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Evaluating Energy Performance of an Integrated Atypical Double-Skin Façade with Agricultural Greenhouse in Hot-Arid Climates

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A B S T R A C T

Horticultural greenhouses are seen as a potential solution to challenges in modern agriculture, such as food crises and climate change. The demand for energy in greenhouses has been increasing, with heated agricultural structures accounting for up to 36% of agricultural energy use. To this end, this study explores the energy efficiency and solar potential of different Box-Windows Double-Skin Façade (DSF) designs integrated with greenhouses in a hot-arid climate. A parametric study using the DesignBuilder energy simulation tool was conducted to examine the effects of various DSF configurations. The study focused on the geometry of the outer skin and the air cavity depth between the two skins. The considered DSF could be mounted on the south face of the construction. Three DSF types were compared: Flat (base model), Deformed from Top Cases (DTC), and Deformed from Bottom Cases (DBC), with cavity widths ranging from 0.6 to 1.2 meters. Results show that adjusting the DSF's outer skin geometry can improve thermal performance and ventilation in hot climates. The DTC model outperformed both the Flat and DBC models, offering up to 35% better performance. This research suggests that optimizing the geometry of DSFs could be a passive solution for improving energy efficiency, natural ventilation, and managing water and humidity in greenhouse environments.

Keywords:
Horticultural greenhouse
Double Skin Façade (DSF) Geometry
Energy efficient
Natural ventilation
Water

1. Introduction

Resource management in agriculture is recognized as a critical concern due to greenhouse farming and agriculture-related activities; it can produce about 10-19% of global greenhouse gas emissions. This problem still needs to be addressed because of the rapid expansion of arable land to meet global food demand (Maraveas et al. 2023). It is known that horticultural greenhouses have been recognized as a potential solution to the challenges in modern agriculture, such as the food crisis and specifically climate change. Based on this fact, the statistics show that the proportion of heated greenhouse area has increased to 36%, and the heating demand in greenhouses is expected to continue to expand. Heating oil and electricity are the main energy sources used for greenhouse environment control, and these energy sources account for 90% of the total area. Recent unstable energy supplies and rising costs have significantly increased the financial pressure on greenhouse operations, making it critical to develop better energy management strategies (Kim et al. 2025). On the other hand, the building and construction sectors consume at least two-thirds of the produced energy in the world, and considering realistic and applicable architectural strategies to reduce this amount (Zari 2008) and also in some recent references it is stated that building construction contributed to nearly 40% energy consumption and 25% greenhouse gas emissions in the world (Zhang et al. 2022; Hong et al.2016). The horticultural greenhouses are structures designed specifically for growing plants, such as fruits, vegetables, flowers, and other crops, in a controlled environment. These greenhouses provide optimal conditions for plant growth by regulating factors like temperature, humidity, light, and air circulation. Such greenhouses could be the representative or a symbol modern agriculture having multiple impacts the economy, society, and on agroecosystems (Jensen and Malter 1995). The facades with integrated design approaches that include daylighting, shading, and natural ventilation systems have

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the potential to significantly reduce energy consumption (Sadineni et al. 2011). The design of the building envelopes, such as Double-Skin Facades (DSF), has a significant impact on improving the overall building energy performance; at the same time, we have to address the aesthetic considerations (Kasinalis et al. 2014; Sozer 2010). Through that, it is possible to utilize this concept as a passive solution to reduce energy consumptions in the current agricultural constructions such as green houses in a very novel way.

The main scope of this study is to integration of an architectural passive design concept with a well-known agricultural construction called horticultural greenhouses. To this end, the literature study assessed total number 93 papers and categorized the study steps in two main sections: first step is based on focusing on design and evaluation of horticultural greenhouses using merely review studies using total number of 40 papers and the second step is to merely focus on the design and energy evaluation of DSF in architectural context, this part is contained using total number 47 papers.

1.1. Literature Review Step One: Studies on Horticultural Greenhouses

Based on the authors knowledge, there has not been found a specific study in the literature that has integrated these two concepts. From 1981 to 2021 there have been published more than 90 review papers regarding greenhouse. There have found extensive body of studies in the literature identifying major research topics and their trends during last few years. The authors analyzed the co-occurrence network of keywords associated with greenhouse engineering publication done by (Blanco et al.2022). Based on the statistics a total number 3804 publications are related to greenhouse design; China, the United States, Spain, Italy and the Netherlands have been the most active countries with more than 36% of the relevant literature. Based on the evaluations so far, there have been suggested five main topics for research in the field of greenhouse studies: energy management and storage; monitoring and control of greenhouse climate parameters; automation of greenhouse operations through the internet of things (IoT) and wireless sensor network (WSN) applications; greenhouse covering materials and microclimate optimization in relation to plant growth; structural and functional design for improving greenhouse stability, ventilation and microclimate. Considering that the several studies published on greenhouse engineering cover a wide range of scientific areas, an advanced visualization methodology, such as science mapping, could provide a useful alternative tool to analyze the pertinent literature and reveal the structure and the evolution of the research activity. Since the scope of study is not reviewing or classifying the trends of the greenhouse engineering, it mostly tries to clarify the main focus of the current work based on the previous published reviews. As known from more than 3804 published studies through past 50 years, and mean 66.1), and even more in the last period 2011–2021 (n = 170–365, mean 226.8) and the main subject areas could be found in the study field by (Blanco et al. 2022) presented in Figure 1.

There could be seen six comprehensive review studies regarding the greenhouse energy, design and control strategies of the greenhouses; the main review studies are Critten and Bailey (2002), Montero et al. (2011), Hannan (2017), Shamshir et al. (2018) Syed and Hachem (2019) and Achour et al. (2021). In the mild climates the energy demand in greenhouses is low but the issues are rising in the harsh climates that is due to the direct dependence of the internal microclimate on the external climatic conditions (Baille 2001). The dominant trend in the regions with harsh climates that is the minimal control of the greenhouse microclimate and it is also limited to natural ventilation, shading techniques and emergency heating (Giacomelli et al.2012).

In the literature, according to the study (Syed and Hachem 2019), the authors reviewed the latest developments in greenhouse designs with the objective of determining the currently prevalent best design practices and lowering their carbon and energy footprint. They provided a review of the existing design trends in the construction, geometry, heating, ventilation, and air-conditioning (HVAC), and indoor climate requirements of agricultural greenhouses. They have tried to develop universal design guidelines for greenhouses. Based on their comprehensive review, the existing design practices and research on the construction, geometry, HVAC systems, and indoor climate requirements of agricultural greenhouses are presented with a decent detail.

According to a review done by (Argento et al. 2024), the authors highlight several key strategies for optimizing the greenhouse environment, including efficient water management through conservation tillage, drainage water reuse, and selecting the most appropriate irrigation systems and timing. Also, the authors have intensified that the light modulation and temperature control—using solar energy for heating and pad-and-fan systems for cooling—are crucial for enhancing both crop performance and resource efficiency.

The focus of this study is the mainly related to the energy and microclimate optimization through temperature and ventilation control and its structural and functional design in the horticultural green greenhouses. As seen from Figure 1 the subsection of structural and functional design contains main study approaches such as heat transfer, ventilation, wind tunnel, and CFD analysis. In terms energy consumption, there are studies which have assessed the effect of different greenhouse parameters and various options such as its orientations, shape, north wall insulation, double wall glazing, thermal screens and cladding materials. These studies were done in order for reducing heat loss and efficient design of greenhouse (Achour et al. 2021; Panwar et al. 2011; Waaijenberg et al.2006). Another subject of greenhouses is the evaluation of inside are flow patterns and temperature distribution using computational fluid dynamics (CFD) which is mostly affected by the slope of the terrain and also it was affected by the height and ventilation configuration (Villagran et al. 2021a,b) It is also stated that by the authors that the ventilation rates could be affected by the greenhouse orientation and roof vent and screen characteristics (Gomez et al. 2010). In countries such as Mexico and Colombia, naturally ventilated structures are mainly used, and based on the studies (Rojano et al.2014; Roha et al. 2021) greenhouse climate dynamics could be primarily affected by the local weather conditions since the greenhouses are not associated with heating and cooling systems. According to the review studies regarding horticultural greenhouses, the most related studies to its architectural design, are those of its geometrical design and also covering material plastic films which could generate huge quantities of post-consumer materials (Blanco et al. 2018). Table 1 synthesizes key greenhouse types discussed in peer-reviewed articles published between 2023 and 2024, focusing on agricultural and environmental science contexts. It highlights structural designs, advantages, disadvantages, quantitative performance metrics (e.g., efficiency, prediction accuracy, growth improvements), and other details like climate suitability and control methods. Information is derived exclusively from the provided sources, emphasizing solar, plastic-covered, and hydroponic-integrated greenhouses. As known that the heat energy consumption for greenhouses are merely depends on the amount of energy getting from sun through solar radiation (Seth and Sharma et al.2007). There are main physical parameters affecting such energy input such as orientation, shape and covering material which determine the absorption coefficient and utilization rate of solar energy (Elsner et al. 2000). Based on the study (Cakir and Sahin 2015) these parameters that are critical factors for successful greenhouse design to reduce heating and cooling loads of installed systems and they save operation costs. It is possible to find several studies in the literature comparing the on various greenhouse shapes to understand the influence of greenhouse shapes on solar radiation. The classifications of the greenhouse shape types have been demonstrated in the study of Zhang et al. (2022) containing some significant studies (Chen et al. 2020; Mobtaker et al. 2019; Vivekanandan et al. 2021). According the studies in the literature it could be classified the shapes of the greenhouses in to even span, uneven span, dome type, Quonset and vinery, as shown in Figure 2.

On the overall, the important variable in the design of greenhouse shapes is considering the aspect ratio and receiving the surface of solar radiation (Zhang et al. 2022). In terms of architectural design point of view the shape of greenhouse could be a variable to be used by the architects. It can play a significant role in energy absorption and utilization during crop cultivation and production. This would be possible by determining shapes that could obtain the lowest possible solar irradiance in summers and maximize it in winters 14 (Ghani et al. 2019). Based on the study that is due to larger receiving area of solar radiation. It is also studied the curve surface of greenhouses which has significant impact on solar radiation and for the elliptic greenhouse, Wael et al (2015) proposed the best aspect ratio of elliptical surface to obtain the optimal solar capture rate. One the main studies related to the design of the greenhouse; it could be referred to the studies done by (Von Elsner et al. 2000; Cakir and Sahin, 2010; Singh 2010), where the authors classified the green houses into wide-span and Venlo-type greenhouses, in relation to the roof design. Plastic film greenhouses range from the simplest tunnel greenhouses to the more complex pitched roof and arch-shaped roof greenhouses. In this regard several types of shapes, such as the gothic arch, vinery, Quonset, even-span and uneven-span, were investigated to evaluate its performance dealing with sun exposure and getting solar radiation (Cakir and Sahin 2015).

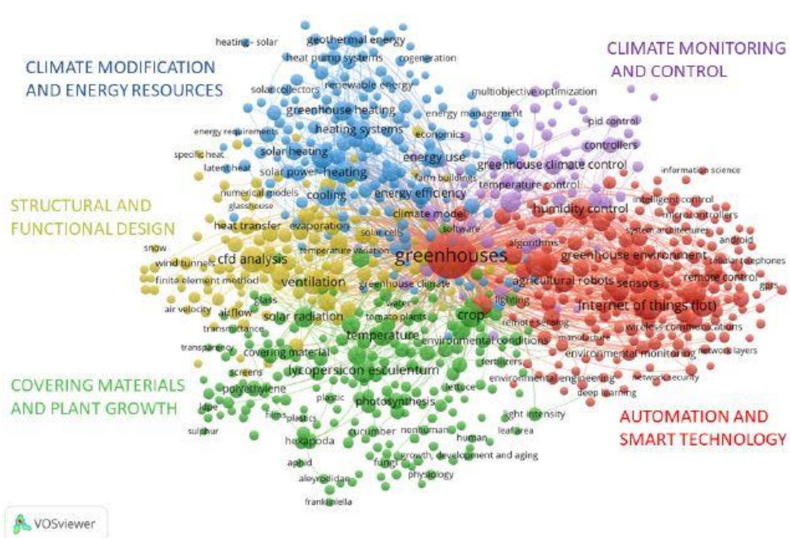

Figure 1. Keyword networks based on the greenhouse engineering publications from 1981 to 2022 studied and classified by (Blanco et al.2022)

Table 1. Classification of key greenhouse types and their properties.

Greenhouse Type	Description	Advantages	Disadvantages	Quantitative Performance Analysis	Other Relevant Details	References
Round-Arch Solar Greenhouse (RASG	Curved, arched structure common in alpine/high-latitude regions, designed for passive solar heating with adjustable ventilation windows and exhaust configurations.	Excellent thermal retention in cold climates; efficient natural ventilation reduces energy needs; promotes sustainable plant production by minimizing high humidity/temperature stress.	Susceptible to uneven airflow distribution affecting crop uniformity; requires precise window angle adjustments to avoid cold air ingress in winter.	Ventilation efficiency up to 25% higher with optimized 25° deviation angle and 900 mm window width (10 m span); summer cooling rate improved by combined south-corner rolling film and north-roof pivoting; winter opening <40° maintains internal cooling without crop frost (model validation R^2 >0.95 via CFD simulation).	Best for high-latitude China; crop canopy airflow modeling enhances microclimate control; supports year-round vegetable growth with 10-15% yield stability gains.	Fan et al. 2023
Plastic-Covered Greenhouse (Colombian Savanna Design)	Innovative plastic enclosure for tropical/subtropical climates, incorporating energy balance models for heat/mass transfer; suited for Bogotá's variable weather.	Accurate thermal prediction for decision-making; adaptable to local architecture and climate; detects phenomena like thermal inversion for proactive control.	Limited availability of region-specific models; higher initial calibration effort for non-standard structures.	Temperature prediction efficiency of 86% post-calibration (RMSE <1.5°C); simulates diurnal temperature swings with 90% accuracy under varying solar radiation (0-800 W/m²).	Focuses on protected agriculture in Colombia; integrates external weather data (e.g., humidity 60-90%) for energy optimization; reduces operational costs by 15-20% via predictive control.	Ortiz et al. 2023
Solar Greenhouse with Multi-Parameter Monitoring	Enclosed solar-heated structure equipped with IoT sensors for real-time environmental tracking (CO_2, temperature, humidity,	Captures nonlinear environmental couplings for precise crop growth forecasting; scalable for large facilities; enhances resource	Higher computational demands for deep learning models; requires robust data fusion from	Prediction accuracy improvements of 56.72-76.89% (MAE reductions) for CO_2, air temp/humidity,	Uses Golden Jackal Optimization-CNN-BiGRU for forecasting; ideal for agricultural production in temperate zones; monitors nodes at 0-2	Yuan et al. 2024

	soil metrics) across multiple nodes.	efficiency in variable climates.	multi-source sensors.	and soil temp vs. LSTM baselines; GCBS model R^2 >0.92 for 4 parameters over 1-year dataset.	m heights for spatial variability.	
IoT-Integrated Greenhouse (General Enclosed Type)	Modular enclosed system with sensors, relays, and communication tech (e.g., Wi-Fi, LoRa) for monitoring/controlling parameters like light, humidity, and soil moisture.	Protects crops from external weather; enables remote, automated control for year-round high-quality production; cost-effective with long-life sensors.	Dependency on reliable power/network; potential sensor drift in humid environments; higher upfront tech costs for small farms.	Crop yield increases of 20-30% via parameter optimization (e.g., temp 18-25°C, humidity 70-80%); communication latency <1s with LoRa (range up to 10 km); sensor accuracy ±2% for temp/humidity.	Versatile for various climates; compares Wi-Fi (high-speed, short-range) vs. Zigbee (low-power, mesh); emphasizes farmer-friendly, sustainable tech adoption.	Singh et al. 2024
Climate-Controlled Greenhouse (MPC/RL Optimized)	Advanced enclosed facility using model predictive control (MPC) or reinforcement learning (RL) for dynamic climate regulation (temp, humidity, ventilation).	Economical resource use for sustainable growth; handles continuous state-action spaces; unifies model-based and learning-based approaches for optimal actions.	RL requires extensive training data; MPC computationally intensive for real-time large-scale ops; potential overfitting in variable weather.	RL (DDPG) achieves 10-15% better energy efficiency than MPC in simulations (cost savings ~12%); temperature control RMSE <0.8°C; RL convergence in 500 episodes for 24-hour cycles.	Simulates global population food needs; compares DDPG-RL vs. MPC in unified framework; suitable for high-demand crops like tomatoes (yield +18%).	Morcego et al. 2023

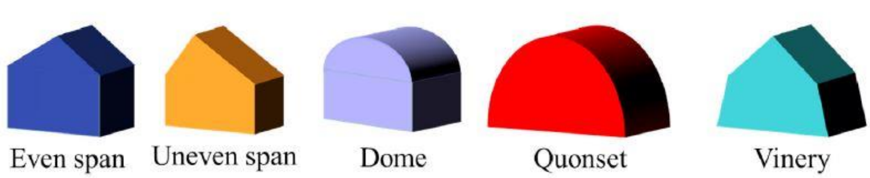

Figure 2. Typical shapes of a greenhouse based on (Zhang et al.2022)

Depending on the specific local climate conditions and the greenhouse dimensions, different shapes have emerged as energy efficient (Blanco et al. 2022). There are studies which have evaluated the performance of the greenhouse with different forms but similar base surfaces (w=34, l= 40 m). The authors presented a new approach to properly estimate energy consumption inside a greenhouse. The optimal greenhouse shapes are affected by aspect ratio.

Under a condition of keeping the same length, width and height of shapes in a greenhouse, Sethi (2009) found that uneven greenhouse received the most solar radiation. Even more optimal shapes could be designed with more complex geometries (such as a sawtooth type) reported by (Chen et al.2020) which could absorb higher solar radiation.

1.2. Literature Review Step Two: Studies on Double Skin Facades (DSFs)

Vukadinovic et al. (2021) have conducted a multi-objective optimization of a sun space using the NSGA-II genetic algorithm. The authors have optimized the structural and architectural parameters of a detached passive building with a sun space. They utilized the DesignBuilder software package coupled to EnergyPlus, a dynamic energy simulation software (Vukadinović et al. 2021). In a study (Erdem and Onan 2025), they optimized the heating efficiency of a sun space and imagined the role of the geometry of the sun space in their study. Based on their definition. The sunspaces, a type of passive heating system, not only provide additional usable spaces but also decrease the heating load of buildings. The authors have studied the effect of the sun's space geometry on energy savings using a simulation done by TRANSYS (Erdem and Onan 2025). Based on the definition of the latter study, sunspaces, a type of passive heating system, not only provide additional usable spaces but also decrease the heating load of buildings. The study evaluated the effect of the roof and depth of the sun space, and different roof slopes and depths were simulated. It was indicated that the depth of the sunspace is often determined based on the area of use, which can limit the full utilization of its energy potential. One of the main findings of this study is the ability of the sunspace (or greenhouse) to better harness solar energy and reduce heating costs through modifying its geometry.

On the other hand, there is a large body of research on various aspects of these types of facades. Some have focused on the specific and overall performance criteria of the building, such as cooling, heating, and daylighting (Kasinalis et al. 2014; Poirazis 2008; Poizaris 2004). Research conducted on the double-skin facades includes studies of heat transfer, fluid flow, the effect of shading devices, the effect of tilt angle, and the size of such devices on the overall energy performance (Gholamalizadeh and Kim 2014; Richter et al. 2014; Ozoe et al. 1974; Joe et al. 2013). Based on the references, several conceptual design elements of the DSFs have been determined to be implemented in planning and design. These design elements include building orientation, geometry/shape, materials, thermal resistance, window to wall ratio, shading devices, thermal mass, renewable energy integration, and air infiltration (Attia et al. 2009; Hemsath 2013; Samuelson et al. 2016) but there are very few studies who just focused on the impact of geometrical configurations of the building envelopes itself on the overall energy performance and daylighting (Hachem et al. 2014; Hachem-Vermette 2018; Hachem and Elsayed 2016). There are some good examples of optimization studies to design and enhance the effect of parameters such as glazing type and cavity depth (not shape) on the energy consumption of the adjacent conditioned zone (Joe et al. 2014; Su et al. 2017). Studies done on DSFs indicate that these systems have the potential to increase the energy efficiency of the building (Barbosa and Ip 2014). For example, it has been shown that the heating and cooling load could be reduced up to 89.1 % and 30 % respectively, in hot climates (Jiang and Long 2006). On the other hand, the risk of overheating on warm sunny days is evident and may lead to a higher cooling demand (Gratia and Herde 2004a; Ding et al. 2005), and recently, some developments were added to DSF design, such as building-integrated photovoltaic (BIPV) and thermal collectors (Agathokleous and Kalogirou 2016; Hestnes 1999), which accentuate more concentration on the design of shape and the geometry of the outer layer in DSFs. As stated, such an overheating process could happen in the greenhouses due to exceeding direct gain from the sun and a low ventilation rate inside the greenhouses. Overcoming the overheating to excel its performance in hot climates provides the subject of some valuable studies (Poirazis 2008; Joe et al. 2014; Høseggen et al. 2008; Hamza 2008; Mateus et al. 2014; Saelens et al. 2008). In the summer, the temperature increases in the cavity due to the greenhouse effect, and to wipe out these problems, it is necessary to utilize natural ventilation effectively to exhaust warm air outdoors (Gratia and Herde 2004b). Nowadays, DSFs can be used even in hot climates. Hashemi et al (2010) showed that DSFs can combine the wind force to reduce increasing air temperature inside the cavity and prevent temperature rise inside the room adjacent to the DSF zone (Hashemi et al. 2010).

The main parameters that are necessary to design DSFs can be stated as follows: the outer layer, cavity, inner layer, top, and bottom openings size, and shading or blinds inside the cavity are the most important ones, which researchers have tried to find the optimum values based on their climatic limitations and conditions (Fallahi et al. 2010; Darkwa et al. 2014; Faggembauu et al. 2003; Mingotti et al. 2011; Manz and Frank 2005). The most important parameters on the performance of DSF are cavity depth, opening sizes on the outer layer, and environmental diffraction between inside and outdoor conditions, which depends on wind pressure on the building envelope, buoyancy effect, and exhaust coefficient on the openings (Poizaris 2004). Studies on the DSFs based on modifying their geometry, are being originated from Oesterle's (2004) work, which classified DSFs as geometric units beyond the origins of the airflow and possible flow paths (Oesterle 2001). Recently, Hachem et al. (Hachem et al. 2014; Hachem-Vermette 2018; Hachem and Elsayed 2016; Hachem et al. 2011) tried to depict the optimized performance of the DSF through modifying its geometry. The paper has referred implicitly to the positive influence of deforming the geometry in the outer layer of the DSF, which would decrease the cooling load during summers.

It was supposed to prove that the rectangular shapes are likely considered as an optimal building shape in terms of energy efficiency design, however, according to Hachem et al. studies, the deviation from the basic flat facades although leads to an increase in heating load are counterbalanced by a reduction in cooling load and a considerable increase in energy generation potential from façade integrated PV systems (Hachem-Vermette 2018; Hachem and Elsayed 2016; Hachem et al. 2011). Thus, it is possible to improve energy performance and electric generation of DSFs using modified geometries such as inclined-plate or saw-tooth shapes. The thermal characteristics of a cavity in a manipulated DSF may vary according to the design since the DSF layers are generally fully glazed. Such thermal characteristics of the cavity influence the thermal and cooling load in adjacent zones. Besides, DSF is a technique developed for colder climates, so few people think about whether or not it can also be used for a hot summer. Zhou et al. 2009 (Zhou et al. 2009) studied it for the hot summer and cold-winter zone in China.

Based on a systematic literature review done by the study (Maraveas et al. 2023), the authors 'findings led to several themes, including the importance of energy-saving techniques for greenhouse systems and systems that could reduce unfavorable external conditions and renewable energy systems. There are also discussed the themes identified regarded energy storage systems, systems for managing conditions in greenhouses, carbon capture and storage, and factors influencing the performance of different technologies to enhance resource management and ensure zero carbon emissions. Evaluation of the performance of the DSF as a passive design solution in order to mitigate energy consumption in the agricultural greenhouses is a topic that has not been conducted. Specifically investigating its geometrical configurations in order to hinder or control solar energy coming into a greenhouse is the main scope of this study. It is necessary to evaluate different DSF configurations to be aware of their potential for heating, cooling, and energy consumption.

Based on the author's knowledge, the integration os such a system with a greenhouse in order to mitigate its high temperature has not been studied yet. Thus, the purpose of this study is to quantitatively analyze the impact of the initial DSF design, regarding outer window tilt angle type and associated cavity depth, on the energy consumption of adjacent zones. The adjacent zone could be residential or agricultural constructions, called greenhouses. In addition to the evaluation of the energy performance, heating, and cooling load, natural ventilation is one of the main parameters that must be evaluated for each deformed geometry.

2. Materials and Methods

The paper discusses three main strategies in the design of the outer skin of a Box-Window DSF aimed at enhancing its energy performance by reducing the cooling load. It presents examples of energy performance based on simulations carried out on the various patterns of the regarded integrated DSF type with a greenhouse. These novel models would show the possible potentials of DSF models with many purposes in terms of enhancing natural ventilation, reducing cooling load, and also increasing the potential of electric generation for BIPVs. The first design approach applies an optimized window-to-wall ratio (WWR) of the northern façade as the main source of providing natural ventilation to reduce overheating hours. After the calculation of the optimized dimension and operation of the north window and south (inner layer) windows, DSFs are equipped on the southern façade. The second strategy applies a flat DSF to the base case. The cavity depth is the parameter that is optimized for this case. The third strategy adopts a deformation of the outer layer in two different models on the same square plan. The deformation could be defined as changing the inclination angle of the outer layer, but we did not refer to this type of definition for the cases. The tilt angle controls the maximum depth of the cavity of the DSF, so the apex or inclination position is defined as the distance relative to the base of the glazed plate of the inclined unit. All the details about the models are shown in the following section (see Figures 3-5). The models based on the considered algorithms were developed and analyzed with DesignBuilder version 4.5. Tehran climatic weather data (EPW) downloaded from the EnergyPlus official site. The process of the simulation was conducted for the entire summer; times means the entire cooling load was assessed to assess their energy performance and cooling load considerations. The basic model validation is conducted using ASHRAE determined benchmarks (ASHRAE, 2011, 2017) in the following.

2.1. Boundary condition and model assumptions in DesignBuilder

Integrating inclined geometry design within DSF allows the freedom to shift the design vertically concerning the interior space since the design of the outer skin is independent of the interior layout, and particularly the positioning of floor slabs. This would permit some benefits, including improvement in thermal performance (heating or cooling), control over the window location of windows, and consequently quality of daylighting (Hachem-Vermette 2018).

The main objective of the study was to generate performance data in the double-skin facade and the resulting cooling loads for the adjacent perimeter offices according to the change of the outer layer geometry. The models were classified into two basic groups. The first models are of a room without DSF to find the optimized northern window with the highest natural ventilation and, least cooling load. And the second group is an optimized-depth square and deformed model. The flat model's configuration and materials used in the study were referenced to Hensen et al (2002) study (Hensen et al. 2002). The main variable in the study is both cooling loads and office zone temperatures.

As shown in Figure 4, the model comprises a typical 7.5 m wide section of the south side of the building, consisting of a "stack" of zones representing the office zones up to a depth of 5 m behind the façade and another "stacked" zone representing the double-skin façade itself. Thus, the base model of rectangular space as an office module was selected, and a Box-Window type DSF was selected as a pilot case and compared with the models of the two deformed cases. The constructed materials, geometry, and all the assumptions were derived from Hansen's (2002) research (Hensen et al. 2002). All the assumptions mentioned are being classified in Table 1 in the following.

Table 1. All configuration and assumptions for modeling in DesignBuilder.

Test Case Geometry	- width 7.5 m, depth 5 m, height 3.7 m
DSF Geometry (Base Model)	- width 7.5 m, depth 0.30 m, height 3.7 m
Construction	- Façade construction from outside to the inside: 80 mm insulation + 200 mm concrete: The standardized thermal resistance R is 2.9 m2K/W or U is 0.32 W/(m^2K) - The roof construction from outside to inside: 0.15 m insulation + 0.28 m concrete The standardized thermal resistance R is 4.35 m2K/W or U is 0.22 W/(m^2K) - The floors: 0. 28m concrete - The interior wall consists of 0.02 m concrete wall
Windows	- The double-skin façade outer glazing: 0.06 m clear float with a visible transmittance of 0.87 nominal U-factor of 5.40 W/(m2K). - The glazing of the offices toward the double-skin façade: double glazing with external blinds: - A visible transmittance of 0.72 [-] and a nominal U-factor of 1.60 W//m2K
Operation	- The natural ventilation calculated mode - The casual gains on working days 7:00–17:00: occupants 233 W sensible + 293 W latent, lights 750 W, equipment 1125 W - There are no casual gains outside working hours.
Control	- The first-floor office zone has a free-floating temperature - The cooling setpoint is 26°C for the other office zones during working days 7:00–17:00
Air Flow Network Parameters	- The inlet opening has a cross-sectional area 7 m × 0.2 m = 1.4 m2 - The outlet opening has a cross-sectional area 7 m × 0.3 m = 2.1 m2

It was assumed an exhaust mode of ventilation operates in DSFs and outdoor air could pass into the cavity through inlets. The exhaust mode extracts air through the cavity to the outside space. The window using this operation exploits cooling from indoor air and buoyancy force from the solar irradiation gained in the cavity. In the air curtain wall, there is no air change between the indoor and outdoor.

The considered model was calculated using a whole year weather data of Tehran downloaded from EnergyPlus official website. Through hourly calculation of building energy simulation tools, the annual variables of heating and cooling energy consumption were obtained. For the load calculations, it has been ideal-air system to satisfy considered thermal domain of 22 ℃ for heating and 34 ℃ for cooling and also 28 ℃ for the natural ventilations have been assumed.

2.2. Model Verification

Before conducting the simulations, the building simulation tools (BES) used has been verified using a benchmark models. This research utilizes the Case 600 benchmark from ANSI/ASHRAE Standard 140-2023 to establish a verified foundation for building energy simulation analysis (ASHRAE, 2011). Case 600 represents a single-zone rectangular building (8 m × 6 m × 2.7 m) with 12 m² of south-facing windows, 0.2 m wall below and 0.5 m above the windows (ASHRAE, 2011; Henninger & Witte, 2015). This standardized single-zone model, characterized by its specific geometry and south-facing glazing, serves as a recognized reference for evaluating the thermal performance of building envelopes and for cross-tool comparison (Karimi et al., 2024). The simulation framework adheres strictly to the benchmark specifications. This includes the defined thermophysical properties of all construction assemblies (ASHRAE, 2011), internal load profiles, infiltration rates, and the site's meteorological conditions. The HVAC is modeled as an ideal, fully convective air system with prescribed heating and cooling setpoints, complying with ASHRAE 90.1 requirements (Goel et al., 2017; Karimi et al., 2024). Simulations were executed for low-mass type of Case 600 configurations using Denver TMY3 weather data. The results were validated against the Standard 140-2007/2011 reference data and comprehensive data regarding building configuration could be found here (ASHRAE, 2017). Figure 3 compares the annual hearing and cooling loads of Case 600 and simulated results.

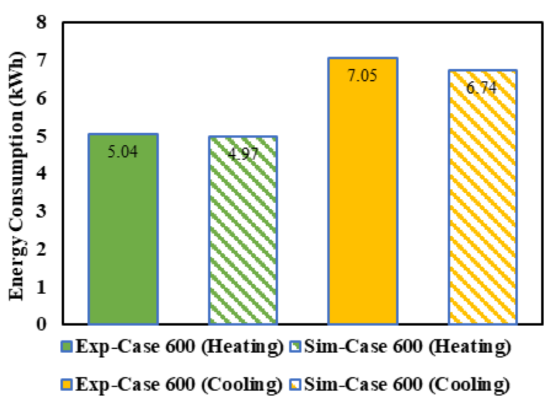

Figure 1. Comparison of the annual heating/cooling loads between ASHARE case 600 vs DesignBuilder simulations.

It is seen that a high degree of accuracy, with heating and cooling load errors within the acceptable thresholds defined by ASHRAE Guideline 14 (ASHRAE, 2014). Annual simulation results indicate relative accuracy errors of approximately 1% for heating and 2% for cooling between ASHRAE Cases 600, as shown in Figure 3. This confirms the model's validity and provides a pre-verified basis for subsequent parametric and optimization studies, negating the need for initial experimental validation.

3. Results and Discussions

In this section, the results of the simulation in DesignBuilder are presented. The openings and their operation time are the most important parameters to utilize natural ventilation inside the room. At first, the optimum operations of the north and south windows (inner layer DSF) are achieved in DesignBuilder to be considered in DSF models.

3.1. Optimized openings operation without DSF

The measurement room with 7.5m by 5m was modeled to depict the best operable schedule of the south and north windows, and the overheating hours of the case are compared based on modified operable areas of the window if there were a sufficient condition and set points of natural ventilation were provided. Table 2 depicts the heating and cooling, and ventilation setpoints in the studied indoor space.

Table 3. The setpoints are considered for sizing the HVAC system and Natural ventilation for operable windows in DesignBuilder.

Heating Setpoint (°C)	Cooling Setpoint (°C)	Natural Ventilation Setpoint (°C)
22	34	28

It is used the Calculated Natural Ventilation simulation method is used in DesignBuilder. This method is often used to undertake simulations in buildings that have features to increase natural ventilation rates, such as DSF, and for summer overheating calculations in buildings without mechanical cooling systems. Calculated natural ventilation simulations are often used to provide evidence that the building is unlikely to suffer from overheating. Just running a quick annual simulation to generate only temperature distribution data will enable meet to confirm the summer overheating hours in the zone. After setting up and running a calculated natural ventilation, DesignBuilder can produce results that indicate the fresh air ventilation rate and internal temperature likely to be in each zone. Some of these results, such as the temperature distribution graph, show how many hours for each zone are below, at, and above the overheating. 28 degrees Celsius is considered an overheating setpoint. For the greenhouse, it is also possible to consider higher temperatures with higher relative humidity, but it mostly depends on the cultivated crops inside the space. The starting point for each analysis is to compare overheating periods simulated by DesignBuilder for the summer periods as an index of the performance of the case alongside the cooling loads. The operations of the inner windows could be scheduled by the user as we tried to set it at 22-28 °C and operable up to 50 percent if the natural ventilation condition would be possible. To utilize natural ventilation from outside the northern window (1.5m widths and height) was modeled on the north façade. Based on Hensen et al. (2002) and Barsbosa and Ip (2014) studies, the considered WWRs are 40 percent for south-facing windows in order to catch high solar gain and derived natural ventilation. Figure 4 shows the overheating period for each case as a function of the operation of the north and south-facing windows, namely. The first value is related to the openable area of the north window, and the second value is for the south-facing window.

As shown in Figure 4, the best model, which has the best performance, including the lowest overheating hours throughout the year, is related to the case 100%-25% of opening windows. It means fully opened north window and 25% opening area of south windows. Through this schedule and operable area, it could have the highest natural ventilation and the least overheating period during hot seasons. So, it is decided to consider this operation as the basis for modeling the natural ventilation calculation of the DSF models. And the maximum overheating hours are related to the case with 50%-50% which implies the situation that north and south, both the openings have equal operational performance.

In Figure 5, the mean airflow rates of the zones for cases 50%-50% and 100%-25% as the worst and best cases in terms of overheating hours count. It could be seen that approximately for all the year, the values of the case 100%-25% are higher than the 50%-50% case from April to October. The maximum flow rate relates to September by 9.67 (ac/h) for the 100%-25% case and is almost 27 % higher than the 50%-50% case. The parametric investigation indicates a general trend that needs to be considered to enhance the energy performance of the base case. The main requirements include air infiltration and natural ventilation through the designed openings on each face. Such configurations (100%-25%) of parameter values allow a reduction of the cooling load by up to 45% as compared to the commonly built case.

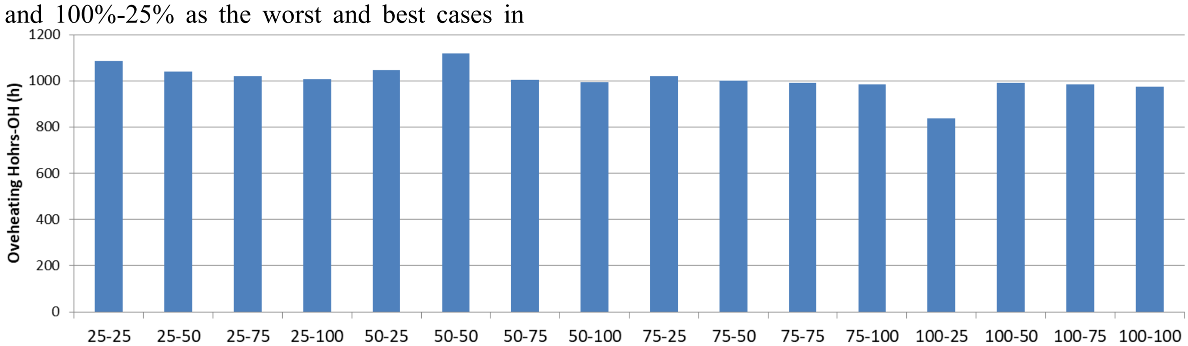

Figure 4. Overheating hours during the year for the case without DSF.

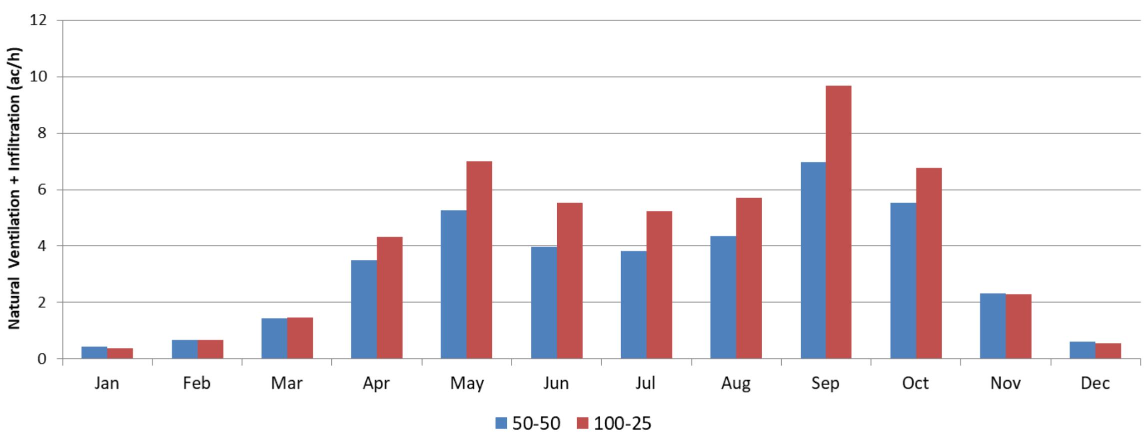

Figure 5. Air flow (ac/h) for the best (100-25) and the worst (50-50) models in providing natural ventilation.

3.2. Impact of outer layer geometry on overheating

To analyze the performance of each façade, there have been simulated modified DSFs embedded on the south face of the indoor space. The model's features and names are all shown in Figures 3-5, respectively. Figure 6 shows a schematic view of natural ventilation and flow patterns inside the test room with and without DSF equipment, accompanied by the north and south windows' operation.

Figure 6. shows the overheating periods (OH) analysis for all Flat and deformed configurations with different cavity depths from 0.3m to 1m. Based on Figure 6, deforming DSF from its basic shapes could change its performance and decrease the OH period significantly. The distribution of maximum OH hours is related to DTC 60 cm by 1821 hours. The case DTC 120 cm is the best case due to having the lowest OH hours by 947.2 h. It could be possible to have a quick comparison between deformed cases with flat modes: that is, some cases of Flat cases (e.g., the cavity depths 0.3m to 1.2m) are getting better through increasing cavity depth; however, it could worsen in some large values because of high building solar heat gain.

There is a tradeoff situation for the flat configurations as mentioned in the earlier studies; in contraction, if the cavity depth in the DTC models (as the cavity depth in height is larger than its base) increases the performance of DSF improves and likely gets better than flat cases and also the minimum value is related to DTC cases (case DTC 120 cm Cavity depth from Top); for the cases with deformation from the base (DBC), the performance of DSF in reducing overheating periods is not very significant however the difference between the maximum and minimum OH hours for DSF and Room zone is larger than two other case types.

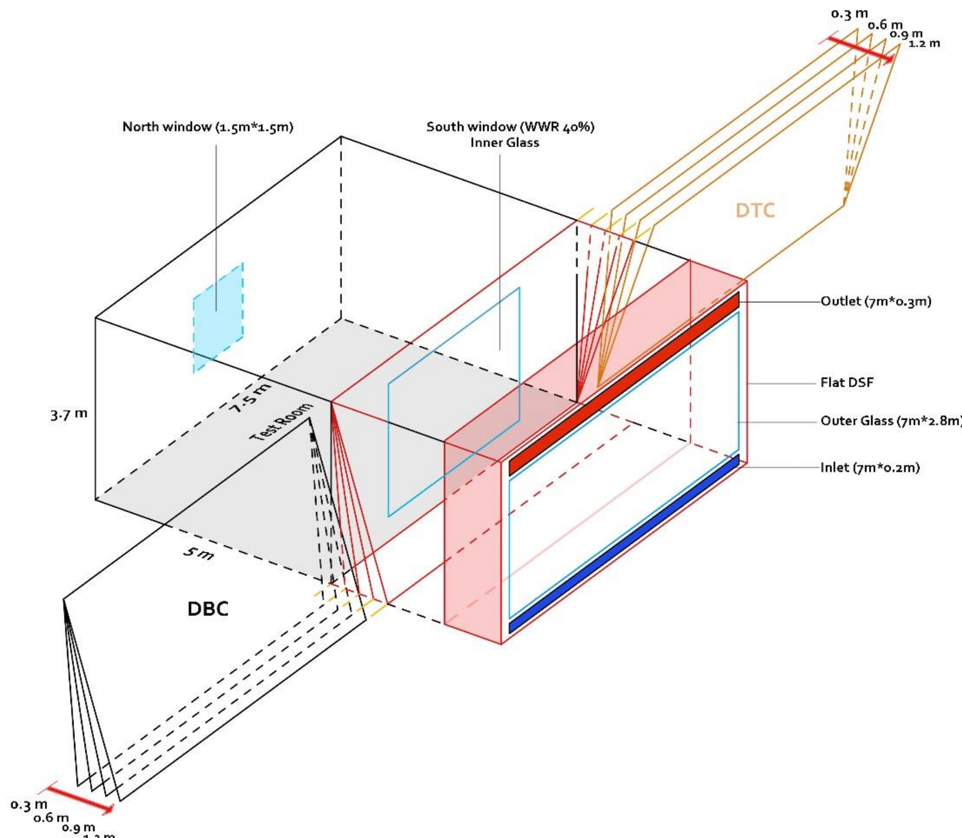

Figure 6. All modeled DSFs and Test Room in DesigBuilder

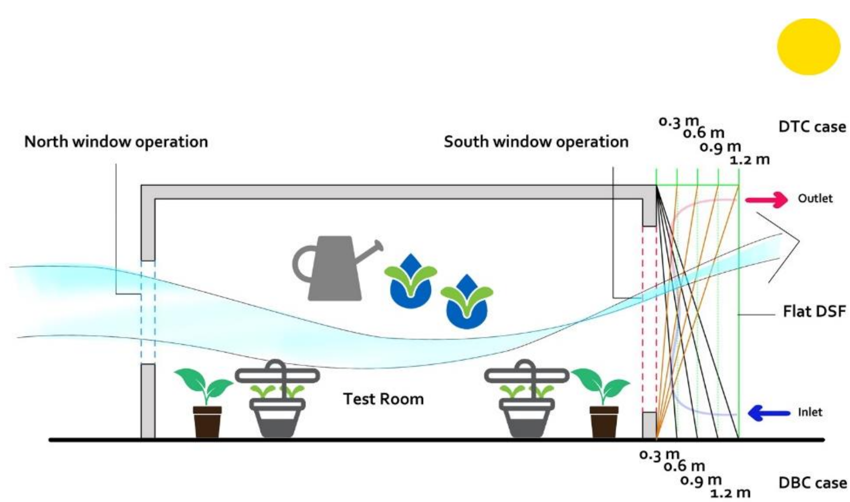

Figure 7. Schematic view of natural ventilation and flow pattern inside the Test Room using the operation of the north and south windows.

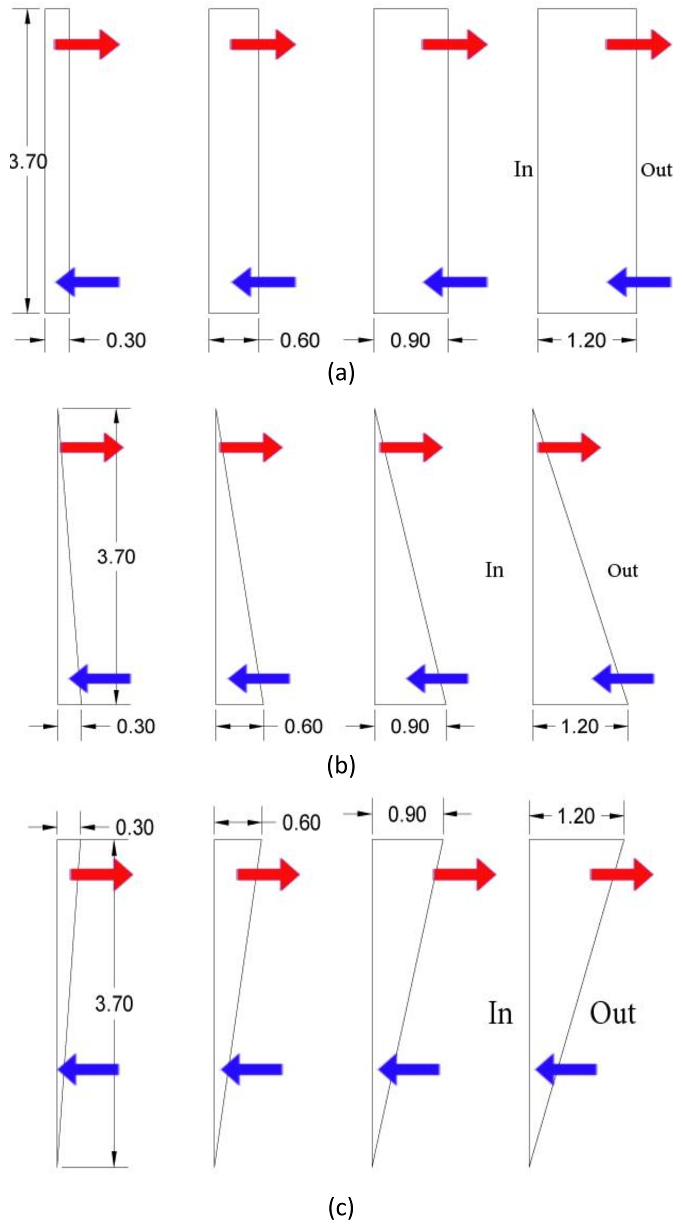

Figure 8. Schematic of all modeled DSFs cavity: (a) Flat, (b) Deformation Bottom Case (DBC), and (c) Deformation Top Case (DTC) cases namely and inlet and outlet position for external air curtain method of ventilation

It is clear that for the DBC cases, increasing the cavity depth from the bottom has caused a decrease in overheating till 0.9 m, but increasing from this value has degraded the deformed façade performance. In DBC cases, the DSF overhearing is almost consistent for all cases, and the room overheating hours decreased gradually, even less than the base case.

The DBC case with 0.9m overhanging from the bottom could be a good design in terms of the high potential for generating electricity and the lowest overheating hours. Nevertheless, other cases do not have this feature. Though the maximum overheating period is related to -DTC 60 cm -model, the room overheating period is much less than the case–Flat 30 cm Cavity- so this can be assumed that deformation would enhance the quality of interior thermal comfort well. Actually, with deformation from the top (DTC), it works as shading and it reduces the solar heat gains during hot summer days. On the other hand, it also caused better performance than in other cases. It would be desirable that DSF and Room zone both have low values and also a low difference, so by this fact, the best case is likely to be –DTC 90 cm cavity- which has the low OH hours in both DSF and Room zone in comparison with other cases.

3.3. Impact of outer layer geometry on cooling load and natural ventilation

The cooling load of each case for all summer periods is shown in Figure 10. It can be seen that the total cooling load of each case has increased until August. The behavior of DTC cases is lower than both the deformed and flat cases as well. This behavior could be attributed to the low heat gain and shading properties of DSF. This has also been shown in previous research, which provides that overhang and shading have the highest effect in cooling load reduction (Hachem-Vermette 2018). The best case, which could have the best performance in terms of low energy consumption dedicated to the DTC 90 cm model, which almost for all the hot season months, has the lowest values in comparison with others.

To have a comprehensive perspective on the results of the integrated DSFs on the adjacent thermal zone, the total cooling loads of each model are presented in Figure 12. The results indicate that the cooling load has changed with the deformation of the facade. For Flat cases, it is reduced with increasing cavity depth, but its growth rate diminishes gradually. It could be understood that deformation from the top has the best modification method to excel in the performance of the DSF. By increasing the depth at the top (DTC), it seems that the performance of DSF gets better due to the utilization of natural ventilation and shading enhancement. The lowest cooling is related to the model DTC 90 cm by 2534.33(kWh), and the maximum value is related to the model DBC 90 cm cavity by 3924.53 (kWh). The result shows that the DTC 90 cm cavity depth-performance is around 35.42 % better than DBC models and also around 21 % better than the best Flat cases. The high value of the DBC 90 cm case is due to the temperature rise inside the DSF zone. The deformation from the floor seems to cause DSF to receive more solar radiation than Flat or DTC models. The results indicate that DBC cases have more advantages during various times of the year in capturing solar irradiation and PV's potential. As the models do not have any sun-controlling systems, it could be possible to enhance DBCs' cooling energy consumption and make it lower than the current one; however, in this study, we did not consider the models with blinds at all. Thus, for Flat cases cooling load is slightly reduced with a larger cavity depth. For DTC cases, decreasing the tilt angle results in increasing the self-shading capacity of the façade, which leads to a decrease in cooling load, and we had the reverse effect for DBC cases. PV generation potential is increased with a low inclination angle of DBCs. The electricity generation will be more accentuated by a more optimized angle, increased PV area, and also better ventilation of DSF, which is feasible for DBC cases at lower cavity depths (with 0.3 m depth). An increase of the cavity depth at the bottom (decrease of the tilt angle) should, however, be applied in moderation due to lowering the heating load in winter.

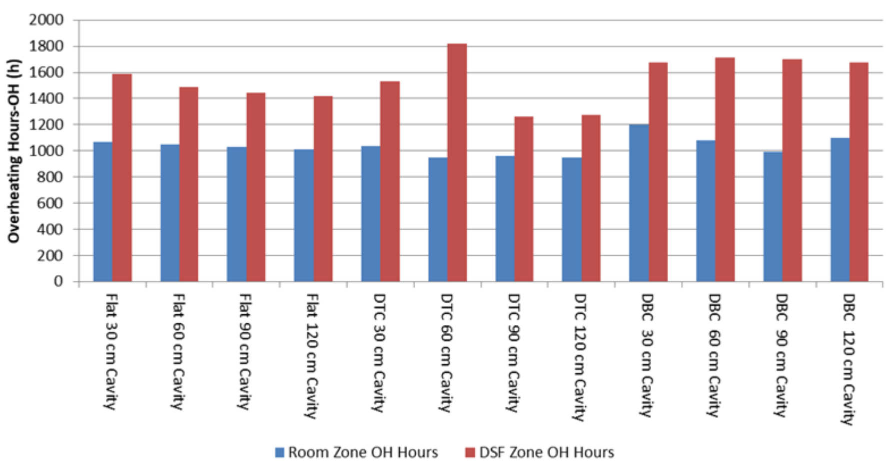

Figure 9. The Overheating hours analysis for all models in the Room and all DSF zones.

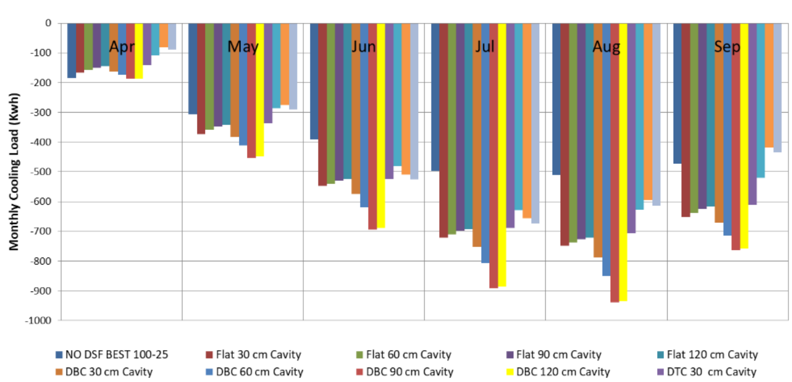

Figure 10. Simulation of Cooling load of all models for all summer period.
The negative values mean it is the energy consumed to cool down the indoor environment.

To have a comprehensive perspective on the results of the integrated DSFs on the adjacent thermal zone, the total cooling loads of each model are presented in Figure 11. The results indicate that the cooling load has changed with the deformation of the facade. For Flat cases, it is reduced with increasing cavity depth, but its growth rate diminishes gradually. It could be understood that deformation from the top has the best modification method to excel in the performance of the DSF. By increasing the depth at the top (DTC), it seems that the performance of DSF gets better due to the utilization of natural ventilation and shading enhancement. The lowest cooling is related to the model DTC 90 cm by 2534.33(kWh), and the maximum value is related to the model DBC 90 cm cavity by 3924.53 (kWh). The result shows that the DTC 90 cm cavity depth-performance is around 35.42 % better than DBC models and also around 21 % better than the best Flat cases. The high value of the DBC 90 cm case is due to the temperature rise inside the DSF zone. The deformation from the floor seems to cause DSF to receive more solar radiation than Flat or DTC models. The results indicate that DBC cases have more advantages during various times of the year in capturing solar irradiation and PV's potential. As the models do not have any sun-controlling systems, it could be possible to enhance DBCs' cooling energy consumption and make it lower than the current one; however, in this study, we did not consider the models with blinds at all. Thus, for Flat cases cooling load is slightly reduced with a larger cavity depth. For DTC cases, decreasing the tilt angle results in increasing the self-shading capacity of the façade, which leads to a decrease in cooling load, and we had the reverse effect for DBC cases. PV generation potential is increased with a low inclination angle of DBCs. The electricity generation will be more accentuated by a more optimized angle, increased PV area, and also better ventilation of DSF, which is feasible for DBC cases at lower cavity depths (with 0.3 m depth). An increase of the cavity depth at the bottom (decrease of the tilt angle) should, however, be applied in moderation due to lowering the heating load in winter.

According to the main scope study, it needs to analyze all the models in a separate study through CFD analysis in order to determine the exact flow pattern inside the space. In order to analyze the performance of the best case and the effect of airflow in reducing the cooling load, Figure 12 is shown in the following.

According to Figure 12, the monthly data of temperature and airflow of each zone are presented. The room was not considered to use cooling or heating systems, and this analysis exactly shows the natural performance of DSF in terms of temperature and air flow rates provided to the inside. The outside dry temperature for all months of the year is always lower than both the DSF and the test room zone of the case DTC 90 cm cavity. The increasing temperature for winter season is really beneficial for reducing heating load however the cooling load is increasing subsequently (see Figure 12). The air flow based on air change per hour in DSF is relatively high, however the high temperature of which do not let this flow could be applicable and all the natural ventilation only usable if it were in low temperature to cool inside high temperature and to evacuate it. In order to verification of the DTC 90 cm performance and results and also to have a more detailed understanding of the airflow inside the room, Figure 13 shows all summer daily data of case -DCT 90 cm Cavity- showing relation of air flow and outdoor condition as wind speed and direction, and their effects on interior for the hottest periods.

3.4. Natural ventilation and cooling effect of the Best Case (DTC 90 cm)

The airflow rate and the average temperature of the DTC 90 cm case for both DSF and Room zones are shown in Figure 9. According to the weather data of Tehran, the outside dry temperature for all months of the year is always lower than both DSF and Room zones for the DTC 90 cm case. The increasing temperature for the winter season is beneficial for reducing the heating load; however, the cooling load has increased subsequently. The airflow based on the air change per hour in DSF is relatively high; however, the high temperature of which do not allow this flow could be applicable, and all the natural ventilation is only usable if it were in a low temperature to cool inside high temperature and to evacuate it. The flow rate due to the buoyant-driven flow gradually increased when we reached to hot months in the room and DSF. The heat balance graph shows a significant cooling effect from the natural ventilation openings. The highest point is for cold morning air, and it diminishes slowly as the ambient air temperature rises during the day. The air change rates in the zone are high throughout the whole day, and the peak value is 23.42 ac/h in July, fourth. The heat balance graph also clearly shows the general trend that natural ventilation cooling reduces as the ambient air temperature increases throughout the day.

Through such enhancements of natural ventilation, it would also be possible to manage water consumption and relative humidity of the indoor space in greenhouses while reducing heating and cooling energy in these constructions. This evaluation needs a more detailed evaluation using more advanced CFD or experimental tools that could provide the next topic for the research groups.

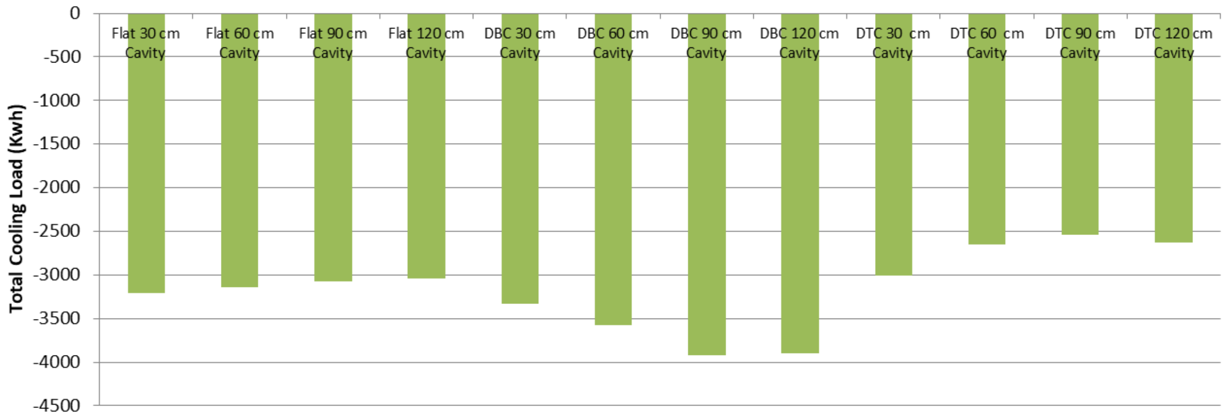

Figure 11. Total cooling load of all cases for all summer period.

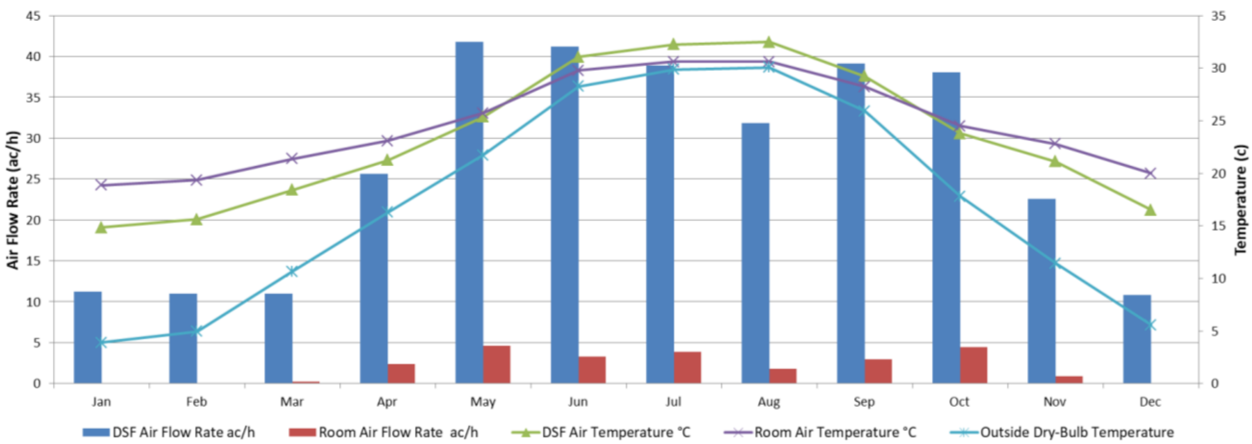

Figure 12. Air flow of DSF and Room zone for the best case (DTC 90cm cavity) and its relation to the temperatures in the cavity and adjacent thermal zone

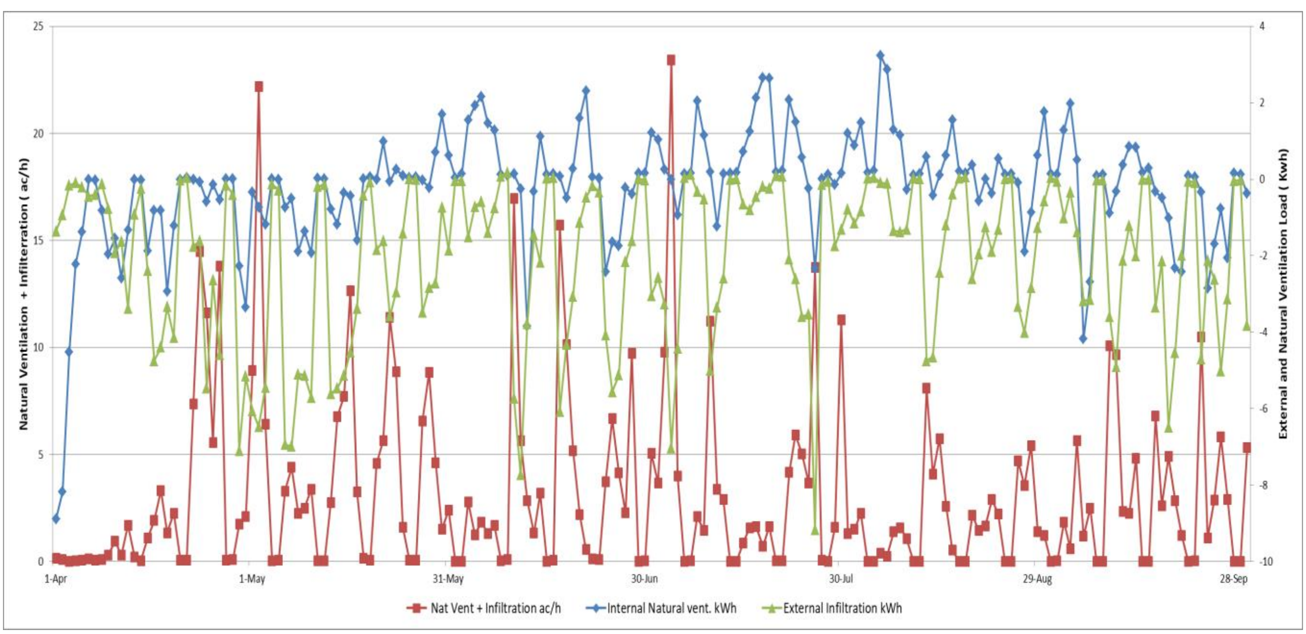

Figure 13. Natural ventilation and cooling effect of case DTC 90 cm.

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4. Conclusion

This study presents three simplified design strategies for improved energy performance (cooling load) of a Box-Window DSF in a hot-climate of Iran. These design strategies must balance many factors including aesthetics, functionality, structure, and energy performance. Regardless of dimensions that are derived from the literature as and the optimum values (8% and 40 % for north and south facade), at first, their operations (opening percentage) were optimized using a parametric study to get the highest natural ventilation capacity of the room without DSF. Then to evaluate the effect of DSF outer layer geometry, three types of DSF named, Flat, deformation at the bottom (DBC), and deformation from the top (DTC) cases were modeled and analyzed in terms of reduction of cooling load and increase of natural ventilation and airflow rate.

This paper has highlighted a new perspective of the design of DSF to show its modified thermal and natural ventilation performance. The main index for comparing through the models is airflow and cooling loads value which shows a great correlation between each one, the higher natural ventilation and airflow rate lead to the less cooling load consequently. No DSF models (7.5*5 m2) were done by BES, Design Builder 4.5 version to determine the best operation of windows and its opening size. The No DSF models with a fully-opened north window (100%) and 25% opened south window were selected as the best operational models so this operation was assumed to work better for analysis of the DSF models. The deformed models (Flat, DBC, DTC) were assessed in terms of reduced overheating hours and cooling load. Comparing the models showed that the models with deformation of the cavity depth at the top (DTC) would cause to improve the performance of the DSF than Flat and DBC cases. The result showed that the DTC 90 cm cavity depth- performance is around 35.42 % and 21% better than DBC models and Flat models respectively. Although for some cases such as Flat and DBC increasing the depth of the cavity could increase the cooling load, but the temperature rise inside the cavity would decrease the heating load in cold seasons. The airflow of DTC cases is relatively high, but the high temperature of outdoor would not cause that natural ventilation would be very beneficial to more cooling purposes for these cases with DSF. There is a need to evaluate different types of DSFs to see their potentials even in hot climates. The study showed that utilizing deformation on the geometry of the outer skin of a simplified DSF could enhance its performance through increasing airflow at the same time decreasing cooling load. This study needs a more detailed analysis in terms of validation and supplementing its scope with separated CFD analysis to understand the nature of the flows induced inside the cavity. Considering the latter point, future study should investigate thoroughly the main DSF design parameters considering their interaction with the variation of the geometry of the inner and outer skins deeply. Improving natural ventilation in such agricultural constructions (and residential buildings) could improve water management and energy savings of irrigations cost which needs more detailed studies in the future.

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