing the WWR was then used as an important variable affecting performance based on reducing energy loss.

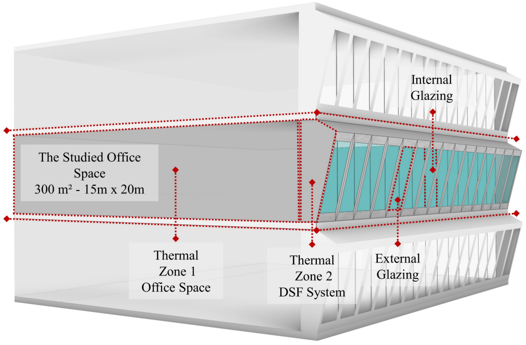

Figure 2 Thermal zones model used for the simulation/visualization process.

The WWR of the vision panel ranged from 70% to 100%. The VSR parameter defines the point at which the spandrel geometry starts formation in the façade. It represents the possible paneling and grid variations that can be applied by a façade designer. The examined ratios of VSR included 50%, 66.6%, and 75%. Such values cover a broad range of practical façade paneling, with a minimum for achieving building aesthetics and user's visual connectivity. The applied ranges for *h* and *d* utilized values that cover most of the space configurations found in office environments that vary from 3 m - 4 m and 0.2 m - 2.4 m, respectively.

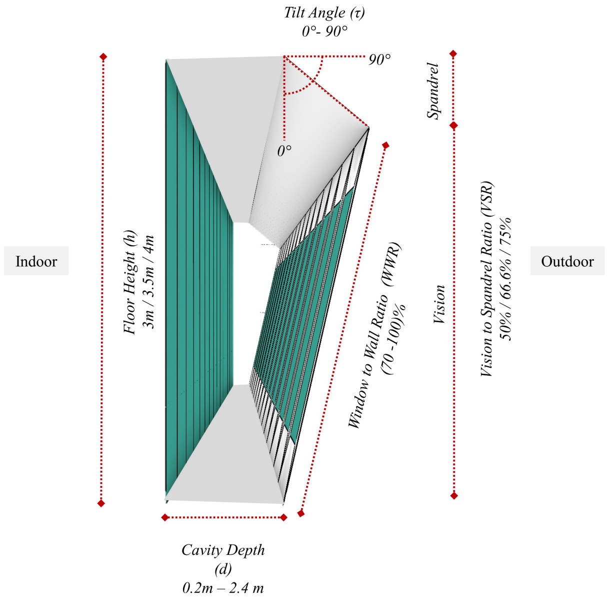

Figure 3 Illustration of the different studied parameters.

The investigation was conducted using an automated parametric simulation process, which utilized the capabilities of several linked software and simulation engines. Rhinoceros 6 and Grasshopper 3D were used to create the geometrical environment of the simulation and the parametric façade system. All the configurations were generated by the automation of the Grasshopper script and simulated with the aid of the plugins DIVA 4.0 and Archsim in addition to the simulation engines of EnergyPlus, Daysim, and Radiance.

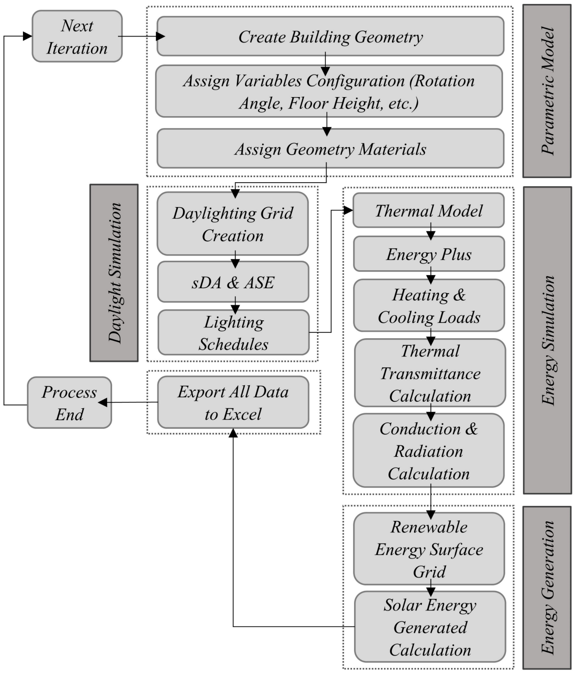

Figure 4 Flowchart of the simulation process.

The flowchart of the simulation process involved three consecutive phases. Figure 4 exhibits this theoretical approach. First, the assessment of the façade system configurations was conducted in terms of visual comfort using the two approved metrics of spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). Second, the resultant energy demand of the façade system was simulated in terms of total energy, and cooling and heating load using EnergyPlus.

The third phase was implemented to conclude the possible solar energy generated from studied configurations. The assessment was conducted in comparison with a base-case DSF composed of a pair of parallel glass layers separated by an air space cavity of 0.2 m (Lucchino et al. 2019). The energy improvement was calculated as a percentage increase measured against the base-case, using the following formula:

$$E_{T-Base} = \frac{(E_{T-Ite} - E_{Pot-Ite})}{E_{T-Base}} \qquad (1)$$

Where E_{T-Base} is the Total Energy Demand Correspondent Base-case (KWh), E_{T-Ite} is the Total Energy Demand Iteration (KWh), and $E_{Pot-Ite}$ is the Potential Generated Energy Iteration (KWh).

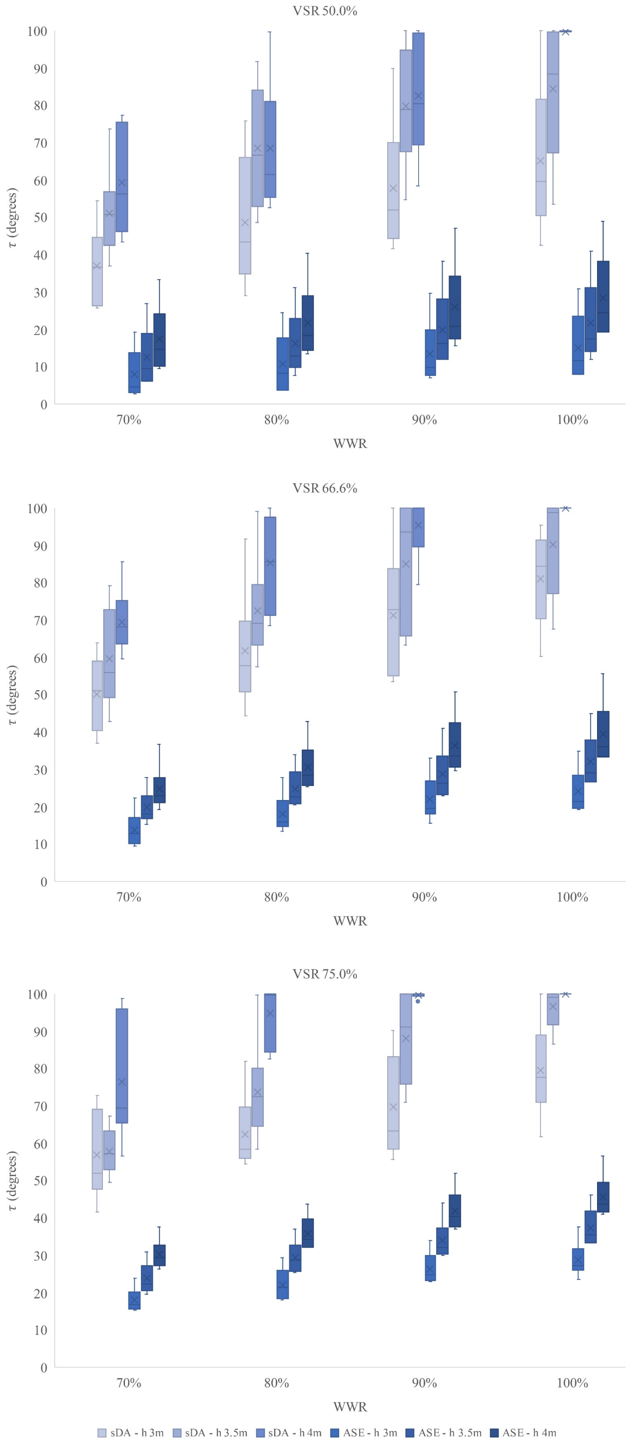

Figure 5 sDA and ASE performance of the different VSR values.

The daylight adequacy was measured and visualized based on the Illumination Engineering Society (IES) approved daylight metrics of sDA 300/50% and ASE 1000/250 hr (IESNA 2012). Visual comfort criteria were based on the Leadership in Energy and Environmental Design's (LEED) Daylight Credit Compliance adequacy, which requires applied sDA value of no less than 55% of the space and applied ASE of no more than 10% of the space to achieve 2 points credit (USGBC 2019).

RESULTS & DISCUSSION

In this section, results are discussed to understand the performance of the DSF's geometric variations. The preliminary outputs of the base-case study with the conventional DSF system were simulated. The base-case achieved ASE levels that range from 47.4% when $h = 3$ m and increased to 69.2% when $h = 4$ m. The corresponding energy consumption for these two heights was 189,343 KWh and 256,256 KWh, respectively. Generally, all configurations of the examined façade achieved higher efficiency with a variety of energy reduction ranging from 15% to 29%.

For visual comfort, a comparison was carried out across the examined VSR ratios within different iterations. The cavity depth was kept constant at a $d = 1.2$ m for this assessment. This value was considered a reasonable depth for balancing daylight levels in interior spaces.

Figure 5 shows the results for the proposed façade configurations, with significant improvements in visual comfort. For example, the least performing iteration, with $h = 4$ m, achieved an improvement of 13% in ASE. In terms of sDA, the majority of cases reached acceptable percentages of day-lit floorplans. A τ of 50° was the most adequate in balancing ASE and sDA ranges with an h of 3 m to 3.5 m.

With an h of 4 m, τ of 20° was the best performing tilt. A 70% WWR emerges as the best performing threshold in the studied range. It is, therefore, recommended to test lower percentages of WWR to understand the most adequate percentage for the studied location.

Figure 6 displays energy improvements, with a constant WWR of 100%. The curves are represented by a third-degree polynomial to balance accuracy and precision. The convexity of top curves is greater than that of the lower curves, which shows the higher rate of energy improvement with respect to tilt for lower VSRs.

The results indicated that the increase in cavity depth directly contributes to the energy efficiency of the space. This is due to the additional overhang provided by the cavity geometry, therefore reducing direct sunlight penetration to the inner space. The energy performance peaked with a d of 1.2 m, thus achieving 45.31% energy improvement with $h = 3$ m.

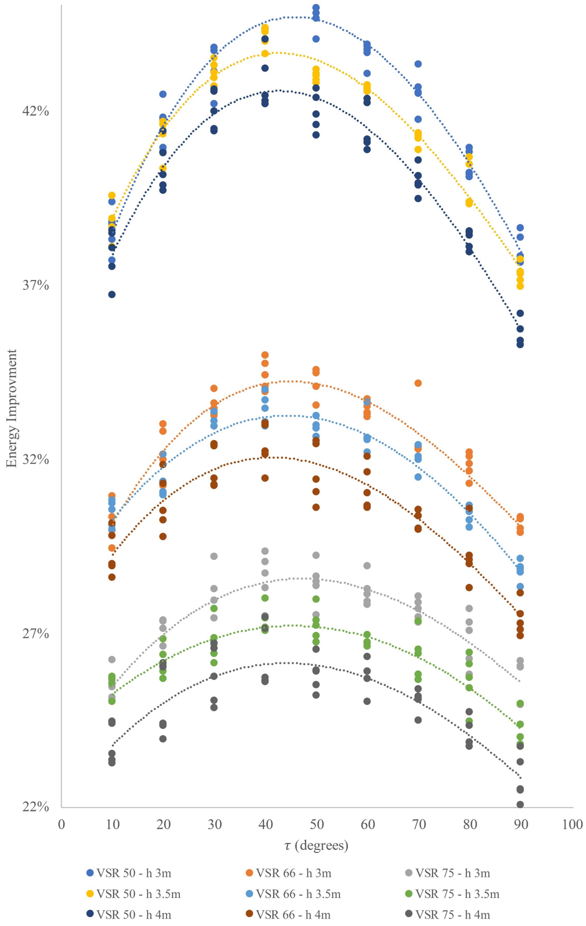

Figure 6 Energy improvement of different iterations with a constant WWR of 100%.

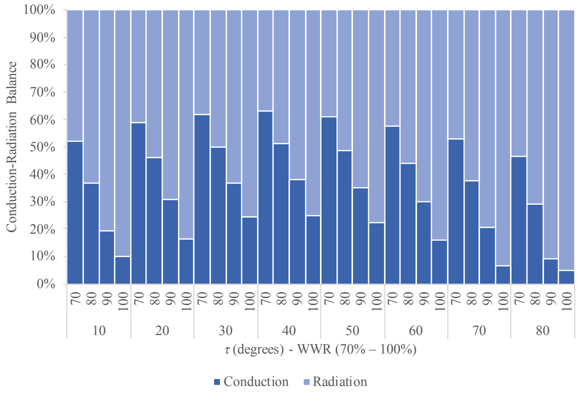

Figure 7 Heat gain from conduction and radiation within the DSF system.

For h = 4 m, 40.8% of energy improvement was attained with the best visual comfort conditions. A τ of 40^o concluded optimum improvement comparable in all floor heights due to the high correlation between the best angle for solar energy and the latitude of the system's site.

From h comparisons, it was concluded that the decrease in the floor height parameter contributes to more efficient energy demands, which can be justified as a result of a reduction in the total volume of the conditioned space. The optimum form factor of the space could be recommended for further analysis in the future. The results revealed that VSR of 50% outperformed all other values.

A rational case to extend these findings lays in comparing the proposed DSF system with a base-case enhanced by a sun shading system, in which the geometry of the shading device is exactly the same as the spandrel panel in the DSF. The justification for this contrast is to understand the essential difference between the DSF and a regular façade with a shading system that can offer an economical alternative advanced by less built space. In this context, the rate of heat transfer through the DSF was simulated to examine the thermal resistance across its layers. DSF showed strong effect in correlating the heat loss with the difference in temperature throughout the façade layers. The additional air barrier through the cavity improved the thermal transmittance of the entire system and lead to improved range of U-values from 0.704 W/m^2-k to 0.221 W/m^2-k. The components of this thermal transmittance were further modeled in the buffer thermal zone in EnergyPlus to determine heat flow due to conduction and radiation. This analysis can provide a better understanding of energy demand figures and reveal the subsequent temperature distribution in the system. Convective heat transfer was neglected from the comparison due to EnergyPlus's limitations and error occurrence with computational fluid dynamics (Lucchino et al. 2019).

The results in Fig. 7 affirmed conduction's responsibility for about 50% of thermal load with WWR 70%. This percentage declines to an average of 20% in the case of 100% WWR. Overall, the DSF system surpassed the shading system results by a range of 8% to 16% in higher energy performance. The major effect of the DSF was reflected in the heating demand, which acknowledges the impact of the added insulating effect of air barrier in cold climates.

Ultimately, a sample of best tested cases is outlined in Fig. 8 to show the balance attained in improving daylight, minimizing direct solar exposure, and reducing energy use. The sDA levels with all cases varied between 56% - 73%. The majority of the cases demonstrated an optimum τ of 40^o - 50^o. Results revealed the positive effect of the DSF system that can provide energy improvements between 38.7% to 45.2%.

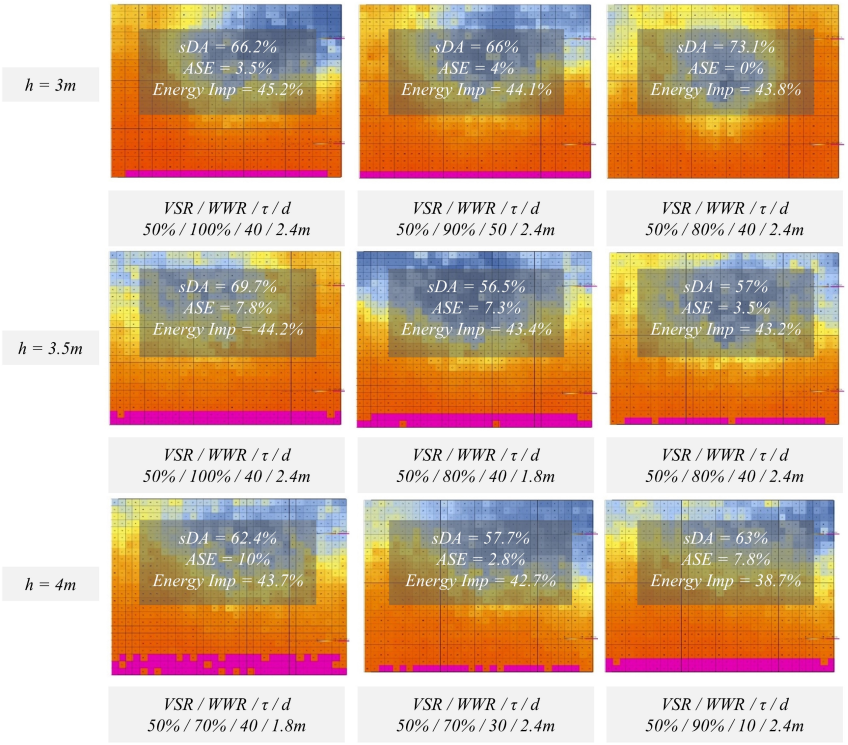

Figure 8 Iterations with optimum balance between visual comfort and energy improvement.

CONCLUSION

Façade enclosures, being the buffer between outdoor and indoor environments, are often considered as one of the most critical elements in overall building performance. This study utilized and developed the capabilities of a DSF system relevant to the optimization of its preliminary form typologies and parametric data in cold climates.

The findings are represented in a new workflow that uses multiple values and diverse parameters of the DSF system while discerning its most effective criteria. The new approach included accurate modeling for the thermal model by using the exact geometry for the system without any simplifications. The simulation results identified various geometric configurations of DSF in terms of improving thermal comfort, daylight availability, and energy efficiency in office spaces.

The research also revealed the importance and applicability of adding a second skin on fully glazed façades in existing buildings. DSF systems can be further optimized and studied to verify the effectiveness of additional parameters and geometric generations to improve the balance between the tested performance criteria. Such parameters would include: computational fluid dynamics, surface area to volume ratio, and other renewable energy sources.

NOMENCLATURE

ASE: Annual Sunlight Exposure (%)

d: Cavity Depth of the DSF system (m)

$E_{Pot-Ite}$: Potential Generated Energy Iteration (KWh)

E_{T-Base}: Total Energy Demand Correspondent Base-case (KWh)

E_{T-Ite}: Total Energy Demand Iteration (KWh)

h: Height of the studied office space (m)

sDA: Spatial Daylight Autonomy (%)

τ: Tilt angle of the spandrel panel (degrees)

VSR: Vision-Spandrel Ratio (%)

WWR: Window to Wall Ratio (%)

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