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MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
جامعة الشهيد الشيخ العربي التبسي-تبسة
CHAHID CHEIKH LARBI TEBESSI UNIVESITY-TEBESSA
كلية العلوم و التكنولوجيا
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# DOUBLE SKIN FAÇADE AS A TOOL TO ENHANCE THERMAL COMFORT IN AIRPORT TERMINAL HALLS IN BSK CLIMATE

Presented and publicly defended on: 11/06/2023 before the jury composed of:

| | | |
|---|---|---|
| **1- Dr. Tartar Nassima** | **Senior lecturer** | **President** |
| **2- Dr. Fazzai Soufiane** | **Senior lecturer** | **Supervisor** |
| **3- Dr. Ahriz Atef** | **Senior lecturer** | **Examiner1** |
| **4- Dr. Gharbi Mohamed** | **Senior lecturer** | **Examiner2** |

**Academic Year:2024/2025**

037 58 46 19 www.univ-tebessa.dz/fst Fac.st@univ-tebessa.dz

# *Dedication*

*To my grandfather, who believed in this journey before he ever saw me reach it, your faith continues to guide me.*

*To my beloved parents, whose love, prayers, and sacrifices have been the pillars of my strength.*

*To my three brothers, with special love to my dear Yahya your support has always brought me comfort and courage.*

*To Touti, your love, patience, and unwavering belief in me have been the heart of this year. In the hardest moments and the quiet victories, you stood by me. I am endlessly grateful for your presence in my life.*

*And to my dear friends, Nour and Hadil, your friendship, kindness, and encouragement have been a light along the way.*

*This work is for all of you….*

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*To Touti — words will never be enough to thank you. Your love, care, and faith in me have carried me through the most challenging times of this journey. You have been my strongest supporter, and I am forever thankful for you.*

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## Abstract:

This research investigates the use of double-skin façades (DSF) as a passive design strategy to enhance thermal comfort in airport terminal halls located in regions with a cold semi-arid climate (BSK), such as Tebessa. The subject was chosen in response to rising energy demands and thermal discomfort in large-scale public buildings, particularly airports in Algeria, where traditional façades often fail to provide adequate environmental control.

Given the importance of indoor environmental quality in airport terminals, this study evaluates DSF performance in terms of insulation and solar protection.

An experimental "generate and test" approach was adopted, using Rhinoceros 3D and the Grasshopper plugin, along with Ladybug and Honeybee for environmental analysis. Various DSF configurations were simulated, defined by different glass thicknesses and cavity depths. A sensitivity response method was used to identify optimal DSF models within each glass category. These optimal cases were then compared to assess their relative thermal efficiency. The best-performing DSF model was finally benchmarked against a single-glazing façade (SGF) to evaluate its added thermal comfort benefits.

The results demonstrate that, when properly designed, DSFs can significantly improve thermal conditions in airport terminal halls, especially when deeper cavities are used. The configuration featuring 12 mm glass and a 0.8 m cavity achieved the highest thermal comfort hours, contributing to improved passenger comfort in cold semi-arid climates.

**Keywords: double skin façade (DSF), single glazing façade (SGF), thermal comfort, airport terminal halls, cold semi-arid climate (BSK).**

**Résumé:**

Cette recherche examine l'utilisation des façades double peau (DSF) en tant que stratégie de conception passive visant à améliorer le confort thermique dans les halls des terminaux aéroportuaires situés dans des régions au climat froid semi-aride (BSK), telles que Tébessa. Le choix de ce sujet résulte de l'augmentation des besoins énergétiques et de l'inconfort thermique observé dans les bâtiments publics de grande échelle, notamment les aéroports algériens, où les façades traditionnelles peinent à assurer un contrôle environnemental adéquat.

Étant donné l'importance de la qualité de l'environnement intérieur dans les terminaux aéroportuaires, cette étude évalue les performances des DSF en matière d'isolation thermique et de protection solaire.

Une approche expérimentale de type « génération et test » a été adoptée, à l'aide du logiciel Rhinoceros 3D et du plugin Grasshopper, complétés par les outils d'analyse environnementale Ladybug et Honeybee. Différentes configurations de DSF ont été simulées, caractérisées par des épaisseurs de vitrage et des profondeurs de cavité variables. Une méthode d'analyse de sensibilité a permis d'identifier les modèles optimaux pour chaque catégorie de vitrage. Ces modèles ont ensuite été comparés pour évaluer leur efficacité thermique relative. Enfin, le modèle le plus performant a été comparé à une façade simple vitrage (SGF) afin d'évaluer les gains supplémentaires en confort thermique.

Les résultats montrent que, lorsqu'elles sont bien conçues, les façades doubles peau peuvent considérablement améliorer les conditions thermiques dans les terminaux, notamment avec des cavités plus profondes. La configuration avec un vitrage de 12 mm et une cavité de 0,8 m a enregistré le plus grand nombre d'heures de confort thermique, contribuant ainsi à une meilleure qualité d'accueil des passagers dans les climats froids semi-arides.

**Mots-clés : façade double peau (DSF), façade simple vitrage (SGF), confort thermique, halls de terminaux aéroportuaires, climat semi-aride froid (BSK).**

**الملخص:**

تتناول هذه الدراسة استخدام الواجهات ذات الطبقة المزدوجة (Double-Skin Façades - DSF) كإستراتيجية تصميم سلبي تهدف إلى تحسين الراحة الحرارية في قاعات المحطات الجوية الواقعة في المناطق ذات المناخ شبه الجاف البارد(BSK) ، مثل مدينة تبسة. جاء اختيار هذا الموضوع استجابةً لزيادة الطلب على الطاقة، ولما يُلاحظ من انعدام الراحة الحرارية في المباني العامة الكبرى، خاصةً المطارات الجزائرية، حيث غالبًا ما تفشل الواجهات التقليدية في توفير تحكم بيئي فعّال.

نظرًا لأهمية جودة البيئة الداخلية في محطات الركاب الجوية، تهدف هذه الدراسة إلى تقييم أداء الواجهات المزدوجة من حيث العزل الحراري والحماية من الإشعاع الشمسي. تم اعتماد منهجية تجريبية تعتمد على مبدأ "الإنشاء والاختبار"، باستخدام برنامج Rhinoceros 3D مع الإضافة البرمجيةGrasshopper ، بالإضافة إلى أدوات التحليل البيئي مثل Ladybugو .Honeybee شملت المحاكاة عدة تكوينات منDSF ، اختلفت حسب سماكة الزجاج وعمق الفجوة الهوائية. وقد استُخدم أسلوب تحليل الحساسية لتحديد النماذج المثلى ضمن كل فئة زجاجية، ثم تمت مقارنة هذه النماذج لتقييم كفاءتها الحرارية النسبية. وأخيرًا، تمت مقارنة النموذج الأفضل أداءً بواجهة ذات زجاج مفرد - Single Glazing Façade) (SGFلقياس مكاسب الراحة الحرارية الإضافية.

أظهرت النتائج أن الواجهات ذات الطبقة المزدوجة، عند تصميمها بشكل مدروس، قادرة على تحسين الظروف الحرارية الداخلية لمحطات المطارات بشكل ملحوظ، خاصةً عند استخدام فجوات أعمق. حيث سجلت التكوينات المكونة من زجاج بسماكة 12 ملم وفجوة بعمق 0.8 متر أعلى عدد ساعات للراحة الحرارية، مما يعزز من راحة المسافرين في المناخات شبه الجافة والباردة.

**الكلمات المفتاحية :الواجهة ذات الطبقة المزدوجة(DSF) ، الواجهة ذات الزجاج المفرد(SGF) ، الراحة الحرارية، قاعات المحطات الجوية، المناخ شبه الجاف البارد.(BSK)**

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## General Introduction:

Thermal comfort, as defined by ASHRAE, is “that condition of mind which expresses satisfaction with the thermal environment” (ASHRAE, 2013). It is a key component of indoor environmental quality, influencing not only human well-being but also productivity and overall interaction with indoor spaces. Ensuring thermal comfort is a fundamental goal in sustainable architectural design.

In large-scale public buildings such as airport terminals characterized by high-energy demand, large glazed surfaces, and varied occupancy patterns, thermal comfort becomes even more critical. These spaces often host users under varying degrees of stress, limited movement, and long waiting times. The ability of an airport terminal to offer a comfortable environment significantly shapes how passengers perceive service quality and spatial experience.

Passive design strategies are, increasingly recognized as essential for achieving energy-efficient and climate-responsive architecture. Among these strategies, the double-skin façade (DSF) has emerged as a promising solution for improving thermal performance. A DSF consists of two layers of glazing separated by an air cavity, which can be naturally, mechanically, or hybrid ventilated. This system serves as a dynamic thermal buffer, helping to regulate internal temperatures through the modulation of solar gains, insulation, and ventilation. Parameters such as cavity depth, ventilation strategy, and glass type are all critical in determining the façade’s thermal behaviour.

However, the application of double skin façades has not been widely studied in cold semi-arid climates (BSK), particularly in airport terminal buildings, which presents a significant gap in research and practice.

In the context of airport architecture, DSFs present a strategic opportunity: they enable visual openness while also enhancing indoor comfort. As airports increasingly function as cultural, economic, and transportation hubs, their architectural envelope must meet the dual challenges of functionality and environmental performance.

This research investigates the effectiveness of DSFs in improving thermal comfort specifically within airport terminal halls located in cold semi-arid climates (BSK), using the case of Tebessa. The study adopts a simulation-based methodology using Rhinoceros 3D with the Grasshopper plugin and environmental analysis tools such as Ladybug, Honeybee, and Skin Designer. Multiple DSF configurations defined by different cavity depths and glazing thicknesses are modelled and evaluated. The aim is to identify optimal design parameters that enhance thermal comfort and to benchmark their performance against a traditional single glazing façade (SGF).

This study contributes to the broader goal of designing climate adaptive airports by providing performance-based insights into the application of double skin façade systems in challenging climatic conditions.

# INTRODUCTORY CHAPTER

## I. Problem statement:

Buildings in BSK climate such as Tebessa face significant challenges related to indoor thermal comfort; traditional glazed envelopes in buildings often fail to provide thermal comfort. In airports, choosing an adequate architectural envelope is a very important decision because it has a key role in reducing or enhancing passenger's comfort, indeed, in this context, it turns out that the construction technique of the façade as well as the choice of materials and their characteristics have a great influence on its thermal behaviour. The double skin façade is one of these rapidly expanding techniques it considered a simple and effective solution to improve the thermal quality of façades.

Despite the wide range of international research on DSFs, their application in cold semi-arid regions remains not widely investigated, particularly in large-scale public buildings such as airport terminals, where maintaining thermal comfort often requires substantial energy consumption. This lack of context-specific studies highlights a critical research gap that this work aims to address.

## II. Research questions:

This research seeks to answer the following main question:

- **How can DSF improve indoor thermal comfort in airport terminals, mainly in BSK climate?**

This question may be divided into sub questions:

- How do the design parameters of DSF affect thermal comfort performance?
- Can DSF improve indoor thermal comfort compared to SGF?

## III. Hypothesis:

- Implementing a DSF in BSK climate may enhance thermal comfort by reducing indoor temperature fluctuations.
- DSF may improve indoor thermal comfort due to its design parameters where it can enhance thermal insulation, reduce indoor temperature fluctuations, and improve occupant comfort.
- DSF may provide better indoor thermal comfort compared to SGF due to their ability to optimize solar gain in winter and reduce overheating in summer.

## IV. Objectives:

- This research focuses on the use of double skin façade to achieve thermal comfort in airport terminals hall.

- Analyse the effectiveness of DSF in improving thermal comfort in airport terminal halls through its design parameters
- Classify and compare the efficiency of single glazing façade and double skin façade on thermal comfort.

## V. Research methodology:

This study adopts a simulation-based methodology with quantitive approach to evaluate the impact of double-skin façades (DSF) on indoor thermal comfort in airport terminal halls. The research is based on a numerical model of an airport located in Tebessa, Algeria, which represents a cold semi-arid (BSK) climate.

The investigation focuses on how specific DSF design parameters namely: cavity depth and glazing thickness, affect thermal performance. The building and façade models were developed and simulated using *Rhinoceros 3D* in combination with *Grasshopper*, and environmental analysis tools including *Ladybug*, *Honeybee*, and *Skin Designer*. These tools enabled precise façade modelling and environmental evaluation, using climate-based data and thermal comfort standards derived from ASHRAE 55:2013.

A sensitivity response method was employed to test multiple DSF configurations. The goal was to identify the optimal combination within each glazing thickness category across different cavity depths, resulting a selection of optimal DSF configurations. Thermal comfort was assessed using the Predicted Mean Vote (PMV) index, which measures occupants' thermal sensation on a scale from cold to hot.

The final step involved a comparative analysis between the best-performing DSF configuration and a conventional single glazing façade (SGF) model, in order to quantify the difference in thermal comfort performance. This methodological approach ensures a comprehensive, data-driven evaluation of DSF systems in the context of climate responsive airport design.

## VI. Structure of the Research

This research is divided into two main parts: (theoretical part and practical part).

Methodology is structured into two main parts: theoretical part (3 chapters) and practical part (two chapters). Below is a detailed explanation of the research structure, aligning with chapters:

**Part One: Theoretical background:**

This section includes three chapters aims to provide an overview of thermal comfort, the design principles of DSF, and their design parameters. Additionally, it will explore the airport

and its components, and thermal comfort in airports, then the previous studies related to the subject, to explore the key parameters influencing indoor thermal comfort performance and find the best software of simulation. Through this review, the objective is to understand the role of DSF in enhancing thermal comfort.

**Part Two: Analytical Section:**

This section outlines the simulation method and protocol, detailing different methods used to assess the performance of DSF, by testing various scenarios based on different design parameters, followed by a comparative analysis is conducted between the optimal model of DSF and SGF.

The findings from this analysis will contribute to a deeper understanding of the effectiveness of DSF in optimizing building performance in BSK climate.

This research is composed of five main chapters as follows:

- **The Introductory Chapter:** presents a general idea about the subject includes the research problem, hypotheses, objectives, and the adopted research methodology.
- **Chapter One:** provides a theoretical background on the concepts of thermal comfort and DSF. It explains their definitions, principles of operation, influencing parameters, types, and classifications, forming the conceptual foundation of the study.
- **Chapter Two:** focuses on the equipment, which in this case is the airport terminal. It includes a study of its functional and architectural aspects, with a detailed investigation of its design components. It also provides the importance of thermal comfort and their conditions in terminals.
- **Chapter Three:** is dedicated to previous studies concerning the application of DSF in various building types, particularly administrative and public facilities. It includes experimental research and evaluations of DSF performance in different climatic contexts. Mainly, those, which are close to BSK climate.
- **Chapter Four:** this chapter outlines the simulation methodology used to evaluate thermal performance of DSF. It presents the tools to create a design model and analyse multiple simulation scenarios with different design parameters, and explains the selection of both fixed and variable parameters
- **Chapter Five:** This chapter interprets the data obtained from the thermal simulations of the different DSF configurations. It compares the performance of each scenario using PMV range, in both winter and summer. The analysis identifies how variations in cavity depth and glazing thickness affect thermal comfort, highlighting performance patterns and thresholds. Referencing findings from relevant literature to validate or contrast the results. The discussion leads to the selection of the most effective DSF configuration and supports the research hypotheses with evidence-based conclusions.

# THEORITICAL PART

# CHAPTER 1: THERMAL COMFORT AND DOUBLE SKIN FAÇADE

## Introduction:

Thermal comfort is a fundamental aspect of indoor environmental quality and plays a crucial role in determining the overall wellbeing, health, and productivity of occupants in a building. It refers to the state of mind that expresses satisfaction with the surrounding thermal environment; it is influenced by a combination of environmental and personal factors.

These include air temperature, relative humidity, air velocity, mean radiant temperature, clothing insulation, and metabolic rate.

In architectural design, ensuring thermal comfort is particularly essential in public buildings, where large numbers of users with diverse thermal preferences converge in spacious, often glazed, environments.

# I. Thermal comfort:

## 1. Definition of thermal comfort:

In agreement with ASHRAE Standard 55, Thermal comfort is *"the condition of mind that expresses satisfaction with the thermal environment",* this means that he feels thermally neutral for the whole body. (ASHRAE, 2013)

Other ways The ISO 7730:2005 standard**:** defines thermal comfort as: '*the thermal sensation experienced by the human body related to its overall thermal balance'*. In addition, the standard takes into account the state of mind under which satisfaction with the thermal environment surrounding the individual is expressed.(ISO, 2005)

While B.W. Magnum define thermal comfort as: *"a requirement that there is no local warm or cold discomfort at any part of the human body, due to asymmetric radiation, draft, warm or cold floors, vertical temperature gradients, non-uniform clothing, etc*".(Mangum and Hill, 1977)

We conclude that thermal comfort is not just about temperature it is about how the whole body feels balanced and neutral, without noticing heat or cold. It depends on both physical conditions, and mental perception. Different parts of the body must feel equally comfortable.

## 2. Factors influencing thermal comfort:

The parameters affecting thermal comfort are divided into two: environmental factors and personal factors:(Hemate, 2016)

### 2.1. Parameters related to environment:

#### 2.1.1. Dry bulb temperature (DBT):

Dry bulb temperature or "mean air temperature " it refers to the temperature of the air, measured by a standard thermometer unaffected by humidity or radiant heat. It is a key factor in determining

thermal comfort and heat exchange between the body and the surrounding environment. (Hemate, 2016, ASHRAE, 2013)

#### 2.1.2. Relative Humidity (RH):

Determines the rate of evaporation or the amount of water vapour pressure in the air. High or low humidity reduces the body comfort. (Hemate, 2016)

#### 2.1.3. Air movement:

Air movement or 'air velocity' means the circulation of air. It accelerates convection and helps evaporation from the skin, which producing cool environment.

'The way air velocity affects comfort is variable depending on the surface temperature and wind speed. For example, a surface temperature of 25ºC would feel the same for air temperature 30ºC at 0.8 m/s and air Temperature of 26ºC at 0.25 m/s'. (Hemate, 2016)

#### 2.1.4. Mean radiant temperature (MRT):

It influences the body's heat lose or gained through radiation and conduction. (Hemate, 2016)

### 2.2. Personal determinants:

#### 2.2.1. Activity:

Determines the rate at which the body converts food into heat (metabolic rate). This process is a function of a person's activity level. (Hemate, 2016)

As suggested by (Gagge et al., 1967), activity is often expressed in met units (1 met = 58 W/m2 corresponding to sedentary activity), The "met" quantifies the metabolic rate and varies from 7.6 for playing basketball to 0.7 for sleeping. These values can be found in Appendix A of ASHRAE 55. (ASHRAE, 2013)

#### 2.2.2. Clothing:

It acts as a thermal insulator or resistance for the body against external factors, serving as an adjustment mechanism that enables adaptation to both cooler and warmer air temperatures. (Hemate, 2016)

The "clo" unit quantifies the level of clothing insulation, where 1 clo equals 0.155 $m^2 \cdot °C/W$. Clo values range from as low as 0.1 for light clothing such as shorts, to between 3 and 4 for heavy garments like a polar weather suit. These values can be found in (Appendix B of ASHRAE 55). (ASHRAE, 2013)

## 3. Metrics to evaluate indoor thermal comfort:

To assess thermal comfort effectively, researchers rely on various metrics that quantify environmental and physiological parameters. These metrics considers the previous factors such as

air temperature, humidity, radiant temperature, air velocity, metabolic rate, and clothing insulation. (ASHRAE, 2013)

The most common used metrics to evaluate indoor thermal comfort are:

### 3.1. Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD):

PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) are intrinsically linked metrics used to evaluate thermal comfort, particularly as defined in ASHRAE Standard 55-2013 (Addendum h). PMV predicts the average thermal sensation of occupants on a 7 point scale, while PPD estimates the percentage of people likely to be dissatisfied with the thermal environment. (ASHRAE, 2013)

The PPD is derived empirically from the PMV, based on experimental data. Even under ideal conditions when PMV equals 0 (neutral) PPD is still 5%, recognizing natural individual variability. As PMV deviates from neutral (toward hot or cold), the PPD increases sharply, indicating a greater proportion of occupants feeling discomfort**.** (ASHRAE, 2013)

The standard sets a comfort threshold of PMV between -0.5 and +0.5, which corresponds to PPD ≤10%, ensuring at least 80% occupant satisfaction. As it is motioned in Appendix D, in ASHREA STANDARD. This integration between PMV and PPD helps designers evaluate and balance thermal neutrality with practical levels of comfort acceptance. (ASHRAE, 2013, (ISO), 1994)

The following table shows the PPD as a function of predicted mean vote, and how values of PPD changes with PMV:

90238b9f8b20/iso-7730-1994

| PMV | PPD | Percentage of persons predicted to vote | | |
|---|---|---|---|---|
| | | 0 | − 1, 0 or + 1 | − 2, − 1, 0, + 1 or + 2 |
| + 2 | 75 | 5 | 25 | 70 |
| + 1 | 25 | 27 | 75 | 95 |
| 0 | 5 | 55 | 95 | 100 |
| − 1 | 25 | 27 | 75 | 95 |
| − 2 | 75 | 5 | 25 | 70 |

Table 1.1 Predicted percentage of dissatisfied (PPD) as a function of predicted mean vote (PMV) ((ISO), 1994)

#### 3.1.1. Predicted Mean Vote (PMV):

The PMV established by Fanger measures the overall thermal sensation of the human body based on metabolism and provides the average votes in reference to a thermal sensation scale. (CIBSE, 2006)

PMV, calculated using six key factors (air temperature, mean radiant temperature, humidity, air speed, metabolic rate, and clothing insulation), predicts the average thermal sensation of occupants on a 7 point scale from -3 (cold) to +3 (hot). ((ISO), 1994, ASHRAE, 2013). As shows table 1.2.

| **PMV Index Values** | **+3** | **+2** | **+1** | **0** | **-1** | **-2** | **-3** |
|---|---|---|---|---|---|---|---|
| **Thermal Sensation** | Hot | Warm | Slightly Warm | Neutral | Slightly Cool | Cool | Cold |

Table 1.2 Correspondence between PMV and Thermal Sensation Scale (ASHRAE, 2013)

### 3.1.2. Predicted Percentage of dissatisfied (PPD):

By exterminating a large number of testes data shows that 5% of the population would be dissatisfied even under the "best" conditions, at the best PMV = 0 level. With departure from this, the percentage dissatisfied rapidly increases. The empirical curve below (figure 1.1) shows the PPD (predicted percentage dissatisfied) as a function of PMV (note that at least 5% of the population would be dissatisfied even under the "best" conditions). (CIBSE, 2006)

The ISO 7730 standard states that to be within the thermal comfort zone, the PMV must be between 0.5 and 0.5, and the PPD must be less than 10%. ((ISO), 1994)

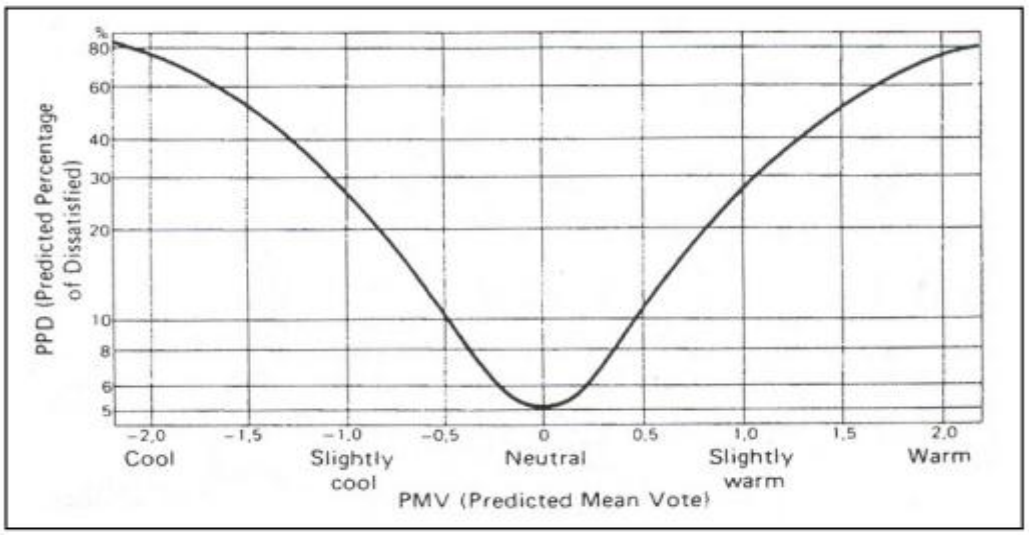



Figure 1.1: Correspondences between PMV and PPD (CIBSE, 2006)

### 3.2. Ambient Air Temperature (Ta)

It represents the most commonly used index for indoor environment control due to the simplicity of its measurement. This parameter does not present significant difficulties in terms of measurement and evaluation; however, it remains somewhat limited for

a comprehensive characterization of comfort. As a widely recognized index, air temperature is extensively used as a comfort indicator in cases where thermal comfort control is not highly stringent. It is used to define reference temperature set points for heating systems during winter and air conditioning systems during summer. (CIBSE, 2006)

### 3.3. Operative Temperature (TOP):

Operative temperature is a thermal comfort index that integrates two physical parameters: ambient air temperature and mean radiant temperature. It is therefore an index used to assess the combined effects of convection and radiation on an individual's comfort. (CIBSE, 2006)

### 3.4. Physiological Equivalent Temperature (PET):

The PET comfort index, derived from the human heat balance model, combines weather and thermo-physiological parameters (clothing and human activities).

It is used to measure the thermal comfort of an individual in a given situation by comparing his physiological responses to those he would have in the reference environment. (CIBSE, 2006)

## 4. Codes and standards:

Thermal comfort codes and standards provide guidelines for maintaining comfortable indoor environments in buildings, ensuring that occupants are neither too hot nor too cold. These standards consider factors such as air temperature, humidity, air velocity, radiant temperature, clothing, and metabolic rate. An overview of major thermal comfort standards used internationally, along with relevant national regulations, is presented below:

### 4.1. International standards:

#### 4.1.1. ANSI /ASHRAE Standard 55 (United States):

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers ASHRAE Standard 55, titled "Thermal Environmental Conditions for Human Occupancy," is one of the most widely used standards globally for ensuring thermal comfort in indoor environments, and ANSI: American national standards institute it contains the following standards and values:

-**Environmental Factors:** Air temperature, radiant temperature, humidity, and air speed. All values of acceptable comfortable ranges are cited in the table 1.3.

| Factor | Acceptable Range / Limit |
|---|---|
| Air Temperature | 22–27°C (summer), 20–24°C (winter) |
| Mean Radiant Temp. | Should not differ more than 5°C from air temp |
| Humidity | Max 60% RH |
| Air Speed | Up to 0.8 m/s |

Table 1.3 ASHRAE 55 – Environmental Parameters (author, 2025)(ASHRAE, 2013)

**-Personal Factors:** Metabolic rate depends on activity level and clothing insulation.

**-Comfort Models:** PMV/PPD Model: Predicts thermal sensation (PMV) and percentage of dissatisfied occupants. All values of acceptable comfortable ranges are cited in the table 1.4.

| Model | Value / Threshold |
|---|---|
| PMV Range | Between -0.5 and +0.5 |
| PPD Limit | ≤ 10% dissatisfied |

Table 1.4 ASHRAE 55 – Comfort Models (author, 2025) (ASHRAE, 2013)

**-Adaptive Model:** Applicable for naturally ventilated spaces; relates indoor temperatures to outdoor conditions. All values of acceptable comfortable ranges are cited in the table 1.5.

| Outdoor Running Mean Temp (°C) | Acceptable Indoor Operative Temp (°C) |
|---|---|
| 10 – 33.5°C | Defined via linear formula ±2.5°C from neutral (80% acceptability) |

Table 1.5 ASHRAE 55 – Adaptive Model (Naturally Ventilated Spaces) (author, 2025) (ASHRAE, 2013)

**-Local Discomfort Criteria:** Addresses factors like draft, vertical air temperature differences, and radiant temperature asymmetry. All values of acceptable comfortable ranges are cited in the table 1.6.

| Parameter | Limit |
|---|---|
| Vertical Temp. Difference | ≤ 3°C (head-to-foot) |
| Radiant Temp. Asymmetry | ≤ 5°C (warm ceiling); ≤ 10°C (cold wall) |
| Draft (air speed) | ≤ 0.2 m/s |
| Floor Surface Temp. | Between 19°C and 29°C |

Table 1.6 ASHRAE 55 – Local Discomfort Limits (author, 2025) (ASHRAE, 2013)

**- Design Compliance:** Provides methods for demonstrating compliance in both new and existing buildings.

This standard aims to advance the science of HVAC and building systems for human welfare.

Members are guided by core values like integrity, collaboration, and diversity, and are expected to avoid conflicts of interest.

The purpose of this standard is to define the combination of indoor thermal environmental factors and personal factors that create thermal conditions acceptable to most occupants in a space.(ASHRAE, 2013)

#### 4.1.2. ISO 7730 (International):

The International Organization for Standardization (ISO) developed ISO 7730, titled "Ergonomics of the Thermal Environment - Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria." It is widely adopted in Europe and other regions globally.

Thermal Comfort Categories: ISO 7730 defines three categories of comfort environments the table below (table 1.7) shows the range of PMV and PPD and its application for each category:

| Category | PMV Range | PPD Limit | Application |
|---|---|---|---|
| A | -0.2 to +0.2 | ≤ 6% | Very high comfort, critical spaces |
| B | -0.5 to +0.5 | ≤ 10% | Normal buildings (offices, schools) |
| C | -0.7 to +0.7 | ≤ 15% | Moderate comfort, less critical |

Table 1.7 ISO 7730 – Comfort Categories (author, 2025)((ISO), 1994)

#### 4.1.3. WELL Building Standard (International):

The WELL Building Standard, developed by the International WELL Building Institute (IWBI), is a performance based system for measuring the impact of buildings on occupant health, including thermal comfort.(IWBI, 2025)

### 4.2. National standards (Algerian standards):

In Algeria, thermal comfort in buildings is influenced by a combination of national building regulations, international standards, and energy efficiency requirements. Although there is no specific, widely recognized thermal comfort standard that is unique to Algeria, the country has adopted regulations related to energy efficiency and thermal performance in buildings that indirectly address thermal comfort. These standards are in line with international frameworks like ISO and ASHRAE.(Tellache, 2025)

#### 4.2.1. DTR C 3-2 (Réglementation Thermique Algérienne - Thermal Regulation of Buildings):

This is the main Algerian standard focused on the thermal performance of buildings. It provides guidelines on the thermal insulation of buildings to reduce energy consumption and improve indoor thermal comfort, especially in residential and commercial buildings. It emphasizes the use of proper insulation materials, ventilation, and building orientation to ensure efficient temperature control and comfort in various climates of Algeria.((CNERIB), 1997)

The following table 1.8 shows the values of each standard:

| Standard / Reference | Parameter | Value / Range |
|---|---|---|
| DTU 65.10 | Base indoor temperature (Tib) | Dwellings: 19°C |
| Decree of October 22, 1969 | Tib by room | Living room: 19°C<br>Bedrooms: 16°C<br>Bathrooms: 22°C<br>Hallways: 19°C |
| Algerian Thermal Regulation (RTA) | Winter indoor temperature | 18°C to 22°C depending on zones |
| RT 2000 (France) | Conventional temperature | 19°C |
| ISO 7730 / ASHRAE 55 | Recommended comfort temperature | 20°C to 24°C |
| ISO 7730 | Relative humidity | 30% – 70% |
| ASHRAE 55 | Air speed | ≤ 0.15 m/s (winter)<br>≤ 0.25 m/s (summer) |

Table 1.8 DTR C 3-2 Thermal Comfort Standards and Values (author, 2025)((CNERIB), 1997)

# II. Thermal design strategies:

## 1. Thermal technics and façade strategies:

Modern façade design emphasizes the integration of active (mechanical, adaptive…ect) and passive (climate-responsive, material-driven…ect) systems to enhance occupant comfort, and architectural innovation. (Böke et al., 2022)

Several studies have explored the integration of thermal design strategies in buildings

to enhance occupant comfort, the flowchart bellow ( figure 1.2) illustrates the key thermal design strategies used in modern buildings to enhance occupant comfort and energy efficiency, which are collected from (Kilaire and Stacey, 2017, Brunoro, 2024, Vighio et al., 2024). It categorizes these strategies into passive techniques with natural climate responsive elements and active techniques that incorporate mechanical and adaptive technologies. These techniques can be an essential element to create an active or passive façade.

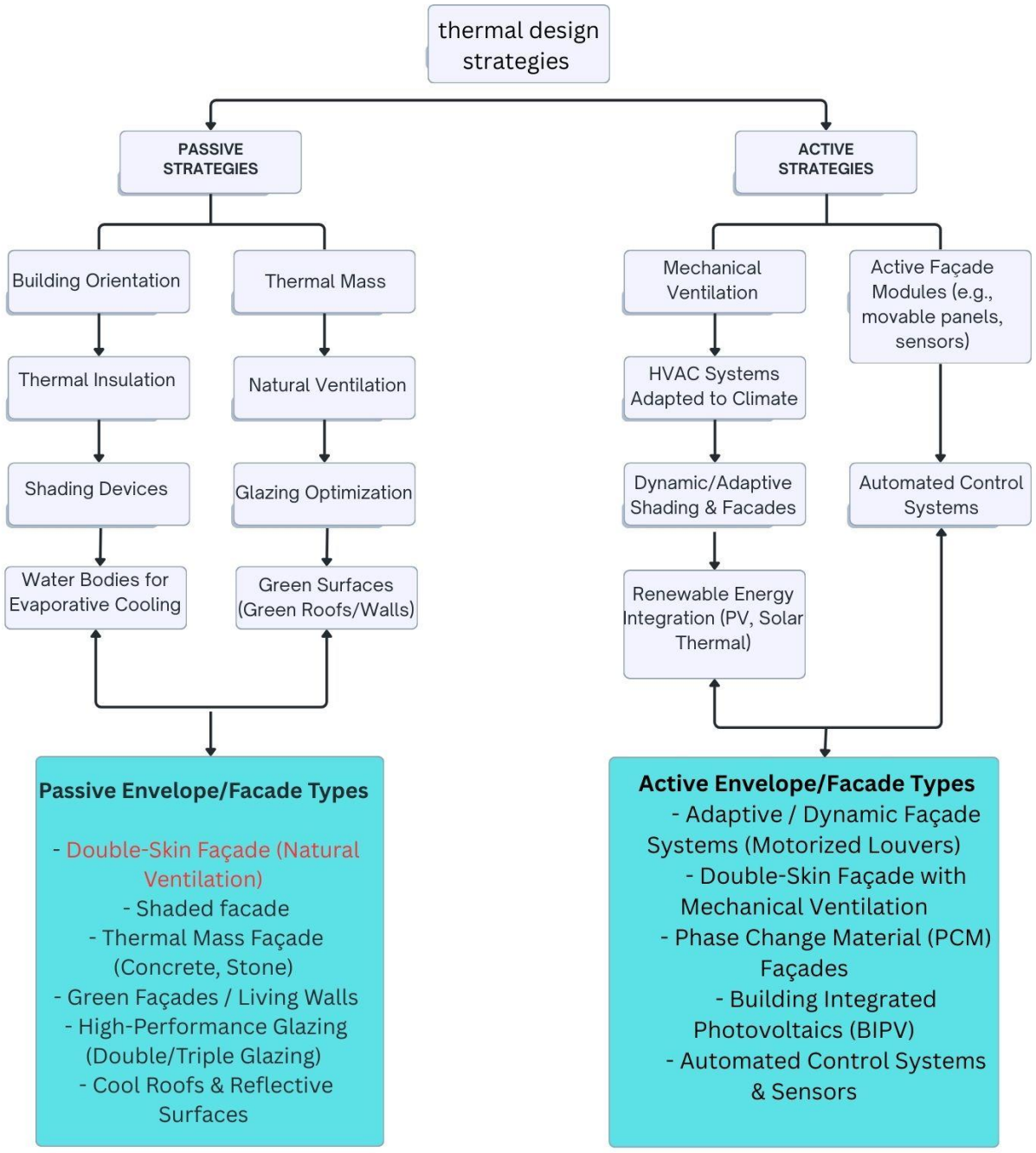



Figure 1.2 Thermal design strategies (author, 2025) (Kilaire and Stacey, 2017, Brunoro, 2024, Vighio et al., 2024)

## 2. Double skin façade:

### 2.1. Definition of double skin façade:

There are many definitions of double skin façade (DFS), In this study, ‘ DSF is a hybrid system composed of an external glazed skin added to the actual building façade, which constitutes the inner skin. The two layers are separated by an air cavity, which has fixed or controlled inlets and outlets and may or may not incorporate shading devices. The cavity may act either as a thermal buffer zone, as a ventilation channel or as a combination of the two. It may be naturally ventilated (NV) or mechanically ventilated (MV), and varies in width and height’. (Brunoro, 2008)




Figure 1.3 components of double skin façade Korniche. (Greiner, 2025)

A Double Skin Façade (DSF) is an architectural system composed of two layers of exterior surfaces typically glazed or a combination of materials separated by an air cavity that ranges in width from 20 centimetres to 2 meters. This ventilated cavity acts as a thermal buffer zone, enhancing the building’s energy efficiency by regulating heat transfer between the interior and exterior environments (Shen and Li, 2016, Lim and Ismail, 2022).

According to Claessens and DeHerde “a second skin façade is an additional building envelope installed over the existing façade. This additional façade is mainly transparent. The new space between the second skin and the original façade is a buffer zone that serves to insulate the building. This buffer space may also be heated by solar radiation, depending on the orientation of the façade. For south oriented systems, this solar heated air is used for heating purposes in the winter time. It must be vented in order to prevent overheating in other periods.”(Poirazis, 2006)

The double skin façade was used for multiple reasons and different functions encompassing aesthetic and technical aspects. It is used to improve natural lighting, optimize thermal and acoustic comfort, provide natural ventilation and minimize energy consumption'.(Shen and Li, 2016)

Harrison and Boake, (2003) in the Tectonics of the Environmental Skin, described the Double Skin Façade system as "essentially a pair of glass "skins" separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against temperature extremes, winds, and sound. Sun-shading devices are often located between the two skins. All elements can be arranged differently into numbersof permutations and combinations of both solid and diaphanous membranes".(Poirazis, 2006)

Uuttu, (2001) describes the Double Skin Façade as "a pair of glass skins separated by an air corridor (also called cavity or intermediate space) ranging in width from 20 cm to several meters. The glass skins may stretch over an entire structure or a portion of it. The main layer of glass, usually insulating, serves as part of a conventional structural wall or a curtain wall, while the additional layer, usually single glazing, is placed either in front of or behind the main glazing. The layers make the air space between them work to the building's advantage primarily as insulation against temperature extremes and sound."(Poirazis, 2006)

Compagno, (2002) describes the Double Skin Façade as "an arrangement with a glass skin in front of the actual building façade. Solar control devices are placed in the cavity between these two skins, which protects them from the influences of the weather and air pollution a factor of particular importance in high rise buildings or ones situated in the vicinity of busy roads." (Poirazis, 2006)

We conclude from the previous definitions that A Double Skin Façade (DSF) is an architectural system consisting of two layers of glazing separated by a ventilated air cavity that acts as a thermal buffer, improving energy efficiency by regulating heat transfer. This additional transparent envelope enhances building performance by providing insulation, natural ventilation, solar heat gain control, and acoustic comfort. DSFs also contribute to aesthetic appeal and protect solar shading devices from weather and pollution, making them particularly valuable in Highrise and urban buildings. Overall, DSFs serve multiple technical and environmental functions, optimizing natural lighting, thermal regulation, and energy consumption.

### 2.2. Classification of double skin façade:

The literature (Poirazis, 2006) mentions various classification ways for Double Skin Façade Systems such as: The façade geometry, cavity ventilation, cavity width, the type of air flow in the cavity, and other factors can be used to classify the systems.

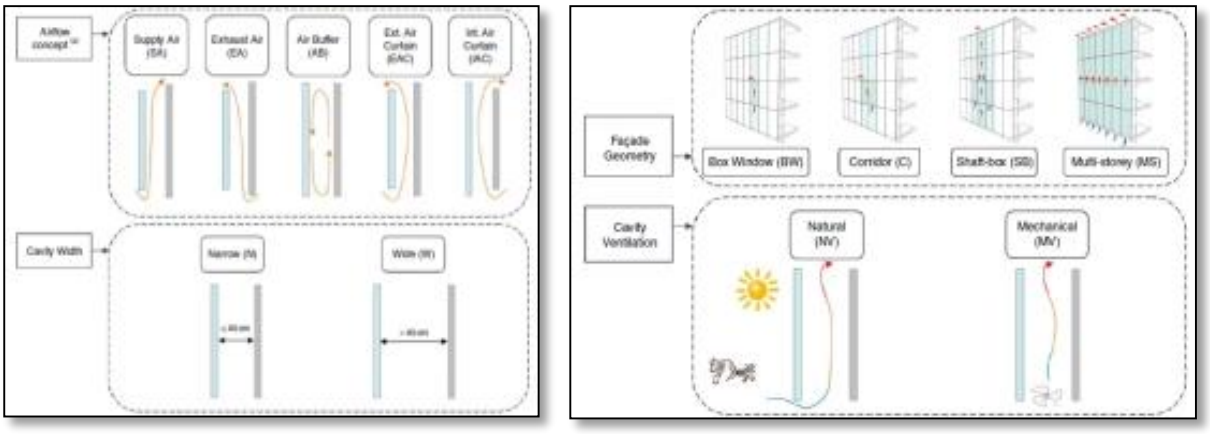



Figure 1.2 Classification of the double skin façade (Pomponi and Piroozfar, 2015)

### 2.2.1. Classification by façade geometry :

The types known by Oesterle et al. (2001), which have been adopted since then, includes(Poirazis, 2006):

• Box windows (BW).

• Corridor (C).

• Shaft box (SB).

• Multi-storey (MS).

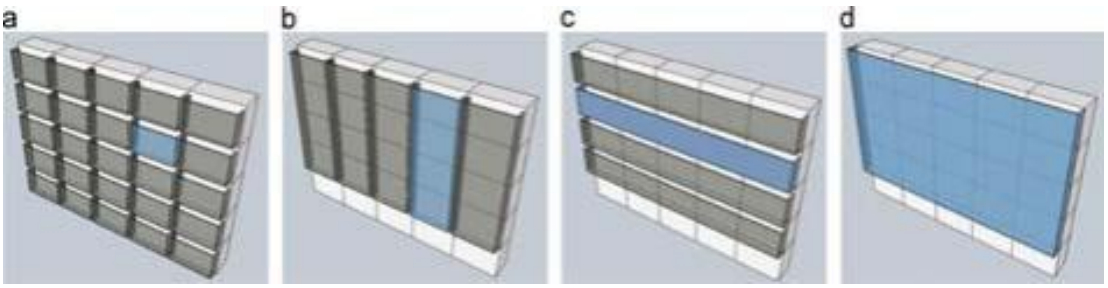



Figure 1.3 DSF classification: (a) Box Window, (b) Shaft Box(c)Corridor(d)Multi Storey Double Skin Façade. (Rezazadeh and Medi, 2017)

#### 2.2.2.1 Box Window DSF :

This type of DSF has a separate air cavity for each floor , barring airflow between floors. It can Enhances thermal and acoustic insulation but limits natural ventilation.

This kind has completely transparent envelopes and a façade that is divided both horizontally and vertically. The façade is divided by both horizontal and vertical partitioning. into separate, smaller boxes, (Figure 1.6) shows the details by different perspectives. The earliest type of DSF is box window. The space between two façade layers is separated along the constructional axes

and floors in a horizontal and vertical manner, respectively. This kind of window is typical in places with high levels of outside noise and particular needs.(Oesterle, 2001)

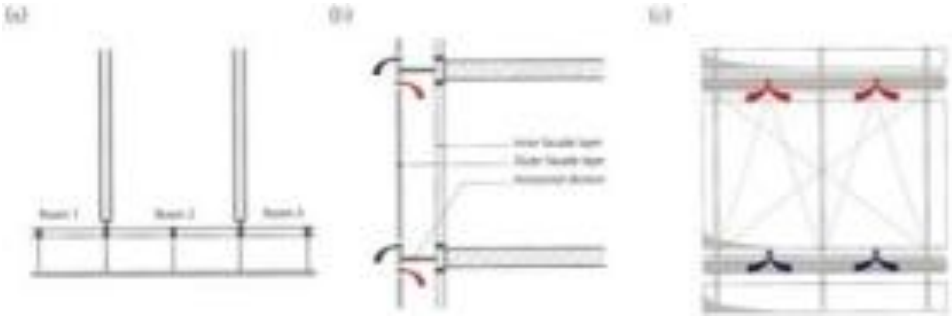


Figure 1.4 Box-window type: Plan (a); section (b); elevation(c) (Oesterle, 2001)

#### 2.2.2.2 Shaft Box DSF:

It includes vertical ventilation shafts inside the air cavity to control airflow. In order to produce a stack effect, a series of box-window elements are positioned within the façade with continuous vertical shafts that run along several stories. An opening connects the vertical shafts on each story to the adjacent box windows. The air is drawn into the vertical shafts from the box window by the stack effect.(Oesterle, 2001)

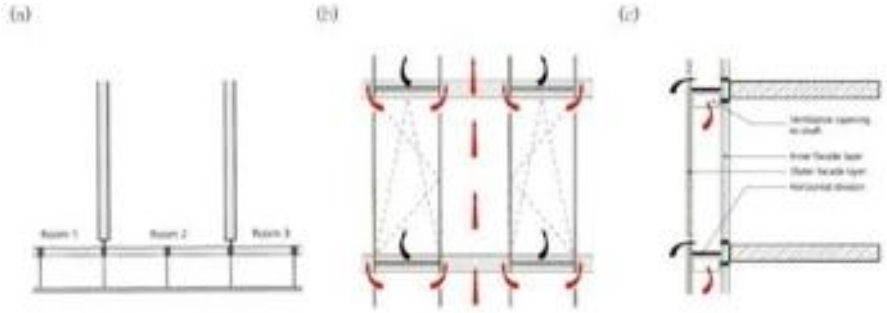


Figure 1.5 Shaft box façade: Plan (a), section (b) and elevation(c)(Oesterle, 2001)

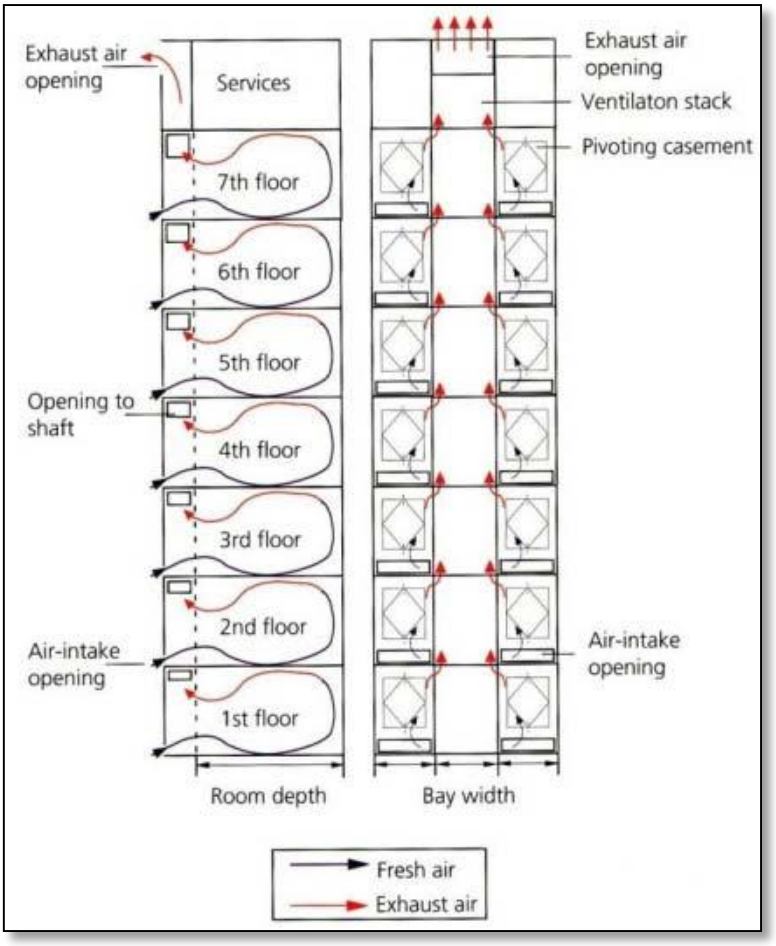



Figure 1.6 Shaft box façade and section(Oesterle, 2001)

#### 2.2.2.3 Corridor DSF:

The air cavity extends vertically, allowing warm air to rise naturally from the bottom to the top of DSF this type Used in high rise buildings to enhance natural cooling.(Oesterle, 2001)

Horizontal divisions are made along the corridor as needed for ventilation or fire safety. The extract and intake apertures are located close to the ceiling and the floor. To stop extracted air from the floor from getting into the area on the floor directly above, they are often spaced apart. (Oesterle, 2001)

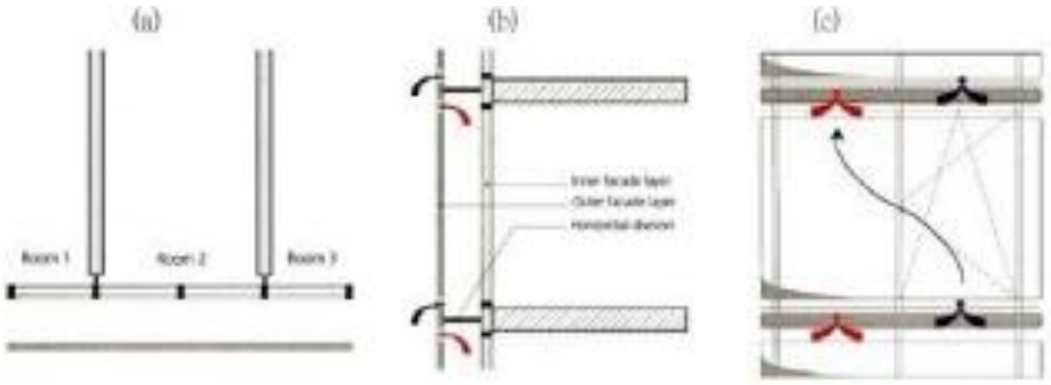


Figure 1.7 Corridor façade: plan (a); section (b) and elevation (c)((Oesterle, 2001)

#### 2.2.2.4 Multi Story DSF:

A multi story double skin façade (DSF) typically includes an air cavity between the external and internal glazing layers, which acts as a ventilated buffer zone for thermal insulation and solar control. (Oesterle, 2001)

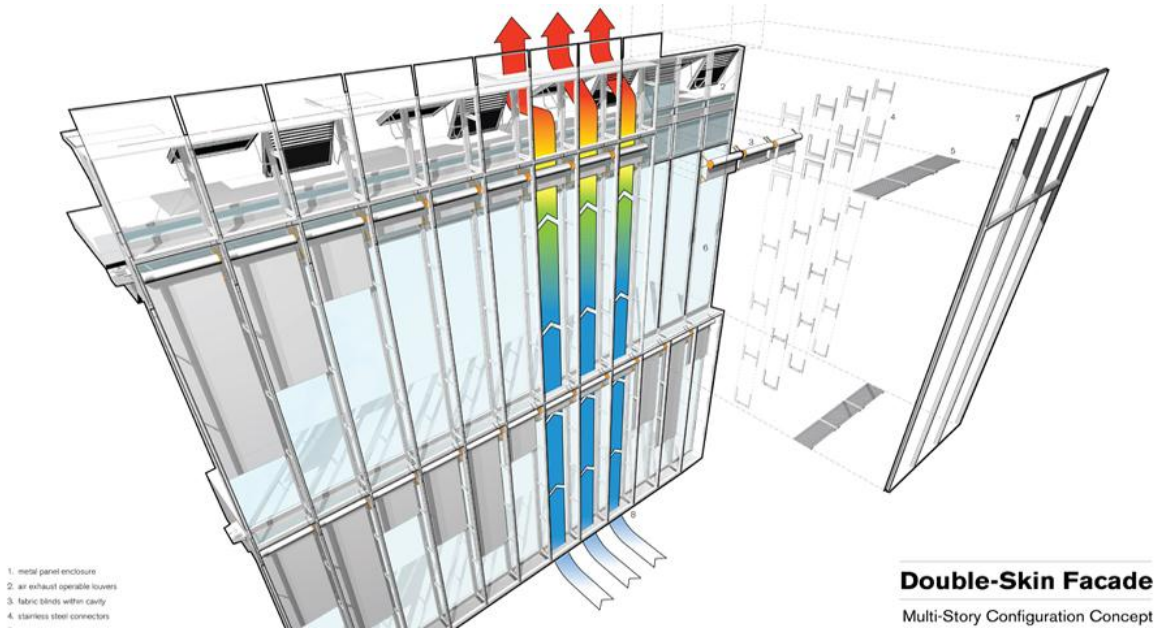



Figure 1.8 multi story configuration concept(Vaglio, 2025)

### 2.2.2. Classification according to cavity ventilation:

#### 2.2.2.1 Internal Airflow (Indoor Air Curtain):

The air circulates between the DSF cavity and the indoor space. Typically, warm indoor air is drawn into the cavity, creating a buffer zone that reduces heat loss in winter. that improves thermal comfort by preheating incoming air. (Naddaf and Baper, 2023), the mechanism of this configuration illustrated in (figure 1.11)

#### 2.2.2.2 External Airflow (Outdoor Air Curtain):

In this case outdoor air enters and exits the cavity without mixing with indoor air. Often used for natural ventilation or cooling the façade by reducing heat gain in summer. and get lowers cooling loads by exhausting hot air. This type is common in hot climates to prevent overheating.(Naddaf and Baper, 2023), the mechanism of this configuration illustrated in (figure 1.11).

#### 2.2.2.3 Static Air Buffer (Sealed Cavity):

The cavity is completely sealed, acting as an insulating layer. No active airflow; relies on trapped air for thermal resistance.it has an Excellent thermal insulation (reduces U-value).and no

mechanical ventilation needed. (Naddaf and Baper, 2023), the mechanism of this configuration illustrated in (figure 1.11)

#### 2.2.2.4 Supply Air (Preconditioned Air Intake):

Outdoor air is drawn into the cavity, preheated or cooled, then supplied indoors. Often integrated with mechanical HVAC systems. this type can Improves indoor air quality with filtered fresh air. and reduces energy demand by preconditioning air. but it requires mechanical systems (fans, filters). (Naddaf and Baper, 2023), the mechanism of this configuration illustrated in (figure 1.11)

#### 2.2.2.5 Exhaust Air (Indoor Air Extraction):

Stale indoor air is expelled through the DSF cavity, often via stack effect or fans.it can be combined with heat recovery systems. This type removes pollutants and excess heat from indoor spaces.

Can improve natural ventilation efficiency. But this may require backup mechanical ventilation in low-wind conditions. (Naddaf and Baper, 2023), the mechanism of this configuration illustrated in (figure 1.11)

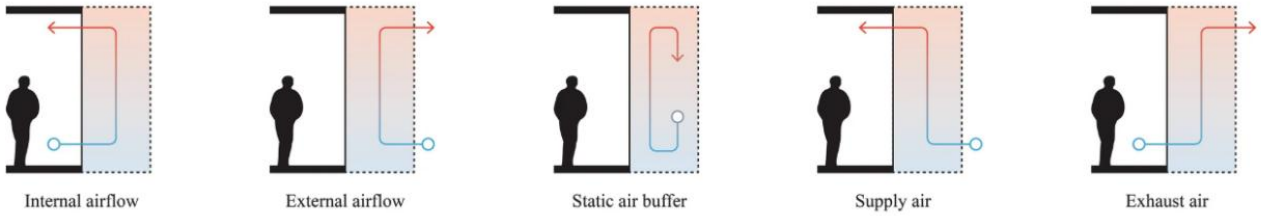



Figure 1.9 DSF ventilation modes (Naddaf and Baper, 2023)

### 2.2.3. Classification according to cavity width:

#### 2.2.3.1 Narrow cavity (<40 cm):

The cavity may restrict airflow, leading to higher temperatures (risk of overheating). For Cold Climates (Wider Cavity = Better Insulation) (Oesterle, 2001) that means, that a wider air cavity (especially when sealed or mechanically ventilated) acts as a thermal buffer, reducing heat loss in cold climates.

#### 2.2.3.2 Wide cavity (>40 cm):

The width allows better natural convection, stack effect, and mechanical ventilation. For Hot Climates (Proper Ventilation Width = Heat Dissipation), (Gratia and De Herde, 2007) Finds that wider cavities (≥ 50 cm) with natural ventilation help expel hot air, reducing cooling loads in warm climates.

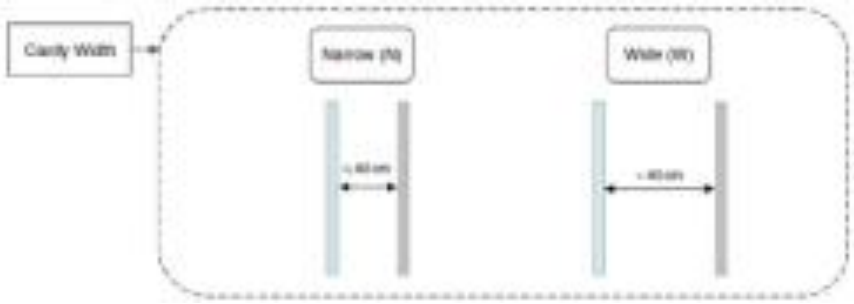
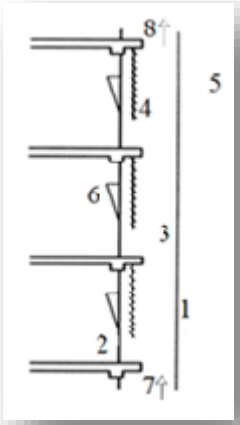



Figure 1.10 variation of cavity in DSF (Pomponi and Piroozfar, 2015)

### 2.3. Components of double skin façade:

Double skin façades are created by adding a second layer to a traditional single skin façade, with a cavity intentionally left between the two layers. When both layers are made of transparent materials, the system is referred to as a "double skin glass façade." (Figure 1.13) illustrates the basic components, installation, and operational principles of such a façade system.

In this configuration, fresh air enters through openings at the bottom of the cavity between the two skins driven (naturally or mechanically). The cavity acts as a buffer zone during both heating and cooling periods. By allowing controlled ventilation of this space, the system contributes to energy efficiency and thermal comfort. (Alemdağ and Beyhan, 2017)




1. External skin with transparent or opaque component.
2. Internal skin with transparent or opaque component.
3. Ventilation cavity.
4. Shading device (louver, blind etc.).
5. Outdoor air.
6. Operable or fixed window.
7. Air inlet.
8. Air outlet.

Figure 1.11 Double skin façade components (Alemdağ and Beyhan, 2017)

### 2.4. The functionality system of double skin façade:

DSF is made up of two material layers with a gap between them. Glass typically. The gap's thickness can be adjusted between 0.2 and 2 meters. The surrounding wind and the pressure differential in the cavity may cause air movements in the gap. The thermal chimney effect, which results from the difference in densities of the warmer air inside and cooler air outside the cavity,

is what causes the pressure differential in the cavity. The cavity depth, shading devices inside the cavities, outer skin glazing properties, type of building structure, and opening sizes are the parameters affecting the DSF performances. (Fernando et al., 2023)

### 2.5. Physics and heat transfer of DSF:

The main physics behind DSFs involves the interaction of solar radiation, air movement, and thermal conduction within the cavity. The outer glass layer absorbs solar radiation, heating the air in the cavity. This creates a temperature difference between the cavity air and the building interior.

The heated air, in the cavity rises due to stack effect, inducing natural ventilation if openings are provided at the top and bottom. This airflow removes heat from the cavity, reducing heat transfer to the interior.(Preet et al., 2022)

The air cavity acts as a thermal buffer zone, slowing down heat transfer by conduction and convection from the exterior to the interior space, And the two glazing layers reduce heat loss in winter by providing insulation and reduce heat gain in summer by controlling solar radiation transmission (Preet et al., 2022), The figure 13 below shows how Heat transfer in double skin façades occurs through three main modes.

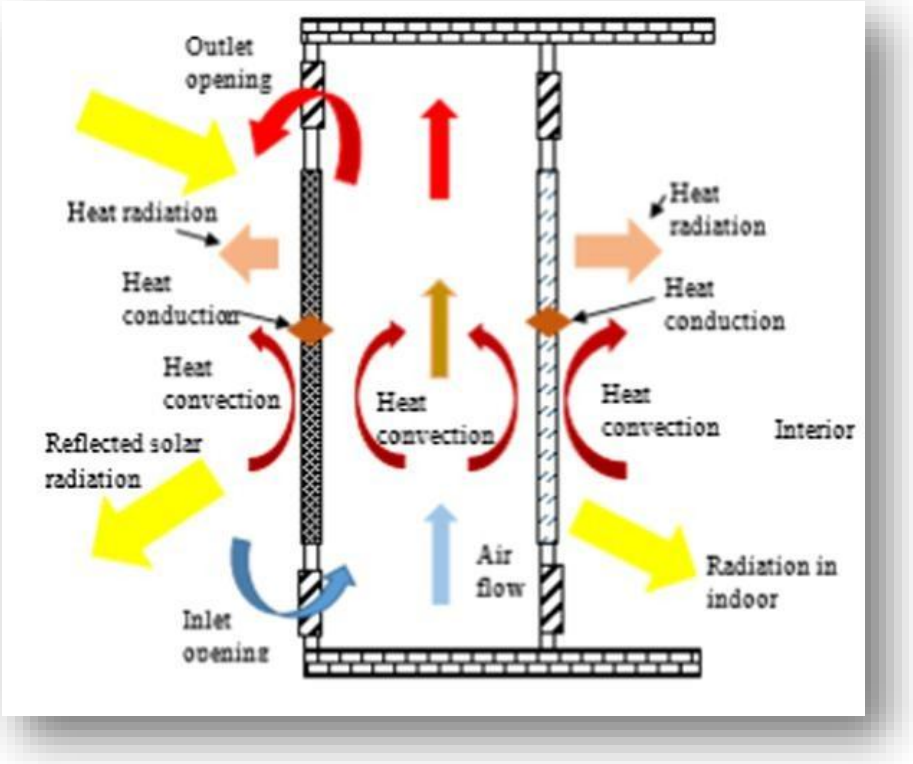



Figure 1.12 DSF heat transfer(Preet et al., 2022)

The figure 1.12 shows that there are three main heat transfer configuration:

- Conduction: Heat is conducted through the glass layers and the air cavity. The air cavity, being a poor conductor, reduces heat flow compared to a single layer façade.(Preet et al., 2022)
- Convection: Natural or forced convection occurs within the cavity. Warm air rises and is replaced by cooler air, which helps in ventilating the cavity and removing heat.(Preet et al., 2022)
- Radiation: Solar radiation passes through the outer glazing, part of which is absorbed and re-radiated as longwave infrared radiation inside the cavity and towards the interior glazing.(Preet et al., 2022)

### 2.6. Advantages of DSF on Thermal Comfort:

- Improve Thermal Insulation due to the air cavity between the two layers which acts as a thermal buffer, reducing heat transfer and maintaining stable indoor temperatures. (Poirazis, 2006)
- Reduced Solar Heat Gain by The outer skin which can incorporate shading devices, minimizing direct solar radiation and overheating in summer. (Oesterle, 2001)
- The cavity allows for adjustable ventilation, helping to dissipate excess heat while maintaining comfort. (Gratia and De Herde, 2007)
- The trapped air in the cavity can act as a thermal barrier, reducing heat loss in cold climates. (Gratia and De Herde, 2007)

### 2.7. Inconvenient of DSF on Thermal Comfort :

- Overheating Risk in Summer , the air cavity can trap heat, increasing indoor temperatures.(Poirazis, 2006)
- Complex Maintenance Requirements.(Oesterle, 2001)
- Higher Initial Costs, The additional layer increases construction expenses without guaranteed thermal benefits in all climates. (Poirazis, 2006)
- Limited Effectiveness in Extreme Climates, in very hot or cold regions, DSF may not sufficiently regulate temperature without mechanical support.(Poirazis, 2006)
- Some ventilation strategies for thermal comfort may reduce sound insulation, affecting indoor environmental quality. (Gratia, 2005)

## Conclusion:

In conclusion, understanding the concepts of thermal comfort and double skin façades lays the foundation for exploring their interrelation. Thermal comfort, as a key aspect of indoor environmental quality, depends on various factors including temperature, air movement,

and insulation.

The double skin façade, defined by its layered structure and ventilated cavity, plays a significant role in regulating these factors. By managing heat gain, enhancing natural ventilation, and improving insulation, the double skin façade emerges as a strategic architectural solution to support thermal comfort in buildings. This connection will be explored further in the next chapters through analysis and case studies

# CHAPTER 2: THERMAL COMFORT IN AIRPORTS

## Introduction:

Airports are complex public spaces designed to manage high volumes of passengers while ensuring safety, efficiency, and comfort. Terminal buildings, in particular, must balance functional design with user experience, accommodating diverse needs and extended waiting periods.

One key aspect of passenger comfort is thermal comfort—the condition in which people feel thermally satisfied. Achieving this in airports is challenging due to large open spaces, varying occupancy, and differing user expectations. This chapter explores the concept of thermal comfort in airport terminals, alongside a theoretical framework of airport design principles, to understand how architecture and environmental control systems contribute to passenger well-being.

## 1. Definitions of airport:

The airport is one of the ground facilities that serve air transport and its organization. it is subject to national legislation and international agreements such as the Chicago Convention of 1971, which aims to unify and coordinate the rules in force in different countries regarding the standard conditions of airports.((ICAO), 2018)

An airport is a facility designed for the take-off and landing of aircraft, including airplanes and helicopters. When used for military purposes, such a facility is typically referred to as an airbase or air station. Depending on their size and function, airports may also be called airfields, airstrips, or aerodromes.(Encyclopedia, 2023)

According to Title 49 of the United States Code (USC) § 47102(2), an airport is defined as a designated area (either land or water) utilized or intended for the landing and take-off of aircraft. This includes any adjacent areas allocated for airport buildings, other related facilities, or rights of way. Additionally, it encompasses all airport buildings and facilities situated within those areas. Notably, this definition also extends to include heliports.(FAA, 2023a)

## 2. History of airports:

The airport is a relatively modern invention, first appearing in the early 20th century. Initially, airports were simple landing fields, but they gradually developed into complex infrastructures as aviation technology and air traffic advanced.

### 2.1. History in the world:

The figure 2.1 below illustrates, The historical timeline of the airports worldwide, and how airport design has evolved over the time.

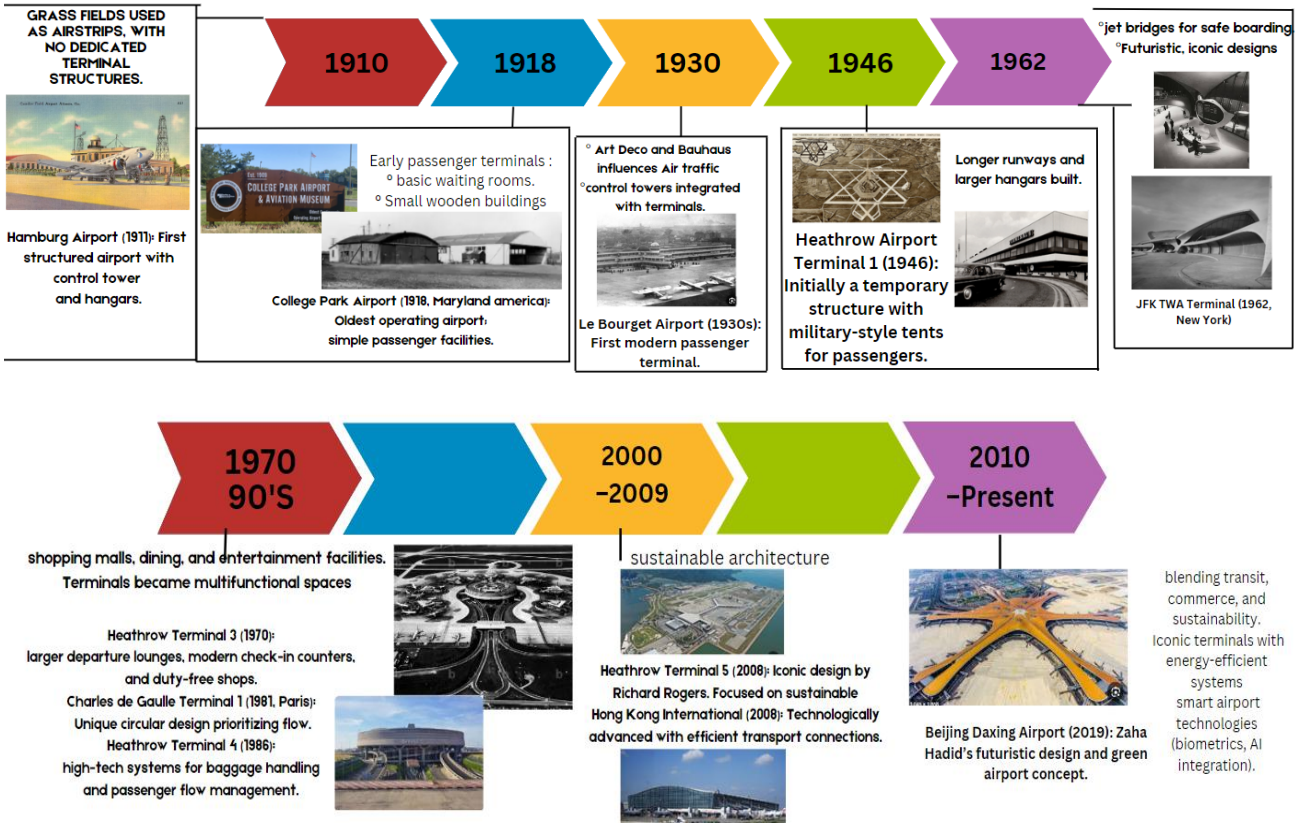



Figure 2.1 historical timeline of airports worldwide from 1920-present (author,2025) (Bednarek, 2001, Ashford et al., 2011, Budd, 2008, Elmoghazy et al., 2025)

## 2.2. History in Algeria:

Algeria passed by different periods of airport development from revolution to post revolution, the figure 2.2 below illustrates timeline of the evolution of airport design and infrastructure in Algeria from the 1930s to the present. Notable airports such as Houari Boumediene (Algiers), Mohammed Boudief (Constantine), and Ahmed Ben Bella (Oran) are showcased as milestones in this progression.

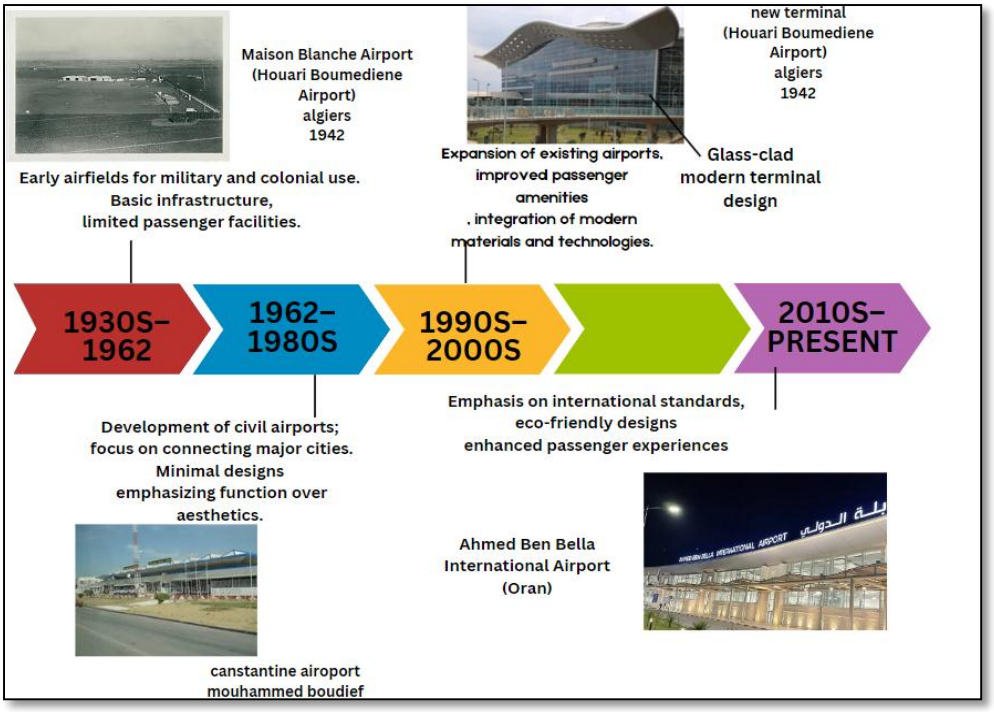



Figure 2.2 timeline of the evolution of airport design in Algeria (author,2025) (Rabnass, 2023, Belarbi, 2020)

## 3. Classification of airports:

Airports can be classified based on several factors, including their size, function, ownership, and geographical local, terminal design. (FAA, 2023)

### 3.1. Based on size:

Airports can be categorized by the number of passengers they serve annually, which helps in understanding their scale and operational capacity. The table below presents a categorization of airports according to their size:

| Category | Usage |
|---|---|
| Small Airports | Less than 1 million passengers |
| Medium Airports | 1–10 million passengers |
| Large Airports | Over 10 million passengers |
| Mega Airports | Over 50 million passengers |

Table 2.1 classifications of airports based on size (author 2024) (FAA, 2023b)

### 3.2. Based on function:

Airports can also be classified according to their primary function, which defines the type of operations they support. The table below presents a categorization of airports according to their function:

| Category | Usage |
|---|---|
| Commercial Airports | Serve passengers and cargo needs |
| Cargo Airports | Focused on freight operations |
| General Airports | Used by private planes and smaller operations |
| Military Airports | For military use |
| Joint Use Airports | Used for both civilian and military operations |

Table 2.2 classifications of airports based on function (author 2024) (FAA, 2023b)

### 3.3. Based on ownership:

Airports can also be categorized by ownership, which determines who is responsible for their management and operations. The table below presents a categorization of airports according to their ownership:

| Category | Usage |
|---|---|
| Public Airports | Owned and operated by government entities |
| Private Airports | Owned by private individuals or corporations |
| Public-Private Airports | Jointly owned or operated by public and private sectors |

Table 2.3 classifications of airports based on ownership (author 2024) (FAA, 2023)

### 3.4. Based on geographical location:

Airports can also be categorized by geographical location; Table 2.4 presents a categorization of airports according to their location, highlighting the distinct roles and characteristics of each type—from urban hubs to isolated remote airstrips.

| Category | Location |
|---|---|
| Urban Airports | Located near major cities |
| Regional Airports | Located in smaller towns or cities |
| Remote Airports | Serve isolated or inaccessible areas |
| Island Airports | Often serve both civilian and military use |

Table 2.4 classifications of airports based on geographical location (author 2024) (FAA, 2023)

### 3.5. Base on terminals design:

Airport terminals can be categorized by their design layout, which influences passenger flow, aircraft movement, and operational efficiency.

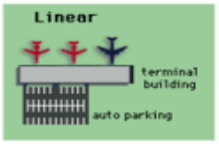
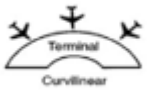
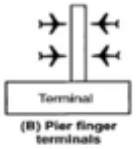
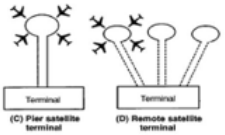
| Terminal Type | Description |
|---|---|
| Linear | The terminal is a long, straight structure with gates arranged along a single axis.   |
| Curvilinear | A terminal design with a curved layout for efficient aircraft and passenger flow.   |
| Pier-Finger | A central terminal connects to multiple 'fingers' or piers extending outward where aircraft gates are located.   |
| Satellite | Isolated gate structures connected to the main terminal via tunnels or automated systems.   |
| Hybrid | Combines elements of multiple designs, offering flexibility in terminal operations. |

Table 2.5 classifications of airports based on terminals design (author 2024) (FAA, 2023)

## 4. Components of airports:

Airports are complex infrastructures composed of various components that support aircraft operations and passenger services.(hasseb, 2017)

These include runways, taxiways, terminals, aprons, and control towers. Each part plays a vital role in ensuring safe, efficient, and organized air travel. The figure bellow shows that An airport is divided into three key operational zones: the landside, where passengers begin their journey through parking lots and drop-off drives; the terminal, a bustling hub for check-in, security, and waiting; and the airside, where aircraft manoeuvre via taxiways and take off from runways.(hasseb, 2017)

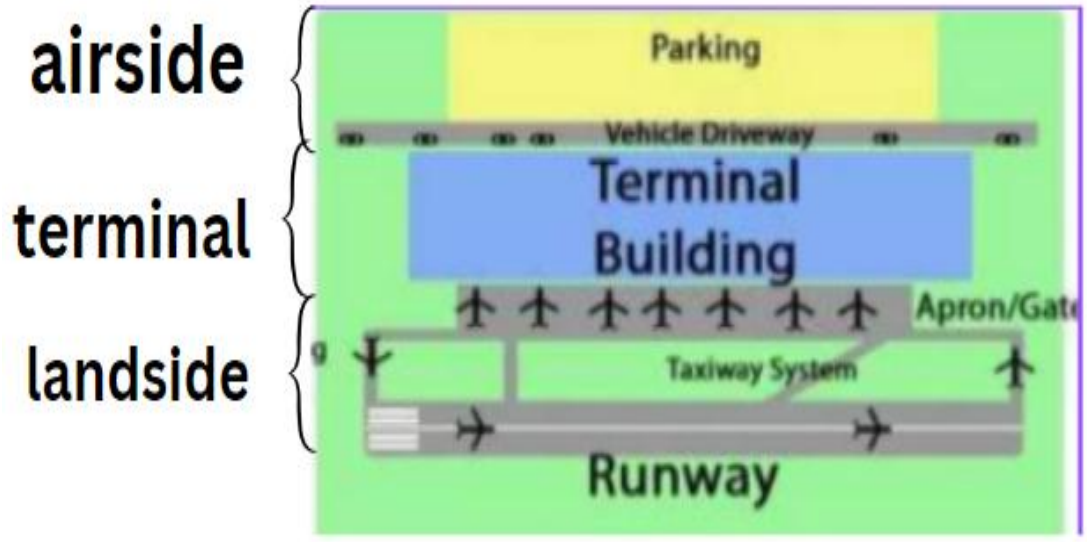



Figure 2.3 essential parts of airport (author2024)(hasseb, 2017)

### 4.1.Terminal definition:

In the context of airport infrastructure, the term *terminal* encompasses a variety of functions and spatial roles. As illustrated in Figure 2.4, the definition of a terminal integrates both functional and spatial dimensions:

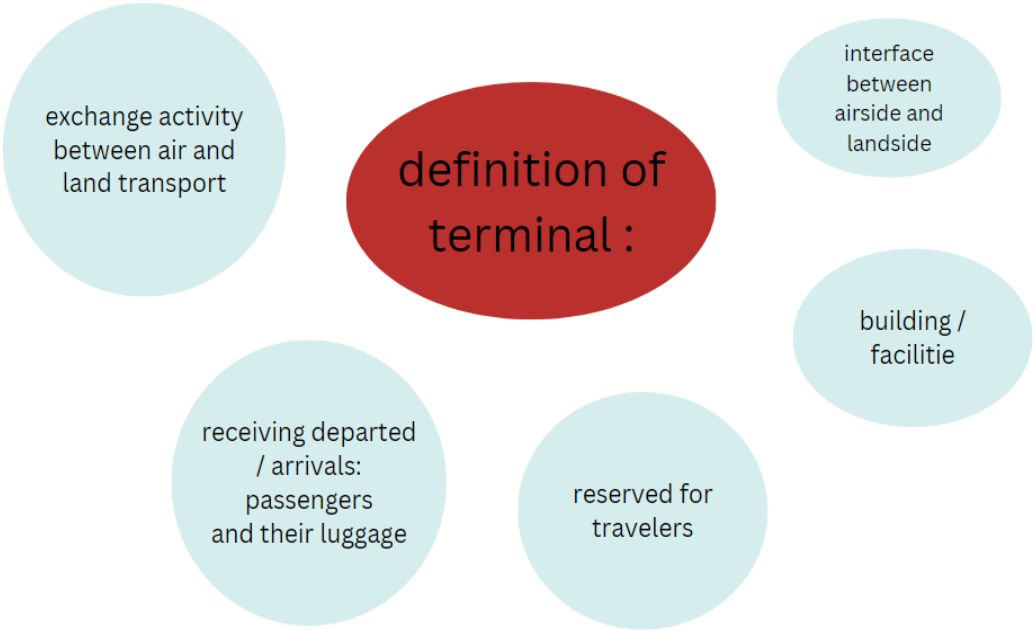



Figure 2.4 definition of terminal (author 2024)(Press, 2025) (IATA, 2019) , (Larousse, 2025)

### 4.2.Types of Passengers traffic:

Understanding the different types of passenger traffic is essential for the functional planning and spatial organization of airport terminals. Passenger traffic is typically, classified into three main categories, as shown in Figure 2.5

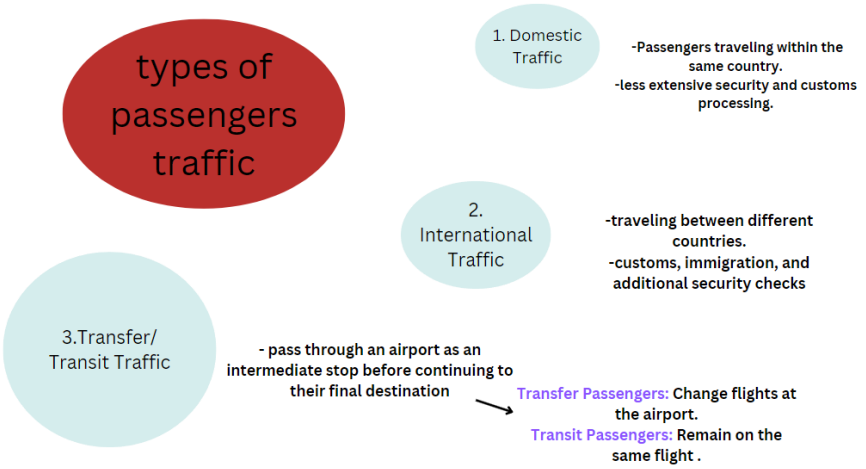



Figure 2.5 types of passenger's traffic (author2024)((ICAO), 2018)

### 4.3.Deferent areas in terminal:

Airport terminals are composed of various spatial zones, each designed to fulfil specific functional roles within the passenger journey. From arrival at the parking lot to final boarding, passengers move through distinct areas that support operations, security, comfort, and efficiency. As shown in Figure 2.6.

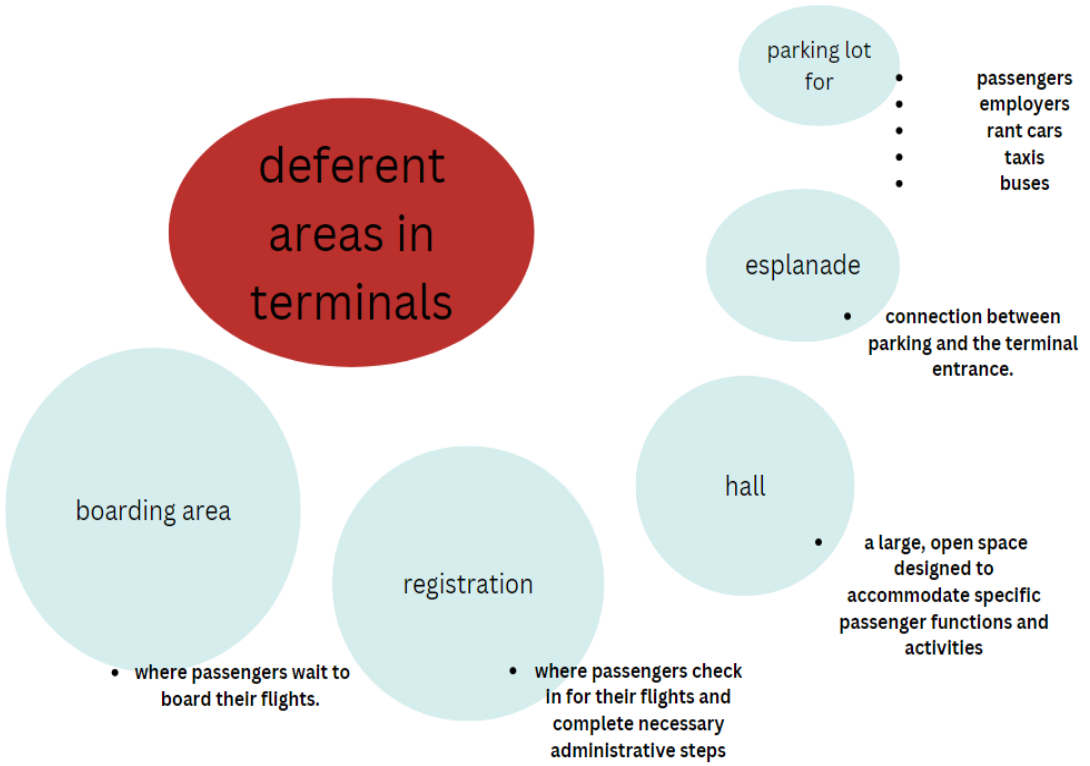



Figure 2.6 Deferent areas in terminal (author2024)((ICAO), 2018)

### 4.4.Users of terminal:

Airports and transport terminals serve a diverse range of users, each with distinct needs and purposes. These users include passengers, visitors, and escorts, among others. The diagram in Figure 2.7 illustrates the various categories of terminal users.

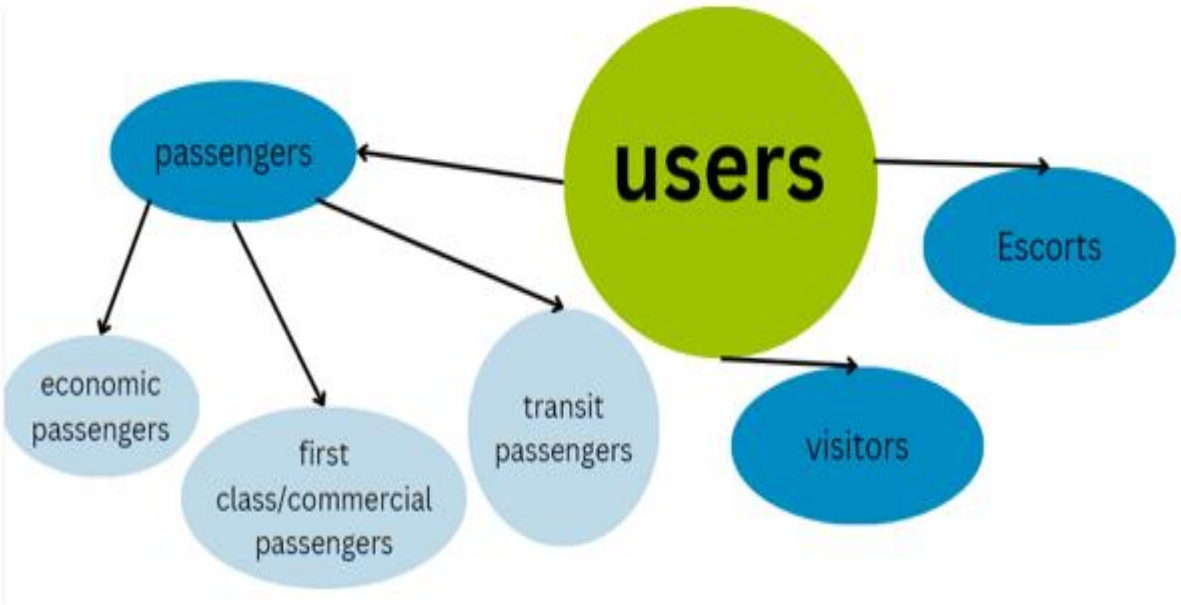



Figure 2.7 users of terminal scheme (author,2025)(Wells and Young, 2004)

### 4.5. Spatial functional organigram:

This illustrates the importance of the hall as the central node of passenger movement and processing. As seen in Figure 2.8, the hall connects various key functional areas such as registration, security checkpoints, shops, and restaurants. It also serves as the transitional space between exterior elements like parking and esplanade, and interior zones leading to customs, baggage claim, and boarding areas.

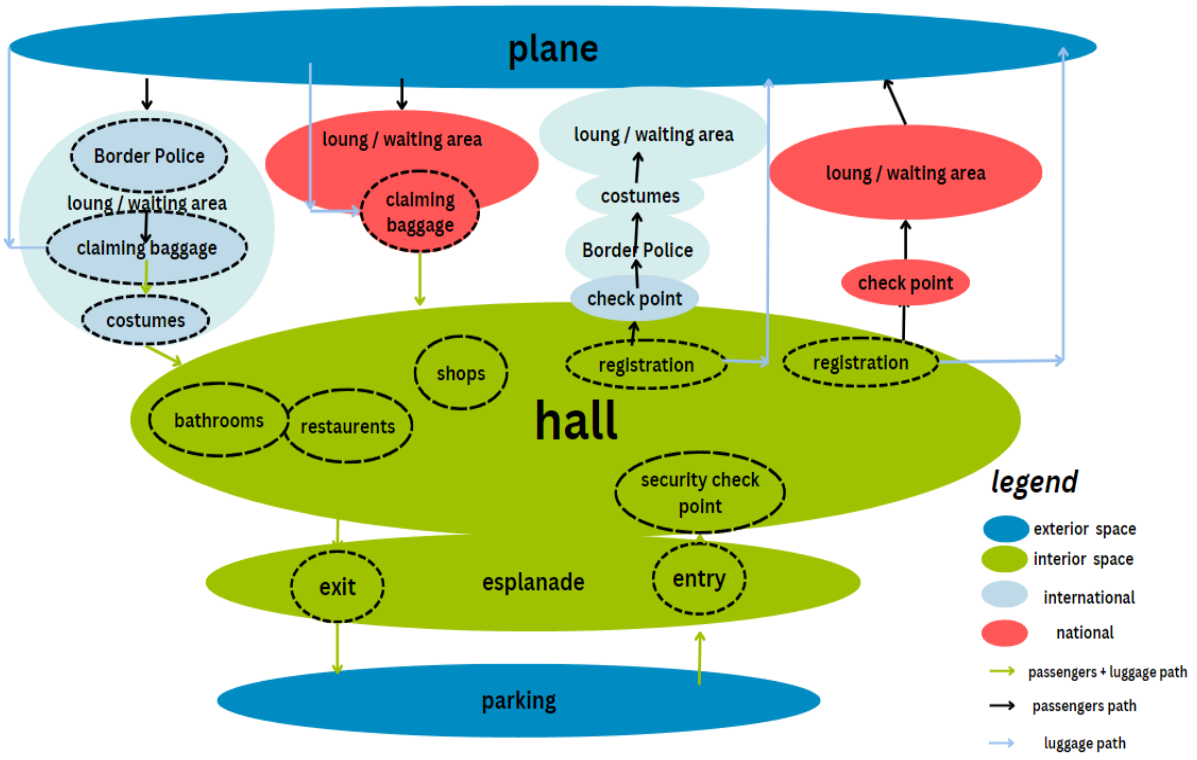



Figure 2.8 spatial functional organigram of terminal (author,2025)

## 5. Importance of thermal comfort in terminals:

Thermal comfort is crucial in airport terminals due to the wide range of users, each with differing needs and levels of thermal adaptability. As noted by (Kotopouleas and Nikolopoulou, 2014).

“Airport terminals are characteristic of the diversity of spaces and the very different groups of population using these buildings. [...] Such differentiation between different terminal users results not only in thermal discomfort but also energy wastage.”(Kotopouleas and Nikolopoulou, 2014)

Several factors influence the thermal needs of terminal users, who are often dressed in outdoor clothing suited to the season. Activity levels also differ between passengers and various categories of staff. In addition, employees typically work under strict conditions with no control over their thermal environment, resulting in a limited ability to adapt.(Kotopouleas and Nikolopoulou, 2014)

This highlights the challenge of providing a comfortable environment for both transient passengers and fixed-position staff, reinforcing the need for thoughtful thermal design in such complex spaces.(Kotopouleas and Nikolopoulou, 2014)

## 6. Thermal conditions for airport terminals:

Both(American Society of Heating, 2003),(CIBSE, 2006)provide recommended design criteria for maintaining thermal comfort in airport terminals. ASHRAE advises a temperature range of 23–26°C, with relative humidity levels of 30–40% in winter and 40–55% in summer.

While, (CIBSE, 2006) offer Use dry resultant temperature ranges as a base for comfort design in airport terminals. These are, determined by Clothing insulation (clo) depending on season metabolic rate (e.g., active workers vs. seated passengers).

- **In winter:**

Temperatures can exceed 19°C, but only without using heating systems (due to energy regulations like the 1974 and 1980 Fuel Orders in the UK). (CIBSE, 2006)This excess warmth can come from:

- Sunlight (solar gains)
- Lighting and equipment
- People (occupant heat gains)

- **In summer:**

For air-conditioned spaces, keep temperatures within comfort limits. for non air conditioned areas, it's acceptable if: Dry resultant temperature does not exceed 25°C for more than 5% of the year (about 125 hours).(CIBSE, 2006)

Additional it allows a wider variation in the internal conditions as showing the table 14 below:

| Building/room type | Winter dry resultant temperature range for stated activity and clothing levels* | | | Summer dry resultant temperature range† for stated activity and clothing levels* | | |
|---|---|---|---|---|---|---|
| | Temp. (°C) | Activity (met) | Clothing (clo) | Temp. (°C) | Activity (met) | Clothing (clo) |
| Airport terminals: | | | | | | |
| — baggage reclaim | 12–19[1] | 1.8 | 1.15 | 21–25[1] | 1.8 | 0.65 |
| — check-in areas[3] | 18–20 | 1.4 | 1.15 | 21–23 | 1.4 | 0.65 |
| — concourse (no seats) | 12–19 [1] | 1.8 | 1.15 | 21–25 | 1.8 | 0.65 |
| — customs area | 18–20 | 1.4 | 1.15 | 21–23[1] | 1.4 | 0.65 |
| — departure lounge | 19–21 | 1.3 | 1.15 | 22–24 | 1.3 | 0.65 |

Table 2.6 recommended design criteria for terminals (CIBSE, 2006)

## 7. Previous studies on thermal comfort in airports:

- **Study 1: Thermal comfort conditions in airport terminals: indoor or transitions spaces?:**

The study *Thermal comfort conditions in airport terminals: Indoor or transition spaces?*

By (Kotopouleas and Nikolopoulou, 2016). Examined thermal comfort in three UK airport terminals: London City Airport and Manchester Terminals 1 and 2 representing international airports of varying sizes. The study aimed to evaluate thermal perceptions and preferences of passengers and staff, identifying differences in comfort requirements and the resulting thermal conflicts within terminal spaces.

Parameters monitored included indoor temperatures ranging roughly from 16.2 to 25.6 °C across seasons, relative humidity, air velocity, and PMV/PPD values, with seasonal surveys conducted in summer and winter.

The methodology combined extensive environmental monitoring with over 3,000 questionnaire guided interviews in diverse terminal zones such as check-in areas and boarding gates. While HVAC performance and building envelope effects (including glazing) were considered, the study primarily focused on occupant comfort. Findings revealed passengers preferred cooler temperatures than staff by 0.4–2.0 °C and tolerated a wider temperature range, whereas staff had narrower comfort zones. Thermal conflicts emerged due to these differing needs, with some terminal areas experiencing overcooling or overheating. The study recommended adaptive comfort models and differentiated thermal strategies tailored to user groups and terminal zones to enhance comfort and reduce energy consumption.(Kotopouleas and Nikolopoulou, 2016)

- **Study 2: Thermal Performance, Indoor Air Quality, and Carbon Footprint Assessment in Airport Terminal Buildings:**

This study *Thermal Performance, Indoor Air Quality, and Carbon Footprint Assessment in Airport Terminal Buildings* of (Akyüz et al., 2024),which was conducted in an airport terminal located in Barcelona, Spain, in a Mediterranean climate.

The main objective was to evaluate the thermal comfort conditions inside the airport terminal, focusing on how well the indoor environment meets occupant comfort needs. The study also aimed to compare the performance of a passive geothermal based radiant high temperature cooling system (HTC) with a conventional all-air cooling system.

This study used IDA-ICE building energy simulation software to model and simulate the thermal performance of the airport terminal and the cooling systems, and the simulation model was validated with on-site measurement data to ensure accuracy.

The study used operative temperature as the main indicator for thermal comfort evaluation. The comfort temperature threshold was set at 26°C, with periods exceeding this considered as discomfort. The study also considered cooling degree days and other climatic parameters relevant to the Mediterranean climate.

Both the HTC radiant cooling system and the all-air system maintained similar thermal comfort levels during average cooling load periods, with operative temperatures slightly exceeding 26°C for about 13% of the occupied time.

The radiant cooling system achieved comparable comfort with 40% lower energy use and 85% lower energy consumption compared to the all air system. And without any cooling system, operative temperatures remained continuously above the comfort limit, confirming the necessity of active cooling in Mediterranean airport terminals.

- **Study 3 :Thermal comfort evaluation of an existing glazed airport terminal in Thailand:**

This study *Thermal comfort evaluation of an existing glazed airport terminal in Thailand The study was conducted at an existing airport terminal in Thailand* by (Pichatwatana et al., 2018) in Thailand which has a tropical climate, characterized by high temperatures and humidity throughout the year, with pronounced wet and dry seasons.

The primary aim was to evaluate the thermal comfort of occupants in a glazed airport terminal building in Thailand.

The study sought to identify how the extensive use of glazing (glass façades) affected indoor thermal conditions and passenger comfort, and to propose recommendations for improving thermal comfort in tropical airport terminals.

Field measurements were, carried out to collect data on temperature, relative humidity, air velocity, and globe temperature inside the terminal.

Thermal comfort surveys were, conducted with passengers and staff to gather subjective comfort votes and perceptions.

The study used the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices, as defined by ISO 7730 and ASHRAE Standard 55, to quantitatively, evaluate thermal comfort conditions.

Data loggers and handheld instruments were used for environmental monitoring.

As a result, the measured indoor thermal environment often exceeded the recommended comfort ranges for temperature and humidity, especially during peak solar gain periods due to the extensive glazing.

The PMV and PPD indices indicated that a significant portion of occupants experienced thermal discomfort, with PMV values frequently above the neutral comfort zone.

Survey responses confirmed that both passengers and staff felt warm or hot, particularly in areas exposed to direct sunlight through glass façades.

The study recommended improvements such as enhanced shading devices, better HVAC zoning, and increased air movement to improve comfort in glazed airport terminals in tropical climates.

Based on the reviewed studies, thermal comfort in airport terminals is influenced by diverse user needs, building design elements such as extensive glazing, and the efficiency of HVAC systems. Passengers typically tolerate a wider temperature range, while staff require more stable conditions, with studies showing a preference gap of about 0.4–2.0 °C between the two groups. Indoor temperatures across terminals ranged from 16.2 °C to over 26 °C, with discomfort commonly occurring when temperatures exceeded the 26 °C comfort threshold. PMV (Predicted Mean Vote) values frequently indicated thermal dissatisfaction, especially in glazed areas exposed to direct sunlight, where values rose above the neutral comfort zone. These variations highlight recurring thermal conflicts and discomfort zones within terminals. Effective thermal comfort management therefore requires a combination of adaptive comfort models, improved HVAC zoning, energy-efficient cooling systems, and passive strategies like shading to maintain PMV within acceptable limits and enhance overall occupant comfort while minimizing energy use.

## Conclusion:

In conclusion, ensuring thermal comfort in airport environments is essential for enhancing passenger experience, and improving staff performance. Given the unique architectural and operational characteristics of airports such as large open spaces, constant human flow, and varying external climatic conditions achieving thermal comfort requires a well-integrated design approach. This includes effective HVAC systems, adaptive façade solutions like double-skin façades, and strategic material choices. As airports continue to evolve into complex transport hubs and commercial spaces, prioritizing thermal comfort becomes not only a matter of human well-being but also a key factor in sustainable architectural design.

# CHAPTER 3:
# PREVIOUS STUDIES

## Introduction:

This chapter focuses on a review of previous studies concerning thermal comfort and the energy performance of double skin façades (DSFs) across various climatic conditions. Numerous researchers have examined the impact of different DSF configurations, including cavity depth, glazing type, ventilation strategies, and shading devices, on indoor thermal comfort and energy consumption. These studies highlight how specific parameters of the double-skin façade can significantly influence building performance in terms of both comfort and efficiency. Based on the insights and data collected from these past investigations and experimental results, this research aims to develop a double-skin façade model tailored to the objectives of our study.

The proposed model incorporates key performance, related parameters, and it will be evaluated using an appropriate simulation method, to assess its effectiveness in enhancing thermal comfort and reducing energy demand in buildings.

## 1. Overview on previous studies:

The table provides a comprehensive and organized review of previous studies focusing on the thermal performance and comfort aspects of double skin façades (DSF) across various climatic conditions. It clearly outlines key elements such as the title, authors, publication dates, locations, climates, tools used, evaluated parameters, objectives, and main findings. This structured approach allows for easy comparison between different studies, highlighting how DSF design variables like cavity width, material selection, orientation, ventilation strategy, and glazing properties influence indoor thermal comfort and energy consumption. By including research from diverse climatic zones. the table gives a broad view of the potential and limitations of DSFs in different contexts.

| Title / Author And Publication date | Location / climate | objectives | Tool used | Parameters | Main Results |
|---|---|---|---|---|---|
| **1**. The Impact of Double Skin Façades on Thermal comfort in Public Buildings in Constantine, Algeria (Saoussen and Youcef, 2024) | Constantine, Algeria (Semi-arid climate) | - Evaluate DSF's thermal performance in semi-arid climates.<br>- Compare temperature differences (indoor vs. outdoor) in winter/summer.<br>- Assess the influence of materials and orientation on thermal comfort. | -Measurements (No simulation software; empirical data collection)<br>- Instruments:<br>- Thermo-hygrometers (PCE-HT 71N)<br>- Multifunction lux meters (ML8000) | -Indoor/outdoor temperature ("T/in", "T/ex")<br>- Relative humidity (RH)<br>- Air speed ("S/air")<br>- Solar radiation (global/diffuse) | - **Winter**: DSF increased indoor outdoor temp difference by up to 10°C (but insufficient to reach comfort zone without heating).<br>- **Summer**: Temp difference reached up to 24°C; terracotta panels outperformed glazed DSF.<br>- **Material/Orientation Impact**: Glazed DSF faced south showed greenhouse effect; terracotta DSF better for summer.<br>- **Energy Savings**: Spaces with fewer openings (e.g., performance halls) required less mechanical cooling. |

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| 2. Energy Performance and Thermal Comfort of Double-Skin and Single-Skin Façades in Warm-Climate Offices (Alibaba and Ozdeniz, 2016) | Gazimagusa, Northern Cyprus (Warm Mediterranean climate) | - Compare DSF vs. SSF energy performance in warm climates.<br>- Evaluate thermal comfort (PMV/PPD) year-round.<br>- Optimize DSF design for heating/cooling efficiency. | TAS Software | -Cavity width (0.3m, 0.6m, 1.2m tested)<br>- Glass properties (U-value, G-value, emissivity)<br>- Ventilation strategies (window openings: 1%–100%)<br>- PMV/PPD for thermal comfort | - Winter (Under-heated period): DSF reduced heat loss by 3× vs. SSF; achieved PMV ≈ 0.5 (comfortable).<br>- Summer (Over-heated period): DSF reduced heat gain by 5× but only contributed 25% cooling (insufficient for full comfort).<br>- Orientation: South-facing DSF caused summer overheating (up to 50°C cavity temperatures).<br>- Cavity Width: 0.3m performed slightly better than 0.6m/1.2m.<br>- Thermal Comfort: DSF maintained PMV ≈ 0.5 (PPD 4%) vs. SSF's PMV ≈ 1.5 (PPD 50%). |

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| 3.Exploring double skin façade as strategy for achieving thermal comfort in proposed mixed use office complex Kano, Nigeria (Bello et al., 2020) | Kano, Nigeria (Hot) | Improve indoor thermal comfort using double skin façade.<br>Test air gap effects on thermal comfort. | Autodesk Ecotect | -Cavity width 0.75 mm, 150 mm, 225 mm tested.<br>Wall/Glass properties:<br>-U-value (w/m2.K) (2.710 and 1.720).<br>-thermal Admittance (w/m2.K) (0.840 and 0.880)<br>-Solar absorption.<br>-Ventilation strategies:<br>Natural ventilation induced by DSF (measured by air velocity inside, up to about 0.8 m/s).<br>-Thermal comfort indices/parameters:<br>-Indoor air temperature. | -The result of the final base case model shows that double skin façade can increase the indoor thermal comfort in a building<br>- The wider the air gap, the higher the thermal comfort by showing the hours of comfort and discomfort to the simulated office building. |

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| | | | | -Relative humidity.<br>-Air velocity.<br>-Radiation (solar gain).<br>-Total hours of discomfort (predicted by simulation for each floor and month) | |
| **4**. Application of the Double Skin Façade Concept in an Effort to Increase the Thermal Comfort of Image Studio Room. (Maknun, 2020) | Indonesia (Tropical) | - Assess DSF's impact on thermal comfort in an image studio (sensitive to heat).<br>- Compare conventional vs. DSF performance in tropical climates. | A specialized numerical simulation software developed by the authors to simulate ( name not mentioned) | - Cavity thickness (variations tested)<br>- Solar radiation absorption<br>- Material properties (glass, shading)<br>- Indoor temperature & humidity levels | - DSF reduced indoor temps by 2–4°C compared to single skin façade.<br>- Optimal cavity thickness: 0.5–0.8m for natural ventilation.<br>- Reduced solar heat gain by ~25%, improving thermal comfort.<br>- Humidity remained a challenge (required supplementary ventilation). |

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| 5. Thermal behaviour of a ventilated double skin façade in hot arid climate. (Hashemi et al., 2010) | Tehran, Iran (Hot arid climate) | -To monitor and analyse the thermal behaviour of a ventilated double skin façade (DSF) in a hot arid climate.<br>-To compare actual field measurements of temperature in summer and winter with simulation results.<br>-To assess the effectiveness of the DSF in reducing heating and cooling loads in such a climate.<br>-To provide insights on how | -Temperature sensors<br>-Energy Plus Version 2.1 | -Temperature of the cavity between the two skins of the façade (Tcav).<br>-Outside air temperature (To).<br>-Indoor room temperatures.<br>-Ventilation rates and vent areas on façade.<br>-Solar radiation and shading effects.<br>-Seasonal variation (summer vs. winter)<br>-Thermal comfort ranges according to Iranian standards<br>-Construction properties of façade layers (glazing, insulation, cavity width 70 cm). | - **Summer**: Cavity temperatures rose 5–7 °C above outdoor temperatures due to solar heating, reaching up to 50 °C with poor ventilation.<br>- **Shading**: Shading devices lowered cavity temperatures by 7–10 °C, showing their importance in preventing overheating.<br>- **Cooling Loads**: Despite DSF use, indoor comfort in summer relied heavily on air conditioning, leading to high energy consumption.<br>-**Winter**: DSF effectively reduced heat loss, with cavity temperatures 5–13 °C higher than outside, supporting heating efficiency. |

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| | | DSF performance can be optimized, including the role of ventilation and shading. | | | |
| 6. Experimental & Simulation Study on DSF in Tropics (Wong, 2008) | Singapore (Hot-humid) | Evaluate DSF for humidity control | Design Builder | SHGC, natural vs. mechanical ventilation | Ventilated DSF reduced indoor temps by 3-5°C but required dehumidification. |
| 7.Guidelines to Improve Efficiency of a Double-Skin Façade in an Office Building (Gratia, 2005) | Belgium (Temperate) | Optimize DSF design for energy savings and occupant comfort. | Tas software | -Window opening (10%, 50%)<br>- Cavity ventilation (forced, natural)<br>-Glass U-value (1.2 W/m²K)<br>- G-value (0.3)<br>- Solar control (external, internal blinds) | -Night ventilation + solar shading reduced cooling needs by 40%; summer performance heavily depends on user control. |

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| 8. Thermal comfort of multiple-skin façades in warm-climate offices (Alibaba and Ozdeniz, 2011) | Turkish Republic of Northern Cyprus Warm climate | Assess thermal comfort of MSFs in warm climates | TAS simulation software | **-Width of the cavity :** Adjustable between 30 cm and 120 cm (tested at 30 cm in the first run)<br>**- openings:** Top and bottom of each floor and cavity, up to 1,800 cm² per opening<br>**-Height of the building:** Test building: 4.70 m wide, 12.20 m long, 3.53 m high<br>**-Orientation of the façade:** Long façades facing south and north<br>**-Type of glazing (glass properties):** External: 6 mm | -Multiple-skin façades (MSFs) can significantly improve thermal comfort in office buildings located in warm climates by reducing overheating and allowing for natural ventilation.<br>**-Effect of Cavity Width :** Increasing the width of the air cavity between the façade layers enhances airflow and improves cooling, but there are diminishing returns beyond a certain width.<br>**-Opening Area and Arrangement** The size and arrangement of openings in the façade play a critical role in facilitating effective natural ventilation and maintaining comfortable indoor temperatures.<br>**-Building Height and Chimney Effect** Taller buildings and the addition of a transparent chimney at the top of the south façade increase the stack effect, improving air movement and cooling performance. |

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| | | | | reflective glass (solar transmittance, absorptance, reflectance, emissivity, U-value, G-value, etc.)<br>Internal: 4+12+4 mm clear double glazing.<br>**-Façade typology:**<br>Box-type double-skin façade<br>**-Ventilation strategy:**<br>Natural ventilation via openings and stack effect (with/without chimney) | **-Energy Savings**<br>Properly designed multiple-skin façades can reduce both cooling and heating energy demands, contributing to overall energy efficiency in office buildings. |
| 9.Thermal performance of a double-skin façade exposed to direct solar | Tropical climate (Malaysia) | Evaluate DSF performance under solar radiation | Energy plus | - Closed cavity<br>- Natural ventilation<br>- Mechanical ventilation | Effective heat gain control, but issues with direct solar radiation. |

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| radiation in the tropical climate of Malaysia (Qahtan, 2019) | | | | | |
| 10.Improvement of Double-Skin Façade Operation for Reducing Heating Load in Winter (Sung and Kim, 2019) | Korea (cold) | Reduce winter heating load via DSF operation | -Energy Plus: for energy and thermal comfort simulation.<br>-TRNSYS : for transient system simulation<br>-ESP-r<br>IDA-ICE<br>CFD (Computational Fluid Dynamics): for detailed airflow and temperature distribution analysis.<br>Tools | -Cavity width (air gap between skins 20 cm to 100 cm)<br>-Glazing properties:<br>Solar transmittance<br>Solar absorptance<br>Reflectance<br>Emissivity<br>U-value (thermal transmittance)<br>G-value (total solar energy transmittance)<br>-Ventilation strategy of the cavity:<br>Natural ventilation<br>Mechanical | · Double skin façades (DSFs) improve indoor thermal comfort by stabilizing temperatures and reducing fluctuations.<br>· DSFs reduce overheating in summer through solar shading and ventilation within the façade cavity.<br>· In winter, DSFs provide insulation, reducing heat loss and cold drafts, enhancing comfort.<br>· The effectiveness depends on ventilation strategies: natural, mechanical, or hybrid.<br>· Climate and building orientation significantly influence DSF thermal comfort performance. |

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| | | | | ventilation<br>Closed cavity (no ventilation)<br>-Shading devices: Presence and control of blinds or shading systems within the cavity<br>-Façade orientation: South, West, North, East<br>Façade typology:<br>-Box-type, corridor, shaft-box, multi-story DSFs<br>-Dynamic control parameters: Operation of ventilation openings and shading devices<br>**-Indices:**<br>-Indoor air | · Simulations and field studies show DSFs help maintain temperatures within recognized comfort standards.<br>· Poor design or ventilation can cause overheating or discomfort in the façade cavity. |

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| | | | | temperature (°C)<br>-Air velocity in the cavity (m/s)<br>-Thermal comfort indices PMV and PPD<br>-Heat transfer coefficient (U-value, W/m²K)<br>-Solar heat gain (W/m² or W)<br>-Heating and cooling loads (kWh or MJ) | |
| 11.Double-Skin Façades in Mediterranean Climate Buildings: Rehabilitating Neighbourhoods (López-Escamilla et al., 2024) | Spain (Mediterranean) | Assess DSF impact on vulnerable neighbourhoods | Design Builder | **-Cavity width**<br>**-Type of glazing** (single, double, low-E, etc.)<br>**-Ventilation strategy**<br>Natural ventilation<br>Mechanical ventilation<br>Hybrid systems<br>**-Façade typology** | The double-skin façade (DSF) reduced indoor air temperature by up to 2.5°C compared to a single-skin façade, helping to maintain indoor temperatures closer to thermal comfort standards.<br>- Improved Comfort Hours<br>-The DSF minimized solar heat gain, reducing the risk of overheating in the interior spaces. |

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| | | | | Box-window<br>Shaft-box<br>Corridor<br>Multi-story<br>**-Shading devices** (external, internal, integrated)<br>**-Façade orientation** (North, South, East, West)<br>**-Control strategies** Automated and manual operation of vents/shading<br>**-Material properties** Solar transmittance, absorptance, reflectance, U-value, G-value<br>**-Indices :**<br>Indoor air temperature<br>-Cavity air | -Natural ventilation within the DSF cavity enhanced heat removal, further supporting thermal comfort.<br>-the DSF also reduced the reliance on air conditioning, indicating potential energy savings. |

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| | | | | temperature<br>-Air velocity in the cavity<br>-Thermal comfort indices<br>• PMV<br>• PPD | |
| 12.DSF for Retrofitting and Climate Change: Central Italy Case Study (Lops et al., 2023) | Italy (Mediterranean) | Use DSF for retrofitting & climate adaptation | numerical simulation software developed by the authors | **-Cavity width**<br>**-Ventilation mode of the cavity**<br>Natural ventilation<br>Mechanical ventilation<br>Closed cavity<br>**-Type of glazing**<br>Single glazing<br>Double glazing<br>Low-E glazing<br>**Shading devices**<br>(blinds, louvers)<br>**-Façade typology**<br>-Box-window | -increase indoor minimum operative temperatures up to 3.8% during the coldest months and reduce the maximum summer ones by 1.9–3.8%, raising comfort levels. |

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| | | | | -Shaft-box<br>-Corridor<br>-Multi-story<br>**-Indices :**<br>Indoor operative temperatures<br>Indoor air temperature<br>Cavity air temperature | |
| 13.A parametric study of the thermal performance of double skin façades at different climates using annual energy simulation (Pekdemir and Muehleisen, 2012) | Chicago USA (humid continental climate) | Demystify the thermal performance of different types of DSFs in varying climates. | IESVE 6.4 | **-DSF type**<br>Box-window<br>Shaft-box<br>Corridor<br>Multi-story<br>**-airflow**<br>Naturally ventilated (openings at top/bottom, open/closed)<br>**-cavity width**<br>**-Façade orientation**<br>North, South, East, West | **-Best configurations:** Juxtaposed Modules (JM) and Shaft Box (SB). Effectiveness due to **shading** by horizontal and vertical partitions.<br>**- Airflow Path Analysis**<br>• **Winter: Static Air Buffer (SAB)** reduces heating loads best.<br>• **Summer: Supply Air (SA)** and **External Air Curtain (EAC)** help reduce cooling loads.<br>**- Cavity Width :**<br>• **Narrow cavities** prone to **overheating**, even in cold climates.<br>• **Recommendation:** Use 4 ft or |

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| | | | | | wider cavities, especially if no additional shading is included. |
| 14.How Double Skin Façade's Air-Gap Sizes Effect on Lowering Solar Heat Gain in Tropical Climate? (Rahmani et al., 2012) | Johor Bahru, Malaysia (Tropical climate) | -Evaluate the effect of DSF air gap size on reducing solar heat gain in office buildings.<br>- Assess impact of different glazing materials and air gap depths.<br>- Determine optimal air gap size for thermal performance. | - CFD Simulation (FloVENT software, by Mentor Graphics) | - Indoor air temperature at multiple floor levels<br>- DSF air-gap size (0.1m, 0.3m, 0.5m, 1.0m, 1.5m)<br>- Glazing type (typical, anti-sun, reflective, plexiglass)<br>- External climate: 31°C, 87% RH, wind 1 m/s | - DSF with 1m air-gap reduced room temperature by up to 3°C compared to single skin façade.<br>- Increasing air-gap up to 1m improves performance; >1m reduces effectiveness.<br>- Best performance: 1m air-gap; further increase reduces stack effect.<br>- Glazing type also influences results; reflective/anti-sun glass further reduce heat gain.<br>- Top floor had highest temperatures (solar absorption by roof).<br>- DSF keeps room temperature more uniform across floors compared to SSF. |
| 15.A new type of double-skin façade configuration for the hot and | Singapore (Hot and humid climate) | - Propose and evaluate a new DSF configuration suitable for hot and humid climates. | ESP-r | - Outdoor/indoor air temperature<br>- Solar radiation<br>- DSF cavity ventilation (natural | - The new DSF configuration reduced cooling loads by up to **25%** compared to single-skin façade.<br>- Improved indoor thermal comfort by lowering indoor air temperature. |

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| humid climate (Wong et al., 2008) | | - Assess its thermal performance and energy saving potential compared to conventional façades. | | and mechanical)<br>- Cavity depth and airflow rate<br>- Shading devices | - Natural ventilation in the DSF cavity was effective in reducing heat gain.<br>- Proper design (cavity depth, ventilation, and shading) is critical for maximizing benefits in hot and humid climates.<br>- Demonstrated that DSF can be adapted for tropical climates with significant energy and comfort gains. |
| 16.Experimental study of a mechanically ventilated double-skin façade with venetian sun-shading device: A full-scale investigation in controlled environment (Gavan et al., 2010) | Lyon, France (Controlled laboratory environment, temperate climate) | - Investigate the thermal and energy performance of a mechanically ventilated double-skin façade (DSF) with venetian blinds.<br>- Analyse the effect of sun-shading and ventilation strategies on heat transfer and indoor condition. | experimental test | - Air temperature (inside DSF cavity, indoor, outdoor)<br>- Surface temperatures<br>- Airflow rates (mechanical ventilation)<br>- Solar radiation<br>- Venetian blind position and operation | - Mechanically ventilated DSF with venetian blinds significantly reduced solar heat gain compared to conventional façade.<br>- Venetian blinds reduced cavity and indoor temperatures, improving thermal comfort.<br>- Mechanical ventilation enhanced heat removal from the cavity.<br>- The combination of blinds and ventilation provided the best performance in limiting overheating.<br>- Results provide practical data for DSF design and operation in similar climates. |

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| 17.A fast assessment method for thermal performance of naturally ventilated double-skin façades during cooling season (Xue and Li, 2015) | China (hot summer climate) | -Analyse influence of design and environmental factors on cavity and indoor temperatures.<br>- Evaluate DSF's effectiveness in reducing cooling loads. | - Analytical modelling (no simulation software required).<br>- Empirical validation using field measurements.<br>- Instruments: Thermocouples, anemometers, pyranometers. | - Cavity air temperature ("T_cavity")<br>- Indoor air temperature ("T_indoor")<br>- Outdoor air temperature ("T_outdoor")<br>- Airflow rate in cavity ("V_cavity")<br>- Solar radiation ($W/m^2$)<br>- Cooling load reduction | - DSF with natural ventilation significantly reduced indoor cooling load compared to single-skin façade.<br>- Cavity ventilation rate and solar radiation were key factors affecting performance.<br>- Wider cavity and larger vent openings improved heat removal.<br>- Rapid assessment tool provided accurate predictions for practical design decisions. |

Table 3.1 Overview of Double Skin Façade Previous Studies (author,2025)

## 2. Discussion:

The review of previous studies highlights the significant role that double skin façades (DSFs) play in improving thermal comfort and enhancing energy efficiency in buildings across various climatic zones. The research consistently demonstrates that when properly designed, DSFs can effectively moderate indoor temperatures, reduce dependence on mechanical heating and cooling systems, and contribute to more sustainable building operations.

We note from the previous studies, especially the closest climate to the BSK climate (cold semi-arid climate), the thermal behaviour and performance of double skin façades,

### 2.1.Double skin façade performance in winter and summer:

In winter, significantly improve thermal comfort by increasing the temperature difference between interior and exterior spaces by up to 10°C. The cavity acts as a thermal buffer, reducing heat loss and often providing a greenhouse effect, which can reduce or eliminate the need for additional heating in glazed DSFs. This leads to warmer indoor conditions and energy savings on heating.

In summer, DSFs can increase the temperature difference up to 24°C. However, without adequate ventilation, the cavity can overheat due to solar gains, causing discomfort and increasing cooling demand. Proper ventilation and shading are essential to prevent the greenhouse effect inside the cavity. Materials like terracotta panels perform better in summer by reducing overheating compared to fully glazed DSFs. Orientation also plays a role.

South facing glazed DSFs are more effective in winter but can overheat in summer if not ventilated properly.

### 2.2.Design parameters:

Across different studies, several common design parameters have emerged as critical for DSF performance: cavity depth, glazing type (U-value and SHGC), ventilation strategy (natural or mechanical), air speed, and solar control methods. Orientation also plays a key role; for example, south facing façades often experience overheating if not properly shaded or ventilated. Material selection, such as the use of terracotta panels instead of fully glazed façades, can also greatly influence performance, particularly in reducing unwanted heat gain.

### 3.3. Indices:

Moreover, occupant comfort indicators, such as PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), and Indoor Air Temperature are most used indices used to assess indoor thermal comfort.

### 3.4. Software:

Various software used to simulate thermal comfort in the previous studies. The following table provides a comparative overview of commonly used software for evaluating thermal comfort in buildings. The comparison considers critical factors such as simulation accuracy, support for irregular 3D models, licensing type (free or paid), compatibility with architectural design software, as well as the main advantages and limitations of each tool. This overview aims to assist in selecting the most appropriate software based on project needs, model complexity, and desired precision.

| **Software** | **Accuracy** | **Supports Irregular 3D Models** | **Free or Paid** | **Compatible Architectural Software** | **Advantages** | **Limitations** |
|---|---|---|---|---|---|---|
| Energy Plus | Very High | Yes | Free | SketchUp (via OpenStudio), Revit | Detailed simulation; flexible; widely validated | Complex interface; steep learning curve |
| Design Builder | Very High | Moderate | Paid | SketchUp, AutoCAD | User-friendly interface for EnergyPlus engine | Limited 3D modelling for very complex forms |
| IES VE | Very High | Yes | Paid | Revit, SketchUp | Advanced simulations, dynamic thermal modelling | Expensive; requires training |

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|---|---|---|---|---|---|---|
| Open Studio | High | Yes | Free | SketchUp | Open-source interface for EnergyPlus; flexible | Less intuitive; requires technical setup |
| Ladybug + Honeybee (for Grasshopper) | High | Yes | Free | Rhinoceros 3D (Grasshopper) | Excellent for parametric and irregular models; integrates environmental data | Depends on Rhinoceros; requires scripting for advanced use |
| Autodesk Insight | Moderate-High | Moderate | Paid (part of Revit) | Revit | Easy to use inside Revit; fast early-stage feedback | Less detailed; suitable for concept phase |
| COMFEN | Moderate | No | Free | None (standalone) | Simple tool for façade studies | Only supports simple geometries |
| Ecotect Analysis (obsolete) | Moderate | Moderate | Paid (discontinued) | AutoCAD, Revit | Visual, intuitive; good for early stages | Low precision compared to modern tools |
| CFD Simulations (e.g., ANSYS Fluent) | Very High | Yes | Paid | Rhino, Revit, AutoCAD | Precise airflow and thermal distribution modelling | Very complex; mainly for advanced studies |
| TRNSYS | High | Limited | Paid | AutoCAD | Good for | Requires |

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| | | | | | multi-zone energy simulations | detailed setup; technical expertise needed |

Table 3.2 various software used to simulate thermal comfort (author,2025)

### 3.4.1. Selection of software:

From the comparison, it is evident that for projects involving complex or irregular 3D models as my project, Ladybug and Honeybee integrated with Grasshopper and Rhinoceros 3D stand out as the most flexible and effective choice. They combine high accuracy, adaptability to parametric designs, and strong environmental analysis capabilities, all while being open-source and free to use. Therefore, for studies involving non-standard geometries and a need for dynamic environmental simulation, Ladybug and Honeybee present the best balance between precision, flexibility, and accessibility.

## Conclusion:

From the review of previous studies, it is evident that double-skin façades can significantly enhance thermal comfort and contribute to energy savings when properly, designed and adapted to the local climate. Key factors influencing DSF performance include cavity size, ventilation mode, glazing type, shading devices, and material properties. Studies consistently show that DSFs are particularly effective in reducing cooling loads in hot climates and improving insulation in colder climates. However, challenges such as overheating risks, humidity control, and proper orientation need to be carefully, addressed. These insights provide a valuable foundation for developing optimized DSF models tailored to specific climatic conditions, aiming to balance energy efficiency and occupant comfort.

# PRACTICAL PART

# CHAPTER 1:
# SIMULATION AND APPLICATION OF RESULTS

## Introduction:

To accurately, assess thermal comfort within buildings particularly when using complex façade systems such as double-skin façades, simulation tools are essential. These tools allow for the modelling of environmental conditions, material behaviours, and user interactions that influence indoor thermal performance. Since real world testing can be time-consuming and limited in scope, simulation provides a reliable, flexible, and efficient method for predicting how a building will perform under various climatic and design scenarios.

## 1. Method and Tools:

### 1.1. Sensitive Response Method (SRM):

The simulation methodology employed in this research is based on the Sensitive Response Method (SRM), which enables a precise evaluation of how sensitive indoor thermal comfort conditions are to variations in double skin façade (DSF) design parameters. This approach allows the study to identify which variables have the most significant impact on thermal performance within the terminal environment.

The SRM involves systematically adjusting key design parameters and analysing the corresponding changes in thermal comfort indicator. Unlike comparative methods that assess general performance shifts, SRM focuses on the rate and magnitude of change in response to incremental modifications of each variable. This provides a deeper understanding of the façade's behaviour and its contribution to indoor climate control.

The aim of this simulation study is to assess the thermal comfort performance of an airport terminal equipped with a double skin façade, and to evaluate the sensitivity of indoor conditions to changes in DSF design parameters, cavity width, and glass thickness. Simulations are conducted using Rhinoceros software and Grasshopper plugins, enabling precise parametric control and performance analysis under varying design scenarios.

### 1.2. Definition of the software:

#### 1.2.1 Rhino version 8:

It is a commercial 3D computer graphics and computer aided design (CAD) application, from rhinoceros company, developed by Robert McNeel & Associates. It is renowned for its capability to model complex and free form geometries with precision, making it widely used in architecture, industrial design, and engineering. (Robert McNeel & Associates, 2025)

#### 1.2.2 Grasshopper:

Grasshopper is a visual programming language integrated within the Rhinoceros 3D computer-aided design (CAD) platform. It is primarily utilized for parametric modelling in the

fields of architecture, design, structural analysis, and digital fabrication.(UNSWmaking, 2025)

#### 1.2.2.1 Plugins:

For indoor thermal comfort study, it is recommended to use a set of grasshopper plugins mainly ladybug, honeybee, in addition to skin designer to generate the double skin façade.

##### 1.2.2.1.1 Ladybug and honeybee:

Ladybug and Honeybee are open-source environmental plugins for Grasshopper that assist designers in creating environmentally conscious architectural designs. Ladybug enables the import and visualization of weather data, while Honeybee supports detailed day lighting and thermodynamic modelling by linking the Grasshopper/Rhino environment to simulation engines like Radiance and Energy Plus/Open Studio. (LLC, 2025)

##### 1.2.2.1.2 Skin designer:

Skin Designer is a Grasshopper plugin developed by Santiago Garay and Payette Architects, designed to rapidly; generate façade geometries from building massing surfaces using repeating, user-defined panel systems. The plugin is optimized to handle large-scale façades efficiently and supports a wide range of geometric configurations. possesses the geometric freedom to construct almost any façade geometry that is composed of similar repeating elements.(Robert McNeel & Associates, 2025)

## 2. Simulation protocol:

### 2.1.Fixed and variable parameters:

The simulation methodology used in this research follows a sensitive response method to ensure an accurate evaluation of thermal comfort performance within terminals. This method enables the analysis of how different design variables impact indoor thermal comfort. The simulation based on different variables and fixed parameters. The table below shows the classification of the latters:

| Fixed parameters | Variables |
|---|---|
| Width of panels 2.4 m. | Cavity width: 0.2 m, 0.4 m, 0.6 m, 0.8 m. |
| Height: adjusted to the height of façade. | |
| Panel system: multi story | |
| Ventilation system: natural ventilation | Glass thickness: 6 mm, 10 mm, 12 mm. |
| Height of façade from floor 0.3m | |
| Inlets and outlets<br>Dry bulb temperature< 26 C° (open openings)<br>Global horizontal radiation> 600 (close openings) | |

Table 1.1 Fixed parameters and variables of the model (author, 2025)

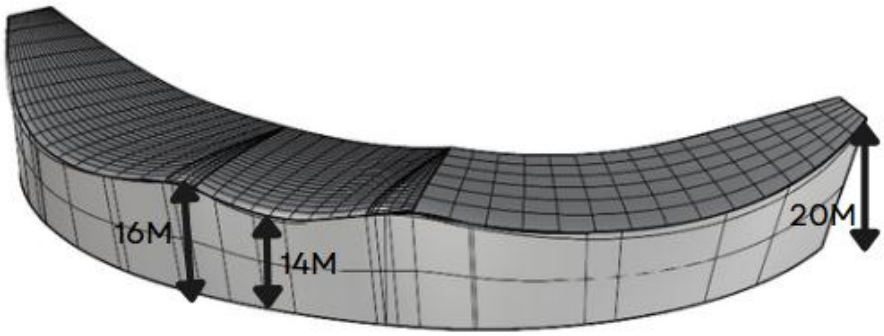



Figure 1.1 Base model geometry (author,2025)

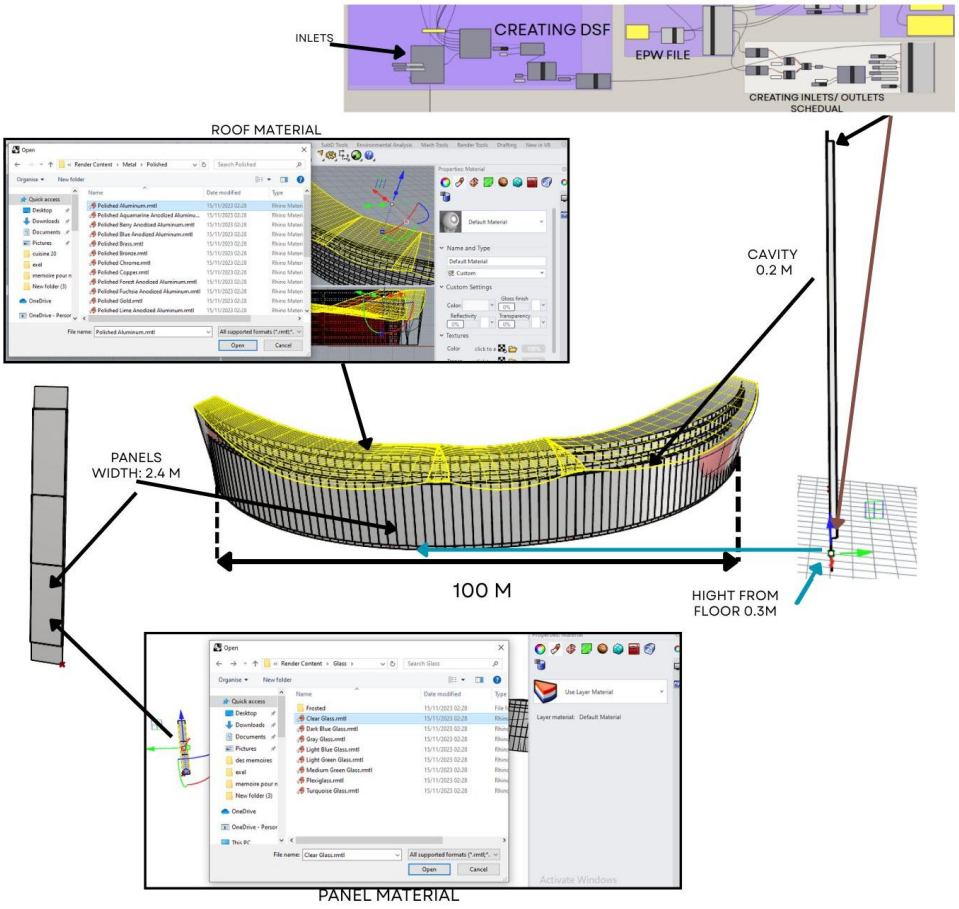



Figure 1.2 base model of double skin façade (author,2025)

## 2.2.Scenarios:

| Cavity/ glass thickness | 0.2 m | 0.4 m | 0.6 m | 0.8 m |
|---|---|---|---|---|
| 8 mm | A1 | A2 | A3 | A4 |
| 10mm | B1 | B2 | B3 | B4 |
| 12mm | C1 | C2 | C3 | C4 |

Table 1.2 table of scenarios of simulation (author, 2025)

In total, we have twelve scenarios analysed to identify the optimal model for enhancing indoor thermal comfort. The final, optimized model for each row will be compared, with next

row to assess the optimal design, and then the last optimal row will be compared with single glazing façade to evaluate its effectiveness in improving thermal performance.

## 2.3. Analysis process and inputs:

### 2.3.1 Step 1: creating base model of DSF:

A detailed 3D model of the building and its façade system created with rhinoceros and skin designer plugin. This model accurately represents the dimensions, materials, and construction characteristics of the building, ensuring that the physical behaviour of the system can be realistically, simulated.

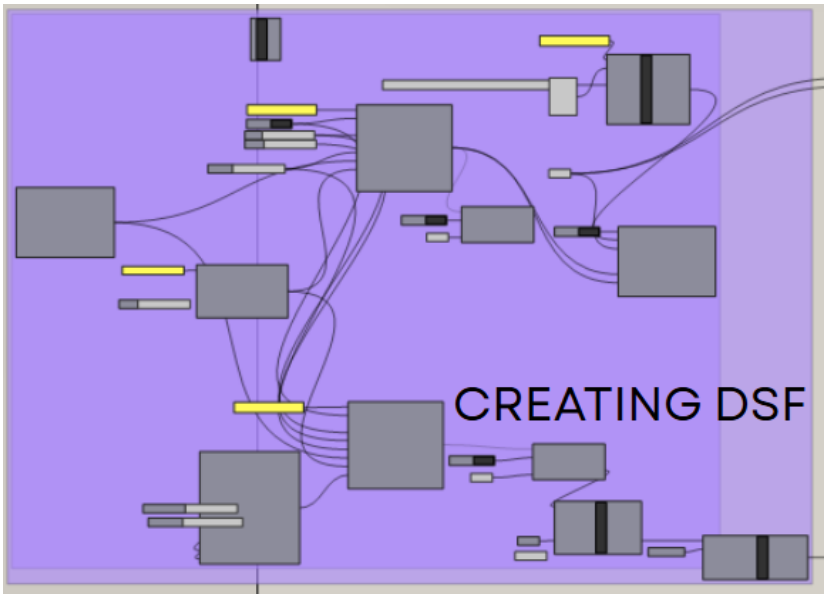



Figure 1**Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.**..3 Creating the base model of DSF WITH Rhino and skin designer ( author,2025)

### 2.3.2 Step2: Selection of Environmental data:

Climate data, including outdoor temperature, humidity, solar radiation, and wind speed, are incorporated into the model. These inputs are, typically based on typical meteorological year (TMY) datasets to represent real world environmental conditions. Climate inputs can be founded in (EPW file).

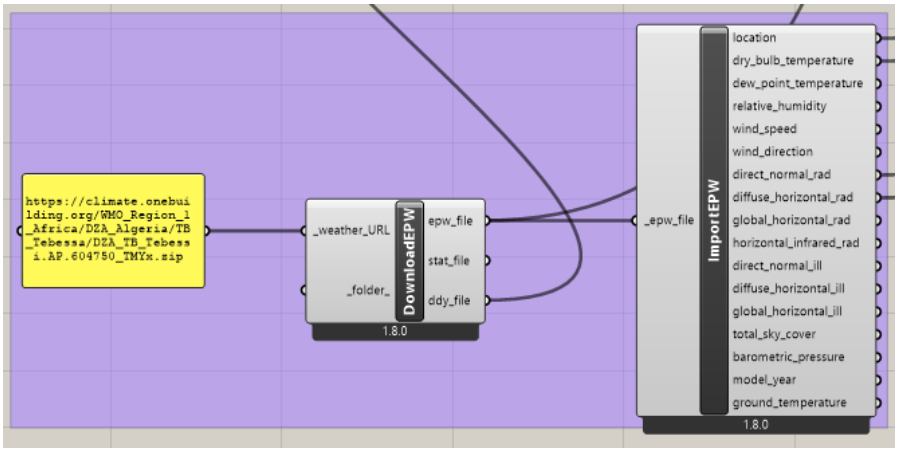



Figure 1.4 climate data inputs (author,2025)

### 2.3.3 Step 3: Simulation of Thermal Behaviour and Comfort Analysis:

The model is then used to perform simulations over the year as airports works all the year over 24H. Key performance indicator calculated thermal comfort indice 'the Predicted Mean Vote (PMV)'.

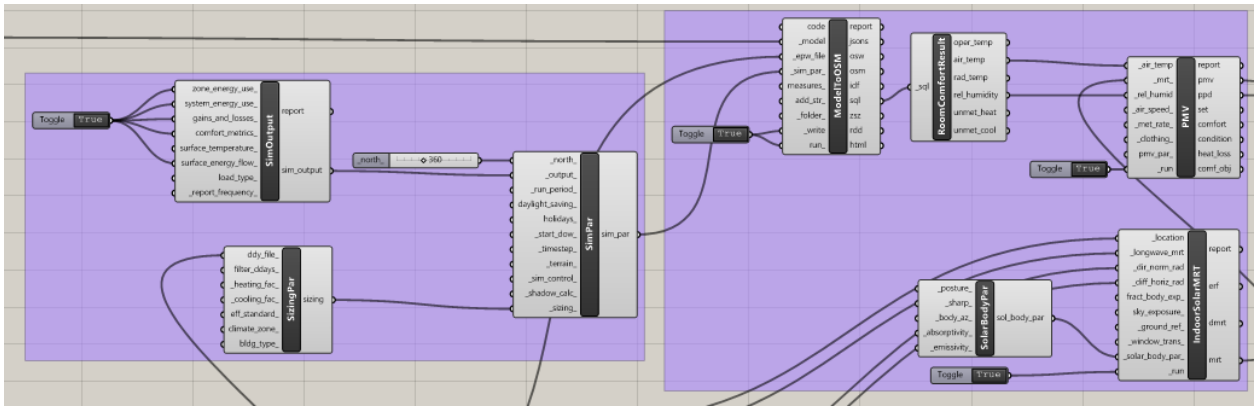



Figure 1.5 PMV simulation and simulation parameters (author,2025)

### 2.4.Result Evaluation and outputs:

Simulation outputs are analysed to assess the building's thermal performance. The comparisons made for the best design scenarios to evaluate the effects of parameters like cavity depth, glass thickness. And to see if the façade improved thermal comfort, we compare it at the end with SGF and we see the difference.

Results are represented in graphs by taking the two typical weeks of each season (winter, summer). The PMV data is plotted over a 24 hour cycle for each representative typical week per season (winter typical week: from 10 to 16 January), (summer typical week: from 15 to 21 July), This temporal resolution allows an hour by hour analysis of thermal comfort dynamics throughout the day in different seasons.

Each graph depicts the thermal comfort performance of the DSF cavities based on simulated

environmental conditions using climate based inputs. This includes both external weather conditions and internal design factors influencing microclimate within the cavity.

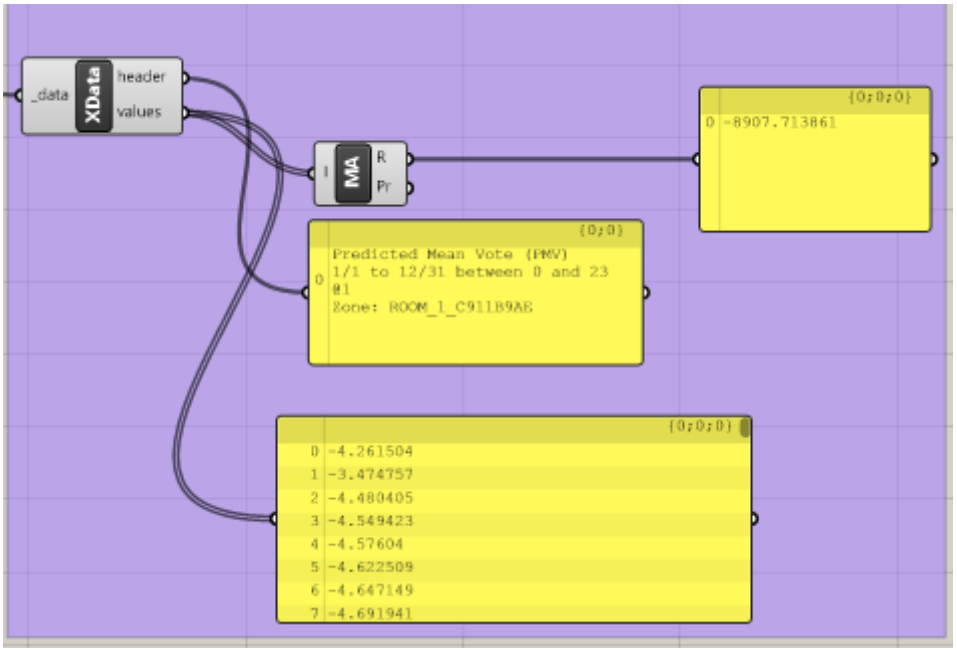



Figure 1.6 visualizing of PMV results (author,2025)

### 2.5.Optimization and Recommendations

Based on the analysis, the most effective design strategies are identified. Recommendations are proposed to enhance thermal comfort, contributing to the development of better performing façade systems.

### 2.6.Protocol flowchart:

After overview the simulation protocol, this flow chart presents the step by step process of my SRM method, from the initial concept to the final analysis. It outlines the key stages, and decisions made to evaluate the impact of the double skin façade on thermal comfort. The visual guide helps clarify the workflow and methodology adopted throughout the research.

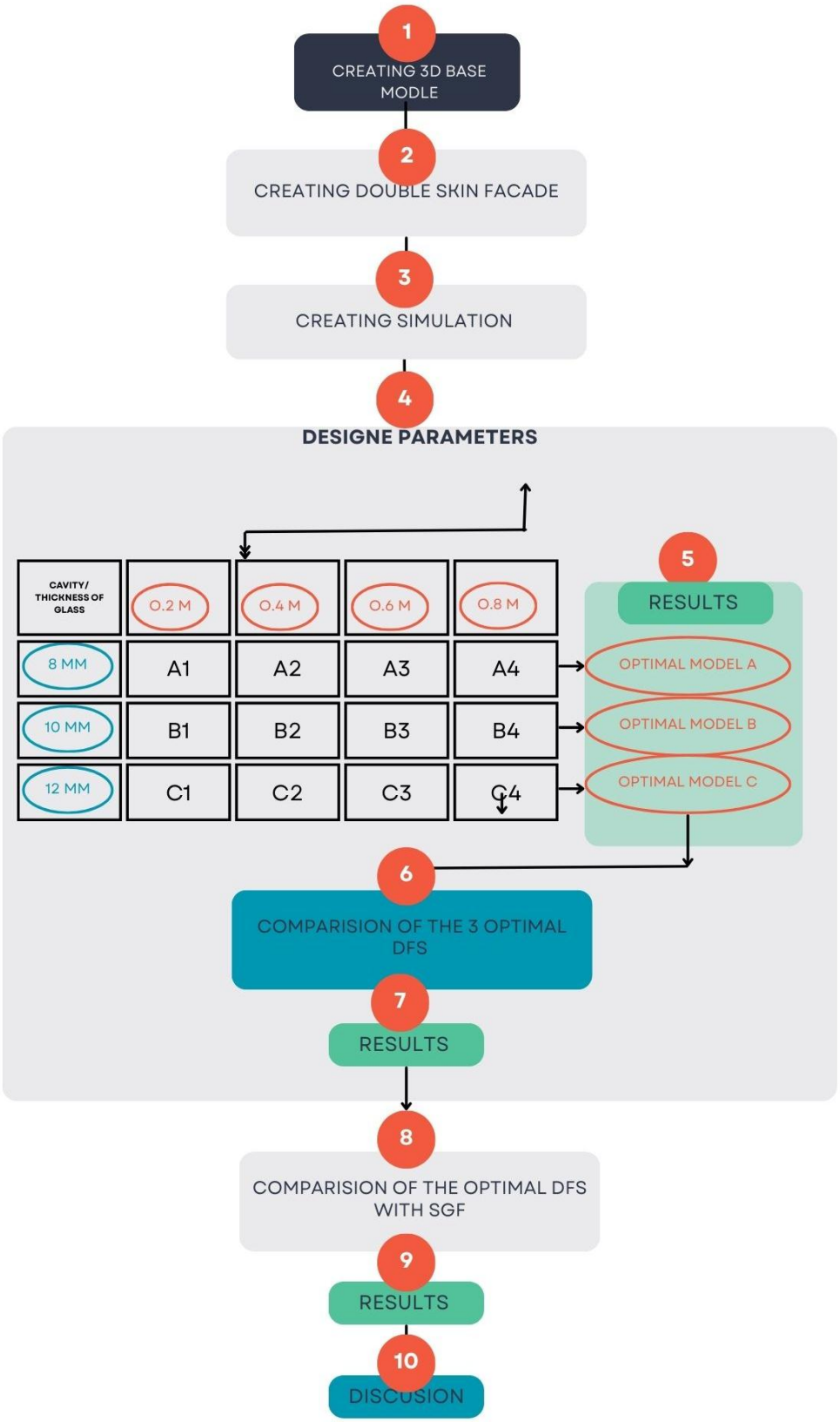



Figure 1.7 simulation protocol flowchart (author,2025)

# CHAPTER 2:
# ANALYSIS AND
# DISCUSSION OF RESULTS

# 1. Analysis and discussion of results:

This chapter presents the analysis and discussion of the simulation results related to the thermal performance of double-skin façades (DSF) in a cold semi-arid climate. It includes a comparison of twelve DSF scenarios with varying cavity depths and glass thicknesses, followed by an evaluation of the three most effective configurations. Finally, it compares the performance of the optimal DSF with a conventional single-glazing façade (SGF) across winter and summer, aiming to identify the most thermally efficient solution for airport terminal design.

## 1.1.Step 1: comparison of different design parameters (cavity and thickness):

We compose twelve scenarios for different cavities and thicknesses as the table below shows:

| Cavity | 0.2m | 0.4m | 0.6m | 0.8m |
|---|---|---|---|---|
| Glass thickness 8mm | A1 | A2 | A3 | A4 |
| Glass thickness 10mm | B1 | B2 | B3 | B4 |
| Glass thickness 12mm | C1 | C2 | C3 | C4 |

Table 2.1 tested scenarios of different design parameters (author,2025)

### 1.1.1 Result and analysis:

- **Scenario A:Comparison of double skin façade PMV with different cavities (thickness 8mm) :**

After simulating the four scenarios, the results are represented in the graphs below:

The graphs presented in Figures 2.1 and 2.2 illustrate the Predicted Mean Vote (PMV) values over the typical weeks in winter and summer, respectively. These values were simulated for a DSF using 8 mm glass thickness, with varying cavity widths of 0.2 m, 0.4 m, 0.6 m, and 0.8 m.

- A general trend can be observed wherein PMV values slightly converge to comfort range with wider cavity widths.

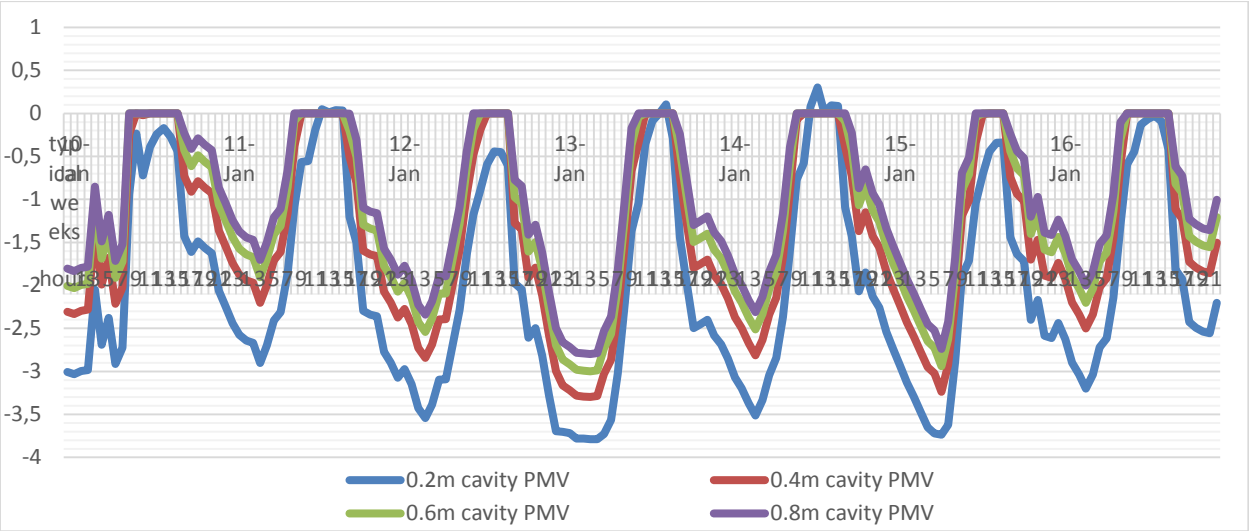



Figure 2.1 comparative PMV graph of different cavity widths in the typical week of winter (8mm glass thickness) (author, 2025)

During winter typical week (figure 2.1), scenario A1 with 0.2 m cavity shows the shortest comfort duration of 6 hours/day between 11:00–17:00, with 0,07≤ PMV≤ 0,086, and discomfort zone period between 17:00–11:00 (18 hours/day), with -0.58≤ PMV≤ -3.51, ranging from slightly cool to cold.

While scenario A2 with 0.4 m cavity Comfort duration: 8 hours/day, (10:00–18:00), PMV values between 0 ≤ PMV≤ 0.06, Shows moderate comfort period improvement over scenario A1 (0.2 m cavity), and reduced discomfort zone period: 16 hours/day (18:00–10:00), PMV values ranging from -0.7≤ PMV≤ -2.81 from slightly cool to cold.

Scenario A3 with 0.6 m cavity Extended comfort duration to 9 hours/day, (10:00–19:00). Shows long duration then 0.4 cavity, with PMV ranging from 0 ≤ PMV≤ -0,4, and discomfort zone period: 15 hours/day (19:00–10:00), generally between slightly cool the cold sensation zone, with less duration than scenario A2 (0.4 cavity), and less PMV values ranging from -0.51 ≤ PMV≤ -2.51.

Scenario A4 with 0.8 m cavity have the best comfort performance with 10 hours/day, from (09:00–19:00). With extended duration compared to scenario A3 (0.6m cavity), discomfort hours show less PMV range of -0.6≤ PMV≤ -2.31 from slightly cool to cold sensation zone, for 14 hours/day (19:00–09:00).

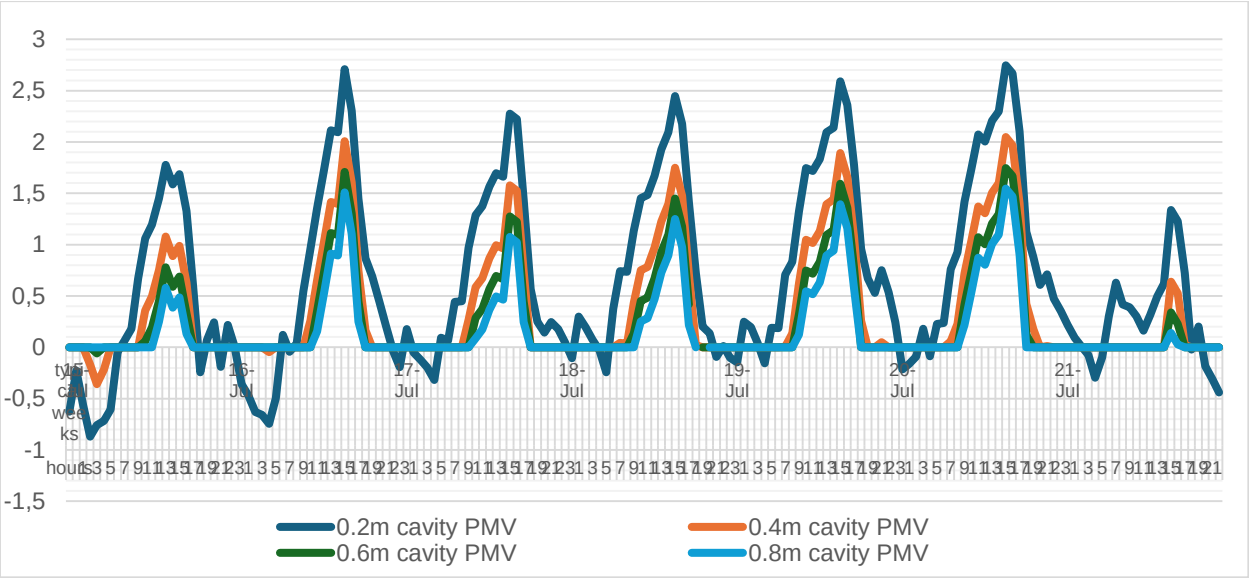



Figure 2.2 comparative PMV graph of different cavity widths in the typical week of summer (8mm glass thickness) (author, 2025)

During summer typical week (figure 2.2), scenario A1 with 0.2 m cavity shows the shortest comfort duration of 8 hours/day between (00:00–08:00), PMV values between -0.28≤ PMV≤ 0.44. Discomfort zone period: (08:00–00:00) (16 hours/day), ranging from 0.51≤ PMV≤ 2.6 from slightly warm to hot.

Scenario A2 with 0.4 m cavity Extended comfort: 15 hours/day, (19:00–10:00), with 0≤ PMV≤ 0.47, shows moderate improvement of comfort hours over scenario A1 (0.2 m cavity). Discomfort zone period: 9 hours/day (10:00–19:00), ranging from 0.53≤ PMV≤ 1.89 from slightly warm to warm cavity, the range of sensation decreased from hot to warm compared to scenario A1 (0.2m cavity).

Scenario A3 with 0.6 m cavity shows a comfort zone period of 16 hours/day, (19:00–11:00), with 0≤ PMV≤ 0.45. This scenario shows a long duration of comfort than scenario A2 (0.4m cavity). Discomfort zone period: 8 hours/day (11:00–19:00), generally within 0.54 ≤ PMV≤ 1.59 from slightly warm to warm zone, with less discomfort duration compared to scenario A2 with 0.4m cavity and less PMV values.

Scenario A4 with 0.8 m cavity indicates best comfort performance, 16 hours/day, 19:00–11:00, Discomfort hours: 8 hours/day (11:00–17:00), and PMV values mostly 0.52 ≤ PMV≤ 1.39, ranging from a slightly warm to warm sensation range which shows that PMV values are less than scenario A3 (0.6m cavity).

- **Scenario B: Comparison of double skin façade PMV with different cavities (glass thickness 10 mm):**

We compose four scenarios for different cavities as the table Bellow shows:

After simulating the four scenarios, the results are represented in the graphs below:

The graphs presented in Figures 2.3 and 2.4 illustrate the Predicted Mean Vote (PMV) values over the typical weeks in winter and summer, respectively. These values were simulated for a DSF using 10 mm glass thickness, with varying cavity widths of 0.2 m, 0.4 m, 0.6 m, and 0.8m.

- A general trend can be observed wherein PMV values slightly converge to comfort range with wider cavity widths.

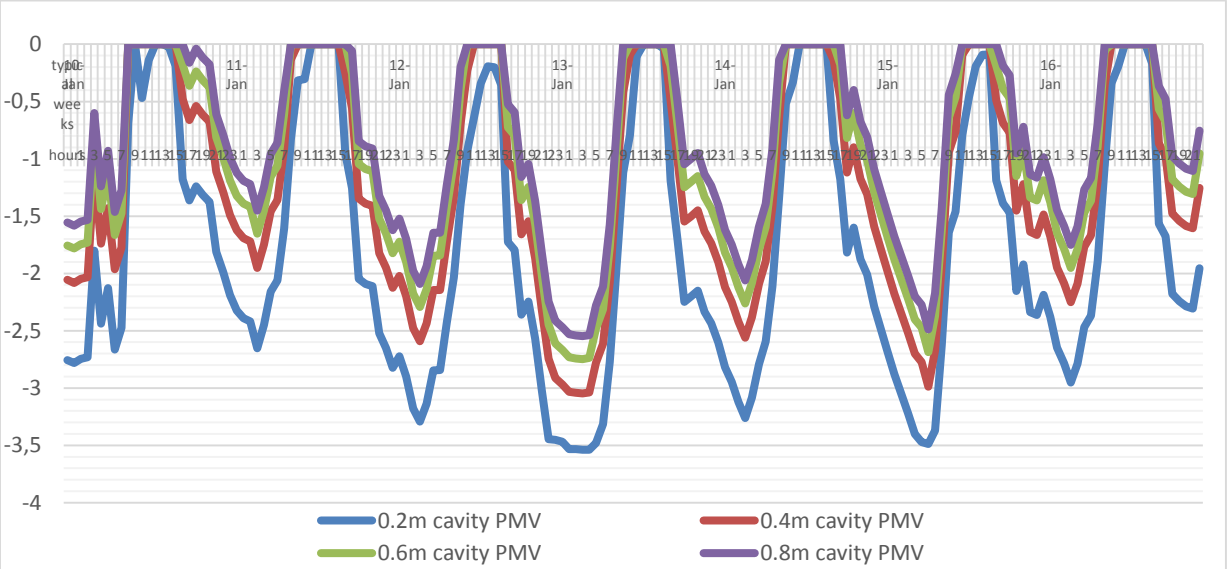



Figure 2.3 comparative PMV graph of different cavity width in the typical week of winter (10 mm glass thickness) (author, 2025)

During winter typical week (figure 2.3), scenario B1 with 0.2 m cavity shows the shortest comfort duration of 6 hours/day between 11:00–17:00, with 0 ≤ PMV≤ -0,33, and discomfort zone period between 17:00–11:00 (18 hours/day), with -0.51≤ PMV≤ -3.26, ranging from slightly cool to cold.

While scenario B2 with 0.4 m cavity Comfort duration: 9 hours/day, (10:00–19:00), PMV values between 0 ≤ PMV≤ -0.47, Shows moderate comfort period improvement over scenario B1 (0.2 m cavity), and reduced discomfort zone period: 15 hours/day (19:00–10:00), PMV values ranging from -0.63≤ PMV≤ -2.56 from slightly cool to cold.

Scenario B3 with 0.6 m cavity Extended comfort duration to 10 hours/day, (09:00–19:00). Shows long duration then scenario B2 (0.4m cavity), with PMV ranging from 0 ≤ PMV≤ -0,33, and discomfort zone period: 14 hours/day (19:00–09:00), generally between slightly cool to the cold sensation zone, with less duration than scenario B2 (0.4 cavity), and les PMV values ranging from -0.59 ≤ PMV≤ -2.26.

Scenario B4 with 0.8 m cavity have the best comfort performance with 10 hours/day, from 09:00–19:00. Even the duration shows there are no changes of duration compared to scenario B3 (0.6m cavity), but discomfort hours show less PMV range of -0.61≤ PMV≤ -2.06 from slightly cool to cold sensation zone, for 14 hours/day (19:00–09:00).

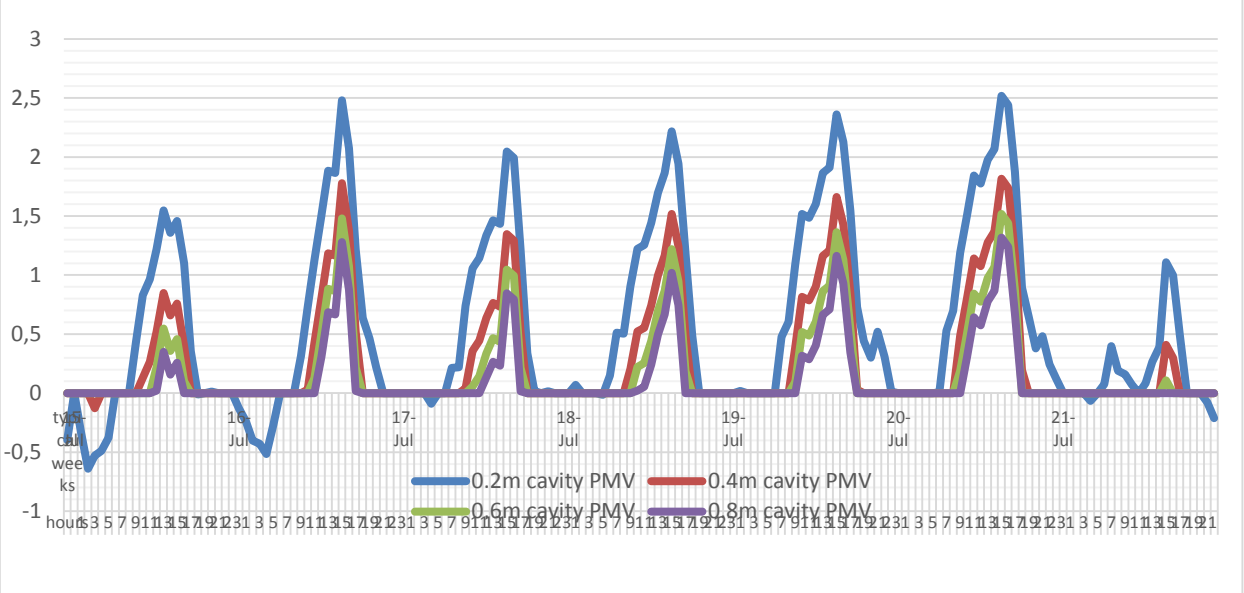



Figure 2.4 comparative PMV graph of different cavity width in the typical week of winter (10 mm glass thickness), (author, 2025)

During summer typical week (figure 2.4), scenario B1 with 0.2 m cavity shows the shortest comfort duration of 11 hours/day between 21:00–08:00, PMV values between 0≤ PMV≤ 0.48. Discomfort zone period: 8:00–21:00 (13 hours/day), ranging from 0.52≤ PMV≤ 2.43 from slightly warm to hot.

Scenario B2 with 0.4 m cavity Extended comfort: 16 hours/day, (19:00–11:00), with 0≤ PMV≤ 0.48, shows moderate improvement of comfort hours over scenario B1 (0.2 m cavity). Discomfort zone period: 8 hours/day (11:00–19:00), ranging from 0.8 ≤ PMV≤ 1.81 from slightly warm to warm cavity, the range sensation decreased from hot to warm compared to scenario B1 (0.2m cavity).

Scenario B3 with 0.6 m cavity shows a comfort zone period of 17 hours/day, (18:00–11:00), with 0≤ PMV≤ 0.18. This scenario shows a long duration of comfort than scenario B2 (0.4m cavity). Discomfort zone period: 7 hours/day (11:00–18:00), generally within 0.51 ≤ PMV≤ 1.51 from slightly warm to warm zone, with less discomfort duration compared to scenario B2 with 0.4m cavity and less PMV values.

Scenario B4 with 0.8 m cavity indicates best comfort performance, 17 hours/day, (18:00–11:00), PMV range between 0 ≤ PMV≤0.3.Discomfort hours to 7 hours/day (11:00–17:00), and PMV values mostly 0.57 ≤ PMV≤ 1.23, ranging from a slightly warm to warm

sensation range which shows that PMV values are less than scenario B3 (0.6m cavity).

- **Scenario C: Comparison of double skin façade PMV with different cavities (glass thickness 12 mm):**

After simulating the four scenarios, the results are represented in the graphs below:

The graphs presented in Figures 2.5 and 2.6 illustrate the Predicted Mean Vote (PMV) values over the typical weeks in winter and summer, respectively. These values were simulated for a DSF using 12 mm glass thickness, with varying cavity widths of 0.2 m, 0.4 m, 0.6 m, and 0.8 m.

- A general trend can be observed wherein PMV values slightly converge to comfort range with wider cavity widths.

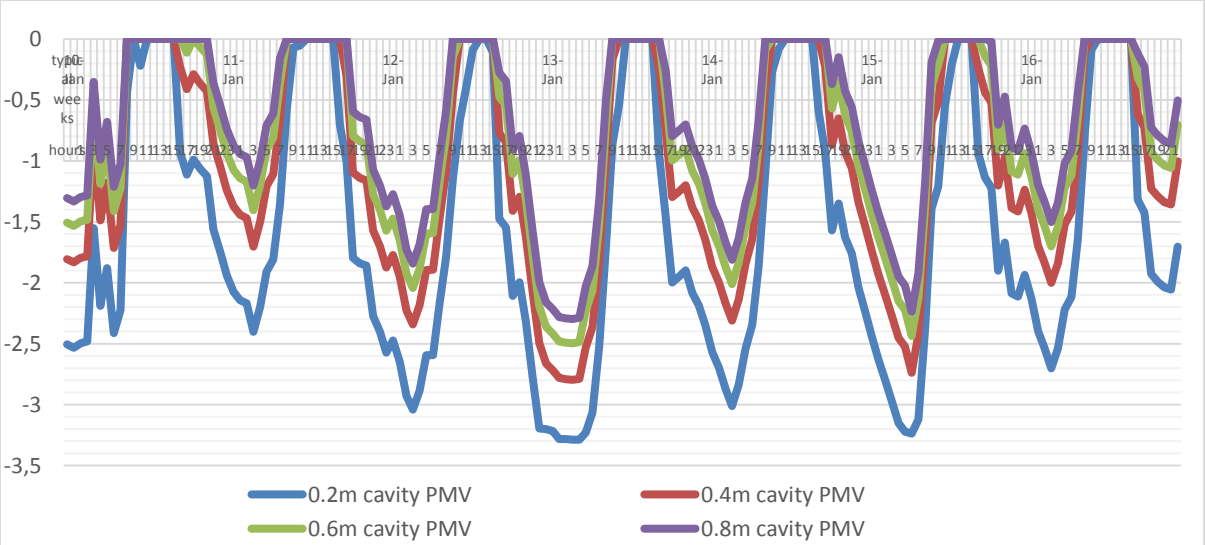



Figure 2.5 comparative PMV graph of different cavity width in the typical week of winter (12 mm glass thickness) (author, 2025)

During winter typical week (figure 2.5), scenario C1 with 0.2 m cavity shows the shortest comfort duration of 7 hours/day between 10:00–17:00, with 0 ≤ PMV≤ -0,26, and discomfort zone period between 17:00–10:00 (17 hours/day), with -0.92≤ PMV≤ -3.01, ranging from slightly cool to cold.

While scenario C2 with 0.4 m cavity Comfort duration: 10 hours/day, (09:00–19:00), PMV values between 0 ≤ PMV≤ 0.38, Shows moderate comfort period improvement over scenario B1 (0.2 m cavity), and reduced discomfort zone period: 14 hours/day (19:00–09:00), PMV values ranging from -0.86≤ PMV≤ -2.31 from slightly cool to cold.

Scenario C3 with 0.6 m cavity Extended comfort duration to 11 hours/day, (09:00–20:00). Shows long duration then scenario B2 (0.4 cavity), with PMV ranging from 0 ≤ PMV≤ -0,34, and discomfort zone period: 13 hours/day (20:00–09:00), generally between slightly cool to the

cold sensation zone, with less duration than scenario B2 (0.4 cavity), and les PMV values ranging from -0.59 ≤ PMV≤ -2.00.

Scenario C4 with 0.8 m cavity have the best comfort performance with 12 hours/day, from 10:00–22:00 with comfort zone range from 0 ≤ PMV≤ -0,42, with a long duration then scenario B3 ( 0.6 m cavity ), discomfort hours show less PMV range of -0.56 ≤ PMV≤ -1.81 from slightly cool to cool sensation zone, for 12 hours/day (22:00–10:00).

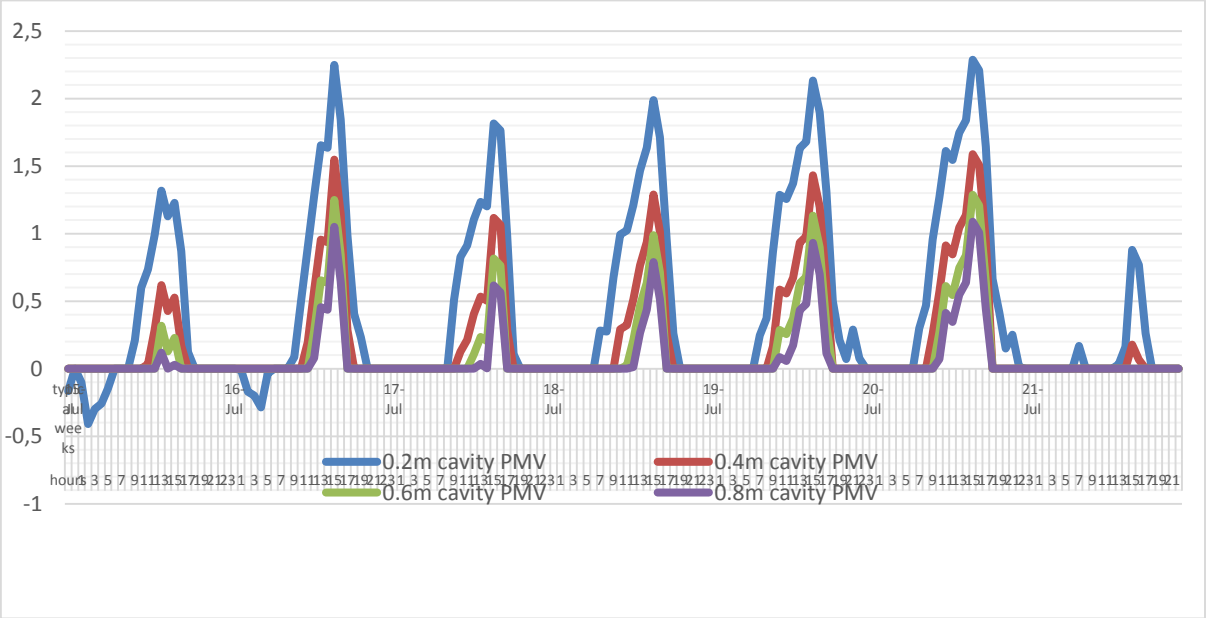



Figure 2.6 comparative PMV graph of different cavity width in the typical week of summer (12 mm glass thickness), (author, 2025)

During summer typical week (figure 2.6 ), scenario A1 with 0.2 m cavity shows the shortest comfort duration of 14 hours/day between 20:00–10:00, PMV values between 0≤ PMV≤ 0.46. Discomfort zone period: 10:00–20:00 (10 hours/day), ranging from 0.66 ≤ PMV≤ 2.28 from slightly warm to hot.

Scenario C2 with 0.4 m cavity Extended comfort: 16 hours/day, (19:00–11:00), with 0≤ PMV≤ 0.25, shows moderate improvement of comfort hours over scenario C1 (0.2 m cavity). Discomfort zone period: 8 hours/day (11:00–19:00), ranging from 0.57 ≤ PMV≤ 1.58 from slightly warm to warm sensation zone, the range of sensation decreased from hot to warm compared to scenario C1 (0.2m cavity).

Scenario C3 with 0.6 m cavity shows a comfort zone period of 17 hours/day, (19:00–12:00), with 0≤ PMV≤ 0.27. This scenario shows a long duration of comfort than scenario C2 (0.4m cavity). Discomfort zone period: 7 hours/day (12:00–19:00), generally within 0.54 ≤ PMV≤ 1.28 from slightly warm to warm zone, with less discomfort duration compared to scenario C2 with 0.4m cavity and less PMV values.

Scenario C4, with 0.8 m cavity indicates best comfort performance, 22 hours/day, 18:00–16:00, with long duration than scenario C3 (0.6 cavity).Discomfort hours further reduced to 2 hours/day (16:00–18:00), and PMV values mostly $0.52 \leq PMV \leq 0.98$, ranging in slightly warm sensation range which shows that discomfort hours and PMV values and are less than scenario C3 (0.6m cavity). And sensation range attend from warm to slightly warm.

### 1.1.2. Discussion:

The analysis evaluates the thermal performance of vented double-skin façades (DSF) in a BSK climate airport terminal, examining how cavity width (0.2–0.8 m) and glass thickness (8–12 mm) impact indoor comfort via PMV (Predicted Mean Vote) simulations. Key findings and evaluation are summarized below:

The study employed Grasshopper plugins and Rhinoceros 3D to simulate 12 DSF configurations across three glass thicknesses (8 mm, 10 mm, 12 mm) and four cavity widths. Seasonal PMV values were analysed for typical winter and summer weeks, with comfort thresholds defined by ASHRAE Standard 55:2013.

**Key Findings:**

The results indicate that increasing cavity width improves thermal comfort; however, this improvement follows a diminishing return trend. The transition from 0.2 m to a 0.4 m cavity produced the most significant enhancement in comfort, reducing cold discomfort during night and early morning hours. Further increases to 0.6 m and 0.8 m continued to yield benefits, but with improvement in thermal comfort always, suggesting that beyond a certain point, the increase in thermal mass and insulation does not proportionally translate into better comfort outcomes.

**Winter Performance:**

- With 8 mm glass thickness, scenario A4 with the wider cavity (0.8 m cavity), helped to prolong the duration of thermal comfort from 6h/day from (11:00-17:00) into 10hours/ day from (09: 00- 19:00). And reduce discomfort hours from 18h/day (17:00-11:00) to 14h/day (19:00-10:00). reducing PMV from-3.51 to -2.31 sitting always in the cold sensation, showing that even the highest performing DSF configuration did not eliminate discomfort, particularly during night hours.
- With 10 mm glass thickness, scenario B4 (0.8 m cavity) helped to prolong the duration of thermal comfort from 6 h/day (11:00–17:00) to 10 h/day (09:00–19:00), and reduce discomfort hours from 17 h/day (17:00–10:00) to 14 h/day (19:00–09:00). PMV values improved from a range of -3.26 in the narrowest

cavity to -2.06 in the widest.

- With 12 mm glass thickness, scenario C4 with the 0.8 m cavity extended the comfort duration from 7 h/day (10:00–17:00) to 12 h/day (10:00–22:00). and shortened the discomfort period from 17 h/day (17:00–10:00) to 12 h/day (22:00–10:00). PMV values were significantly moderated from -3.01 in the narrowest cavity to -1.81 in the optimal scenario, showing improved sensation from cold to cool.

**Summer performance:**

- With 8mm glass thickness, wider cavity scenario A4 (0.8 cavity) helped to prolong the duration of thermal comfort from 8h/day from (00:00-08:00) into 16hours/ day from (19: 00- 11:00), and reduced the PMV range of discomfort zone from 2.6 to 1.36 from hot to warm zone, also discomfort hours reduced from 16h/day (08:00-00:00) to 8h/day (11:00-19:00).
- With 10 mm glass, scenario B4 (0.8 m cavity) helped to extend the duration of thermal comfort from 10 h/day (21:00–07:00) to 16 h/day (18:00–10:00), and reduced the PMV range in the discomfort zone from 2.43 to 1.23, shifting sensations from hot to slightly warm. Discomfort hours decreased from 14 h/day (08:00–22:00) to 8 h/day (10:00–18:00).
- With 12 mm glass, scenario C4 (0.8 m cavity) significantly enhanced summer comfort by extending the comfort duration from 14 h/day (20:00–10:00) to 22 h/day (18:00–16:00), and reducing discomfort hours from 10 h/day (10:00–20:00) to just 2 h/day (16:00–18:00). PMV values during discomfort periods dropped from 2.28 to 0.98, indicating a shift from hot to slightly warm sensation.

**Optimal Configuration**

- The 0.8 m cavity consistently delivered the best performance across all glass thicknesses, balancing extended comfort hours and minimized PMV fluctuations.
  - The results align with previous research on DSF mechanisms:

The improvement in thermal comfort observed with increased cavity depth in the vented double skin façade with 8mm glass thickness is attributable to a combination of interrelated physical phenomena: enhanced thermal resistance (R-value), moderated airflow dynamics (stack effect), reduced solar heat gain, lower solar transmittance, and thermal phase lag. ((Xu and Ojima, 2007, Gratia and De Herde, 2004)

As the cavity depth increases from 0.2 m to 0.8 m, the air layer between the two skins acts

more effectively as a thermal buffer, slowing down the transmission of external temperature fluctuations into the interior. This behaviour aligns with findings from *(*Poirazis, 2006*)*and *(*Saelens, 2002*),* who highlight that wider cavities reduce conductive and radiative heat transfer.

In winter, the inlets of the DSF remain closed during early morning hours when exterior temperatures are low, allowing solar radiation to warm the trapped air within the cavity. This stored heat is gradually released to the interior during colder evening hours, a phenomenon analogous to the Trombe wall effect and known as thermal phase shift or lag as discussed by(Zlateva et al., 2024). This mechanism explains the extended comfort duration observed in scenarios with 0.6 m and 0.8 m cavities, as the delay in heat release reduces night time cold discomfort.

In summer, when temperatures rise, the DSF inlets open to facilitate natural ventilation, enabling the hot air accumulated in the cavity to escape. This promotes a stack effect and helps limit heat gain to the indoor space, as supported(Gratia and De Herde, 2004). The deeper cavities enhance this ventilation driven cooling by increasing airflow volume and improving chimney like extraction.

Therefore, the progressive enhancement in comfort with increased cavity depth is not linear but follows a pattern of diminishing returns (significant between 0.2 m and 0.4 m, and moderate beyond) due to the interplay of insulation, thermal inertia, and airflow efficiency within the cavity, beyond a certain depth, these benefits begin to plateau due to diminishing heat transfer gradients and reduced airflow velocity this align with results founded by (Pilechiha et al., 2019).

The results affirm the initial hypothesis that DSF can enhance indoor thermal comfort, particularly by mitigating cold stress and reducing hot sensation in BSK climate conditions. The previous study also confirms that design parameters, especially cavity width, plays a pivotal role in determining the façades effectiveness in enhancing thermal comfort ,as the study of (Poirazis, 2006)

**Conclusion:**

This three phase sensitivity analysis aimed to evaluate the impact of varying cavity depths (0.2 m, 0.4 m, 0.6 m, 0.8 m) across three glazing thicknesses (8 mm, 10 mm, and 12 mm), with 12 different scenarios, on the thermal comfort performance of vented double skin façade in a BSK climate airport terminal. Across all scenarios, the results consistently confirmed that increasing cavity depth significantly improves thermal comfort in both summer and winter conditions.

For scenario A (8 mm glazing), scenario A4 (0.8 m cavity**)** emerged as the most effective configuration, offering the highest number of comfort hours and the lowest PMV values,

particularly during summer when overheating risk is critical.

For scenario B (10 mm glazing), the results reaffirmed the importance of cavity depth, with scenario B4 (0.8 m cavity) again being the optimal model, showing improved comfort in both winter and summer due to minimizing PMV values and discomfort hours.

For scenario C (12 mm glazing), Scenario C4 (0.8 m cavity) once more delivered the best thermal comfort results, extending comfort duration to 12 hours/day in winter and up to 22 hours/day in summer, with PMV values consistently within the slightly cool to slightly warm zones.

Across all steps, the optimal configuration remains the 0.8 m cavity depth, with all glass thickness of (8 mm, 10mm and 12 mm).

### 1.2.Step 2: Comparison of optimal scenarios of double skin façade PMV:

Following the simulation and evaluation of 12 different design scenarios, three configurations emerged as optimal based on their thermal performance:

| Scenario | A4 | B4 | C4 |
|---|---|---|---|
| Cavity and glass thickness | 0.8 cavity 8 mm glass | 0.8 cavity 10 mm glass | 0.8 cavity 12m glass |

Table 2.2 scenarios of the optimal models of DSF (authot,2025)

#### 1.2.1. Result and analysis:

The comparative results are presented in the graphs below:

The graphs presented in Figures 2.7 and 2.8 illustrate the Predicted Mean Vote (PMV) values over the typical weeks in winter and summer, respectively. These values are comparing the thermal performance of the three optimal double-skin façade configurations, highlighting the variations in occupant comfort achieved by each scenario.

- A general trend can be observed wherein PMV values slightly converge to comfort range with thicker glass.

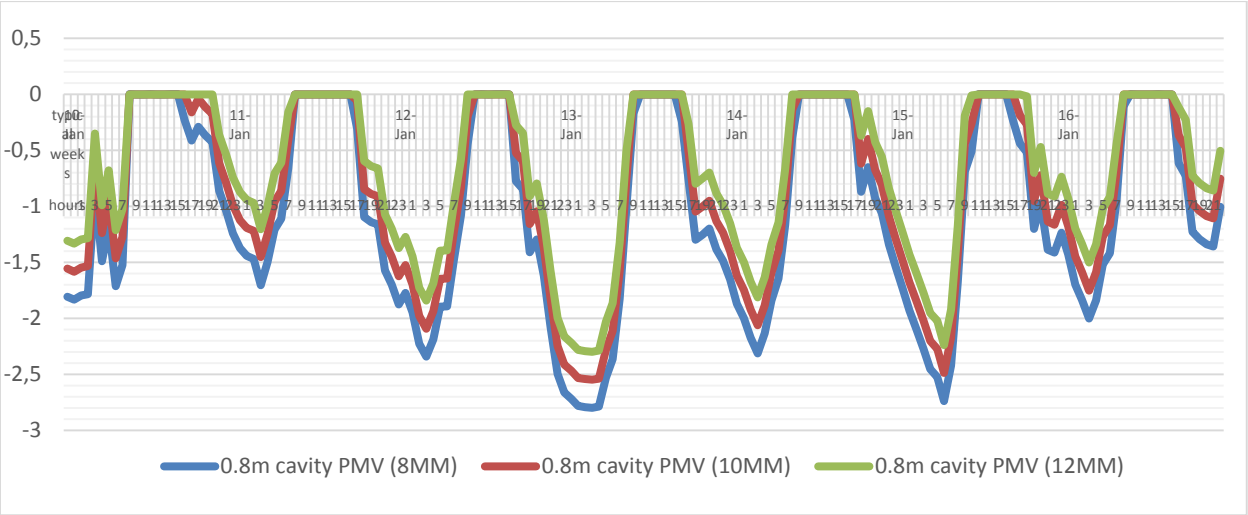



Figure 2.7 comparative PMV graph of optimal models in the typical week of winter (author, 2025)

During the winter typical week (figure 2.7), Scenario A4 with (8 mm glass thickness and a 0.8 m cavity) shows a comfort duration of 10 hours/day, from 09:00–19:00, discomfort hours show PMV range of -0.6≤ PMV≤ -2.31 from slightly cool to cold sensation zone, for 14 hours/day (19:00–09:00).

While Scenario B4 with (10 mm glass thickness and a 0.8 m cavity), have a comfort performance of 10 hours/day, from 09:00–19:00. Even the duration shows there are no changes of duration compared to scenario A4 (8 mm glazing and a 0.8 m cavity), but discomfort hours show less PMV range of -0.61≤ PMV≤ -2.06 from slightly cool to cold sensation zone, for 14 hours/day (19:00–09:00).

Scenario C4 (12 mm glass thickness and a 0.8 m cavity), have the best comfort performance with 12 hours/day, from 10:00–22:00 with comfort zone range from 0 ≤ PMV≤ -0,42, and a long duration then scenario B4 (8 mm glazing and a 0.8 m cavity), discomfort hours show less PMV range of -0.56 ≤ PMV≤ -1.81 from slightly cool to cool sensation zone, for 12 hours/day (22:00–10:00).

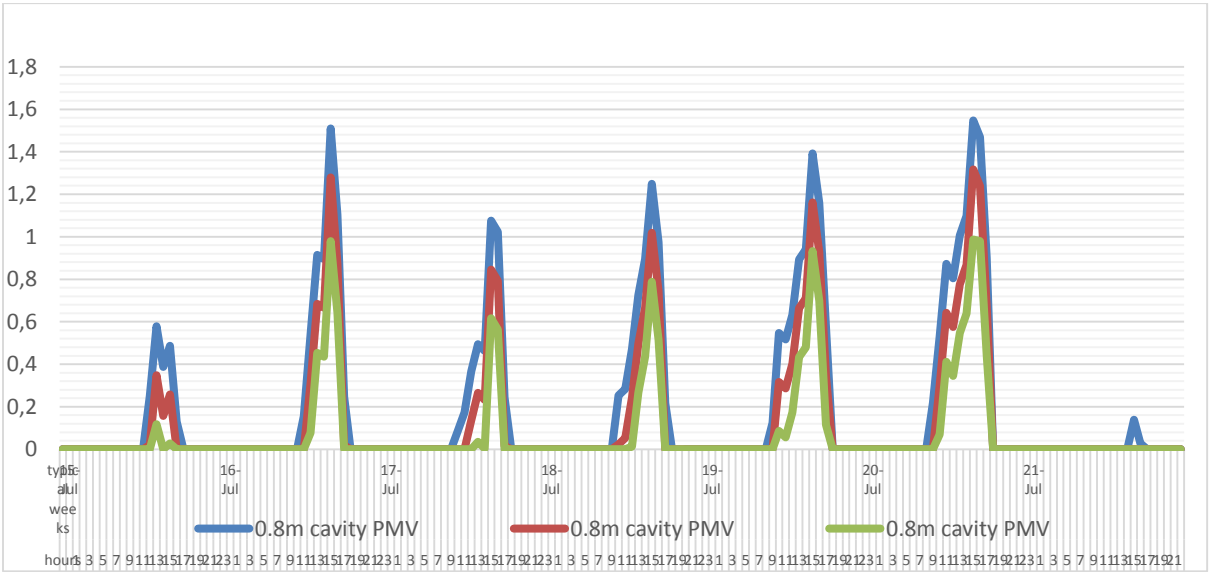



Figure 2.8 comparative PMV graph of optimal models in the typical week of winter (author, 2025)

In summer ( figure 2.8), scenario A4 with (8 mm glass thickness and a 0.8 m cavity) indicates comfort performance of 16 hours/day, (19:00–11:00), Discomfort hours: 8 hours/day (11:00–17:00), and PMV values from $0.52 \leq PMV \leq 1.39$, ranging from a slightly warm to warm sensation range which shows that PMV values are less than scenario A3 (0.6m cavity).

Scenario B4 with (10 mm glass thickness and a 0.8 m cavity) indicates best comfort performance, 17 hours/day, (18:00–11:00), PMV range between $0 \leq PMV \leq 0.3$.with longer duration then scenario A4 ,Discomfort hours last for 7 hours/day (11:00–17:00), and PMV values mostly $0.57 \leq PMV \leq 1.23$, ranging from a slightly warm to warm sensation range which shows that PMV values are less than scenario A4.

Scenario C4 with (12 mm glass thickness and a 0.8 m cavity) indicates best comfort performance, 22 hours/day, (18:00–16:00), with long duration than scenario C3 (0.6 cavity).Discomfort hours further reduced to 2 hours/day (16:00–18:00), and PMV values mostly $0.52 \leq PMV \leq 0.98$, ranging in slightly warm sensation range which shows that discomfort hours and PMV values are less than scenario B4. And sensation range attend from warm to slightly warm.

### 1.2.2. Discussion:

The comparative analysis of the three optimal DSF configurations A4 (8 mm glass + 0.8 m cavity), B4 (10 mm glass + 0.8 m cavity), and C4 (12 mm glass + 0.8 m cavity) highlights how variations in glazing thickness influence thermal comfort through PMV simulations. Key findings and evaluation are summarized below:

**Key findings:**

While the increase in glass thickness from 8 mm to 12 mm resulted in only a slight improvement in thermal comfort compared to the more pronounced effect of cavity depth, it still proved beneficial enhancing thermal inertia, reducing temperature fluctuations, and contributing to more stable indoor conditions, particularly during extreme weather hours.

**In winter:**

All three scenarios maintained a comfort duration of at least 10 hours/day, indicating the dominant influence of the 0.8 m cavity in mitigating cold stress.

- Scenario A4 and B4 both achieved 10 comfort hours (09:00–19:00), but B4 exhibited slightly improved performance by reducing PMV intensity during discomfort hours (−2.06 compared to −2.31 in A4). This reflects a small improvement in insulation capacity as glazing thickness increases from 8 mm to 10mm.
- Scenario C4, with 12 mm glazing, outperformed the others by extending the comfort duration to 12 hours/day (10:00–22:00) and shifting PMV values during discomfort from a cold −2.31 in A4 to cool −1.8, suggested that thicker glazing enhances thermal inertia and interior temperature stability, particularly in cold hours.

**In summer:**

- Scenario A4 provided 16 hours of comfort (19:00–11:00) and 8 hours of discomfort, with PMV values reaching up to 1.39, indicating warm indoor conditions.
- Scenario B4 improved upon this by extending comfort to 17 hours/day (18:00–11:00) and reducing maximum PMV to 1.23, slightly lowering the peak overheating risk.
- The most substantial improvement was observed in Scenario C4, which delivered 22 hours/day of thermal comfort (18:00–16:00), with discomfort reduced to only 2 hours/day and PMV values capped at 0.98. This placed the entire thermal experience in the “slightly warm” zone, marking a considerable enhancement in thermal sensation.

**Optimal Configuration:**

- Scenario C4 consistently delivered the best performance, balancing extended comfort hours with minimized PMV fluctuations. It maintained thermal sensations within the cool zone during winter and the slightly warm zone during summer.
- The results align with previous research on DSF mechanisms:

The additional glass thickness appears to enhance thermal inertia, contributing to slower heat gain and improved thermal stability. This observation aligns with findings from several studies.

(Pérez-Grande et al., 2005)in*Influence of Glass Properties on the Performance of Double-Glazed Façades*analysed energy flow in double-glazed façades and concluded that thicker glass enhances thermal performance by improving the façade's ability to buffer temperature changes and help stabilize indoor temperatures by delaying heat transfer. Additionally, research on evacuated glazing systems titled *Effect of glass thickness on the thermal performance of evacuated glazing* confirms that increasing glass thickness improves both thermal resistance and inertia, thereby reducing peak heat gains (Fang et al., 2007). These findings support the current study's results, showing that while increase in glass thickness (from 8 mm to 12 mm) had a effect on PMV values, it meaningfully contributed to a more stable internal environment through enhanced thermal inertia.

These results reinforce the hypothesis that design parameters particularly (cavity depth and glazing thickness) play a dominant role in optimizing the thermal performance of double-skin façades.

**Conclusion:**

The comparative evaluation of the three optimal DSF configurations Scenario A4, Scenario B4, and Scenario C4confirms that cavity depth remains the most influential parameter in enhancing thermal comfort in BSK climate conditions. However, the progressive increase in glass thickness from 8 mm to 12 mm also contributed meaningful, though more moderate, improvements through enhanced thermal inertia and greater temperature stability.

Among all tested models, Scenario C4 (12 mm glass + 0.8 m cavity) demonstrated the best overall thermal performance. As the optimal model of DSF.

## 1.3.Step 3: Comparison of optimal scenarios of double skin façade and single glazing façade PMV:

### 1.3.1. Result and analysis

To complete the evaluation of thermal performance strategies, this step compares the best performing double skin façade configuration which is Scenario C4 (12 mm glass + 0.8 m cavity) with Single Glazing Façade (SGF):

The comparative results are presented in the graphs below:

The graphs presented in Figures 2.9 and 2.10 illustrate the Predicted Mean Vote (PMV) values over the typical weeks in winter and summer, respectively. These values are comparing the thermal performance of the of the DSF optimal model (C4) and the SGF.

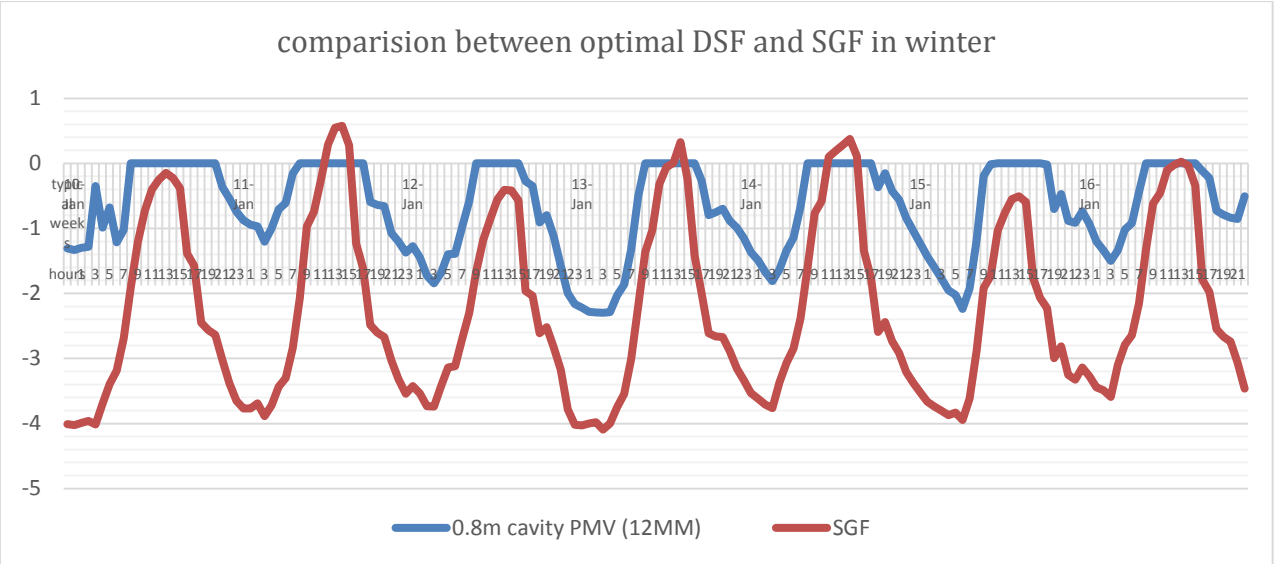



Figure 2.9 comparative PMV graph of DSF optimal model (C4) and the SGF in the typical week of winter) (author, 2025)

During the typical winter week (Figure 2.9), the Single Glazing Façade (SGF) exhibited a limited comfort duration of only 4 hours/day (12:00–17:00), with PMV values ranging between -0.31≤ PMV≤ 0.32, discomfort prevailed for 20 hours/day (17:00–12:00), with PMV values ranging between -1.04≤ PMV≤ -4, indicating thermal sensations from slightly cool to cold.

By comparison, the optimal DSF configuration (Scenario C4: 12 mm glass + 0.8 m cavity) significantly enhanced thermal performance. It provided 12 hours/day of thermal comfort (10:00–22:00), extending the comfort period by 8 hours more than SGF. The comfort PMV range was also more stable, between 0 ≤ PMV≤ -0,42, the discomfort duration was reduced to only 12 hours/day (22:00–10:00), and the PMV range was notably less severe, between -0.56 ≤ PMV≤ -1.81, remaining within the slightly cool to cool sensation zone.

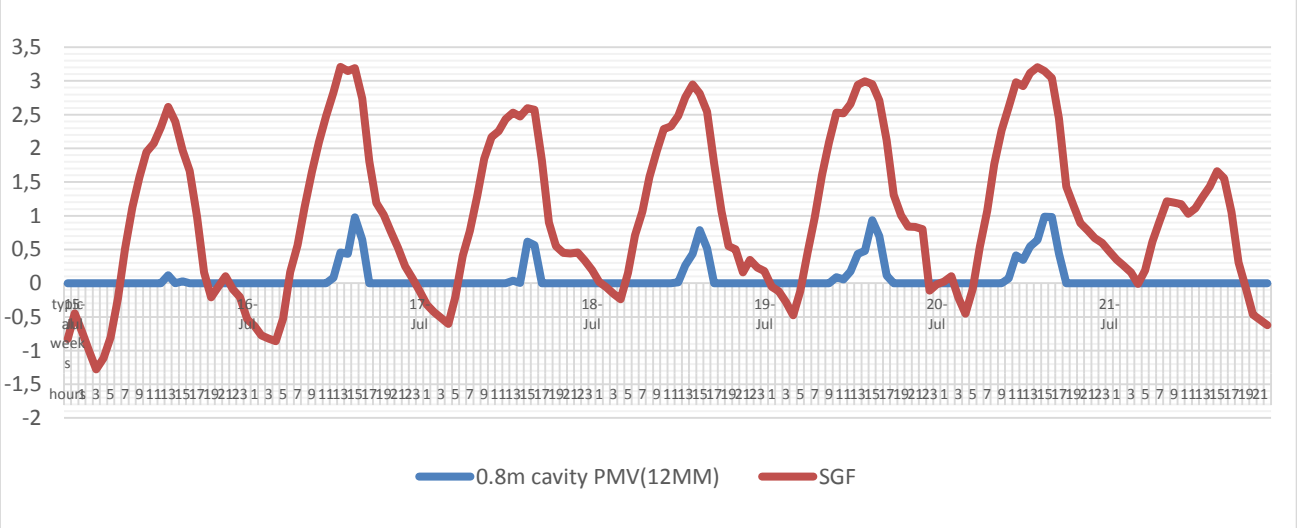



Figure 2.10 comparative PMV graph of DSF optimal model (C4) and the SGF in the typical week of summer (author, 2025)

During the typical winter week (Figure 2.10), the Single Glazing Façade (SGF) exhibited a comfort duration of 7 hours/day (00:00–07:00), with PMV values ranging between -0.42≤ PMV≤ 0.22, discomfort prevailed for 16 hours/day (07:00–00:00), with PMV values ranging between 0.54≤ PMV≤ 3.1, indicating thermal sensations from slightly warm to hot.

Scenario C4 with (12 mm glass thickness and a 0.8 m cavity) indicates best comfort performance, 22 hours/day, (18:00–16:00), with long duration than scenario C3 (0.6 cavity).Discomfort hours further reduced to 2 hours/day (16:00–18:00), and PMV values mostly 0.52 ≤ PMV≤ 0.98, ranging in slightly warm sensation range.

### 1.3.2 Discussion:

The final phase of this study compares the thermal performance of the optimal DSF configuration Scenario C4 (12 mm glass + 0.8 m cavity) with Single Glazing Façade (SGF), to evaluate the effectiveness of the double skin strategy against a typical baseline solution. The comparison was based on comfort duration, PMV values, and thermal sensation zones over typical winter and summer weeks.

**Key findings:**

**Winter performance:**

- The SGF system exhibited a limited comfort duration of only 4 hours/day (12:00–17:00), with PMV values ranging from −0.31 to 0.32. However, discomfort dominated for 20 hours/day (17:00–12:00), with PMV values dropping as low as −4, reflecting exposure to intense cold conditions.
- In contrast, Scenario C4 significantly improved winter performance by providing 12 hours/day of comfort (10:00–22:00)—an extension of 8 additional hours compared to SGF. The discomfort period was reduced to 12 hours/day (22:00–10:00), and PMV values were notably moderated to a range of −0.56 to −1.81, representing a milder thermal sensation zone from slightly cool to cool. These results confirm the effectiveness of the DSF in providing better insulation, buffering cold air, and maintaining indoor thermal stability during winter.

**Summer performance:**

- The SGF scenario performed poorly under high external temperatures, providing only 7 hours/day of comfort (00:00–07:00), with PMV values ranging from −0.42 to 0.22. For the remaining 16 hours/day (07:00–00:00), the interior experienced discomfort, with PMV values between 0.54 and 3.10, extending into the "hot"

sensation zone and exceeding thermal comfort limits for a significant portion of the day.

- Scenario C4 delivered outstanding performance by maintaining 22 hours/day of thermal comfort (18:00–16:00), and reducing discomfort to only 2 hours/day (16:00–18:00). PMV values during discomfort hours remained within the slightly warm range (0.52 to 0.98), with no exposure to hot conditions.

➢ These findings align with the previous studies:

Studies confirm, that DSFs provide superior thermal insulation and reduced heat loss compared to single skin façades. Particularly in warm and hot climates. For instance, (Alibaba and Ozdeniz, 2016) conducted a simulation study on office buildings in warm climates and found that DSFs effectively reduce cooling demands in summer and heating demands in winter, leading to improved thermal comfort throughout the year.

DSFs have also been proven to reduce overheating by facilitating natural ventilation and limiting direct solar gains. A study by (Qahtan, 2019)in warm climates confirmed that DSFs help control solar heat gain, improving indoor thermal comfort compared to SGF.

These findings support the current results of Scenario C4 the optimal model of DSF, which maintained PMV values in both hot and cold seasons compared by SGF.

These results validate the hypothesis that the DSF system superior performance over SGF confirms its value as a passive design solution for airport terminal envelopes in BSK climate.

**Conclusion:**

The comparative analysis between the optimal double-skin façade configuration and single glazing façade demonstrates the clear thermal performance advantage of the DSF system in both winter and summer conditions. Affirm that the DSF system, when designed with appropriate cavity depth and glazing thickness, serves as an effective passive strategy to stabilize indoor temperatures, mitigate thermal stress, and improve thermal comfort.

## General Conclusion:

This research aimed to investigate the use of double skin façades (DSF) as a passive design strategy to enhance thermal comfort in airport terminal halls, specifically in the cold semi-arid (BSK) climate of Tebessa, Algeria. The study was driven by three main objectives: to analyse the impact of DSF design parameters (Cavity depth and glazing thickness) on thermal comfort; to classify and compare the performance of DSF and traditional single-glazing façades (SGF); and to identify the optimal DSF configuration suitable for airport applications. Based on these objectives, three research hypotheses were formulated: that DSF can reduce temperature fluctuations in BSK climates; that its design parameters influence performance; and that DSF can outperform SGF in thermal comfort regulation.

To test these hypotheses, a simulation-based methodology was employed using Rhinoceros 3D in combination with Grasshopper, Ladybug, Honeybee, and Skin Designer. Twelve DSF configurations were modelled based on varying cavity depths (0.2 m, 0.4 m, 0.6 m, and 0.8 m) and glazing thicknesses (8 mm, 10 mm, and 12 mm). The performance of these design parameters were evaluated using PMV (Predicted Mean Vote) values and daily comfort hours in both typical weeks of winter and summer scenarios. A sensitivity response method (SRM) was used to determine the optimal configuration.

The results confirmed the initial hypotheses. DSF configurations were found to significantly reduce temperature fluctuations, especially when deeper cavities were used. The optimal model (Scenario C4, with 12 mm glass and 0.8 m cavity) provided the highest thermal comfort levels throughout the year. These findings directly respond to the research questions by demonstrating how specific design parameters influence DSF effectiveness, and by confirming that DSF systems can provide superior comfort performance compared to SGF in airport buildings under BSK climate conditions.

From a practical perspective, the findings suggest that DSFs can significantly enhance indoor thermal comfort in airport terminals in BSK climates, reducing both cold stress in winter and overheating in summer. This passive strategy has the potential to minimize dependence on mechanical systems, leading to improved energy efficiency and passenger experience, particularly in waiting areas and high-occupancy zones. Additionally, DSFs offer aesthetic and architectural value through transparency, daylighting, and façade articulation.

Based on the finding of this study, several practical recommendations can be made, to guide to the effective implementations of DSF in airport terminal design, particularly in BSK climate.

Include:

- Integrate DSFs into airport terminal designs during early planning phases to optimize performance.
- Use cavity depths of at least 0.6 to 0.8 meters in BSK climates to ensure sufficient thermal buffering.
- Select glazing thickness based on climate severity, with 12 mm proving beneficial for thermal inertia.
- Incorporate external or internal shading devices, such as overhangs or louvers, to reduce direct solar gain during peak summer hours.
- Consider injecting inert gases like argon into closed cavities to enhance insulation properties and minimize conductive heat transfer.
- Explore the use of thermochromic or electrochromic glass to dynamically adjust solar transmittance based on temperature or light conditions.

Despite promising findings, this study has several limitations. the use of a limited institutional access or unofficial versions of the simulation software, which occasionally produced instability, bugs, and incomplete results. This may have limited the accuracy or completeness of some simulation outputs, such as testing multiple orientations to assess solar gain differences.

The findings, while robust for Tebessa, should not be generalized across all BSK regions or airport types without additional validation, especially given local variations in orientation, usage patterns, and construction methods.

To address these gaps and strengthen the body of knowledge, the following research directions are proposed:

- Test wider cavity depth beyond 0.8 m, which may offer additional benefits. However, this should be approached with caution, as finding in this study suggest diminishing returns beyond a certain threshold. Wide cavities may achieve reversible performance depending on the seasonal balance between insolation, airflow, and heat gain.
- Applying this configuration to other public building types such as hospitals, schools, or transportations hubs, to generalize DSF performance in similar climate (BSK).
- Expanding the study to include energy performance analysis (heating and cooling loads.).
- Explore acoustic insulation and visual transparency benefits.
- Investigate photovoltaic integrated DSF systems or hybrid ventilated façade, that combined passive and active design elements.

Overall, this study demonstrates that carefully configured double-skin façades can play a critical role in improving passive thermal comfort in airport buildings within cold semi-arid climates. It contributes to the growing body of evidence supporting climate-responsive architecture and offers practical guidance for more sustainable, user centered terminal design.

# References and bibliography

**Articles**


1. AKYÜZ, M. K., AÇıKKALP, E. & ALTUNTAŞ, Ö. 2024. Thermal Performance, Indoor Air Quality, and Carbon Footprint Assessment in Airport Terminal Buildings. *Buildings,* 14**,** 3957.
2. ALEMDAĞ, E. L. & BEYHAN, F. 2017. A research on construction systems of double skin facades. *Gazi University Journal of Science,* 30**,** 17-30.
3. ALIBABA, H. Z. & OZDENIZ, M. B. 2011. Thermal comfort of multiple-skin facades in warm-climate offices. *Scientific Research and Essays,* 6**,** 4065-4078.
4. ALIBABA, H. Z. & OZDENIZ, M. B. 2016. Energy performance and thermal comfort of double-skin and single-skin facades in warm-climate offices. *Journal of Asian Architecture and Building Engineering,* 15**,** 635-642.
5. BELLO, H., HAMZA, B. & ABDULHAMID, F. 2020. Exploring double skin façade as strategy for achieving thermal comfort in proposed mixed use office complex Kano, Nigeria. *Dutse Journal of Pure and Applied Sciences,* 7.
6. BÖKE, J., DENZ, P.-R., SUWANNAPRUK, N. & VONGSINGHA, P. 2022. Active, passive and cyber-physical adaptive façade strategies: a comparative analysis through case studies. *Journal of Facade Design and Engineering,* 10**,** 1-18.
7. BRUNORO, S. 2008. An assessment of energetic efficiency improvement of existing building envelopes in Italy. *Management of environmental quality: an international journal,* 19**,** 718-730.
8. BRUNORO, S. 2024. Passive Envelope Measures for Improving Energy Efficiency in the Energy Retrofit of Buildings in Italy. *Buildings,* 14**,** 2128.
9. BUDD, L. 2008. A history of airport technology. *Loughborough University Institutional Repository*.
10. ELMOGHAZY, Z. A. A. E., AFIFY, H. M. N. & ALZENIFEER, B. M. 2025. Redefining Airport Terminal Design Through Identity Indicators—Case Studies from Airport Terminals in Saudi Arabia. *Buildings,* 15**,** 1261.
11. FANG, Y., EAMES, P. C. & NORTON, B. 2007. Effect of glass thickness on the thermal performance of evacuated glazing. *Solar Energy,* 81**,** 395-404.
12. FERNANDO, D., NAVARATNAM, S., RAJEEV, P. & SANJAYAN, J. 2023. Study of technological advancement and challenges of façade system for sustainable building: Current design practice. *Sustainability,* 15**,** 14319.
13. GAGGE, A. P., STOLWIJK, J. A. J. & HARDY, J. D. 1967. Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environmental Research,* 1**,** 1-20.
14. GAVAN, V., WOLOSZYN, M., KUZNIK, F. & ROUX, J.-J. 2010. Experimental study of a mechanically ventilated double-skin façade with venetian sun-shading device: A full-scale investigation in controlled environment. *Solar Energy,* 84**,** 183-195.
15. GRATIA, E. & DE HERDE, A. 2004. Natural ventilation in a double-skin facade. *Energy and buildings,* 36**,** 137-146.
16. GRATIA, E. & DE HERDE, A. 2007. The most efficient position of shading devices in a double-skin facade. *Energy and buildings,* 39**,** 364-373.
17. HASHEMI, N., FAYAZ, R. & SARSHAR, M. 2010. Thermal behaviour of a ventilated double skin facade in hot arid climate. *Energy and buildings,* 42**,** 1823-1832.
18. KILAIRE, A. & STACEY, M. 2017. Design of a prefabricated passive and active double skin façade system for UK offices. *Journal of Building Engineering,* 12**,** 161-170.
19. KOTOPOULEAS, A. & NIKOLOPOULOU, M. 2016. Thermal comfort conditions in airport terminals: Indoor or transition spaces? *Building and Environment,* 99**,** 184-199.

20. LAROUSSE 2025. Terminal.
21. LIM, Y. & ISMAIL, M. R. 2022. Aptitudes of double skin façade toward green building within built environment. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences: It is published by SEMARAK ILMU PUBLISHING,* 100**,** 146-70.
22. LÓPEZ-ESCAMILLA, Á., HERRERA-LIMONES, R. & LEÓN-RODRÍGUEZ, Á. L. 2024. Double-skin facades for thermal comfort and energy efficiency in Mediterranean climate buildings: rehabilitating vulnerable neighbourhoods. *Buildings,* 14**,** 326.
23. LOPS, C., DI LORETO, S., PIERANTOZZI, M. & MONTELPARE, S. 2023. Double-skin facades for building retrofitting and climate change: A case study in central Italy. *Applied Sciences,* 13**,** 7629.
24. MAKNUN, J. 2020. Application of the Double Skin Facade Concept in an Effort To Increase the Thermal Comfort of Image Studio Room. *Journal of Architectural Research and Education,* 2**,** 90.
25. NADDAF, M. S. & BAPER, S. Y. 2023. The role of double-skin facade configurations in optimizing building energy performance in Erbil city. *Scientific Reports,* 13**,** 8394.
26. PEKDEMIR, E. A. & MUEHLEISEN, R. T. 2012. A parametric study of the thermal performance of double skin facades at different climates using annual energy simulation. *Proceedings of SimBuild,* 5**,** 211-218.
27. PÉREZ-GRANDE, I., MESEGUER, J. & ALONSO, G. 2005. Influence of glass properties on the performance of double-glazed facades. *Applied Thermal Engineering,* 25**,** 3163-3175.
28. PILECHIHA, P., MAHDAVINEJAD, M., MIRHOSSEINI, S. N. & AHMADI, J. 2019. Depth optimisation of double skin façade, considering thermal properties: Case study of Karaj, Iran. *African Journal of Engineering Research,* 7**,** 57-63.
29. POMPONI, F. & PIROOZFAR, P. A. 2015. Double skin façade (DSF) technologies for UK office refurbishments: a systemic matchmaking practice. *Structural Survey,* 33**,** 372-406.
30. PREET, S., MATHUR, J. & MATHUR, S. 2022. Influence of geometric design parameters of double skin façade on its thermal and fluid dynamics behavior: A comprehensive review. *Solar Energy,* 236**,** 249-279.
31. QAHTAN, A. M. 2019. Thermal performance of a double-skin façade exposed to direct solar radiation in the tropical climate of Malaysia: A case study. *Case Studies in Thermal Engineering,* 14**,** 100419.
32. RAHMANI, B., KANDAR, M. Z. & RAHMANI, P. 2012. How double skin façade's air-gap sizes effect on lowering solar heat gain in tropical climate. *World Applied Sciences Journal,* 18**,** 774-778.
33. REZAZADEH, N. & MEDI, H. 2017. Thermal behavior of Double Skin Facade in terms of energy consumption in the climate of North of Iran-Rasht. *Space Ontology International Journal,* 6**,** 33-48.
34. SAELENS, D. 2002. Energy performance assessment of single storey multiple-skin facades.
35. SAOUSSEN, B. & YOUCEF, L. 2024. The impact of double skin facades on thermal comfort in public buildings in Constantine, Algeria. *Studies in Engineering and Exact Sciences,* 5**,** e6541-e6541.
36. SHEN, C. & LI, X. 2016. Thermal performance of double skin façade with built-in pipes utilizing evaporative cooling water in cooling season. *Solar Energy,* 137**,** 55-65.
37. SUNG, U.-J. & KIM, S.-H. 2019. A study on the improvement of double-skin facade operation for reducing heating load in winter. *Sustainability,* 11**,** 6238.
38. TELLACHE, A., LAZRI, Y., LAAFER, A., AND ATTIA, S 2025. Development of a Benchmark Model for Residential Buildings with a Mediterranean Climate: The Aero-

Habitat in Algiers City. *Sustainability,* 17.
39. VIGHIO, A., ZAKARIA, R., AHMAD, F., MUNIKANAN, V., WAHI, N., AMINUDDIN, E., JIA, T., MOHD, K., UMRAN, N. & PAWŁOWICZ, J. 2024. Overall Thermal Transfer Analysis of Glazing Facade Design for Passive Building Energy Efficiency. *Civil and Environmental Engineering Reports,* 34**,** 503-520.
40. WONG, N. H. C., Y.; ONG, C. L.; SIA, A. 2008. Experimental and simulation study of double skin facade in tropical climate. *Energy and Buildings,* 40.
41. WONG, P. C., PRASAD, D. & BEHNIA, M. 2008. A new type of double-skin façade configuration for the hot and humid climate. *Energy and Buildings,* 40**,** 1941-1945.
42. XU, L. & OJIMA, T. 2007. Field experiments on natural energy utilization in a residential house with a double skin façade system. *Building and Environment,* 42**,** 2014-2023.
43. XUE, F. & LI, X. 2015. A fast assessment method for thermal performance of naturally ventilated double-skin façades during cooling season. *Solar Energy,* 114**,** 303-313.
44. ZLATEVA, P., YORDANOV, K., PETKOVA-SLIPETS, R. & IVANOV, M. 2024. NUMERICAL SIMULATION OF DOUBLE SKIN FACADES IN WINTER CLIMATES. *Journal of Chemical Technology and Metallurgy,* 59**,** 1363-1374.

**Books**

1. AMERICAN SOCIETY OF HEATING, R. A. A.-C. E., INC. (ASHRAE) 2003. Chapter 3: Commercial and Public Buildings. *ASHRAE Handbook—HVAC Applications.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
2. ASHFORD, N. J., MUMAYIZ, S. & WRIGHT, P. H. 2011. *Airport engineering: planning, design, and development of 21st century airports*, John Wiley & Sons.
3. BEDNAREK, J. R. D. 2001. *America's airports: airfield development, 1918-1947*, Texas A&M University Press.
4. HEMATE, N. 2016. *Climate and comfort passive design strategies for Lebanon*.
5. MANGUM, B. W. & HILL, J. E. 1977. *Thermal Analysis--human Comfort--indoor Environments: Proceedings of a Symposium Held at the National Bureau of Standards, Gaithersburg, Maryland, February 11, 1977*, US Government Printing Office.
6. OESTERLE, E. L., ROLF-DIETER; LUTZ, MICHAEL; HEUSLER, WOLFGANG 2001. *Double Skin Facades – Integrated Planning,* Munich, Germany, Prestel Verlag.
7. WELLS, A. T. & YOUNG, S. B. 2004. *Airport planning & management*, McGraw-Hill.

**Conferences**

1. GRATIA, E. D. H., ANDRÉ 2005. Guidelines to Improve Efficiency of a Double-Skin Façade in an Office Building. Air Infiltration and Ventilation Centre (AIVC).
2. KOTOPOULEAS, A. & NIKOLOPOULOU, M. Airport terminal buildings: Indoor or transitional spaces. CIBSE ASHRAE Technical Symposium, 2014.
3. PICHATWATANA, K., WANG, F. & ROAF, S. Thermal comfort evaluation of an existing glazed airport terminal in Thailand. Proceedings of the Institution of Civil Engineers-Engineering Sustainability, 2018. Thomas Telford Ltd, 184-197.

**Encyclopedia**

1. ENCYCLOPEDIA, N. W. 2023. Airport. New World Encyclopedia.

**Reports**

1. CIBSE 2006. CIBSE-Guide-A-Environmental-design. London: The Chartered Institution of Building Services Engineers.
2. POIRAZIS, H. 2006. Double Skin Façades: A Literature Review. Lund, Sweden:

Department of Architecture and Built Environment, Division of Energy and Building Design, Lund Institute of Technology, Lund University.

**Standarts**

1. (CNERIB), C. N. D. É. E. D. R. I. D. B. 1997. Document Technique Réglementaire D.T.R. C 3-2 : Réglementation thermique des bâtiments d'habitation – Règles de calcul des déperditions calorifiques. Alger, Algérie: Ministère de l'Habitat.
2. (ICAO), I. C. A. O. 2018. Annex 14 to the Convention on International Civil Aviation: Aerodromes. Volume I: Aerodrome Design and Operations, 8th Edition, July 2018, incorporating Amendment 14. Montreal, Canada: International Civil Aviation Organization (ICAO).
3. (ISO), I. O. F. S. 1994. ISO 7730:1994 Moderate thermal environments – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. Geneva.
4. ASHRAE 2013. ANSI/ASHRAE Standard 55-2013: Thermal Environmental Conditions for Human Occupancy. Atlanta, GA: ASHRAE.
5. ISO 2005. ISO 7730:2005 Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Geneva: International Organization for Standardization.

**Web pages**

1. BELARBI, A. M. 2020. *History of the aviation industry in Algeria 1938 2020* [Online]. algeria: Youtube. Available: https://www.youtube.com/watch?v=VhUfN3JlZgQ&t=8s [Accessed].
2. FAA. 2023a. *AIP Handbook: Definitions of terms used in this handbook – Airport (based on 49 U.S. Code § 47102)* [Online]. Washington, D.C.: U.S. Department of Transportation. Available: https://www.faa.gov/airports/aip/aip_handbook/?Chapter=Appendix [Accessed].
3. FAA. 2023b. *Airport Categories and definitions* [Online]. Washington, D.C.: U.S. Department of Transportation. Available: https://www.faa.gov/airports/planning_capacity/categories [Accessed].
4. GREINER, R. 2025. *Double skin facades: selecting the right combination of glass to optimise their benefits* [Online]. Available: https://www.glassnews.co.uk/double-skin-facades-selecting-the-right-combination-of-glass-to-optimise-their-benefits/ [Accessed].
5. HASSEB, J. 2017. *Components of an Airport* [Online]. AboutCivil.Org. Available: https://www.aboutcivil.org/airport-components [Accessed].
6. IWBI. 2025. *WELL Certified* [Online]. New York: International WELL Building Institute. Available: https://v2.wellcertified.com/en/wellv2/overview/ [Accessed].
7. LLC, L. T. 2025. *Ladybug Tools* [Online]. Available: https://www.ladybug.tools/ [Accessed].
8. PRESS, C. U. 2025. *Air terminal* [Online]. Cambridge University Press. Available: https://dictionary.cambridge.org/dictionary/english/air-terminal [Accessed].
9. RABNASS. 2023. *RUBRIQUE TRANSPORT ET VOYAGES قسم النقل والسفر [YouTube Video]* [Online]. algeria: Rabnass Archives d'Algérie2.0. Available: https://www.youtube.com/watch?v=-qCEfn4HICw [Accessed].
10. ROBERT MCNEEL & ASSOCIATES. 2025a. *Food4Rhino* [Online]. Available:

https://www.food4rhino.com/en [Accessed].
11. ROBERT MCNEEL & ASSOCIATES. 2025b. *Rhinoceros 3D* [Online]. Available: https://www.rhino3d.com/ [Accessed].
12. UNSWMAKING. 2025. *Grasshopper basics: Getting started with Grasshopper in Rhino* [Online]. University of New South Wales. Available: https://www.making.unsw.edu.au/learn/grasshopper-basics [Accessed].
13. VAGLIO, J. 2025. *Aerophysics of Double-Skin Facades: Simulation-Based Determination of Pressure Coefficients for Multi-Story Double-Skin Facades)* [Online]. Available: https://www.jeffvaglio.com/#/dsf/ [Accessed].