ENERGY PERFORMANCE OF DIFFERENT TYPES OF DOUBLE SKIN FACADES IN VARIOUS CLIMATES

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ABSTRACT: This paper explores thermal and energy performance of double skin facades (DSFs) in different climate types, specifically focusing on three typologies: box window, corridor type and multistory DSFs. These systems were investigated and analyzed to answer the question of how the different DSFs perform in comparison to each other, as well as a typical curtain wall (single skin facade used as a baseline), in a multitude of climate applications. The utilized research methods included two-dimensional heat transfer analysis (finite element analysis) and energy modeling. Heat transfer analysis was used to determine heat transfer coefficients (U-values) of all analyzed facade types. Results indicate that there is little variation in thermal performance of the different DSF types, but that all DSF facades would have significantly improved thermal performance compared to the baseline single skin facade. Energy modeling was conducted for an office space, which would be enclosed by the analyzed facade types. Individual energy models were developed for each facade type and for 15 different climates, representing various climate zones and subzones. The results were analyzed to compare energy performance of DSFs and baseline single skin facade, as well performance of DSFs in various climate types. The results indicate significant differences between the DSFs and single skin facade, but less variations between the different typologies of investigated DSFs. Moreover, the results show what would be the effect of DSFs in different climate types on energy performance, heating, cooling and lighting loads.

KEYWORDS: Double skin facade, energy efficiency, energy consumption, energy use intensity, climate types

INTRODUCTION

Double skin facades (DSFs) are an emerging type of building facades, aimed to improve thermal performance of glazed envelopes. Different from conventional single glazed facades' 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 wall. Basic DSF types are box window facades, corridor facades, shaft box facades, and multistory facades (Aksamija, 2013). The physical behavior of the DSFs depend on the typology, as well as ventilation mode of the air cavity and material components. Ventilation mode can include natural ventilation, mechanical and mixed mode.

There is significant research available relating to the thermal and energy performance of DSFs in temperate and colder climates, while less research is available for warmer climates. A previous literature review was conducted, which systematically reviewed and compared 55 research articles focusing on energy performance analysis of DSFs in temperate climates (Pomponi et al., 2016). The study analyzed the energy consumption of multiple DSF types, in a variety of temperature climate types. 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. Additionally, studies that systematically investigate thermal and energy performance of DSFs facades in all types of climates currently do not exist. Studies that also investigate different typologies of DSFs and their energy performance are currently not available. Therefore, this section reviews available literature and results of previous studies, which typically focus only on one climate type.

For example, Gratia and Herde looked extensively at DSFs in a temperate climate, analyzing behavior for various sun orientations, and how applying the DSF affected heating and cooling loads (2007). Energy performance and analysis, specifically for heating, cooling and ventilation energy usage, was also included in a study comparing DSF to other facade alternatives for a specific building application in central Europe (Gelesz and Reith, 2015). The authors simulated box window DSF and its single glazed alternative, and the results indicate that DSF can reduce energy consumption by 7% on average. In addition, closed cavities have overheating problem even on the coldest days in south orientation (Gelesz and Reith, 2015). For hot climate areas, summer ventilation for DSF leads to increased cooling loads (Eicker et al., 2007). Zhou and Chen looked at applying ventilated DSF in hot and cold climate zones in China (2010). Wong et al. studied the performance of DSF in Singapore by using energy and CFD simulations (2005). Through CFD simulation and comparative analysis, horizontal and vertical ventilation schemes were evaluated for double skin facade in Mediterranean climate (Guardo et al., 2011). Brandl et al. studied the airflow characteristics and temperature profile of multifunctional facade 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 (2014).

Since there is lack of research that systematically compares energy performance of different types of DSFs in all climate types, this research study focused on addressing this gap in knowledge.

1.0 RESEARCH OBJECTIVES AND METHODS

The objective of this research was to investigate energy performance of different types of DSFs (in relation to single skin glazed facade, and based on differences between individual DSF typologies), in all climate types. Research questions that were addressed include:

- What is the effect of different types of DSFs on energy consumption for commercial office spaces in all climate types?
- How do openings affect the energy performance of DSFs?
- 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?

Figure 1 shows the basic properties of these different types of facade systems. Box window DSF consists of horizontal divisions between different levels, as well as vertical divisions and an air cavity between the two glazed surfaces. Corridor type DSF has horizontal divisions between different levels, but air can freely move within the air cavity within each individual level. Multistory DSF does not have any horizontal or vertical divisions, and air can move freely between different levels within the air cavity. In all DSF scenarios, a curtain wall with double insulated glazing unit was placed on the interior side of the facade, while a single lite of glass was placed on the exterior side. Each of the DSF models was tested in three variations: without openings and with openings (holes and with vents). Scenarios without openings were used to simulate “air curtain” air flow type, which would trap air within the air cavity and create thermal buffer between the exterior and interior environment. Vents and holes were used to simulate scenarios where the air cavity would be open to exterior environment, to allow natural ventilation of the cavity. Vents were modeled as continuous horizontal openings on the exterior, with metal grilles that would be able to open and close, depending on the season. Scenarios with holes were modeled as continuous horizontal openings, but without grilles (these would remain open throughout the entire year). Since the components of these different DSF types are different, it was expected that their physical behavior (effects on energy consumption) would be different.

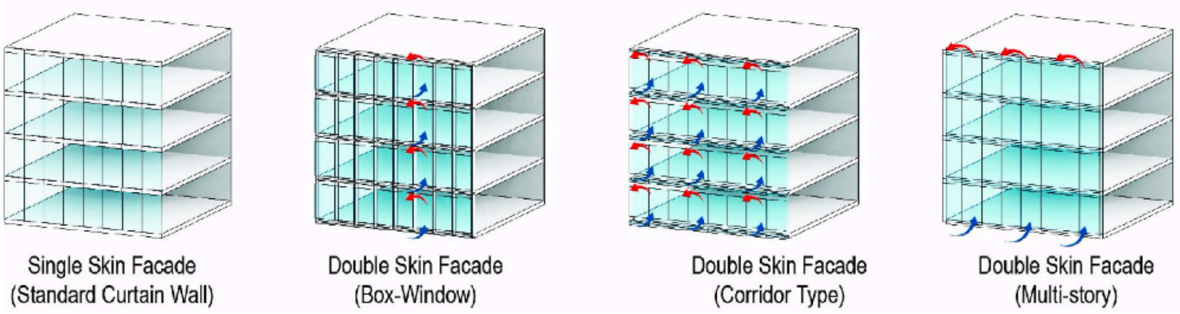

Figure 1: Diagram showing investigated facade types, basic components and airflow patterns.

All DSF facade systems used 1 in double low-e IGU with argon gas fill on the interior side of the facade, and 0.5 in single tempered glazing on the exterior side. Single skin facade consisted of 1 in double air low-e IGU. The framing members for the typical curtain wall and the interior layer of the DSF included aluminum mullions. The outer layer of the DSFs did not include aluminum framing members—the assumption was that structural silicone would be used for glazing, and that the structural support for the exterior 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 aluminum. For the corridor type DSF, the assumption was that the horizontal division panels between floors would also be constructed out of aluminum.

2.0 HEAT TRANSFER ANALYSIS

The heat transfer analysis utilized a 2D finite element analysis method, using THERM and WINDOW modeling software programs. THERM was developed by Lawrence Berkeley National Laboratory (LBNL), and it is widely used for thermal analysis of facade 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 facade assembly.

The different analyzed facades (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 and definitions of material properties, as well development of boundary conditions that represent exterior and interior environmental conditions. Simulation inputs for environmental conditions were determined based on the NFRC 100-2004 Standard, with exterior temperature of -18°C (0°F) and interior temperature of 21°C (70°F). The results were evaluated to determine relative thermal performance of investigated facade types and compare the calculated U-values.

3.0 ENERGY MODELING

Energy modeling was performed in Design Builder, and geometry models were created in Revit. The geometry models were imported into Design Builder, where inputs for energy modeling were defined and simulations were performed. The methodology for energy modeling consisted of building individual models for each type of investigated facade, which would enclose a commercial south-oriented office space. Each type of DSF had three variations (without openings, openings-holes, and openings-vents), which resulted in ten models being simulated for 15 different climate types (totaling 150 energy models), representing all climate zones in the U.S. Table 1 shows representative cities that were chosen for energy modeling.

Table 1: Climate zones and representative cities that were incorporated into energy modelling.

	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	-

In all of the simulated models, four floors were modeled so that the multistory DSF could be accurately simulated. Each floor was 40 ft deep, 40 ft wide, and the floor-to-floor height was 10 ft. All of the DSF types had an air cavity of 2 ft.

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 2013). Operating schedule was based on a typical office space operation (weekday schedule from 8 AM to 6 PM). The HVAC system consisted of a packaged heating/cooling pump with 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. Also, Energy Usage Intensity (EUI) was determined for all scenarios. The following section discusses the results in detail.

4.0 HEAT TRANSFER ANALYSIS RESULTS

U-values were calculated for conventional curtain wall, as well as three investigated DSF types, and Figure 2 shows thermal gradients within DSF assemblies. Table 2 shows the results, indicating the relative thermal performance of each investigated facade type. All DSF types have much lower U-value than a standard curtain wall, indicating that these facade types would have improved thermal performance. The differences between different DSF typologies are relatively small; however, multi-story DSF would have the smallest U-value, followed by box window and corridor type DSF. Nevertheless, the significant difference between U-values of DSF types and conventional curtain wall suggests that all types of DSFs would provide savings in heating and cooling loads due to improved thermal performance.

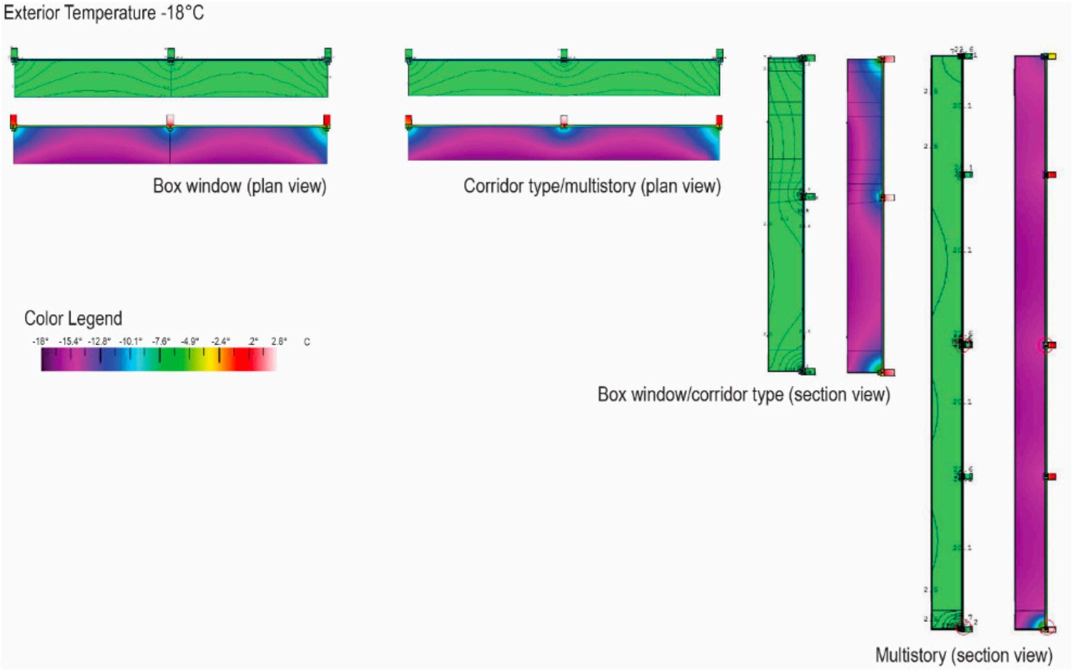

Figure 2: Results of heat transfer analysis, showing thermal gradients within investigated DSFs.

Table 2: Calculated U-values for the investigated facade types.

	Single skin (conventional curtain wall)	**Box window DSF**	**Corridor DSF**	**Multistory DSF**
U-value (Btu/h-ft^2-°F)	0.18	0.032	0.036	0.031

5.0 ENERGY MODELING RESULTS

Energy consumption for heating, cooling and interior lighting were calculated, as well as the EUI, for all investigated facades and design scenarios. Figure 3 shows the EUI for all facade types (without openings) in all climate types. Table 3 shows the amount of energy savings as a percent, for each type of DSF, across all climate types. Almost all DSF types performed better than the base case, a single skin conventional curtain wall. 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. Box window with vents performed better in warmer climates, while the box window with vents performed well across all climates. 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 multistory saw the least variation in savings.

Table 3 shows the energy savings for lighting for all DSF types and climate types. Lighting usage has increased across all facade and climate types. Locations in lower latitudes saw the worst performance, due to higher sun angles. Locations in higher latitude 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. For all three DSF types, holes generally performed the best while vents performed the worst.

With the exception of climate zone 3C, warmer climates saw less energy savings in cooling than colder climates, as shown in Table 5. Humid climates also saw less 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 multistory with holes was the worst performer across all climate types. Climate zone 3C saw similar savings to zone 8.

Warmer climate zones saw greater energy savings in heating, while colder zones saw the least savings (with the exception of zone 5A), as shown in Table 6. Zones 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.

Figure 3: Results of energy modeling, showing EUI for all climates and investigated facade types (DSF without openings).

Table 3: Amount of energy savings in EUI as a percentage for investigated DSFs, compared to single skin facade type.

Zone	**Corridor**			**Box Window**			**Multistory**		
	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 4: Lighting energy consumption for investigated DSFs, compared to single skin as a percentage.

Zone	**Corridor**			**Box Window**			**Multistory**		
	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 5: Cooling energy savings for investigated DSFs, compared to single skin as a percentage.

Zone	Corridor			Box Window			Multistory		
	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 6: Heating energy savings for investigated DSFs, compared to single skin as a percentage.

Zone	Corridor			Box Window			Multistory		
	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%

Figure 4 compares heating, cooling and lighting loads for all investigated climate types and facades.

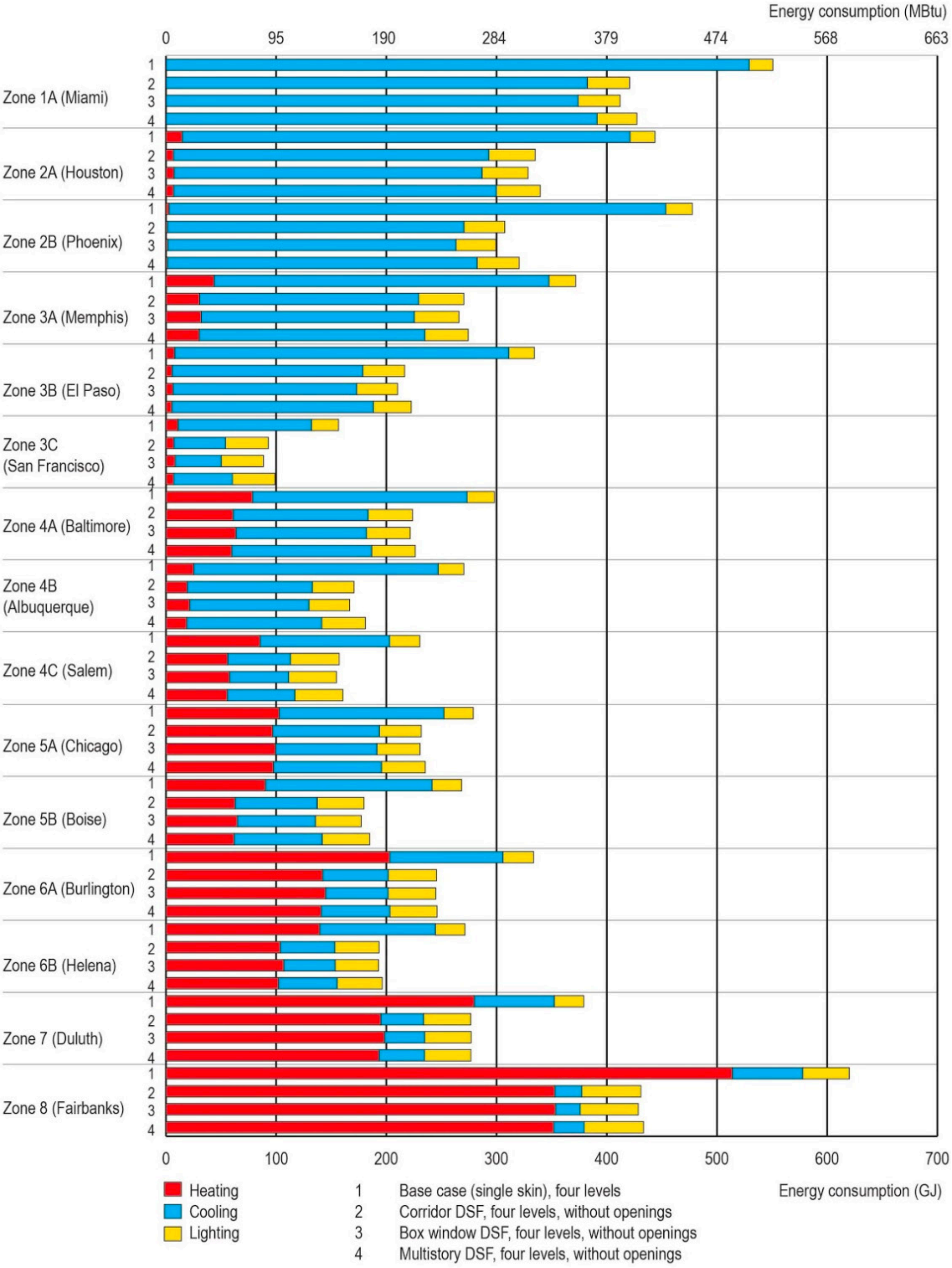

Figure 4: Results of energy modeling, showing energy usage for all climates and investigated facades.

CONCLUSION

The purpose of this research was to investigate energy performance of different types of DSFs in all climate types. The research addressed several aspects: 1) energy performance of different types of DSFs (box window, corridor type and multistory); 2) the effects of openings on the energy performance of DSFs; 3) energy performance of DSFs in different climate types; and 4) the effects of DSFs on heating, cooling, and lighting loads. Research methods consisted of heat transfer analysis for calculating U-values and modeling energy consumption for a south-oriented office space in 15 different climate types, which would be enclosed by the investigated facades. The base case considered single skin facade, consisting of a standard curtain wall.

Results of heat transfer analysis show that investigated DSF types have much lower U-value than a standard curtain wall, indicating that these facade types would have improved thermal performance. The differences between different DSF typologies are relatively small; however, multi-story DSF would have the smallest U-value, followed by box window and corridor type DSF.

Results of energy modeling showed that all DSF types would improve energy performance compared to the base case scenario (standard curtain wall). Variations in DSF design had a significant impact on the energy performance of the investigated types. However, the energy savings vary depending on the climate type and DSF type. The box window DSF type with openings (holes and vents) was found to be the best performing across all climate types. Multistory 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 of the facades. As expected, southern climates saw greater energy usage due to high sun angles, while northern climates performed better than southern locations due to lower sun angles. In heating-dominated climates, cooling loads are significantly reduced (40-70%), while cooling-dominated climates have lower savings (25-40%). In cooling-dominated climates, heating loads are significantly reduced (50-90%), while heating-dominated climates have lower savings (30-40%). The results of this research systematically compare performance of different types of DSFs in terms of energy usage across all climates, and provide an insight how these advanced facade types would affect lighting, cooling and heating loads compared to conventional single skin facade.

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