buildings

MDPI

Article

Multi-Disciplinary Characteristics of Double-Skin Facades for Computational Modeling Perspective and Practical Design Considerations

Ali M. Memari [1], Ryan Solnosky [2,*] and Chengcong Hu [3]

[1] Architectural Engineering and Civil and Environmental Engineering Departments, The Pennsylvania State University, University Park, PA 16802, USA
[2] Architectural Engineering Department, The Pennsylvania State University, University Park, PA 16802, USA
[3] Civil and Environmental Engineering Departments, The Pennsylvania State University, University Park, PA 16802, USA
* Correspondence: rls5008@psu.edu

Abstract: Vertical building enclosures known as Double-skin façades (DSFs) have become recognized as a promising façade type for buildings that place emphasis on sustainable, green, and energy-efficient design performance. DSFs are highly integrated across engineering and architecture; however, there remain limited centralized knowledge repositories that offer designers' insight into these performance trends, multi-disciplinary collaboration, and tradeoff metrics, as well as how to go about modeling DSFs for performance under applicable loading systems when conducting design. As such, the main objective of this paper is to provide a better understanding of different types of DSF systems and their attributes from the perspective of multiple disciplines, as well as different modeling approaches. The methodology adopted is rooted in the principles of systematic literature review of design standards, research papers, and software manual literature, as well as a qualitative evaluation based on structural performance aspects. From the study, many different configurations of DSFs exist that impact each engineered system, where those system attributes impact multiple systems. This results in a need to parametrically iterate configurations within software to find a balance in DSF performance. Furthermore, there exists software easily capable of simulating these systems, yet the designer must carefully construct the models with different levels of sophistication towards DSFs and the software. This paper contains concise summaries of key attributes that designers need to consider when their project has a DSF system, along with different software modelers from which they can choose, correlating to the complexity of the design stage along with the appropriateness of the calculations.

Keywords: glazing system; energy performance; curtain wall; double skin façade; modeling

check for updates

Citation: Memari, A.M.; Solnosky, R.; Hu, C. Multi-Disciplinary Characteristics of Double-Skin Facades for Computational Modeling Perspective and Practical Design Considerations. *Buildings* **2022**, *12*, 1576. https://doi.org/10.3390/buildings12101576

Academic Editor: Xingxing Zhang

Received: 23 August 2022
Accepted: 23 September 2022
Published: 30 September 2022

1. Introduction

Double skin façades (DSFs) are a modern architectural enclosure system trend, which started in Europe to overcome the disadvantages of single skin facades such as low energy efficiency, sick building syndrome, and insufficient sound isolation [1,2] among others. From a building type perspective, DSF systems have only recently started to be recognized as a viable solution in the United States [3].

DSFs have several advantages over traditional enclosures. When designed properly, DSF systems can increase a building's energy efficiency over traditional enclosures, especially when looking at solutions for high-end office buildings [4,5]. The skin cavity not only enables regulating natural ventilation through the window opening, but it also provides protection from the sun using shading devices, which also work better in the cavity than inside the room [6–8]. The buffer zone in a DSF provides advantages for both summer climates and winter climates in terms of reducing heat losses and increasing passive thermal gain, while also being able to ventilate to limit overheating [2,9]. Other advantages for utilizing DSFs include sound isolation enhancement from the exterior. Selkowitz [10] and Saelens et al. [11] acknowledge the potential benefits of utilizing DSFs, which are made possible due to the advances achieved in structure, façade, and glazing technologies.

Over the last two decades, studies have been carried out in Europe and North America resulting in a better understanding of the energy performance of such systems [12]. DSF performance depends on multiple contributing factors [13], including the type and use of building, insulation quality of the facade, the ratio between transparent and opaque surfaces of the inner layer, the location of shading devices between the outer and inner layers, the quality and size of openings within DSFs, acoustics, lighting, fire, service life, cost, sustainability, and the feature of inner and outer glazing of double skin façades [11,14]. Limited research has been carried out on the structural engineering side [15,16].

However, many aspects of such systems are not well understood by designers. Many implemented DSF around the world were built relying on the expertise of different designers and contractors specific to those climates, projects, and situations [2]. Vaglio [17] explores the development and adoption of DSFs in the United States and notes that due to the lack of familiarity of many U.S. architects/engineers with this type of system and also the process of early integration of façade design into the design stage, building codes in general and social expectations have limited their adoption [17]. With this, designers must have multi-disciplinary teams due to parameters such as: technical attributes of the cavity and external layer, the building's physical form, and the site's environmental conditions [18], which all will have tradeoffs that need to be understood. Furthermore, multi-disciplinary aspects and interrelated notions are lacking for DSFs, which results in a knowledge gap in understanding the comprehensive behavior of DSF systems that are gradually becoming of interest as part of green, sustainable, and multi-functional building façade systems [6,9]. Other challenges that designers, as well as owners, need to understand in design include: initial cost as well as high cost of cleaning, operating, inspection, and maintenance [19]; the high risk of unacceptable performance based on the contradictory economic viewpoints reported in recent years [18,20]; uncertainties in geometric attributes and glass type selection, shading, and ventilation strategy and wind loads [21]; as well as maintenance and cleaning [22].

The objective of this paper is to provide several key insights into DSF design and performance characteristics that can best benefit industry designers for better understanding the challenges on how to approach DSF design. Based on the literature review, it seems that core performance studies of DSFs leave fragmented work on how designers can take that knowledge to be applicable for widespread adoption within a design and simulation work setting. Accordingly, our contributions to the DSF body of work include recommendations on modeling techniques and packages for different simulations along with how to consider DSF design in a broader more multi-disciplinary nature. Core areas being addressed include important materialities, configurations, and modeling assumptions. Designers and modelers within the building industry can utilize the summaries and discussions presented to advance their state of practice when they encounter a building with a proposed DSF.

2. A Need for Better Envelope Performance

According to the 2011 Buildings Energy Data Book [23], buildings (both residential and commercial) consume approximately 40% of the energy in the U.S., with commercial buildings accounting for 18% of annual energy consumption (or 45% of energy used in building), a number that is continuously growing [24]. Berardu [25] reported that similar trends were found globally with a 30–40% average across the US, EU, and China. The magnitude of impact is related to: fuel type and consumption, energy codes, and regulations, along with building design types and configurations [25]. Charalambides and Wright [26], Oesterle et al. [27], and Silvestre et al. [28] identified the following building factors that contribute to energy usage: building type and use, aspect ratio, location and orientation, building opening, size, proportion, and temperature difference between the indoor and outdoor environments all affect the building energy demand [29]. These factors can be tied into the shape and configuration of the building enclosure selected for a project. Incropera [30] observed that while a building enclosure takes up approximately 36% of the total building area (exterior and interior via plan and elevation), it is responsible for 60–70% of building heat conduction [10,29]. Studies such as those by Ihm et al. [31] and Shehabi et al. [32] have found that by changing the enclosure performance from a daylighting standpoint, an estimated 30% in energy savings can be achieved. Johnson et al. [33] found that a good-performing enclosure can reduce total building peak demand by up to 14–15% [23,34].

Knowing the importance of the need for energy reduction and the role enclosures play, new innovative methods need to be studied and developed, while at the same time, designers need to be willing to adopt new practices. One solution that designers should be considering is DSFs [35–38]. From the perspective of this paper, presented here will be key modeling discussions on energy modeling techniques and considerations that designers should be doing based on sound research.

3. Study Methodology

This study utilized the principles of systematic literature review as defined by Pickering and Byrn [39] and Boell and Cezec-Kecmanovic [40]. The following steps were taken following Pickering and Byrn [39]'s recommendations. (1) Define topic, (2) identify keywords, (3) identify and search databases, (4) read and assess publications, then (5) produce and review summaries.

Using this approach, the core topics and keywords that were used at the start of this paper are listed in Table 1. These core areas and keywords allowed the researchers to find the appropriate papers for important materialities, configurations, and modeling assumptions useful for designers. American Society of Civil Engineering (ASCE) publication library, Elsevier Main Website, and Google Scholar websites were the three primary digital connection points for identifying the papers based on topics and keywords.

Table 1. Paper Selection Criteria for Identification of Articles.

Core Topic	Keywords
Double Skin Façade Modeling	• Energy Modeling • Thermal Modeling • Solar Modeling • Structural Modeling • Numerical Simulation
Double Skin Façade Performance	• Structural Performance • HVAC Performance • Double Skin Roofs • Sustainability • Energy performance • Operations and Maintenance
Double Skin Façade Types and Configuration	• Geometric Configurations • Vertical Skins • Mullion Configurations • Structural Configurations • Double Skin Configurations
Double Skin Façade Materials	• Façade Materials • Glazing • Mullions • Glazing Coatings • Double Skin Composition

4. DSF System Types and Configurations

Due to the integrated multi-disciplinary nature of DSFs, several configurations are possible to build depending on the governing design requirements [2,28,38]. DSF systems vary from project to project due to: unique features for each design, complexity of the climate, expectations and needs for the DSF space, mechanical performance, structural support, etc. [1,16,41–43]. While this uniqueness creates difficulty in categorizing designs, previous researchers have tried to find a typology that can reflect key characteristics of DSF systems. Many different designers and researchers have attempted different formats to classify the typologies, including types of layers and configurations, verticality of the skin cavity, the way air enters and leaves the cavity, etc.

Arons [1] established a descriptive method that simplifies the functional understanding of DFS systems by using two primary identifiers and five secondary identifiers. The two primary identifiers that distinguish the types of façades by their design purposes and how they function include airflow pattern and building height [1,2]. While the airflow pattern describes the air movement into and out of the cavity, the building height indicates the main purpose of using a double-skin façade on a certain building. The five secondary identifiers consist of other characteristics that separate one façade from the others and include the following: layering composition, depth between layers, cavity width and height, and operation method [1,6,15].

From a cavity perspective (space between the two skins), Compagno [43] and Knaack et al. [42] developed a "conceptual" typology to describe the shape and volume of the cavity. From there, they further refined several key functionalities, benefits, and challenges with these types of DSFs. Table 2 provides a breakdown of seven typologies, which consider both the vertical connection of the space (single for multiple connected floors) and the horizontal connection around the building. These seven typologies are largely governed by architectural visions and constraints, but equally important is how the air is utilized in these from a mechanical perspective. Representative typology schematics are provided (Figure 1) based on the referenced documents to illustrate key aspects of the types listed in Table 2.

Table 2. DSF Cavity Typology Configurations.

Typology	Key Features	Reference
Building-high double-skin	• Vertical airflow is not restricted throughout the height. • Air inlet is usually located near the bottom of the building. • This type of DSF is not suitable for natural ventilation, as the ventilation rate is not balanced throughout the building. • Fire protection and noise transmission between floors are a concern.	[7,41,44,45]
Story-high double-skin	• Vertical airflow is restricted to one floor. • Horizontal airflow is not restricted. • Air inlets and outlets are located at the bottom and top of each floor. • This type of DSF enables natural ventilation and improves fire protection.	[7,27,44,45]
Box double-skin façade	• Airflow is restricted by vertical partitions on each floor and horizontal partitions at each box unit. • Natural ventilation and better sound insulation within the cavity can be achieved.	[7,41,44]
Shaft façade	• Combines story-high cavity and vertical building-high shafts. • Air flows into the story-high cavity through the inlets on each floor and converges at the vertical shafts. • Natural ventilation is made possible even with little airflow from outside due to buoyancy in the shaft.	[27,41,44]

Table 2. *Cont.*

Typology	Key Features	Reference
Louvers façade	• This type of façade is very similar to the building-high double-skin façade with the main difference being that the exterior skin of the louver façade is made of pivoting louvers, which are not completely airtight when closed.	[7,27,45]
Alternating façade	• Double-skin and single-skin areas alternate to achieve simplicity of single-skin façade and the buffering effect of DSFs. • In winter, cavity air heated by the sun enters the building through double-skin parts of the façade, thus heating up the building. • In summer, single-skin parts of the façade ventilate to counteract the buffering effect from double-skin parts.	[7,46]
Integrated façade	• Integrated façade that is often called 'modular façade' or 'hybrid façade' generally refers to DSFs, which consists of functions other than ventilation such as air-conditioning and lighting.	[7,26,46]

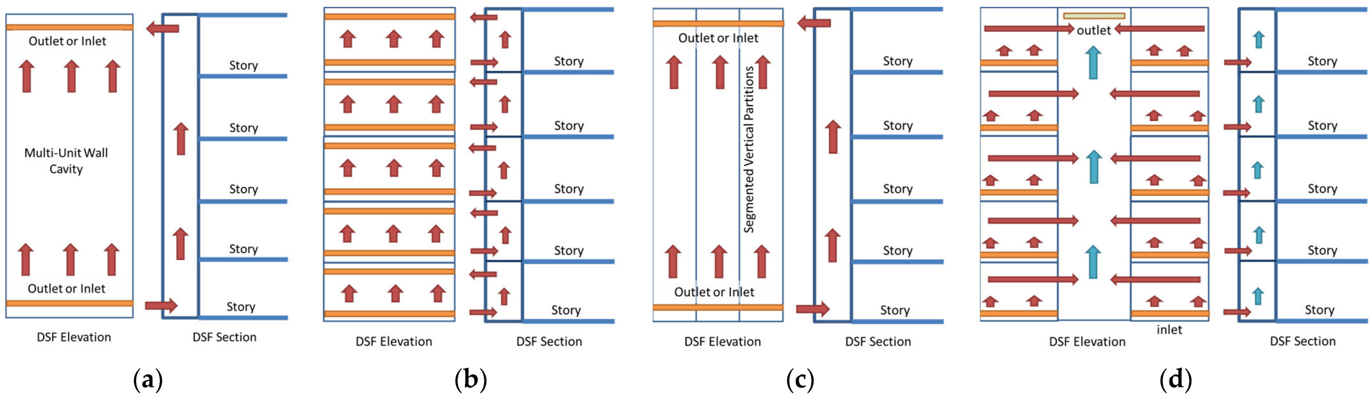


Figure 1. Representative DSF Cavity Configurations: (**a**) Building High Configuration; (**b**) Story High Configuration; (**c**) Box Configuration; (**d**) Shaft Configuration.

The types of ventilation designed for within a DSF include natural ventilation, mechanical ventilation, and hybrid ventilation [44]. Hybrid ventilation is a combination of natural and mechanical ventilation, while natural ventilation is used as much as possible until natural forces are inadequate to yield the desired performance. Natural ventilation is a combined result of stack effect and wind pressure. Mechanical ventilation is driven by powered air circulating devices. Table 3 lists design attributes that each type of DSF has in regards to ventilation type while Figure 2 provides simple schematics of how each ventilation type is established.

Table 3. Ventilation Design Attributes.

Attribute	Summary of Features	Possible Locations
Outdoor air curtain	Air introduced into the cavity comes from the outside and is immediately rejected toward the outside.	Forms an air curtain enveloping the outside façade layer.
Indoor air curtain	Air comes from the inside of the room and is returned to the inside of the room or via the ventilation system.	Forms an air curtain enveloping the inside façade layer.

Table 3. *Cont.*

Attribute	Summary of Features	Possible Locations
Air supply	Ventilation of the façade is created with outdoor air. This air is then brought to the inside of the room or into the ventilation system.	These can be located at: • Top or bottom of the building • Top or bottom of each story • Top or bottom of each compartmentalized space
Air exhaust	Air comes from the inside of the room and is evacuated towards the outside thus making it possible to evacuate the air from the building.	These can be located at: • Top or bottom of the building • Top or bottom of each story • Top or bottom of each compartmentalized space
Buffer zone	An air-tight cavity forms a buffer zone between the inside and the outside, with no ventilation of the cavity being possible.	Any layer: • Outside of the DSF • Inside of the DSF • Within the DSF

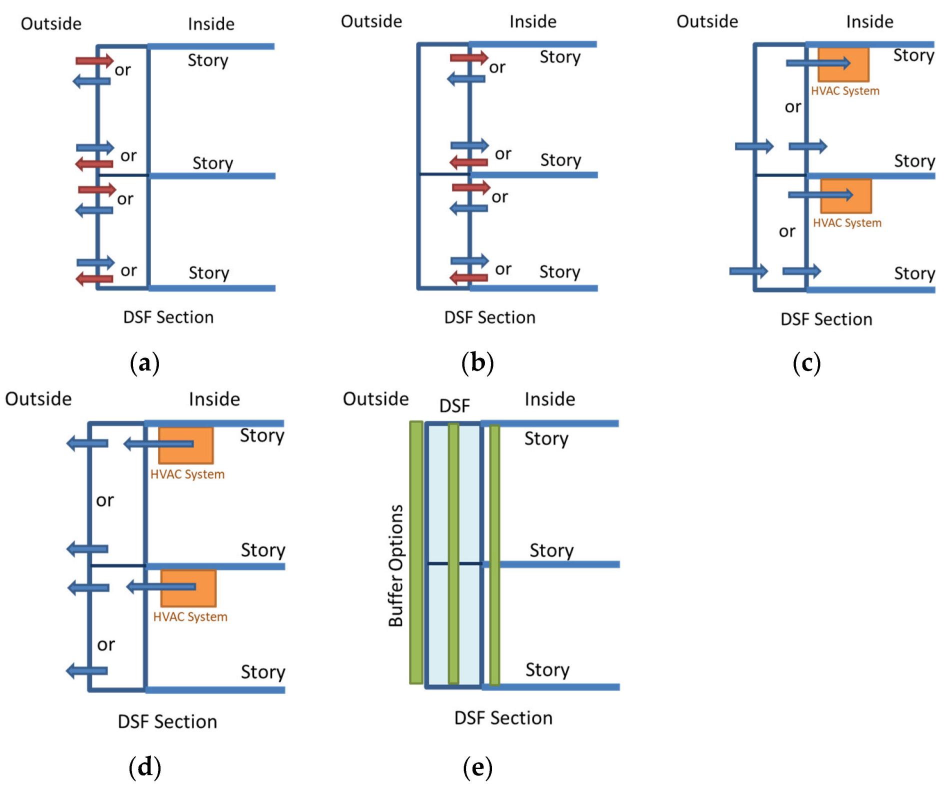


Figure 2. Representative DSF Ventilation Configurations: (**a**) Outdoor Air Curtain Configuration; (**b**) Indoor Air Curtain Configuration; (**c**) Air Supply Configuration; (**d**) Air Exhaust Configuration; (**e**) Buffer Zone Configuration.

In expanding upon DSF configuration typologies, Lang and Herzog [7], Boake, et al. [47], and Saelen [9] developed a set of defining characteristics to subdivide the typologies of airflow pattern functionality. The typology includes classifications and sub-classifications [1] as follows: airflow intake and exit points (both top and bottom and inside and outside), buffer zones, direction of air travel, type of air movement (generation), façade compartmentalization, and air driving force (mechanical vs. natural ventilation). Loncour et al. [45] and Gelesz and Reith [41] improved upon the airflow methodology by incorporating the types of ventilation, partitioning, and ventilation modes. These airflow pattern typologies are listed in Table 4. Partitioning refers to the pattern of the physical division of cavity space.

Figure 3 provides a more visual representation of how the different configurations can be mixed to complement Table 4.

Table 4. DSF System Ventilation Mode Typologies (adapted from Gelesz and Reith [41]).

Ventilation Mode		**Mechanically Ventilated Exhaust–Air Systems**	**Non-Ventilated Buffer Systems**	**Partly or Fully Naturally Ventilated**
Construction type \ Operation Mode		indoor air curtain (air exhaust)	buffer zone	outdoor air curtain air supply air exhaust (buffer zone)
Cavity Typology Configurations	vertically and horizontally partitioned	exhaust–air façade	buffer façade	box-type window façade
	horizontally partitioned			corridor façade
	multi-story	multi-story exhaust–air façade		multi-story DSF
	mixed partitioning mode	-	-	shaft-box-type façade

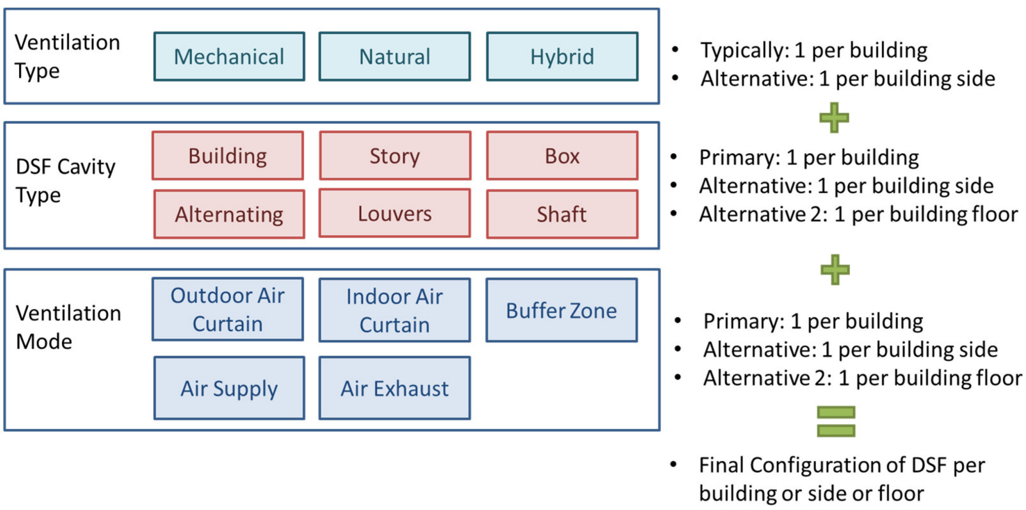


Figure 3. Possible Combinations of Different DSF Configurations.

Designer Takeaways on Types and Configurations

Early in the design phase of the building (even before the building enclosure is finalized), designers need to consider DSFs. The reason for this is that if a DSF is possible, the geometric identity of the building will be impacted. At the same time, designers need to carefully study the different DSF system types and configurations presented here in Section 4, specifically Tables 2–4. Within the types, designers need to study the architectural impact of the geometry (plan, section, and in 3D) to ensure there is a cohesive design aesthetic while concurrently working with other engineering disciplines to ensure that the cavity is engineered correctly to enhance the building performance. Table 5 provides representative multi-disciplinary considerations when designing DSF Types.

Table 5. Multi-disciplinary Consideration Takeaways of DSF Configurations.

Core DSF Configuration Attribute	Disciplines Involves	Considerations to Review
Ventilation Typologies	• Primary: Mechanical HVAC and Energy Engineers • Secondary: Architecture; Electrical Engineers; Owner (operations); Construction.	• Aesthetics of the ventilation system. • HVAC and energy performance. • Operations and maintenance of the system (ease of use, repair, and replacement). • Constructability and cost impact.
Cavity Typologies	• Primary: Architecture; Mechanical HVAC and Energy Engineers • Secondary: Structural Engineers; Owner (operations); Construction.	• Aesthetics • Impact on mechanical heating and cooling. • Impact on daylighting. • Structural support and loading. • Maintenance of the system (cleaning, repair, and replacement). • Constructability and cost impact.
Geometric Typologies	• Primary: Architecture; Structural Engineers; Mechanical HVAC and Energy Engineers • Secondary: Owner (operations); Construction.	• Aesthetics • Structural support and loading. • Impact on mechanical heating and cooling. • Impact on daylighting. • Maintenance of the system (cleaning, repair, and replacement). • Constructability and cost impact.

5. DSF Glazing

The material composition of DSF systems can vary from case to case, but such systems usually consist of these basic components: exterior glazing, interior glazing support mullions, structural attachments, and shading devices [22,41]. Kallioniemi [48] talks about common materials that are typically used in glass–steel facades including glass, steel, stainless steel, and aluminum. When choosing a type of glass, thermal insulation, light transmittance, solar energy transmittance, fire resistance, safety, and appearance should be taken into account [48,49]. To better design DSF wall systems for buildings, designers need to consider the types of glazing, the characteristics of the glazing units within a DSF, and the structural properties of the glazing, as discussed in the following sub-sections.

5.1. Glazing Types

Glazing is a versatile construction material made most commonly of glass [50,51]. Glazing is typically the weakest energy performance link of a building [34,52]. Despite extensive developments in building materials for suitable energy efficiency, glazing as a whole still underperforms holistically compared to other envelope/cladding components [53]. Criteria that may be more important for the selection of when or if glazing should be used and the type of glazing to use include the following: energy efficiency, sustainability, durability, maintenance, fire resistance, noise control, visual appearance, and structural performance under natural disasters [54,55]. Glazing has the ability to provide advantages such as increasing natural daylight, but has a tradeoff on heating or cooling demands.

The choice of the glazing material can reduce the solar heat gain component in summer and also heat loss in winter [49,56]. Currently, there is a broad range of different technologies that could be implemented to improve fenestration energy performance (Table 6) [49]. Several technologies rely on coatings to reduce the emittance of the glazing, while other products use “honeycomb”-like fill layers between glazing layers that improve thermal insulation. In addition, other products use polycarbonate or similar materials toward achieving improved performance [57]. Thermochromic glazing systems are considered intelligent glazing systems [58]. New technologies are being developed with concepts such as: wavelength selective coatings, transparent insulation materials, prismatic elements, and variable shading devices [49,59,60].

Table 6. Available Glazing Technologies (adapted from Ariosto et al. [49]).

Glazing Class	Glazing Sub-Class	Attributes
Unitized Fill Materials	Gases	Utilization of gas to suppress both convection and conduction behavior between the unitized lite panes.
	Aerogel	A silica-based lightweight material that is translucent in makeup with high thermal insulation characteristics incorporated into the system via a granular form.
Compartmentalized Systems	Slat Structure	Reduces conduction within the glazing airspace by dividing it into smaller sections.
	Multi-wall	Systems composed of a polycarbonate sheet or membrane that incorporates complex cellular structures.
	Honeycombed	Utilize a honeycombed layer arrangement placed between glass lites.
Spectrally Selective Systems	Films	A monolithic or IUG system with a spectrally selective film suspended between the two lites or adhered to a lite.
	Tints	Products that are applied directly to the glazing reduce the level of transparency of glazing as a means of reducing solar heat gain.
	Coatings	Products that are applied directly to the glazing to control solar heat gain by limiting those wavelengths of light that are allowed to pass through.
Specialty Glazing	Photochromic	Products that regulate a passive transition from clear to tinted appearance based on the amount and intensity of light striking.
	Thermochromic	Products that regulate a passive transition from clear to tinted appearance based on surface temperature.
	Liquid Crystal Devices	Liquid crystals that when introduced to current change from random orients (opaque) to align crystals (clear view).
	Electrochromatic	A coating on the glazing that when varying the amount of current through varies the degree of tint in the window.
	Gasochromic	A glass-filled lager that relies on a diluted hydrogen gas to cause the color change when exposed to current.

Glazing products fall into two categories: Transparent and Translucent Systems [49,56]. There is potential for the use of advanced window systems such as switchable electrochromic or gas chromic windows in reducing the overall energy load [59,61]. Transparent systems provide a high level of visual transparency, but typically result in broader heat swings with higher direct sunlight glare. In contrast, translucent systems offer limited outside views, yet usually generate superior light diffusion including a more stable thermal performance.

From a more high-tech approach, chromogenic materials are a class of 'smart' glazing to modify the incoming visible light and solar energy in buildings as well as for other see-through applications [57,62]. According to Piccolo et al. [63] electrochromic (EC) technology is able to regulate radiant energy through the windows by their optical transmittance under low electrical voltage [57,64,65]. Pierucci et al. [66] describe thermochromic (TC) windows as passive glazing that regulates daylight and solar heat gains through windows [57]. Photovoltachromics (PVCCs) can be considered the natural technological evolution of electrochromic and photo electrochromic glazing [57,66]. PVCCs are multi-functional smart glazing that allow electric generation and smart modulation of transmittance, reducing undesired solar gains and maximizing daylighting use indoors. Semi-transparent photovoltaic (STPV) windows that admit daylight into space can also generate electricity [67]. Silica aerogel is a new type of building energy-efficient material owing to ultra-low thermal conductivity, yet it has a lower visual transmittance performance due to its slightly blue hue tone [68–70].

The performance of each class (Table 6) is not directly comparable when looking at multiple discipline attributes. As such, the pros and cons of each glazing product must be measured with the building's requirements. Blanc et al. [71] estimated that the widespread use of advanced glazing technologies will be limited as long as the issues of high initial costs and lack of technical expertise to engineer the products for mass production are not addressed.

5.2. Structural Glazing and Support Materials

Given that glass is a brittle material, catastrophic failure without noticeable elastic deformations can occur. As a result, flexible or absorbing materials are typically added between the glass and support in traditional construction. Several types of strengthened glass have been developed to counter the brittleness of glass such as tempered glass, laminated glass, and wired glass [72]. Tempered glass types (i.e., Heat-strengthened, Fully-tempered) are heat-treated to create surface compression so that ultimate tensile and bending strengths as well as thermal fatigue resistance of the panel increase [73,74]. Laminated glass is produced by inserting a layer of polyvinyl butyral (PVB) sheet between two glass panes, which can normally be annealed, heat-strengthened, or fully-tempered (toughened) glass [72,73]. Here, the laminated PVB interlayer catches the glass shards if the pane breaks, while also providing a possible mechanism for applying lighting performance coatings. From a structural perspective, glazing technology is also evolving in the areas of: structural sealant of glazing panels [75], seismic racking performance of glazing [76], dry-glazed mullion pockets [77], impact resistance of glazing [78], and blast performance of glazing [79].

The common materials used for the DSF supporting structure include [2,10,76,80]: painted steel, stainless steel, aluminum, hot galvanized steel, and weathering steel. Aluminum is long-lasting, light, and corrosion resistant, but has low strength and high thermal expansion. The majority share of building enclosures in today's market are made from extruded aluminum sections, which are either stick built or unitized [2]. With its high strength-to-weight ratio, steel has advantages but requires additional protection against corrosion [80]. Stainless steel does not corrode easily, resulting in a longer life span, but it is significantly more expensive than regular steel and aluminum while also having a sizable difference (3-4x) to that of glass. The three basic types of stainless steel used in curtain walls are [80]: martensitic, ferritic, and austenitic; among which austenitic steel is the most widely used.

5.3. Glazing Properties for Design

Citherlet et al. [81] indicate that three main performance parameters need to be considered when specifying an enclosure system: the thermal U-factor for the entire enclosure, then both the Solar Heat Gain Coefficient (SHGC) and the Visual Transmittance (Tvis) for the glazing [76]. Solar Heat Gain Coefficient (SHGC) measures the amount of incident solar heat gain transmitted through the system/material and varies from 0 (no solar gain transmitted) to 1 (solar gain completely transmitted) [60]. Visual Transmittance (Tvis) describes the visible portion of the solar spectrum (in percentage) that is transmitted through glazing. A Tvis of one indicates that all of the visible light is transmitted, while a Tvis of zero means no transmission of visible light. Ariosto et al. [49] and [57] found that the primary challenge of specifying glazing comes from weighing the importance of and tradeoffs of each interrelated value regardless of the building enclosure type. Adjustments in U-factor and SHGC often impact the degree of transparency.

5.4. Designer Takeaways on Glazing

Knowing several key attributes to glazing, both in general and relative to DSFs, designers need to consider which glazing they will need for their project. As the glazing is a material that will be in layers, designers have a slight advantage with DSFs, which can be tailored more at a layer level, whereas with other façade systems, a single layer must do it all, in terms of performance. That said, glazing still remains multi-disciplinary as it is at the center of the DSF system. Table 7 provides several key insights into DSF glazing from a multi-disciplinary performance standpoint. Design and construction teams must carefully create solutions, simulate them, and then evaluate which is best for that project.

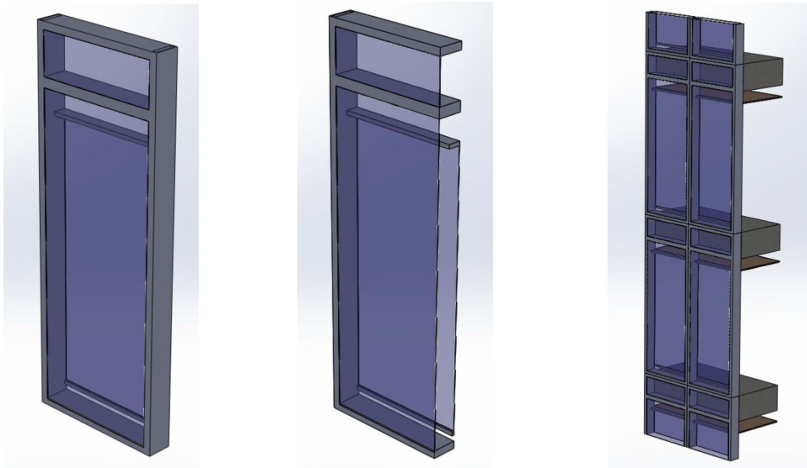
Table 7. Multi-disciplinary Consideration Takeaways of Glazing.

DSF Glazing Attribute Class	Disciplines Involves	Considerations to Review
Glazing Material	• Primary: Architecture; Mechanical HVAC and Energy Engineers, Lighting Designers. • Secondary: Structural Engineers; Owner (operations); Construction.	• Aesthetics of the glazing (color and shape). • Glazing finishes. • Availability of the material. • Durability and lifespan of the material. • Cost of the material. • Visibility through the material.
Glazing Layers	• Primary: Architecture; Mechanical HVAC and Energy Engineers, Lighting Designers. • Secondary: Structural Engineers; Owner (operations); Construction.	• Mixing of the aesthetics of the layers. • Impact on mechanical heating and cooling performance in how behavior crosses the layers. • Impact on daylighting and shading. • Glazing performance of each level. • Maintenance of the system (cleaning, repair, and replacement). • Constructability and cost impact.
Glazing Performance	• Primary: Structural Engineers; Mechanical HVAC and Energy Engineers; Lighting Designers. • Secondary: Architecture; Owner (operations); Construction.	• Thermal resistance. • Visual transmission • Incident solar heat gain • Structural impact resistance • Structural pressure resistance

6. DSF Structural Support and Construction Assembly

6.1. DSF Unitized Composition

With recent advancements in the technology of prefabricated/unitized façade systems, there is a greater tendency for architects to choose unitized DSF systems, which are not only lower in initial investment, but also easier to install and repair [82,83]. For each unitized DSF panel, the top horizontal transom is secured to the floor slab. Below the top transom and above the ventilation ductwork, a second horizontal transom is normally located (Figure 4) [84]. These two members secure the exterior glass skin. With only one layer of façade, this part of the unitized panel limits the height of the airflow in the cavity to one story. The lower transom secures the top of the exterior skin below it. Below the ventilation ductwork, at around the ceiling height, often a narrower horizontal member attaches the top of the interior skin and the sun shading devices while allowing the air to flow through the cavity into the ventilation duct. The very bottom horizontal member of the panel, which sits on top of the panel below, supports the bottom of the exterior glazing. Above that, a small horizontal device supports the end of the interior skin [82,84]. A small gap between the two members at the bottom enables airflow into the cavity.



(**a**) (**b**) (**c**)

Figure 4. Unitized DSF 3D rendering: (**a**) Single Unitized Unit; (**b**) a cross section of a unit showing glazing and mullion composition; (**c**) Series of units in a curtain wall.

All horizontal members except the very top and bottom ones are solely supported by two vertical members. Loads on these members such as self-weight, weight of interior glass, and sun shading devices are transferred to the top and bottom members by the vertical components [85]. Eventually, the weight of the whole panel is transferred to the bearings on the building's primary structures through the top and bottom members. Each panel also has built-in connecting mechanisms on each side for ease of installation and stability [82,86]. Furthermore, the narrow air cavity (particularly found in unitized DSF panels) eliminates the need for horizontal members to function as service platforms. However, it does make cleaning more challenging.

6.2. DSF Support Structure Typologies

Uuttu [8] thoroughly describes the types of DSF support structures. Here the structure can be separated into three sub-types [1,2,8]: (1) primary structure that consists of load-bearing components such as columns, walls, floors, and bracings; (2) secondary structure that is not part of the load-bearing system such as roof structures and façade elements; and (3) tertiary structure that is part of the secondary structure without the function of stabilizing the secondary structure such as window within a façade structure. The support structures in DSFs (secondary structure) can be categorized into three types [8,16,87]: (1) cantilever bracket structure, (2) suspended structure, and (3) frame structure. The cantilever bracket structure, as its name suggests, utilizes cantilever brackets to connect the outer skin to the primary load-bearing structure to transfer the dead load of glass, service live load, and wind load. The cantilever bracket can be connected to the intermediate floor or column with a cleat or by extending the cantilever bracket to the floor.

In the suspension structural configuration, the mullions and transoms hold glass panels that are suspended at the end of the two tension rods/flat bars, one horizontal and one diagonal [5]. Glass panels can be mounted to the façade support structure with plates applying pressure, structural sealant, or point fixing supports [76]. When using pressure plates in dry-glazed systems, glass panels sit on (rubber) setting blocks and are secured by the pressure exerted by the glazing pressure plates [72,77]. When structural sealant is used, glass panels are secured by adhesive (e.g., structural silicone) applied between the glass and the supporting structure. Point fixing requires drilling holes in the glass panels, which are used to place the mounting devices [76].

The structural design of the system becomes critical due to its complexity. DSF systems using cantilever beams or suspension rods to connect the two faces are expected to experience amplified vertical acceleration during an earthquake [74,83]. Exterior glazing spanning from floor to floor needs to be designed for wind loads and seismic-induced inter-story drifts [75]. One concern is that glazing would be supported by unconventional and custom framing extending from the main structural frame, requiring special attention to the gravity support system for DSF systems, which varies from case to case, and also the load path continuity in such systems [76,82]. When designing DSFs, the difference in thermal expansion of different materials should be taken into account [80]. For example, expansion joints and sliding connections may be needed on the supporting structure, and enough expansion margin may be required between the glass panel and support.

6.3. Designer Takeaways on Construction and Structural

While the geometric and cavity layer composite are paramount to DSF performance as well as general feasibility, other considerations such as structural support and construction assembly should be reviewed to ensure those attributes fit within the larger context. As it was discussed earlier in Section 6.1, the composite configuration of the DSF, whether it be stick or unitized, and how these components are attached to the structure, need to be coordinated. Within these two domains, Table 8 provides context into which designers need to review the construction and structure while looking for specific areas of interest that may impact performance.

Table 8. Structural and Construction Takeaway cross considerations.

DSF Domain	Disciplines Impacted	Considerations to Review
Construction Assembly	• Primary: Architecture; Construction • Secondary: Structural Engineers; Owner (operations); Mechanical HVAC and Energy Engineers; Lighting Designers.	• Performance of the Unitized or stick-built joints for water and air infiltration. • Weight impact on the structure of the Units • Complexity and available labor to build the assembly. • Mockup testing of the assembly. • Speed of construction and constructability.
Structural Support	• Primary: Structural Engineers; Architecture; Construction • Secondary: Mechanical HVAC and Energy Engineers, Lighting Designers.	• Attachment impact on other systems (invasion into the architectural spaces). • Attachment impact on thermal breaks. • Visual aesthetics of the structural supports of the layers.

7. DSF Research Threads

Over the last 15 years, many studies have looked into DSFs from performance, configuration, and discipline-focused research. Table 9 provides a summary of representative key research studies that have advanced DSF knowledge. These six main areas span the different key disciplines that contribute to DSF designs.

Research has examined energy performance, daylighting and shading on DSF for better building performance [88–91]. Including these domains, other studies have looked into human comfort and ventilation performance to try to find material and system compositions that best support mechanical systems [14,92–94]. Other studies built upon this work to see if configurations were impacted significantly by climatic zones and how designs can best be altered [95–97]. In all of these studies, the research has led to recommendations on how to properly model and select configurations for DSFs. These results allow designers to have better insights into selecting configurations previously mentioned. Unlike DSFs in cold climate regions where DSFs are often used for the buffering effect caused by the sun heating up trapped air to reduce heating demand, DSFs in warm climate regions are often designed to include shading devices and operable windows to reduce solar heat gain as well as enable natural ventilation to lower energy consumption and improve occupant comfort [90–92,98].

Other trends in the applications of DSF include decision making based on life cycle assessment (payback period) [99], renovation of older buildings for improved performance and modern appearance [100,101], and innovation in the façade structural system for transparency and aesthetics [102]. Selkowitz [10] cautions that for such DSF systems, there remain difficulties in achieving and proving research benefits as DSFs pose tremendous challenges to the design and manufacturing communities. This is due to the number of factors involved as well as the complexity of each factor [103]. Some of the claimed advantages lack proof of solid evidence and may be counteracting each other, such as natural ventilation versus acoustical performance [11].

Table 9. Summary of Key DSF Research Trends.

Discipline Classification	Research Thrusts	Reference
Solar effects	• DSF effects on solar heat gain with different configurations to key parameters. • Solar shading effects on solar heat gain across the different layers. • The usage of plants over solar shade for heat and light control.	[88] [26] [89]
Ventilation	• Solar chimney effects and configuration to improve energy performance. • Gap pressures impacts on DSF performance. • Shading elements impact to lower cooling demand. • Automated operational strategies of DSFs in high rises. • Root causes of performance limitations in regards to thermal discomfort, condensation, and overheating in DSFs.	[93] [97] [14] [91,98] [103]
Sustainability	• Glazing layer numbers impact on energy consumption. • Life cycle energy impact of different configurations via Life cycle analyses (LCA).	[94] [10,28]
Human Comfort	• Dynamic buffer zones (DBZ) to combat condensation and freeze–thaw problems raised by the requirement of higher indoor humidity levels for human comfort.	[104]
Safety	• Smoke mitigation and movement control between multi-story layers.	[105]
Structural	• DSFs as structural motion control devices for tall buildings to reduce human discomfort due to excess lateral drift. • Mechanical and environmental load impacts on differential movements. • Panelized High-Performance Green Hybrid Fiber-Reinforced Concrete (HP-G-HyFRC) to increase resiliency. • DSF systems performance against blast pressures.	[15,106] [46,107] [108] [109]

From the safety and structural perspective of DSFs, research thrusts have looked into using DSFs as a way to actively and passively control the building. Smoke mitigation was studied because certain DSF configurations can provide paths for fire and harmful smoke to travel [105]. Building motion from a discomfort as well as a structural and mechanical performance level/perspective has been studied to determine if DSFs can aid in these issues for tall buildings [15,106,107]. Other multi-disciplinary studies have looked at the materiality of DSFs in relation to sustainability [107,108]. These are important areas of research as designers are required to study more than just energy; for example, embodied carbon is another design factor. Another thrust in recent years has been on the enhanced performance of DSFs against aggressive threats such as terroristic and accidental incidents [109]. The use of DSF systems supports the mandate to build resilient provisions for occupant safety.

8. DSF Modeling

While DSFs have significant potential, the lack of reliable performance and operation data still needs to be addressed [96,110]. Accordingly, researchers have utilized computational tools for DSF system evaluations [91,111]. Simulation studies to date have looked at DSF behavior such as: shading elements in the cavity (including plants) [89], airflow analysis [112,113], fire and smoke spreading issues [105,114], and natural ventilation [93,95]. Numerous studies about DSF performance have revealed the use of specialized methods such as airflow networks and Computational Fluid Dynamics (CFD) simulations for different analyses [95,115]. To help guide modelers in what parameters they may want to consider and what software they may want to utilize, a summary of different considerations is provided in this section with respect to thermal and ventilation modeling, energy modeling, structural modeling, and life cycle assessment modeling.

8.1. Thermal, Ventilation, and Energy Modeling

Numerical models are becoming essential in the design phase of these complex DSF systems. Discussions here will focus on a variety of modeling methodologies, software packages, and parameters to consider thermal, ventilation, and energy performance. Discussion of the modeling methods in this paper is intended to provide a view on the state-of-the-art advancement in this area. The literature reviewed can be grouped into four broad distinct classes with respect to their complexity:

- Empirical correlations and simple analytical models;
- Combined thermal and airflow networks models;
- Intermediate explicit models;
- Computational fluid dynamics (CFD) models.

8.1.1. Energy and Ventilation Modeling Methodologies

To date, DSF modeling has included studies such as De Gracia et al. [116] with a focus on aspects such as analytical and lumped models, non-dimensional analysis, airflow network modeling, control volume approach, zonal approach, numerical solution of partial differential equations, computational fluid dynamics (CFD), and integration between building energy and airflow models. Balocco [117] used non-dimensional analysis (NDA), which can be used to determine the thermal performance of a natural and mechanical ventilated DSFs [118]. Hensen et al. [111] stated that the airflow network method supported by ASHRAE treats every building component and relevant HVAC system as a network of nodes representing rooms, parts of rooms, and system components, with internodal connections. Saelens et al. [119] and [11] used the control volume method (CVM) to study the annual energy performance with different multiple-skin facades in TRNSYS. Jiru and Haghighat [120] developed the zonal modeling approach (ZMA) to evaluate the thermal performance of a DSF with Venetian blinds. ZMA is an intermediate approach mixing the lumped modeling and CFD. Manz and Frank [92] developed spectral optical and a CFD model hybrid model that looked at air movement with the impact of a radiation analysis. Xaman et al. [121] utilized CFD modeling to numerically study the fluid flow and heat transfer by natural convection in a DSF using both laminar and turbulent models. Zollner et al. [122] modeled the effects of external air circulated by both supply and exhaust naturally ventilated DSFs.

8.1.2. Hygrothermal Modeling of DSF Systems

The hygrothermal behavior of building envelopes (facades and roofs) has been the subject of numerous studies [123–128] where the primary focus is looking at the behavior of surface and interstitial condensation phenomena. The models may take into account a single component of the building envelope in detail or a multi-zonal building [129], where the heat, air, and moisture (HAM) models combine the flow equations with the mass and energy balances [130]. The real-life performance of building facades can be modeled using an hourly based dynamic heat and moisture simulation [129,130]. Critical to hygrothermal analyses are the boundary conditions. Designers must decide upon temperature and relative humidity measurements from both the internal and external sides of the structure, weather data (solar radiation, precipitation, wind speed, and direction) from a nearby weather station, and time intervals (within a day and for how many days) for the study. Besides environmental data, details on the façade construction and material composite are needed.

At varying levels of complexity, there are nine commercial programs for hygrothermal analysis: 1D-HAM, Sim2000, DELPHIN, GLASTA, hygIRC-1D, IDA-ICE, MATCH, MOISTURE-EXPERT, and WUFI; and the five freeware programs: EMPTIED, HAM-Lab, HAM-Tools, MOIST, and UMIDUS [131–135]. Table 10 provides a summary of commonly available hygrothermal modeling packages along with their key attributes. While none are specifically designed for DSF applications, the referenced literature has shown their suitability for DSF applications.

Both simulation models are frequently used in literature with studies by Alsaad et al. [136]; Salata et al. [137], and Sontag et al. [138], all conducted using the listed software, providing validation for their applications of complex and double-skin facades. In other DSF applications, Ciampi et al. [139] and Charde and Guptra [140] developed an analytical models for naturally ventilated roofs to predict thermal loads to evaluate the energy-saving potential. Gagliano et al. [141] and Li et al. [142] used the CFD analysis in order to evaluate the thermal performance of naturally ventilated roofs, varying different influencing parameters both geometric and climate. Wakili et al. [143] studied roof facades using numerical analysis with steady-state and transient conditions using the Glaser method [144] and the WUFI simulation software, respectively [144–146].

Table 10. Key hygrothermal modeling software summary for package selection.

Software Package	Key Features	Reference
ENVI-Met	• Is a high-resolution meteorological model that can simulate the interaction between urban geometry, vegetation, and the outdoor environment. • Is able to calculate the influence of the plants on air temperature, velocity, relative humidity, wind direction, and radiation of the living wall.	[133,134,138]
Delphin	• Is a simulation package for coupled heat and moisture transport in capillary porous building materials. • Is capable of traditional hygrothermal simulations.	[133,135]
WUFI	• A 1D heat and mass transfer numerical simulation tool. • Is based on finite volume method to perform dynamic hygrothermal simulations.	[131,132,144]
HAM-Tools	• Simulation of transfer processes related to building physics (heat, air, and moisture) transport in buildings and building components in operating conditions.	[131]

8.1.3. DSF Energy Modeling Software Platforms for Industry

Andelkovic et al. [147] and Lucchino et al. [148] have reported that in DSF energy performance research, many authors are using various total building simulation tools such as EnergyPlus, TRNSYS, ESP-r, BSim, TAS, etc., to conduct their studies, while some are matching them to experimental techniques. These building energy simulation (BES) tools have the potential to provide results that are meaningful to multiple stakeholders [149]. Loutzenhiser et al. [150] found that these tools are reliable when modeling conventional building envelope systems; however, DSF modeling with these BES tools is still a challenging task. The most popular BES tools used today are EnergyPlus [90], IDA–ICE, IES Virtual Environment, ESP-r, and TRNSYS [24,151–160]. Table 11 provide a summary of these representative industry software platforms and their key features that would be of interest to designers. While none are specifically designed for DSF applications, the referenced literature has shown their suitability for DSF applications.

Table 11. Key Energy Modeling Software summary for package selection.

Software Package	Key Features	Reference
EnergyPlus	• Is accurate to simulate the relationship between the airflow and transient heat transfer for multi-zone airflow conditions that are driven by outdoor wind, buoyancy, and forced air. • Pressure and airflow are based on AIRNET. • Provides modelers with a wide selection of different methods for calculating both exterior and interior heat transfer coefficients such as the TARP method [156], the MoWiTT method [157], and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) method [111].	[111,131,153–157]
IES Virtual Environment	• It is a commercial program where users cannot add simulation modules; instead, the airflow network approach is integrated into the software. • Uses a module called MacroFlo for zone modeling to study balance and inter-zone flow–pressure relationships.	[151,158,159]
ESP-r	• Uses a nodal network for airflow modeling and is integrated with the thermal model network. ESP-r follows the same approach adopted in EnergyPlus for ventilated cavities.	[90]
IDA-ICE	• Is an indoor climate and energy software package that can study thermal indoor climates as well as energy consumption. • Provides users with two different zone model capabilities, the detailed zone model with full Stefan–Boltzmann long-wave radiation and the simplified zone model for energy simulation. • Based on a building geometrical depiction. • Calculates energy balance dynamically taking into account climatic variations, which dynamically vary the time step as needed. • Modelers need to properly represent in the model the building geometry, construction, HVAC conditions, and internal heat loads. • Users have the ability to input measured climate and weather with respect to air temperature, relative humidity, wind direction and speed, direct normal radiation, and diffused radiation on a horizontal surface. • Includes multi-zone airflow model and can handle four different types of air flows. • Climate zone model is only available for rectangular box-shaped zones.	[160–168]
TRANSYS	• Is a platform developed by solar thermal systems with the capabilities to model multi-zone buildings. It is possible to define the thermal capacity of the air enclosure and additional heat capacity (i.e., blinds) within the model. • Considers the attached room to a DSF as a well-mixed thermal zone, and its bulk temperature is represented with one temperature. • Is coupled with a CFD model to receive an average inner pane surface temperature of a DSF as a boundary condition at each time step. • Ceiling, floor, and walls are modeled according to the ASHRAE transfer function approach, including provisions for windows.	[169,170]
CONTAM	• Is a multi-zone indoor air quality and ventilation analysis software designed to determine infiltration, exfiltration, and room-to-room airflows in building systems. • Can examine airflow driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by the indoor and outdoor air temperature differences.	[156,171,172]

8.1.4. Modeling Considerations and Parameters

According to Andelkovic et al. [147], when selecting a DSF modeling method, care needs to be taken to match the procedures with the results expected. Researchers such as Hensen et al. [111] found that early studies were conducted without measurement validation, but of course, now the modeling technology has evolved [110]. To achieve good simulation accuracy, Table 12 provides a list of key information, which is typically needed to build thermal, ventilation, and energy models of DSFs. To iteratively adjust the model for better performance understanding, parametric studies, sensitivity analysis, and experience from similar models should be used to obtain the most accurate results.

Table 12. Model Parameters to Capture for Energy Modeling.

Main Class	Information Needed to Build the Model
DSF Physical Configuration	• Boundary conditions of the cavity • Glazing type, locations, thickness, area • Dimensions of all constructive layers
DSF Performance Data	• Level of air infiltration • U-value • Transmittance • Thermo-physical properties
Mechanical Systems	• Existing HVAC systems performance and energy • Number of occupants • Interior design and operating temperatures
Electric Lighting System	• Lighting system effects • Automated shading systems • Lighting requirements
Environmental Data	• Levels of shadowing • Wind pressure data • Outdoor and indoor temps • Wind temperature, direction, and speed • Solar radiation

8.2. Structural Modeling of DSF

Another class of modeling for DSF is from the structural domain. Here engineers and designers need to create models that can properly support the DSF while also understanding the structural behavior. Structural modeling can lead designers to look at DSFs in several traditional and unique instances. Pipitone et al. [173] used models to evaluate the structural vibration performance of the DSF under different boundary conditions. Both Fu et al. [174] and Azad et al. [175,176] used modeling to study the DSF impact on inter-story drift as if the DSF was a tuned mass damper.

8.2.1. Software Packages Capable of DSF Modeling

Structural engineering computational capabilities have both enhanced and evolved dramatically since the adoption of computers in practice [177]. While many methods from decades ago still are valid and useful, new approaches and software platforms continue to be generated. Solnosky [178] documented that there is a natural progression of software and analytical method complexity as each phase of the design advances. There is a wide range of computational techniques used in structural engineering for structural analysis, from simplified approximations to the most advanced Finite Element Methods (FEM) [179].

For DSF modeling, the primary types of software adopted are those for commercial full building scale platforms such as SAP 2000, Etabs 9, and RISA 3D or software that is more robust and fundamental in the finite element domain such as Abaqus, ANSYS, and LS-DYNA. Compared to other more complex structural software, SAP2000 is often utilized for smaller structures or portions of a larger structure. These characteristics make SAP2000 an ideal choice for modeling double-skin façade systems. LS-DYNA can be used by modelers to conduct in-depth modeling studies in great detail [180,181]. Additionally, LS-DYNA can be used to simulate blast wave transmission, blast–structure interaction, and nonlinear large displacement behavior of DSFs [109,180].

8.2.2. Idealization of Supports

In order to construct models of DSF systems, the most critical information needed is as follows: (1) the way the two glass skin layers are connected; (2) the support mechanism to attach the DSF to the main structure; and (3) the nature of loading on the DSF. Idealization of each structure configuration (previously listed) needs to be established before the structure can be modeled. For a cantilever bracket structure (Figure 5a), the cantilever bracket that is the bearing part of the structure is connected to the intermediate floor using a moment connection. The other end of the cantilever bracket supports the glass framing with a simple connection. For suspended structures (Figure 5b), the bearing component consists of a horizontal rod or flat bar and a diagonal rod. The horizontal bar is simply supported at both ends, and the diagonal bar is also simply supported at both ends with one end connected to the horizontal bar. For frame structures (Figure 5c), the bearing part of the structure is a rectangular frame with the height matching the floor height. The vertical component is fixed supported at two ends by the horizontal components, which are fixed supported on the other end.

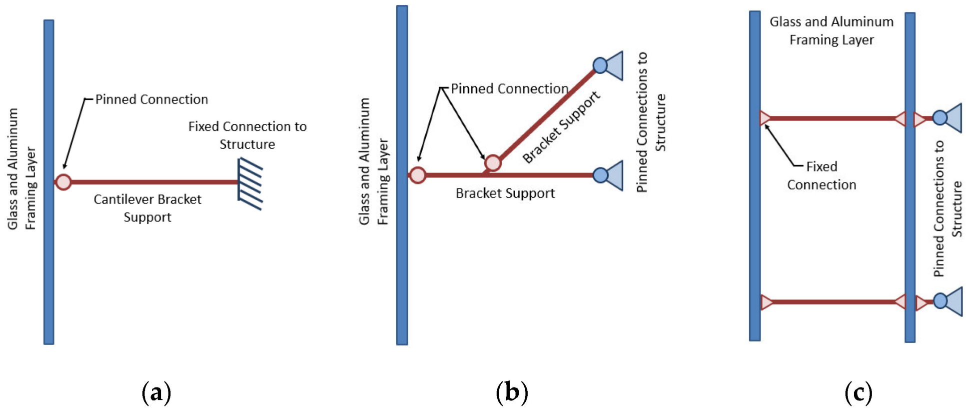


Figure 5. Support Mechanisms for DSF: (**a**) cantilever bracket; (**b**) suspended structure; (**c**) frame structure.

8.2.3. Loading Conditions

Conventional loading to consider includes gravity, wind, and seismic loads, as shown in Table 13. For DSF systems, gravity loads include dead loads, such as the weight of glass and steel framing, while the live load is present if there is a walking platform (catwalk) within the cavity (Figure 6). Here, a live load for a catwalk of 40 psf would be applicable. In terms of lateral loading, wind loading per ASCE 7 Chapter 30 Component and Cladding pressures should be used to properly determine the design loads for the glass, mullions, and connections. For seismic loading, ASCE 7 Chapter 13, which is focused on non-building structural loads, should be used.

Table 13. Loading Model Parameters for Structural Modeling.

Load Type	Item	Location in/on the Model	Note
Dead	Exterior glass	Automatically calculated and applied	Program: Modulus of Elasticity Program: Material Density
	Glass frame and connection—steel		
	Catwalk	Location 1 Figure 4	Depending on how it is modeled—line, point, or area loading
Live	Catwalk for maintenance access	Location 1 Figure 4	Depending on how it is modeled—line, point, or area loading
Wind	C&C wind pressure on exterior skin	Location 2 Figure 4	ASCE7-16 Chapter 30
Seismic	Seismic demand—horizontal—exterior glass and glass frame	Location 3 Figure 4	ASCE7-16 Equations 13.3-1, 13.3-2, and 13.3-3 For location 4, it can be horizontal in the plane of the model or out of plane of the model depending on connections.
	Seismic demand—horizontal—connection and catwalk	Location 4 Figure 4	
	Seismic demand—vertical—connection and catwalk	Location 5 Figure 4	ASCE7-16 13.3.1: ±0.2DDSWP
	Seismic demand—vertical—exterior glass and glass frame	Location 6 Figure 4	

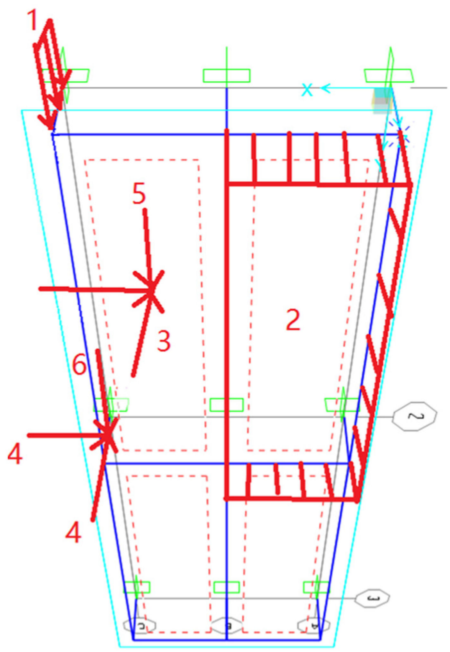


Figure 6. Representative SAP2000 model with locations of possible load applications. For descriptions of loading, please see Table 13.

8.2.4. Capturing Failure Mechanisms

There are four types of failure modes that can be anticipated for DSFs [78,79,182]. The first is the deformation of the glass framing under extreme loading conditions, which may cause glass fallout or breakage. The second failure mode is that the outer skin of the system may experience excessive in-plane and out-of-plane displacements due to wind and seismic loads, causing damage to the exterior skin or other components such as ventilation inlet and outlet devices [78]. The third failure mechanism can be the formation of plastic hinges on the connecting devices between the inner and outer skins due to the combined effect of gravity and seismic loads, causing instability in the façade supporting structure. Lastly, connections in the façade supporting structure may fail due to corrosion from water penetration or fatigue. These failure modes can occur independently or simultaneously with each other [76,79]. However, due to the uniqueness of connection design in each DSF application and the very detailed finite element modeling necessary to obtain meaningful results in such connections, the evaluation of connection failure is beyond the scope of this paper.

The first and second failure modes can be detected in the computer model by analyzing the displacement of certain joints. The third failure mode can be predicted if there is any point of stress concentration in the connecting member between the two skins. By analyzing the models for potential failures, structural engineers can obtain a better understanding of DSF systems' structural behavior and further studies such as mockup tests of DSF systems can lead to the development of more guidelines to prove the structural soundness of such systems.

8.3. LCA Modeling for DSF Designs

Alongside modeling for structural performance, a holistic approach is needed to evaluate embodied energy, operational energy, and recurring embodied energy resulting from maintenance [8] and for sustainability [108]. Designers may consider Life Cycle Analysis and embodied carbon as a way to appraise design performance [183]. Several studies with LCA have shown promise for DSF systems. Barbosa and Ip [18] found that design with the right glass layers can lead to reduced operational energy. Pomponi et al. [184] discuss that mixing timber framing with steel or aluminum framing in DSFs can lead to low-carbon refurbishments. The next section of the paper will discuss the common platforms available for modeling LCA and embodied carbon.

Software Packages to Calculate DSF LCA

Life Cycle Inventory (LCI) for the production of various materials can be calculated in several different ways [185]. While several tools exist to calculate LCA given different LCI [186–189], no software is explicit for DSF applications. That said, Table 14 provides a summary of available packages for designers to pick from. Besides those listed in Table 14, some energy and/or other design document software such as Energy Plus and COMFEN can be used to evaluate energy consumption and CO_2 emissions [157] of façades due to their built-in material calculators.

Table 14. Key LCA software summary for package selection.

Software Package	Key Features	Reference
SimaPro 8	• Robust LCI databases that provide accurate scientific cradle-to-grave information for building materials and products, transportation, and construction and demolition processes. • Impact assessment methods include: Characterization, Damage assessment, Normalization, Weighting, and Addition. • Shows modelers which substances are not included in the selected impact assessment method. • Currently, SimaPro includes six categories of methods: European, Global, North American, Single Issue, water Footprint, and Superseded.	[29,187]
GreenConcrete LCA tool	• This is a web-based Excel-formatted tool. • Accounts for supply-chain environmental impacts of each process in the production of concrete and its materials. • Considers environmental impacts of the production of concrete and its constituents (such as cement, aggregates, admixtures, and supplementary cementitious materials). • The supply chain impacts of each process during the production of concrete and its materials are evaluated. • Air emissions released from major processes (fuel pre-combustion, fuel combustion, electricity generation, transportation, and process-specific, e.g., calcination) that take place within the defined system boundary are considered.	[188]

Table 14. *Cont.*

Software Package	Key Features	Reference
Sphera LCA (GaBi)	• Creates a unit process to describe your specific situation's production chain. • Visual display of your model and results of your study to easily see performance. • User-defined variables and dependencies in your model to permit advanced modeling functionalities such as scenario management. • Provides a cradle-to-grave accounting of the energy and material flows into and out of the environment that is associated with producing a material, component, or assembly. • NREL's U.S. LCI Database integrated t into GaBi format.	[89,185]
OpenLCA	• Robust LCI databases that provide accurate scientific cradle-to-grave information for building materials and products, transportation, and construction and demolition processes. • Capable of running Monte Carlo simulations of multiple samples for each scenario with a defined uncertainty. • Data sources are assessed according to the following five independent characteristics: reliability, completeness, temporal correlation, geographic correlation, and further technological correlation. • Has built-in climate change impact category of impact assessment method ILCD 2011.	[29,186,187,190]
Athena Impact Estimator	• Provides cradle-to-grave implications in terms of Global Warming • Acidification, Human Health Respiratory Effects, Ozone Depletion, Photochemical Smog, Eutrophication, and Fossil Fuel Consumption. • Based on mid-point impact estimation methods developed by the US EPA and reported in their Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI, 2012 version). • Provide Green Globes and LEED v4 project level and comparison reports.	[29,186,187,191]

8.4. Designer and Modeler Takeaways on Computational Simulations of DSFs

Knowing the compositions, attributes, and materiality of DSFs, as discussed in Sections 3 and 4, designers must couple this knowledge with the simulation discussions presented here in Section 7. Models for structural, LCA, hygrothermal, and energy will be iteratively developed throughout the life cycle of design and even into early construction depending on the project delivery method. Often early studies set the tone for feasibility but more likely are simplistic proof of concept models. That said, if the configuration has never been tried before or has no reference for performance success, some firms will spend extra time building more complex models to provide designs that can actually work. Table 15 is created to show core multi-disciplinary considerations that need to be undertaken within each modeling subset. In conjunction with Table 15, Table 16 provides a starting checklist of key categories for each major simulation that may be conducted as part of a DSF design. This list can be filled out by the design team to alert them of the level of complexity the model should include along with when that simulation should be undertaken.

Table 15. Multi-disciplinary Modeling Considerations and Stakeholders.

Modeling Discipline	Core Multi-Disciplinary Considerations	Disciplines to Collaborate with	Simulation Complexity in the Design Stages
Structural	• Coordination of the construction sequence for loading • Architectural geometry to model/support and its location • Weights and materials to be modeled	Architecture, Mechanical HVAC, Construction	Modeling typically would be performed after the geometry is set for establishing the strategy to support. As the design progresses, the model complexity increases to fully understand behavior.

Table 15. *Cont.*

Modeling Discipline	Core Multi-Disciplinary Considerations	Disciplines to Collaborate with	Simulation Complexity in the Design Stages
LCA	• Material composition and quantities of the DSF • Location the materials are coming from for simulations	Architecture, Mechanical HVAC, Construction, Structural	Typically performed early in design to ensure the best LCA system is being reached. Often performed at the end of design to confirm LCA has been met.
Hygrothermal	• Architectural geometry to model/support and its location • Material properties to put into the model for thermal studies	Architecture, Mechanical HVAC, Energy, Structural	Often performed towards the later stages of design to confirm the performance of the system at a complex level. Could be performed early when generating configurations to ensure there are no major setbacks.
Thermal, Ventilation, and Energy	• Locations of each system within the DSF for base model generation • HVAC demand loads and set points for design performance • Lighting performance requirements	Architecture, Mechanical HVAC, Energy, Lighting	This will start out as a more simplistic model early in the design; to verify DSF is a good concept. As the design progresses, the complexity increases to see the impact on other engineered systems.

Table 16. Modeling Checklist of Items to Consider.

Modeling Discipline	Major Model Categories	Priority Level to Capture	Stage of Design to Consider
Structural	Supports	H M L NA	P SD CD CA
	Dimensional Coordinates (2D or 3D)	H M L NA	P SD CD CA
	Loading	H M L NA	P SD CD CA
	Material Behavior	H M L NA	P SD CD CA
	Analysis Capturing	H M L NA	P SD CD CA
	Design Features	H M L NA	P SD CD CA
LCA	Material Types	H M L NA	P SD CD CA
	Project Location	H M L NA	P SD CD CA
	Database of performance	H M L NA	P SD CD CA
	Material Location and Travel	H M L NA	P SD CD CA
Hygrothermal	Dimensional Coordinates (1D, 2D, or 3D)	H M L NA	P SD CD CA
	Physical Configuration of Materials	H M L NA	P SD CD CA
	Material Properties	H M L NA	P SD CD CA
	Sophistication of Analysis	H M L NA	P SD CD CA
Thermal, Ventilation, and Energy	DSF Physical Configuration	H M L NA	P SD CD CA
	DSF Performance Data	H M L NA	P SD CD CA
	Mechanical Systems	H M L NA	P SD CD CA
	Electric Lighting System	H M L NA	P SD CD CA
	Environmental Data	H M L NA	P SD CD CA

Note: Users need to define the priority level for that stage of modeling and the intent of the model. Levels are: H = High, M = Medium, L =Low, and NA= Not applicable. Stages are: P = planning, SD = schematic design, DD= design development, CD = construction documentation, and CA = construction administration.

9. Case Studies

As mentioned previously, while more modern in application, DSFs are not a new concept [4]. Early forms of mechanically ventilated multi-layer skin façades were proposed as early as the mid-19th century [9]. In the early 20th century, Le Corbusier explored the basic concept of DSFs [192]. Moving forward, DSF utilization advanced in the late

1970s and early 1980s [3]. As a more recent project, one can consider the 71-story Pearl River Tower, which is a commercial office building [189] designed by Skidmore, Owings & Merrill along with Adrian D. Smith and Gordon. Pearl River Tower is considered one of the most environmentally friendly buildings in the world for its emphasis on the implementation of energy conservation systems. It also utilizes a DSF as part of the energy conservation strategy [193]. The internally ventilated DSF utilizes a controlled ambient air temperature on the inside surface to decrease temperature differences but more importantly to better control mean radiant temperatures [193,194]. Volume control and smoke dampers in the return ductwork balance the DSF air volume, and in the event of a fire, seal off the DSF [193,195]. For added sustainability performance, Pearl River Tower utilizes a PV system that is mounted into the external shading system as part of the DSF components [193,196]. Table 17 provides a summary of several other building projects with DSF systems.

Table 17. DSF Case Study Projects with Overview Facts.

	Foundry Square	**One Angel Square**	**Cambridge Public Library**	**Pearl River Tower**
Location:	San Francisco, CA, USA	Manchester, England	Cambridge, MA, USA	Guangzhou, China
Architect:	STUDIOS Architecture	3DReid	William Rawn Associates	Adrian D. Smith and Gordon Gill
Façade engineer	N/A	Waagner Biro, Buro Happold	Ann Beha Architects	Skidmore, Owings & Merrill LLP
Façade type:	Multi-story façade	Multi-story façade	Multi-story façade	Multi-story façade
Façade supporting structure type	Suspended structure	Cantilever bracket	Frame structure	Frame structure
Cavity size:	0.911 m (3 ft)	0.610 m (2 ft)	0.911 m (3 ft)	0.305 m (1 ft)
Shading device type	No shading device	No shading device	0.305 m (1ft) deep operable sunshades	Daylight reflectors, Motorized blinds/sunshade devices
Ventilation devices	Open inlet and outlet	Operable upper and lower vents	Operable upper and lower vents Operable window on inner skin	Low-level inlets with a ducted return air connection

10. Conclusions

The reviews presented reveal that DSF systems allow the incorporation of advanced glazing technologies for energy control, including (a) coatings on the glass (e.g., thermochromic, photochromic, electrochromic, gasochromic, liquid crystal, wavelength selective, and switchable electrochromic or gas chromic); (b) compartmentalized structure, e.g., honeycomb structure between glazing layers, slat structure, and multi-wall system; and (c) a variety of transparency (e.g., transparent vs. translucent, aerogel, gases). There are pros and cons related to each system, and therefore, the best applicability depends on the building's specific needs. Furthermore, the concept of unitized curtain walls can be extended to also be applicable to DSF systems. More specifically, DSF systems can be advantageously used to enhance the energy efficiency of building envelope systems. DSFs can be designed to allow improvement in indoor air quality through natural air ventilation as well as hybrid ventilation, i.e., a combination of natural and mechanical ventilation. Although the DSF concept has been around for decades, this technology still has not seen widespread acceptance and implementation in the US due to various reasons including general lack of familiarity of the designers with the concept, lack of adequate standards, high initial costs, and maintenance cost. This paper has categorized various aspects of building performance studies on DSFs along with materiality, configurations, and modeling assumptions needed by designers and engineers to better advance the utilization of DSF systems. The resulting summaries gathered from the presented literature review provide a good resource reference for practitioners.

From the typology study, it can be concluded that vertical airflow, air inlet, natural daylighting, noise control, structural resistance against wind and building movement, fire protection, maintenance, HVAC, and aesthetics are among the most important parameters for the design of DSF systems, and because of this variety, a multi-disciplinary approach for its design is highly desirable. Summary Figure 7 showcases different key attributes that professional designers need to carefully examine, study, and iterate through for an effective DSF design. Given the multi-disciplinary nature of DSF systems, designers need to consider the following aspects as applicable: aesthetics, durability, cost, visibility, ventilation, impact on HVAC system, impact on daylighting and shading, maintenance, constructability, solar gain, weight, structural movement and resistance, thermal resistance, visual transmittance, unitized vs. stick-built, among others. With respect to modeling, among others, the following parameters need to be considered: shading, air flow, natural ventilation, fire and smoke, structural loading, energy performance, and LCA consideration. Along with Figure 7, Table 18 provides designers with a checklist that has the team establish the varying performance attributes across disciplines. This list, when completed by designers for a given project, can show where emphasis should be placed. Furthermore, Table 18 complements the earlier modeling checklist (Table 16).

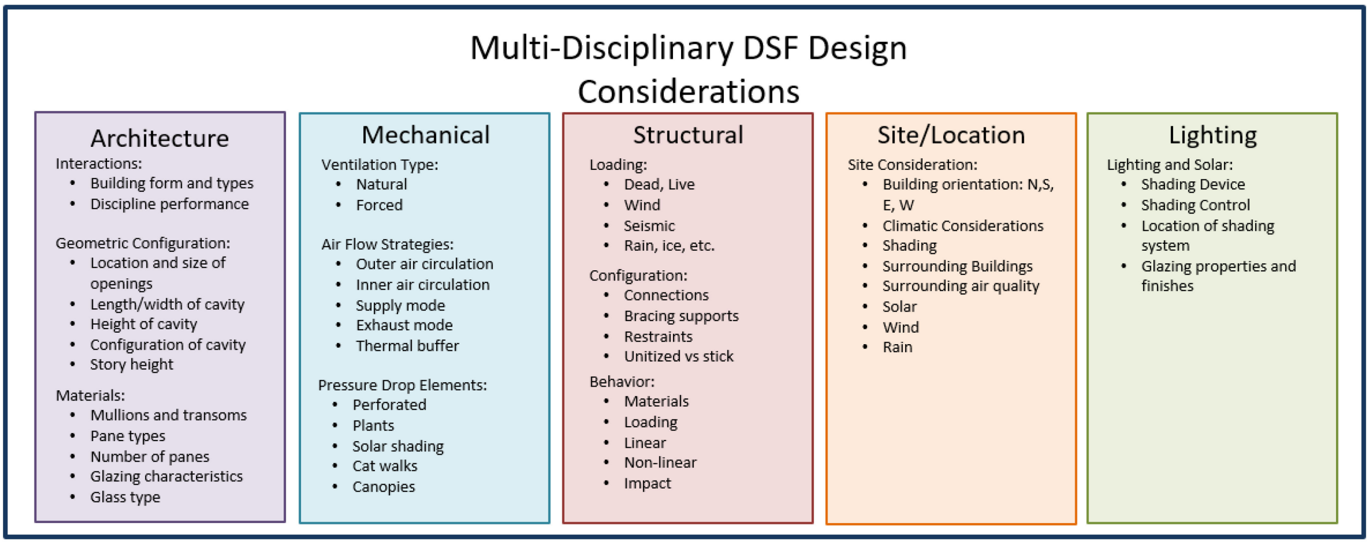


Figure 7. Representative SAP2000 model with locations of possible load applications.

In an effort to improve the design side of DSF practices and adoption, besides all the advantages mentioned, there are also some risks and challenges that need further research and development. These include potential for excessive glass deformation/fallout/breakage/movement under extreme loading conditions, and also the potential for damage to the framing system that supports inner and outer glazing and the connection of such framing systems to the building structural system due to excessive loading, fatigue, or moisture-related corrosion. Nonetheless, the benefits of using DSFs significantly outweigh such challenges, which can be managed and properly designed for. On the other hand, another area of limitation is the numerical modeling guidance on setting up detailed models. While the research work has been extensive, it largely has looked at the verification of experimental results or demonstrated case studies without sufficient detailed guidance on the design process and construction procedures.

Table 18. Modeling Check List of Items to Consider.

DSF Discipline	Major Categories/Considerations	Priority Level to Design towards	Target Level of Performance
Structural	Strength performance	H M L NA	H M Co NA
	Serviceability performance	H M L NA	H M Co NA
Architecture	Building form and space	H M L NA	H M Co NA
	Architectural performance	H M L NA	H M Co NA
	Materiality	H M L NA	H M Co NA
	Functionality	H M L NA	H M Co NA
	Integration of systems	H M L NA	H M Co NA
	Operations and Maintenance	H M L NA	H M Co NA
Mechanical	Thermal Comfort	H M L NA	H M Co NA
	Acoustical performance	H M L NA	H M Co NA
	Energy performance	H M L NA	H M Co NA
	Ventilation performance	H M L NA	H M Co NA
Lighting	Light control	H M L NA	H M Co NA
	Daylight harvesting vs. electric light	H M L NA	H M Co NA
	Visual comfort	H M L NA	H M Co NA

Note: Users need to define the priority level for that stage of modeling and the intent of the model. Design Levels are: H = High, M = Medium, L =Low, and NA= Not applicable. Performance targets are: H= high (well above code), M =Moderate (above code), Co = code minimum, and NA = not applicable.

Author Contributions: Conceptualization, A.M.M.; methodology, A.M.M., R.S. and C.H.; formal analysis, C.H. and R.S.; investigation, C.H. and R.S.; writing—original draft preparation, A.M.M. and R.S.; writing—review and editing, A.M.M. and R.S.; visualization, R.S. and C.H.; supervision, A.M.M.; project administration, A.M.M. All authors have read and agreed to the published version of the manuscript.

Funding: The authors declare no funding sources.

Data Availability Statement: This report contains all available data within it given the nature of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Arons, D. Properties and Applications of Double-Skin Building Facades. Master's Thesis, Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA, USA, 2000.
2. Bestfacade. *WP 5 Report Best Practice Guidelines. Best Practice for Double Skin Facades*; Intelligent Energy Europe: Brussels, Belgium, 2007.
3. Crespo, A.M. History of the Double Skin Façades. n.d. Available online: http://envelopes.cdi.harvard.edu/envelopes/content/resources/PDF/doubleskins.pdf (accessed on 15 February 2019).
4. Boake, T.; Harrison, K.; Chatham, A. *The Tectonics of the Double Skin: Green Building or Just More Hi-Tech Hi-Jinx?* University of Waterloo: Waterloo, ON, Canada, 2001.
5. Straube, J. A Critical Review of the Use of Double Façades for Office Buildings in Cool Humid Climates. *J. Build. Enclos. Des.* **2007**, 48–53.
6. Penić, M.; Vatin, N.; Murgul, V. Double skin facades in energy efficient design. In *Applied Mechanics and Materials*; Trans Tech Publications Ltd.: Zurich, Switzerland, 2014; Volume 680, pp. 534–538.
7. Lang, W.; Herzog, T. Using Multiple Glass Skins to Clad Buildings. Architectural Record. 2000. Available online: http://archrecord.construction.com/features/green/archives/0007edit-1.asp (accessed on 20 June 2015).
8. Uuttu, S. Study of Currnet Structures in Double-skin Facades. Master's Thesis, Department of Civil and Environmental Engineering, Helsinki University of Technology, Helsinki, Finland, 2001.
9. Saelen, D. Energy Performance Assessments of Single Storey Multiple-Skin Facades. Ph.D. Thesis, Laboratory for Building Physics, Department of Civil Engineering, Catholic University of Leuven, Brussels, Belgium, 2002.
10. Selkowitz, S. Energy efficiency perspectives: Intelligent networks and the challenge of zero energy buildings. In Proceedings of the Presentation to Connected Urban Development Global Conf., Amsterdam, The Netherlands, 10 April 2008.
11. Saelens, D.; Roels, S.; Hens, H. Strategies to improve the energy performance of multiple-skin facades. *Build. Environ.* **2008**, *43*, 638–650. [CrossRef]

12. Pollard, B.; Beatty, M. Double skin façades more is less? In Proceedings of the ISES-AP—3rd International Solar Energy Society Conference—Asia Pacific Region, Sydney, Australia, 25–28 November 2008.
13. Danesh, M.; Escamilla, E.; Pariafsai, F.; Ostadalimakhmalbaf, M. Characteristics of Glazing Layers of Double-Skin Facades and Energy Consumption: A Case Study in Arid Climate of Tehran. In *AEI 2019: Integrated Building Solutions—The National Agenda*; American Society of Civil Engineers: Reston, VA, USA, 2019; pp. 204–215.
14. Gratia, E.; De Herde, A. Guidelines for improving natural daytime ventilation in an office building with a double-skin facade. *Sol. Energy* **2007**, *81*, 435–448. [CrossRef]
15. Moon, K.S. Structural Design of Double Skin Facades as Damping Devices for Tall Buildings. In Proceedings of the Twelfth East Asia-Pacific Conference on Structural Engineering and Construction, Hong Kong, China, 26–28 January 2011; pp. 1351–1358.
16. Siebert, B. Double Skin Facades Made of Glass—Aspects of Structural Design and Static Analysis. In *Structures and Archetecture: Concepts, Applications and Challenges*; Cruz, P.J.S., Ed.; Taylor & Francis Group: London, UK, 2013; pp. 289–298.
17. Vaglio, J.; Patterson, M.; Hooper, S. Emerging Applications and Trends of Double-skin Facades. In Proceedings of the International Conference on Building Envelope Systems and Technologies, ICBEST, Vancouver, BC, Canada, 27–30 June 2010.
18. New Barbosa, S.; Ip, K. Perspectives of double skin façades for naturally ventilated buildings: A review. *Renew. Sustain. Energy Rev.* **2014**, *40*, 1019–1029. [CrossRef]
19. New Kalyanova, O. *Double-Skin Facade: Modelling and Experimental Investigations of Thermal Performance*; Department of Civil Engineering, Aalborg University: Aalborg, Denmark, 2008.
20. New Høseggen, R.; Wachenfeldt, B.; Hanssen, S. Building simulation as an assisting tool in decision making: Case study: With or without a double-skin façade? *Energy Build.* **2008**, *40*, 821–827. [CrossRef]
21. New Ghaffarianhoseini, A.; Ghaffarianhoseini, A.; Berardi, U.; Tookey, J.; Li, D.H.W.; Kariminia, S. Exploring the advantages and challenges of double-skin façades (DSFs). *Renew. Sustain. Energy Rev.* **2016**, *60*, 1052–1065. [CrossRef]
22. Diprose, P.R.; Robertson, G. *Towards A Fourth Skin? Sustainability and Double-Envelope Buildings*; Department of Architecture, University of Auchland: Auckland, New Zealand, 1996.
23. DOE. Buildings Energy Data Book. Energy Efficiency and Renewable Energy Dept. 2011. Available online: http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2010_BEDB.pdf (accessed on 27 December 2016).
24. Crawley, D.B.; Hand, J.W.; Kummert, M.; Griffith, B.T. Contrasting the capabilities of building energy performance simulation programs. *Build. Environ.* **2008**, *43*, 661–673. [CrossRef]
25. Berardi, U. A cross-country comparison of the building energy consumptions and their trends. *Resour. Conserv. Recycl.* **2017**, *123*, 230–241. [CrossRef]
26. Charalambides, J.; Wright, J. Effect of early solar energy gain according to building size, building openings, aspect ratio, solar azimuth, and latitude. *J. Archit. Eng.* **2013**, *19*, 209–216. [CrossRef]
27. Oesterle, E.; Oesterle, R.-D.; Lutz, L.M.; Heusler, W. *Double Skin Facades—Integrated Planning*; Prestel Verlag: Munich, Germany, 2001.
28. Silvestre, J.D.; de Brito, J.; Pinheiro, M.D. Building's external walls in life-cycle assessment (LCA) research studies. In *Proceedings of the of SB10–Sustainable Building Affordable to All*; iiSBE–Portugal: Vilamoura, Portugal, 2010; pp. 629–638.
29. Saleem, M.; Chhipi-Shrestha, G.; Túlio Barbosa Andrade, M.; Dyck, R.; Ruparathna, R.; Hewage, K.; Sadiq, R. Life cycle thinking–based selection of building facades. *J. Archit. Eng.* **2018**, *24*, 04018029. [CrossRef]
30. Incropera, F.P. *Introduction to Heat Transfer*; John Wiley and Sons: New York, NY, USA, 2011.
31. Ihm, P.; Krarti, M.; Nemri, A. Estimation of lighting energy savings from daylighting. *Build. Environ.* **2009**, *44*, 509–514. [CrossRef]
32. Shehabi, A.; DeForest, N.; McNeil, A.; Masanet, E.; Greenblatt, J.; Lee, E.S.; Masson, G.; Helms, B.A.; Milliron, D.J. U.S. energy savings potential from dynamic daylighting control glazings. *Environ. Energy Build.* **2013**, *66*, 415–423. [CrossRef]
33. Johnson, R.; Selkowitz, S.; Sullivan, R. How Fenestration Can Significantly Affect Energy Use in Commercial Buildings. In Proceedings of the 11th Energy Technology Conference, Washington, DC, USA, 19–21 March 1984.
34. Jafari, A.; Valentin, V. *An Investment Allocation Approach for Building Energy Retrofits*; ConstructionResearch Congress (CRC): San Juan, Puerto Rico, 2016; p. 107. [CrossRef]
35. Aksamija, A.; Peters, T. Heat transfer in facade systems and energy use: Comparative study of different exterior wall types. *J. Archit. Eng.* **2017**, *23*, C5016002. [CrossRef]
36. Fuliotto, R.; Cambuli, F.; Mandas, N.; Bacchin, N.; Manara, G.; Chen, Q. Experimental and numerical analysis of heat transfer and airflow on an interactive building facade. *Energy Build.* **2010**, *42*, 23–28. [CrossRef]
37. Taborianski, V.M.; Prado, R.T. Methodology of CO2 emission evaluation in the life cycle of office building façades. *Environ. Impact Assess. Rev.* **2012**, *33*, 41–47. [CrossRef]
38. Moghtadernejad, S.; Mirza, M.S.; Chouinard, L.E. Facade design stages: Issues and considerations. *J. Archit. Eng.* **2019**, *25*, 4018033. [CrossRef]
39. Pickering, C.; Byrne, J. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. *High. Educ. Res. Dev.* **2014**, *33*, 534–548. [CrossRef]
40. Boell, S.; Cezec-Kecmanovic, D. Are systematic reviews better, less biased and of higher quality? In Proceedings of the ECIS 2011 Proceedings, Helsinki, Finland, 9–11 June 2011; p. 223.
41. Gelesz, A.; Reith, A. Classification and re-evaluation of double-skin facades. *Int. Rev. Appl. Sci. Eng.* **2011**, *2*, 129–136. [CrossRef]

42. Doebber, I.; McClintock, M. Analysis process for designing double skin facades and associated case study. In Proceedings of the Second National IBPSA-USA Conference, San Francisco, CA, USA, 2–4 August 2006; pp. 160–167.
43. Knaack, U.; Klein, T.; Bilow, M.; Auer, T. *Façades: Principles of Construction*; Birkhäuser: Boston, MA, USA, 2014.
44. Compagno, A. *Intelligent Glass Facades*; Birkhauser: Boston, MA, USA, 1999.
45. Loncour, X.; Deneyer, A.; Blasco, M.; Flamant, G.; Wouters, P. *Ventilated Double Facade: Classification and Illustration of Facade Concepts*; Belgian Building Research Institute: Saint-Gilles, Belgium, 2004.
46. Patterson, M.; Matusova, J. High-performance facades. *Insight* **2013**, *3*, 134–149.
47. Boake, T.M.; Harrison, K.; Collins, D.; Balbaa, T.; Chatham, A.; Lee, R.; Bohren, A. *The Tectonics of the Double Skin: Green Building or Just More Hi-Tech Hi-Jink?—What Are Double Skin Façades and How Do They Work?* University of Waterloo: Waterloo, ON, Canada, 2008; Available online: http://www.architecture.uwaterloo.ca/faculty_projects/terri/ds/tectonic.pdf (accessed on 4 July 2013).
48. Kallioniemi, J. Joint and Fastenings in Steel-Glass Facades. Master's Thesis, Department of Civil and Environmental Engineering, Helsinki University of Technology, Helsinki, Finland, 1999.
49. Ariosto, T.; Memari, A.M.; Solnosky, R. A Comparative Energy Efficiency Study Of Different Glazing Systems In Residential And Commercial Building Applications. *Int. J. Archit. Eng. Constr.* **2019**, *8*, 1–18. [CrossRef]
50. Schittich, C. *Glass Construction Manual*; Birkhauser Architecture: Boston, MA, USA, 2007.
51. Oldfield, P.; Trabucco, D.; Wood, A. Five Generations of Tall Buildings: An Historical Analysis of Energy Consumption in High Rise Buildings. *J. Archit.* **2009**, *14*, 591–613. [CrossRef]
52. Minor, J.E. Focus on Glass. *APT Bull. J. Preserv. Technol.* **2001**, *32*, 47–50. [CrossRef]
53. Goupil, J.; Kestner, D.M.; Lorenz, E. *Sustainability Guidelines for the Structural Engineer*; ASCE Press: Reston, VA, USA, 2010.
54. Jayasinghe, C. Embodied energy of alternative building materials and their impact on life cycle cost parameters. *ICSECM* **2011**, *201*, 1–20.
55. Haynes, R. Embodied Energy Calculations within Life Cycle Analysis of Residential Buildings. 2010. Available online: http://etool.net.au/wp-content/uploads/2012/10/Embodied-Energy-Paper-Richard-Haynes.pdf (accessed on 25 July 2018).
56. Ghoshal, S.; Neogi, S. Advance Glazing System—Energy Efficiency Approach for Buildings a Review. *Energy Procedia* **2014**, *54*, 352–358. [CrossRef]
57. Ariosto, T.; Memari, A.; Solnosky, R. A comparative thermal properties evaluation for residential window retrofit solutions for U.S. markets. *Adv. Build. Energy Res.* **2018**, *15*, 87–116. [CrossRef]
58. Binions, R.; Ridley, I.; Warwick, M.E.A. The effect of transition gradient in thermochromic glazing systems. *Energy Build.* **2014**, *77*, 80–90.
59. Issa, R.R.A.; Olbina, S.; Raheem, A.A. Environmental Performance and Economic Analysis of Different Glazing–Sunshade Systems Using Simulation Tools. *J. Comput. Civ. Eng.* **2016**, *30*, C5016001. [CrossRef]
60. Hernández, J.A.; Sierra, P. Solar heat gain coefficient of water flow glazings. *Energy Build.* **2017**, *139*, 133–145.
61. IEA (International Energy Agency). Technology Roadmap Energy Efficient Building Envelopes. 2013. Available online: http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyEfficientBuildingEnvelopes.pdf (accessed on 25 December 2013).
62. Papaefthimiou, S. Chromogenic technologies: Towards the realization of smart electrochromic glazing for energy-saving applications in buildings. *Adv. Build. Energy Res.* **2010**, *4*, 77–126. [CrossRef]
63. Piccolo, A.; Marino, C.; Nucara, C.; Pietrafesa, M. Energy performance of an electrochromic switchable glazing: Experimental and computational assessments. *Energy Build.* **2018**, *165*, 390–398. [CrossRef]
64. Granqvist, C.G. Electrochromic tungsten oxide films: Review of progress 1993–1998. *Sol. Energy Mater. Sol. Cells* **2000**, *60*, 201–262. [CrossRef]
65. Lee, E.S.; Gehbauer, C.; Coffey, B.E.; McNeil, A.; Stadler, M.; Marnay, C. Integrated control of dynamic facades and distributed energy resources for energy cost minimization in commercial buildings. *Sol. Energy* **2015**, *122*, 1384–1397. [CrossRef]
66. Pierucci, A.; Cannavale, A.; Martellotta, F.; Fiorito, F. Smart windows for carbon neutral buildings: A life cycle approach. *Energy Build.* **2018**, *165*, 160–171. [CrossRef]
67. Zhang, W.; Lu, L.; Peng, J.; Song, A. Comparison of the overall energy performance of semi-transparent photovoltaic windows and common energy-efficient windows in Hong Kong. *Energy Build.* **2016**, *128*, 511–518. [CrossRef]
68. Cuce, E.; Cuce, P.M.; Wood, C.J.; Riffat, S.B. Toward aerogel based thermal superinsulation in buildings: A comprehensive review. *Renew. Sustain. Energy Rev.* **2014**, *34*, 273–299. [CrossRef]
69. Berardi, U. The development of a monolithic aerogel glazed window for an energy retrofitting project. *Appl. Energy* **2015**, *154*, 603–615. [CrossRef]
70. Martinez, R.G.; Goiti, E.; Reichenauer, G.; Zhao, S.; Koebel, M.; Barrio, A. Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale. *Energy Build.* **2016**, *128*, 111–118. [CrossRef]
71. Blanc, S.L.; Hakkarainen, P.; Lee, E.S.; Levi, M.S.; McClintock, M.; McConahey, E.; Myser, M.P.; Sbar, N.L.; Selkowitz, S.E. Active load management with advanced window wall systems: Research and industry perspectives. In *ACEEE 2002 Summer Study on Energy Efficiency in Buildings: Teaming for Efficiency*; American Council for an Energy-Efficient Economy: Washington, DC, USA, 2002.
72. Weggel, D.C.; Zapata, B.J. Laminated glass curtain walls and laminated glass lites subjected to low-level blast loading. *J. Struct. Eng.* **2008**, *134*, 466–477. [CrossRef]

73. Tenhunen, O.; Lintula, K.; Lehtinen, T.; Lehtovaara, J.; Viljanen, M.; Kesti, J.; Mäkeläinen, P. Double Skin Facades-Structures and Building Physics. In Proceedings of the 9th Nordic Steel Construction Conference, Helsinki, Finland, 18–20 June 2001; pp. 141–148.
74. Shirazi, A. *Development of a Seismic Vulnerability Evaluation Procedure for Architectural Glass Curtain Walls*; The Pennsylvania State University: University Park, PA, USA, 2005.
75. Memari, A.M.; Hartman, K.H.; Kremer, P.A. *Racking Test Evaluation of EN-WALL 7250 Unitized Curtain Wall System with 3M™ VHB™ Structural Glazing Tape*; Report Submitted to 3M Industrial Adhesives & Tapes Division; Penn State University: St. Paul, MN, USA, 2011; p. 72.
76. Memari, A.M. (Ed.) *Curtain Wall Systems—A Primer, Consisting of 12 Chapters*; American Society of Civil Engineers (ASCE): Reston, VA, USA, 2013.
77. Dow Corning. *Silicone Structural Glazing Manual*; Form Number 62-0979H-01; Dow Corning Europe: Brussels, Belgium, 2011.
78. Jain, A. Hurricane Wind-Generated Debris Impact Damage to the Glazing of a High-Rise Building. In Proceedings of the Seventh Congress on Forensic Engineering, Miami, FL, USA, 15–18 November 2015; pp. 361–370.
79. Adhikary, S.D. Review of Glazing and Glazing Systems under Blast Loading. *Pract. Period. Struct. Des. Constr.* **2015**, *21*, 4015009. [CrossRef]
80. Fu, T.S.; Zhang, R. Integrating double-skin façades and mass dampers for structural safety and energy efficiency. *J. Archit. Eng.* **2016**, *22*, 4016014. [CrossRef]
81. Githerlet, S.; Gay, J.B.; Guglielmo, F. Window and advanced glazing systems life cycle assessment. *Energy Build.* **2000**, *32*, 225–234. [CrossRef]
82. Wiener, M. *Unitized Double Skin Façade Assemblies: Achieving the Needs of Future Envelope Systems through Construction and Performance Advances*; University of Southern California: Los Angeles, CA, USA, 2012.
83. Eli, U.S.C.; Center, E.B.; Square, F.; Center, S.J. Double-Skin Facades in the United States. Available online: https://enclos.com/wp-content/uploads/2020/08/Insight01-Chapter03-Emerging_Applications_and_Trends_of_Double-Skin_Facades.pdf (accessed on 8 September 2019).
84. Schmid, F.; Cseh, X.; Rohrer, E.; Teich, M. Double-Skin Façades: Boundary Conditions, Challenging Examples and Developments. *CE/Papers* **2018**, *2*, 103–112. [CrossRef]
85. Brown, B. An Introduction to the Design and Application of Double Skin Facades in North American High-Rise Architecture. Ph.D. Thesis, Institute of Technology, Cork Irland, Ireland, 2016.
86. Eslamirad, N.S.; Sanei, A. Double Skin Facades in Use, a Study of Configuration and Performance of Double Skin Façade, Case Studies Some Office Buildings. In Proceedings of the 2nd International Conference on Research in Science and Technology, Istanbul, Turkey, 14 March 2016.
87. Poirazis, H. *Double Skin Façades for Office Buildings–Literature Review*; Report EDB-R—04/3; Department of Construction and Architecture, Lund University of Technology: Lund, Sweden, 2004.
88. Gratia, E.; De Herde, A. The most efficient position of shading devices in a double-skin facade. *Energy Build.* **2007**, *39*, 364–373. [CrossRef]
89. Stec, W.; Van Paassen, A.; Maziarz, A. Modelling the double skin façade with plants. *Energy Build.* **2005**, *37*, 419–427. [CrossRef]
90. Chan, Y.C.; Protzman, B.; Tzempelikos, A. Solar optical properties of roller shades: Modeling approaches, measured results and impact on energy use and visual comfort. In Proceedings of the 3rd International High Performance Buildings Conference, West Lafayette, IN, USA, 14–17 July 2014; Purdue University: West Lafayette, IN, USA, 2014.
91. Choi, W.; Joe, J.; Kwak, Y.; Huh, J.O. Operation and control strategies for multi-storey double skin facades during the heating season. *Energy Build.* **2012**, *49*, 454–465. [CrossRef]
92. Manz, H.; Frank, T. Thermal simulation of buildings with double-skin façades. *Energy Build.* **2005**, *37*, 1114–1121. [CrossRef]
93. Ding, W.; Hasemi, Y.L.; Yamada, T. Natural ventilation performance of a double-skin façade with a solar chimney. *Energy Build.* **2005**, *37*, 411–418. [CrossRef]
94. Moghtadernejad, S.; Chouinard, L.E.; Mirza, M.S. Design strategies using multi-criteria decision-making tools to enhance the performance of building façades. *J. Build. Eng.* **2020**, *30*, 101274. [CrossRef]
95. Guardo, A.; Coussirat, M.; Valero, C.; Egusquiza, E.; Alavedra, P. CFD assessment of the performance of lateral ventilation in Double Glazed Façades in Mediterranean climates. *Energy Build.* **2011**, *43*, 2359–2547. [CrossRef]
96. Yellamraju, V. Evaluation and Design of Double-Skin Façades for Office Buildings in Hot Climates. Master's Thesis, College of Architecture, Texas A&M University, College Station, TX, USA, 2004.
97. Silva, F.M.; Gomes, M.G. Gap inner pressures in multi-storey double skin facades. *Energy Build.* **2008**, *40*, 1553–1559. [CrossRef]
98. Ock, J.; Issa, R.R.A.; Olbina, S. Climate Responsive Automatic Operation Strategies for Double Skin Façade (DSF) System of High-Rise Buildings. In *Computing in Civil and Building Engineering*; ASCE: Reston, VA, USA, 2014; pp. 917–924. Available online: https://itc.scix.net/pdfs/w78-2014-paper-114.pdf (accessed on 7 August 2022).
99. Cole, R.J.; Kernan, P.C. Life-cycle energy use in office buildings. *Build. Environ.* **1996**, *31*, 307–317. [CrossRef]
100. Lee, E.; Selkowitz, S.; Bazjanac, V.; Inkarojrit, V.; Kohler, C. *High-Performance Commercial Building Façades*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2002.
101. Barkkume, A. *Innovative Building Skins: Double Glass Wall Ventilated Façade*; New Jersey School of Architecture: Newark, NJ, USA, 2007.

102. Mohotti, D.; Lunmantara, R.; Ngo, T.; Mendis, P. Improving the safety of buildings through an innovative sustainable façade system. In Proceedings of the International Conference on Sustainable Built Environment (ICSBE), Kandy, Sri Lanka, 13–14 December 2010; University of Moratuwa: Kandy, Sri Lanka, 2010.
103. Hens, H.; Saelens, D.; Meulenaer, V.D.; Elsen, P. Multiple-skin facades: High tech blessing or not? In Proceedings of the 8th Symposium on Building Physics in the Nordic Countries, Copenhagen, Denmark, 16–18 June 2008; pp. 1–8.
104. Colantonio, A.; Quirouette, R. Verification of dynamic buffer zone (DBZ) wall assembly performance using infrared thermography. In *Thermosense XXIV*; International Society for Optics and Photonics: San Diego, CA, USA, 2002; Volume 4710, pp. 288–298.
105. Chow, W.; Hung, W.; Gao, Y.; Zou, G.; Dong, H. Experimental study on smoke movement leading to glass damages in double-skinned façade. *Constr. Build. Mater.* **2007**, *21*, 556–566. [CrossRef]
106. Moghtadernejad, S.; Mirza, S. Service life safety and reliability of building facades. In *Vulnerability, Uncertainty, and Risk: Quantification, Mitigation, and Management*; ASCE: Reston, VA, USA, 2014; pp. 116–124.
107. Popovic, P.L.; Arnold, R.C. Preventing failures of precast concrete facade panels and their connections. In Proceedings of the 2nd Forensic Engineering Congress, San Juan, Puerto Rico, 21–23 May 2000; ASCE: Reston, VA, USA, 2000; pp. 532–539.
108. Hay, R.; Ostertag, C.P. Innovative Double Skin Façade (DSF) with High Performance Green Hybrid Fiber-Reinforced Concrete (HP-G-HyFRC) for Resilient and Sustainable Buildings. In Proceedings of the AEI 2015, Milwaukee, WI, USA, 24–27 March 2015; pp. 120–133.
109. Ding, C.; Ngo, T.; Mendis, P.; Lumantarna, R.; Zobec, M. Dynamic response of double skin façades under blast loads. *Eng. Struct.* **2016**, *123*, 155–165. [CrossRef]
110. Kim, D.; Park, C. Difficulties and limitations in performance simulation of a double skin façade with EnergyPlus. *Energy Build.* **2011**, *43*, 3635–3645. [CrossRef]
111. Hensen, J.; Bartak, M.; Drkal, F. Modelin and simulation of a double skin facade system. *ASHRAE Trans.* **2002**, *108*, 1251–1259.
112. Pasut, W.; De Carli, M. Evaluation of various CFD modelling strategies in predicting airflow and temperature in a naturally ventilated double skin façade. *Appl. Therm. Eng.* **2012**, *37*, 267–274. [CrossRef]
113. Safer, N.; Woloszyn, M.; Roux, J.J. Three-dimensional simulation with a CFD tool of the airflow phenomena in single floor double-skin facade equipped with a venetian blind. *Sol. Energy* **2005**, *79*, 193–203. [CrossRef]
114. Chow, C.L. Numerical studies on smoke spread in the cavity of a double-skin facade. *J. Civ. Eng. Manag.* **2011**, *17*, 371–392. [CrossRef]
115. Pappas, A.; Zhai, Z. Numerical investigation on thermal performance and correlations of double skin façade with buoyancy-driven airflow. *Energy Build.* **2008**, *40*, 466–475. [CrossRef]
116. De Gracia, A.; Castell, A.; Navarro, L.; Oró, E.; Cabeza, L.F. Numerical modelling of ventilated facades: A review. *Renew. Sustain. Energy Rev.* **2013**, *22*, 539–549. [CrossRef]
117. Balocco, C. A non-dimensional analysis of a ventilated double façade energy performance. *Energy Build.* **2004**, *36*, 35–40. [CrossRef]
118. Balocco, C.; Colombari, M. Thermal behavior of interactive mechanically ventilated double glazed façade: Non-dimensional analysis. *Energy Build.* **2006**, *38*, 1–7. [CrossRef]
119. Saelens, D.; Roels, S.; Hens, H. The inlet temperature as a boundary condition for multiple-skin facade modelling. *Energy Build.* **2004**, *36*, 825–835. [CrossRef]
120. Jiru, T.E.; Haghighat, F. Modeling ventilated double skin façade—A zonal approach. *Energy Build.* **2008**, *40*, 1567–1576. [CrossRef]
121. Xaman, J.; Alvarez, G.; Lira, L.; Estrada, C. Numerical study of heat transfer by laminar and turbulent natural convection in tall cavities of facade elements. *Energy Build.* **2005**, *37*, 787–794. [CrossRef]
122. Zöllner, A.; Winter, E.R.F.; Viskanta, R. Experimental studies of combined heat transfer in turbulent mixed convection fluid flows in double-skin-facades. *Int. J. Heat Mass Transf.* **2002**, *45*, 4401–4408. [CrossRef]
123. Irfan, M.; Abas, N.; Saleem, M.S. Thermal performance analysis of net zero energy home for sub zero temperature areas. *Case Stud. Therm. Eng.* **2018**, *12*, 789–796. [CrossRef]
124. Abas, N.; Kalair, A.R.; Khan, N.; Haider, A.; Saleem, Z.; Saleem, M.S. Natural and synthetic refrigerants, global warming: A review. *Renew. Sustain. Energy Rev.* **2018**, *90*, 557–569. [CrossRef]
125. Abas, N.; Khan, N. Carbon conundrum, climate change, CO2 capture and consumptions. *J. CO2 Util.* **2014**, *8*, 39–48. [CrossRef]
126. Abas, N.; Kalair, A.; Khan, N.; Kalair, A.R. Review of GHG emissions in Pakistan compared to SAARC countries. *Renew. Sustain. Energy Rev.* **2017**, *80*, 990–1016. [CrossRef]
127. Stritih, U.; Tyagi, V.V.; Stropnik, R.; Paksoy, H.; Haghighat, F.; Joybari, M.M. Integration of passive PCM technologies for net-zero energy buildings. *Sustain. Cities Soc.* **2018**, *41*, 286–295. [CrossRef]
128. Habash, G.; Chapotchkine, D.; Fisher, P.; Rancourt, A.; Habash, R.; Norris, W. Sustainable design of a nearly zero energy building facilitated by a smart microgrid. *J. Renew. Energy* **2014**, *2014*, 1–11. [CrossRef]
129. Raj, B.P.; Meena, C.S.; Agarwal, N.; Saini, L.; Hussain Khahro, S.; Subramaniam, U.; Ghosh, A. A Review on Numerical Approach to Achieve Building Energy Efficiency for Energy, Economy and Environment (3E) Benefit. *Energies* **2021**, *14*, 4487. [CrossRef]
130. Straube, J.; Burnett, E.F.P. Overview of hygrothermal (HAM) analysis methods. Chapter 5. In *Moisture Analysis and Condensation Control in Building Envelopes*; Trechsel, H.R., Ed.; ASTM: West Conshohocken, PA, USA, 2001; pp. 81–89.
131. Delgado, J.M.P.Q.; Ramos, N.M.M.; Barreira, E.; De Freitas, V.P. A critical review of hygrothermal models used in porous building materials. *J. Porous Media* **2010**, *13*, 221–234. [CrossRef]

132. Zirkelbach, D.; Schmidt, T.; Kehrer, M.; Künzel, H.M. *Wufi® Pro–Manual*; Fraunhofer Institute: Stuttgart, Germany, 2007.
133. Susorova, M.; Angulo, P.; Bahrami, B. Stephens, A model of vegetated exterior facades for evaluation of wall thermal performance. *Build. Environ.* **2013**, *67*, 1–13. [CrossRef]
134. Bruse, M.; Fleer, H. Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environ. Model. Softw.* **1998**, *13*, 373–384. [CrossRef]
135. Grunewald, J. *Documentation of the Numerical Simulation Program DIM3.1, Volume 2: User's Guide*; Institute of Building Climatology, Faculty of Architecture, University of Technology Dresden: Dresden, Germany, 2000.
136. Alsaad, H.; Hartmann, M.; Voelker, C. The effect of a living wall system designated for greywater treatment on the hygrothermal performance of the facade. *Energy Build.* **2022**, *255*, 111711. [CrossRef]
137. Salata, F.; Golasi, I.; Vollaro, A.L.; Vollaro, R.L. How high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study. *Energy Build.* **2015**, *99*, 32–49. [CrossRef]
138. Sontag, L.; Nicolai, A.; Vogelsang, S. *Validierung der Solverimplementierung des Hygrothermischen Simulationsprogramms DELPHIN*; Technical Report; Technische Universität Dresden: Dresden, Germany, 2013.
139. Ciampi, M.; Leccese, F.; Tuoni, G. Energy analysis of ventilated and microventilated roofs. *Sol. Energy* **2022**, *79*, 183–192. [CrossRef]
140. Charde, M.; Gupta, R. Effect of energy efficient building elements on summer cooling of buildings. *Energy Build.* **2013**, *67*, 616–623. [CrossRef]
141. Gagliano, A.; Patania, F.; Nocera, F.; Ferlito, A.; Galesi, A. Thermal performance of ventilated roofs during summer period. *Energy Build.* **2012**, *49*, 611–618. [CrossRef]
142. Li, D.; Zheng, Y.; Liu, C.; Qi, H.; Liu, X. Numerical analysis on thermal performance of naturally ventilated roofs with different influencing parameters. *Sustain. Cities Soc.* **2016**, *22*, 86–93. [CrossRef]
143. Wakili, K.G.; Simmler, H.; Frank, T. Experimental and numerical thermal analysis of a balcony board with integrated glass fibre reinforced polymer GFRP elements. *Energy Build.* **2007**, *39*, 76–81. [CrossRef]
144. Cascione, V.; Marra, E.; Zirkelbach, D.; Liuzzi, S.; Stefanizzi, P. Hygrothermal analysis of technical solutions for insulating the opaque building envelope. *Energy Procedia* **2017**, *126*, 203–210. [CrossRef]
145. Leccese, F.; Salvadori, G.; Barlit, M. Ventilated flat roofs: A simplified model to assess their hygrothermal behaviour. *J. Build. Eng.* **2019**, *22*, 12–21. [CrossRef]
146. Tian, Y.; Bai, X.; Qi, B.; Sun, L. Study on heat fluxes of green roofs based on an improved heat and mass transfer model. *Energy Build.* **2017**, *152*, 175–184. [CrossRef]
147. Anđelković, A.S.; Mujan, I.; Dakić, S. Experimental validation of a EnergyPlus model: Application of a multi-storey naturally ventilated double skin facade. *Energy Build.* **2016**, *118*, 27–36. [CrossRef]
148. Catto-Lucchino, E.; Goia, F.; Lobaccaro, G.; Chaudhary, G. Modelling of double skin facades in whole-building energy simulation tools: A review of current practices and possibilities for future developments. In *Building Simulation*; Tsinghua University Press: Beijing, China, 2019; Volume 12, pp. 3–27.
149. Clarke, J.A.; Hensen, J.L.M. Integrated building performance simulation: Progress, prospects and requirements. *Build. Environ.* **2015**, *91*, 294–306. [CrossRef]
150. Loutzenhiser, P.G.; Manz, H.; Felsmann, C.; Strachan, P.A.; Maxwell, G.M. An empirical validation of modeling solar gain through a glazing unit with external and internal shading screens. *Appl. Therm. Eng.* **2007**, *27*, 528–538. [CrossRef]
151. Aschaber, J.; Hiller, M.; Weber, R. TRNSYS17: New features of the multizone building model. In Proceedings of the 11th International IBPSA Building Simulation Conference, Glasgow, UK, 27–30 July 2009; pp. 1983–1988.
152. Hand, J.W. *The ESP-r Cookbook: Strategies for Deploying Virtual Representations of the Built Environment*; University of Strathclyde: Glasgow, UK, 2011.
153. US Department of Energy. *EnergyPlus Version 8.9.0: Engineering Reference*; US Department of Energy: Washington, DC, USA, 2018.
154. Walton, G.N. *AIRNET: A Computer Program for Building Airflow Network Modeling*; Technical Report, DE-AI01-36CE2101-3; US Department of Commerce, National Institute of Standards and Technology, National Engineering Laboratory: Gaithersburg, MD, USA, 1989.
155. Walton, G.N.; Dols, W.S. *CONTAMW 2.0 User Manual. NISTIR 7251*; US Department of Commerce, National Institute of Standards and Technology: Washington, DC, USA, 2002.
156. Walton, G.N. *Passive Solar Extension of the Building Loads Analysis and System Thermodynamics (BLAST) Program*; Technical Report; United States Army Construction Engineering Research Laboratory: Gaithersburg, MD, USA, 1981.
157. Mitchell, R.; Yazdanian, M.; Zelany, K.; Curcija, C. *COMFEN 4.1*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2012.
158. MacroFlo. MacroFlo Calculation Methods. *Techniques*, 1–25. 2012. Available online: https://www.iesve.com/downloads/help/Thermal/Reference/MacroFloCalculationMethods.pdf (accessed on 7 August 2022).
159. Hensen, J.; Djunaedy, E. Building simulation for making the invisible visible-air flow in particular. In Proceedings of the International Conference on Energy Efficient Technologies in Indoor Environment, Delft, The Netherlands, 24–25 February 2005.
160. Kalamees, T. IDA ICE: The simulation tool for making the whole building energy and HAM analysis. *Annex* **2004**, *41*, 12–14.
161. Hilliaho, K.; Lahdensivu, J.; Vinha, J. Glazed space thermal simulation with IDA-ICE 4.61 software—Suitability analysis with case study. *Energy Build.* **2015**, *89*, 132–141. [CrossRef]

162. Kropf, S.; Zweifel, G. *Validation of the Building Simulation Program IDA-ICE According to CEN 13791 "Thermal Performance of Buildings–Calculation of Internal Temperatures of a Room in Summer without Mechanical Cooling–General Criteria and Validation Procedures"*; Hochschule Technik + Architektur Luzern: Horw, Switzerland; HLK Engineering: Horw, Switzerland, 2001.
163. Mazzeo, D.; Matera, N.; Cornaro, C.; Oliveti, G.; Romagnoni, P.; De Santoli, L. EnergyPlus, IDA ICE and TRNSYS predictive simulation accuracy for building thermal behaviour evaluation by using an experimental campaign in solar test boxes with and without a PCM module. *Energy Build.* **2020**, *212*, 109812. [CrossRef]
164. TC; ISO. *Thermal Performance of Windows, Doors and Shading Devices—Detailed Calculations*; ISO: Berlin, Germany, 2001.
165. Loutzenhiser, P.G.; Manz, H.; Moosberger, S.; Maxwell, G.M. An empirical validation of window solar gain models and the associated interactions. *Int. J. Therm. Sci.* **2009**, *48*, 85–95. [CrossRef]
166. Karlsson, F.; Rohdin, P.; Persson, M.L. Measured and predicted energy demand of a low energy building: Important aspects when using building energy simulation. *Build. Serv. Eng. Res. Technol.* **2007**, *28*, 223–235. [CrossRef]
167. Bring, A.; Sahlin, P.; Vuolle, M. *Models for Building Indoor Climate and Energy Simulation*; Report of IEA SHC Task; International Energy Agency for Solar Heating and Cooling Programme: Cedar, MI, USA, 1999; p. 22.
168. Equa Simulation AB. User Manual, IDA Indoor Climate and Energy, Version 4.5. 2014. Available online: http://www.equaonline.com/iceuser/pdf/ICE45eng.pdf (accessed on 20 August 2021).
169. *TRNSYS User Manual*; Version 16; University of Wisconsin: Madison, WI, USA, 2004.
170. El-Sadi, H.; Haghighat, F.; Fallahi, A. CFD analysis of turbulent natural ventilation in double-skin façade: Thermal mass and energy efficiency. *J. Energy Eng.* **2010**, *136*, 68–75. [CrossRef]
171. Walton, G.N.; Dols, W.S. *CONTAM User Guide and Program Documentation*; US Department of Commerce, Technology Administration, National Institute of Standards and Technology: Gaithersburg, MD, USA, 2013.
172. Weber, A.; Koschenz, M.; Holst, S.; Hiller, M.; Welfonder, T. *TRNFLOW: Integration of COMIS into TRNSYS TYPE 56*; University of Wisconsin Madison: Madison, WI, USA, 2002.
173. Pipitone, G.; Barone, G.; Palmeri, A. Optimal design of double-skin façades as vibration absorbers. *Struct. Control. Health Monit.* **2018**, *25*, e2086. [CrossRef]
174. Fu, T.S. Double skin façades as mass dampers. In Proceedings of the 2013 American Control Conference, Washington, DC, USA, 17–19 June 2013; IEEE: Washington, DC, USA, 2013; pp. 4742–4746.
175. Azad, A.; Ngo, T.; Samali, B. Control of wind-induced motion of tall buildings using smart façade systems. *Electron. J. Struct. Eng.* **2015**, *14*, 33–40. [CrossRef]
176. Samali, B.; Attard, M.M.; Song, C. (Eds.) *From Materials to Structures: Advancement through Innovation*; CRC Press: Boca Raton, FL, USA, 2013; pp. 431–435.
177. Carpenter, L.D. Influences on structural engineering. *Struct. Des. Tall Spec. Build.* **2005**, *14*, 419–425. [CrossRef]
178. Solnosky, R.L. Analytical, Communication, and Information Technology Directions in the Structural Industry. *Pract. Period. Struct. Des. Constr.* **2016**, *21*, 4015002. [CrossRef]
179. Solnosky, R.L. Integrated structural processes on innovative multidisciplinary projects supported by building information modeling. *J. Archit. Eng.* **2017**, *23*, 5016004. [CrossRef]
180. Ding, C.; Ngo, T.; Ghazlan, A.; Lumantarna, R.; Mendis, P. Numerical simulation of structural responses to a far-field explosion. *Aust. J. Struct. Eng.* **2015**, *16*, 226–236. [CrossRef]
181. Ngo, T.; Ding, C.; Lumantarna, R.; Ghazlan, A.; Zobec, M. Structural performance of double-skin façade systems subjected to blast pressures. *J. Struct. Eng.* **2015**, *141*, 4015064. [CrossRef]
182. Hu, G.; Hassanli, S.; Kwok, K.C.; Tse, K.T. Wind-induced responses of a tall building with a double-skin façade system. *J. Wind. Eng. Ind. Aerodyn.* **2017**, *168*, 91–100. [CrossRef]
183. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.S. Suh Recent developments in life cycle assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef] [PubMed]
184. Pomponi, F.; D'Amico, B.; Moncaster, A.M. A method to facilitate uncertainty analysis in LCAs of buildings. *Energies* **2017**, *10*, 524. [CrossRef]
185. Ortiz, O.; Castells, F.; Sonnemann, G. Sustainability in the construction industry: A review of recent developments based on LCA. *Constr. Build. Mater.* **2009**, *23*, 28–39. [CrossRef]
186. Jones, C.; Hammond, G. Inventory of Carbon & Energy (ICE) Version 2.0. In *Sustainable Energy Research Team (SERT)*; SERT, Ed.; University of Bath: Bath, UK, 2011.
187. SimaPro. SimaPro Database Manual Methods Library. Available online: https://simapro.com/wp-content/uploads/2022/07/DatabaseManualMethods.pdf (accessed on 12 September 2022).
188. GreenConcrete LCA. GreenConcrete LCA Web Tool. Available online: http://greenconcrete.berkeley.edu (accessed on 1 September 2022).
189. Sphera. GaBi Sphera US LCI Database. Available online: https://gabi.sphera.com/america/databases/us-lci-database/ (accessed on 4 September 2022).
190. Pratiwi, A.; Ravier, G.; Genter, A. Life-Cycle Climate-Change Impact Assessment of Enhanced Geothermal System Plants in the Upper Rhine Valley. *Geothermics* **2018**, *75*, 26–39. [CrossRef]
191. Athena Institute. Athena Impact Estimator for Buildings V5. Available online: https://calculatelca.com/software/impact-estimator/ (accessed on 4 September 2022).

192. Bryan, H. Le Corbusier and the 'Mur Neutralisant: An Early Experiment in Double Envelope Construction. In Proceedings of the Ninth International PLEA Conference, Seville, Spain, 24–27 September 1991; pp. 257–262.
193. Tomlinson, R.; Baker, W.; Leung, L.; Chien, S.; Zhu, Y. Case Study: Pearl River Tower. *CTBUH J.* **2014**, *2*, 12–17.
194. SOM. Pearl River Tower Deep Dive into Sustainable Design. Available online: https://www.som.com/projects/pearl-river-tower/#deep-dive-an-extra-sustainable-design (accessed on 7 August 2022).
195. Gonchar, J. Pearl River Tower. Architectural Record. March 2014. Available online: https://www.architecturalrecord.com/articles/7971-pearl-river-tower (accessed on 7 August 2022).
196. Architizer. Pearl River Tower. Available online: https://architizer.com/projects/pearl-river-tower/ (accessed on 7 August 2022).