

Thermal, energy and daylight analysis of different types of double skin façades in various climates

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Abstract

This article explores the thermal, energy, and daylighting performance of double skin façades (DSFs) in different climate types, specifically focusing on three typologies: box window, corridor, and multi-storey DSFs. These systems were investigated and analysed to determine how different DSFs perform in comparison to each other, as well as a typical curtain wall (single skin glazed façade used as a baseline), in a multitude of climate applications. The utilised research methods included two-dimensional heat transfer analysis (Finite Element Method analysis), Computational Fluid Dynamics (CFD) analysis, energy modelling, and daylight simulations. Heat transfer analysis was used to determine heat transfer coefficients (U-values) of all analysed façade types, as well as temperature gradients through the façades for four exterior environmental conditions. CFD analysis investigated three-dimensional heat flow, airflow, and air velocity within the air cavity of DSFs. Energy modelling and daylight simulations were conducted for an office space that was enclosed by the analysed façade types. Individual energy models were developed for each façade type and for fifteen different climates representing various climate zones and subzones, from very hot to arctic. For daylighting simulations, multiple models were developed to study investigated typologies of DSFs, depth of air cavity between the two skins, orientations and four climate types, as well as different sky conditions. Results indicate that there is not a lot of variation in thermal performance of the different DSF types, but that all DSF façades would have significantly improved thermal performance compared to the baseline single skin façade. Energy modelling results indicate significant differences in performance between the DSFs and single skin façade, but fewer variations between the different typologies of investigated DSFs. Moreover, the results show the effect of DSFs in different climate types on energy performance, heating, cooling, and lighting loads. Daylighting results indicate that all types of DSFs would decrease daylight levels compared to a conventional curtain wall, however, the differences between lighting levels are also dependent on the orientation, air cavity depth, façade type and climate.

Keywords

Double skin façades, energy consumption, energy use intensity, daylight, simulations, finite element method (FEM) analysis, computational fluid dynamics (CFD), energy modelling

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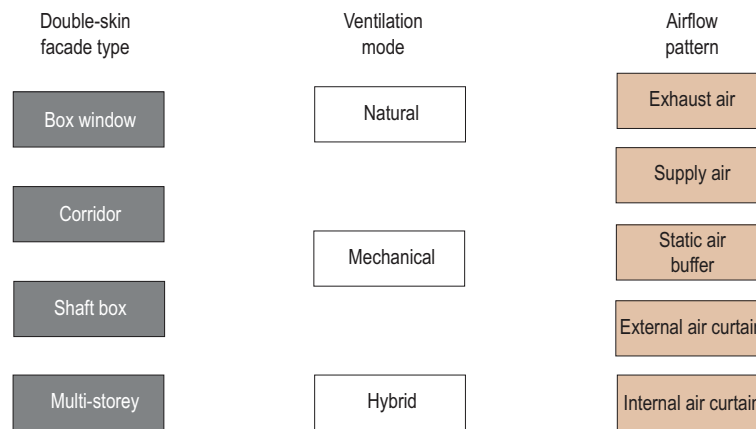


FIG. 1 Classification of double skin façades.

1 INTRODUCTION

Double skin façades (DSFs) are an emerging type of building façades, aimed to improve thermal performance of glazed envelopes. Different from a conventional single glazed façade configuration, DSFs consist of three distinct layers – interior glazed wall system, ventilated air cavity, and exterior glazed wall system. The ventilated air cavity serves as a thermal buffer between interior and exterior glazed walls. Basic DSF types are box window, corridor, shaft box, and multi-storey façades (Aksamija, 2013). The physical behaviour of the DSFs depends on the typology, as well as on the ventilation mode of the air cavity and material components. Ventilation mode can include natural ventilation, mechanical, and mixed mode. Double skin façades are classified according to ways the air cavity is partitioned (the façade type), the ventilation mode, and the airflow pattern, as seen in Figure 1. These three variables can be combined in numerous ways for a wide variety of design possibilities. The selection of the type of glazing, the width and partitioning of the air cavity, and ventilation mode depends on climate, building orientation, and design requirements.

Basic DSF types include:

- Box window façades, which have horizontal partitions at each floor level, as well as vertical partitions between windows. Each air cavity is typically ventilated naturally.
- Corridor façades, which have uninterrupted horizontal air cavities for each floor level, but are physically partitioned at the floor levels. All three ventilation modes are possible.
- Shaft box façades, which are similar to corridor façades, but use vertical shafts for natural stack-effect ventilation. Hybrid-mode ventilation is often used for this façade type.
- Multi-storey façades, which have uninterrupted air cavities spanning the full height and width of the façade. All three ventilation modes can be used.

DSFs have been primarily used in cold and temperate climates, although there are some examples in warmer climate types. The objective of this research was to investigate the thermal and energy performance of DSFs across all climates (fifteen different climate zones, representing heating-dominated, cooling-dominated, and mixed climates), and to determine the behaviour of three different types (box window, corridor type, and multi-storey DSFs). Diagrams, as well as partial elevations, sections, and plans for these DSF types are shown in Figures 2 to 5. Daylighting performance of DSFs was also investigated at different latitudes, orientations, and cavity depths.

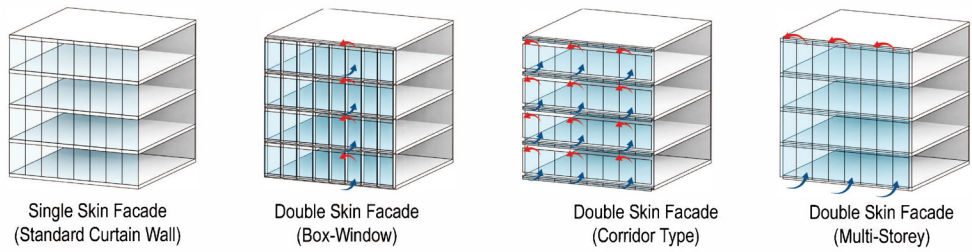
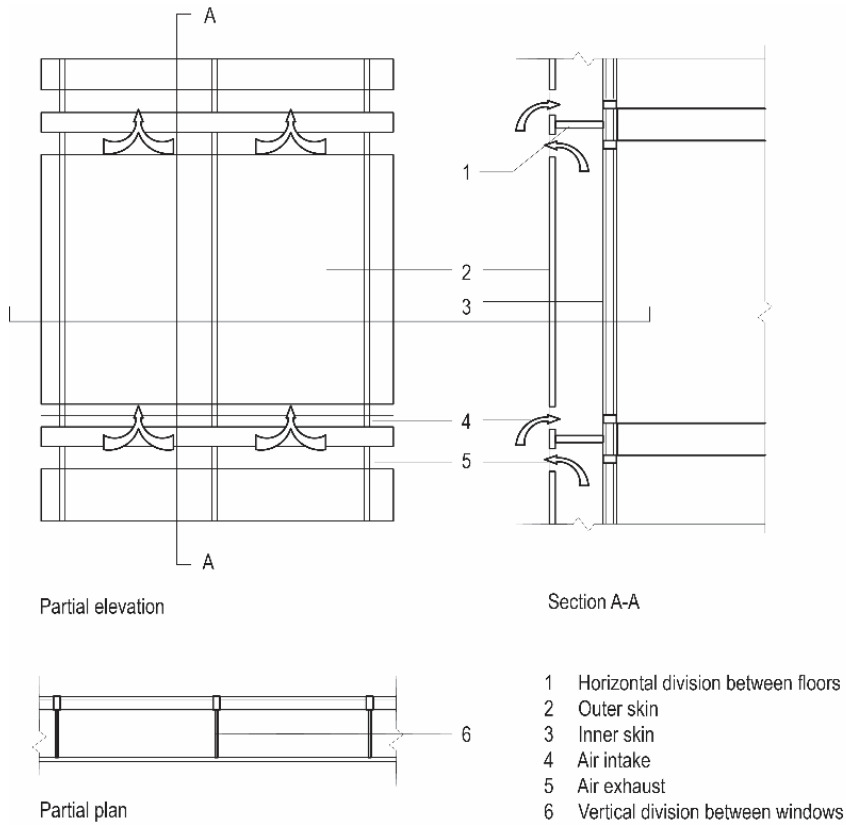
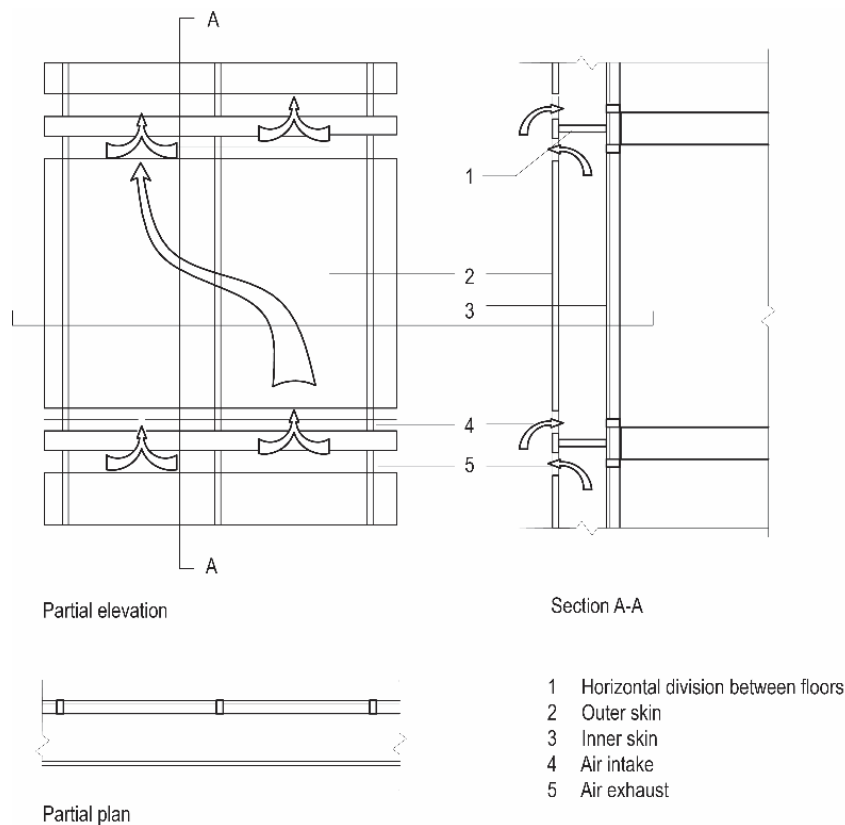


FIG. 2 Diagram showing investigated façade types, where the basic components and airflow patterns are indicated.



Air cavity divided horizontally and vertically, openings can be placed on external skin
 Each window requires own air intake and exhaust openings

FIG. 3 Box window DSF.



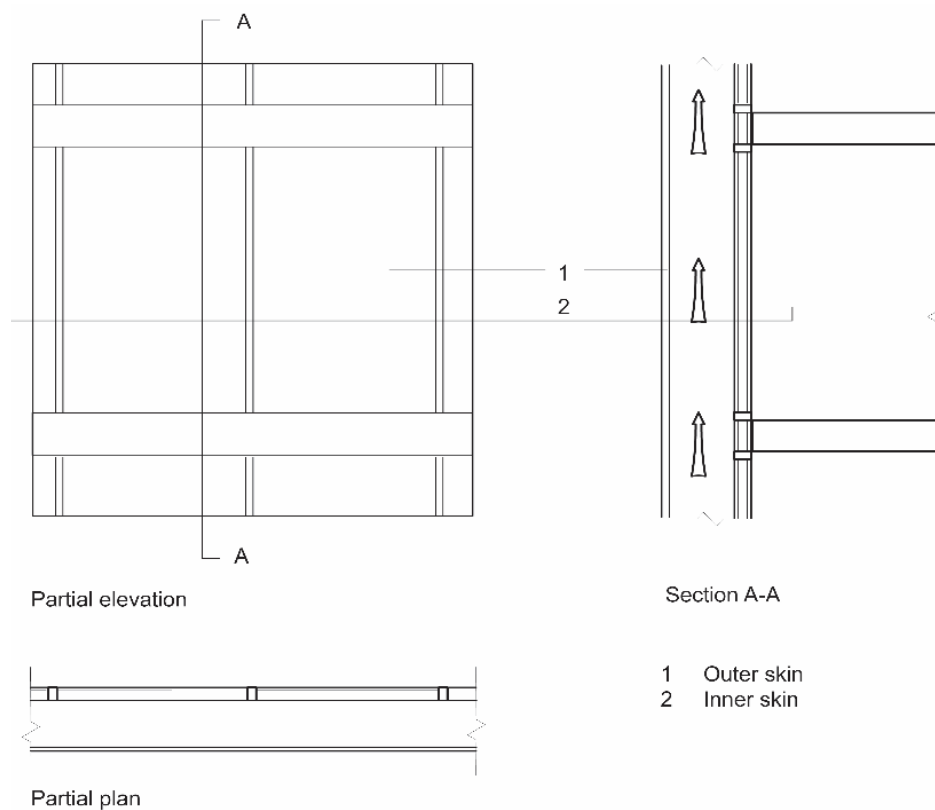
Air cavity divided horizontally
 Each floor requires own air intake and exhaust openings

FIG. 4 Corridor type DSF.

2 LITERATURE REVIEW

There is significant research available relating to the thermal and energy performance of DSFs in temperate and colder climates, as evident in a previously published literature review by Pomponi, Piroozfar, Southall, Ashton, and Farr (2016). This literature review provided an overview of a number of research articles focusing on energy performance analysis of DSFs in temperate climates. Energy savings for heating and cooling were compared across different DSF types, but the study could not verify the impact of DSF types on energy consumption for lighting.

Gratia and Herde (2007) looked extensively at DSFs in a temperate climate, analysing behaviour for various orientations, and how applying the DSF affected heating and cooling loads. Another study was conducted to compare a DSF to other façade alternatives for a specific building application in central Europe (Gelesz & Reith, 2015). The authors simulated box window DSF and its single skin alternative, and the results indicate that DSF can reduce energy consumption by 7% on average. In addition, closed cavities have overheating problems even on the coldest days, when oriented in a southerly direction. Thermal performance in regard to interior cavity temperatures was also analysed as part of this study. Cavity temperatures were shown to increase in colder seasons when compared to external temperatures, but also overheat when external temperatures are hotter, even with the application of shading during those summer conditions.



Air cavity is joined vertically and horizontally between floors
 Air intake located at the bottom of the facade, exhaust at the top

FIG. 5 Multi-storey DSF.

For hot climate areas, summer ventilation for DSF leads to increased cooling loads (Eicker, Fux, Bauer, Mei, & Infield, 2008). Zhou and Chen (2010) looked at applying ventilated DSFs in hot and cold climate zones in China. Wong et al. (2005) studied the performance of DSF in Singapore by using energy and CFD simulations. Guardo, Coussirat, Valero, and Egusquiza (2011) used CFD simulations and comparative analysis to evaluate horizontal and vertical ventilation schemes for a DSF in a Mediterranean climate. Brandl, Mach, Grobbauer, and Hochenauer (2014) studied the airflow characteristics and temperature profile of multifunctional façade elements through comprehensive analysis and comparison by using CFD models, and the results identified that the ventilation effects of side openings can help decrease cavity temperature.

Studies have also been conducted that look specifically at a comparison of thermal comfort in single skin glazed façades compared to DSF, where thermal comfort is defined as 80% of individuals not expressing dissatisfaction with interior temperature (ASHRAE, 2013a). The Predicted Mean Vote-Percentage of People Dissatisfied (PMV-PPD) method is typically used to quantify thermal comfort, and acceptable limits for discomfort are within 20% range (ASHRAE, 2013). Wong et al. (2005) looked specifically at a typical office building application on two specific days of the year in Singapore to represent Singapore's two main seasons, June for the warm and dry season, and December for the cool and rainy season. Results showed a baseline percentage of people dissatisfied (PPD) in a single façade building application as being 24.5% in June, and 22% in December. The application of a DSF using only stacking effect (without mechanical ventilation) decreased PPD to 19.6% in June,

and 18% in December, equalling an average of 5% of people showing greater satisfaction. The same double skin façade with mechanical ventilation was then tested. The PPD decreased slightly in June to 19.5%, and in December remained at 18%. This evidence points to the application of a DSF to enhance thermal comfort. This study did not look specifically at calculating the U-value of the DSF when addressing thermal performance.

Viljoen, Dubiel, Wilson, and Fontoynt (1997) studied a 32-storey Brussels DSF office building and simulated thirteen DSF assemblies using scale models and computer simulations. Simulations assumed unobstructed sky view, and assessed how far the daylit zone could extend into the office. A comparative study between a scale model and computer simulations using Radiance provided results. It was concluded that the components of a DSF, a light shelf, reflectivity, perforation of materials, and location of walkways had significant effects on interior daylighting. Findings also indicated that glazing orientation and surface area would have significant impacts on daylighting. The findings of this study are applicable to buildings with DSFs, but lack comparison with single glazed façade daylighting.

Shameri et al. (2013) simulated the daylighting conditions of twelve existing DSF offices located in tropical, subtropical, and temperate climate zones. The analysed façades had cavity depths ranging from 0.8 m (2.6 ft) to 2.5 m (8.2 ft), with glazed values ranging from 70% to 100%. The research concluded that daylighting values inside the DSF offices were at comfortable levels. However, all DSF models failed to achieve standard indoor illuminance requirements of the office space. Kim and Song (2007) conducted simulations to assess the performance of a daylight dimming control installed in an office with a DSF. The simulations placed photosensors at three different locations, three shielding conditions, and three sky conditions. They found that a partially shielded condition with clear and partly cloudy skies showed adequate dimming function in a DSF structure.

Konis (2013) evaluated a 56,206 m² (605,000 ft²) office building in San Francisco. Both the northwest and southeast façades are fully glazed with two different DSFs, where the southeast DSF consisted of perforated metal panels allowing solar transmission of 50%, and the northwest façade consisted of a DSF with laminated glass and plastic fins. Subjective responses on daylighting were paired with simultaneous measurements of global horizontal illuminance, and vertical luminance. Daylight illuminance levels were calculated by subtracting electrical lighting contributions from physical illuminance measurements. Daylight transmission to the core zones was found to be insufficient based on subjective and physical measures. Daylight only contributed 15% of the total illuminance measured in core zones. Although façade light transmission was significantly reduced, daylighting in perimeter zones was considered sufficient and met or exceeded the anticipated energy reduction target of 25%. Respondents also indicated adequate lighting even below common thresholds. Visual comfort responses indicated that glare analysis should be incorporated into design simulations.

There is lack of research that systematically compares thermal, energy, and daylight performance of different types of DSFs in all climate types. Additionally, studies that systematically investigate thermal and energy performance of DSFs façades in all types of climates currently do not exist. Moreover, studies that also investigate different typologies of DSFs and their energy performance are currently limited. Few studies have evaluated the effect of DSFs on daylighting. Most studies indirectly address daylighting while evaluating the performance of other effects of DSFs, leading to limited results and evaluations that pertain to specific buildings. A broader understanding of DSF impacts on daylighting is unavailable. Therefore, this research study focused on addressing these gaps in knowledge.

3 RESEARCH OBJECTIVES AND METHODOLOGY

The objectives of this research were: 1) to investigate the thermal performance of different types of DSFs (in relation to single skin glazed façade, and based on differences between individual DSF typologies); 2) to investigate effects on energy performance in all climate types; and 3) to investigate daylighting performance of DSFs. Research questions that were addressed include:

- What is the thermal performance of different types of DSFs, specifically in terms of heat transfer coefficients (U-values)?
- How does the outside temperature affect the oscillation of temperatures in the air cavity between internal and external glazing in different types of DSFs?
- What is the effect of outside temperature and solar radiation on airflow patterns and air velocity in the air cavity for different types of DSFs?
- What is the effect of different types of DSFs on energy consumption for commercial office spaces in all climate types?
- How do DSFs influence the heating and cooling loads in different types of climates? What are the energy saving potentials for different DSFs? How is energy consumption for lighting impacted by different types of DSFs?
- How does the daylighting performance of DSFs compare to conventional single skin façades? How are daylighting values impacted at different orientations? How does the air cavity depth influence daylight performance of DSFs?

3.1 HEAT TRANSFER ANALYSIS

The heat transfer analysis utilised a 2D finite element method analysis, using THERM and WINDOW modelling software programs. THERM was developed by Lawrence Berkeley National Laboratory (LBNL), and it is widely used for thermal analysis of façade systems. WINDOW was also developed by LBNL, and it is interoperable with THERM. It can be used to calculate optical and thermal properties of glazing systems. THERM calculates conductive heat transfer, considering interior and exterior environmental conditions, and the conductive properties of air and materials in the façade assembly. The benefit of the software is that it can determine thermal gradients, heat flux, and U-value of various façade assemblies. Another benefit is that the properties of glazing units can be imported from WINDOW. The drawback is that it only considers conductive heat transfer, and calculation is performed in two dimensions.

PROPERTIES	STANDARD CURTAIN WALL m (ft)	BOX WINDOW DSF m (ft)	CORRIDOR TYPE DSF m (ft)	MULTI-STOREY m (ft)
Height	3.1 (10)	3.1 (10)	3.1 (10)	6.1 (20)
Cavity depth	N/A	.31 (1)	.31 (1)	.31 (1)
Upper opening width (box window and corridor type)	N/A	.31 (1)	.31 (1)	N/A
Lower opening width (box window and corridor type)	N/A	.15 (.5)	.15 (.5)	N/A

TABLE 1 Basic geometry and dimensions of analysed façade systems.

FAÇADE ELEMENT	MATERIAL TYPE	THERMAL CONDUCTIVITY W/m·°C (Btu/h-ft·°F)
Mullions	Aluminium alloy (oxidised)	525.2 (92.5)
Mullion gasket	Silicone	1.65 (0.29)
Box window and corridor type cavity partitions	Aluminium alloy (oxidised)	525.2 (92.5)

TABLE 2 Material properties of opaque façade elements.

GLAZING ELEMENT	GLAZING TYPE	U-VALUE W/m ² ·°C (Btu/h-ft ² ·°F)	SHGC	VISUAL TRANSMITTANCE
Exterior façade glazing	1.25 cm (1/2 in) tempered glass	18.4 (3.24)	0.44	0.79
Interior façade glazing	2.50 cm (1 in) double insulated low-e glazing with argon	6.02 (1.06)	0.35	0.63

TABLE 3 Properties of glazing.

The different analysed façades (single skin, as well as different types of DSF) were initially drafted as 2D sections in CAD, and then imported as an underlay in THERM to develop thermal analysis models. THERM relies on detailed 2D representations of all components and materials, placement of appropriate materials, definitions of material properties, and application of boundary conditions that represent exterior and interior environmental conditions. Table 1 and Figure 6 identify major characteristics of simulated DSFs, and their geometric properties.

All DSF façade systems used 2.5 cm (1 in.) double low-e insulated glazing unit (IGU) with argon gas fill on the inside of the façade, and 1.25 cm (0.5 in.) single tempered glazing on the outside. It was assumed that the air cavity between the two skins would rely only on natural ventilation and stack effect, where openings at the bottom and top of the façade would be used to ventilate the cavity. The single skin façade consisted of a 2.5 cm (1 in.) double air low-e IGU. The properties of IGUs were calculated in WINDOW and imported into THERM. The framing members for the typical curtain wall and the interior layer of the DSF included aluminium alloy (oxidised) mullions. The outer layer of the DSFs did not include aluminium framing members—the assumption was that structural silicone would be used for glazing, and that the structural support for the outside skin would be provided by point-supports and cables. For the box window DSF, the assumption was that the horizontal and vertical division panels between floors and individual windows would be constructed out of aluminium. For the corridor DSF, the assumption was that the horizontal division panels between floors would also be constructed out of aluminium with an equivalent thermal conductivity. Material properties are listed in Tables 2 and 3.

Each façade type was simulated for four different exterior temperatures: 32°C (90°F), 16°C (60°F), -1°C (30°F) and -18°C (0°F), in order to represent various climatic conditions. These values were chosen to represent typical winter conditions in colder climates, intermediate conditions (fall/spring) in temperate and warmer climates, and summer conditions in warm climates. Both sections and plans were simulated for all façade types, since this particular method uses 2D heat transfer analysis. The interior temperature was held constant at 20°C (68°F). Results were represented as thermal gradients, indicating temperature differentials within the cavity. The results were analysed in section and plan views, and are discussed in more detail in later sections of this article. U-values were also calculated, where the simulation inputs for environmental conditions were determined based on the NFRC 100-2004 Standard, with an exterior temperature of -18°C (0°F) and interior temperature of 21°C (70°F). The results were evaluated to determine the relative thermal performance of investigated façade types and compare the calculated U-values. Therefore, twenty different models were developed, where results for sixteen models were used to determine thermal gradients for various exterior environmental conditions, and four models were used to calculate U-values.

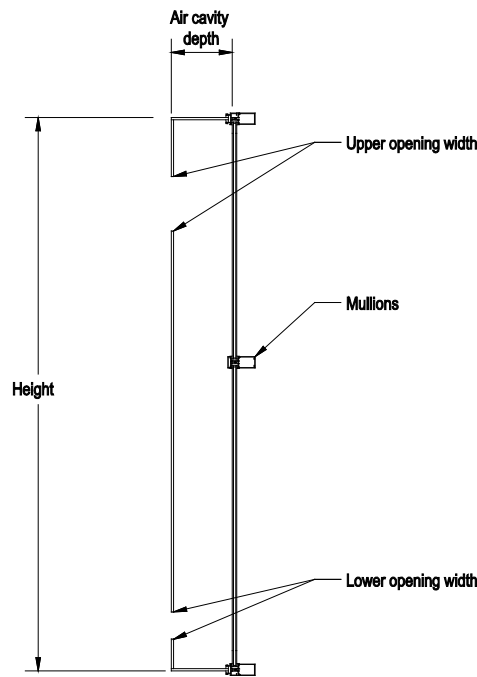


FIG. 6 Sectional diagram of DSF, showing components of simulated models.

3.2 COMPUTATIONAL FLUID DYNAMICS ANALYSIS

Computational Fluid Dynamics (CFD) analysis implements numerical simulation methods to seek solutions to fluid flow problems. The advantage of the CFD method in evaluating airflow and heat transfer is that it allows 3D model application, and it can be used to study various building components, effects of natural and mechanical ventilation, as well as solar radiation on building performance. For this study, Ansys Fluent CFD simulation program was used, where models for the investigated DSF types were developed using the same dimensions, components, and materials properties as THERM heat transfer analysis.

Different scenarios were developed to simulate how box window, corridor, and multi-storey DSFs perform under various environmental conditions. For each façade type, different models were developed to represent exterior temperatures of 32°C (90°F), 16°C (60°F), -1°C (30°F), and -18°C (0°F), while the interior temperature was constant at 20°C (68°F). The geometries were built as 3D models in Rhino modelling software, and imported into Fluent. A homogenous mesh with fine grids was implemented for all models. Also, the exterior and interior surfaces, as well inlets and outlets were identified for the meshed models.

Fluent provides two options for solvers: pressure-based and density-based. The pressure-based solvers take momentum and pressure as the primary variables in calculations, and are applicable for a wide arrangement of applications to investigate flow patterns. Pressure-based solvers also require less computing power. The density-based solver takes into account density, energy, momentum, and is applicable to situations where high speed compressible flow with combustion, hypersonic flows, or shock interactions are present. The applied solver in this study was pressure-based, since it is suitable to understand the velocity and flow patterns in the DSF air cavities. To mimic the real environment, gravity was set as -9.8 m/s on the Z axis. Boundary conditions for each identified façade component were set according to different temperature scenarios. The vertical sides of the

Exterior temperature	32°C (90°F)	16°C (60°F)	-1°C (30°F)	-18°C (0°F)
Direct solar irradiation (kW/m ²)	0.90	0.90	0.90	0.85
Diffuse solar radiation on vertical surface (kW/m ²)	0.08	0.08	0.06	0.06
Ground reflected solar radiation on vertical surface (kW/m ²)	0.10	0.08	0.05	0.40
Wind speed (m/s)	3.9	4.7	4.9	5.2

TABLE 4 Solar radiation and wind speed inputs for the CFD analysis, based on exterior temperature conditions.

DSFs were identified as adiabatic and the velocity input for air inlet depends on wind speed in different seasons. CFD can account for exterior wind and solar radiation (unlike 2D heat transfer analysis using THERM). Therefore, changes in velocity and airflow pattern, as well as changes in temperature within the air cavity can be simulated. The inputs for wind speed and solar radiation were determined based on analysing climate data for several cities in the U.S., and the daily average values in January, March, May, and July. Inputs for solar radiation and wind speed, based on exterior temperature conditions, are listed in Table 4.

Since the simulations are performed in three dimensions, the sides of the DSF models were assumed to be enclosed, and the ventilation openings were identical to dimensions shown in Table 1. The exterior thermal boundary was exposed to both radiative and convective heat flux, and the internal thermal boundary was exposed to convective heat flux. The simulations were performed, and the results consisted of thermal gradients and velocity within the cavity for each type of DSF and exterior temperature conditions, indicating heat transfer and airflow patterns. Sixteen different models were developed, representing four façade types and four exterior environmental conditions. The results were analysed, and are discussed in detail in a later section.

3.3 ENERGY MODELLING

The methodology for energy modelling consisted of building individual simulation models for each type of investigated façade, which would enclose a commercial south-oriented office space. Energy modelling was performed in Design Builder, and geometry for the models was created in Revit. Design Builder calculates heating and cooling loads using a heat balance method, while lighting loads consider solar distribution and visible light transmittance. The air cavities within the DSFs were modelled as separate zones without additional cooling or heating, relying only on natural ventilation. Each type of DSF had three variations (without openings, openings-holes, and openings-vents), representing different ventilation modes and airflow patterns for the air cavity. Models without openings represented static air buffer airflow pattern, while models with openings represented natural ventilated cavities that can operate as external air curtain. Mechanical ventilation or mixed mode ventilation of the cavity was not considered. Table 5 shows representative cities that were chosen for energy modelling in order to investigate the effects on energy consumption in different climates. Therefore, ten different models were developed for tested climates, resulting in 150 models.

	CLIMATE ZONE	CITY	STATE	ZONE	REGION
1	1A	Miami	Florida	Very hot	Moist
2	2A	Houston	Texas	Hot	Moist
3	2B	Phoenix	Arizona	Hot	Dry
4	3A	Memphis	Tennessee	Warm	Moist
5	3B	El Paso	Texas	Warm	Dry
6	3C	San Francisco	California	Warm	Marine
7	4A	Baltimore	Maryland	Mixed	Moist
8	4B	Albuquerque	New Mexico	Mixed	Dry
9	4C	Salem	Oregon	Mixed	Marine
10	5A	Chicago	Illinois	Cool	Moist
11	5B	Boise	Idaho	Cool	Dry
12	6A	Burlington	Vermont	Cold	Moist
13	6B	Helena	Montana	Cold	Dry
14	7	Duluth	Minnesota	Very cold	-
15	8	Fairbanks	Alaska	Subarctic	-

TABLE 5 Climate zones and representative cities that were incorporated into energy modelling simulations.

The dimensions and material properties of the façades were identical to previously discussed characteristics. The baseline model was a standard curtain wall, and all other models were enclosed by the different types of DSF (box window, corridor type and multi-storey). The energy models represented a single zone per floor, totalling 148.6 m² (1,600 ft²) per floor, with a 12.2 m (40 ft) wide and 12.2 m (40 ft) deep office space. Models were developed for a four-storey application in order to investigate the effects of height on the performance of multi-storey DSFs.

The inputs for occupancy loads, system loads, equipment loads, lighting, and ventilation were based on ASHRAE 90.1 energy code and recommendations prescribed by ASHRAE 189 standard (ASHRAE, 2014; ASHRAE 2013b). The material properties and optical properties of glazing were identical to heat transfer analysis. Operating schedule was based on a typical office space operation (weekday schedule from 8 AM to 6 PM). The heating, ventilation and air-conditioning (HVAC) system consisted of a packaged heating/cooling pump with direct expansion (DX) coils, and natural gas used for heating. The results were calculated for all models, where total annual energy consumption was determined for each individual scenario, as well as the heating, cooling, and lighting loads. In addition, Energy Usage Intensity (EUI) was determined for all scenarios. The results are discussed in more detail in a later section.

3.4 DAYLIGHT ANALYSIS

Modelling and simulation tools were used to evaluate daylighting performance for all investigated façade types. A detailed model of an office space was created in Revit, with identical dimensions as the energy modelling. The baseline model was a standard curtain wall, while all other models were enclosed by different types of DSF (box window, corridor type, and multi-storey). Each DSF was tested with .6 m (2 ft) and .9 m (3 ft) cavities. These cavity depths were chosen for daylight analysis because deeper cavities are needed for access and maintenance, but would reduce daylighting. The objective was to quantify the impacts of different cavity depths on daylighting. All models were also simulated at four different orientations (north, south, east, and west). Interior materials consisted of white paint

on walls, carpet as flooring, and acoustic tile for the ceiling. The models were then imported into Ecotect, where the Radiance plug-in was used to calculate illuminance levels. Four U.S. cities were evaluated: Duluth, Chicago, San Francisco, and Miami. These cities were chosen for their different latitudes. Each simulation model was tested under different sky conditions, considering overcast sky (for January simulations), partly cloudy (for October simulations), and sunny conditions (for July simulations) for each location, with global illuminance values derived from the weather file. A dataset of 336 simulations was produced.

4 RESULTS

4.1 HEAT TRANSFER ANALYSIS RESULTS

The results of the 2D heat transfer analysis consisted of two sets of data—the first set of data indicated thermal gradients through investigated façade systems for four exterior environmental conditions, and the second set of data demonstrated U-values. Figures 7 to 10 show thermal gradients for DSF types and four exterior environmental conditions, with air temperatures of 32°C (90°F), 16°C (60°F), -1°C (30°F) and -18°C (0°F) used as external boundary conditions.

Figure 11 indicates temperatures within upper and lower parts of cavities for all three DSF types, and for all four exterior environmental conditions. Results indicate that for lower exterior temperatures of -1°C (30°F) and -18°C (0°F), there is a larger difference in temperature within the lower and upper parts of the air cavity. As the exterior temperature increases, such as 16°C (60°F) and 32°C (90°F), there is less differentiation between the lower and upper parts of the air cavity. Another observation is that there is slight variation in results based on the DSF typology. For example, the multi-storey DSF shows smaller discrepancies than corridor type or box window DSF. Figure 12 indicates temperatures within the outer, inner, and central part of the cavity for the four investigated external air temperatures.

Heat transfer coefficients (U-values) were calculated for conventional curtain wall, as well as three investigated DSF types. The air cavity was assumed to be closed for U-value calculations. Table 6 shows the results, indicating the relative thermal performance of each investigated façade type. All DSF types have much lower U-value than a standard curtain wall. The differences between different DSF typologies are relatively small; however, a multi-storey DSF would have the smallest U-value, followed by the box window and corridor type DSFs. Nevertheless, the significant difference between U-values of DSF types and conventional curtain walls suggests that all types of DSFs would provide savings in heating and cooling loads due to improved thermal performance for the majority of building types and climates.

Exterior Temperature -18°C

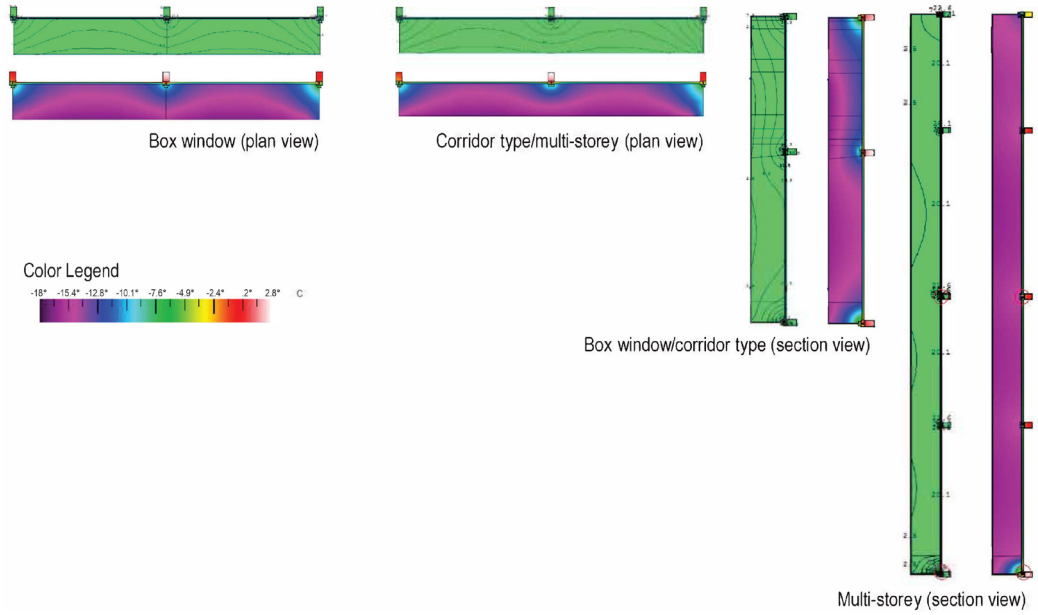


FIG. 7 Thermal gradients for DSF types: exterior temperature of -18°C (0°F).

Exterior Temperature -1°C

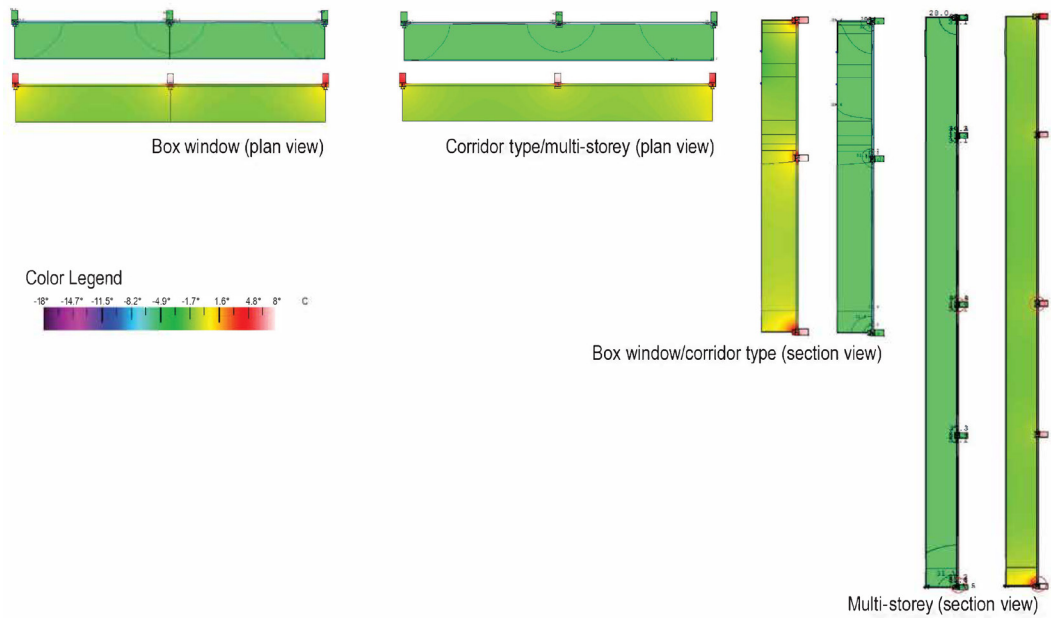


FIG. 8 Thermal gradients for DSF types: exterior temperature of -1°C (30°F).

Exterior Temperature 16°C

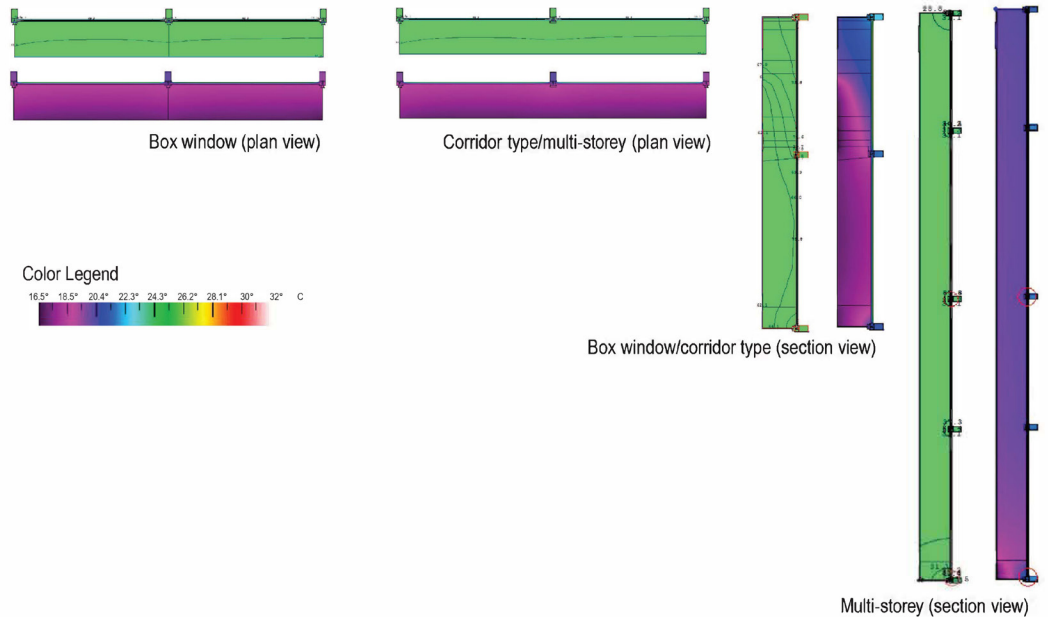


FIG. 9 Thermal gradients for DSF types: exterior temperature of 16°C (60°F).

Exterior Temperature 32°C

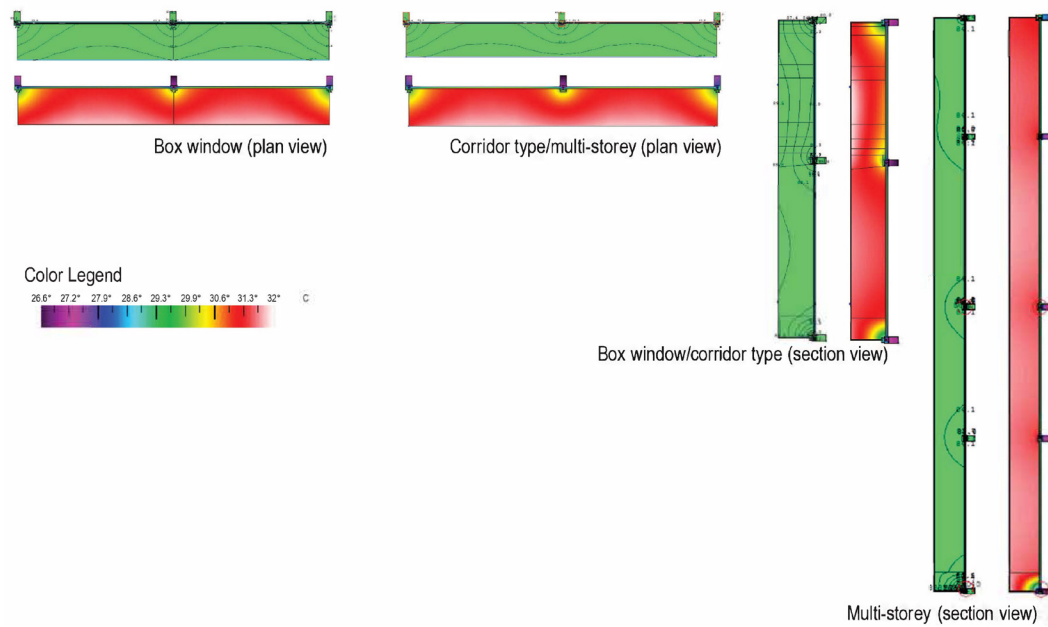


FIG. 10 Thermal gradients for DSF types: exterior temperature of 32°C (90°F).

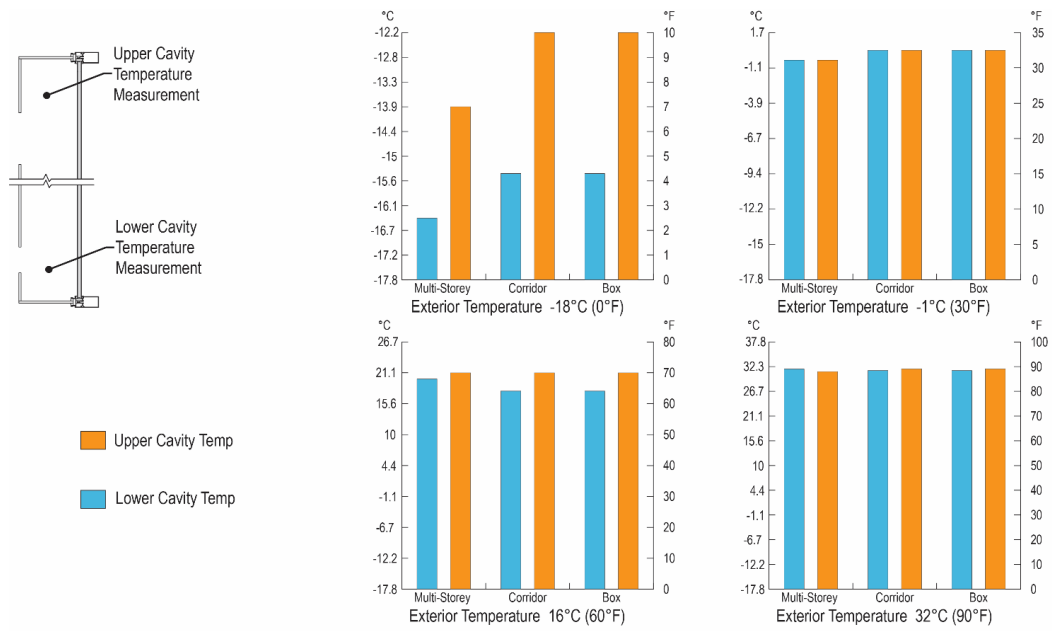


FIG. 11 Temperatures at the upper and lower parts of air cavity for investigated DSF types.

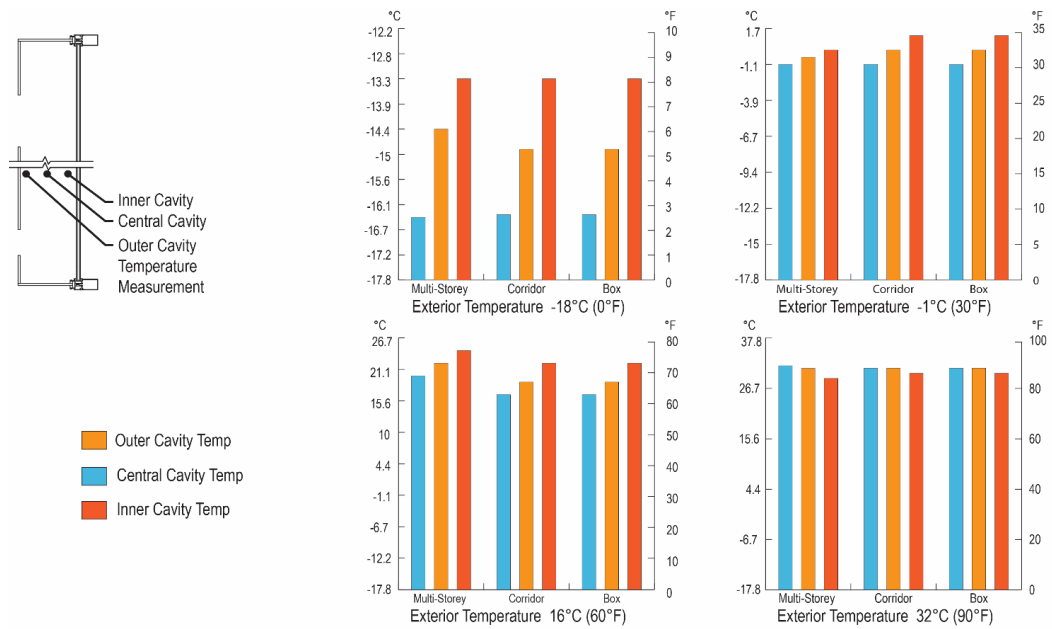


FIG. 12 Temperatures at the inner, central and outer parts of air cavity for investigated DSF types.

	SINGLE SKIN (CONVENTIONAL CURTAIN WALL)	BOX WINDOW DSF	CORRIDOR TYPE DSF	MULTI-STOREY DSF
U-value W/m ² .°C (Btu/h-ft ² .°F)	1.02 (.18)	.18 (0.032)	.20 (0.036)	.18 (0.031)

TABLE 6 Calculated U-values for the investigated façade types.

4.2 COMPUTATIONAL FLUID DYNAMICS ANALYSIS RESULTS

The results of CFD analysis indicated temperature gradients within the air cavity of the investigated DSF types in 3D form, as well as air velocity and airflow patterns. CFD analysis results for multi-storey DSFs show that when the exterior temperature was -18°C (0°F), the temperature in the air cavity fluctuated between -17.7°C (0.2°F) and -15.3°C (4.4°F). The upper part of the cavity demonstrated a higher temperature, as seen in Figure 13. The velocity was relatively stable within the air cavity. Inlet velocity was 4.9 m/s and outlet velocity was 5.9 m/s , and the increased velocity value may be due to the stack effect, since the warmer air rises. When the exterior temperature was increased to -1°C (30°F), air temperature inside the cavity was between -1°C (30.2°F) and 2.9°C (37.2°F). If the exterior temperature was increased to 16°C (60°F) or 32°C (90°F), temperatures within the cavity fall within the range between 15.7°C (60.2°F) and 19.7°C (67.5°F), and 32.3°C (90.2°F) and 36.2°C (97.2°F). The simulation results demonstrate a consistent temperature change pattern. Within the cavity of a multi-storey DSF, there is a temperature fluctuation caused by solar radiation, exterior and interior temperature, as well as the ventilation effects. However, the temperature change is not significant mainly because of the configuration characteristics of the multi-storey DSF.

Compared to multi-storey, the corridor type DSF showed a similar rising trend in cavity temperature (Fig.14). With an exterior temperature of -18°C (0°F), the cavity area's temperature fluctuated between -17.7°C (0.1°F) and -17.3°C (0.8°F). With exterior temperature of -1°C (30°F), the temperature inside the cavity was between -7.3°C (18.9°F) and 1.8°C (35.2°F), which is lower than the temperature gradient for the multi-storey DSF. In addition, with exterior temperatures of 16°C (60°F) and 32°C (90°F), the temperatures within the cavity area fluctuated between 15.6°C (60.1°F) and 16.3°C (61.4°F), and 31.7°C (89.1°F) and 33.8°C (92.8°F), respectively. The cavity temperature also showed discrepancies in the lower and the upper parts. The higher temperature in the upper part of DSF cavity indicates that the warm air rises. Moreover, airflow patterns were different from the multi-storey DSF due to the addition of horizontal partitions between floors. This caused more turbulence within the air cavity.

The results for the box DSF indicate that the cavity temperatures are relatively constant (Fig.15). With an exterior temperature of -18°C (0°F), the temperature within the cavity fluctuates between -17.7°C (0.1°F) and -17°C (1.4°F). When the exterior temperature increased to 16°C (60°F), the cavity temperature showed a range between 15.5°C (59.9°F) and 15.6°C (60.1°F). Also, for the exterior temperature of 32°C (90°F), the cavity temperature was between 32.2°C (89.9°F) and 32.3°C (90.1°F). The smaller ranges in temperatures could be due to the geometry and components of the box window DSF, since this typology has horizontal and vertical divisions that limit the movement of air within the cavity. However, these components influence airflow patterns and create patterns that are more turbulent than other types of DSFs.

CFD analysis and THERM analysis provided slightly different results for temperatures within the air cavity in all DSF cases. This is caused by the fact that THERM considers 2D convective heat transfer, while CFD analysis considers 3D heat transfer and takes into account radiation, convection, and the effects of wind on a naturally ventilated system. Tables 7, 8 and 9 compare results for all analysed DSF façades under different external environmental conditions, where temperatures within the air cavity are listed for both simulation methods.

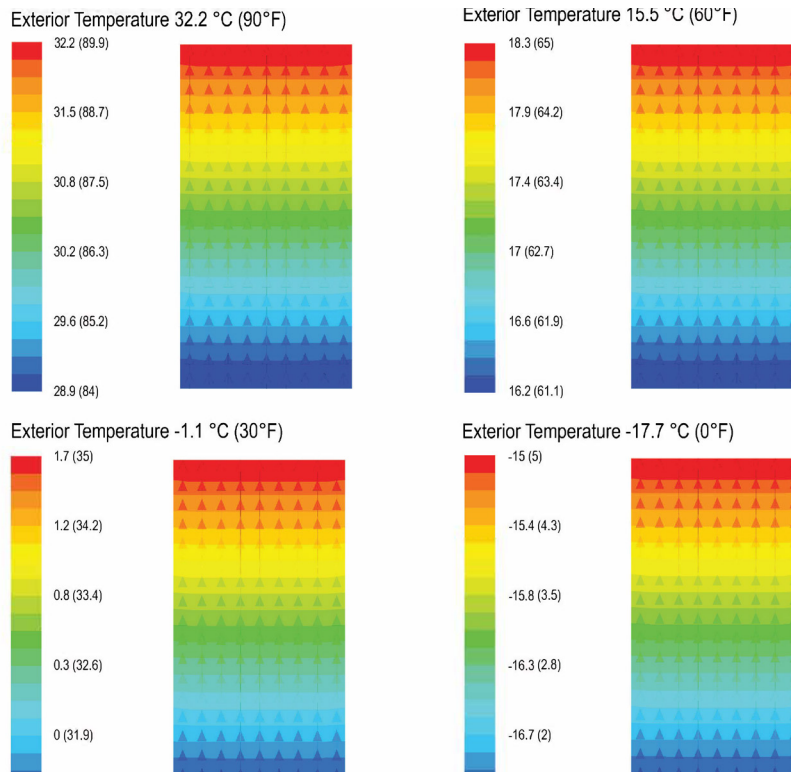


FIG. 13 Results of the CFD analysis, showing temperature within air cavity and airflow pattern for multi-storey DSF.

Exterior temperature	32 °C (90°F)	16 °C (60°F)	-1 °C (30°F)	-18 °C (0°F)
CFD analysis air cavity temperature range °C (°F)	32.3 to 36.2 (90.2 to 97.2)	15.6 to 19.7 (60.2 to 67.5)	-1 to 2.8 (30.2 to 37.2)	-17.7 to 15.8 (0.18 to 3.48)
THERM analysis air cavity temperature range °C (°F)	27.8 to 29.4 (82.0 to 85.0)	20 to 23.9 (68.0 to 75.0)	-1.1 to 0 (30.0 to 32.0)	-16.4 to 13.3 (2.50 to 8.00)

TABLE 7 Comparison of CFD and THERM analysis results for multi-storey DSF.

Exterior temperature	32 °C (90°F)	16 °C (60°F)	-1 °C (30°F)	-18 °C (0°F)
CFD analysis air cavity temperature range °C (°F)	32.7 to 34.9 (90.9 to 94.8)	16.4 to 19.3 (61.6 to 66.7)	-1.1 to 1.5 (30.1 to 34.7)	-17.7 to 15 (0.0 to 5.0)
THERM analysis air cavity temperature range °C (°F)	28.3 to 29.3 (83.0 to 84.7)	16.7 to 22.8 (62.0 to 73.0)	-1.1 to 1.1 (30.0 to 34.0)	-16.3 to -13.3 (2.60 to 8.00)

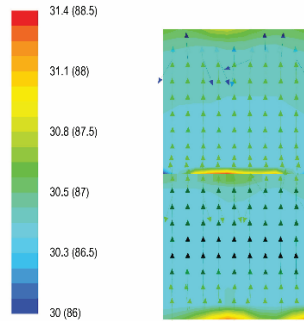
TABLE 8 Comparison of CFD and THERM analysis results for corridor type DSF.

Exterior temperature	32 °C (90°F)	16 °C (60°F)	-1 °C (30°F)	-18 °C (0°F)
CFD analysis air cavity temperature range °C (°F)	32.2 to 32.3 (90.0 to 90.1)	15.6 to 15.6 (60.0 to 60.1)	-1.1 to 1.1 (30.0 to 30.1)	-17.7 to 17.7 (0.0 to 0.1)
THERM analysis air cavity temperature range °C (°F)	28.3 to 29.3 (83.0 to 84.7)	16.7 to 22.8 (62.0 to 73.0)	-1.1 to 15.6 (30.0 to 34.0)	-16.3 to 13.3 (2.60 to 8.00)

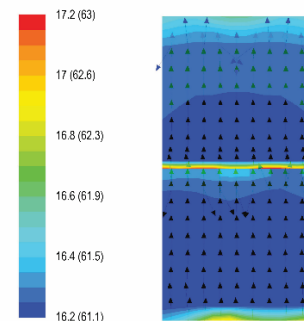
TABLE 9 Comparison of CFD and THERM analysis results for box window DSF.

Corridor Type DSF

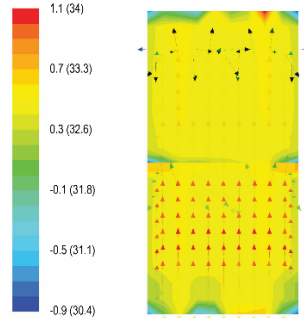
Exterior Temperature 32.2 °C (90°F)



Exterior Temperature 15.5 °C (60°F)



Exterior Temperature -1.1 °C (30°F)



Exterior Temperature -17.7 °C (0°F)

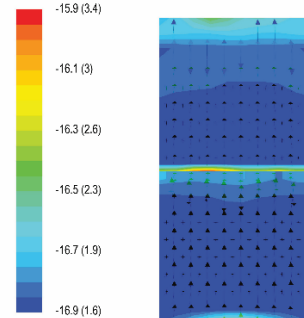
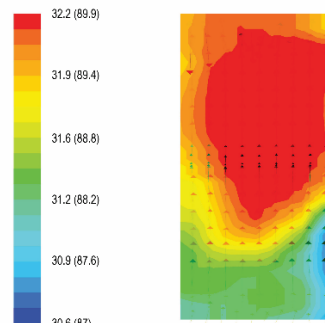


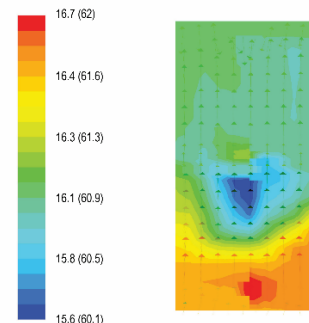
FIG. 14 Results of the CFD analysis, showing temperature within air cavity and airflow pattern for corridor type DSF.

Box Window DSF

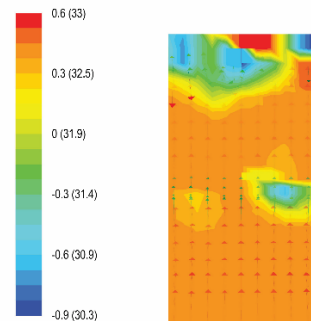
Exterior Temperature 32.2 °C (90°F)



Exterior Temperature 15.5 °C (60°F)



Exterior Temperature -1.1 °C (30°F)



Exterior Temperature -17.7 °C (0°F)

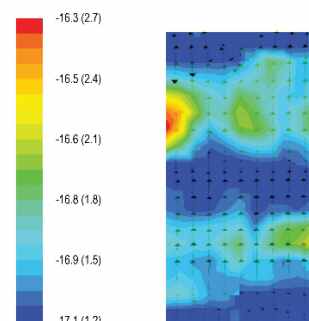


FIG. 15 Results of the CFD analysis, showing temperature within air cavity and airflow pattern for box window DSF.

4.3 ENERGY MODELLING RESULTS

Although benefits of DSFs in temperate and heating dominated climates have been reported in numerous earlier studies as discussed by Pomponi et al. (2016), this study investigated the effects of DSFs on energy consumption in all climate types. As stated earlier, the methodology consisted of modelling the EUI and annual energy consumption of a south-oriented office space, which would be enclosed by the investigated façade types. Four levels were simulated to accurately depict the application of the multi-storey façade. Energy consumption for heating, cooling, and interior lighting was calculated, as well as the average EUI.

Table 10 shows the percentage of energy savings for each type of DSF across all climate types, compared to a single skin curtain wall. Figures 16 to 18 show the EUI for all façade types, for the three DSF variations (without openings, holes, and vents), in all climates. All DSF types performed better than the base case, a single skin conventional curtain wall, with the exception of the multi-storey DSF with holes in climate zone 6B. The DSF types without openings resulted in similar savings within the same climate zone. In all climate types, the box window DSF performed better than the other DSF types. Hotter, drier climates saw the greatest energy savings (2B Phoenix: 30%), while humid climates saw lower savings compared to dry or marine climates in the same zone (2A Houston: 19%). Box window saw the greatest variation in savings within the subtypes (without openings, holes, and vents), while multi-storey saw the least variation in savings. This may be caused by the variations in façade components, since box window DSF includes horizontal and vertical divisions in the air cavity, and multi-storey does not have any divisions. These elements influence temperature gradients, air flow within the cavity, and visible light transmittance to the interior space.

CLIMATE ZONE	CORRIDOR			BOX WINDOW			MULTI-STOREY		
	wo/ openings	holes	vents	wo/ openings	holes	vents	wo/ openings	holes	vents
1A (Miami)	14%	13%	15%	15%	19%	21%	13%	11%	13%
2A (Houston)	14%	14%	15%	16%	19%	19%	14%	12%	13%
2B (Phoenix)	25%	23%	27%	26%	28%	30%	22%	20%	22%
3A (Memphis)	17%	16%	17%	18%	21%	21%	16%	18%	16%
3B (El Paso)	23%	21%	25%	25%	27%	28%	20%	18%	20%
3C (San Francisco)	22%	21%	23%	24%	27%	28%	20%	17%	19%
4A (Baltimore)	14%	15%	13%	14%	20%	18%	13%	12%	13%
4B (Albuquerque)	23%	22%	24%	24%	27%	28%	20%	18%	20%
4C (Salem)	18%	19%	17%	19%	23%	22%	17%	16%	17%
5A (Chicago)	16%	16%	14%	17%	17%	14%	15%	15%	12%
5B (Boise)	20%	20%	20%	21%	26%	26%	18%	17%	18%
6A (Burlington)	15%	17%	14%	15%	22%	20%	15%	15%	15%
6B (Helena)	16%	18%	15%	17%	24%	22%	16%	0%	16%
7 (Duluth)	16%	18%	14%	16%	25%	22%	16%	16%	16%
8 (Fairbanks)	21%	22%	20%	21%	29%	28%	21%	20%	20%

TABLE 10 Amount of energy savings in EUI as a percentage, compared to the single skin façade type.



FIG. 16 EUI for investigated façade scenarios, considering DSFs without openings.

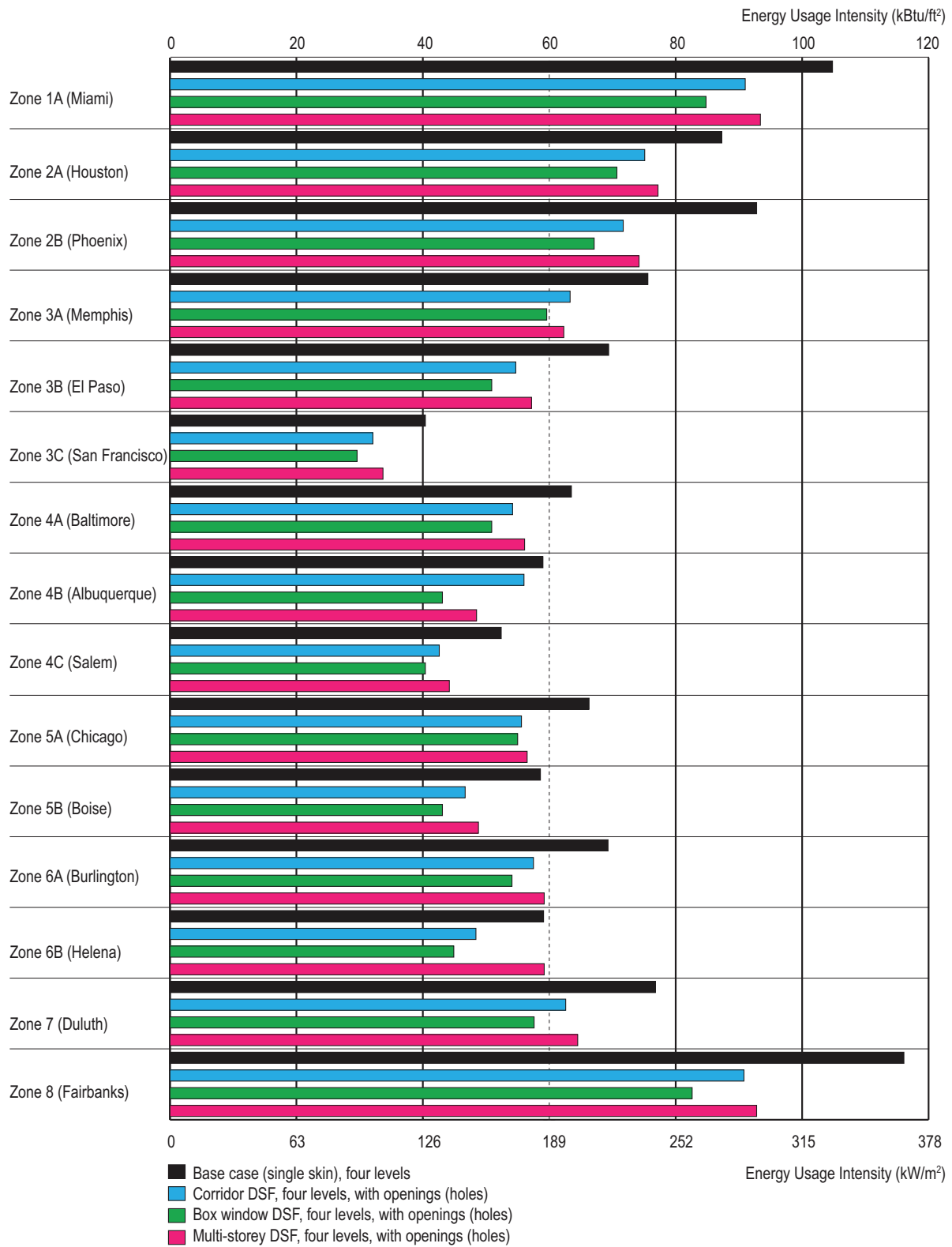


FIG. 17 EUI for investigated façade scenarios, considering DSFs with openings (holes).

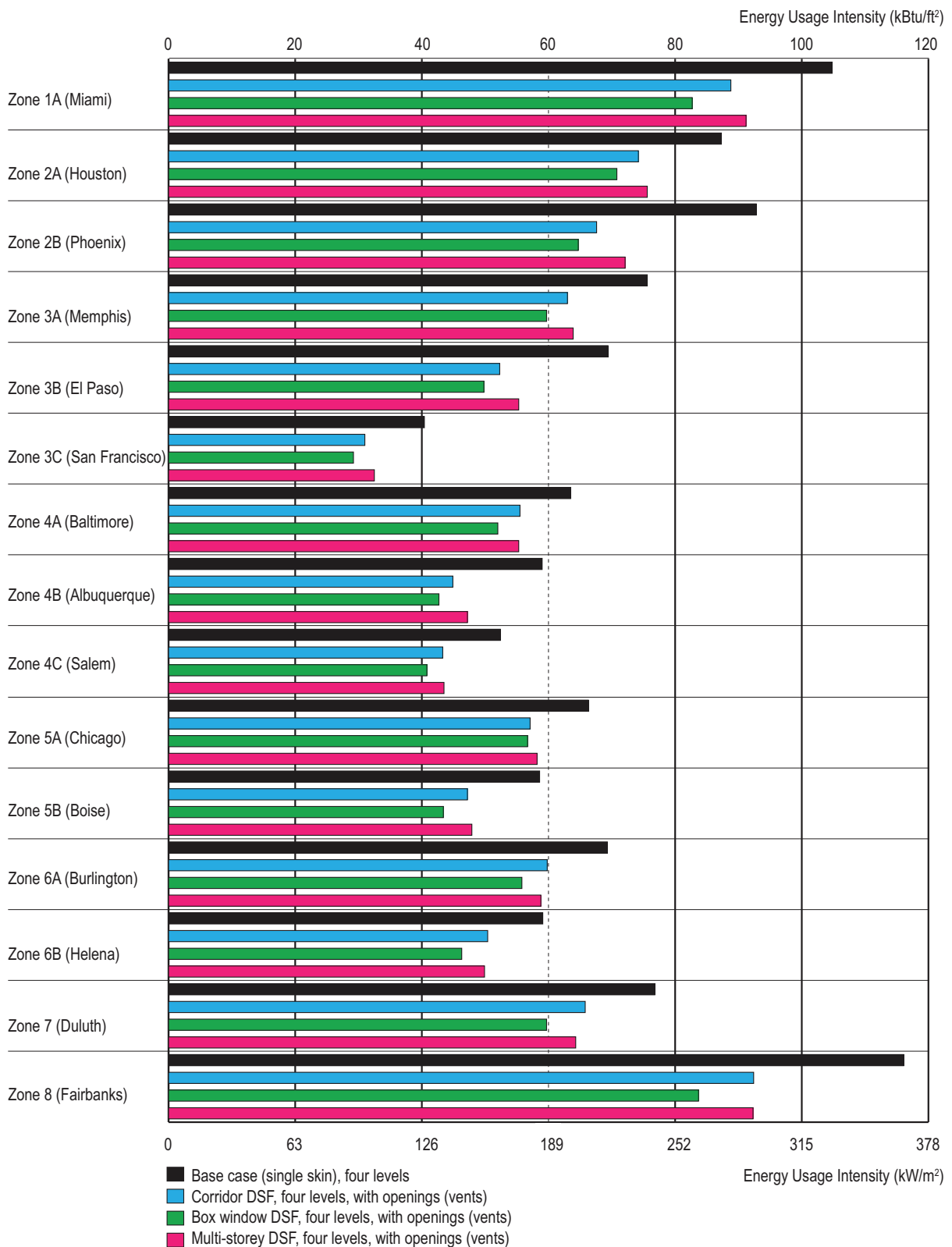


FIG. 18 EUI for investigated façade scenarios, considering DSFs with openings (vents).

CLIMATE ZONE	CORRIDOR			BOX WINDOW			MULTI-STOREY		
	wo/ openings	holes	vents	wo/ openings	holes	vents	wo/ openings	holes	vents
1A (Miami)	-79%	-54%	-106%	-78%	-61%	-115%	-69%	-62%	-69%
2A (Houston)	-87%	-63%	-112%	-85%	-68%	-103%	-76%	-70%	-76%
2B (Phoenix)	-54%	-37%	-71%	-51%	-36%	-58%	-58%	-49%	-58%
3A (Memphis)	-68%	-49%	-89%	-67%	-50%	-77%	-62%	-56%	-62%
3B (El Paso)	-64%	-46%	-83%	-61%	-46%	-72%	-49%	-57%	-66%
3C (San Francisco)	-59%	-44%	-75%	-57%	-43%	-65%	-58%	-52%	58%
4A (Baltimore)	-62%	-45%	-82%	-60%	-44%	-70%	-59%	-54%	-59%
4B (Albuquerque)	-63%	-47%	-79%	-59%	-45%	-67%	-71%	-61%	-71%
4C (Salem)	-62%	-46%	-79%	-59%	-43%	-65%	-59%	-54%	-59%
5A (Chicago)	-53%	-44%	-77%	-47%	-39%	-74%	-50%	-34%	-92%
5B (Boise)	-58%	-44%	-72%	-55%	-39%	-58%	-60%	-54%	-60%
6A (Burlington)	-58%	-43%	-75%	-56%	-40%	-66%	-54%	-50%	-54%
6B (Helena)	-50%	-38%	-64%	-47%	-33%	-52%	-53%	-55%	-53%
7 (Duluth)	-60%	-45%	-76%	-57%	-41%	-63%	-57%	-52%	-57%
8 (Fairbanks)	-27%	-19%	-35%	-25%	-10%	-21%	-27%	-25%	-27%

TABLE 11 Energy savings for lighting loads (as a percentage), compared to single skin façade.

Table 11 shows the impact on lighting loads for all DSF types and climate types, compared to a single skin. Lighting usage has increased across all DSFs and climate types, as seen in Figures 19 to 21. Locations at lower latitudes saw the worst performance, due to higher sun angles. Locations at higher latitudes saw better performance due to lower sun angles. The corridor DSF type with vents was found to be the worst performer in all but two climate zones. The corridor DSF type with holes was found to be the best performer in four of the warmer climate zones, while the box window with holes was the best performer in 11 out of 15 climate zones.

With the exception of climate zone 3C, warmer climates saw lower energy savings in cooling than colder climates, as seen in Figures 19 to 21. Humid climates also saw lower energy savings compared to dry or marine climates in the same zone. In all but one zone (4A), the box window with vents was the best performer, while the multi-storey with holes was the worst performer across all climate types. Climate zone 3C saw similar savings to zone 8, as seen in Table 12.

Warmer climate zones saw greater energy savings in heating, while colder zones saw the least savings (with the exception of zone 5A). Zone 1A saw the greatest variation in savings (89% to -73%), while zone 8 saw the lowest variation (31% to 38%). The best performing DSF types were corridor with holes, and box window with holes. The worst performing DSF types were corridor with vents, and box window with vents, as shown in Table 13.

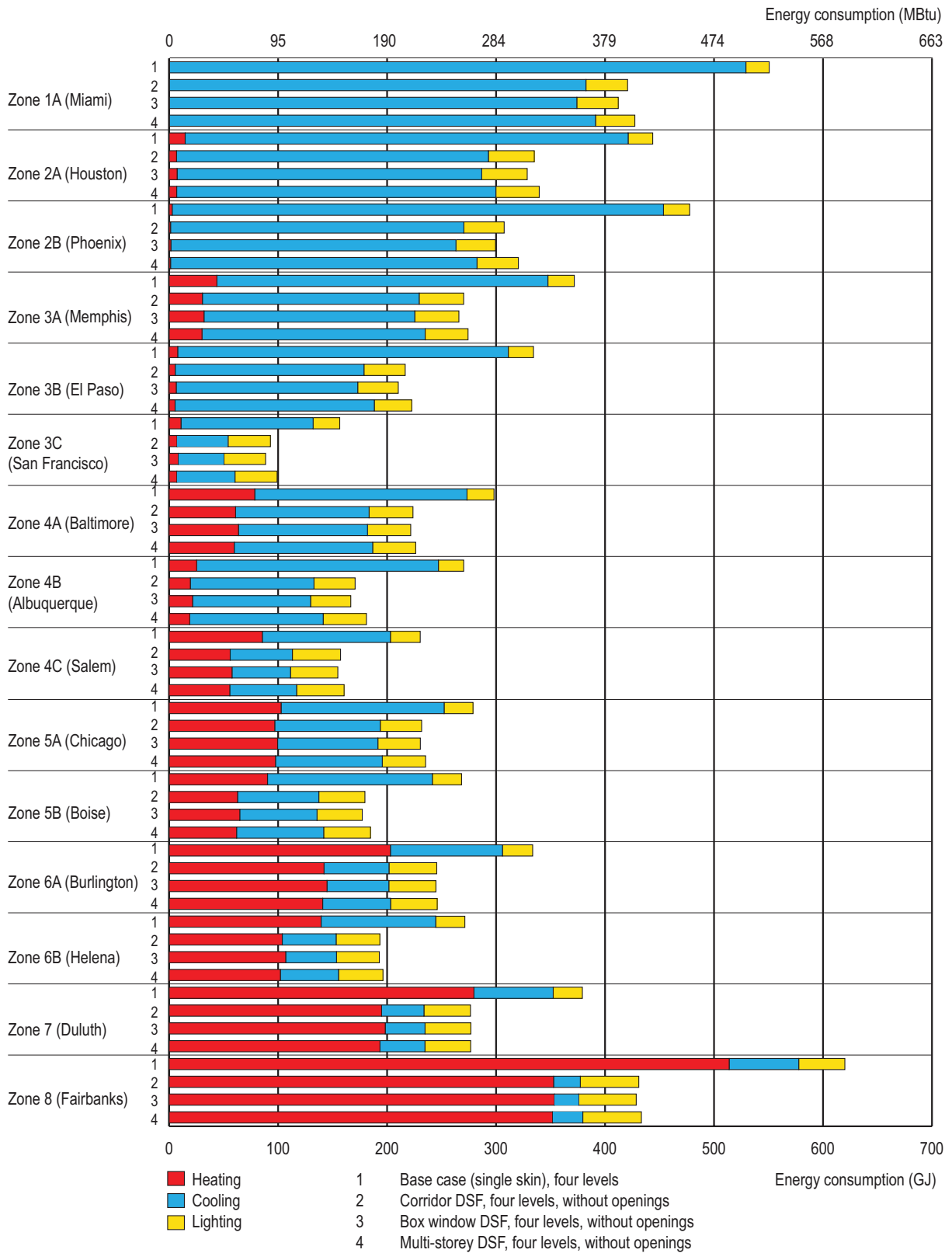


FIG. 19 Energy consumption for investigated façade scenarios, considering DSFs without openings.

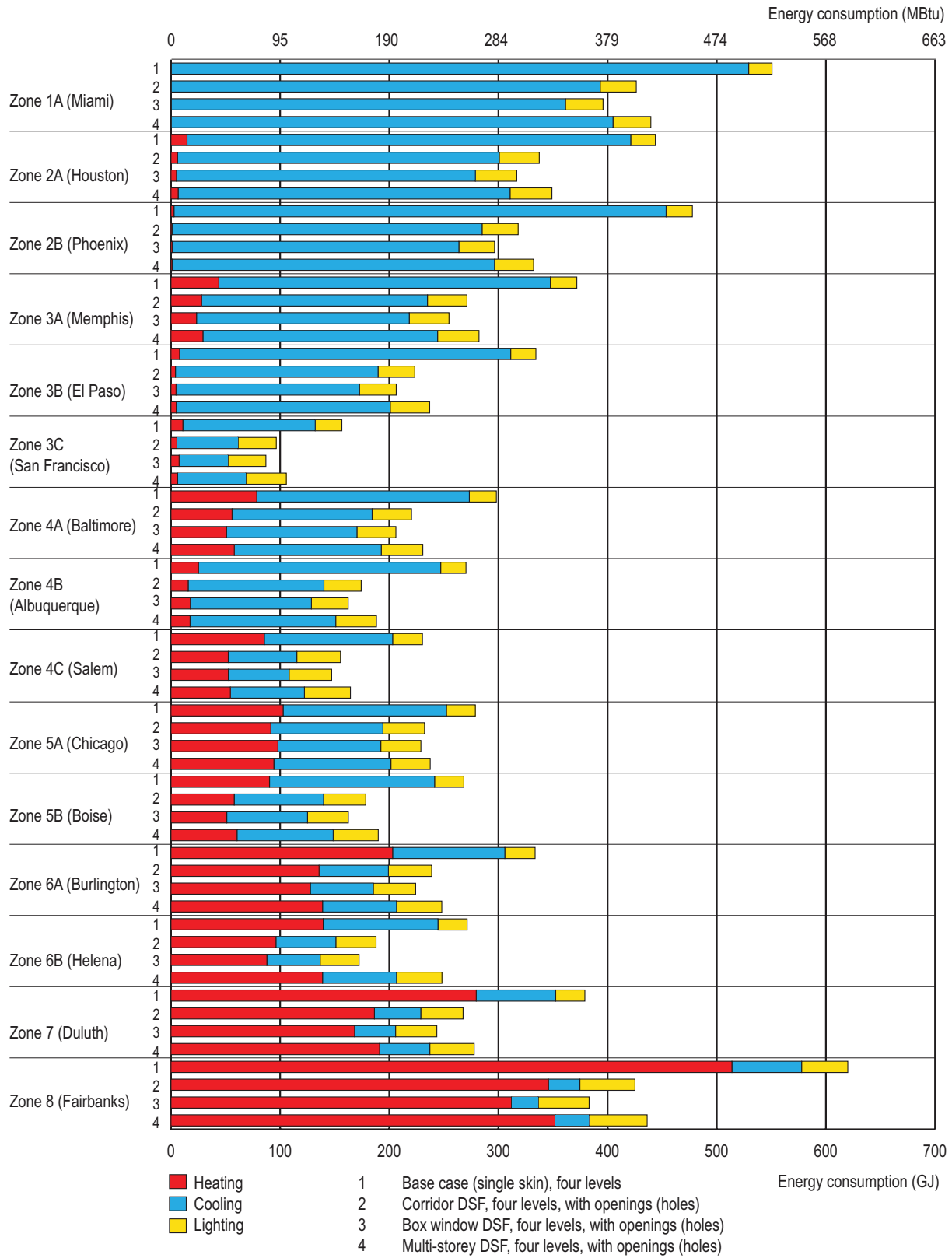


FIG. 20 Energy consumption for investigated façade scenarios, considering DSFs with openings (holes).

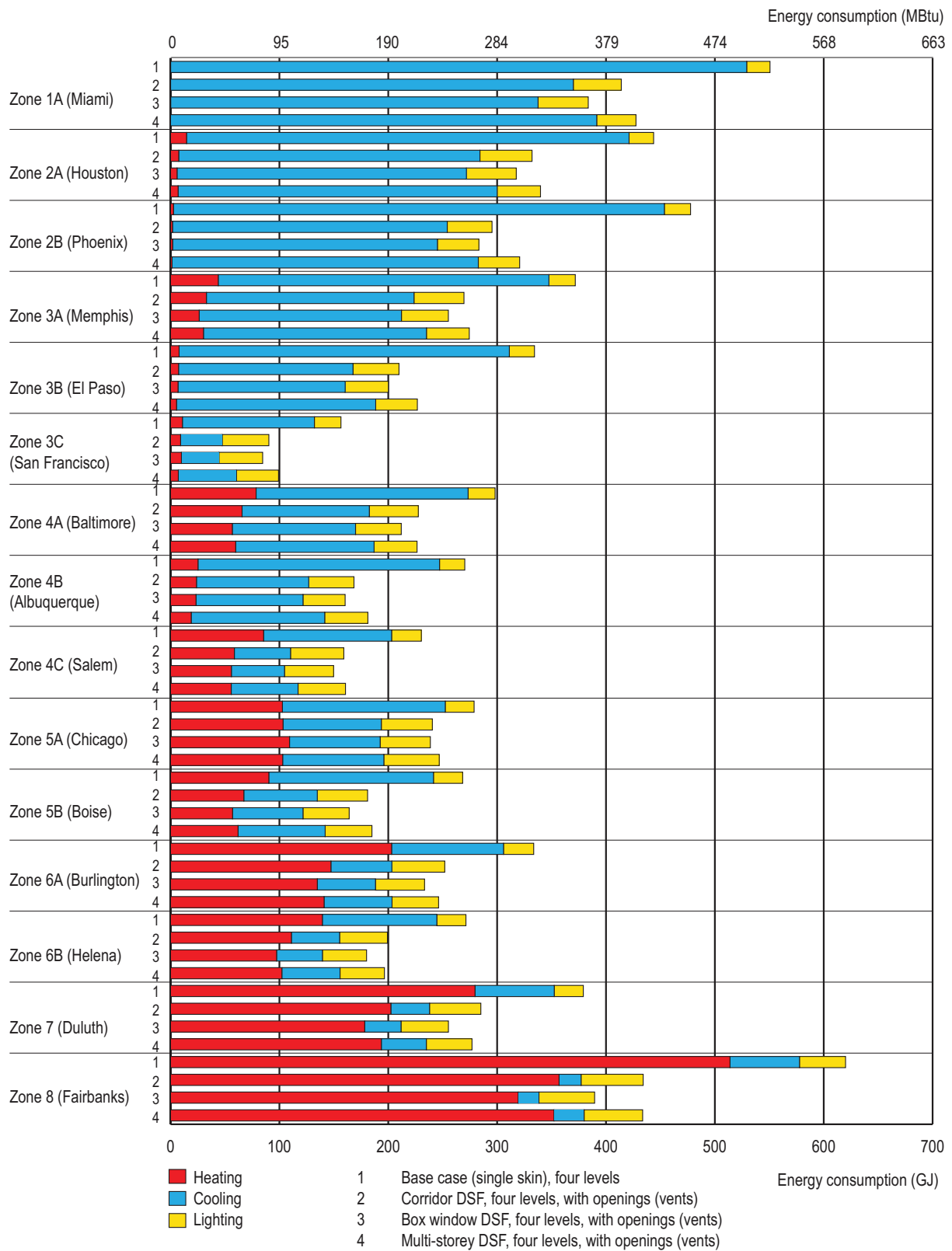


FIG. 21 Energy consumption for investigated façade scenarios, considering DSFs with openings (vents).

CLIMATE ZONE	CORRIDOR			BOX WINDOW			MULTI-STOREY		
	wo/ openings	holes	vents	wo/ openings	holes	vents	wo/ openings	holes	vents
1A (Miami)	28%	26%	30%	29%	32%	36%	26%	23%	26%
2A (Houston)	30%	28%	32%	31%	33%	35%	28%	25%	28%
2B (Phoenix)	40%	37%	44%	42%	42%	46%	38%	35%	38%
3A (Memphis)	35%	32%	37%	36%	36%	39%	33%	29%	33%
3B (El Paso)	43%	39%	47%	45%	45%	50%	40%	35%	40%
3C (San Francisco)	61%	54%	68%	66%	63%	72%	56%	49%	56%
4A (Baltimore)	37%	34%	42%	37%	34%	40%	35%	31%	35%
4B (Albuquerque)	49%	44%	54%	51%	50%	56%	45%	40%	45%
4C (Salem)	51%	47%	56%	54%	53%	58%	48%	42%	48%
5A (Chicago)	35%	31%	40%	38%	37%	44%	34%	28%	38%
5B (Boise)	51%	46%	55%	53%	51%	57%	47%	42%	47%
6A (Burlington)	42%	38%	46%	45%	44%	48%	39%	34%	39%
6B (Helena)	53%	48%	58%	56%	54%	60%	49%	36%	49%
7 (Duluth)	47%	42%	51%	50%	48%	54%	43%	37%	43%
8 (Fairbanks)	62%	55%	68%	65%	62%	70%	57%	51%	57%

TABLE 12 Energy savings for cooling loads (as a percentage), compared to single skin façade.

CLIMATE ZONE	CORRIDOR			BOX WINDOW			MULTI-STOREY		
	wo/ openings	holes	vents	wo/ openings	holes	vents	wo/ openings	holes	vents
1A (Miami)	68%	89%	38%	50%	39%	-73%	69%	82%	68%
2A (Houston)	54%	59%	49%	50%	66%	59%	53%	55%	53%
2B (Phoenix)	52%	65%	34%	42%	52%	30%	52%	59%	51%
3A (Memphis)	30%	36%	25%	27%	47%	40%	31%	33%	31%
3B (El Paso)	29%	48%	6%	17%	41%	12%	31%	38%	30%
3C (San Francisco)	33%	50%	15%	22%	32%	8%	35%	43%	34%
4A (Baltimore)	22%	29%	16%	19%	35%	28%	24%	26%	24%
4B (Albuquerque)	23%	38%	6%	15%	30%	7%	25%	31%	25%
4C (Salem)	34%	39%	31%	33%	39%	35%	35%	36%	35%
5A (Chicago)	6%	11%	-1%	3%	5%	-6%	5%	8%	0%
5B (Boise)	30%	36%	25%	28%	43%	37%	31%	33%	31%
6A (Burlington)	30%	33%	27%	29%	37%	34%	31%	32%	31%
6B (Helena)	26%	31%	20%	23%	37%	30%	27%	0%	27%
7 (Duluth)	30%	33%	28%	29%	40%	36%	31%	32%	31%
8 (Fairbanks)	31%	33%	31%	31%	33%	38%	32%	31%	31%

TABLE 13 Energy savings for heating loads (as a percentage), compared to single skin façade.

4.4 DAYLIGHT ANALYSIS RESULTS

Overall, DSFs reduced the amount of daylight compared to single skin glazed façade. All DSFs show a decreasing amount of daylight as the distance from the façade increases inside the building. However, as the distance from the perimeter increases, the difference in daylighting between the DSF façades and the typical single glazed façade decreases.

Duluth exhibited lower lighting levels in the northern and eastern orientations compared to other cities. In the southern and western orientations, it experienced higher lighting levels, due to the lower sun angles and light reaching farther into the space. In the same orientations during the fall and winter, Duluth experienced similar or lower lighting levels than the other cities. Chicago's results were similar to those observed in Duluth. North and east façades had considerably lower lighting levels than the south and west, regardless of the time of year. Daylight performance of the single skin façade is best, followed by the multi-storey DSF, the corridor DSF, and finally the box DSF. However, there is some variation. The box DSF outperforms the multi-storey DSF and the corridor DSF when using a 0.6 m (2 ft) cavity. Its daylight values closest to the perimeter are lower in most cases compared to multi-storey and corridor DSFs, but it retains higher values as the distance from the perimeter increases. The multi-storey DSF consistently has the highest daylight values closest to the façade, but reduces as the distance from the façade increases, as seen in Figures 22 and 23. For San Francisco, DSF performance during summer months is worse compared to previously mentioned cities, as the decreasing latitude results in the sun being higher in the sky. The box window DSF with a 0.6 m (2 ft) cavity brings in the most amount of light across the full 12.2 m (40 ft) depth of the space, except within the first 0.3m (1 ft), where the multi-storey DSF outperforms all others. In July, the one with a westerly orientation experiences the greatest variation in light levels (as seen in Figure 23), while all orientations during January experience the least variation. The multi-storey DSF performs best with a 0.9 m (3 ft) cavity depth and outperforms all other DSFs with this depth. Miami's daylighting results are unique in comparison to other locations. The north and east façades feature lower lighting levels than the south and west during summer months, as is typically with the other locations. The southern façade is the only orientation that does not have very high daylight levels during July, for all façade types, while the western orientation has extremely high values during the summer months. In general, the daylighting performance of the single skin façade is the best, followed by the multi-storey DSF, the corridor DSF, and finally the box DSF. The box DSF appears to most effectively transmit light into the interior when a 0.6 m (2 ft) cavity is used. The box DSF with a 0.9 m (3 ft) cavity performs poorly when compared to other façade types. The multi-storey DSF performs best close to the perimeter, but daylight levels significantly reduce farther into the space. Both the multi-storey DSF and corridor DSF perform better than the box DSF close to the façade, but values quickly diminish as distance increases. Miami features winter lighting levels that are higher than the other analysed cities. The north orientation during the winter months sees the most consistency in lighting levels for all DSF types in the 0.6 m (2 ft) cavity.

Daylighting performance was also analysed using a 500 lux (46 fc) threshold to see what percentage of the 12.2 m (40 ft) x 12.2 m (40 ft) office space floor would be adequately daylit for each façade type. The north façade data indicates that the multi-storey and corridor DSF perform better with a 0.9 m (3 ft) cavity, while the box window performs best with a 0.6 m (2 ft) cavity, as seen in Table 14. During the month of July, the northern locations saw greater variation in the result of the DSF types (Duluth: 0% to 30%), while southern locations saw more uniform results across five of the six DSF

ORIENTATION	TIME	FAÇADE TYPE	DULUTH	CHICAGO	SAN FRANCISCO	MIAMI
North	July	Single	46%	54%	56%	57%
		Multi-storey with .6 m (2 ft) air cavity	7%	14%	17%	24%
		Multi-storey with .9 m (3 ft) air cavity	30%	33%	35%	37%
		Corridor with .6 m (2 ft) air cavity	6%	7%	8%	21%
		Corridor with .9 m (3 ft) air cavity	13%	14%	16%	22%
		Box window with .6 m (2 ft) air cavity	10%	13%	17%	22%
		Box window with .9 m (3 ft) air cavity	0%	0%	0%	4%
	October	Single	18%	24%	23%	30%
		Multi-storey with .6 m (2 ft) air cavity	4%	5%	4%	7%
		Multi-storey with .9 m (3 ft) air cavity	5%	7%	8%	17%
		Corridor with .6 m (2 ft) air cavity	0%	0%	0%	2%
		Corridor with .9 m (3 ft) air cavity	0%	0%	3%	1%
		Box window with .6 m (2 ft) air cavity	0%	0%	0%	0%
		Box window with .9 m (3 ft) air cavity	0%	0%	0%	0%
	January	Single	17%	24%	27%	52%
		Multi-storey with .6 m (2 ft) air cavity	3%	4%	6%	8%
		Multi-storey with .9 m (3 ft) air cavity	0%	5%	14%	20%
		Corridor with .6 m (2 ft) air cavity	0%	0%	0%	2%
		Corridor with .9 m (3 ft) air cavity	0%	0%	5%	7%
		Box window with .6 m (2 ft) air cavity	0%	0%	0%	6%
		Box window with .9 m (3 ft) air cavity	0%	0%	0%	0%

TABLE 14 Percent of the floor area that has an illuminance value of 500 lux (46 fc) or more at ground level in a northern orientation.

ORIENTATION	TIME	FAÇADE TYPE	DULUTH	CHICAGO	SAN FRANCISCO	MIAMI
East	July	Single	46%	50%	54%	55%
		Multi-storey with .6 m (2 ft) air cavity	7%	13%	15%	16%
		Multi-storey with .9 m (3 ft) air cavity	27%	30%	31%	36%
		Corridor with .6 m (2 ft) air cavity	0%	6%	8%	10%
		Corridor with .9 m (3 ft) air cavity	16%	17%	24%	20%
		Box window with .6 m (2 ft) air cavity	6%	10%	20%	24%
		Box window with .9 m (3 ft) air cavity	0%	0%	0%	0%
	October	Single	23%	27%	29%	31%
		Multi-storey with .6 m (2 ft) air cavity	7%	6%	7%	7%
		Multi-storey with .9 m (3 ft) air cavity	11%	12%	26%	20%
		Corridor with .6 m (2 ft) air cavity	0%	0%	0%	0%
		Corridor with .9 m (3 ft) air cavity	0%	0%	3%	4%
		Box window with .6 m (2 ft) air cavity	0%	0%	0%	1%
		Box window with .9 m (3 ft) air cavity	0%	0%	0%	0%
	January	Single	16%	23%	26%	33%
		Multi-storey with .6 m (2 ft) air cavity	7%	4%	5%	8%
		Multi-storey with .9 m (3 ft) air cavity	0%	4%	14%	23%
		Corridor with .6 m (2 ft) air cavity	0%	0%	0%	2%
		Corridor with .9 m (3 ft) air cavity	0%	1%	1%	7%
		Box window with .6 m (2 ft) air cavity	0%	0%	0%	6%
		Box window with .9 m (3 ft) air cavity	0%	0%	0%	0%

TABLE 15 Percent of the floor area that has an illuminance value of 500 lux (46 fc) or more at ground level in an eastern orientation.

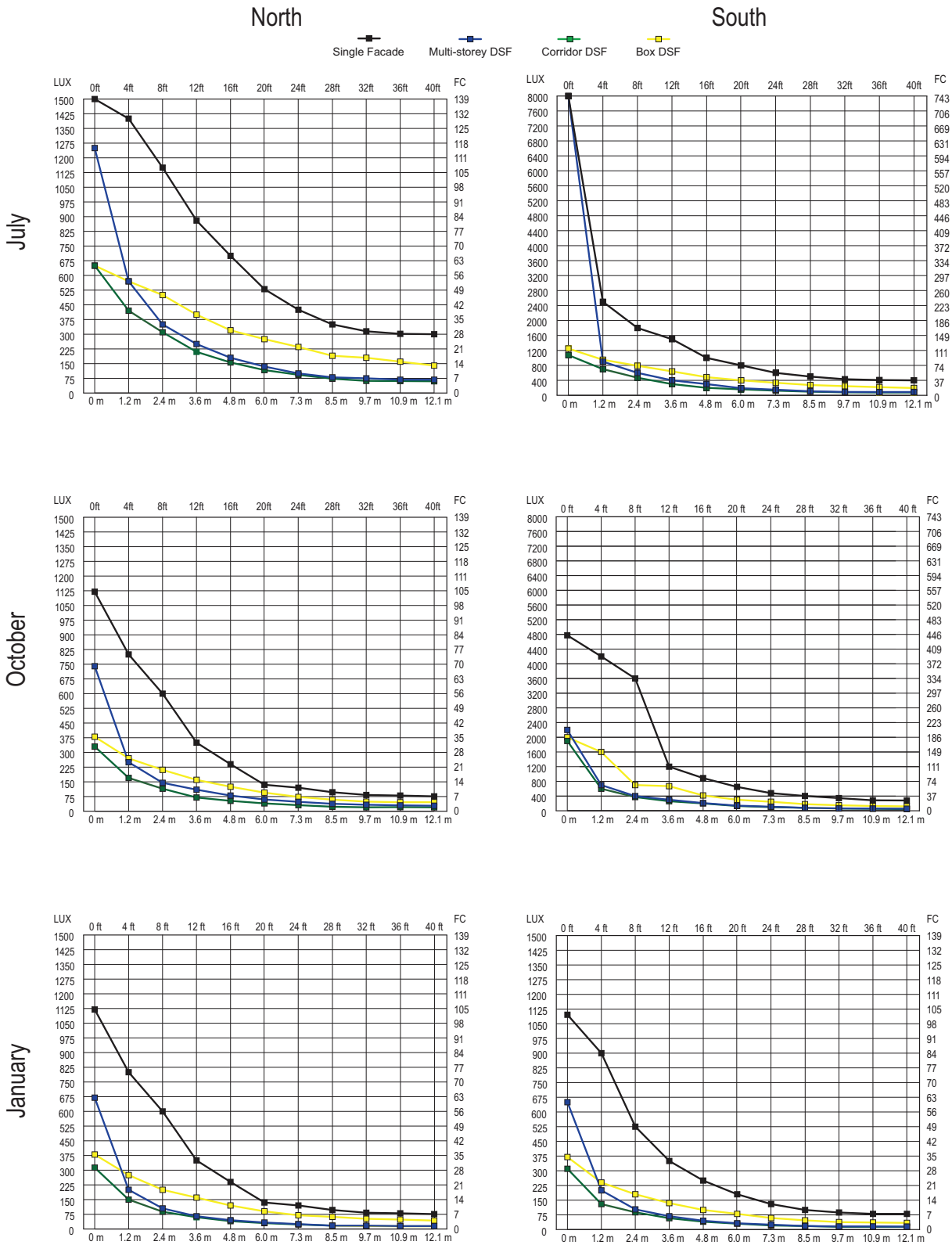


FIG. 22 Daylighting values for Chicago, .6m (2ft) cavity multi-storey DSF north and south orientations.

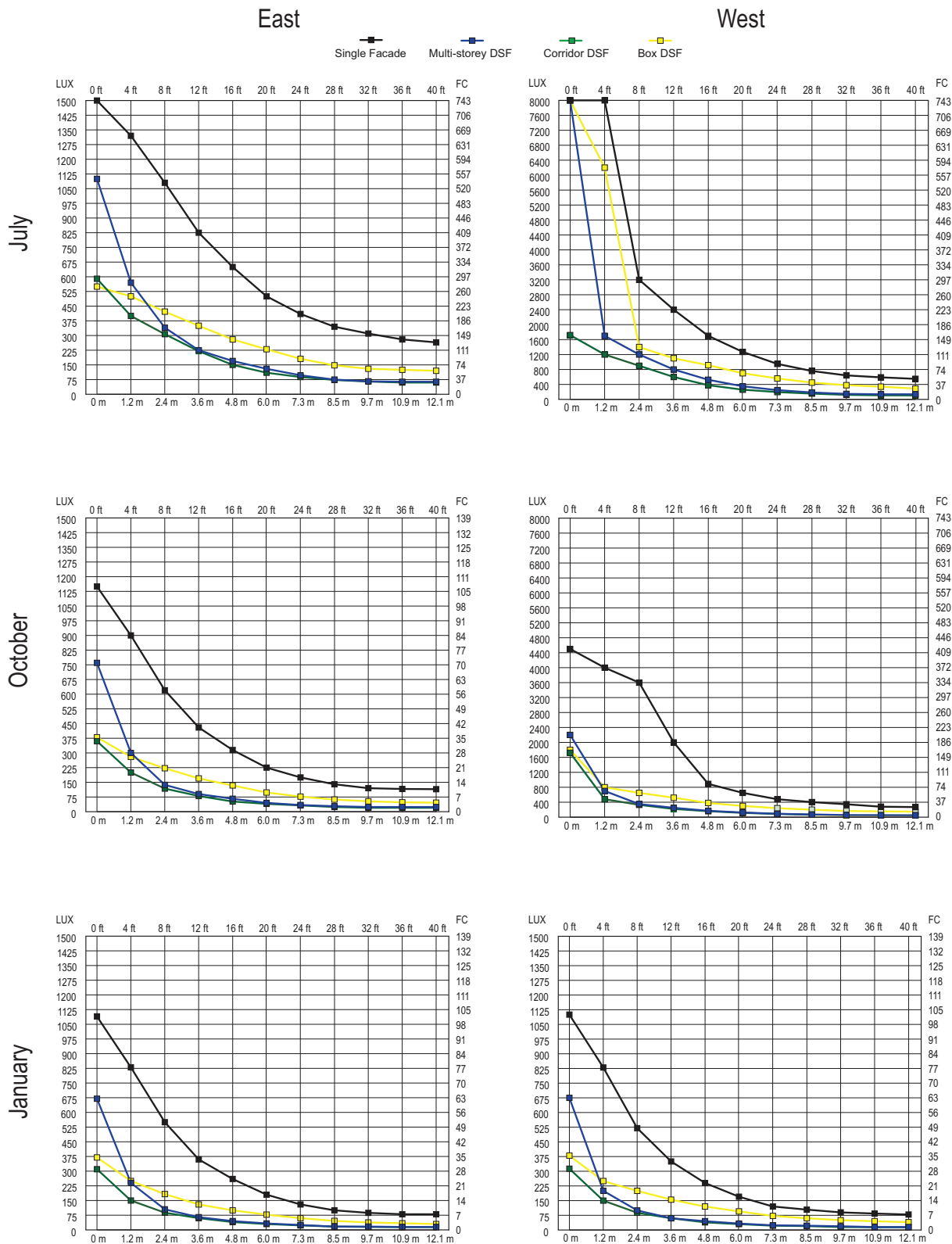


FIG. 23 Daylighting values for Chicago, 0.6m (2ft) cavity multi-storey DSF east and west orientations.

types (Miami: 21% to 37%). During intermediate and winter months, the daylighting performance at higher latitudes decreased significantly, while performance in lower latitudes saw less of a reduction. In January, 54% of the results showed that there would not be sufficient daylight within the interior space. There is a significant reduction in performance between the 0.9 m (3 ft) and 0.6 m (2 ft) multi-storey façade during summer months. During the intermediate and winter months 0.6 m (2 ft) multi-storey DSFs perform more consistently across all latitudes than their 0.9 m (3 ft) counterpart, although at reduced light levels. The 0.9 m (3 ft) box DSF is the poorest performer.

The east façade performs similarly to the northern façade, as seen in Table 15. Data indicated that the multi-storey with a 0.9 m (3 ft) cavity performs the best in most cases, out of all DSF types. The multi-storey with a 0.9 m (3 ft) cavity during July naturally illuminates 27 - 36% of the office space. During intermediate months, it daylights 11 to 20% of the floor area, while during winter months it provides 0 to 23% daylighting. This façade shows less variation in daylighting values in Miami across seasons, while northern latitudes see a larger variation from summer to winter. The 0.6 m (2 ft) multi-storey DSF shows minimal variation in daylight percentages; observed values decrease during intermediate and winter months, but remain relatively consistent across latitudes, unlike steep drop-offs in values observed with the 0.9 m (3 ft) multi-storey DSF (particularly in the winter). The 0.9 m (3 ft) box window DSF performs poorly with daylight percentages of 0% observed across all times of year. The 0.6 m (2 ft) box window and corridor DSFs admit some daylight during summer months (0 to 24%), but admit an average of 0% during intermediate and winter months.

The southern orientation provides significantly higher daylighting percentages than north or eastern orientations, as seen in Table 16. It was observed that locations in higher latitudes saw greater light levels during July and October, while lower latitudes saw greater levels during the winter. Both summer and intermediate results indicate that significant daylighting can be achieved, with less variation across seasons compared to the other orientations. However, winter months show a significant reduction in daylighting values. Data indicates that the 0.9 m (3 ft) cavity multi-storey DSF performs best out of all DSF types, with the summer months seeing 37 to 46% of the space daylit above the threshold. During intermediate months, daylighting values range from 40 to 49% of the floor area, while the values during winter range from 0 to 20%. The second best performing DSF varies for each season. The 0.9 m (3 ft) corridor DSF performs best in the summer, while the 0.6 m (2 ft) box window performs best in October and the 0.6 m (2 ft) multi-storey in the winter. The northern latitudes saw less variation across all DSF types than the southern latitudes. Winter months provide the lowest levels of daylighting, with daylit floor percentages hovering around 0% for more than half of the DSF types. Overall, southern oriented DSFs perform best during intermediate and summer months.

The results for west orientation indicate that it has the highest potential for DSF daylighting during summer months, as seen in Table 17. However, all of the data indicated large amounts of glare in the first 0 to 1.2 m (0 to 4 ft) from the façade. This contributed to higher light levels deeper in the space, but if solar shading is used to reduce glare, light levels will be reduced further into the space. This was the only orientation in which the single glazed façade resulted in values of 100% for all climates. During the summer, the 0.6 m (2 ft) box window DSF performed the best in Duluth (67%) and Chicago (66%), while the 0.9 m (3 ft) multi-storey DSF performed the best in San Francisco (54%) and Miami (52%). During the intermediate months, the 0.9 m (3 ft) multi-storey DSF performed the best (35 to 37%), while in January it performed the best in all locations except Duluth. Minimal daylighting percentages are provided during winter months (although higher than north and east orientations).

ORIENTATION	TIME	FAÇADE TYPE	DULUTH	CHICAGO	SAN FRANCISCO	MIAMI
South	July	Single	70%	70%	60%	55%
		Multi-storey with .6 m (2 ft) air cavity	34%	25%	24%	24%
		Multi-storey with .9 m (3 ft) air cavity	46%	45%	45%	37%
		Corridor with .6 m (2 ft) air cavity	25%	18%	17%	13%
		Corridor with .9 m (3 ft) air cavity	42%	30%	29%	28%
		Box window with .6 m (2 ft) air cavity	40%	38%	33%	24%
		Box window with .9 m (3 ft) air cavity	23%	20%	15%	11%
	October	Single	63%	60%	64%	64%
		Multi-storey with .6 m (2 ft) air cavity	18%	16%	20%	18%
		Multi-storey with .9 m (3 ft) air cavity	49%	42%	44%	40%
		Corridor with .6 m (2 ft) air cavity	18%	14%	15%	15%
		Corridor with .9 m (3 ft) air cavity	37%	30%	30%	30%
		Box window with .6 m (2 ft) air cavity	38%	37%	38%	34%
		Box window with .9 m (3 ft) air cavity	36%	24%	20%	20%
	January	Single	17%	22%	26%	33%
		Multi-storey with .6 m (2 ft) air cavity	3%	4%	6%	8%
		Multi-storey with .9 m (3 ft) air cavity	0%	5%	15%	20%
		Corridor with .6 m (2 ft) air cavity	0%	0%	0%	2%
		Corridor with .9 m (3 ft) air cavity	0%	0%	1%	7%
		Box window with .6 m (2 ft) air cavity	0%	0%	0%	6%
		Box window with .9 m (3 ft) air cavity	0%	0%	0%	0%

TABLE 16 Percent of the floor area that has an illuminance value of 500 lux (46 fc) or more at ground level in a southern orientation.

ORIENTATION	TIME	FAÇADE TYPE	DULUTH	CHICAGO	SAN FRANCISCO	MIAMI
West	July	Single	100%	100%	100%	100%
		Multi-storey with .6 m (2 ft) air cavity	40%	42%	36%	36%
		Multi-storey with .9 m (3 ft) air cavity	51%	56%	54%	52%
		Corridor with .6 m (2 ft) air cavity	33%	35%	30%	27%
		Corridor with .9 m (3 ft) air cavity	43%	46%	44%	37%
		Box window with .6 m (2 ft) air cavity	67%	66%	50%	47%
		Box window with .9 m (3 ft) air cavity	29%	36%	28%	27%
	October	Single	49%	58%	49%	56%
		Multi-storey with .6 m (2 ft) air cavity	7%	15%	16%	17%
		Multi-storey with .9 m (3 ft) air cavity	37%	35%	36%	37%
		Corridor with .6 m (2 ft) air cavity	8%	10%	10%	13%
		Corridor with .9 m (3 ft) air cavity	27%	29%	27%	27%
		Box window with .6 m (2 ft) air cavity	25%	32%	28%	30%
		Box window with .9 m (3 ft) air cavity	7%	14%	16%	15%
	January	Single	17%	22%	27%	32%
		Multi-storey with .6 m (2 ft) air cavity	3%	4%	5%	8%
		Multi-storey with .9 m (3 ft) air cavity	0%	5%	13%	20%
		Corridor with .6 m (2 ft) air cavity	0%	0%	0%	2%
		Corridor with .9 m (3 ft) air cavity	0%	0%	0%	7%
		Box window with .6 m (2 ft) air cavity	0%	0%	0%	6%
		Box window with .9 m (3 ft) air cavity	0%	0%	0%	0%

TABLE 17 Percent of the floor area that has an illuminance value of 500 lux (46 fc) or more at ground level in a western orientation.

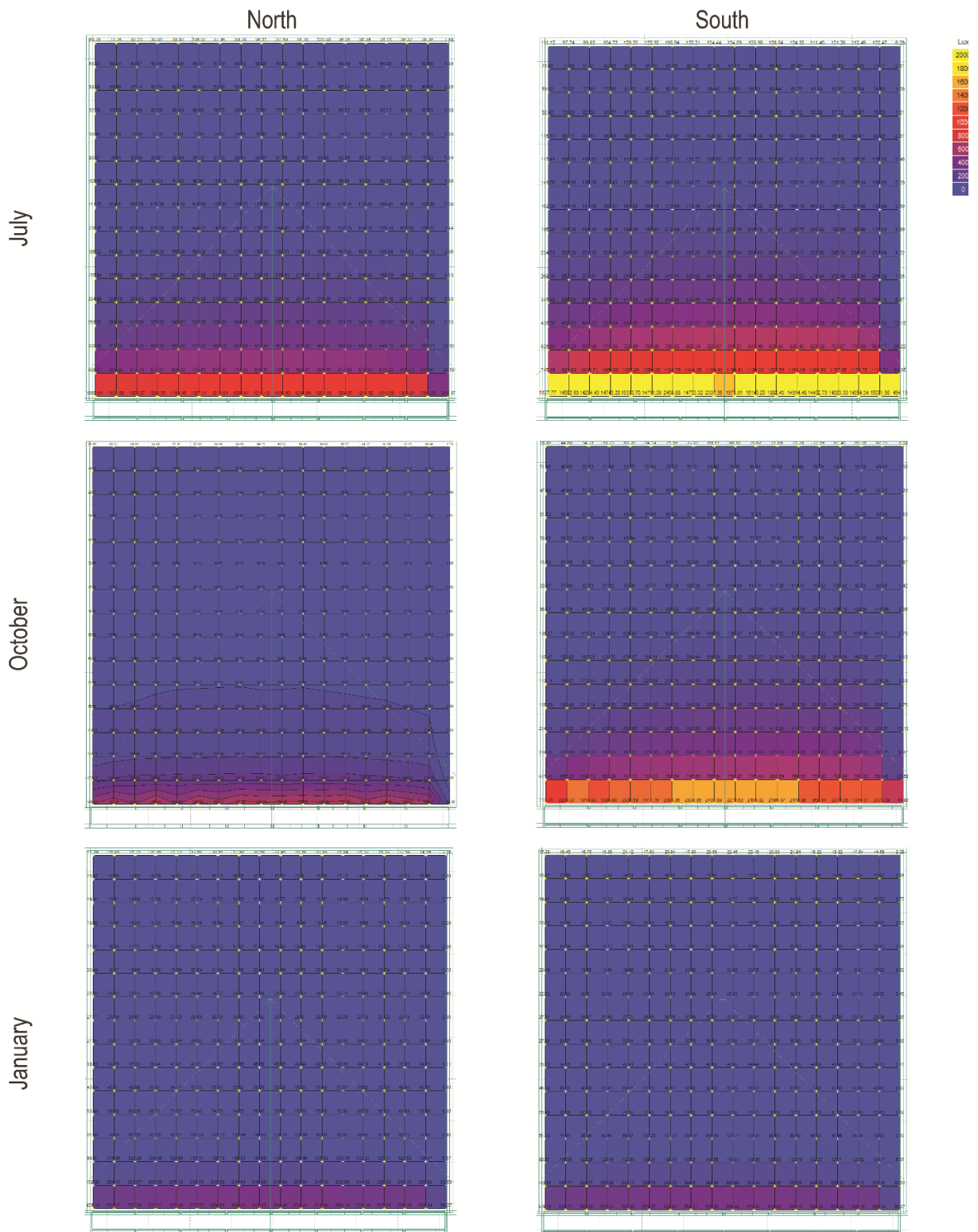


FIG. 24 Radiance illuminance plan renderings for Chicago, 0.6m (2ft) cavity multi-storey DSF north and south orientations.

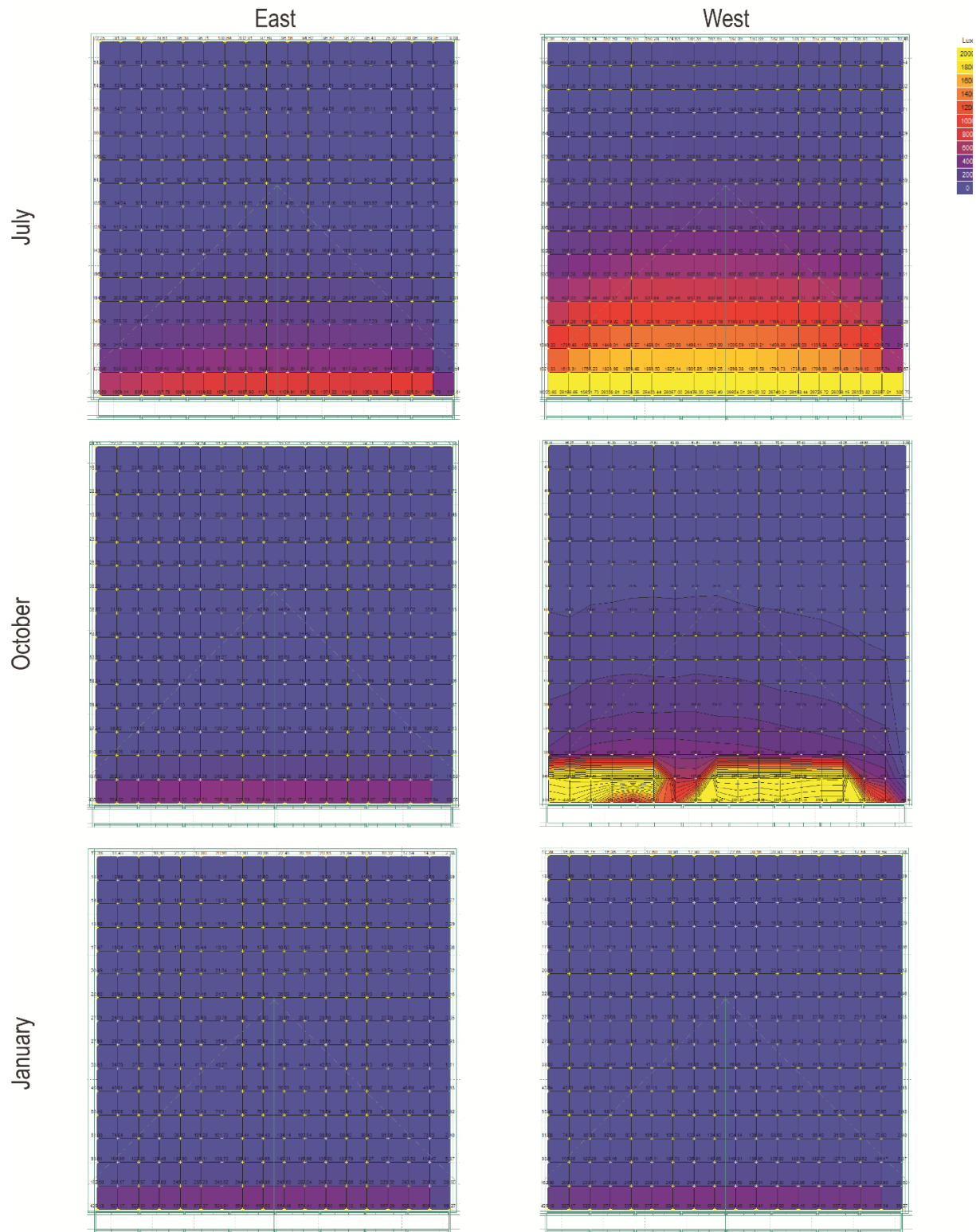


FIG. 25 Radiance illuminance plan renderings for Chicago, 0.6m (2ft) cavity multi-storey DSF east and west orientations.

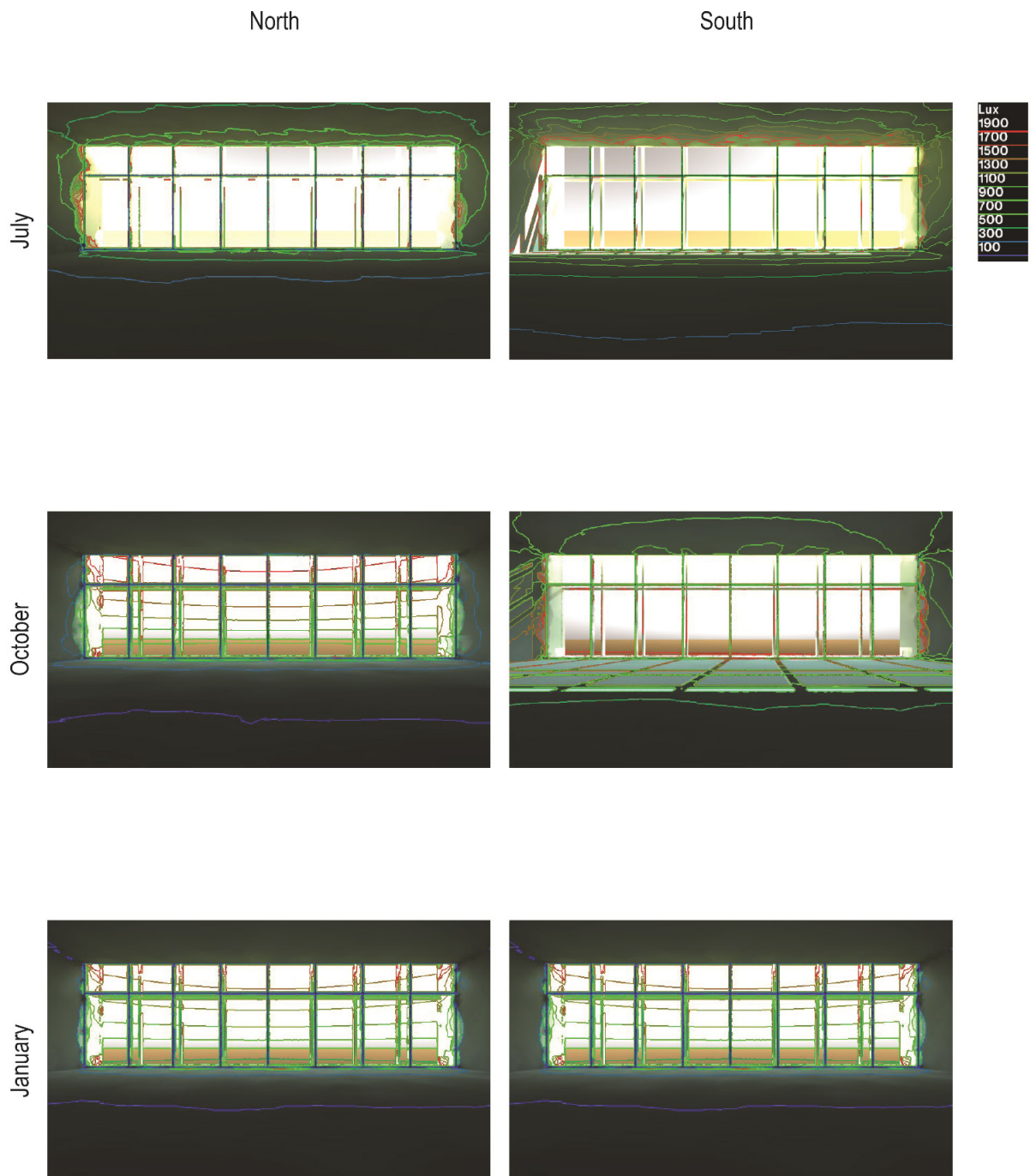


FIG. 26 Radiance illuminance interior renderings for Chicago, 0.6m (2ft) cavity multi-storey DSF north and south orientations.

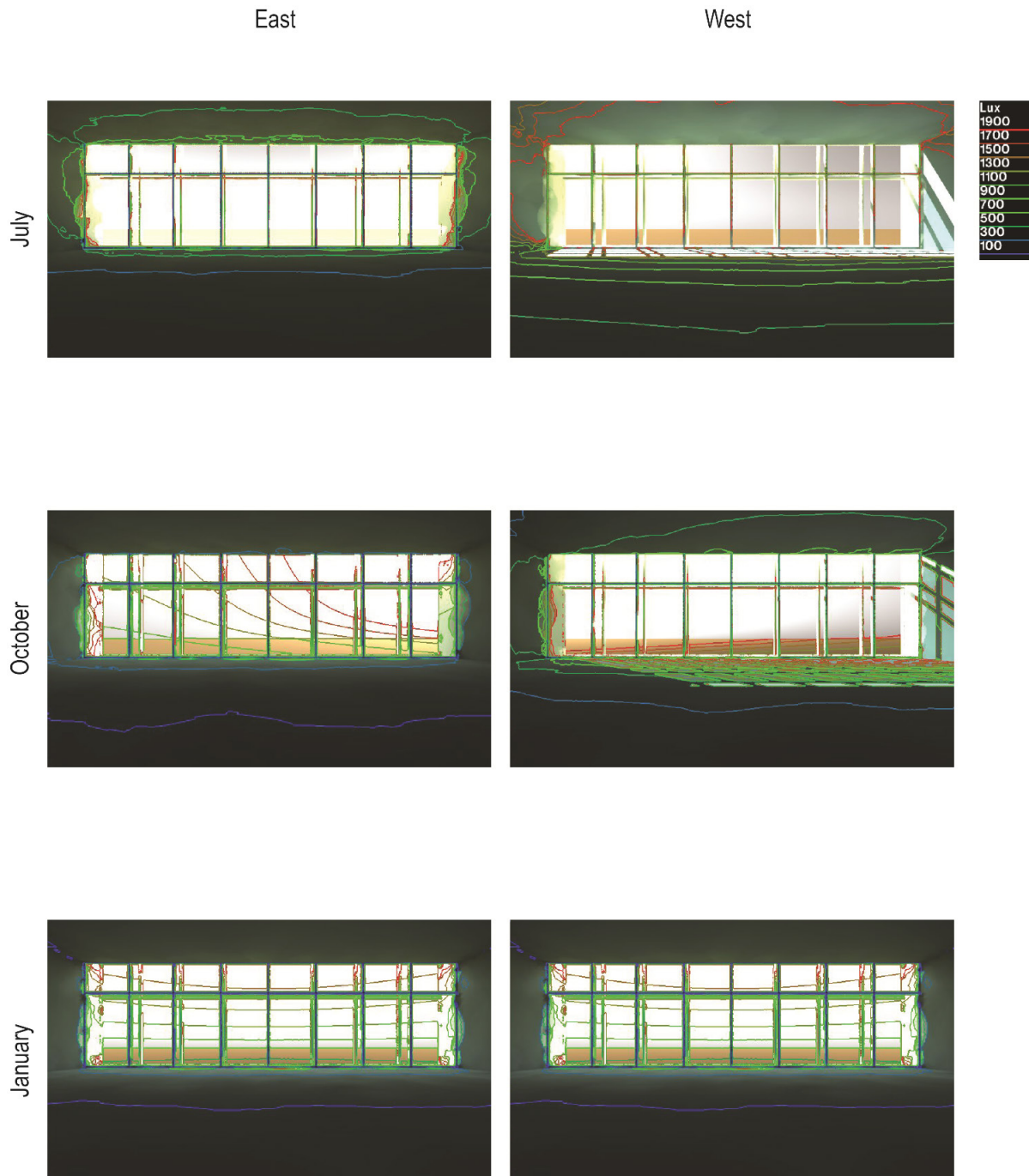


FIG. 27 Radiance illuminance interior renderings for Chicago, 0.6m (2ft) cavity multi-storey DSF east and west orientations.

5 CONCLUSION

The purpose of this research was to investigate thermal, energy, and daylight performance of different types of DSFs in various climates. The research addressed several aspects: 1) thermal performance of different types of DSFs (box window, corridor type, and multi-storey); 2) the effects of outside temperature and solar radiation on air cavity temperature and airflow patterns within the air cavity of different types of DSFs; 3) energy performance of DSFs in various climate types; 4) the effects of DSFs on heating, cooling, and lighting loads; and 5) daylight performance of DSFs, taking into account façade characteristics, orientation, and different sky conditions.

Research methods consisted of simulations and modelling, with different modelling techniques being used for specific parts of the study. Specifically, 2D heat transfer analysis was used to investigate the thermal behaviour of analysed façade types under varying exterior temperatures, and to calculate heat transfer coefficients. CFD analysis was used to determine 3D heat flow within the air cavity of investigated DSFs, as well as airflow patterns and air velocity. Energy modelling was used to investigate energy performance, where south-oriented office space was modelled for all different climate types, which would be enclosed by the investigated façades. The base case considered a single skin façade, consisting of a standard curtain wall. Daylight simulations were used to investigate daylight performance.

Results of heat transfer analysis show that all DSF types have much lower U-values than a standard curtain wall, indicating that these façade types would have improved thermal performance. The differences between different DSF typologies are relatively small. Multi-storey DSF has the smallest U-value, followed by box window and corridor type DSF. Results of CFD analysis showed that solar radiation would have an impact on the temperature and air flow within the air cavity of investigated DSFs. Within the cavity of multi-storey DSF, there is a temperature fluctuation caused by solar radiation, exterior and interior temperature, as well as the ventilation effects. However, the temperature change is not significant, mainly because of the configuration characteristics of the multi-storey DSF. The corridor DSF had a more turbulent air flow pattern within the air cavity. Box window DSF had the smallest ranges in temperatures of the air cavity, which could be caused by the geometry and components, since this type has horizontal and vertical divisions that limit the heat transfer through the cavity. However, this DSF type exhibited more turbulence within the air cavity compared to other DSFs. Comparison of 2D heat transfer and CFD analysis results indicated slight variations in results, which can be attributed to different calculation methods.

Results of energy modelling showed that all DSF types would improve energy performance compared to the base case scenario (standard curtain wall). However, the energy savings vary depending on the climate and DSF type. In heating-dominated climates, heating loads are significantly reduced, as well as cooling loads due to lower U-values of investigated DSFs. In cooling-dominated climates, cooling loads are also lower for DSFs. Results also indicate that there is very little variation in energy consumption between different types of DSFs (box window, corridor type, and multi-storey DSF). The box window DSF type with openings (holes and vents) was found to be the best performing in terms of reducing EUI across all climate types. The multi-storey DSF with holes was found to be the worst performing for EUI across all climate types. All DSF types saw increased energy consumption for lighting, due to the geometry and additional façade layer. As expected, southern climates saw greater energy usage due to high sun angles, while northern climates fared better due to lower sun angles.

Results indicate that all types of DSFs would decrease daylight levels compared to a conventional curtain wall; however, the differences between lighting levels are dependent on the orientation, air cavity depth, façade type, and climate. Moreover, the results show that the discrepancies are largest in the area closest to the glazed façade, and that the differences between lighting levels decrease with the depth of the interior space. Results indicate that latitude and sky conditions are important for daylight performance of DSFs, as well as façade orientation. DSFs provide most daylighting during summer months, with the highest values observed in south and west orientations. DSFs provide most daylighting during intermediate months in south and west orientations, with minimal daylighting provided in north and east orientations. DSF daylighting during winter months is consistently low in all orientations, due to overcast sky conditions. Cavity depth appears to influence DSF daylighting in ways that were not anticipated. Multi-storey and corridor type DSFs showed noticeably better performance with 0.9 m (3 ft) cavities, compared to 0.6 m (2 ft) cavities. Box window DSFs showed better performance in a 0.6 m (2 ft) configuration than with a 1.9 m (3 ft) cavity.

The results of this research can be used in design decision making when implementing DSFs. Specifically, a selection of DSF typologies that are suitable for specific climate types, as well as air cavity depth and orientation can be made, taking into account the effects on thermal performance, energy, and daylight.

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