de-VAP

Decentralized Desiccant Enhanced Evaporative cooling integrated facade

PRETHVI RAJ // 4738659

Sustainable Design Graduation Studio - Master Thesis

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Low ex-cooling integrated facades for offices in Delhi

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ABSTRACT

The objective of the thesis is to reduce the cooling load of the offices in Delhi, India by integrating passive strategies and low-ex cooling (evaporative) technology through facades as a decentralized ventilation system.

The cooling demand in India is going to increase up to 8 folds by 2030. Almost 50% of the energy is spent on space cooling for offices in Indian climatic conditions. In order to reduce the cooling demand alternative low ex cooling technologies are being researched and implemented. In this thesis, various types of evaporative cooling and their various properties and its application on Delhi's climatic scenario and its limitations were studied as one of the low-ex techs. The study concludes by choosing Dew-point indirect evaporative cooler because of its high wet bulb effectiveness with no addition of humidity. For continuous operation, the humidity in the air needs to removed before supplying it to the cooler. So, the design involves a combination of Dew-point Indirect evaporative cooler (D-IEC) coupled with Desiccant coated heat exchanger (DCHE). The system also requires a source for heating and cooling down the water for Regeneration cycle and Dehumidification cycle, evaporative cooler respectively.

The cooling demand of the building needs to be addressed by multiple devices in a decentralized ventilation system. The total number of devices required determines the cost of installation and ease of maintenance over the years and it depends on the cooling load. So, it is necessary to reduce the cooling demand of the building using passive strategies before integrating the evaporative cooler. The building's cooling load has been reduced to 50W/m2 by adapting suitable passive strategies like shading systems, reducing U values of walls, glazing and roof, reducing infiltration and the internal heat gain.

The above-mentioned strategies result in 146.41kWh/m2/yr with a water-based chiller (CENTRALIZED), and it is efficient when compared to the recommended national figure of 180 kWh/m2/yr. But using the De-VAP systems (DECENTRALIZED) cuts down the energy by even much further to up to 40% (92.26kWh/m2) in which almost 1/3rd of the energy can be generated by installing PV on the roof. This design takes us further one step closer to the NET ZERO building.

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CONTENT

01 INTRODUCTION 10

1.1 BACKGROUND 11
1.1.1 GROWTH AND DEMAND IN COMMERCIAL SECTOR 11
1.1.2 INDIA COOLING ACTION PLAN (ICAP) 11
1.2 PROBLEM STATEMENT 12
1.3 FOCUS AND RESTRICTION 13
1.4 RESEARCH QUESTIONS 13
1.4.1 MAIN RESEARCH QUESTION 13
1.5 METHODOLOGY 14

02 CONTEXT 17

2.1 CLIMATIC CHARACTERISTIC 18
2.2 PSYCHROMETRIC CHART 19
2.2.1 NEW DELHI - PSYCHROMETRIC CHART 20
2.2.2 ENERGY DEMAND (SIMULATION) 21
2.3 POLLUTION 23

03 PASSIVE STRATEGIES 25

3.1 BUILDING LEVEL 26
3.2 NATURAL VENTILATION 26
3.3 PASSIVE BUILDINGS IN COMPOSITE CLIMATE 27
3.3.1 CASE STUDIES 28
3.3.2 RESULTS 32
3.4 SUMMARY 32
3.4.1 ENERGY CONSERVATION BUILDING CODE 32

04 EVAPORATIVE COOLING 33

4.1 LOW EXERGY COOLING TECHNOLOGIES IN INDIA 34
4.2 EVAPORATIVE COOLING 34
4.2.1 DIRECT EVAPORATIVE COOLING (DEC) 36
4.2.2 INDIRECT EVAPORATIVE COOLING (IEC) 37
4.2.3 DEW POINT IN-DIRECT EVAPORATIVE COOLING (DIEC) 38
4.2.4 TWO STAGE EVAPORATIVE COOLING (IEC/DEC) 40
4.3 SUMMARY 41
4.3.1 TEMPERATURE 41
4.3.2 HUMIDITY 42
4.3.3 OTHERS 42

05 DECENTRALIZED ? 43

5.1 DE-CENTRALIZED SYSTEM 44
5.2 CENTRALIZED VS DECENTRALIZED SYSTEM 44
5.2.1 TROX 45
5.2.2 DeAL 48
5.2.3 Comparison 52
5.2.4 Summary 53
5.3 FACADE INTEGRATED VENTILATION (FIV) 54
5.3.1 WORKING 54
5.3.2 VARIOUS INTEGRATION 55
5.3.3 SUMMARY 56

06 COOLER DESIGN: 57

6.1 FACTORS INFLUENCING DESIGN 58
6.2 PASSIVE STRATEGIES TO REDUCE COOLING CAPACITY (Q) 60
6.2.1 SIMULATION PARAMETERS 60
6.2.6 SUMMARY 64
6.3 DEHUMIDIFICATION TO INCREASE DT: 64
6.4 LAYOUT OF THE SYSTEM 65
6.4.1 DE-HUMIDIFICATION STRATEGIES 66
6.4.2 FRESH AIR 69
6.4.3 MIXING AIR 69
6.4.4 DEHUMIDIFICATION BY DCHE 71
6.4.5 COOLING BY D-IEC 73
6.5 THE COMPLETE CYCLE 74

07 FAÇADE DESIGN: 76

7.1 SIZING - COOLER 77
7.2 FACTORS AFFECTING THE SIZE / EFFECTIVENESS OF THE COOLER 77
7.2.1 CHANNEL GAP 77
7.2.2 CHANNEL LENGTH 77
7.2.3 AIR VELOCITY 78
7.2.4 INFLUENCE OF WORKING TO INTAKE AIR RATIO 78
7.3 SIZING THE COOLER 78
7.3.1 OPENING SIZE 79
7.4 SIZING THE COOLER 79
7.5 INTEGRATION CONCEPTS 81
7.5.1 SILL INTEGRATION WITH DISPLACEMENT VENTILATION 81
7.5.2 WALL INTEGRATION WITH MIXED VENTILATION: 82
7.5.3 COMPARING SILL VS WALL SYSTEM: 83
7.6 EVALUATING VENTILATION SYSTEMS: 84
7.6.1 MODEL PARAMETERS: 84
7.6.2 RESULTS : TEMPERATURE / VELOCITY DISTRIBUTION: 92
7.7 THERMAL RESISTANCE: 92
7.8 DESIGN OPTIONS: 93
7.8.1 PROCESS OF THE AIR 93
7.8.2 VARIATION 01 94
7.8.3 VARIATION 02 103
7.9 GUIDELINES FOR INTEGRATION - NUMBER OF SYSTEMS VS COOLING LOAD 111

08 EVALUATION 118

8.1 WATER PUMP: 120
8.1.1 HEAD OF THE PUMP 120
8.1.2 CLOSED AND OPEN LOOP SYSTEM 120
8.2 BLOWER 122
8.3 INTEGRATING SOLAR: 122
8.3.1 PHOTOVOLTAIC PANEL 122
8.3.2 MODULE INTEGRATED DESIGN 123
8.3.3 RESULTS: 126
8.3.4 ROOF INTEGRATED DESIGN 126
8.3.5 SOLAR COLLECTORS 132
8.4 FEASIBILITY OF COMBINATION OF PV / SOLAR COLLECTOR / HEAT PUMP 134
8.4.1 HEAT PUMP 134
8.4.2 RESULTS 135
8.5 COMPARISON OF CENTRALIZED SYSTEM & DECENTRALIZED SYSTEM 137

09 CONCLUSION 141

10 REFERENCE 145

11 APPENDIX 148

1
INTRODUCTION

Chapter Overview

This chapter introduces the various climatic character in India especially the complexity posed by the composite climate in Delhi. The Psychometric properties of the weather is briefly described with required cooling and heating strategies throughout the year. Moreover it also discusses the localor site specific challenges that needs to be considered from the basic design.

1.1 BACKGROUND:

The energy demand is peaking around the globe in recent decades. The energy demands of the buildings stand at the 3rd position in the global energy consumption [1] and the greatest share of it is spent on space cooling using conventional HVAC systems, especially in hot climates. The vapor compression systems are predominantly used for cooling in residential and commercial areas and they are energy intensive. Space cooling plays an important aspect when it comes to the economic growth of a developing country as electricity is a key indicator of economic development.

India is becoming a power-hungry nation as the demand is expected to grow from 255GW (2014) to 903 GW (2024) with 9% of annual increase [2]. More is the demand as more people have gained access to cooling devices for comfort and also interrupted power supply is becoming more common in Indian cities than before. In addition, the distribution and Transmission loss are about 20 - 30% [3]. It is essential to know the value of electricity supplied in this context and make sure it is used efficiently.

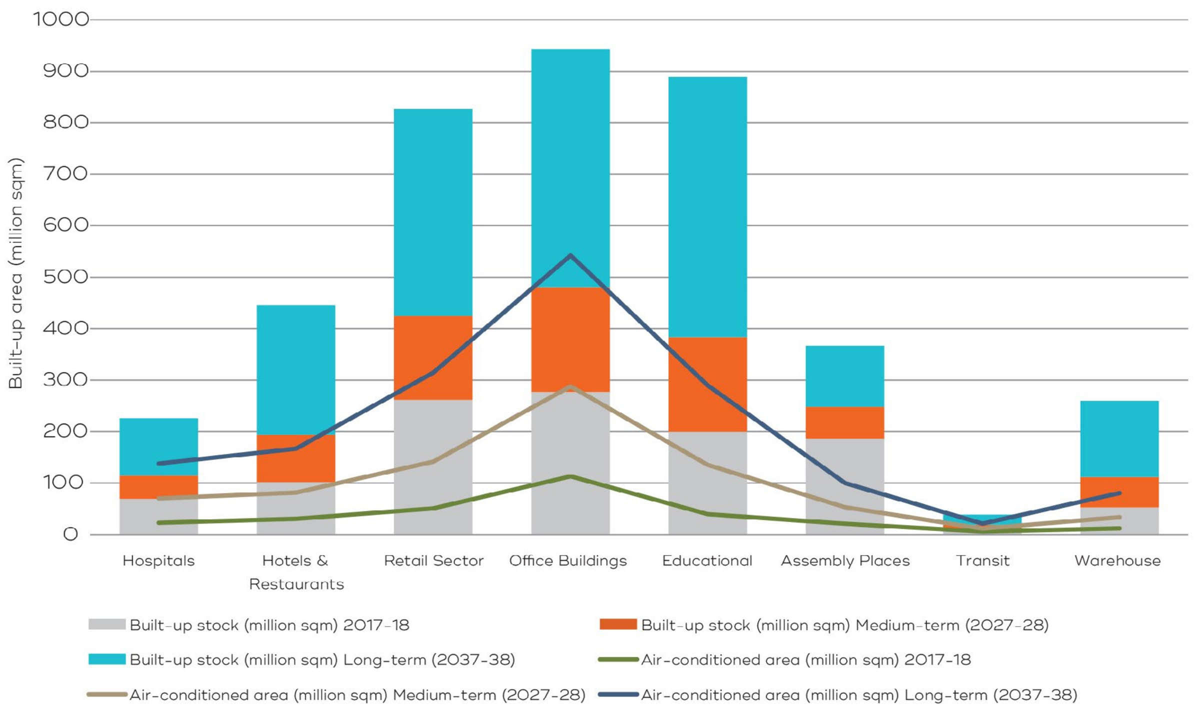


Figure 1.1: Commercial sector builtup and air conditioned stock (million sqm)[5]

1.1.1 GROWTH AND DEMAND IN COMMERCIAL SECTOR:

India is having tremendous growth in the building sector due to many policies like housing for all, smart cities and solar cities. From 2005 to 2010 the Energy Performance Index(EPI) for the commercial sector has tripled from 61 kWh/m2/year to 202 kWh/m2/year.[4] The energy demand in India is indeed exploding and by 2030 the office sector is expected to triple its size and even more in terms of space cooling.

1.1.2 INDIA COOLING ACTION PLAN (ICAP):

The cooling requirement for India is expected to grow 8 times by 2037-38 compared to 2017-2018. Especially the space cooling is increasing rapidly almost to 11 times than the current requirement (2017-18).

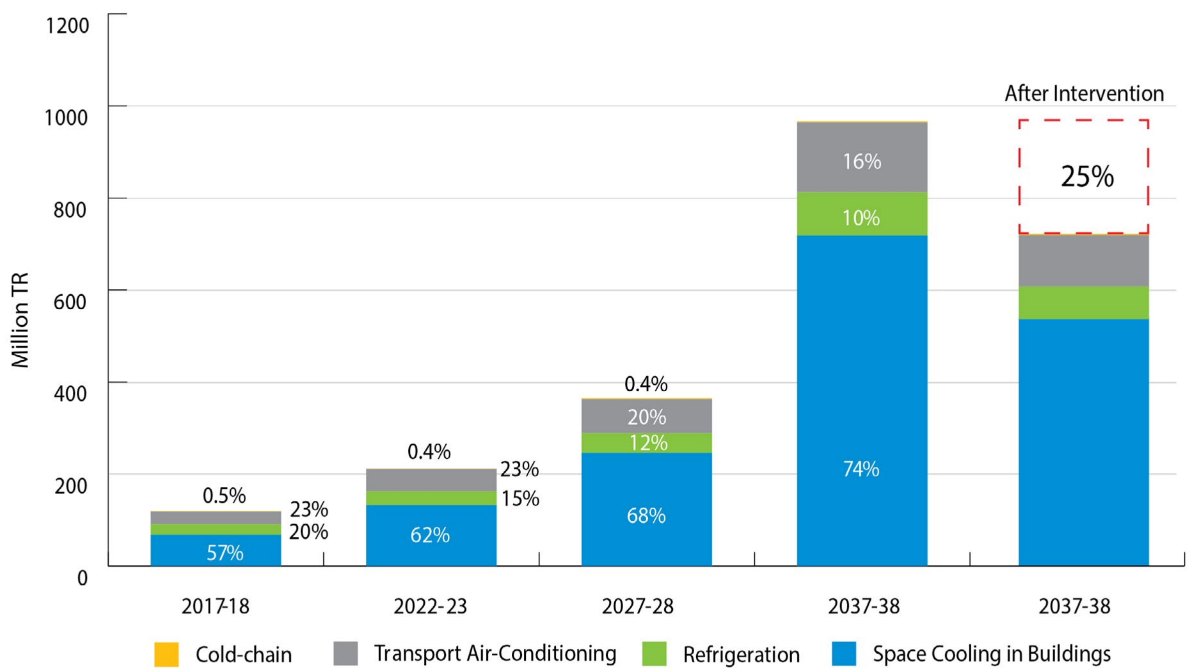


Figure 1.2: Commercial sector builtup and air conditioned stock (million sqm) [6]

In this scenario, India is the first country to develop a document, which addresses cooling requirements over several sectors and it also has listed the set of actions which needs to be taken listed under the division "Intervention", both in terms of policies and research and implementation of sustainable technologies. This will create a direct impact on the reduction of emissions. [6]

"The overarching goal of ICAP is to provide sustainable cooling and thermal comfort for all while securing environmental and socio-economic benefits for the society"

(Press Information Bureau, Government of India, 2018)

The goal of ICAP:

1. Recognition of "cooling and related areas" as a thrust area of research under the national science and technology programme to support the development of technological solutions and encourage innovation challenges.
2. Reduction of cooling demand across sectors by 20% to 25 % by the year 2037-38
3. Reduction of refrigerant demand by 25% to 30% by the year 2037-38
4. Reduction of cooling energy requirements by 25% to 40% by the year 2037-38
5. Training and certification of 100,000 servicing sector technicians by the year 2022-23, synergizing with Skill India Mission

1.2 PROBLEM STATEMENT

The Capital (Delhi) officially National Capital Territory of Delhi, is growing rapidly in all directions, bringing nearby cities under its control to accommodate the needs of the ever-growing population. As it extends more rapidly than before the population increased from 11 million to 26 million [7], making it as the world's 3rd largest city by population after Tokyo and Jakarta according to UN [8]. Delhi consumes three times more power than rest of the metropolitan cities in the country. On average, an electrified household in Delhi consumed about 260-kiloWatt-hour (kWh) of electricity monthly in 2016-2017, which is almost three times the national figure of 90 kWh.

As the cooling demands are increasing, other passive techniques and advancement in sustainable cooling strategies are being developed in parallel at a much faster pace. Moreover, the facades are getting way smarter than before as they are getting integrated with multiple functions in them. But, the integration of these two main aspects is rarely done. Especially, decentralized cooling by ventilation through facades reduces the ceiling height and saves lots of space in the structure as it eliminates ducts and huge HVAC systems. Butthis also increases the complexity of maintenance (pollution, non-conventional cooling system), the size of the façade systems and its role to structure.

So, in this project, the potential for decentralization of ventilation through facade is studied in detail with various promising cooling technologies in India. The most suitable cooling system relating to climate, effectiveness, size, easy to maintain is designed.

1.3 FOCUS AND RESTRICTIONS

As there are multiple passive systems, strategies and various typologies of buildings involved, choosing the focus and limiting plays a major role in the depth of the study.

This research project focuses only on office buildings in Delhi due to its ever-growing demand. Even though Delhi has the composite climate, the research and design focus on reducing the pre-dominant cooling load as heating is very minimal. But, in order to save energy, many passive factors need to be considered such as WWR, Natural ventilation, Glazing type, Shading system, Insulation and etc.

Similarly, among the numerous passive cooling systems direct/indirect evaporative cooling system has been chosen, because it is an upcoming promising technology that not only saves energy, but has a lot of relevance to the context which will be discussed later. The design research is more about the integration in size and maintenance and it is not trying to explore the maximum efficiency of the system but to meet the basic thermal comfort standards required for an Indian office. (Fore.g.: Set Point temperature: 24-25°C as recommended by the Indian govt. etc.). In terms of air supply strategies, ventilating interior spaces of an office building is not considered in this scope of work and only the peripheral ventilation via the façade has been designed.

1.4 RESEARCH QUESTIONS

1.4.1 MAIN RESEARCH QUESTION

This project tries to answer the following research question by considering many possibilities and limitations of the context:

" To what extent a decentralized evaporative cooling system can be integrated on a façade to reduce the cooling demand of offices in Delhi (composite climate)? "

1.4.2 SUB RESEARCH QUESTION

In order to answer the main research question, the sub-questions are categorised into three segments Context, System and Evaluation.

Context:

1. What are the desired passive strategies that need to be integrated in a Composite climate (Delhi) for thermal comfort and air quality requirements for Delhi?
2. Which type of evaporative cooling is more suitable for the climate of Delhi?

System:

3. What are the advantages and limitations of de-centralized system over centralized and what are the state of the art Façade Integrated ventilation systems in the market?
4. What are the components and the layout of the system that are required to supply desired air flow and temperature?
5. How this system can be designed in form of a facade that can be integrated over the built structure?

Evaluation:

6. To what extent the solar energy can be used to produce heat and energy for the sustainable operation of the evaporative facade?
7. What is the saving potential in the cooling load by this façade system compared to a conventional centralized system?

1.5 METHODOLOGY

Keywords : Facade Integrated Ventilation, De-centralized ventilation, Evaporative cooling, Energy in offices, Office Cooling in Delhi, Cooling in Composite climate, Dewpoint evaporative cooling, Indirect evaporative cooling

Search Engines : Google Scholar, TU Delft library, Research gate, World cat, Academia

1. LITERATURE REVIEW:

i)Decentralized and Ventilation through facade:

The initial literature review to get the background information is split into two branches. The first approach towards the project is to get a broad picture of ventilation through facade, so the literature review of decentralized vs centralized and existing product analysis (Facade Integrated Ventilation) helps in achieving them.

ii)Evaporative Cooling:

Further investigation is done over the low ex cooling technology (Evaporative Cooling) that is feasible under numerous factors: Climate relevance, Size, Energy efficiency, Effectiveness, and Technological possibility along with the passive measures of the building. But the focus is on the integration of cooling system itself. More, detailed study and how the cooling system works, factors influencing, market trends are also reviewed.

The comparison of FIV and the low - ex cooling technology gives an idea on the similarities and differences between the size, cooling capacity and power consumption. So it guides the design in a more integrated approach.

2. SIMULATING THE BUILDING - INTEGRATION OF PASSIVE STRATEGIES:

The design of the system or the size of the system solely depends upon the volume of the room and the cooling demand posed by that building in Delhi. So, the cooling load and other energy demands are determined by simulation with the possible passive design strategies from the literature review and adapting them in design builders simulation. An energy comparison between the conventional cooling system and the designed low - ex cooling system at the end of the thesis for the same building, shows how much it can save.

3. SYSTEM CALCULATIONS

The next series of research would be understanding chosen technologies with Psychometric property of the air at each and every stage and see how it can be re-designed to provide the desired temperature. By understanding the cooling demand of the building and the effectiveness of the evaporative cooler through calculations, this can be evaluated.

4.DESIGN / EVALUATION

The design of the cooling system is satisfactory if the system is able to provide the recommended supply temperature of 25°C. A series of options needs to be designed initially in terms of various ways of integration of the system, based on maintenance and other practical factors, a design will be chosen and further detailed. The design of the cooling system will be based on simulations and hand calculations.

5. DETAILED DESIGN

The final output of the thesis includes details and energy calculation. The detaling of the façade system, includes size of the module, connection of the system to the façade, assembly and maintenance. The final energy calculation includes comparison of the De-VAP to a conventional water based chiller.

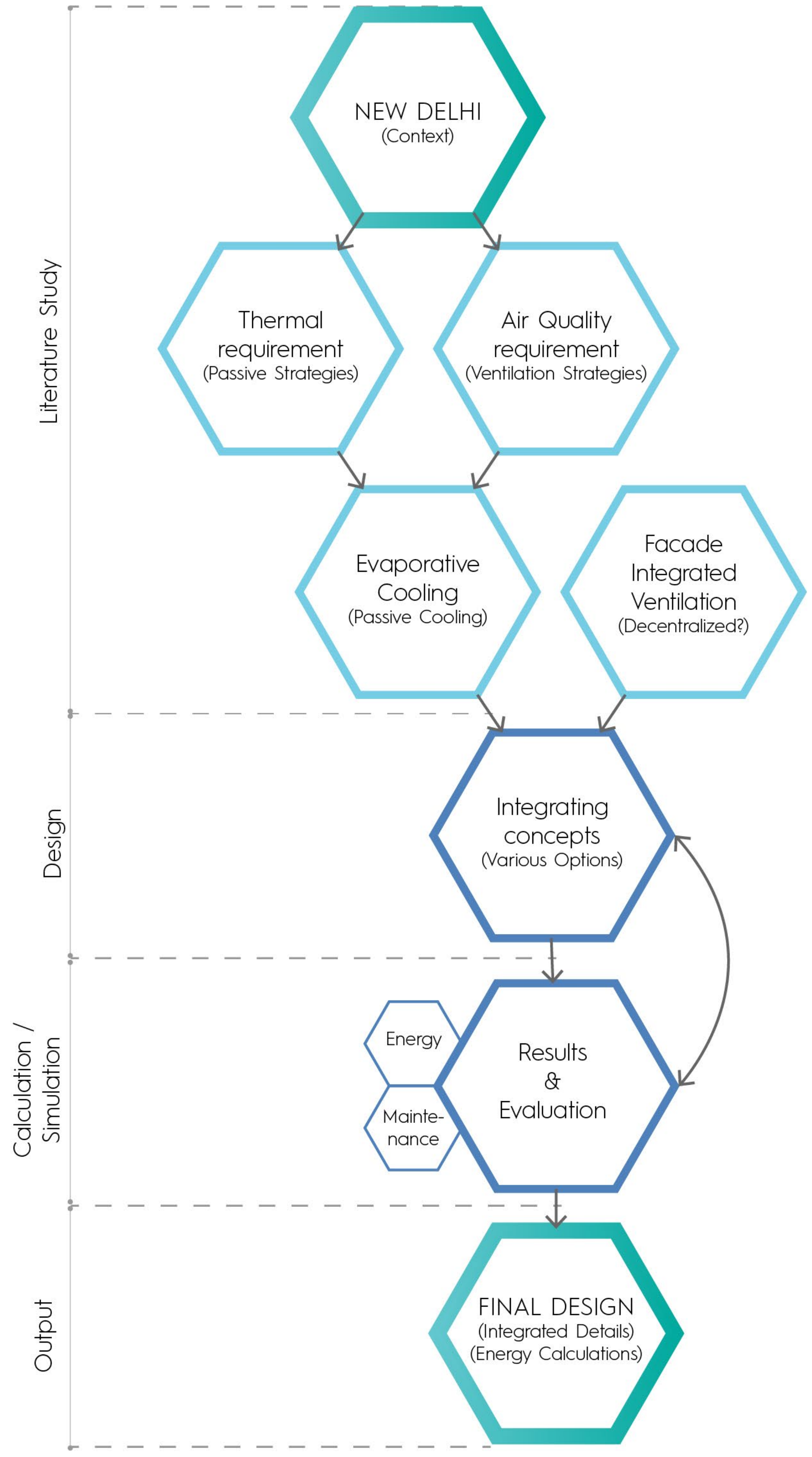


Figure 1.3: Scheme of the Thesis

2
CONTEXT

Chapter Overview

This chapter introduces the varied climatic characters of India; with focus given to the layers of complexity posed by the composite climate in Delhi. The psychometric properties of the weather are briefly described with required cooling and heating strategies listed for throughout the year. Moreover, it also discusses the local or site-specific challenges that need to be considered for the fundamental design development.

2.1 CLIMATIC CHARACTERISTIC

India has wide range of climatic characteristics; varying regionally. The geographical expanse of the subcontinent has six major climatic conditions as shown in figure 2.1 according to the Koppen's system. The country majorly has four seasons Summer, winter, monsoon and post-monsoon [16}

Among the six zones of Koppen's classification, the composite climate covers the central part of India. Delhi region being part of it has an overlap of Semi-arid and Humid subtropical climate. It has a huge variation from harsh summers to cold winters and short monsoon period. The intensity of solar radiation is very high in summer with diffused radiation amounting to a small fraction of the total. In monsoons, the intensity is low with predominantly diffused radiation. Winters are critical for a shorter span of seven to eight weeks.

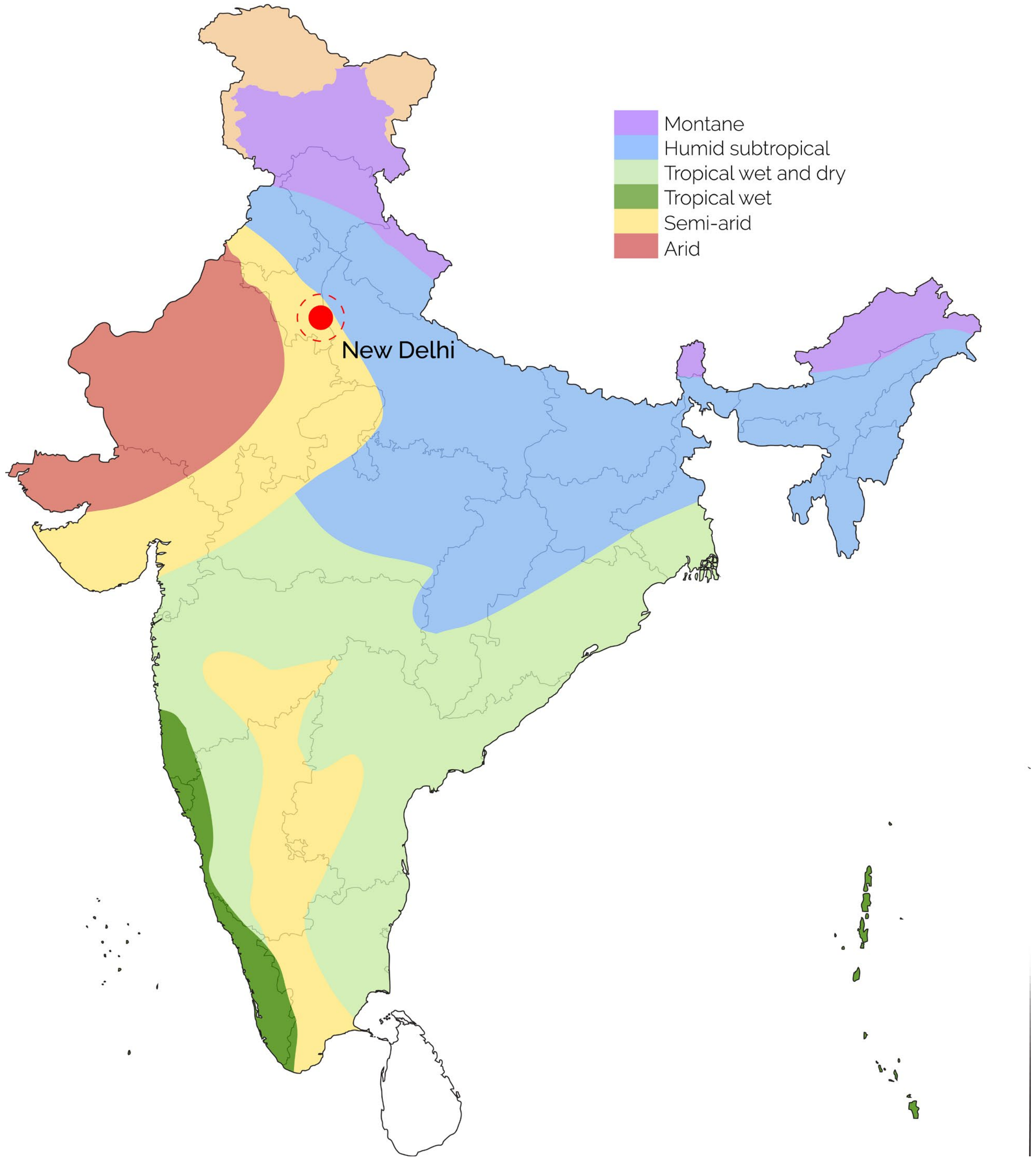


Figure 2.1: Climate Classificaton - India

In summer, temperature ranges between 24°C and 40°C. Delhi has only one heavy monsoon period from June to September which accounts for more than 75% of the rainfall; that results in heavy humidity. October seems to be a reasonable month with a temperature of less than 30°C. From the months of October to February the temperature falls to the minimum of 2°C; determining the adversity of winters. Hence, as a region of composite climate, Delhi experiences higher humidity level in monsoon and lower temperature differences between summer and winter in comparison to the hot and dry zones of west.

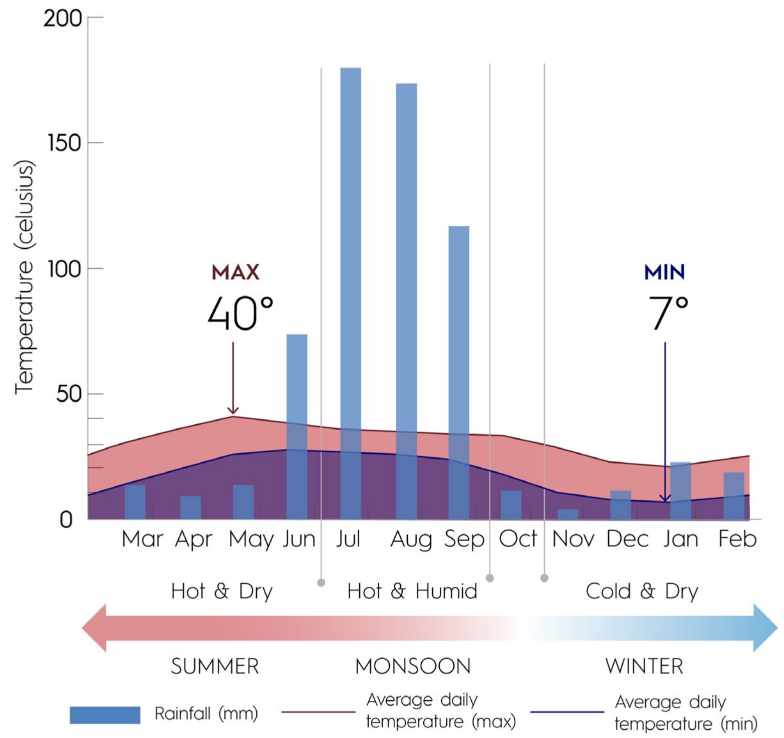


Figure 2.2: Climate of Delhi

Month	Season	Type
Nov., Dec., Jan., Feb.,	Winter	Cold and Dry
Mar., Apr., May., Jun.,	Summer	Hot and Dry
Jul., Aug., Sept.,	Monsoon	Hot and Humid

Table 2.1 : Climate Classificaton - Delhi

2.2 PSYCHROMETRIC CHART

The psychometric chart is a graphical representation of the varied psychometric properties of air including dry bulb temperature, wet bulb temperature, relative humidity and humidity ratio. The data recorded every hour throughout the year (8760 hrs) and plotted on the graph gives the consolidated information. Based on the position of the plotted points as shown in figure 2.3 , the climatic characteristics of a particular place can be identified with a suitable heating and cooling technique.

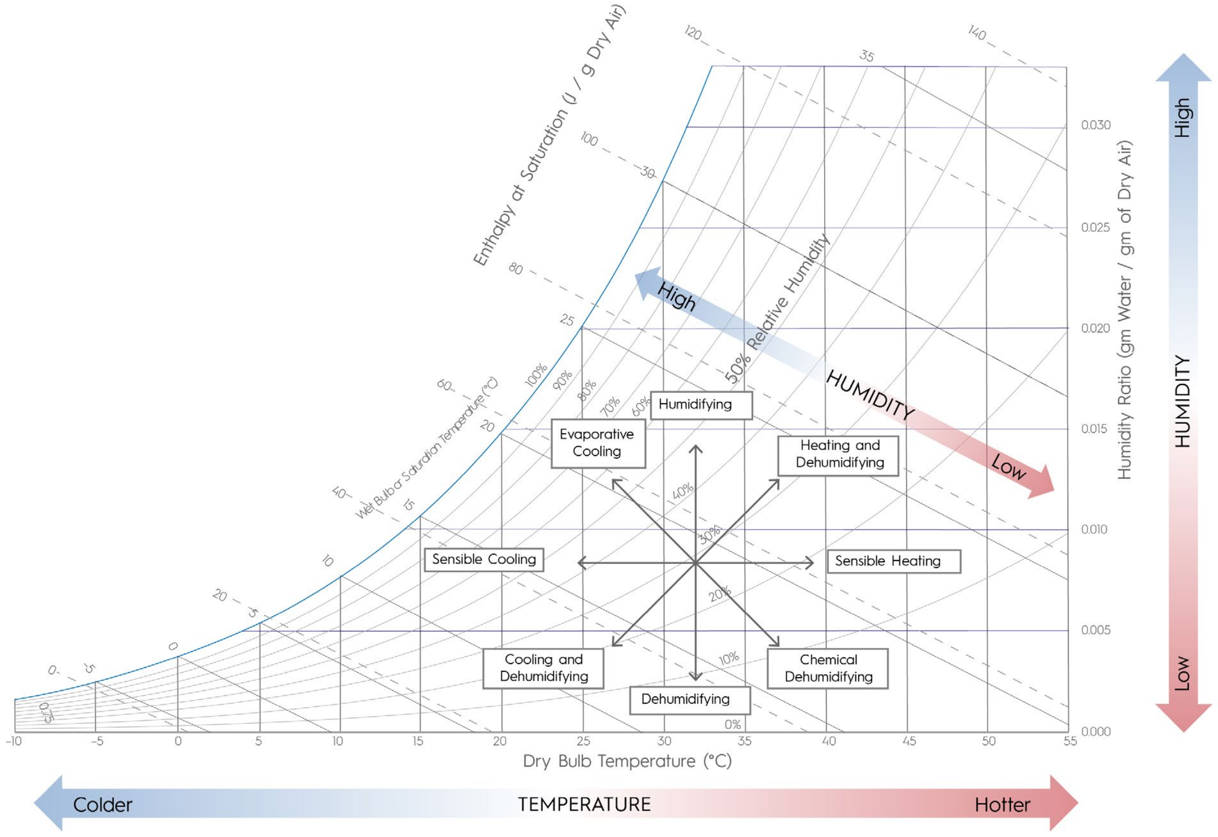


Figure 2.3: Psychometric chart with cooling and heating strategy

2.2.1 NEW DELHI - PSYCHROMETRIC CHART

The weather data of Delhi is collected at 28.58° North, 77.2° East on an elevation of 216m and is graphically represented in the Climate consultant 6.0 Software. The psychrometric chart figure 2.4 shows that the dots are concentrated on three patches all over, showing the characteristics of a composite climate. Throughout the year approximately 1294 hrs (54 days) are comfortable in Delhi according to ASHRAE standard 55 using Predicated Mean Voting (PMV).

In a year upto 60% of its time the space need to be cooled down due to harsh summer and monsoons, and upto 10% of the time goes for space heating during the winters. The demand for cooling the space is more prominent then heating. However, the passive strategies can be implemented to avoid both the cooling and heating demand. The most suitable strategies affecting the above loads are shading strategies and internal heat gain.

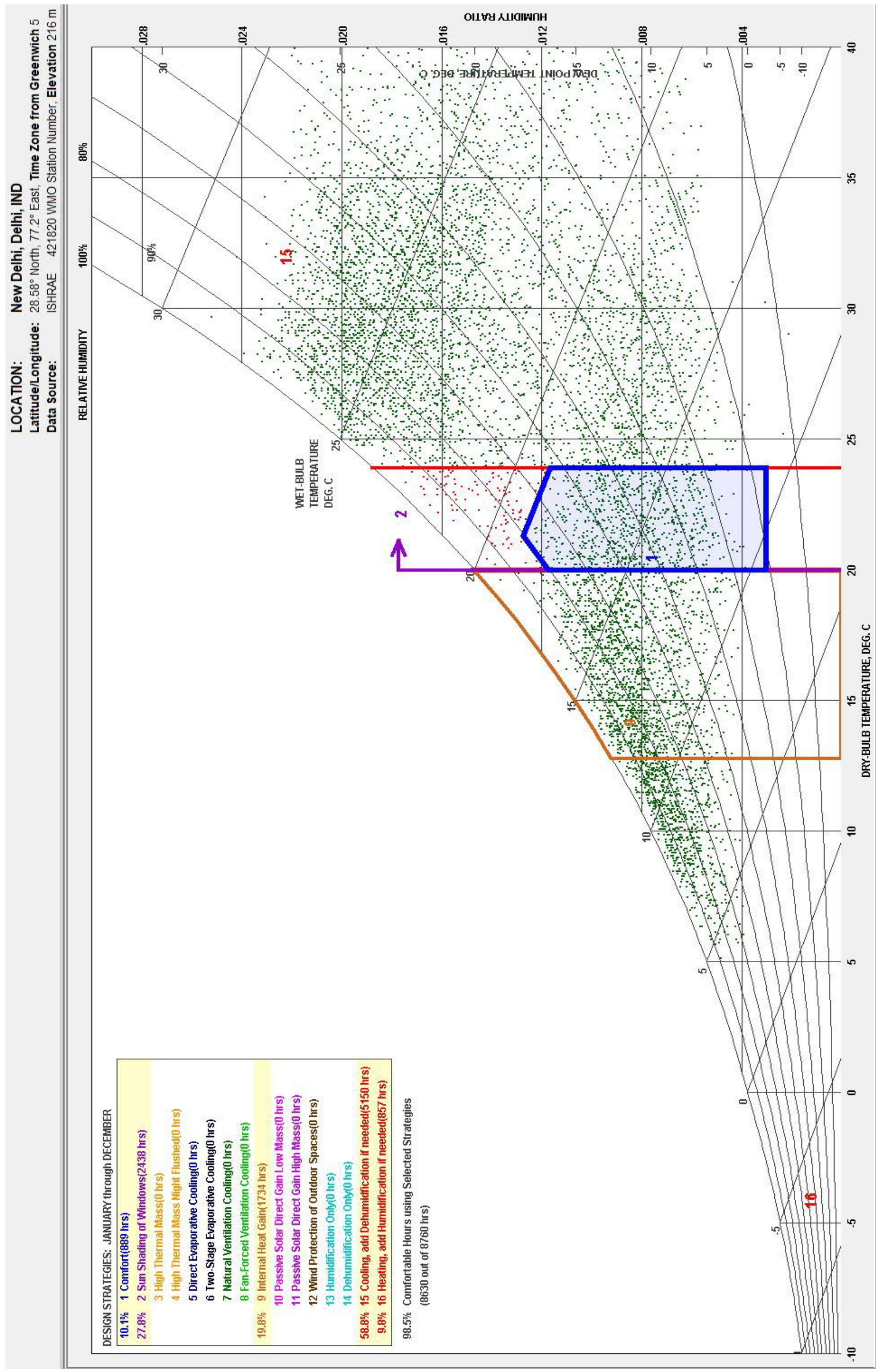


Figure 2.4: Psychometric chart of Delhi Source : Climate Consultant 6.0

2.2.2 ENERGY DEMAND (SIMULATION)

A study done by India Institute of Technology, Bombay on the energy demand of commercial buildings over various climates of India was released as handbook; that serves as a guide to design energy efficient buildings. In the study, a 7 storey commercial building with open floor plan and a single level basement (Figure 2.5) was modelled to run the simulation for calculating heating and cooling load in Delhi.The building was oriented NW and SE direction. The ground and basement were partially conditioned and the rest was fully air-conditioned. It had 5 air changes per hour at ground floor and in rest of the floors had one air change per hour. The building accommodates 560 people on a regular weekday in the total built-up area of 7074 m2 excluding basement; in which 5400 m2 carpet area is centrally air-conditioned. [17]

Through the simulation experiment, the following derivations have been made. May, June April and July are the months with the highest cooling load and the heating load is required in December and January (Figure 2.6). The surface and internal heat gain has to be maximized to control the heating demands during the winter. The heating through convection is prominent during the months of November to March and the surface area heat gain through sun is maximum during the period of April to October (Figure 2.7). Air changes may help to reduce the load in November to March but this may also increase the cooling load in summer. Scheduling the air changes helps in reducing the total energy demand. Well, at the same time the surface heat gain needs to be maximized only in the months of December and January to reduce cooling demand. By reducing WWR and designing sun shading to direct solar radiation reduces the total energy demand.In this way, Delhi has more cooling demand and less or negligible heating demand. [17]

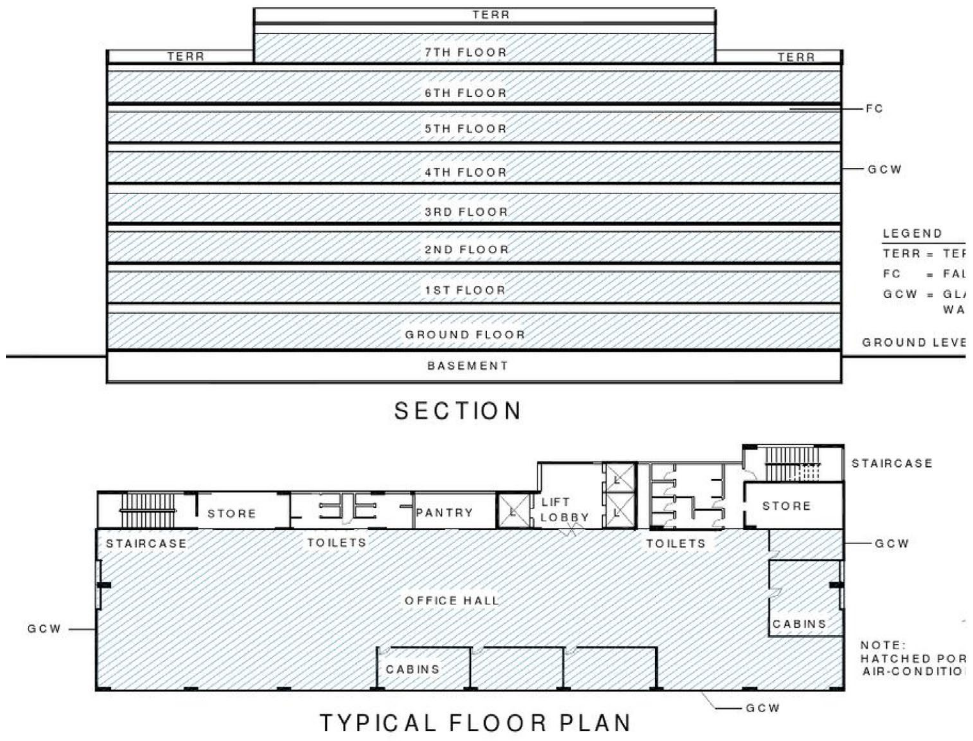


Figure 2.5: Simulated - Commercial building in Delhi [17]

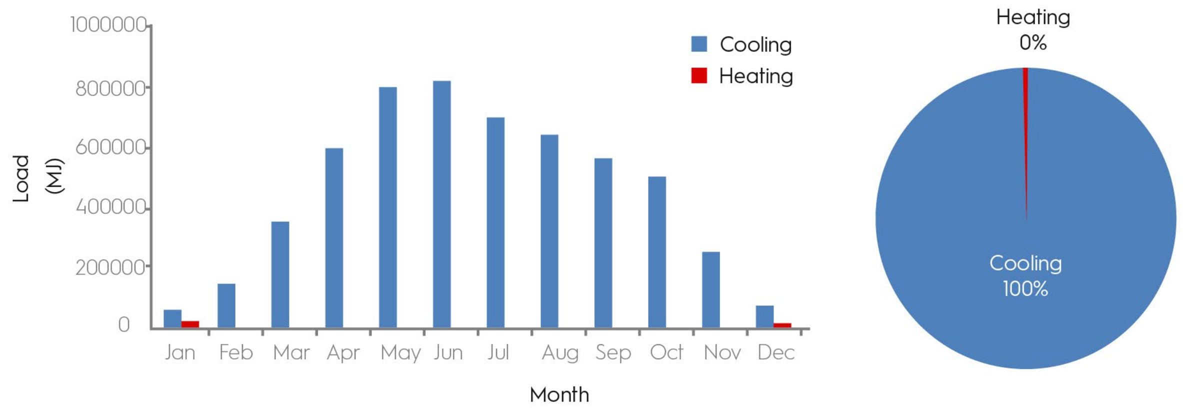


Figure 2.6: Monthly and annual heating and cooling loads in New Delhi[17]

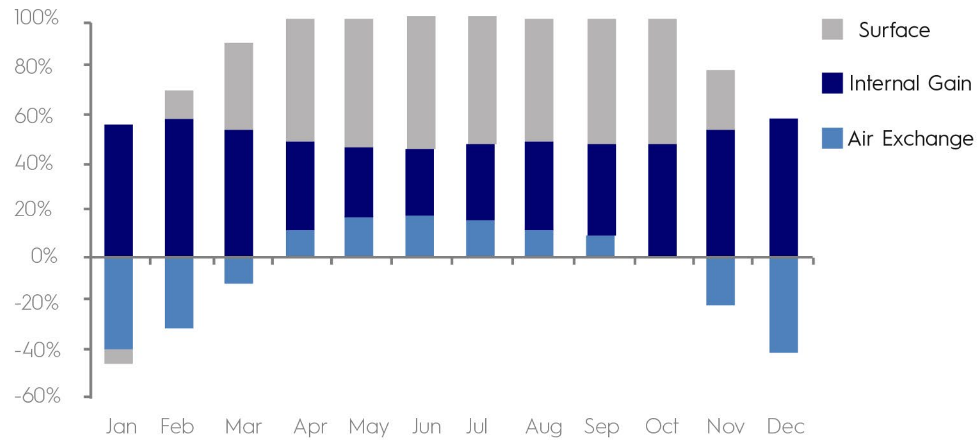


Figure 2.7:Component-wise distribution of percentage heat gains and losses on a monthly basis[17]

2.3 POLLUTION

People spend nearly 90% of the time indoors, so the Indoor Air Quality (IAQ) plays a crucial role in the health of the employees. Fine airborne particles in the air have adverse effects on human health. Based on the acceptancy of human inhalation with respect to suspended particulate matter, UN classifies them in to two ranges; 2.5μm to 10 μm and below 10. In Delhi, a fraction of their exposure always exists throughout the year by outdoor infiltration either through natural ventilation or through mechanical ventilation.[23]. Smaller the particle more hazardous it is, as they can go deep inside when inhaled. By data comparison, PM level of Delhi is twice the level of Beijing and it is way more than the recommended UN standards or Indian standards. (Figure 2.8)

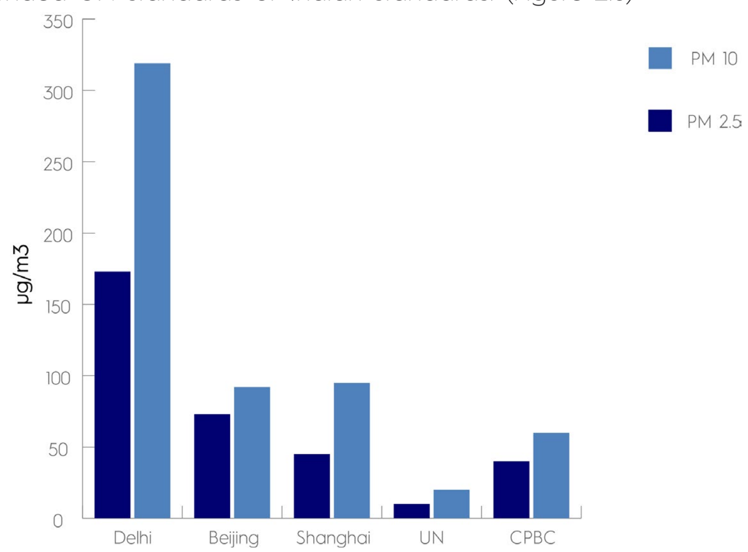


Figure 2.8: PM concentration in different cities

Delhi has always been in the top five most polluted cities by particulate matter concentration with respect to both PM2.5 and PM10 (Figure 2.9). Many research papers are also available in this subject explaining the status of outdoor pollutant infiltration, sick building syndrome due to Mechanical ventilation and higher Indoor pollutants / Outdoor pollutants ratio in the context of Delhi. The climate of Delhi plays a crucial role in the level of the PM, as the monsoon decreases the level of the pollutants and winter worsens them as smog (Figure 2.8). Hence, the design of ventilation system needs to consider not only the desired temperature but also the level of pollutants in the air and way to filter them.

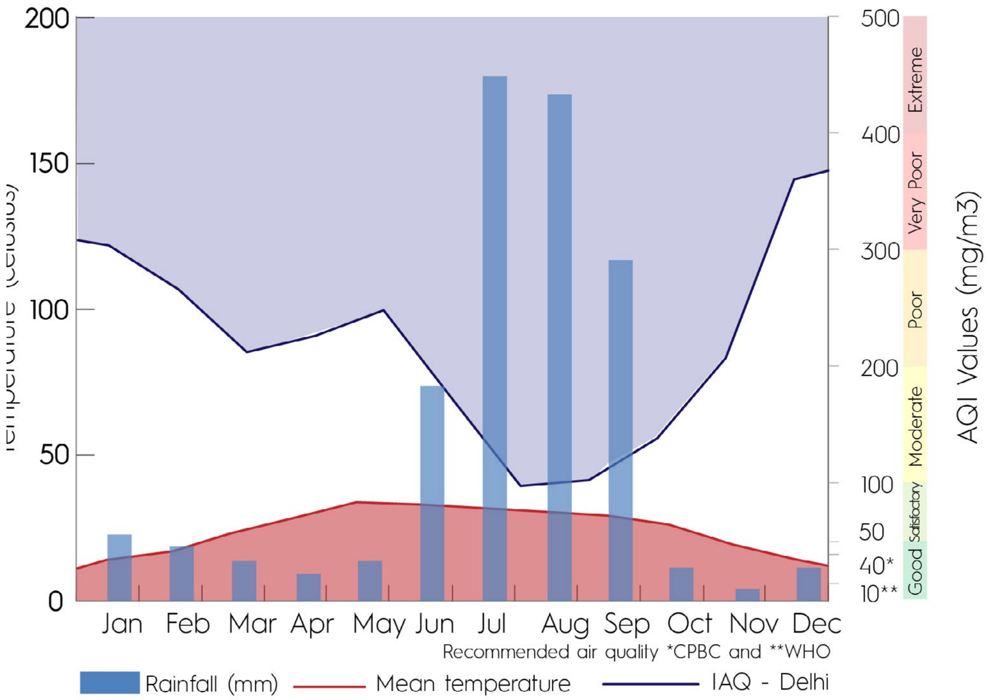


Figure 2.9: Relationship between Climate and concentration of pollution

Figure 2.10: India Gate - Heavy air pollution in Delhi

3

PASSIVE DESIGN

Chapter Overview

This chapter discusses various passive design strategies for composite climate reviewed through literature and detailed case studies. The basic literature study suggests various heat gain and heat loss techniques and also proves that natural ventilation is not possible due to high-level pollutants. The Case studies, on the other hand, are reviewed and compared based on EPI (Energy Performance Index) and various other parameters which summarize the requirements for an energy efficient office building in composite climate.

3.1 BUILDING LEVEL:

The cooling demand of the structure is quite high as the buildings are light and fully glazed. The energy consumption and reduction need to be dealt in a holistic way as active cooling will become ineffective if the structure is not designed passively.

The composite climate is characterized by heavy radiation and ambient temperature during the summers with low humidity; hence it is desired to resist the heat out with natural ventilation during the monsoons. At the same time, during winters the internal heat gain needs to be stored, to avoid the discomfort and attain maximum heat from the sun.

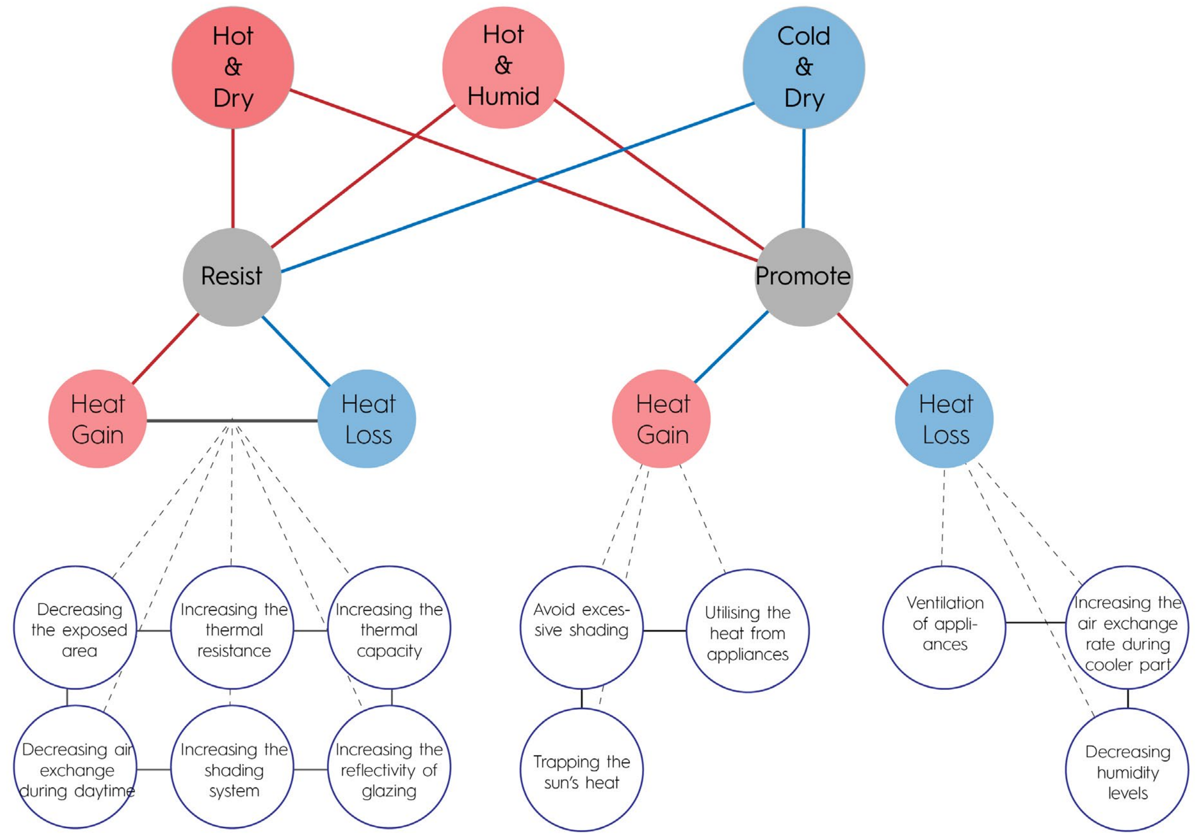


Figure 3.1: Passive Strategies for Composite Climate [17]

3.2 NATURAL VENTILATION:

Even though the natural ventilation is favorable during the monsoon season for thermal comfort and mixed mode ventilation that saves energy; the pollution in Delhi makes it not suitable for cross ventilation. Cross ventilation, mixed ventilation (Mechanical and Natural ventilation) can help in reducing the energy consumption for the built structure. Especially cross ventilation is recommended in places with high humidity so that the rate of perspiration increases resulting in thermal comfort. In our context avoiding ventilation during harsh summers and cold winters, but allowing them during the desirable weather like in the night time or even in daytimes during the monsoon can make a significant impact. The adaptive thermal comfort can be an appropriate approach to save more energy with natural ventilation [22]. But as the city experiences the worst polluted outdoor environment which can be inhaled as Particulate matters (PM), the balance between natural ventilation and exposure to pollutants need to be maintained.

The study by Radha Goyal and Prashant Kumar took an effort in measuring the ratio of Indoor/ Outdoor particulate matter (I/O) of a mixed-use commercial building that is both mechanically and naturally ventilated in Delhi. During the study period, theIndoor Air Quality monitoring was done in the working hours. The results of this clearly stated that the naturally ventilated spaces have high I/O ratios i.e. the pollutants settle in these spaces and also have high infiltration of PM; whereas, the mechanically ventilated spaces have their ratio always below one and even further lower. So, the infiltration can be reduced by using mechanical filtration. [25] From the analysis, it is clear that even though the cross ventilation is effective during the monsoon season; they are not desirable in the summers or in the winters because of the temperature. But, the exposure to the PM due to heavy pollution in Delhi also becomes a crucial factor while considering natural ventilation. A fine and effective filter needs to be attached to the mechanical ventilation system or an electrostatic filter on the windows is must. If this is not possible the air needs to be recirculated and prefiltered which helps in reducing pollutant level. But in this air exchange rate between outdoor and indoor needs to be kept minimal not only to reduce the cooling load but also for the quality.

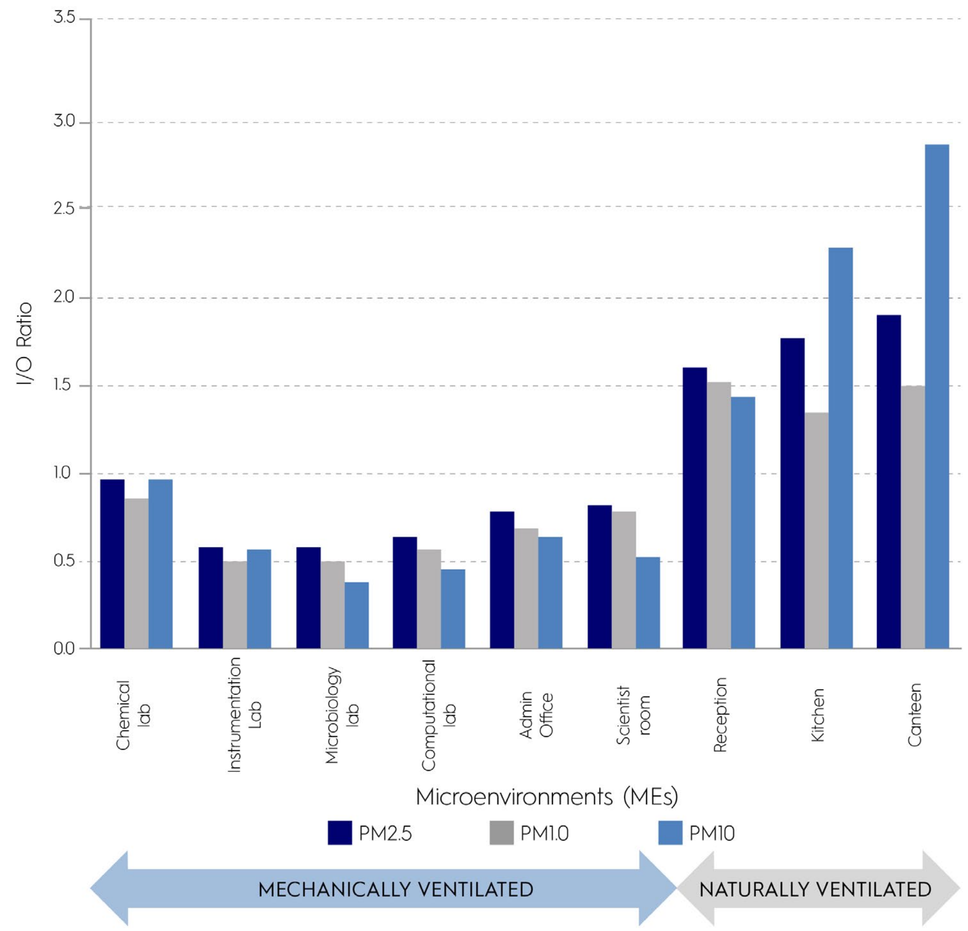


Figure 3.2: I/O of varying Particulate Matter in different rooms [25]

3.3 PASSIVE BUILDINGS IN COMPOSITE CLIMATE:

In order to design an efficient low ex – cooler, the cooling capacity of the building has to be brought down by passive climate responsive design. Since we are dealing with composite climate, 4 sustainable high-rise office buildings located in Delhi and Gurgaon were chosen as case studies to study the energy consumption pattern and the design features. The selection criteria for the buildings include its rating system, building occupancy and its scale (minimum of 5 floors and different geometry). [35]

Since there are multiple variables affecting the energy, Energy performance index was used as a common factor to compare the energy use of the buildings. EPI is total energy consumed by the building throughout the year in kWh divided by the gross floor area in m2.

$$EPI = \frac{\text{Total Energy consumed in a year (kWh)}}{\text{Total Floor Area of the building } (m^2)}$$

3.3.1 CASE STUDIES:

The detailed energy consumption and design strategies are discussed further below.

3.3.1.1 WIPRO TECHNOLOGIES, GURGAON:

Wipro Technology's design is an inverted cone which is placed at the junction of the two roads for maximum visibility. The landscaped courtyard cools down the building in summers, the open floor office space that overlooks the courtyard, helps in increasing the daylight and maximizes the outside view. The overall heat conductance is reduced by incorporating terrace gardens, high-performance glazing with optimum visual light transmittance, exterior light shelves, overhangs on all the windows, efficient chillers, efficient lighting, and sufficiently daylit interior spaces. [35]

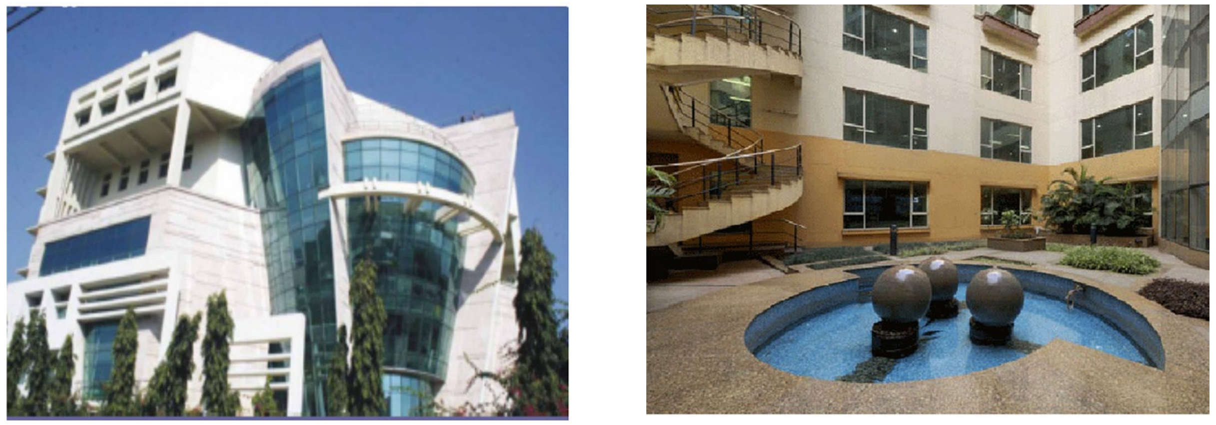


Figure 3.3: Wipro Technologies and the courtyard, Gurgaon

3.3.1.2 SKYVIEW CORPORATE PARK, GURGAON:

Skyview corporate park is the phase I of a multiphase project that has been proposed to be developed on a 21 – acre site that faces National highway. The building achieved LEED platinum under IGBC (Indian Green Building Council). The structure has open rectangular floor- plan with the core at itscenter. The building faces N-S orientation rather than the preferred E-W orientation. This is due to its adjacency to NH and to increase the frontage of the building. The Low-e double glazed façade reduces the heat conductance and the air – conditioning system includes microfilters to decrease the amount of pollutant from the exterior into the office. [35]

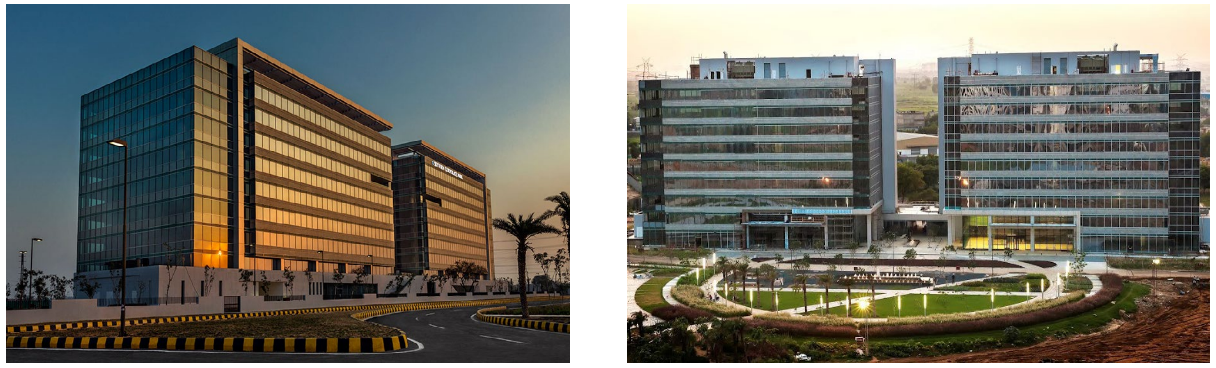


Figure 3.4: Skyview Corporate Park, Gurgaon

3.3.1.3 VOLVO-EICHER CORPORATE HEADQUARTERS (VECH), GURGAON:

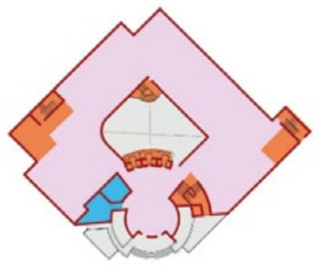
The Vech building has unique diagonally braced steel structure outside the main envelope. The building is composed of two square-shaped building blocks made of glass and steel. This column-free building has optimal and flexible workspace with better daylight penetration. The external structure is fitted with double-curved louvres reflecting an even light intensity, which reduces the artificial light requirement. A large amount of recycled and reused materials was used during the construction.the construction.

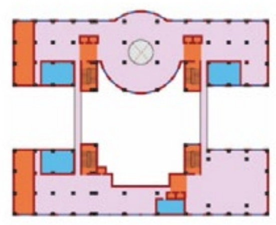
Figure 3.5: Volvo - Eicher Corporate Headquarters (VECH), Gurgaon

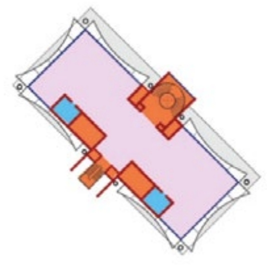
3.3.1.4 INDIRA PARYAVARAN BHAWAN (IPB), NEW DELHI:

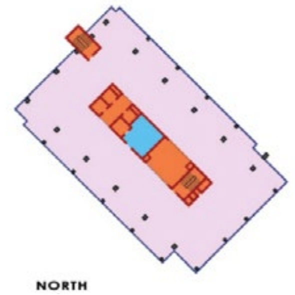
IPB has the highest green rating in India. The structure is oriented towards N-S with the large courtyard in the center that allows for cross ventilation and deep daylight penetration. The structure has shaded landscaped region, insulated walls and double glazing in fenestration to bring down the ambient temperature and reduce the heat transfer. [35]

Figure 3.6:Indira Paryavaran Bhawan (IPB), New Delhi









Toilet   Office   Core

	Units	WIPRO Gurgaon	IPB New Delhi	VECH Gurgaon	SKY VIEW Gurgaon
Year of Completion	**Units**	2005	2014	2012	2015
Significance		Platinum rated by LEED	Platinum rated by LEED	Platinum rated by LEED	Platinum rated by LEED
% of Conditioned space	N.A	65	38	100	100
Building Configuration					
Orientation	N.A	N.A(Square)	Longer axis (E-W)	Longer axis (N-S)	Longer axis (N-S)
Placement of core	N.A	Central, East and West	Central, East and West	Central	Central
Typical floor Area	m2	1726	3,150	1,246	2,730
Total Floor Area	m2	16,258	31,400	9,972	23,500
No. of Floors	Nos.	6 (G+5)	8 (G+7)	6 (G+5)	9 (G+8)
Floor to Floor height	m	3.6	3.9	3.6	3.6
Plan Depth	m	12	15	17	34(13m from core)
Window Parameter					
Over WWR	%	35	20	80	55
Shading Device	Type	Horizontal Louvres	Box	Double Curved lourve	No Shading
Building envelope material					
Wall Assembly - U value	W/m2K	0.63 (Fly-ash based AAC blocks)	0.34 (AAC block masonry wall)	1.1 (Cavity wall clas with tiles)	1.1 (Cavity wall)
Roof Assembly - U value	W/m2K	0.31 (75mm XPS with high reflective roof finish)	0.5 (150 mm RCC slab with insulation)	0.25 (Roof Garden)	0.3 (Reflective Insulated roof)
Glazing Type - U value	W/m2K	1.8 (6/12/6 - ST150, light blye gray high performance glass)	1.8 Double glazed VLT = 0.6	2.1 Double glazed SHGC = 0.69	1.8 Dual pane low-e glass SHGC = 0.62
Occupancy and Energy					
Working hours	hrs	10h (5 days)	7h (5 days)	7h (5 days)	7h (6 days)
HVAC type and Capacity	kW	Central 2850 kW	Chilled beam, Geothermal Cooling 563kW	HVAC under floor 563kW	Central 6357 kW
Lighting Fixtures	Type	T5 & CFL lamps	Light shelves,T-5 & LED(dayight sensor)	LED with motion sensor	T-5 & LED fixture (daylight sensors)
LPD (ECBC benchmark 10.8)	W/m2	5.4	5	4	9.5
Lighting Performance Index	kWh/m2/year	10	9.2	7	16.9
HVAC performance Index	kWh/m2/year	58	27	71	79
EPI (ECBC benchmark 179)	kWh/m2/year	85 (53% reduction)	45.25 (75% reduction)	96 (46% reduction)	112 (37% reduction)
Renewable energy	kWp	NA	930 kWp	NA	NA

Table 3.1: Comparison of various design strategies and energy pattern of the case studies [35]

Table 3.1: Comparison of various design strategies and energy pattern of the case studies [35]

3.3.2 RESULTS:

3.3.2.1 EPI :

The IPB, Delhi has the lowest energy performance index of 45.25 kWh/m2/year (Table 3.1). Multiple climatic design approaches with optimum plan depth, less conditioned space, responsive orientation, WWR, natural ventilated spaces, high insulated glazing/wall makes it the most passive building. This is the only structure to include a low-ex cooling strategy with geothermal heat rejection system and chiller beams. Moreover the PV on the terrace produces 14,91,000kWh/year which exceeds the buildings consumption of 14,21,000 kWh/ year making it is an energy - positive structure. [35]

The VECH and Skyview building are completely air-conditioned with higher WWR. Even though the glazing ratio of VECH is 80% with full height dual pane glass the EPI of VECH (96kWh/m2/year) is lower than Skyview (112kWh/m2) because of its integration with external louvres, the position of the core and slab concealed ducts. This reduces the cooling load of the structure, moreover, the slender plan helps the structure to reduce the lighting load compared to deep Skyview's plan.

3.3.2.2 LIGHTING:

The lighting load plays a major factor in cooling load. The lighting performance index is the total energy used by the artificial lighting system in a year divided by the total floor area. The high WWR (85%) with a slender plan (8.5m) results in 95% daylit office space. The column-less structure allows maximumnatural light penetration and the doubly curved louvres inclined at a specific angle further helps in deepening it with even distribution.

The VECH building has the lowest Light performance index as 7kWh/m2/year and has 95% of the lights as LED with a motion sensor. The square proportion of IPB and WIPRO have a larger penetration of light on all sides with higher glazing have lighting demand of 9.2 and 10 kWh/m2/year. The Skyview building has deep plan office (13m to the core). Even though the WWR is high (55%) due to the broad plan it has high artificial lighting demand (17kWh/m2/year). [35]

3.4 SUMMARY

- The use of low U value walls with an insulated reflective roof and double-glazed high-performance window can reduce the HVAC load under composite climate
- The internal heat gain plays a significant role in the cooling load, so more efficient artificial lighting and natural lighting is recommended.
- Use of Low-ex cooling technology (IPB – Geothermal cooling) significantly can help reduce the energy performance index of the building as HVAC consumes 60% of the annual demand.
-A very low WWR reduces the cooling load but it increases the lighting load and heating associated with it. Integration of proper shading system with 40% of WWR and depth of 15m is the optimal balance between different loads resulting in lesser EPI.

3.4.1 ENERGY CONSERVATION BUILDING CODE INDIA

The energy council of India has already published a guideline for energy efficient buildings. For the composite climate, the code suggests the WWR ratio from 40% to 60% and the values should not exceed 60%. [20]

WWR		≤ 40%	40% < WWR ≤ 60%
Month	Maximum U-factor	Maximum SHGC	Maximum SHGC
Composite	3.30 W/m2K	0.25	0.20

Table 3.2: SHGC and U-Factor requirements for different WWR

4

EVAPORATIVE COOLING

Chapter Overview

This chapter explores various possible low ex-cooling strategies feasible in India. The evaporative cooling has been discussed in detail in the following chapter. The study includes wet-bulb effectiveness, efficiency, Psychometric process, application on Delhi's climatic scenario and limitations of different types of evaporative cooling techniques. The study concludes by choosing Dew-point Indirect evaporative cooler because of its high WB effectiveness with no addition of humidity

4.1 LOW EXERGY COOLING TECHNOLOGIES IN INDIA

Space cooling dominates a huge share in the present and the upcoming cooling demand in India. In the Cooling Action Plan, the technology used for space cooling is divided into three categories:

Refrigerant based cooling system: Split AC, Chiller systems, Packaged DX, VRF etc.,
· Non-Refrigerant based cooling system: Fan, Air cooler
· Not - in - kind: Less energy intensive cooling system

Energy Council of India identified the low energy cooling technologies on the basis of energy savings, climate applicability, reduced costs, increased reliability, peak demand reduction, GHG reduction and reduced complexity. The following are the upcoming promising passive cooling technologies that have been executed on a commercial scale and have also known for its better IAQ, noise reduction and integration of IOT (Internet of Things):[6]

· Radiant cooling
· Indirect-direct evaporative cooling (IDEC)
· Desiccant Cooling
· Geothermal Cooling
· Vapor Absorption Machines
· Structure Cooling

Among them, the IDEC have replaced nearly 0.1 million tons of refrigeration in more than 800 buildings within 2008 - 2015 and projections till March 2017. This is nearly 43 million cubic feet per minute air flow. The assessment includes also includes low capital and operational cost with less maintenance.) [6].

4.2 EVAPORATIVE COOLING

The air cools down when in contact with the dry air. This happens all over in nature in the lake, waterfalls and streams. The best example would be cooling due to evaporation of the sweat. The evaporation technique was even used to make Ice in India during the nights along with night sky radiation. Even now the people cover their doors with dried "vetiver" grass. This grass is wetted by using a recirculating pump and a catch basin which evaporates when in contact with air and provides cooling. So, it is basically a heat and mass transfer process where the heat of the air is collected by the water and the air temperature decreases. [26]

The evaporative coolers are classified into three major systems. (Figure 4.1) The Active DEC is classified further upon by the usage of different pads for DEC and Passive DEC techniques are vernacular techniques that have been used for centuries. Well, in order to increase the efficiency of the IDEC they are classified into three cooling systems. In order to have both DEC and IDEC advantages combined systems with both IEC/DEC is designed. Moreover, this combined system can be coupled with refrigerant and desiccant systems also. [27], [28], [29]

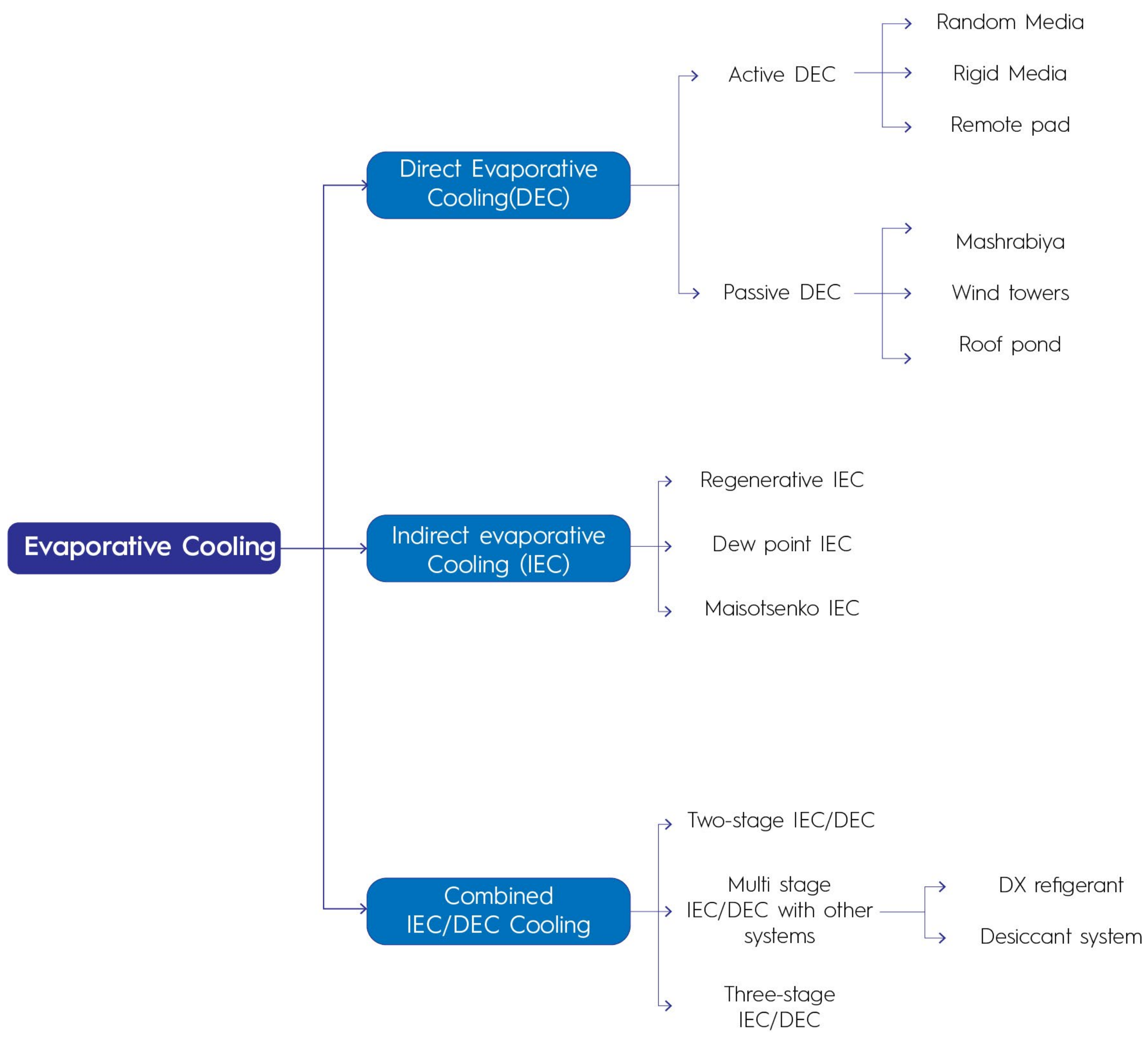


Figure 4.1: Types of Evaporative cooling

4.2.1 DIRECT EVAPORATIVE COOLING (DEC)

The simplest evaporative cooling technique is the direct evaporative cooling. The temperature of the air brought down by adding water to the dry outdoor air (via., sprayed or wetted medium). So, cool and humid air enters the building. The sensible heat of the air is absorbed by the water as latent heat and this heat evaporates the water giving the cooling effect to the air and increase the humidity of the air at the same time. The humidity of the primary air plays a crucial role in DEC, if the air is hot and dry it increases the rate of evaporation and it can accommodate more vapour and better the cooling performance, as the rate of evaporation not only depends on temperature but also on the level of humidity in the air. The major limitation of the system is that it cannot be used in coastal or more humid regions.

In a typical system, only a fraction of power is used by the air blower and water recirculating pump. When designed ideally the system has energy saving up to 90% compared to a conventional system [27]. It comprises an evaporative medium, water tank to collect the drained water, an air blower, water distribution and recirculation system. The efficiency of the system mainly depends upon the type of cooling pad that has been used, a tight cellulose pad can provide efficiency up to 90%. A major factor about the direct evaporative cooling is that the temperature of the primary air can never be brought below the wet bulb temperature. In theory, the air can be brought down to 100% wet bulb effectiveness, but due to the short time of contact between the air and the pad, other heat sources., insufficient water in pad etc. this is not possible The commercially available system has a wet-bulb effectiveness of 70-95% [27]. One of the most commonly discussed issues regarding direct evaporative cooling is the disease associated with them. As the humid air enters the room, the suspended water droplets have bacteria, when inhaled this causes a lungs inflammation causing legionnaires to disease fatal pneumonia. But, the studies have shown that this can be avoided with proper maintenance of the cooler pad by completely drying them at certain intervals, the bacteria's growth can be controlled if the temperature of the water is below 25°C. These things are addressed in the modern coolers or in the recent design.[32]

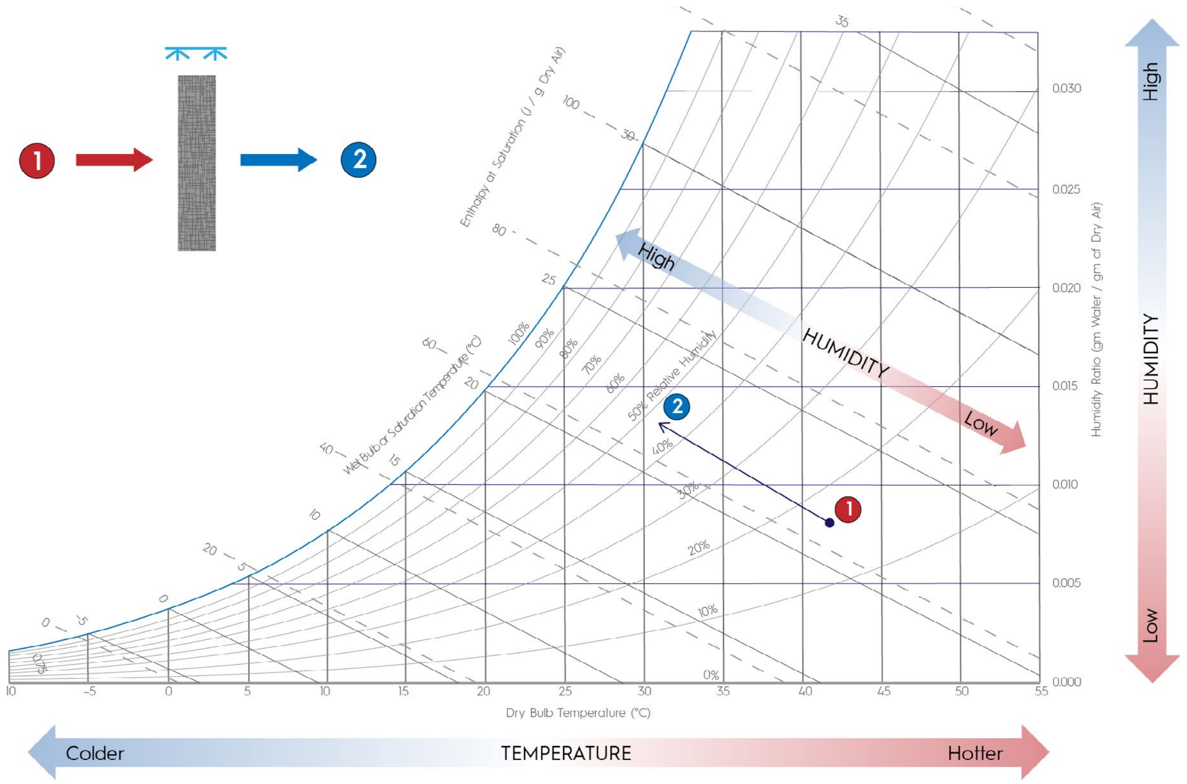


Figure 4.2: Direct Evaporative Cooling - Process on Psychometric Chart

4.2.2 INDIRECT EVAPORATIVE COOLING (IEC)

The IEC a heat exchanger has a series of dry and wet channels. The primary (supply) air flows through the dry channel and the secondary air flows through the wet channel simultaneously in the opposite direction. The secondary air flow absorbs the sensible heat of primary air and cools down the supply air without any addition in humidity. The wet bulb effectiveness of IEC is 40 - 80 % [28] which is less then DEC, as the amount of energy lost in the water is lower. But, again in theory 100% wet bulb effectiveness is possible if the air flows through an infinite surface area of the heat exchanger at a proper air flow rate. But, there is always a limited surface area, uneven distribution of the water sprayed on the wet channels and proper counter flow of this air is also not possible. [28] The heat exchangers that are used in the systems are plate heat exchangers either placed horizontally or vertically and tubular heat exchangers are also in practice in which the primary air flows through the pipe and the secondary air cools down from outside.

In both scenarios DEC and IEC it is not possible to reduce the temperature of the primary air below the wet bulb temperature. [28] In the case of IEC, the cooling is limited by the WB temperature of the secondary air flow at the inlet. An advantage over the indirect cooling system is that altering the flow, distribution of air and water in several ways can lead to an increase in the WB effectiveness of the system. Even though it might get a bit complicated from the existing simpler version, the results at that can be obtained is promising. The other versions are Regenerative IEC, Dew Point IEC and Maisotsenko IEC.

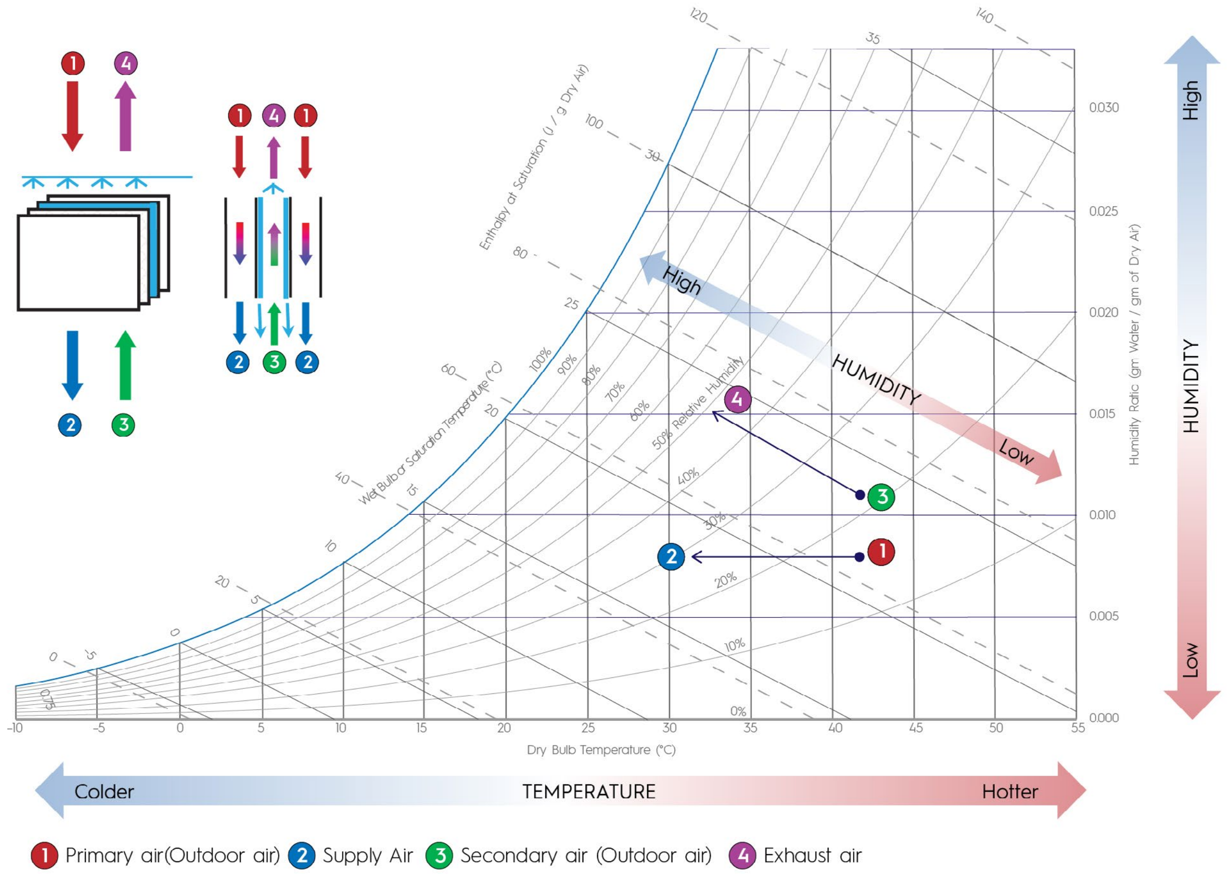


Figure 4.3: Indirect Evaporative Cooling - Process on Psychometric Chart

4.2.3 DEW POINT INDIRECT EVAPORATIVE COOLING (DIEC)

In order to enhance the performance of the IEC system and to provide the supply air temperature closer or even lesser than the WB temperature, this system was developed. The working of DIEC is similar to IEC, the ambient air is drawn into the dry channel and it gets cooled down by the wet channel, but instead of the secondary air flowing through them, a small fraction of the primary air itself is diverted into the wet channels [29]. So, this fraction of primary air gets humidified and takes away the heat from the dry channel then it is exhausted. In this way the supply air's temperature is reduced below the WB temperature and closer to dew point without any increase in humidity. However, the primary flow rate is reduced due to this diversion and more power is required to operate the system.

In theory, it is possible to attain the dew point temperature of the primary air at the supply. The wet bulb effectiveness is closer to 92 - 114 % and the dew point temperature is nearly 58 - 84% [33]. When combined with a dehumidifying unit like cooling coil or desiccant system on a typical summer in a hot and humid region the WB and DP effectiveness is 102 and 76 % respectively. [33]

A numerical and laboratory experiment focusing on the performance of the D-IEC system and its influence of inlet air temperature, humidity and air velocity on the supply or the outlet air temperature. was studied. In that research the evaporative cooler was designed with plate heat exchanger of 1200 mm by 80mm with 5mm spacing made of the cotton sheet coated with polyurethane of 0.5 mm thick. [33]

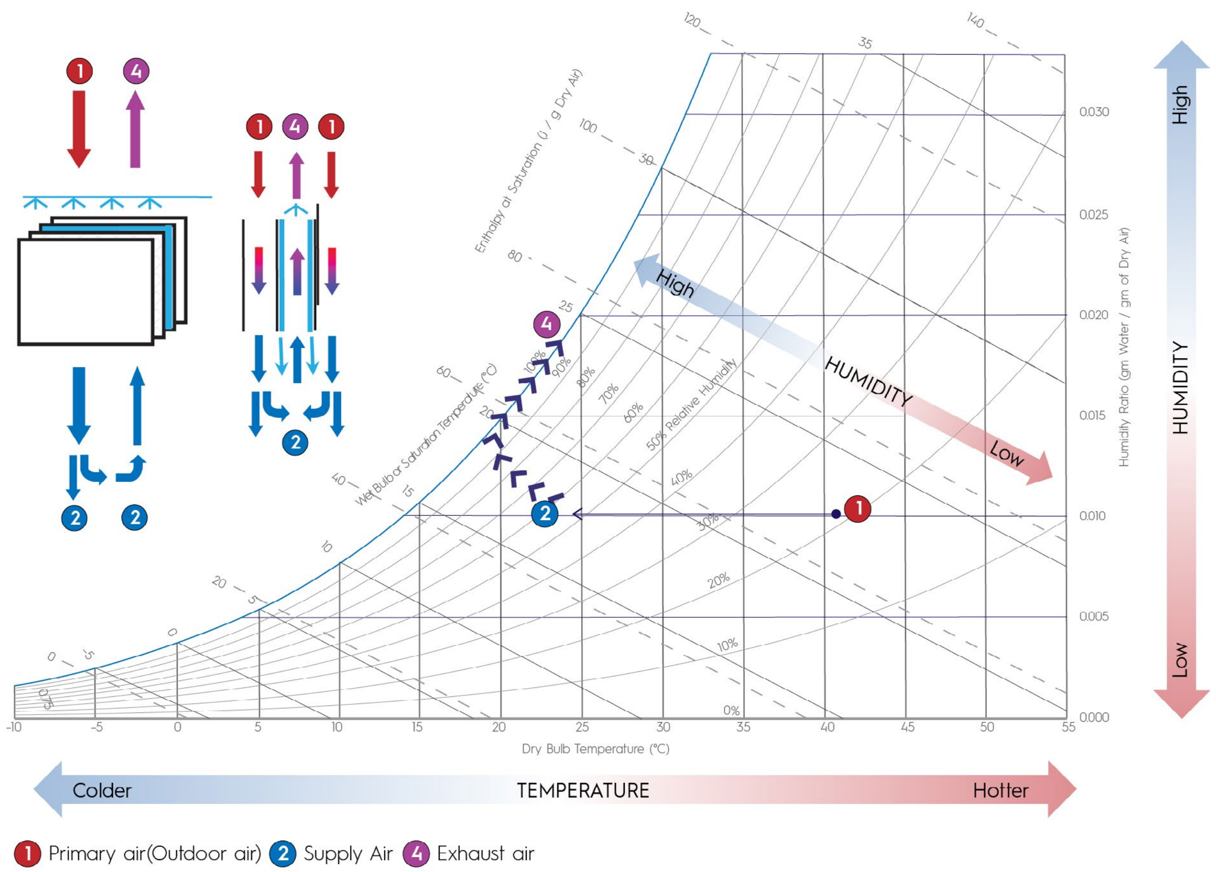


Figure 4.4: Dew point Indirect Evaporative Cooling - Process on Psychometric Chart

4.2.3.1 inlet vs outlet tempertaure:

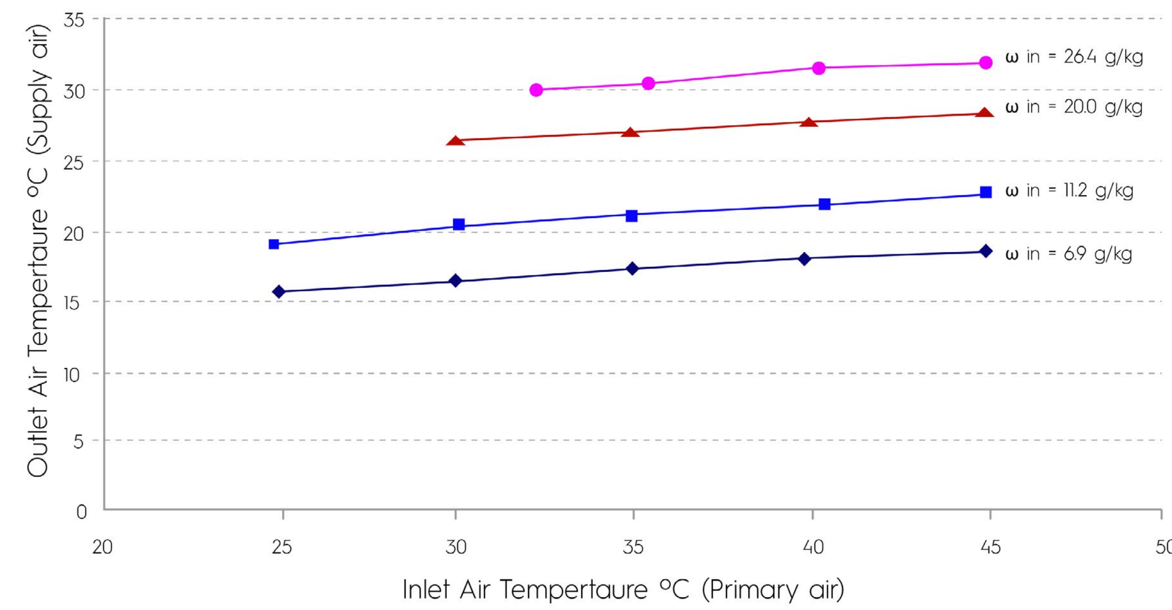


Figure 4.5: Inlet vs Outlet temperature for varying humidity

It is evident from the result that the increase in humidity rises the supply air temperature and reduces the cooling performance. The difference in rising of temperature between inlet and outlet is almost similar for varying humidity. So, if the humidity is below 20 grams of water/kg and the external condition is below 35°C, the system can provide the supply air around 26°C (Figure 4.5). [33]

4.2.3.2 Air Velocity:

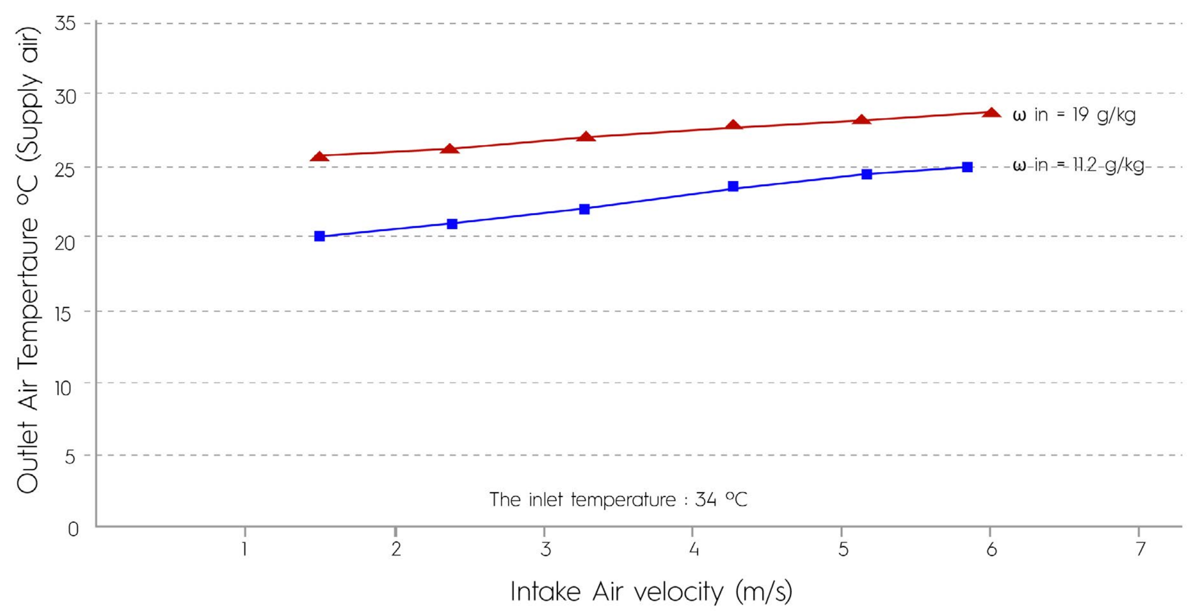


Figure 4.6: Outlet temperature vs Intake air velocity

The slower the intake air velocity the lower the supply temperature as there is more time to lose the heat in a heat exchanger. Both the WB's and DB's effectiveness increases with lower inlet temperature. The results suggests that the air velocity needs to be maintained below 2.5m/s to obtain wet bulb temperature effectiveness over 100%.

4.2.4 COMBINED IEC/DEC SYSTEM / TWO - STAGE EVAPORATIVE COOLING

The DEC systems increase the humidity and the IEC systems have low WB effectiveness, a combination of these systems can supply much colder air with less moisture.

The major components would be water and air distribution system with the heat exchanger and the cooling pad [27]. So, the outdoor air gets cooled down by IEC and it flows through DEC which further cools down the air below the WB temperature but with a slight increase in humidity. However the system is getting a bit bigger and complex, but it has a WB effectiveness of 109% - 116% with the increased consumption of water by 55% [34].

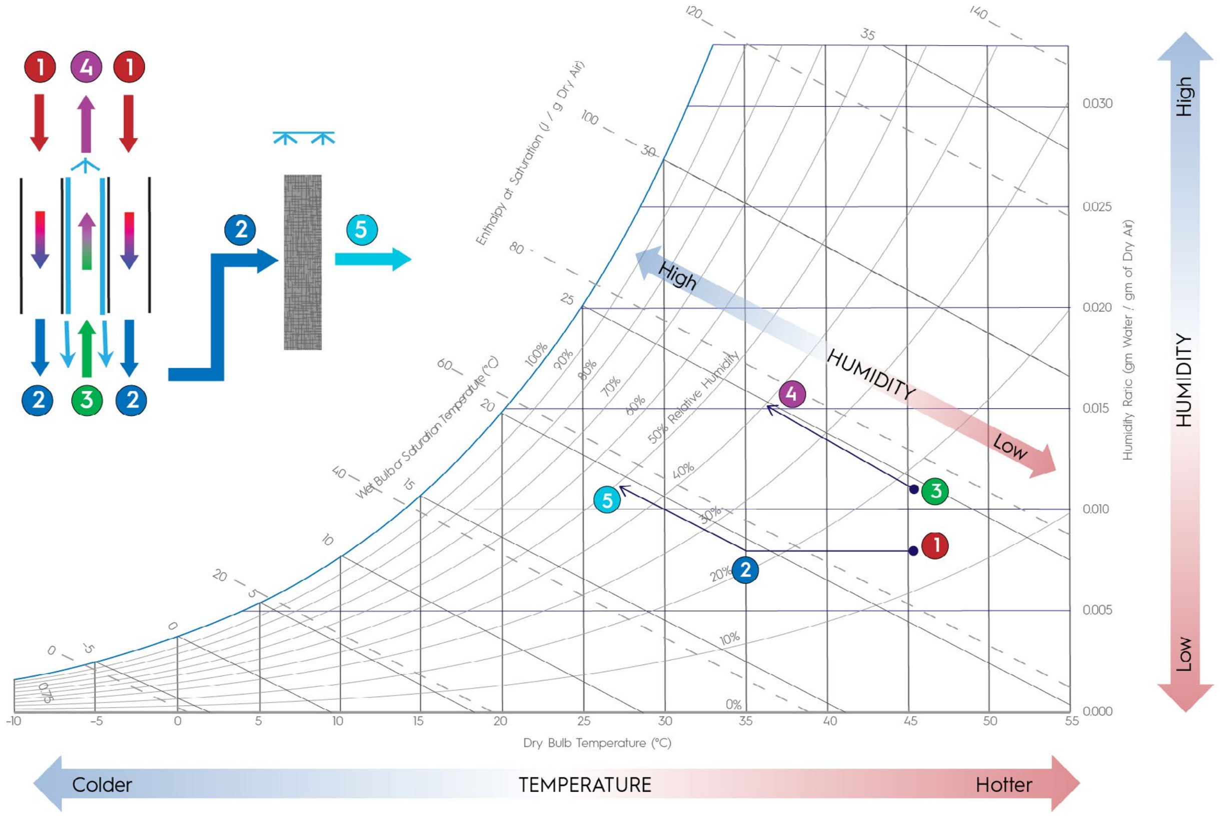


Figure 4.7: Combined IEC/DEC - Process on Psychometric Chart

4.2.3.1 Evaporative coolers performance in Delhi:

A research conducting simulations for finding the performance of DEC, IEC and IEC/DEC system in Delhi was studied. The results show that during the months of Summer (May-Hot&Dry) apart from IEC due to its low WB effectiveness both the performance of DEC and IDEC is within the thermal comfort zone.

But, during the months of Monsoon (June - Hot & Humid) the performance of the DEC system is not satisfactory due to the high humidity level in the air, but the combination of IEC/DEC has the potential to create thermal comfort due to its high WB effectiveness.[35]

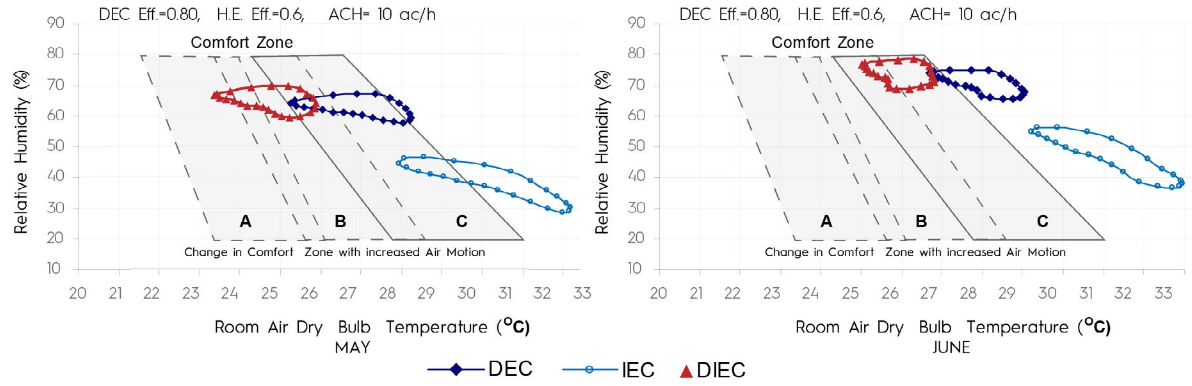


Fig.4.8- Hourly Variation of Room Condition for Different Evaporative Cooling Scheme [35]

4.3 SUMMARY

From the contextual study of evaporative cooling it is evident that the system has enough potential to address the cooling demand.

Sl.No	System	WB Effectiveness %	Cost	Climate - Delhi
1	Direct Evaporative Cooling (DEC)	75 - 90 %	Low	The system performs better in Hot and dry seasons but increased humidity results in lower performance during monsoon. Moreover adding humidity a over long period results in undesired results.
2	Indirect Evaporative Cooling (IEC)	40 - 60 %	Mid	The system performs without causing discomfort on both the seasons, but the effectiveness is very low resulting in higher water and power consumption.
3	Dewpoint IEC (D-IEC)	92 - 114 %	Mid	The advanced IEC cooler has complicated air flow, but it cools down the space without adding humidity. This system has a WB of 102 % even in hot and humid climate.
4	DEC/IEC Cooling	109 - 116 %	High	It has the flexibility that the Delhi requires. and has better potential in both the dry and humid seasons.

Table 4.1 : Cooling system vs Effectiveness vs Context of Delhi

4.3.1 TEMPERATURE

The WB effectiveness of IDEC and IEC/DEC is similar so, taking the WB effectiveness as 122%, the temperature that can be achieved by these systems in Delhi is presented in the fig.4.9.(Refer Calculations in Table 6.1) The effectiveness increases if the difference between DB and WB are high. From the results it is evident that supply temperature is as low as 14°C in the winters and 26°C during the monsoon.

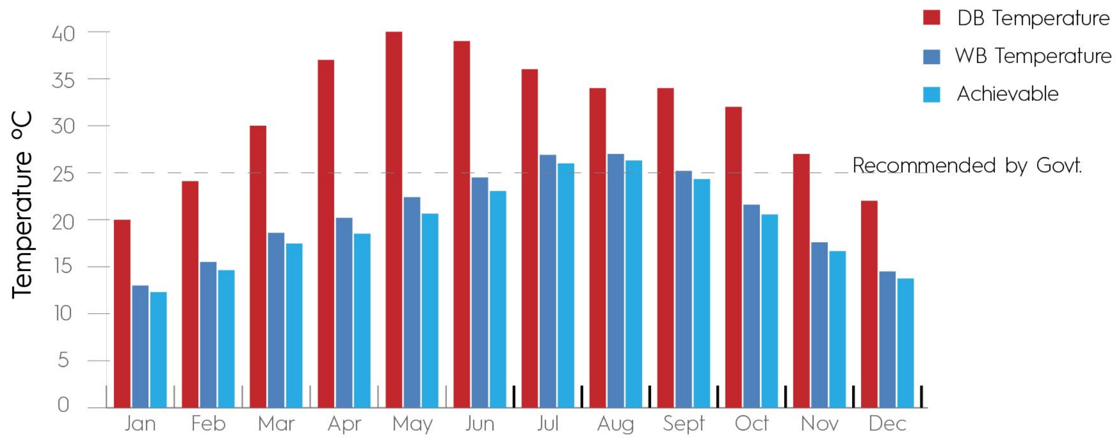


Fig 4.9 :Monthly DB / WB / Achievable Temperature at WB effectiveness of 122%

4.3.2 HUMIDITY

The variation of temperature is negatively correlated to the relative humidity. If the dry bulb temperature is 40°C with rH 33% in the month of May of Delhi and if it is cooled down to 25°C without adding moisture (D - IEC) the rH shoots up to 84%, which is relatively the borderline comfort for rH. But, if space is cooled down by (IDEC) with the addition of humidity the value goes beyond 84% causing discomfort in the space.

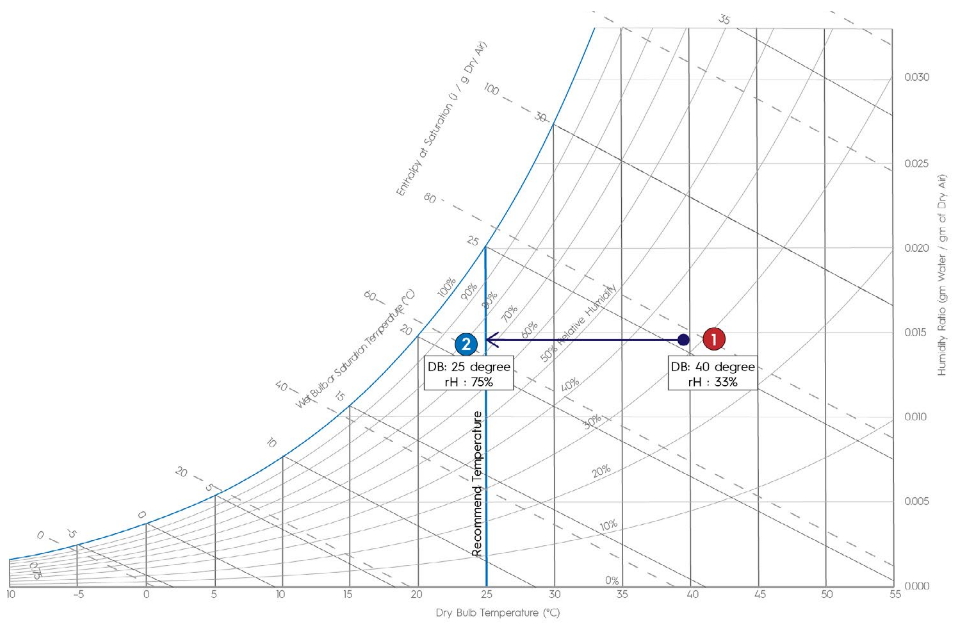


Fig 4.10 : May in Delhi (Increase in rH from 33% to 75%)

4.3.3 OTHERS

The IEC/DEC system consumes nearly 55% of water compared to a typical IEC or DEC system. The system itself is more complex with a lot of components required for both IEC and DEC, like cooling pad and heat exchanger, two water re-distribution systems this increases the complexity of integration within the facade system itself.

So, from the above discussion, Dew-point indirect evaporative cooler is chosen for its high wet-bulb effectiveness, cooling down space with no additional humidity and relatively a less complex and small system when compared to the combined evaporative cooler.

5

DECENTRALIZED?

Chapter Overview

The previous chapter discusses what kind of low-ex cooling will be designed. Well in this chapter describes how it will be integrated. It compares the decentralized and centralized ventilation strategies through literature and case studies. The advantages and limitations of the Decentralized systems are summarized clearly which helps to identify the scenario when the decentralized ventilation is feasible over-centralized. The study also shows various DVS (Decentralized Ventilation Products) and their integration over the facade.

5.1 DE-CENTRALIZED SYSTEM:

Buildings are designed to be well insulated and airtight, many strategies are incorporated to reduce energy demand associated with ventilation. Strategies like mixed ventilation which includes natural ventilation along with mechanical ventilation have been practised as a sustainable solution. But, the modern commercial buildings are becoming more complex as designing a flexible floor plan becomes of higher priority. This pre-conditioned requirement for flexibility is high in offices, as multiple organisations operating at various hours on various floors has different requirements. Hence, a similar level of flexibility is expected out of the ventilation control systems by the users. So, increasing this user flexibility on the ventilation devices would solve the user needs and also reduce the cost by decreasing the energy consumption.[9]

Decentralized ventilation systems (DVS) are the next state of the art technology when it comes to ventilation with a high level of flexibility for varied favourable performances. The advantages like individual control, high energy efficient systems and reduced spatial need, are one of the demanding factors for commercial structures. In recent years more investigation has been done to bring the technology into the realm of integrated energy solutions than ever before.[10]

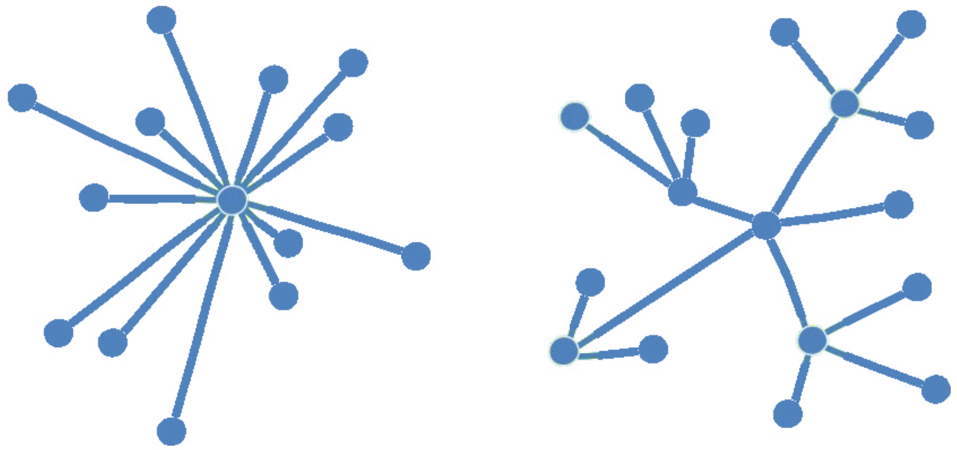


Figure 5.1: Centralised vs Decentralized

5.2 CENTRALIZED VS DecentralizED SYSTEM:

Both centralised and Decentralized systems have their own pros and cons which is elaborated under this topic. The most obvious difference is the air intake and exhaust. A conventional centralized system has a central chiller from which ducts run through the entire building. This chiller takes the unconditioned fresh air, treats them and supplies them to the building through the ducts; at the same time extracting the heat from the spaces. Whereas in the decentralized system, the fresh air is taken through the facade and in certain cases the air is treated by the facade and supplies them into the room. In terms of exhaust, the air either is ejected by the same component locally or it has a central system which helps in removing the exhaust air.

The comparisons of these systems on several aspects including capital cost, installation process, energy usage, maintenance etc. were further illustrated in the following text based on the literature study done with simulations and real-time analysis.

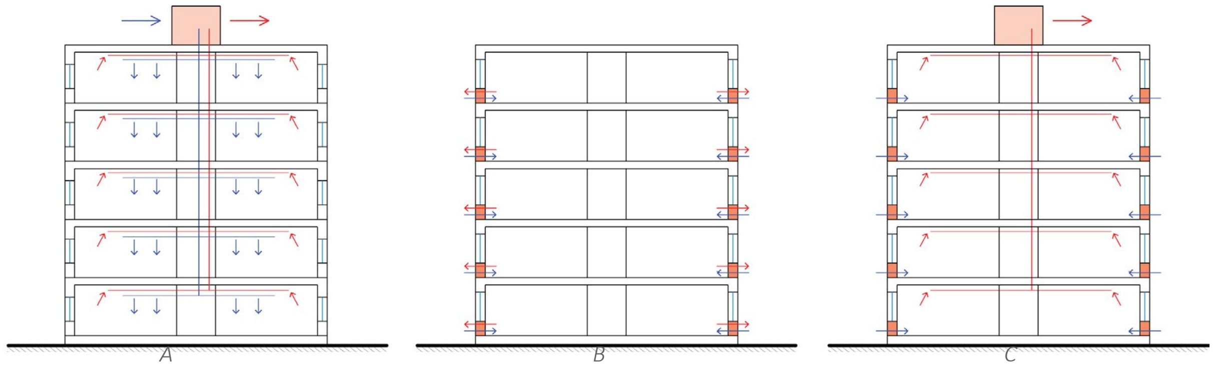


Figure 5.2: A - Conventional Centralized System, B and C - Decentralized system where the exhaust is local(B) or Central(C)

5.2.1 TROX:

To explore the pros and cons of the system, TROX conducted a study through simulations of the same building under two scenarios; with a centralized and decentralized system. The office tower consisted of 30 floors, with the same percentage of glazing on each facade. This square building was assumed to have an open floor plan and the required temperature is the same all over. [9]

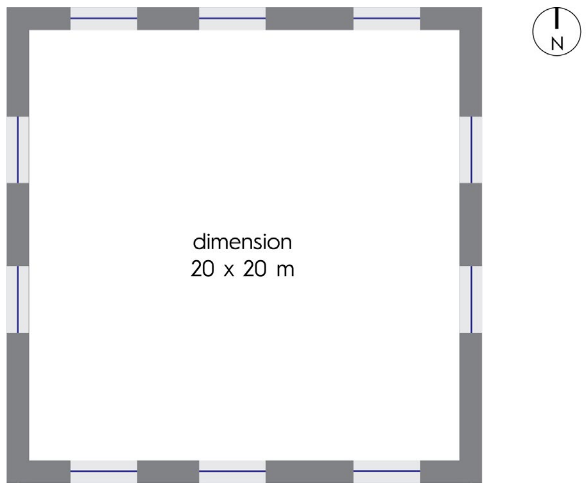


Figure 5.3: Building sketch and Layout - TROX Simulation

5.2.1.1 ENERGY: CENTRALIZED vs DecentralizED

The office complexes in present day situation are commonly rented out in pieces to various organisations whose working hours vary based on the services they provide. The centralised plant doesn't allow the flexibility to shut down the control of multiple places at different timings; which puts the need to function throughout, even on spaces that are not occupied. In a decentralized system, the ability to control flexibly has a huge advantage. When this system is in use, by partial shut down or reducing the supply to an unoccupied space considerable energy savings can be achieved. [9]

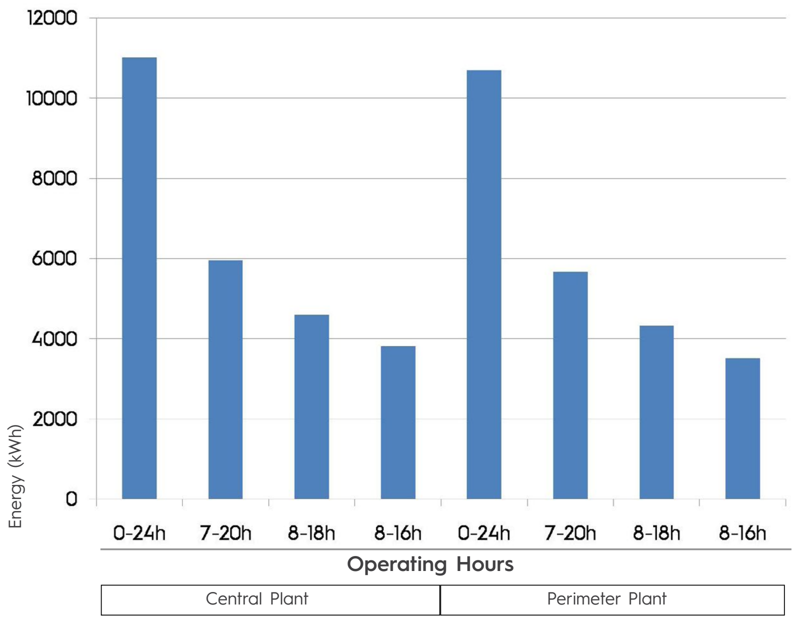


Figure 5.4: Energy to condition the external air for operation

5.2.1.2 HEIGHT: CENTRALIZED vs DecentralizED

The decentralized System has a huge advantage in reducing the height of the structure and ease the execution process with less constructional complexity. They avoid the cost of fire protection dampers, air distribution ducts that need to be installed throughout the system in the other case. The system also saves a lot on the floor to floor height by saving the space in the false ceiling voids. It also avoids mechanical floors or roofs. The savings for construction is nearly up to 20% as the building's cost increase as we go vertical. If a false ceiling of 600 mm can be avoided and the height of the floor is reduced, on every 5th floor, one new floor can be added. [9]

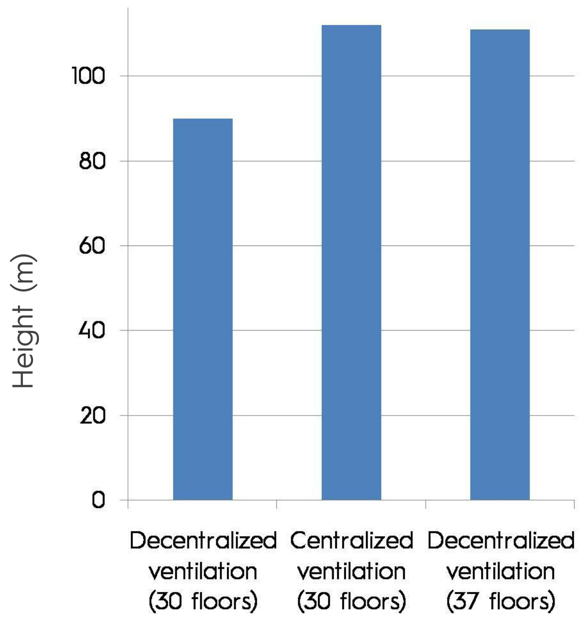


Figure 5.5: Height of the building - Decentralized system compared to Centralized system

5.2.1.3 Maintenance: CENTRALIZED vs DecentralizED

	Centralised air conditioning 1 central unit 9600m³/h	**Decentralized air conditioning** 96 perimeter ventilation devices each 100m³/h
Cleaning	1 unit at 120 min/unit twice a year 4 h at 35 EUR/hr **140 EUR**	Twice a year complete 96 devices at 10 min/device Twice a year sampling 12 devices at 10 min/device Total 36 h at 35 EUR/hr **1,260 EUR**
Change of filter	1 device at 520 EUR 4 times a year* 1 device at 30 min (efficiency) 4 x 0.5 h at 35 EUR/hr **2,150 EUR**	96 devices at 7 EUR/device (material) 4 times a year 96 devices at 2 min/device (efficiency) 4 x 3.2 h at 35 EUR/hr **3,136 EUR**
Inspection of fire dampers	18 pieces at 6 min/unit 1.8 h at 35 EUR/hr annually **63 EUR**	0 pieces at 6 min annually **0 EUR**
Cleaning air ducts and air diffusers	Cleaning of the supply system through an air duct cleaning service. Cleaning of 350 m2 duct at 10 EUR/m2, 48 air diffusers (5 min each) and 24 return air devices (10 min each) 8 h at 40 EUR/hr every two years 1,910 EUR/year	Is included in the device cleaning costs
Annual Maintenance	**4,263 EUR**	**4,396 EUR**

Table 5.1: Comparison of the annual maintenance costs for centralised and Decentralized air conditioning

5.2.2 DeAL:

Decentralized ventilation systems (DVS) have been installed over 50 buildings since 2000 - 2007, in western Europe. A research project over two years over a 10 buildings which have installed DVS is inspected under the full operation in respect of comfort, satisfaction and energy efficiency.[11] This research was conducted by Steinbeis along with Project partners like TransSolar Energy Technology GmbH and the Institute for building Stuttgart, Germany and solar technology (IGS) of the Technical University of Braunschweig. It was funded by Federal Ministry of Economics and Technology of germany.

					
Location	Zurich	Zurich	Berlin	Neckarsulm	Stuttgart
Area(m²)	7741	6317	9027	6114	3454
Occupied since	2004	2002	2003	2007	2002
No. of DVS	313	200	166	200	272
Function	- Supply air (passive) - Heating - Cooling	- Supply/ Recirculation/ Return Air (active) - heating - cooling -Humidification	Supply/ Recirculation Return Air (active) heating cooling Humidification	- Supply Air (active) - Heating - Cooling - Humidificati on	- Supply Air (active) - Heating - Cooling - Humidificati on
Integration	Floor	Parapet	Parapet	Floor	Parapet
					
Location	Düsseldorf	München	Hamburg	Freiburg	Leverkusen
Area(m²)	43000	20900	10142	2110	23100
Occupied since	2005	2007	2002	2006	2002
No. of DVS	815	800	0	65	800
Function	- Supply Air / Return Air (active) - Heating - Cooling	- Supply Air / Return Air (active) - Heating - Cooling	- Supply Air (passive) - Heating - Cooling	- Supply Air (active) - Heating - Cooling - Recirculation Air	- Supply Air (passive) - Heating - Cooling
Integration	Facade	Parapet	Floor	Floor	Floor

Table 5.2: Characteristics of the 10 buildings investigated in detail

5.2.2.1 RESULTS

USER SATISFACTION

The survey was conducted to assess the range of user satisfaction with respect to the expected outcome for the installed equipment. The average overall performance of all the devices was recorded to be on a higher note than expected except for the two systems out of sixteen which primarily had issues with noise generation and the temperature modulation (too hot or too cold).[11]

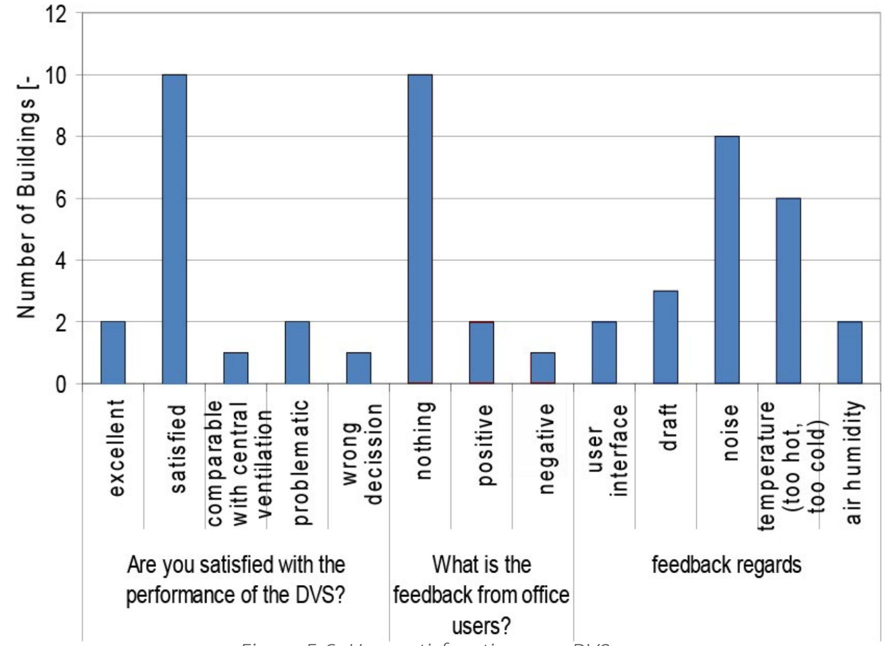


Figure 5.6: User satisfaction over DVS

HEATING DEMAND

The heating demand comparison of decentralized systems to a centralized system was deduced based on various research projects under the influence of relatable floor area.[11] From the analysis of results, the DVS seemingly has heating demand from 25 to 75 kWh/m2 whereas the existing studies have a range from 167 to 245 kWh/m2 with average heating of 97 to 140 kWh/m2. EVA study shows comparable results in terms of building typology, age and methodology. This stands as an indication that the DVS has low heat consumption in comparison to an average office building.

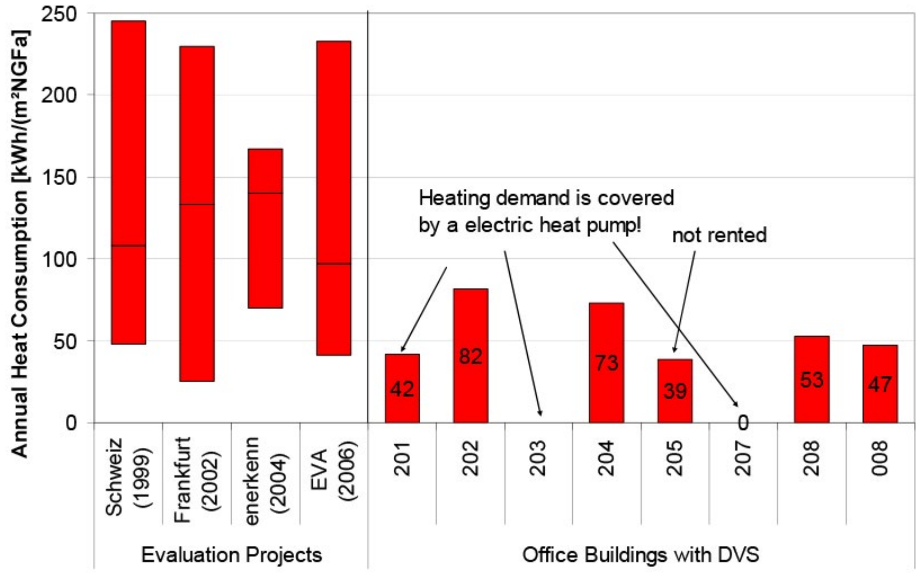


Figure 5.7: Heating demand of DVS

ELECTRICITY DEMAND

The analysis also reveals the electricity consumed to the net floor area. The average energy consumption of the other researches ranges from 83 to 160 kWh/m2. The more relatable building EVA has a value of 90 kWh/m2. The following results show that the DVS has its trend towards lower consumption. Four of the analyzed structures had their value below the referred value. The reason for the highest power consumption in 204 is because of the usage of high power demanding computer centre owned by an insurance company.[11]

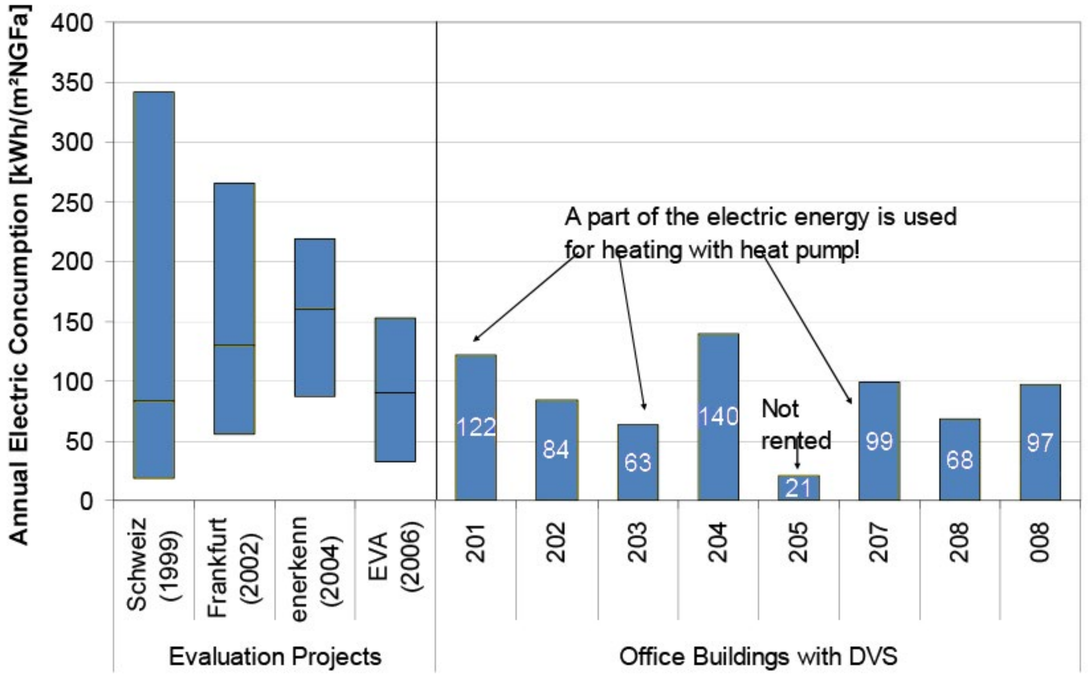


Figure 5.8: Electricity consumption of DVS

SPACE EFFICIENCY

Space efficiency is defined as the ratio of floor area occupied by the mechanical equipment to the area of the usable space. The space efficiency of medium centralized equipment takes up to 10.3% to 11.5%[11],[12]. The results clearly show that four of the buildings has a range of 2.3% - 6.5%, which is nearly 5 - 8% of the usable area. Except for two buildings which also has a centrally ventilated system with huge garages for underground parking.[11]

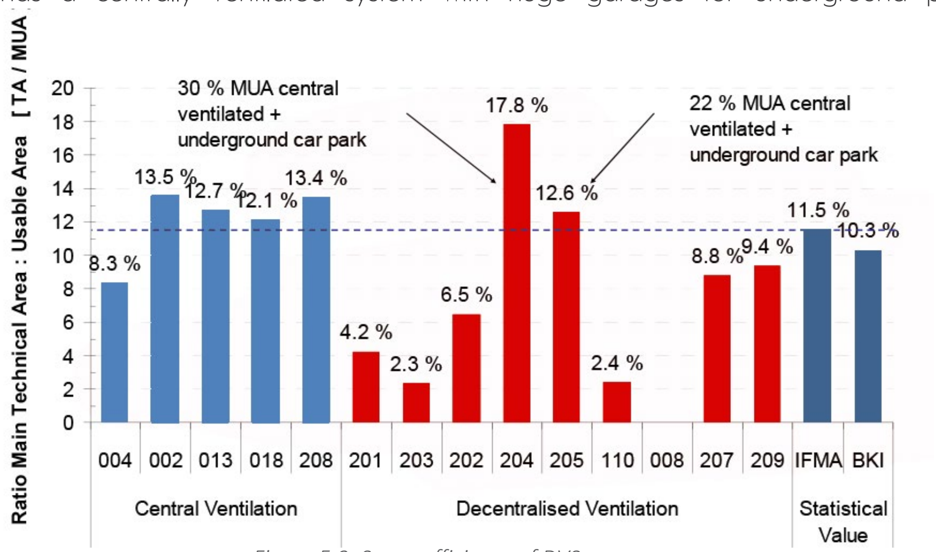


Figure 5.9: Space efficiency of DVS

POTENTIAL REDUCTION OF HEIGHT

Like in the previous study by TROX, the reduction in height due to the elimination of ducts is also studied here. This major advantage was not adapted to most of the buildings as the decision to add this system was not conceived during the preliminary design. Except for in few buildings with an effective reduction of 30cm which leads to a 10% increase in saving.[11]

ROOM TEMPERATURE LONGER RUN

The temperature is measured by recording data at 4 workplaces over the period of a year at 110 cm. The data proved that the temperature hardly exceeds 26°C throughout the year except for a very few hours during summer. But, the holistic performance throughout the year is satisfactory. [11]

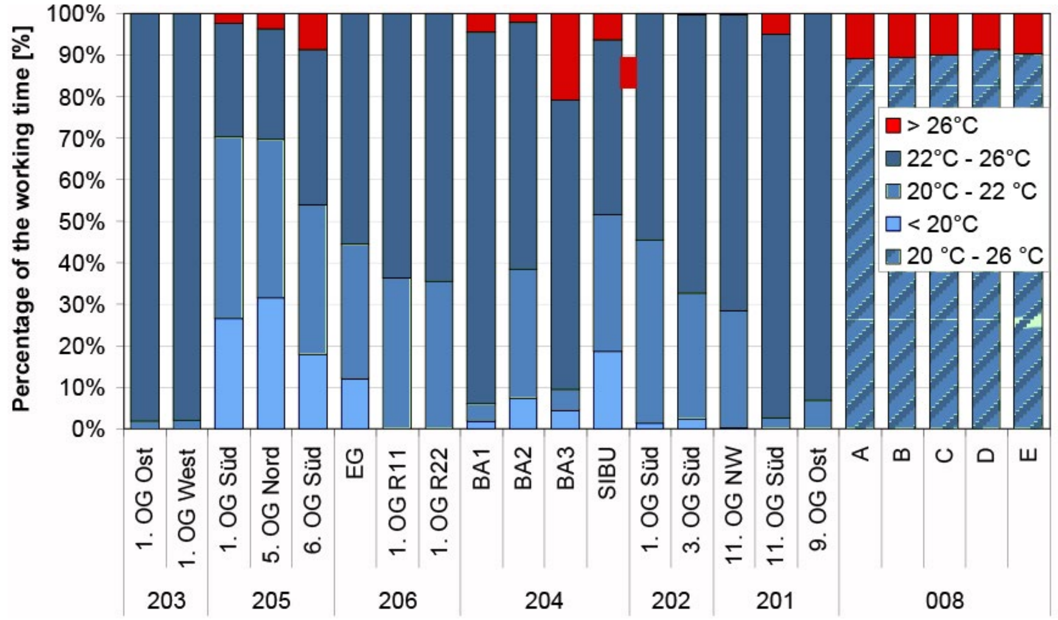


Figure 5.10: Temperature distribution throughout a year

NOISE LEVEL

The system conditions the fresh air at the floor level with all its components in a compact box. This creates the potential chance for an increase in noise level, but surprisingly they have comparatively lower noise emission than a conventional device. Most of the values fall under 30 dB, which falls under the limit of 40dB (a typical split ac system has 30 - 40 dB). But, if the device is used for much more flow volume than designed, it results in more noise above the advised limits. [11]

MAINTENANCE

The biggest argument against a decentralized system is in terms of maintenance. The exact validation of the maintenance cost is not possible to record as no such record for maintenance. The Facility Management of the respective structure takes care of respective systems. But this important factor has been evaluated qualitatively recorded and evaluated. The system does not require much of technical knowledge. The change of filters can be made so accessible even without tools or using magnetic or velcro fasteners. The maximum complexity that it will lead to is to use a normal tool (screwdriver). It takes 5 minutes to clean a DVS in of the projects, but with 815 systems, it requires at least 8 whole days to clean and change the filter in them. This system supplies a total volume of 48,900 m³/h, well for the central system to handle this capacity, it will require 3 to 4 days. So, the effort to maintain a DVS technology is 2 to 3 times higher than a conventional centralized system. [11]

5.2.3 COMPARISON:

	Centralised System	Decentralized System
Equipment	Large area for central plant	Space efficiency
Pressure loss in distribution	High	Not Applicable
Efficiency of Fans	High	Low
Area for air distribution	High	Not Applicable
Fire protection	High	Small
Condensate removal	Less work	More Work
Interference to Facade	Little	High
Air quality	High	Varies
Air conditioning comfort	Full air conditioning is possible	Reasonable thermal comfort is achievable
Pollutant transmission	Negligible	Low
Building Mass for heat/cold storage	Not possible due to false ceiling	Possible due to concrete core activation
Time to install	High	Low
Effectiveness Ventilation	High	Low due to short-circuiting between facades
Shutdown	All the space are affected	Respective area possible
Refit	Expensive and more effort	Easily achievable with pre-planning
Acoustic Influence	Very low	Falls under 40dB(below standards)
Acceptance	Moderate	High due to local control
Consumption allocation	On overall basis. Approx.	Specific to the user is possible
Procurement	Multiple vendor	Less vendor mostly one
Load sharing	High possibility centrally connected	Not possible
Mechanical room	4% to 6% of built space with 4.3 m high ceiling	No required
Knowledge	Highly trained specialized people	Less technical and easy to work with
Heat recovery	Cheap	Expensive
Energy cost	Moderate	Moderate
Structural cost	Higher space requirement for air conditioning, False ceiling to hide the system	Large effect on the facade design Less assembly
Maintenance costs	Moderate	Moderate - A bit more than centralized due to multiple elements
Fire protection expenditure	High	Low

Table 5.3: Centralized vs Decentralized

5.2.4 SUMMARY

Decentralized air conditioning system seems to address the new requirements and the complexity of a modern office.

- The system **can't** achieve the temperature as low as an existing conventional system but it can satisfy the basic thermal comfort that an office demands.
- The performance of the system in terms of electricity consumption, heating, cooling is incomparable to the central systems in a longer run, sometimes even **lower** due to individualized control.
- It is **hard to maintain** the system, as it is going to take more than 1.5 times to 2 times that of the existing ones, but the difference in cost for maintenance between them is not really that high.
- The **space efficiency** is going to be **high**; in terms of both vertical height and floor area; height(10 % gain) more due to the absence of false-ceiling and in floor area it consumes less than 5% in comparison to the 11.5% by a central system.
- The system is not going to be loud, as most of them **falls under 40dB** noise level. The noise of a modern split ac system is 30 - 40 dB as same as DVS.
- **Heat recovery** is very restricted to the application and **not** economically feasible.

5.3 FACADE INTEGRATED VENTILATION (FIV):

The supply air to the room is provided by the device through the openings in the facade with the exhaust by a central system or by itself.

Post tower in Bonn is one of the prominent examples for FIV. [10]. These systems are compact and can be efficiently integrated, with the upcoming advancements they can perform all the tasks that have been done by a central system. The flexibility in the air circulation, heating, cooling and even humidification is possible.[10]

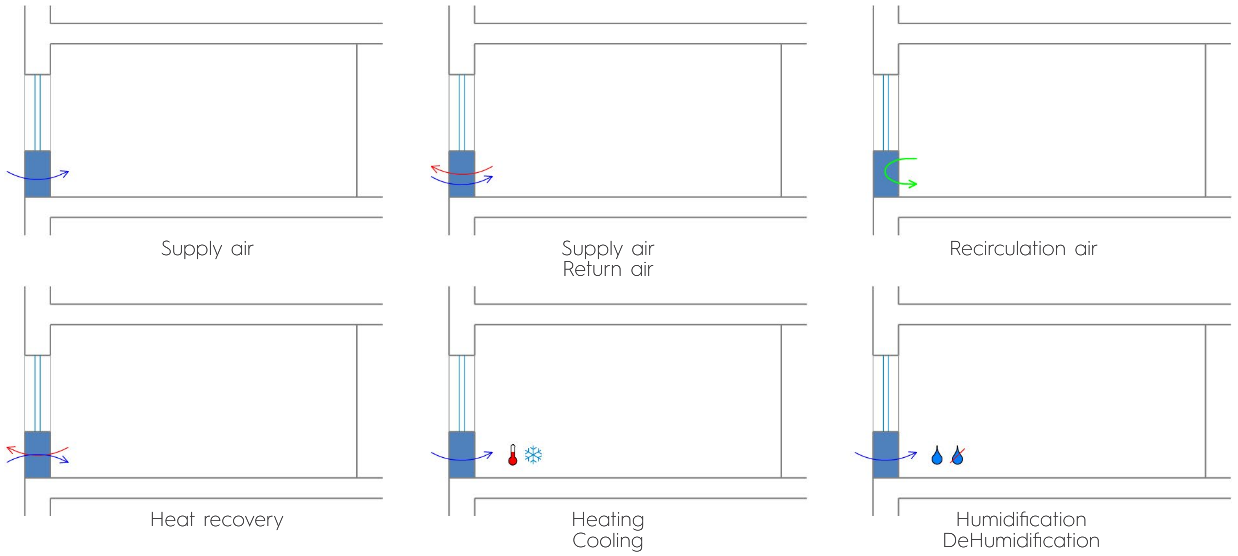


Figure 5.11: Various functions of a FIV system

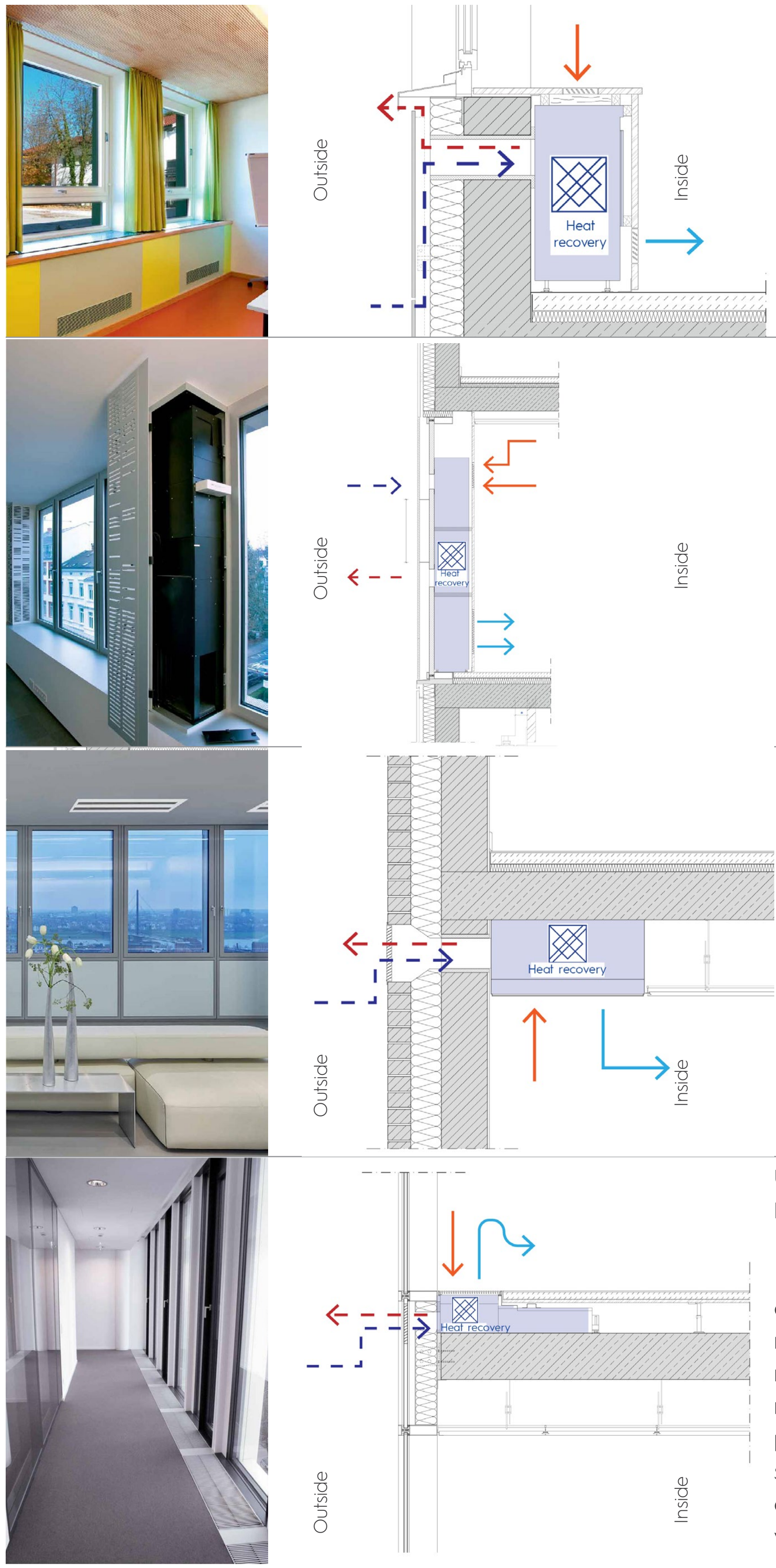
5.3.1 WORKING:

A typical Facade integrated Ventilation device consist of an air supply unit which controls pressure and airflow, with a filter to remove the fine particulate matters in the air. A controller fixed to this system controls the flow rate and dampers operate on the basis of the external condition. The existing system either has a 2 pipe or 4 pipe system with copper piping as a heat exchanger unit, through which the cold or warm water is supplied based on the needs and they condition the air through convection.[14] In order to reduce the power consumption cross heat plate exchangers are used. The efficiency of these systems is limited to 50% to 60%. Apart from these major functional components, condensate trough, sound, thermal insulation, Cover grating etc. are also integrated.[10]

The FIV Systems can be integrated into 4 possible configerations. They are easy to install in a new or to a retrofit project.

The current existing systems can be categorised into four possible positions:
i) Under the sill
ii) Ceiling Installation
iii) Vertical Installation
iv) Underfloor Installation

5.3.2 VARIOUS INTEGRATION



SILL LEVEL

They are integrated like heaters under the window sill and are panelized. They supply hot and cold air by pumping hot or cold water, and the air is distributed by displacement flow.[14]

VERTICAL INSTALLATION

They can be integrated behind a solid part or even glazing.[14] They are full height systems that are placed over the floor or a raised sill. .

CEILING INSTALLATION

They can be integrated below the slab near the external wall. Ideal for air daycare, classrooms or meeting rooms in office buildings which requires more air changes.[14]

UNDERFLOOR INSTALLATION

Many office buildings, data centre have started using raised floors for cable management. The spaces near the glazing can be potentially used by these systems; fixed underneath only the grilles will be visible on the top. [14]

Figure 5.12: Types of Integration into facades

	UNIT	TROX						EMCO [15]
NAME		FSL-B-ZAB/ SEK	SCHOOL AIR-B-HE	FSL-V-ZAB Type I	SCHOOL AIR-V-HV	FSL-U-ZAS	SCHOOL AIR-D-4L	EMCOVENT UZS
UNIT LOCATION		SILL	SILL	VERTICAL	VERTICAL	UNDER FLOOR	CEILING	UNDER FLOOR
WIDTH	mm	1085	2090	699	600	1100	5720	1150
HEIGHT	mm	630	750	1700	2000	190	400	200
DEPTH	mm	320	420	313	408	860	800	682
VOLUME	m^3	2035	3260	2712	3008	2150		
VOLUME FLOW RATE	m^3/h	60-150	150-400	60-180	150-360	60-120	150-300	170--340
TOTAL HEATING CAPACITY	kW	2.4	3.4	2.74	3.1	1.1	1530	
TOTAL COOLING CAPACITY	kW	0.7	1.75	0.77	1.68	0.377	1350	0.84
HEAT RECOVERY	%	23	82	60	84	55	55	
POWER CONSUMPTION	kW	0.023	0.075	0.025	0.042	0.037	52	
SOUND PRESSURE LEVEL	dB	22-30	25-41	19-36	28-42	20-35	26-38	22-36

Table 5.4: Existing FIV products

6

COOLER DESIGN

Chapter Overview

The chapter is divided into two segments both discussing the system's relationship to the cooling capacity of the building. The first half of the chapter discusses various passive strategies that have been incorporated into the simulation to bring down the cooling load. The second chapter discusses the minimum supply temperature that can be achieved by the evaporative cooler with and without dehumidification. This establishes the significance of integrating a desiccant-coated heat exchanger with the evaporative cooler. The layout of the system with the Psychometric properties of the air at each stage is explained followed by that.

6.1 FACTORS INFLUENCING DESIGN

The cooling demand of the building needs to be addressed by multiple devices in a decentralized ventilation system. The total number of devices required to determine the cost of installation and ease of maintenance over the years. So, it is necessary to reduce the cooling demand of the building and other possible factors to reduce the size of the system, making this a feasible solution.

The Volume flow rate needs to be calculated in order to determine the number of systems required and it's sizing. The equation of the cooling capacity helps in establishing the relationship between the mass flow rate (from which the volume flow rate can be determined) and the difference in temperature. [36]

$$\dot{Q} = \dot{m} * C_p * \Delta T$$

$$\dot{m} = \dot{Q} / (C_p * (T_{set} - T_{sup}))$$

$$\dot{V} = \dot{Q} / (\rho * C_p * (T_{set} - T_{sup}))$$

$\dot{Q}$	87.65	kW	Design cooling capacity of one floor (From Design Builder)
ρ	1.1652	kg/m3	Density of Moist air at 25°C, 48.3% rH https://www.omnicalculator.com/physics/air-density
C_p	1.02	kJ/kg K	Specific Heat Capacity of Air
T_{set}	25 °C	°C	Indoor Temperature (Desired temperature inside the space)
T_{sup}	16 °C	°C	Supply Temperature (During the month of august)

$$\dot{Q} = \dot{m} * C_p * \Delta T$$

$$87.65 = \dot{m} * 1.02 * (25 - 16)$$

$$\dot{m} = 9.55 \text{ kg/s} \quad \text{-- (6.1)}$$

$$\dot{V} = 8.19 m^3/s$$

From the equation, it is prominent that the Cooling Capacity and the temperature difference are the most influential parameter for the decentralized system. The required cooling capacity needs to be reduced by integrating various passive strategies on the built structure. The temperature difference between desired set-point temperature and the supply temperature has to be high; which can be achieved by increasing the effectiveness of the evaporative cooler.

6.2 PASSIVE STRATEGIES TO REDUCE COOLING CAPACITY (Q) :

Multiple climate responsive strategies need to be integrated at various levels for passive design. A base case building is chosen from the presented case studies for simulation. Skyview corporate park is the phase I of a multiphase project that has been proposed to be developed on a 21 – acre site that faces National highway. The building achieved LEED platinum under IGBC (Indian Green Building Council). [35]

Skyview, Gurgaon is one of the typical modern structures with higher glazing ratio with less or no shading strategies built in the composite climate zone near Delhi. The rectangular G+8 structure has an open floor plan with the core at the centre.

Figure 6.1: Skyview Corporate Park, Gurgaon

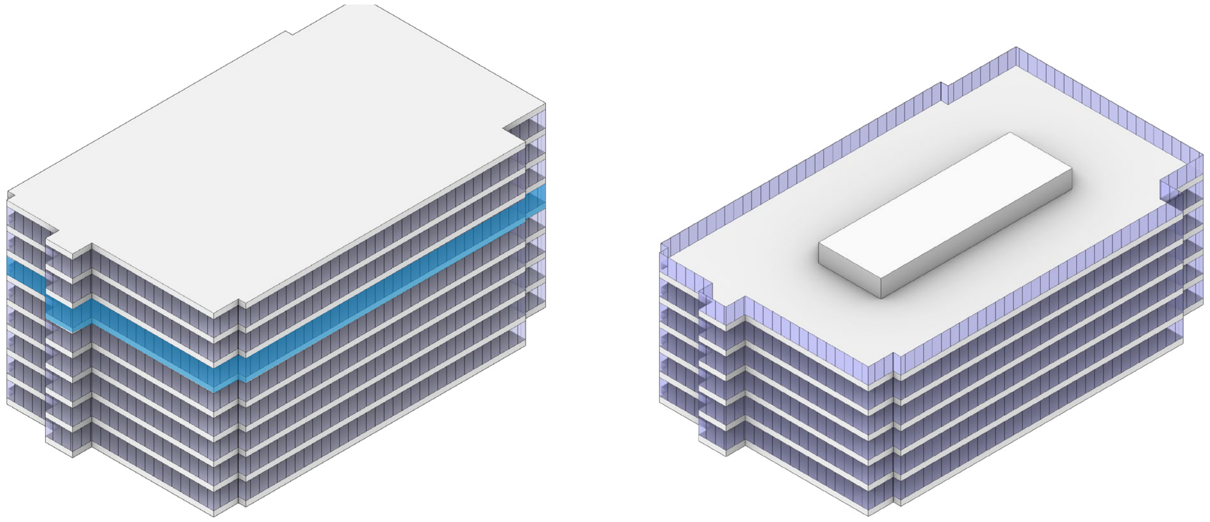


Figure 6.2: The chosen floor plate for simulation

Figure 6.3: Typical open office floor plan of Skyview park

6.2.1 SIMULATION PARAMETERS:

The building is modelled in Design-Builder 5.5 for the simulation of cooling design for New Delhi. The results of each simulation include Energy Performance Index (EPI), Cooling capacity and cooling load per m2. The cooling load per m2 is the cooling capacity divided by the gross floor area. The cooling capacity gives the total design capacity of cooling required which varies with form, WWR, U-Values, Lighting and Infiltration etc.

The goal of the simulation is to incorporate passive strategies until the value of the cooling load per m2 is below 50W/m2 (Appendix 11.1). The cooling load of the base case is too high (109.6 W/m2) due to the use of conventional construction material, with no shading strategies and no lighting control. The passive strategies were applied in four stages including internal heat gain, ventilation, U values and Shading which are discussed below:

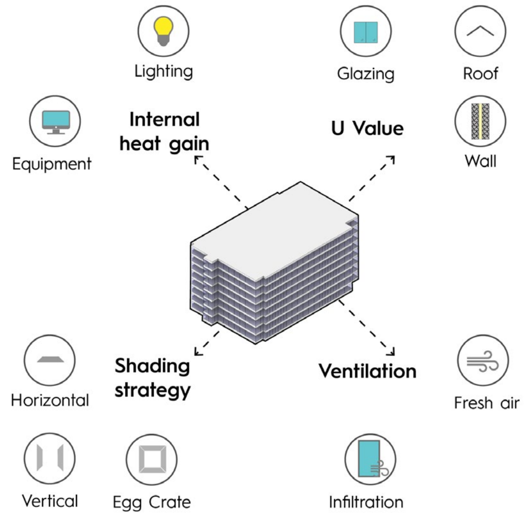


Figure 6.4: Passive strategies incorporated in simulation

6.2.1.1 INTERNAL HEAT GAINS:

LIGHTING:

LPD – Lighting power density is a load of any lighting equipment in watts per square foot of the lighting equipment per 100 lux. The base case is incorporated with 5 W/m2/100 lux, but the LEDs are significantly energy efficient and has lighting load of 2 W/m2/100 lux [35], with linear control which increases and decreases the lighting demand based on the duration of the day and environmental conditions.

EQUIPMENT:

The heat from the devices and computers also has an impact on the cooling load(11.77W/m2). But the advancement in technology creates much efficient and smarter devices with very less heat radiating out. (9 W/m2)

6.2.1.2 VENTILATION:

INFILTRATION:

The cooling load of the building is significantly affected by air leakage through the building's envelope. This is called infiltration and it happens in openings and cracks in doors and windows. In addition to the cooling load, they also affect indoor air quality. The base case has an infiltration value of 0.7 ac/h which can be reduced to 0.3 ac/h by integrating proper details for an airtight façade system.

FRESH AIR PER PERSON:

The amount of fresh air required to be cooled needs to be minimized to reduce the cooling load of the system. The standard ASHRAE norms suggest 10l/s per person as default value if the number of occupants and area is not known or it needs to be calculated if area and number are known. Well, the fresh air required can be calculated using the following equation 6-1 from ASHRAE standard 62.1 :

$$V_{bz} = (R_p * P_z) + (R_a * A_z)$$

V_{bz}		CFM	breathing zone outdoor airflow (CFM)
R_p	5	cfm/ person	outdoor airflow rate required per person (NBC,India -2016)[37]
P_z	200	Nos.	zone population: the number of people in the ventilation zone during typical usage.
R_a	0.06	cfm / ft²	outdoor airflow rate required per unit area (NBC,India -2016) [37]
A_z	19288.91	ft²	zone floor area: the net occupiable floor area of the ventilation zone

$$V_{bz} = (5*200)+(0.06*19288.91)$$

$$V_{bz} = 2157.33 \text{ CFM}$$

$$V_{bz} = 2157.33 / 200$$

$$V_{bz} = 10.78 \text{ CFM / person or } 5.09 \text{ l/s/person} \quad \text{-- } (6.2)$$

By calculating the exact amount of fresh air required, the standard value 10 l/s/ person gets reduced to 5.09 l/s/person. This means the minimum fresh air requirement in a breathing zone is reduced by half leaving a huge impact on the cooling load. Even though the mixed mode ventilation strategy has energy saving potential, natural ventilation is turned off during the entire simulation due to the pollution.

By implying the above internal heat gain and ventilation strategies the cooling load is reduced by 25% (109.6 W/m2 to 83.4 W/m2.)

6.2.1.3 U-VALUE:

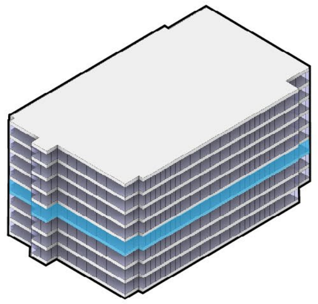
The U-value of the materials for construction has the largest share on cooling load. By integrating properly insulated building components and meeting the guidelines of the energy conservation building code this energy can be saved.

The base case is made of a brick cavity wall with a clear double glazed window and 300 mm roof slab with U value of 1.56, 2.7 and 2 W/m2K. According to the guidelines the solid envelope needs to be 0.3 W/m2K for walls and 0.2 W/m2K for roof along with high-performance glazing The proposed solid parts are treated with insulation and the glazing with low emissivity coating and lower SHGC. [20]

These strategies help in further reduction of the cooling load by 32% (83.4 to 57.2 W/m2).

6.2.1.4 SHADING:

Horizontal overhang, vertical fins, and egg crate are the shading strategies that were implemented to the existing model to see which configuration creates a better impact on cooling load. The combination of horizontal and vertical shades around the window has more impact on the cooling demand reducing up to 13 % (50W/m2) of the existing load compared to horizontal 9% (51.3W/m2) and vertical shades 5% (54.4W/m2).



WWR	Location	Floor Area	Orientation
60%	New Delhi	1792m2	Longer axis N-S

Category	Strategy	Base		Improved
Ventilation / Internal heat gains	Lighting	**5** W/m2/ 100 lux	>	**2** W/m2/ 100 lux LED linear control
	Equipment	**11.77** W/m2	>	**9** W/m2
	Fresh air	**10** l/s - person	>	**5.2** W/m2
	Infiltration	**0.7** ac/h	>	**0.3** W/m2
U-Value	Wall	**1.56 W/m²K** Cavity brick wall with dense plaster	>	**0.3 W/m²K** 100mm Insulated Cavity brick with dense plaster
	Glazing	**2.7 W/m²K** 6/13/6 Double glazing with air	>	**1.7 W/m²K** 6/13/6 LoE Double glazing with air
	Roof	**2 W/m²K** 300mm Slab	>	**0.2 W/m²K** 150mm Insulated Roof
Shading Strategy	Horizontal	**1m** Overhang	>	Segmental mask
	Vertical	**1m fin** Spacing 1.5m	>	Radial mask
	Egg Crate	**1m by 1m** 1.5m spacing	>	Combinative mask

Figure 6.5: Passive strategies incorporated in simulation

	Energy Performance Index kWh/m²/year	Cooling Capacity kW	Cooling load per m2 kW/m2
Base Case	**343.2**	**190.72**	**109.6**
Ventilation / Internal heat gains	183.4	145.6	83.4
U-Value	168.54	100.3	57.2
Shading Strategy	151.35	89.3	51.3
	157.45	95.4	54.4
	146.41	**87.65**	**50**

Figure 6.6: Step by step reduction of cooling load for various passive strategies

6.2.5 SUMMARY:

The reduction in the sizing of the system depends on two major factors reducing cooling load and increasing the temperature difference between supply and set point temperature. In this simulation, the cooling capacity of the building is brought down to the desired load (50 W/m2) satisfying the first requirement. The following chapter deals with the temperature difference.

6.3 DEHUMIDIFICATION TO INCREASE DT:

The temperature difference between desired set-point temperature and the supply temperature has to be high which can be achieved by increasing the effectiveness of the evaporative cooler. [27]

dT = (Set point temperature – Supply temperature)

Setpoint temperature = 25°C

$$\varepsilon_{wb} = \frac{t_{p,db,in} - t_{p,db,out}}{t_{p,db,in} - t_{p,wb,in}}$$

For example calculating for the month of august:

ε_{wb}	122	%	Wet bulb effectiveness (From Literature study)
$t_{p,db,in}$	30	°C	Dry bulb temperature of Incoming air
$t_{p,db,out}$		°C	Dry bulb temperature of supply air
$t_{p,wb,in}$	27	°C	Wet bulb temperature of incoming air

$$1.22 = (30 - t_{p,db,out}) / (30 - 27)$$

$$t_{p,db,out} = 26.3\ °C$$

$$dT = 26.3 - 25$$

$$dt = -1.3\ °C$$

Wetbulb Effectiveness Calculations				
Month	Incoming °C		Supply °C	dT °C
	Dry Bulb ($T_{p,db,in}$)	Wet Bulb ($T_{p,wb,in}$)	Supply temperature($T_{p,db,out}$)	
Jan	14.3	13	12.7	12.3
Feb	16.8	15.5	15.2	9.8
Mar	22.3	18.6	17.8	7.2
Apr	28.8	20.2	18.3	6.7
May	32.5	22.4	20.2	4.8
June	33.4	24.5	22.5	2.5
July	30.8	26.9	26	-1.0
Aug	30	27	26.3	-1.3
Sept	29.5	25.2	24.3	0.7
Oct	26.3	21.6	20.6	4.4
Nov	20.8	17.6	16.9	8.1
Dec	15.7	14.5	14.2	10.8
Avg.			15.2	

Table 6.1: Wetbulb effectiveness by the D-IEC at 122%

The short-coming of the indirect evaporative cooler is that the temperature of the supply air is limited by the Wet bulb temperature of the working air. These systems are preferred mostly in the hot and dry regions as there is a huge difference between Dry bulb and Wet bulb temperature. But, with the given climatic conditions of Delhi, the supply temperature of the Dew-Point indirect evaporative cooler is calculated throughout the year using the Wet-bulb effectiveness formula.

The temperature difference is high during the months of the Winter (Nov-Feb) with low supply temperature. But, during the months of rainy seasons (July, August, September) the supply temperature is equal to the setpoint temperature resulting in no cooling effectiveness. This ineffectiveness is due to the higher levels of humidity in the air. In the month of August due to high humidity, the difference between the wet bulb and the dry-bulb temperature is low. Hence, this month is chosen for all the calculations, if the system performs well during this period it would work more efficiently throughout the year.

So, in order to increase the temperature difference (dT) the incoming air of the cooler needs to be dehumidified which results in lower wet bulb temperature.

6.4 LAYOUT OF THE SYSTEM:

The layout of the system (figure 6.7) consists of the Mixing chamber, Dehumidifier, Dewpoint evaporative cooler with a supply duct to the room and a return back to the mixing chamber. The working air of the Dew point evaporative cooler acts as the exhaust in the proposed layout.

The demand for dehumidification of primary fresh air needs to be cut down at multiple levels as follows:

1) The dehumidifier needs to be placed before the evaporative cooler; as the drier, the air better the performance of the evaporative cooler.

2) By calculating the exact amount of fresh air (Eq. 6.2) required the standard value 10 l/s/person gets reduced to 5.09 l/s/person. This reduces the load on both evaporative cooler and dehumidifier.

3) The return air is slightly humidified by the occupants but still drier than the incoming fresh air so it is advisable to mix them before the dehumidifier.

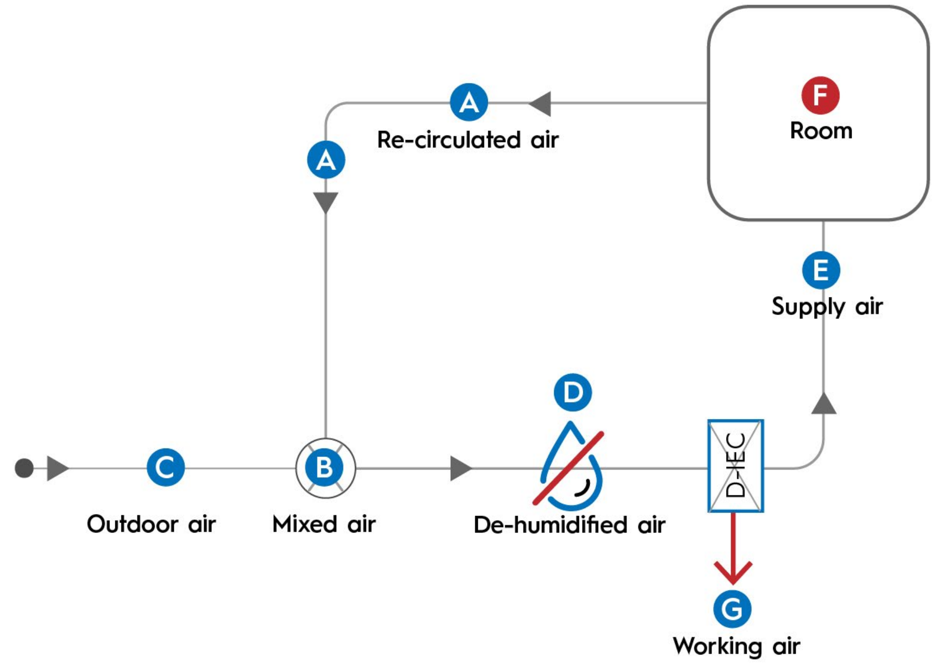


Figure 6.7: Layout of the system with dehumidifier

6.4.1 DE-HUMIDIFICATION STRATEGIES

There are two procedures that are primarily used for dehumidification:

1 Dehumidification through Condensation.

2 Dehumidification through Sorption.

6.4.1.1 DEHUMIDIFICATION THROUGH CONDENSATION:

The condensation process involves cooling the humid air below the dew point by passing it through a cold surface of the heat exchanger. These conventional systems are highly efficient in drying. But the vapour compression system uses mechanical compressors which demands heavy electrical input. Moreover, using the cooling coil reduces not only the humidity but also the temperature, making the use of evaporative cooler ineffective.

6.4.1.2 DEHUMIDIFICATION THROUGH SORPTION:

The principle of absorption is behind the dehumidification cycle in the DCHE to reduce the moisture in air. The dry desiccant and humid air have direct contact. The rH is the direct function of desiccant's adsorption capacity. The capacity increases/decreases with relative increase/decrease in temperature or humidity. The desiccant system cannot absorb indefinitely due to its capacity. For continuous operation of the system, the water needs to be removed which is achieved by a heat source.

The desiccants are classified into two broad categories:

- Solid Desiccants
- Liquid Desiccants

Besides the extensive use of the liquid desiccant, the prominent setback of the system is its capability to stay chemically reactive with moist air and harming people. The solid desiccants are environmentally friendly, inexpensive and have been used in the market prominently making it as the alternative to the cooling coil. [38] Solid Desiccants are further classified into three broad categories:

A) FIXED BED SYSTEMS:

The desiccant is deposited in a flatbed and humid air passes through them for dehumidification and alternatively, hot air passes for regeneration. Multiple beds will be installed with alternate cycles of dehumidification and regeneration.[38]

B) ROTARY DESICCANT SYSTEMS:

The desiccant is impregnated on the wheels in the rotary desiccant system. One portion of the wheel dehumidifies and the rest regenerates. As the wheel rotates slowly both the cycle happens simultaneously.

In both above the systems, the heat released by the desiccants during adsorption reduces the adsorption capacity.[38]

C) DESICCANT COATED HEAT EXCHANGERS:

The DCHEs were developed to address the drawbacks in the previous systems. The heat exchanger fins are coated with the desiccants on which the humid air flows. When the desiccant has reached the adsorption capacity, hot water flows through the tube and carries the moisture away. Well, in order to overcome the shortcomings of the fixed bed and rotary desiccant system during dehumidification a cool fluid flows in the coil reducing the heat released during the adsorption and increases its capacity. For continuous operation, two heat exchangers are required. This, in fact, reduces a larger portion of the latent heat from the air. The common desiccant used in the system is Silica gel with the regeneration temperature of 60°C. [38]

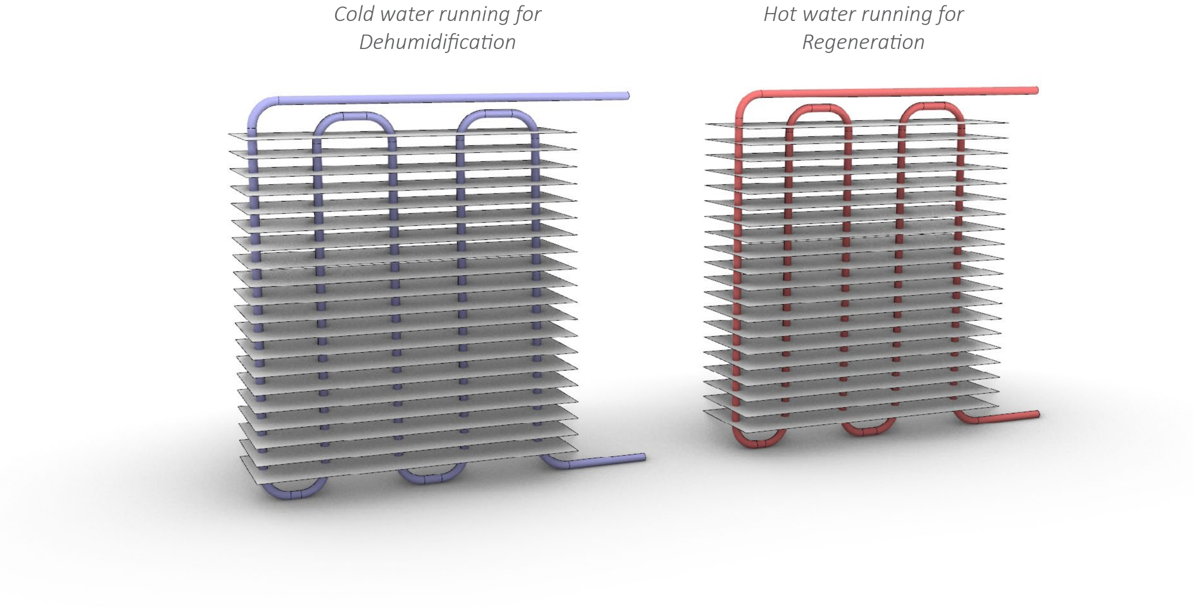


Figure 6.8: Process in Desiccant coated heat exchanger (left), D-CHE (Dehumidification) and D-CHE (Regeneration) (Right)

Properties	Fixed Bed dehumidifiers	Rotary Wheel dehumidifiers	DCHE's
Adsorption capacity	Low		High because of simultaneous cooling
Total cooling load	Total cooling load remains the same. The reduction in latent load of air is converted to an equivalent increase in sensible load		Reduction in cooling load is observed as the cooling water takes away a portion of sorption heat/latent heat
Heat transfer efficiency	Low, because of higher irreversibility associated with multiple heat transfer resistances		High, because of internal heating and high thermal conductivity of metallic fins
Continuous dehumidification	Possible with two beds	Possible using a single rotary wheel	Only possible with two DCHEs
Pressure drop	High	Low	Low
Desiccant material utilization	Low	High	High

Table 6.2: Comparison of Desiccant systems [38]

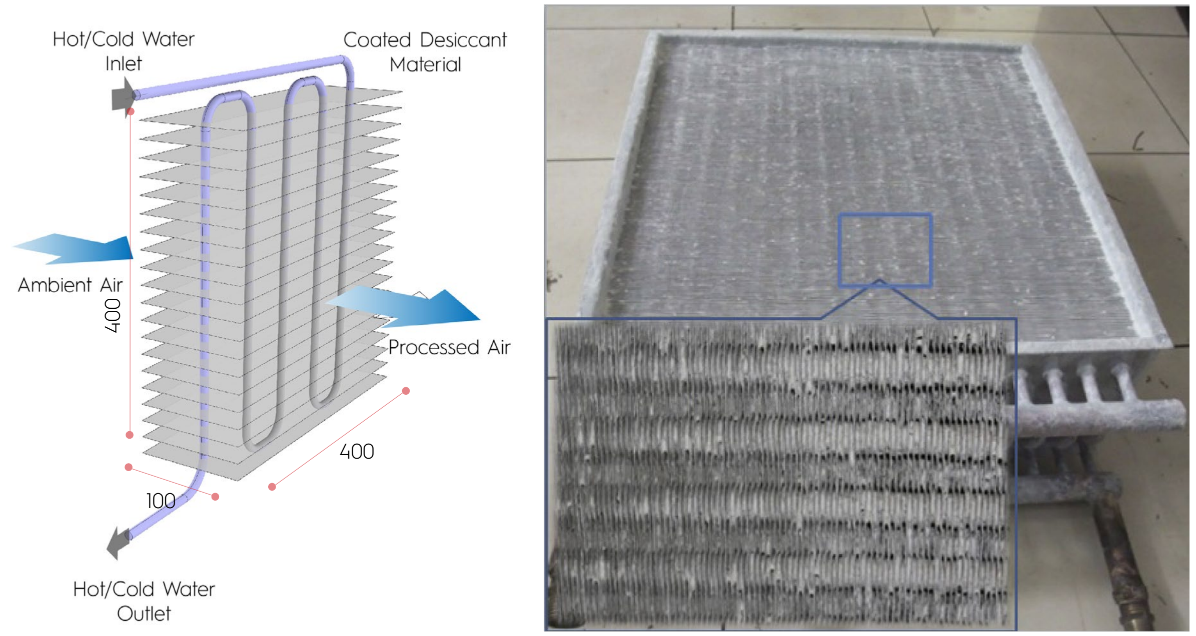


Figure 6.9: Schematic figure of SCHE (left), Physical and detailed photo of the SCHE (Right)

D) SILICA GEL COATED HEAT EXCHANGERS – EXPERIMENT AND RESULTS:

Y.Zhao, T.S.Ge, Y.J.Dai*, R.Z. conducted both numerical and experiments for investigating the dehumidification of silica gel coated heat exchanger. The setup consists of two silica gel coated heat exchangers which are switched alternatively for continuous dehumidification operation. They are experimented and analyzed under Shanghai summer conditions (Hot and Humid) similar to the monsoon period in Delhi.

Two SCHEs run in parallel with respect to two modes: dehumidification and regeneration process mode. Process/ambient air is divided into two parts for dehumidification and regeneration, respectively. In other words, during the first half cycle cooling water is pumped into SCHE B through 3-way water valves. The process air can be dehumidified and cooled down at the same moment. Outlet supply air from SCHE B is supplied to the conditioned room. Meanwhile, SCHE A operates in the regeneration process mode. The SCHE A is heated by hot water, and therefore, desiccant material is regenerated. The exhaust air, with high temperature and high humidity ratio from SCHE A, is exhausted to the environment. In the second half cycle, SCHE A and SCHE B are switched into the regeneration process and dehumidification process, respectively. By switching between the first and the second cycle, the whole desiccant dehumidification unit can realize a continuous process of moisture absorption and cooling. [39],[40],

Results show that the system can provide a stable and continuous dehumidification capacity. The average moisture removal of the desiccant system is 5.08g/kg. at 600s cycle time.

Run no	Ambient Air		Outlet		Moisture removal	
	Temp °C	HR g/kg	Temp °C	HR g/kg	Avg. g/kg	Max. g/kg
1	28.76	16.86	29.7	11.3	5.56	7.51
2	26.99	16.17	27.16	10.97	5.2	7.28
3	25.94	16.41	26.02	11.35	5.06	7.85

Table 6.3: Experimental performance of experimental apparatus.

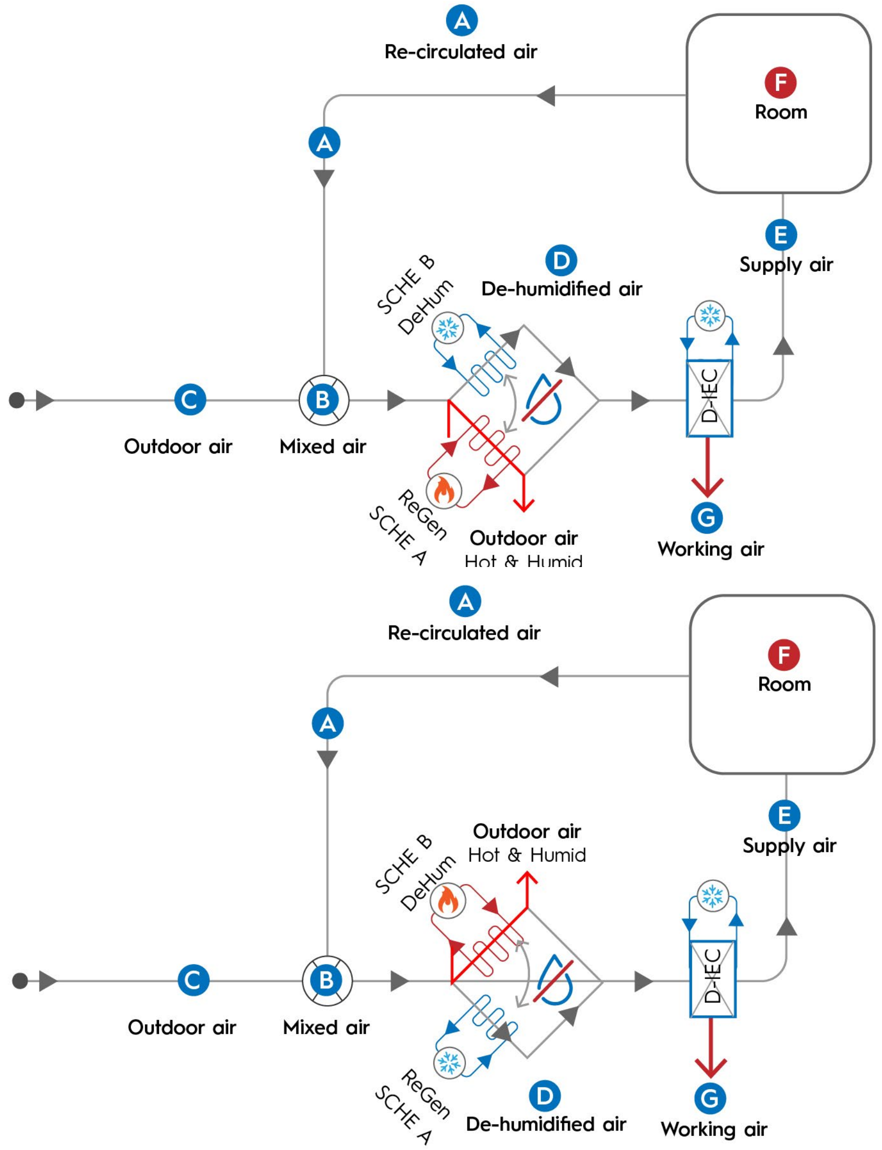


Figure 6.10: The change of cycle between dehumidification and regeneration in DCHE

6.4.2 FRESH AIR

Please refer Eq. 6.2 for the fresh air calculations. By calculating the exact amount of fresh air required the standard value 10 l/s/ person gets reduced to 5.0 l/s/person. Thus, keeping the fresh air to a minimum the optimum load on cooling is established.

6.4.3 MIXING AIR

The fresh incoming air is mixed with the recirculated air to reduce both the temperature and humidity. The recirculated air is comparatively drier and cooler than the ambient air outside.

The required setpoint temperature and desirable rH inside the room are 25°C and 50% respectively. In order to cool down the entire floor, the evaporative cooler needs to supply a mass flow rate of 9.55kg/s of air at 16°C.ref – (1). But the working air required to operate the evaporative cooler is 30% of the primary air. So, in order to supply 9.55 kg/s with the exhaust in the working air, the mass flow rate entering the evaporative cooler should be 13.64 kg/s. The working air of 30% of 13.64 kg/s – (4.09 kg/s) is exhausted and the remaining 9.55 kg/s is supplied into space.

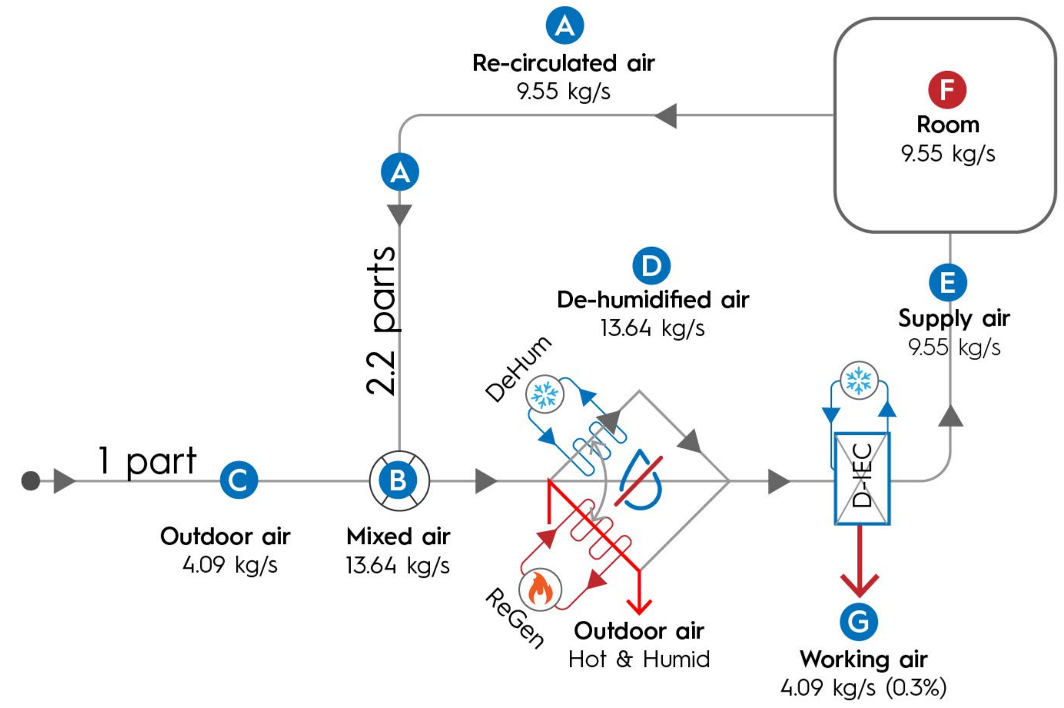


Figure 6.11: Airflow mass flow rate at various stages - Mixing Ratio

The fresh air is kept to the minimum and the return is re-circulated in the system which is mixed with the fresh air intake. The intake air can be pre-cooled and dried by the return air as it is relatively cooler and drier. The proportion of mixing the re-circulated air and intake air needs to be calculated. When air with two different psychometric properties (A and C) mix, the resulting point (B) will be on a straight line in the psychrometric chart. The position of point B depends on the air volume of the air in state A and C. Both the humidity ratio and the resultant temperature are affected by this.

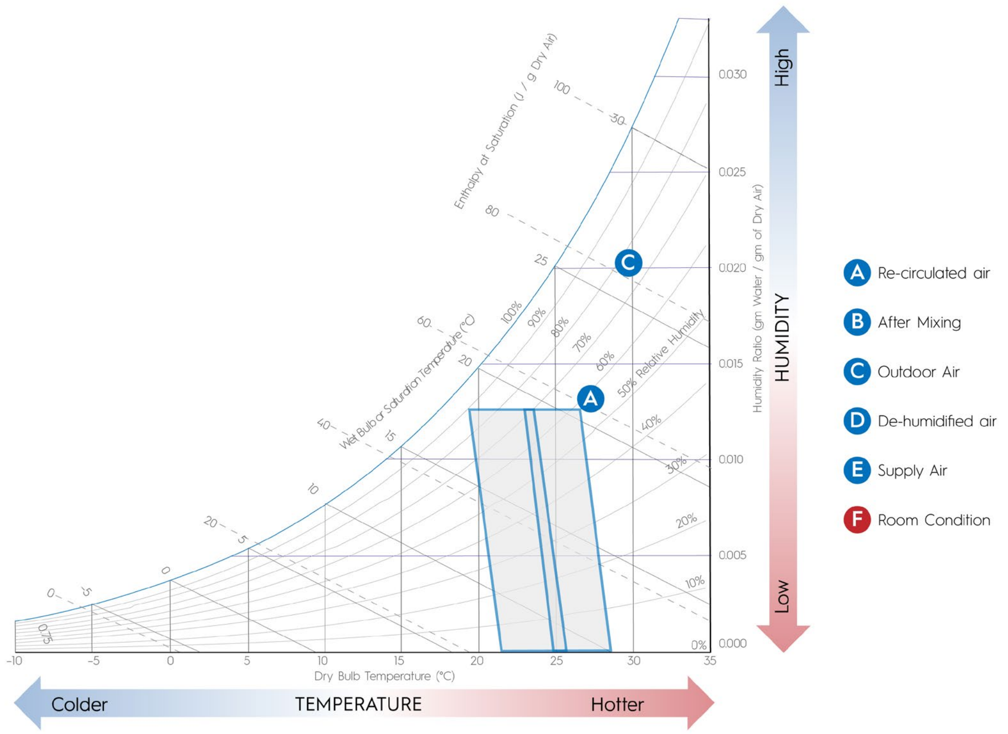


Figure 6.12: The Psychometric points of Recirculated air (A) and Outdoor air (C)

After 1 part of fresh outdoor air(C) and 2.2 parts of recirculated air (A) gets mixed (B), the resultant humidity ratio can be calculated by following equation [41]:

$$X_B = \frac{(Q_A*X_A)+(Q_C*X_C)}{(Q_A+Q_C)}$$

Q_A	2.2	m³	Volume of recirculated air
X_A	0.0113	kg.w/kg.da	Humidity ratio of recirculated air (From Psychometric chart)
Q_C	1	m³	Volume of fresh outdoor air
X_C	0.0196	kg.w/kg.da	Humidity ratio of outdoor air (From Psychometric chart)
X_B		kg.w/kg.da	Humidity ratio of resultant mixed air

X_B = (2.2*0.0113)+(1*0.0196)/(1+2.2)

Humidity ratio of resultant mixed air X_B = 0.0138 ≈ 0.014 kg of water / kg of dry air

After 1 part of fresh outdoor air(C) and 2.2 parts of recirculated air (A) gets mixed (B), the resultant resultant temperature can be calculated by following equation [41]:

$$T_B = \frac{(Q_A*T_A)+(Q_C*T_C)}{(Q_A+Q_C)}$$

Q_A	2.2	m³	Volume of recirculated air
T_A	27	°C	Temperature of recirculated air (From Psychometric chart)
Q_C	1	m³	Volume of fresh outdoor air
T_C	30	°C	Temperature of outdoor air (From Psychometric chart)
T_B		°C	Temperature of resultant mixed air

T_B = (2.2*27) + (1*30) / (1+2.2)

Temperature of resultant mixed air X_B = 27.9 °C

6.4.4 DEHUMIDIFICATION BY DCHE:

The resultant humidity ratio of the air before entering the desiccant-coated heat exchanger is 0.014 kg. /kg. Well from the case study we have learnt that with the temperature around 27°C and 0. 016kg.w/kg.da the DCHE can absorb and reduce the humidity ratio approx. 0.005 kg.w / kg.da [39] [40] . So, the resultant humidity ratio of the air will be around (0.014 - 0.005 = 0.009 kg.w/kg.da) after passing through DCHE. The adsorption is an exothermic process and it increases the temperature of the air passing through thus resulting in reduced performance of dehumidification. This also increases the cooling load of the evaporative cooler, but the cooler fluid passes through the coil during dehumidification, counterbalances the heat generated during dehumidification. Thus the temperature of the air is left undisturbed with reduced moisture. [40]

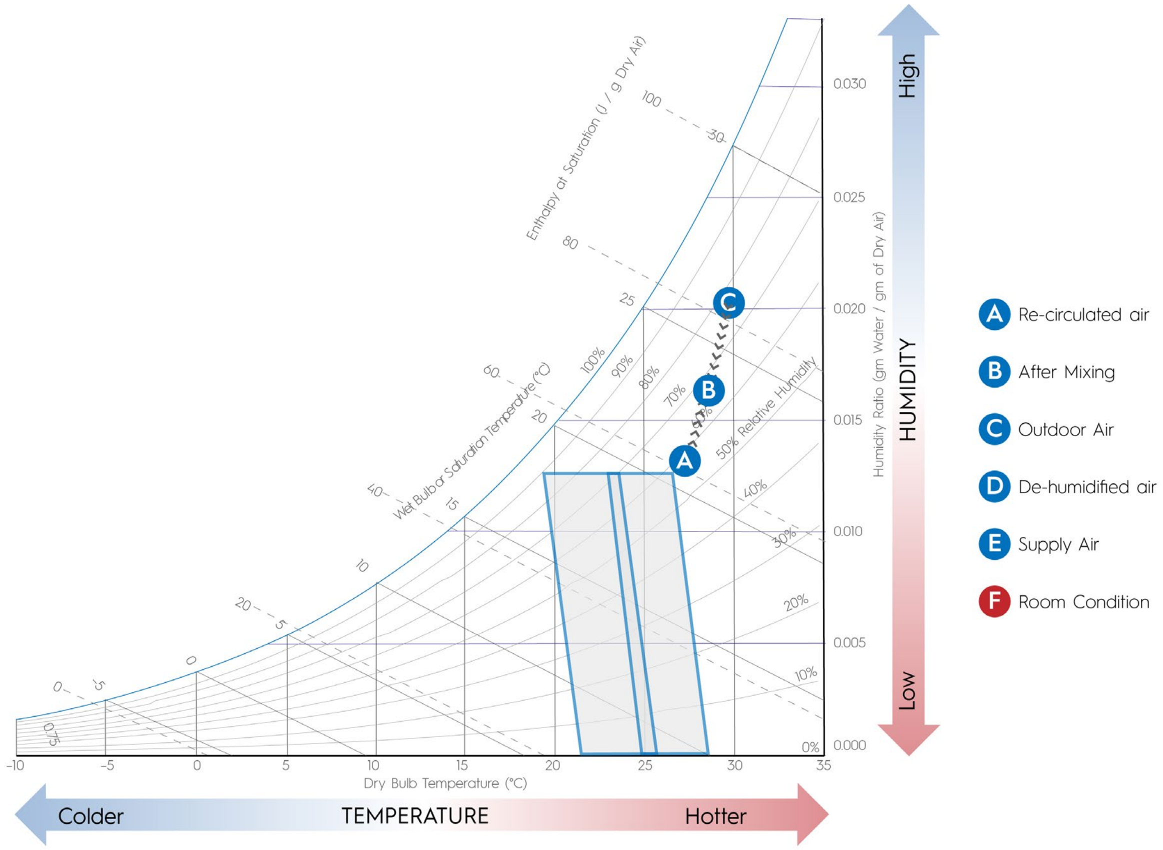


Figure 6.13: The resulting temperature and humidity of mixed air (B)

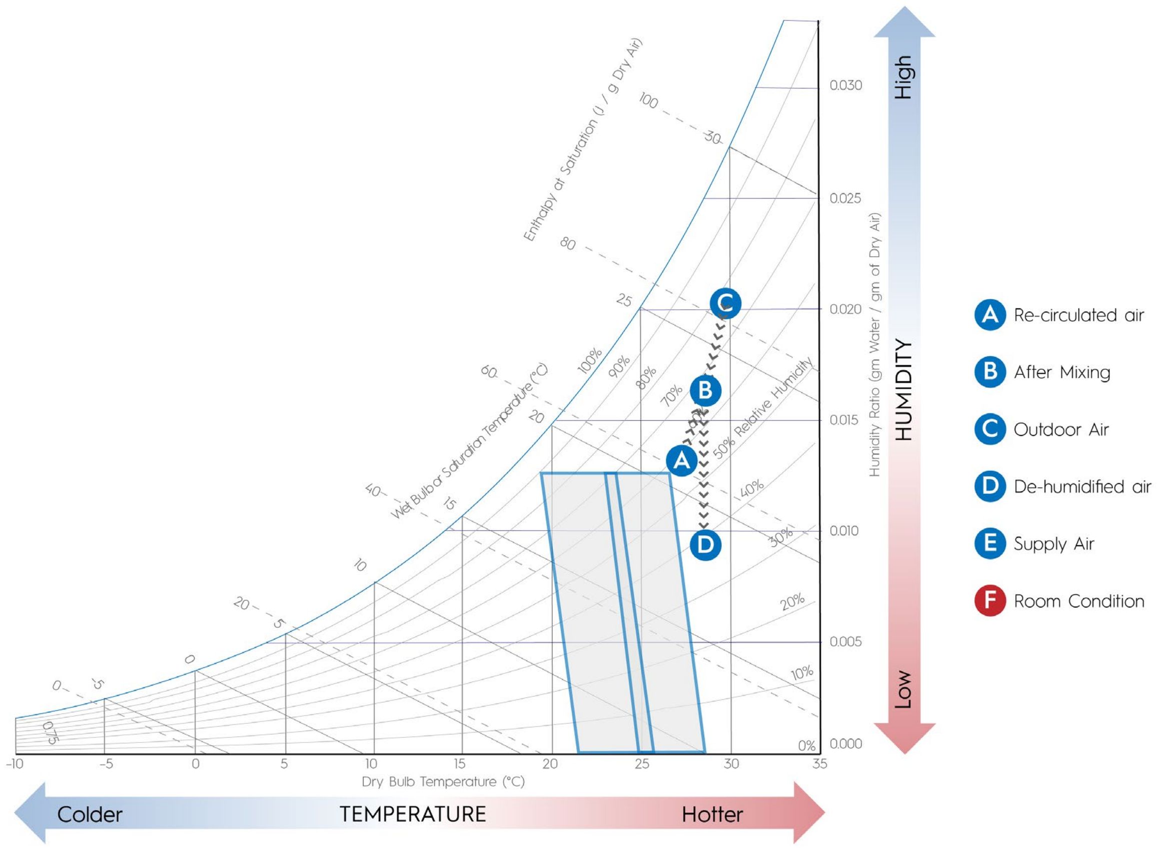


Figure 6.14: The resulting temperature and humidity of after dehumidification (D - Dry air)

6.4.5 COOLING BY D-IEC:

The dry air after the dehumidification has a temperature of 27.9°C with the humidity ratio of 0.009kg.w / kg.da. By plotting these two values the wet bulb temperature of 18.2°C can be found for the month of August. The cooler has high wet bulb effectiveness of 122% and the supply air's temperature can be found using the calculation below [27]

$$\varepsilon_{wb} = \frac{t_{p,db,in} - t_{p,db,out}}{t_{p,db,in} - t_{p,wb,in}}$$

For example calculating for the month of august:

ε_{wb}	122	%	Wet bulb effectiveness (From Literature study)
$t_{p,db,in}$	27.9	°C	Dry bulb temperature of mixed incoming air before the cooler
$t_{p,db,out}$		°C	Dry bulb temperature of supply air
$t_{p,wb,in}$	18.2	°C	Wet bulb temperature of mixed incoming air before the cooler

$$1.22 = (27.9 - t_{p,db,out}) / (27.9 - 18.2)$$

$$t_{p,db,out} = 16.1\ °C$$

$$dT = 25.5 - 16.1$$

$$dt = 9.4\ °C$$

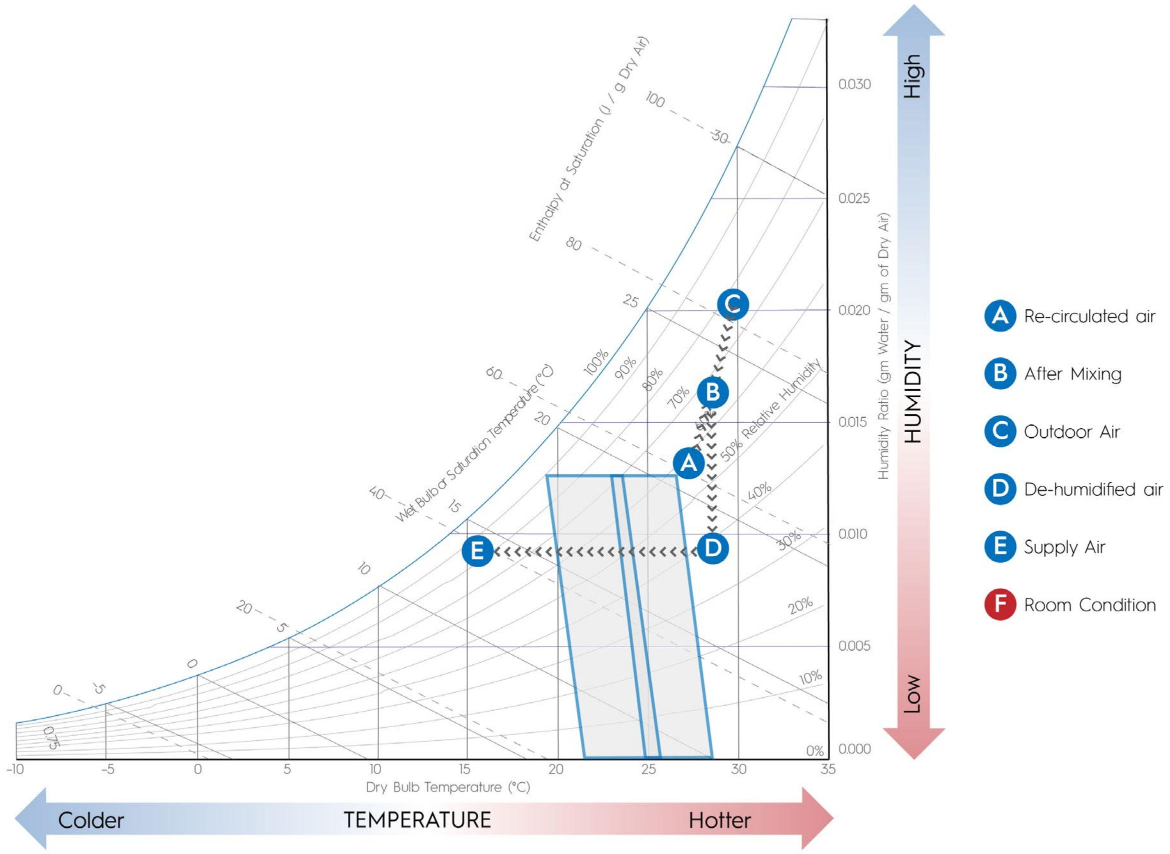


Figure 6.15: The supply temperature (E) after passing through D-IEC

Similarly, the supply temperature for the whole year is calculated using the wet bulb effectiveness formula in the following table:

Wetbulb Effectiveness Calculations						
Month	Before Mixing	After Mixing	Before	After	Wet Bulb °C ($T_{p,wb,in}$)	Supply temperature °C ($T_{p,db,out}$)
	Outside Air Dry Bulb °C	Incoming Dry bulb °C ($T_{p,db,in}$)	Dehumidification	Dehumidification		
Jan	14.3	23	0.010	0.0048	12.7	10.4
Feb	16.8	23.8	0.010	0.0048	13	10.6
Mar	22.3	25.5	0.010	0.0052	14.1	11.6
Apr	28.8	27.6	0.010	0.0054	15.1	12.4
May	32.5	28.7	0.011	0.0059	15.9	13.1
June	33.4	29	0.012	0.0075	17.1	14.8
July	30.8	28.2	0.014	0.0089	18.2	16.0
Aug	30	27.9	0.014	0.0089	18.2	16.1
Sept	29.5	27.8	0.013	0.0078	17.2	14.9
Oct	26.3	26.8	0.011	0.0062	15.5	13.0
Nov	20.8	25.1	0.010	0.0054	14.1	11.7
Dec	15.7	23.5	0.010	0.0049	13	10.7
Avg.						12.9

Table 6.4 : The resulting temperature and humidity of after dehumidification (D - Dry air)

6.4.5.1 SUPPLY TEMPERATURE AFTER DEHUMIDIFICATION:

The silica-coated heat exchanger has a high dehumidification capacity. The supply temperature is around 16°C in the August irrespective of high humidity due to heavy rainfall. It is 10° C lower than the supply of evaporative cooler without dehumidification (26°C). The average supply temperature is around 13°C throughout the year. The system can supply much lower temperature in the other months, creating a huge difference between supply and desired set point temperature.

This temperature difference is crucial as it helps in determining the volumetric flow rate and ultimately the size of the system. If temperature difference between desired set-point temperature and the supply temperature is high the size of the system reduces.

6.5 THE COMPLETE CYCLE:

In a short summary, the recirculated air (A) gets mixed with Outdoor air (C) resulting in mixed air (B). This mixed air is dried by the desiccant system to (D) de-humidified air which is cooled down by D-IEC to (E). This supply air (E) has lower dry bulb temperature with higher rH(90%) which is not desirable. When it is supplied in the room the temperature increases due to the internal heat resulting in the desired setpoint temperature (25°C) optimal for the room (F). This rapid increase in temperature with very less moisture addition results in rH of 50 %. The exhaust leaves the room with a little addition of heat and humidity for recirculation (A) and the cycle continues.

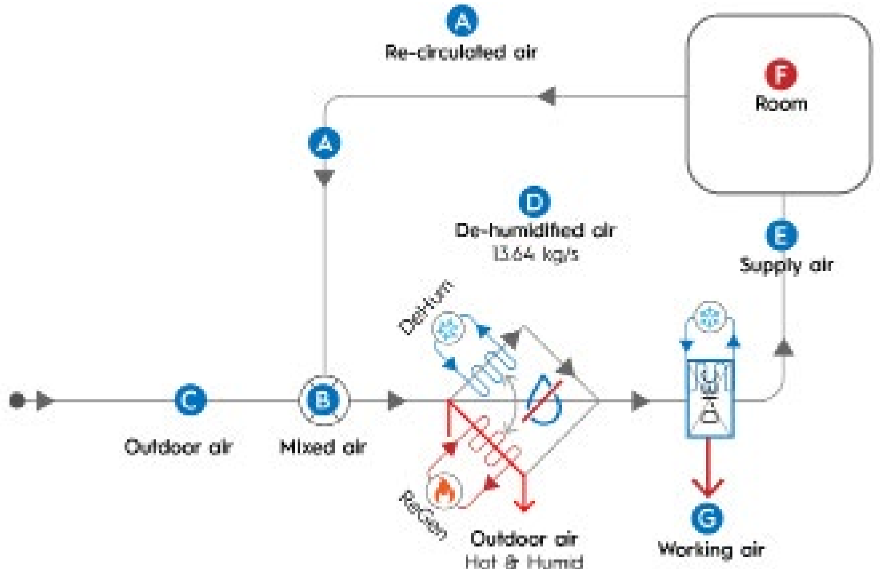


Figure 6.16: The full pschrometric cycle of the air passing through the system

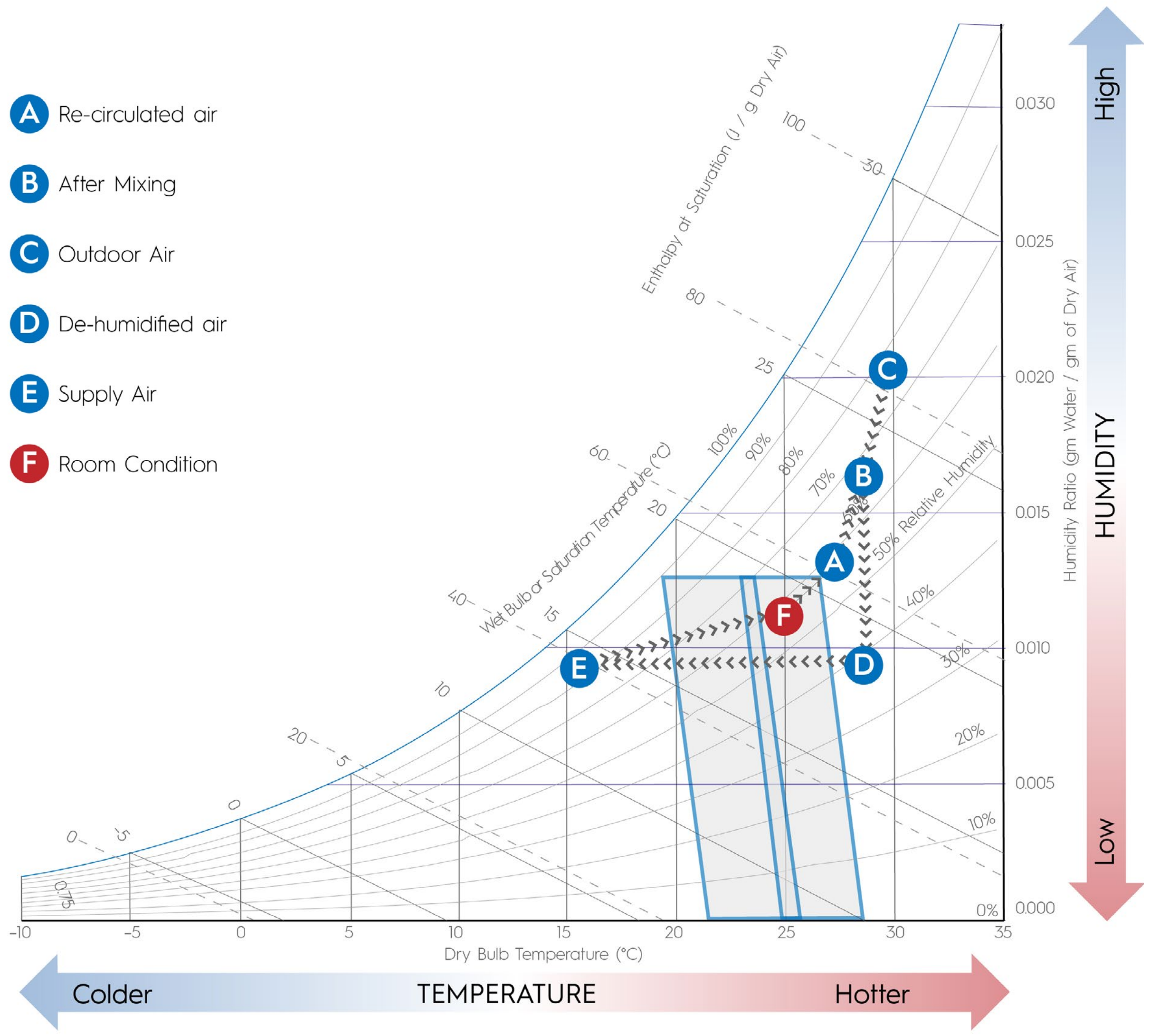


Figure 6.17: The full pschrometric cycle of the air passing through the system

7

FACADE DESIGN

Chapter Overview

The previous chapter discusses the cooling demand requirements and the airflow layout. This chapter has been categorized into two segments focusing on design concepts and its evaluation, integration of the design in micro (detailing) and macroscale (Overall form/facade of the building) respectively. The first half of the chapter provides varied sizing of the cooler over the facade based on determined cooling demand. These options were evaluated on the parameters of aesthetics, ventilation strategy, maintenance etc. and detailed options were developed. The second half of the chapter explores various designs of the buildings with different WWR and cooling loads. This attempts to display the balance between the number of systems over the facade as a design element to its respective cooling demand.

7.1 SIZING – COOLER:

From the previous chapter, the volume flow rate of the entire floor is calculated and reduced to its minimum by decreasing the cooling capacity and increasing the temperature difference. The number of devices that are required to supply the flow rate in demand can be calculated by sizing the equipment.

The sizing of the cooler not only depends on the proportion over the façade and its handling with a number of devices; but more particularly on achieving more than 100% of WB effectiveness. The thickness and the length of the channel, thickness between the channels even the velocity of the air and the working air ratio plays a crucial role to achieve WB effectiveness of over 100.

7.2 FACTORS AFFECTING THE SIZE/EFFECTIVENESS OF THE COOLER:

A numerical and experimental study conducted on the dew point evaporative cooling gives us a comprehensive understanding on the proportion and sizing system to achieve higher wet bulb and dew point effectiveness in a hot and humid climate similar to the conditions during monsoons in Delhi. For all the cases below the temperature of the air at the inlet is 35°C with WB bulb 28°C and the results are discussed below [33], [42]:

7.2.1 CHANNEL GAP:

The channel thickness has a great impact on the dew point and wet bulb effectiveness. Both the values are inversely proportional to the thickness of the channel. The channel gap should be chosen below 5mm for obtaining wet bulb effectiveness over 100% to attain high cooling effectiveness.(Figure 7.1)

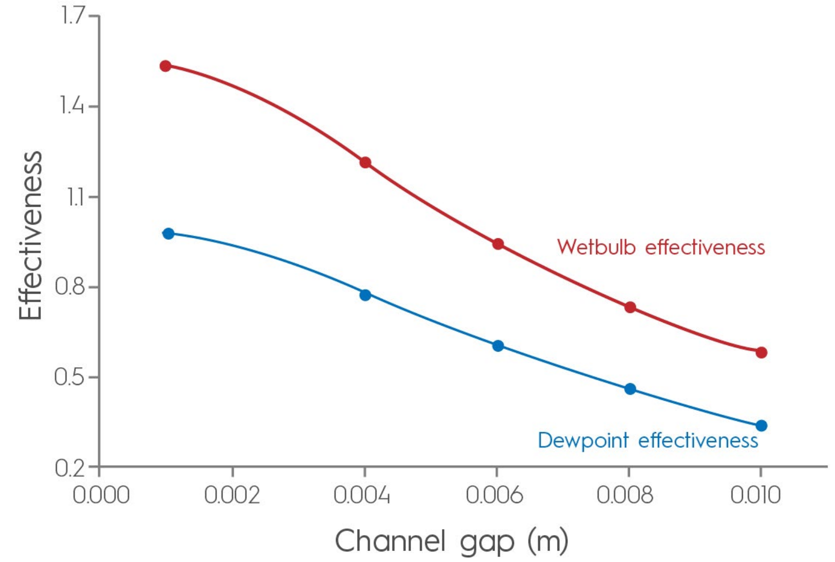


Figure 7.1: Outlet temperature vs Intake air velocity

7.2.2 CHANNEL LENGTH:

The effectiveness shows significant results with the increase in the length of the system. The increase in length enhances the heat and mass transfer process as the contact time and area increases. The effectiveness attains saturation over 3m length (Figure 7.2) but the initial cost(large system) and operational cost(friction loss) need to be considered while deciding the length. The effectiveness attains over 100% when the length of the cooler is over 1m. [42]

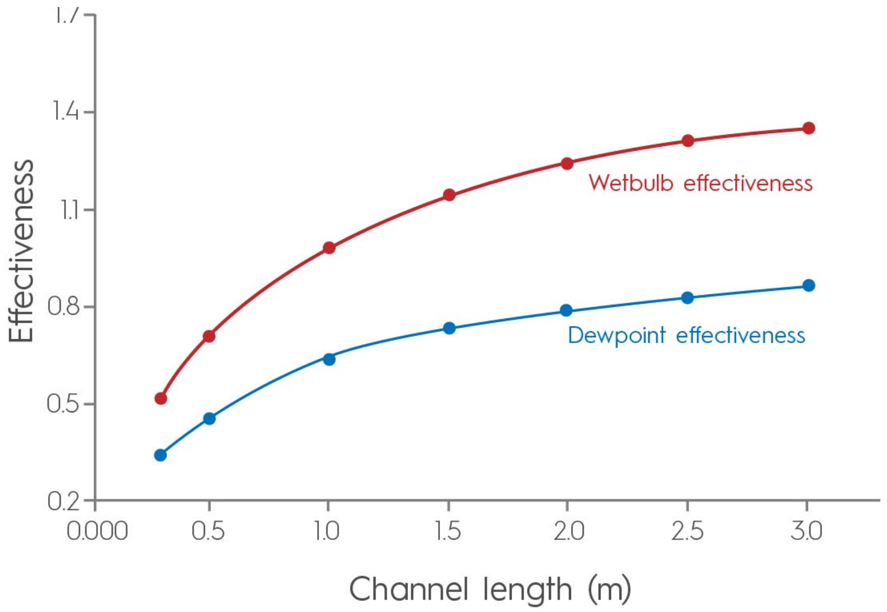


Figure 7.2: Outlet temperature vs Intake air velocity

7.2.3 AIR VELOCITY:

The (figure 7.3) shows the impact of the inlet air velocity over the performance of the system. Well, increasing the velocity of the air results in lower WB effectiveness. This is due to the fact that the duration of the contact between water and air is reduced resulting in lower heat and mass transfer. The wet bulb and dew point will be greater than 100% if the intake velocity of the air is less than 2.5m/s. [42]

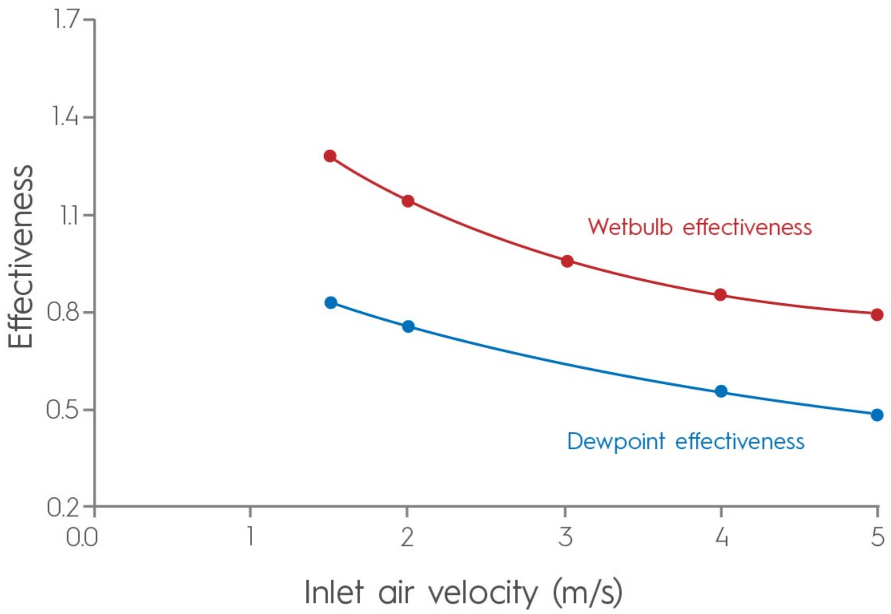


Figure 7.3: Outlet temperature vs Intake air velocity

7.2.4 INFLUENCE OF WORKING TO INTAKE AIR RATIO:

The working air helps in removing the heat of the primary air, so with the increase in the working air ratio; the wet bulb effectiveness value also increases. But this has a huge impact on the supply flow rate. From the experiments, it is known that the working air ratio of 30% - 60% have high cooling effectiveness with WB effectiveness over 100%. (figure 7.4). [42]

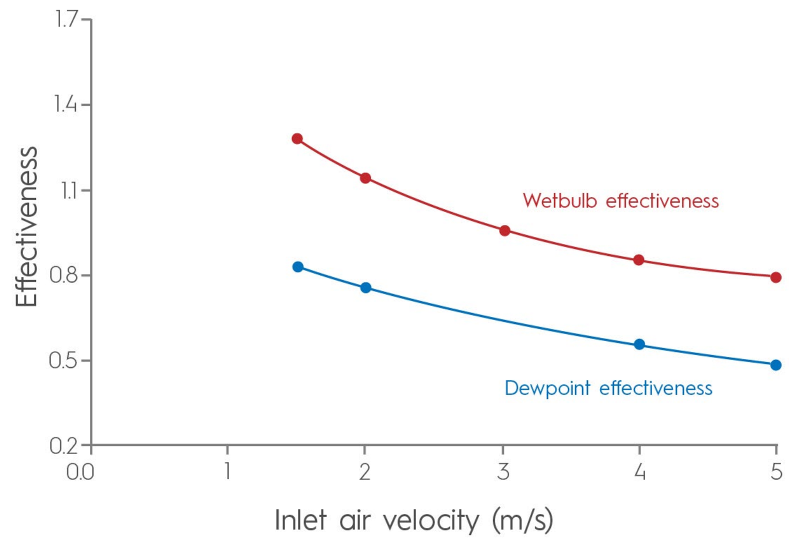


Figure 7.4: Outlet temperature vs Intake air velocity

7.3 SIZING THE COOLER:

The results from the experiment were developed based on the heat and mass transfer affecting the performance of the evaporative cooler. From the results of the experiments by B. Riangvilaikul, S. Kumar the system should be designed and operated at channel height more than 1m, with channel thickness less than 5mm, 30% as working air ratio and inlet velocity of 2.5 m/s to obtain more than 100% of WB. [42]

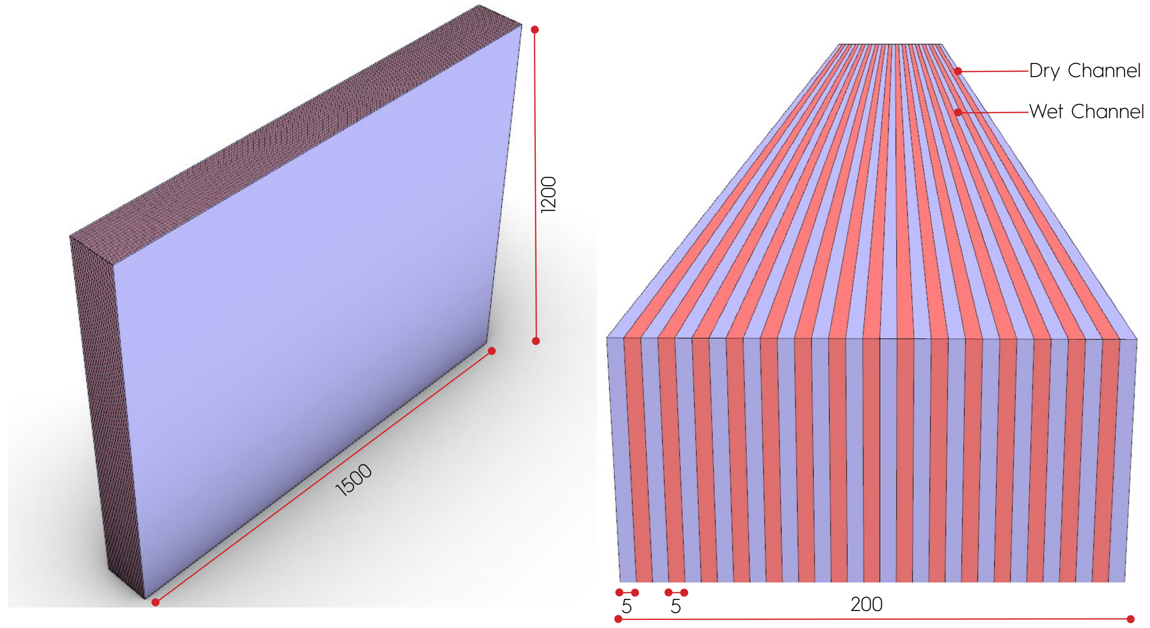


Figure 7.5: Sizing the cooler to acheive more than 100% Wet bulb Effectiveness

7.3.1 OPENING SIZE:

Dew- point evaporative cooler has a series of dry and wet channels, for primary air and working air respectively. It is the dry channel which handles the supply rate for the space and area of its opening needs to be determined using the total volume flow rate to determine the width, depth and number of the system. [42]

7.3.1.1 TOTAL OPENING AREA REQUIRED:

From (Eq. 6.1). the mass flow rate is 9.55 kg/s, volume flow rate 8.19 m3/s is calculated.

The total opening area for the required volume flow rate can be calculated using the following formula:

$$Q = v * A$$

Q	**8.19**	m^3/s	Volume flow rate
v	**1.5**	m/s	Flow velocity (v) - IEC attains WB effectiveness over 100% with velocity less than 2 m/s. [3],[4].
A		m^2	Area of opening

8.19 = 1.5 * A

Area of the opening (A) : 5.46m²

The size of the evaporative cooler is influenced by numerous factors to achieve WB effectiveness over 100% .

Length	1.5 m	Based on the grid size of the facade
Width	0.2 m	Based on number of channels
Height	1.2 m	For WB effectiveness more than 100% the length needs to be 1m [42] or more. Or the length should be 200 times the channel thickness [43]
No. of Channels	39	
No. of Dry Channels	20	
No. of Wet Channels	19	
Channel Thickness	5 mm (0.005m)	The effectiveness is higher when the thickness is less than 6mm.[3] (Fiber, cellulose, ceramic, zeolite and carbon are used for construction of the channels)[42]
Thickness of the plate	0.5 mm (0.0005m)	Less thickness with high thermal conductivity [42],[43]
Opening Area of Dry Channels	0.15m2	= (Length x Width x no. of channels) = (1.5*0.005*0.2)

7.3.1.2 TOTAL NUMBER OF SYSTEMS (PER FLOOR) :

A total number of systems can be found by dividing opening area required for the volume rate by the area of the dry channel of the cooler.

Total area : 5.46 m2

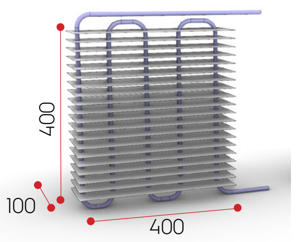
Area of dry channel : 0.15m2

No. of systems req.	36.42 devices approx. per floor	= Total opening area / Area of one system = 5.46 / 0.15

Figure 4.6: Outlet temperature vs Intake air velocity

7.4 SIZING THE DCHE:

The size of the desiccant coated heat exchanger is 400mm x 400mm x 200mm. Two these exchanger needs to be placed before a cooler for a continuous operation. Each of these desiccant systems can handle the volume flow rate only one cooler. Incase of more volume flow rate or multiple evaporative coolers, the size of heat exchanger also increases. [39],[40]



7.5 INTEGRATION CONCEPTS:

7.5.1 SILL INTEGRATION WITH DISPLACEMENT VENTILATION:

The proposed evaporative cooler is coupled with a desiccant-coated heat exchanger (DCHE) for a required supply volume flow rate (figure 7.6). Each and every system has a couple of blowers for primary and working air, with water redistribution system for an evaporative cooler and the desiccant system. Each of these prototypes can be integrated into the facade as a sill unit (figure 7.7) below the windows similar to many decentralized cooling/heating market products with displacement ventilation.

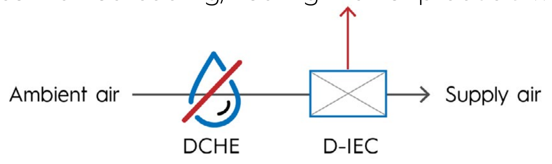


Figure 7.6: Outlet temperature vs Intake air velocity

7.5.1.1 DISPLACEMENT VENTILATION:

The displacement ventilation system (DV) is an air-distribution strategy in contrast to the conventional mixed ventilation strategy. The cool air is introduced at the floor level in low velocity near the floor via diffusers. This air rises up and gets heated up via multiple heat sources (sun, human body, equipment etc.) and in a typical scenario, the exhaust is collected by the ceiling level. The air needs to be supplied at a higher temperature with lower velocity to avoid drafts, but it has a significant impact on the improvement of the air quality. In the design, the air is supplied via the diffuser below the evaporative cooler near the floor and the exhaust is placed on the side of the cooler. [44]

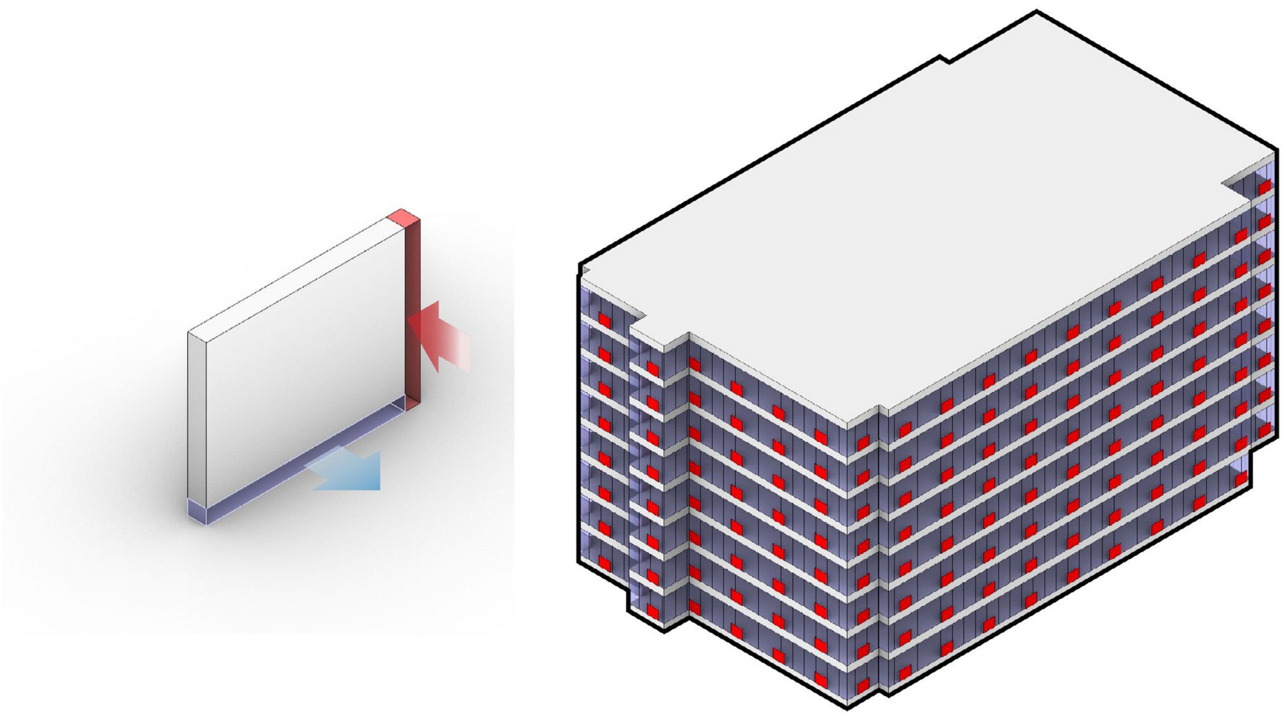


Figure 7.7: Sill Integrated - Displacement ventilation (left) Overview of the facade (36 sill devices)

7.5.2 WALL INTEGRATION WITH MIXED VENTILATION:

The two of these proposed evaporative coolers is coupled with two sets of desiccant-coated heat exchanger (DCHE) for the required supply volume flow rate. These systems can be installed as a full solid wall system from the inside (figure 7.10). The length of the evaporative cooler affects the WB effectiveness but the rate of increase in the WB effectiveness decreases with an increase in length and almost saturates at 3m. However, the cooler with the length of 1.2m almost achieve 120% WB effectiveness. Two of these coolers can be stacked one over the another to achieve double the flow rate but with half the number of blowers, filters and distribution system. The ambient air passes through the desiccant-coated heat exchanger which is split into two of the evaporative coolers that have been stacked one over the another and converges into a single diffuser for supply. (figure 7.8)

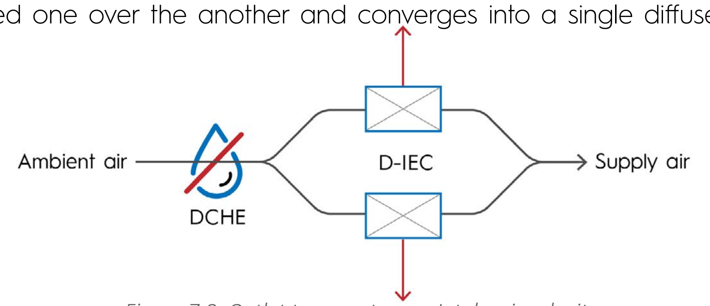


Figure 7.8: Outlet temperature vs Intake air velocity

7.5.2.1 MIXED VENTILATION:

The wall integrated systems have two ventilation strategies. The mixed-ventilation system is a conventional ventilation strategy. The cold air is introduced and return air is exhaust via ceiling through diffusers. There is an even distribution of temperature throughout but comparatively with a higher level of contamination to displacement ventilation.

There are two options by which wall integrated systems can supply air. In the first option (figure 7.9 (left)), the air is supplied via the diffusers at the top of the cooler near the ceiling. With a return for exhaust between the coolers. In the other option (figure 7.9(right)), both the mixed and displacement ventilation has been integrated for supply with the exhaust in the middle. [44]

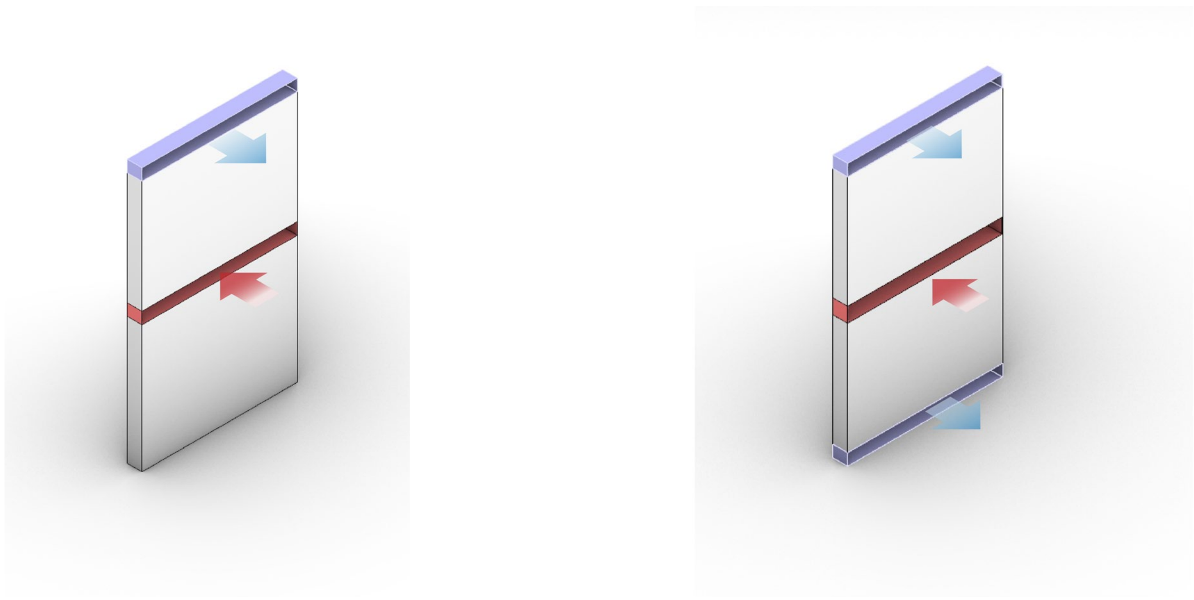


Figure 7.9: Mixed ventilation Strategy (left) , Mixed and Displaced ventilation strategy

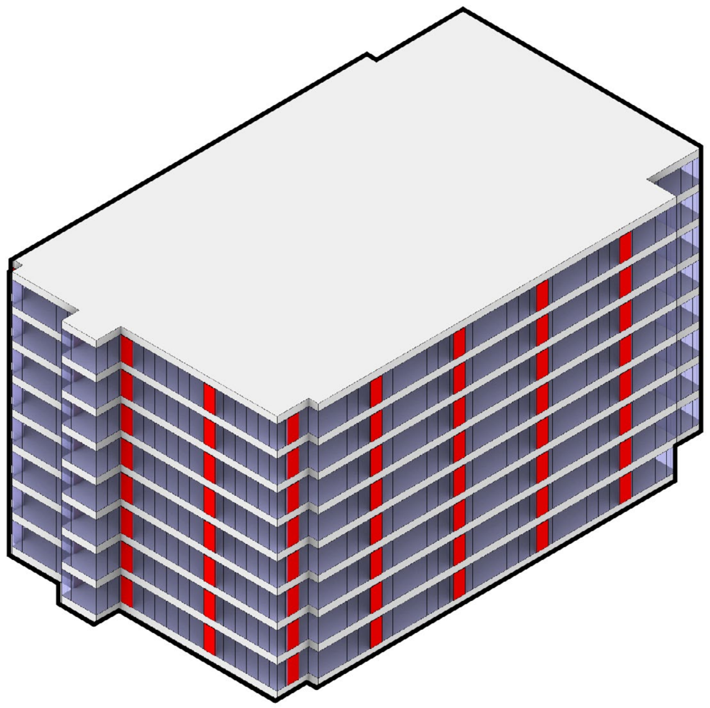


Figure 7.10: Sill Integrated - Overview of the facade (18 wall devices)

7.5.3 COMPARING SILL VS WALL SYSTEM:

The wall system has a cleaner finish over the facade compared to the sill system and significantly reduces the installation and maintenance by half when compared to the sill system. But the thermal comfort due to the difference in the ventilation strategy is also significantly important and have been studied and analyzed later. The wall integrated systems tend to have an advantage over the sill system in numerous aspects as below:

Parameters	Sill Integrated	Wall Integrated
Number of Devices	36	18
No. of Blowers/Filters	36	18
No. of Coolers & Desiccant	36	36
Dimensions	1.2x1.5x0.2	1.2x3.0x0.2
Interference to facade	High	Less
Ventilation strategy	Displacement	Mixed
Thermal comfort	Comparatively less	Comparatively high
Maintanence	Less	More
Window Integration	Possible	Not possible
Others	The height of the unit is 1.3m approx from the floor, obstructing the view of the people sitting next to them.	Here it becomes completely solid with very few hinderance over the facade.

Table 7.1 : Comparison of Sill vs Wall integrated systems

7.6 EVALUATING VENTILATION SYSTEMS:

Taking into the consideration that the position of outlets has an impact on the design and thermal comfort of the space, a CFD analysis was done focusing on the comparison of the common ventilation systems: Displacement, Mixed and both.

A typical part of the floor plan will be evaluated with all the three options with the same environmental conditions (Cooling load, Occupancy, Equipment, the volume of the room, etc.,). The comfort level is identified by the temperature distribution, draft rate near the occupant's working zone. The simulations for the above systems are done using the academic version of Design-Builder 5.5.

7.6.1 MODEL PARAMETERS:

7.6.1.1 BUILDING MODEL :

The current study is for office space in New Delhi. As the floor plan is vast and free-flowing, a typical portion (27m*13m*3m) (figure 7.11) covering the full depth (13m) on the southern portion is chosen to be modelled in the design-builder with occupant density of 0.11 people/m2 working with the computer, the model is fully glazed with the egg crate shading strategy.

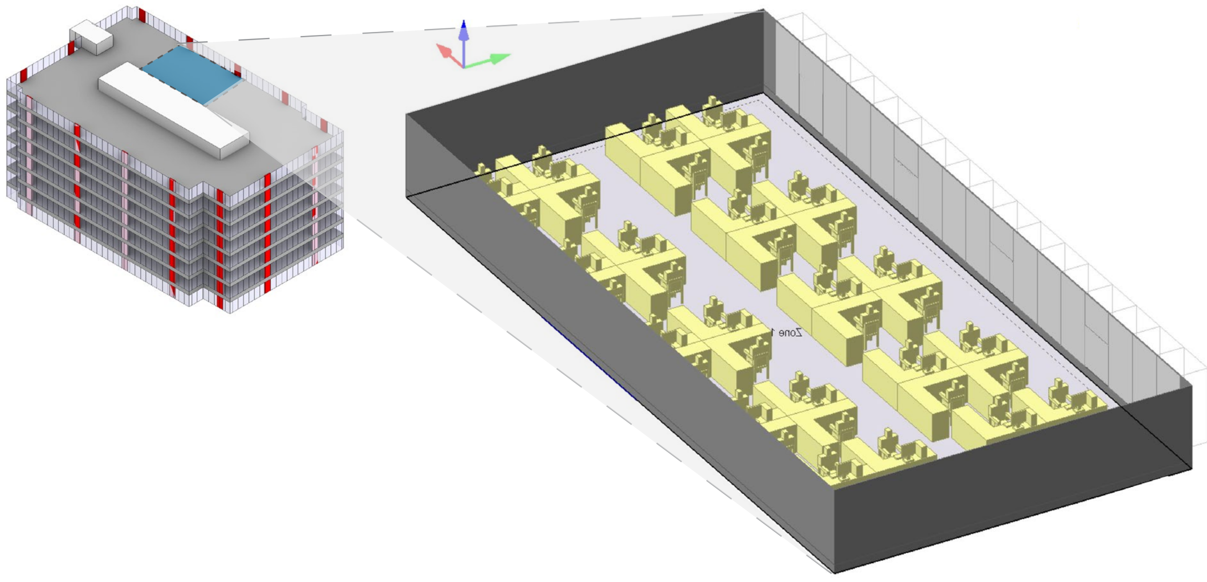


Figure 7.11: Key plan of the building (left), Modeled space with internal heat sources with shades

7.6.1.2 BOUNDARY CONDITIONS AND GRID SIZE:

A) GRID SIZE : The mesh of the virtual model has been created using the automated quadrilateral grid (figure 7.12). The default grid size of 0.3 m has been used in the model for faster simulation with fine mesh near the heat sources, inlets and outlets for accuracy. (APPENDIX 11.2)

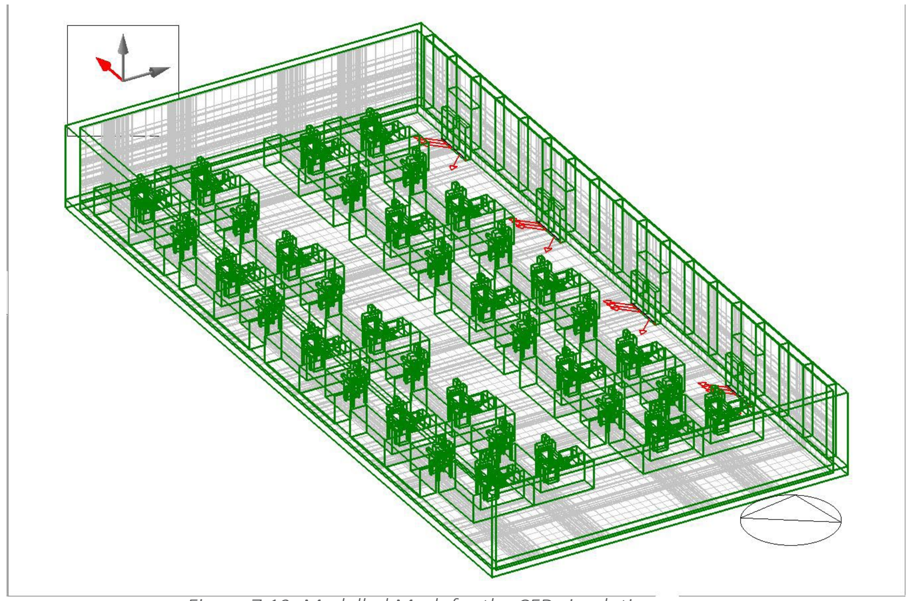


Figure 7.12: Modelled Mesh for the CFD simulation

B) BOUDARY CONDITIONS : Importing precise boundary conditions helps in getting more reliable results. Boundary condition in design-builder has two major parameters, flow balance and the temperature. The total flow in and out needs to be balanced for the simulation, and the values for the total flow is the flow rate per device in l/s. (APPENDIX 11.3)

The surface temperature of the walls, floors and windows influences the movement of air and this temperature can be imported using energy plus in the design-builder by running an hourly simulation for a summer design week. (APPENDIX 11.4)

7.6.1.3 MODELING DIFFUSERS:

Three options were validated based on the size and the position of the diffusers:

A) OPTION 1:

The Sill integrated option was modelled as a component with diffuser supplying at at 12°C with a velocity of 1.5 m/s. The supply and the exhaust flow rate is 225 l/s (Table 7.2) and needs to be the same for balance.

Number of devices on the floor: 36
Number of devices simulated: 4
Distance between the devices: 4.5 m

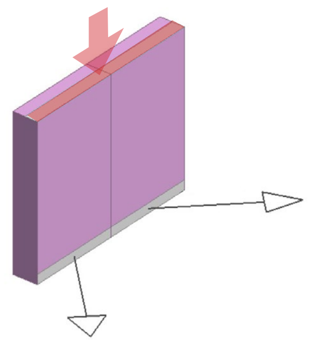


Figure 7.13: Option 01 - Sill integrated displacement ventilation system

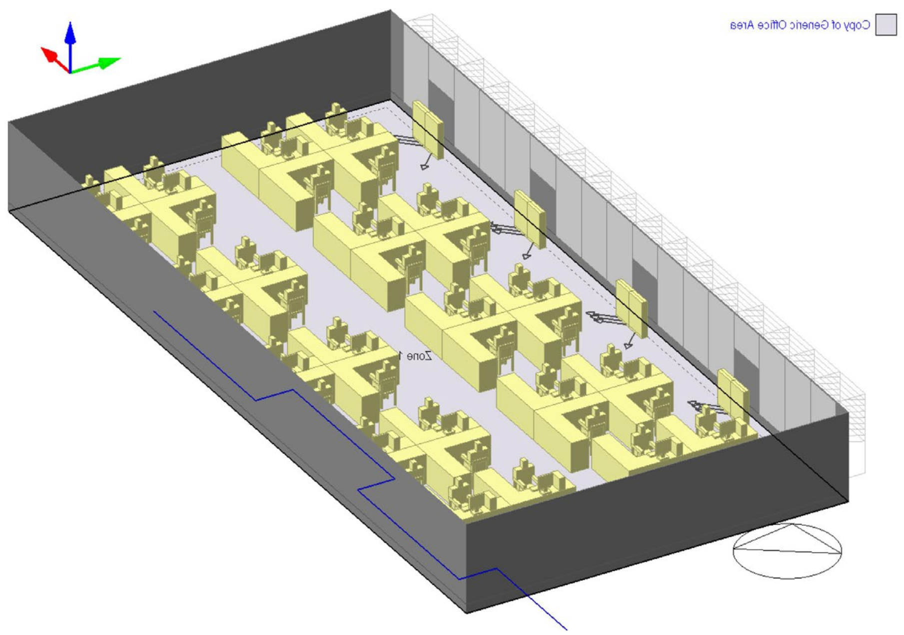


Figure 7.14: Displacement ventilation Sill model

B) Option 2:

The Wall integrated option has two evaporative coolers with two diffusers and one return. The diffusers are supplying at 12°C with the velocity of 1.5 m/s.

The supply through each diffuser is 225 l/s (Table 7.2) and 450 l/s in the exhaust to balance the mass.

Number of devices on the floor: 18
Number of devices simulated: 2
Distance between the devices: 9 m

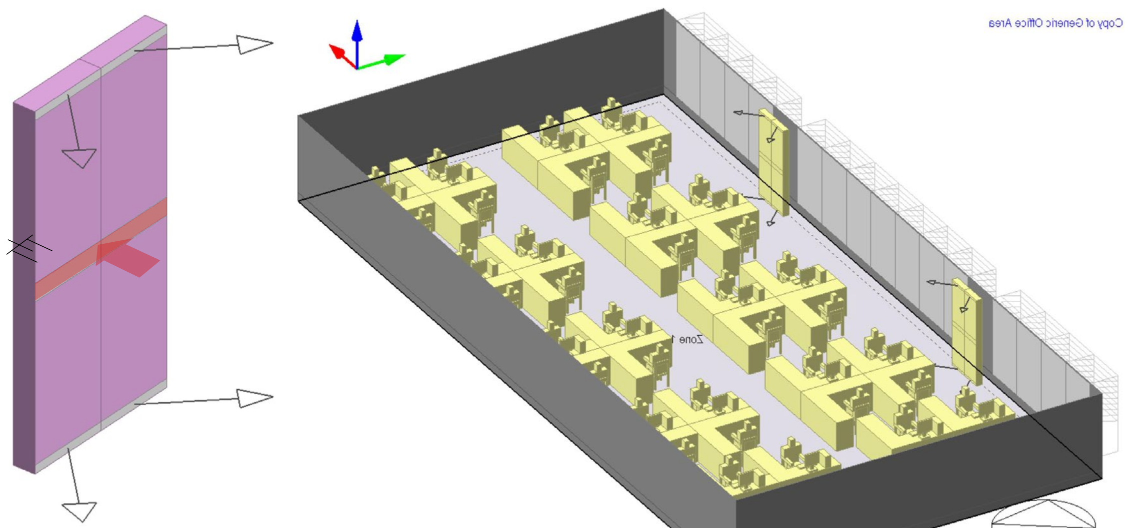


Figure 7.15: Option 02 - Mixed and Displacement ventilation Wall model

C) Option 3:

The Wall integrated option has two evaporative coolers with one supply and one return. The diffusers are supplying at 12°C with the velocity of 1.5 m/s.

The supply through the diffuser is 450 l/s (Table 7.2) and 450 l/s in the exhaust to balance the mass.

Number of devices on the floor: 18
Number of devices simulated: 2
Distance between the devices: 9 m

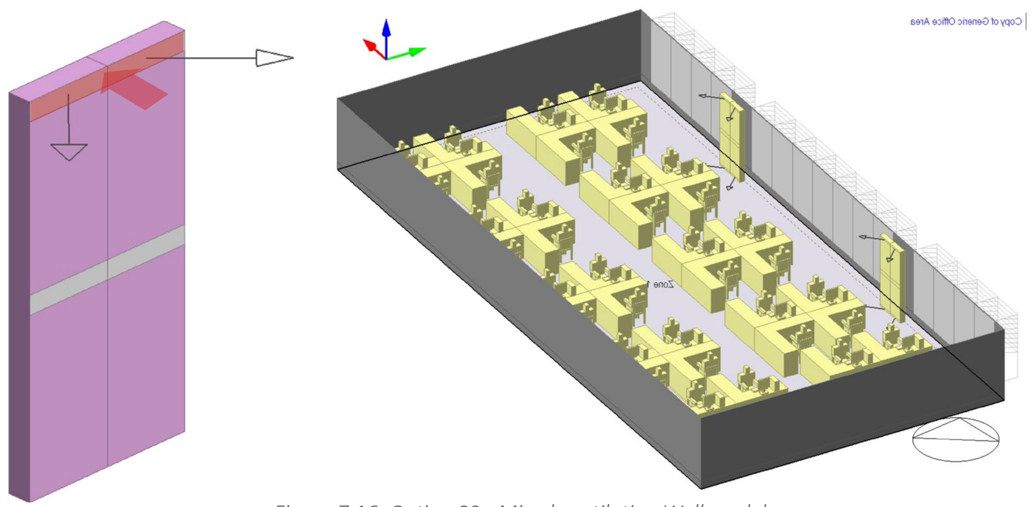


Figure 7.16: Option 03 - Mixed ventilation Wall model

Options	Length	Width	Height	Total Flow Rate	No. of Diffusers	No. of devices per floor	Flow rate per device
	(m)	(m)	(m)	m3/s	nos.	nos.	l/s
Option 01	1.5	.2	1.2		1	36	225
Option 02	1.5	.2	3	8.19	2	18	450
Option 03	1.5	.2	3		1	18	450

Table 7.2 : Flow rate per devices for various option for CFD

Option 01

Total Flow rate : 8.19 m3/s
Number of Devices : 36
Flow rate device :
(8.19 / 36) * 1000
= 225 l/s

Case 2 : 50% of SC

Total Flow rate : 8.19 m3/s
Number of Devices : 18
Flow rate device :
(8.19 / 18) * 1000
= 450 l/s - split over two diffusers = 450 / 2 = 225 l/s

Case 3 : 0% of SC

Total Flow rate : 8.19 m3/s
Number of Devices : 18
Flow rate device :
(8.19 / 18) * 1000
= 450 l/s

7.6.1.4 AIM AND RESULTS

The aim of the simulation is to understand and analyze which ventilation strategy has more even distribution of temperature and to avoid drafts for the occupants. With the above setup, each option was simulated and examined.

For all the cases temperature and velocity fields were analyzed with three different planes based on the human body prone to drafts: 0.4m feet, 1.1m seating posture and 1.8m standing.

Option 1: Displacement Ventilation

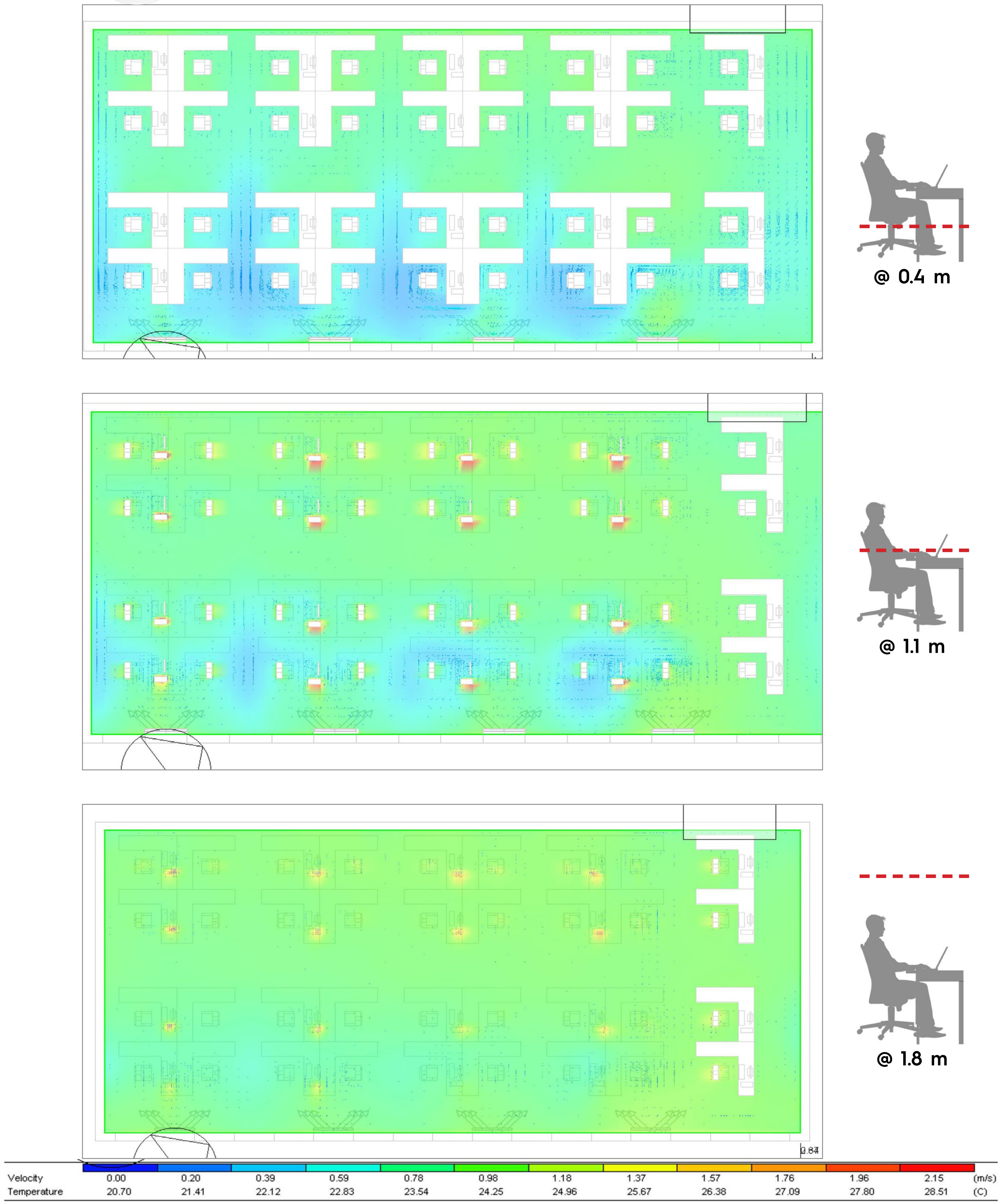


Figure 7.17: Option01 - Displacement ventilation - Temperature Plane at 0.4m, 1.1m and at 1.8m

Option 2: Mixed / Displaced Ventilation

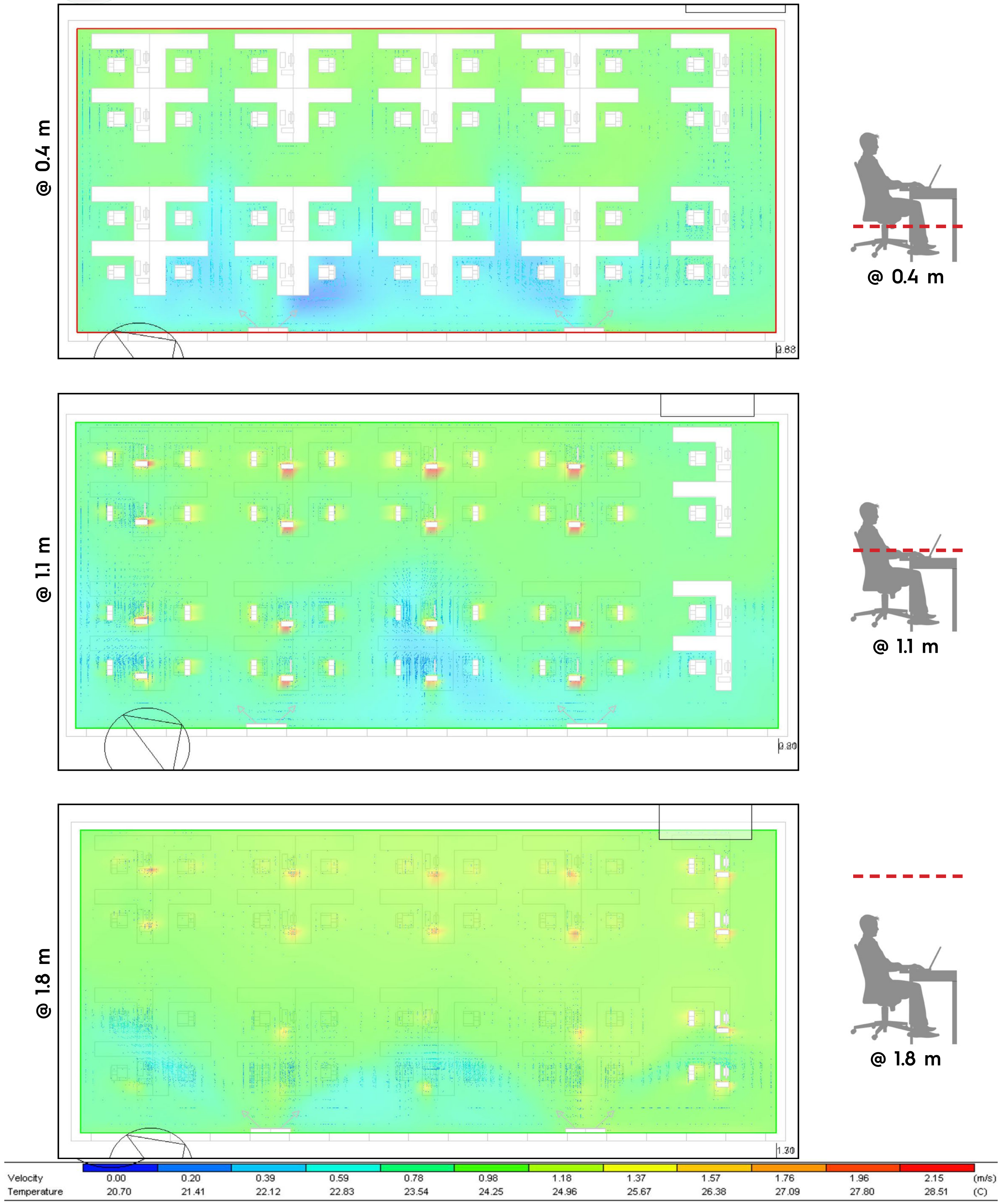
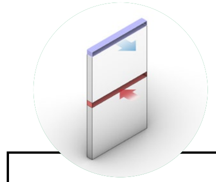


Figure 7.18: Option02 - Displacement / Mixed ventilation - Temperature Plane at 0.4m, 1.1m and at 1.8m



Option 3: Mixed Ventilation

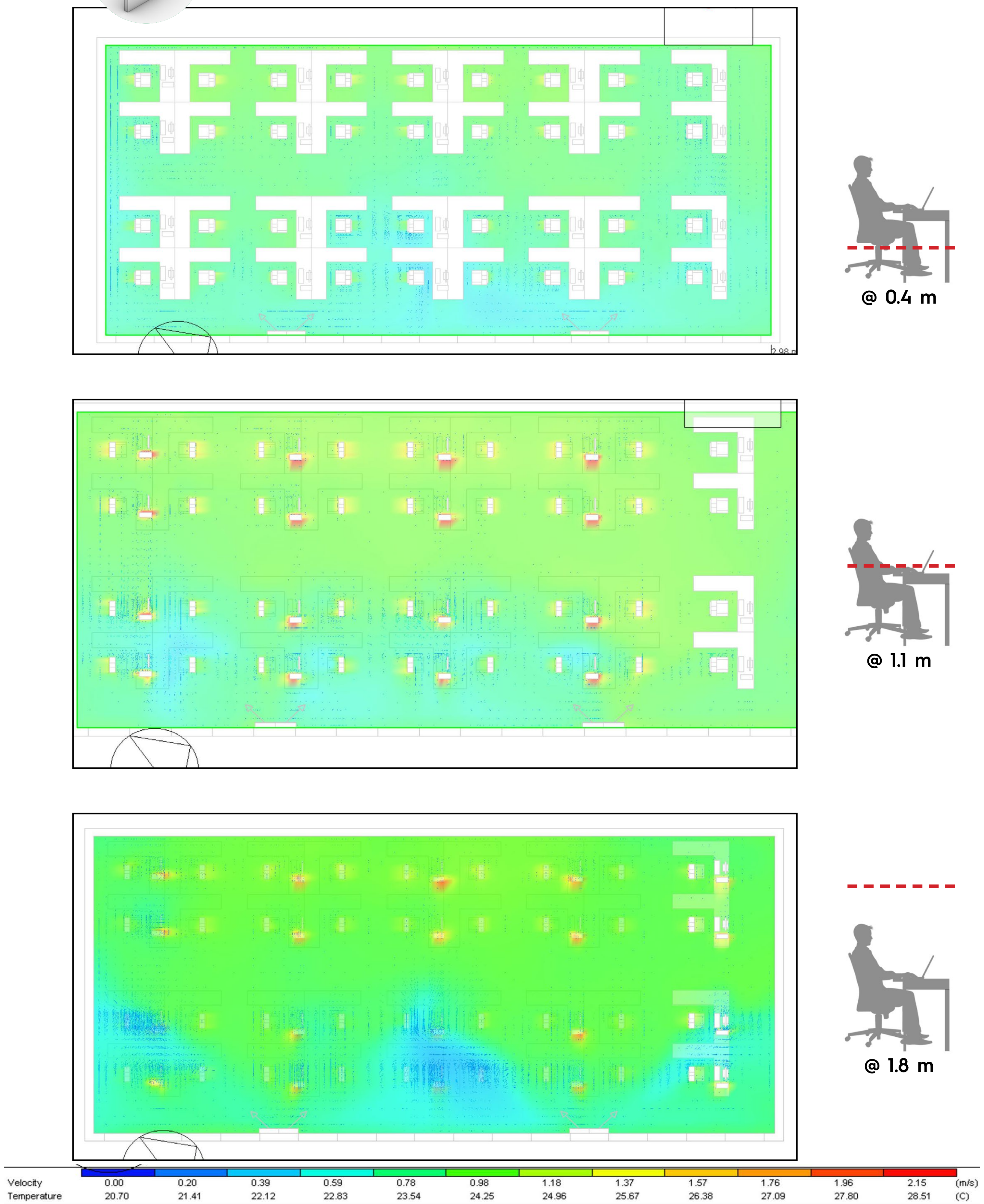


Figure 7.19: Option03 - Mixed ventilation - Temperature Plane at 0.4m, 1.1m and at 1.8m

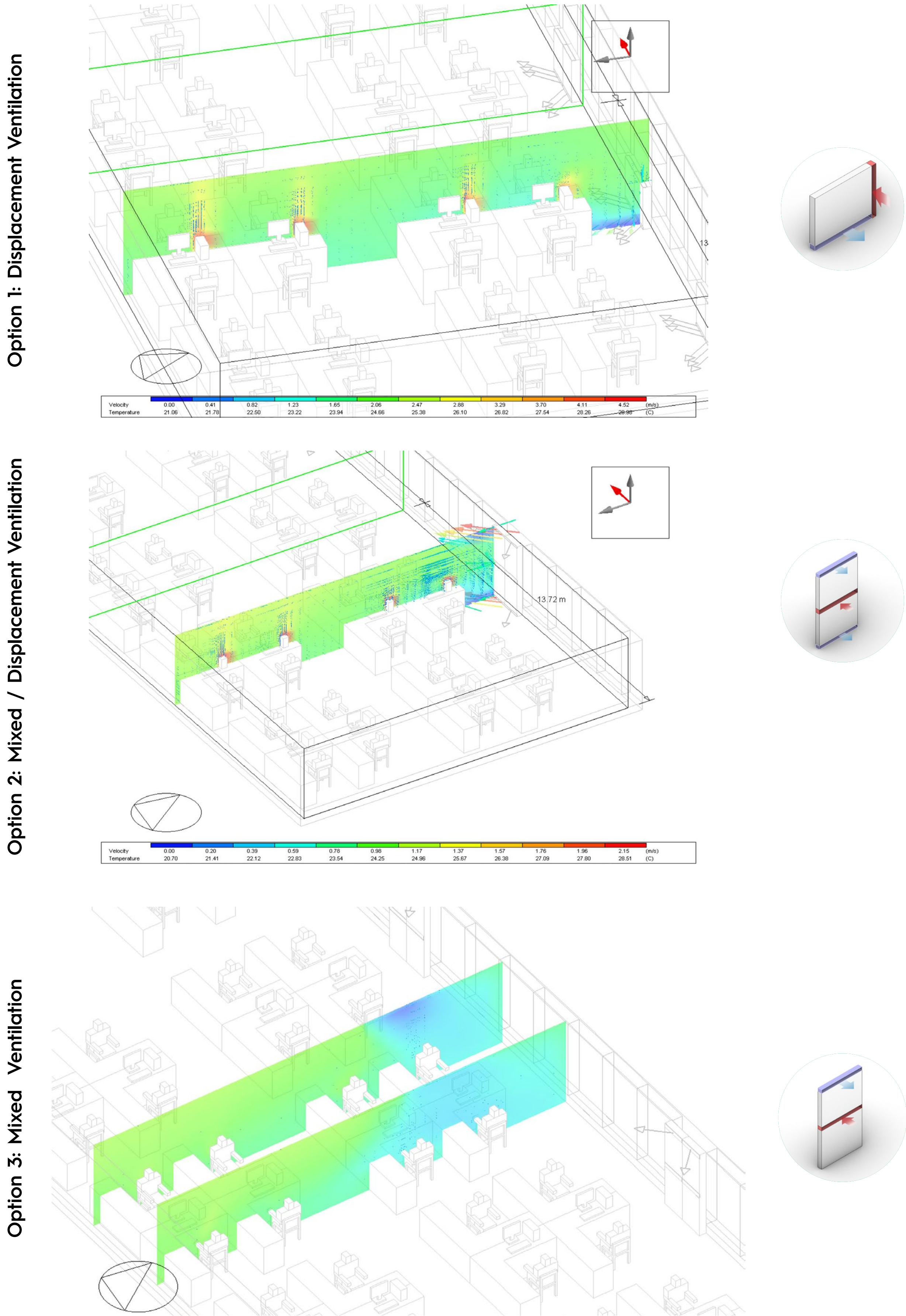


Figure 7.20: Option03 - Velocity plane for the Displacement, Mixed/Displacement, Mixed ventilation

7.6.2 RESULTS : TEMPERATURE / VELOCITY DISTRIBUTION:

The existing flow rate in all the cases results in 25°C throughout the space which is the required set point temperature. The disturbances in the temperature distribution are seen as blue patches resulting in the draft or thermal discomfort in those zones. For all the ventilation strategies the temperature stratification is apparent. The temperature ranges from 20°C to 28°C and it increases with height. This pattern occurs because the air that is supplied near the floor level gets heated up by the indoor heat sources (human occupancy, machinesetc.). The disturbance in distribution of the temperature for option 01 (figure 7.17) and option 02 (figure 7.18) at the level of the diffuser (0.4m) is more so a person sitting next to the device with displacement ventilation experiences draft.

The disturbance in the temperature distribution reduces with height but despite that, the mild discomforts can be observed at the working level. Displacement ventilation strategies need to be implemented with much higher temperature with lower velocity resulting in a higher mass flow rate which either needs to be addressed by increasing the number of devices or the size.

Even though the mixed ventilation strategy option 03 (figure 7.19) has more disturbance at the level of diffuser it has a much better distribution of temperature at the working level. The airspeeds under the ASHRAE guidelines is 0.2m/s. The velocity at the diffuser is ranging from 1.5 - 2.15 m/s (figure 7.20). But the velocity drops significantly with distance and reaches less than 0.2 m/s at the workstation. Thus, resulting in very minimal or no drafts near the devices.

7.7 THERMAL RESISTANCE:

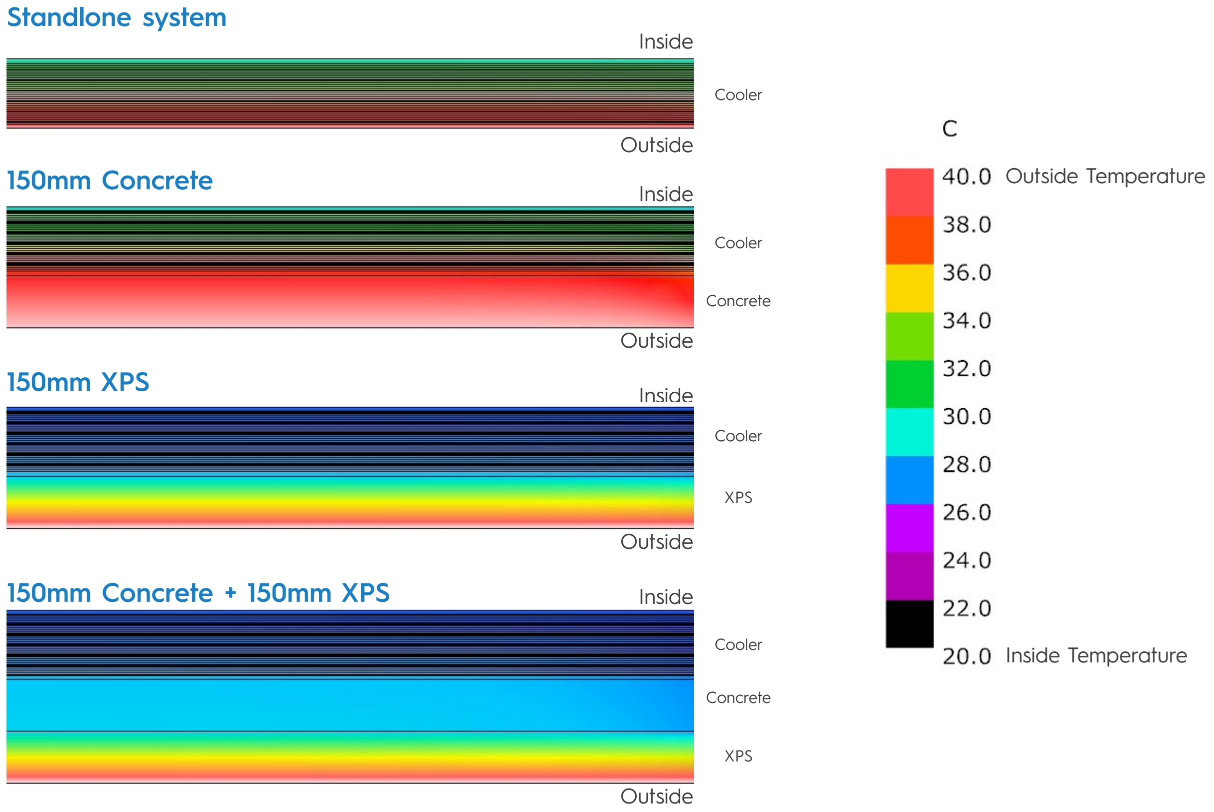


Figure 7.21: Heat propagation through different materials

The aim of the THERM simulation is to find the required resistance for heat from outside so that it doesn't affect the performance of the cooler. (APPENDIX 11.9)

The boundary conditions include a temperature of 40°C on the outside and 25°C on the inside with the cooler as a building block/facade module through which the heat propagates. Four simulations were performed :

1) Evaporative cooler as a standalone system
2) Evaporative cooler with 150mm Concrete
3) Evaporative cooler with 150mm XPS
4) Evaporative cooler with 150mm XPS + 150mm Concrete

The results (figure 7.21) suggest that the evaporative cooler cannot work as a standalone facade module. Because of the harsh hot conditions outside, the cooler gets heated up affecting its performance. The 150 mm concrete provides a solid enclosure for the cooler but still, there is penetration of heat through it. The modules with XPS ranging from 100 - 150mm and the combination of XPS and concrete has better resistance towards heat from the external ambient air.

Sl.no	Variations	Thickness	Thermal Conductivity	Result
1	Standalone system	200mm	----	Poor
2	Concrete	150mm	1.3	Not Satisfactory
3	XPS	100mm	0.029	Good
4	XPS	150mm	0.029	Good
5	XPS + Concrete	150mm + 150mm	0.029 / 1.3	Good

Table 7.3: Thermal conductivity and performance of various materials

7.8 DESIGN OPTIONS:

The wall system has more reliable advantages compared to the sill system and various design options of the wall systems have been further explored

All the variations have similar air handling process, where the air gets mixed, dried and cools down later. The Psychometric property of the air (Figure 7.28) varies a lot at each stage and have been explained below:

7.8.1 PROCESS OF THE AIR:

The wall integrated system has two sets of coolers and desiccant coated heat exchangers. Fresh hot and humid air (C) (Figure 7.27) enters via the inlet through filters placed on the outer surface and gets mixed with the exhaust of the room (A) recirculated air in the mixing chamber. This mixing of air reduces both the temperature and the humidity of the outside air. After mixing, the air needs to be dried further down before entering the cooler. The air passes through the heat exchanger during the dehumidification cycle and loses all its moisture. The air tends to heat up during dehumidification but the cold water inside the heat exchanger coil counterbalances the heat, resulting in the air with the same temperature but with low humidity (D). This processed air splits into two branches of streams each one of them passing through a dew-point evaporative cooler making it cold and dry air (E)(Figure7.26 (left)). The two streams of air are supplied via common diffuser through a mixed flow ventilation strategy. The cold and dry air (E) when enters the room, gets heated up resulting in an ambient room temperature (F). The air gets heated up with less moisture and enters the mixing chamber for recirculation(A) and the cycle continues.

De-humidification and regeneration need to happen simultaneously for continuous operation. The outdoor air (C) passes through DCHE during the regeneration cycle and absorbs the collected moisture and 30% of (D) cold and dry air is diverted again into the cooler as a working air are the exhausts of the system. (Figure7.26 (right))exhausts of the system. (Figure7.26 (right))

7.8.2 VARIATION 01:

In this full wall length integrated system, the desiccant heat exchanger is placed on the side. The ambient air passes through the desiccant-coated heat exchanger which is split into two of the evaporative coolers that have been stacked one over the another and converges into a single diffuser for supply. The width of the cooler is 1.5m which can be designed based on the grid size of the facade and the system is integrated on the floor slab because of its sleek design.

One of the major advantages of integrating a de-centralized system is to avoid ducts over the ceiling thus eliminating the space required for it. The height of the built structure can be reduced from a typical height 3.3 m or 3.0 m to 2.7m. (Figure7.29)

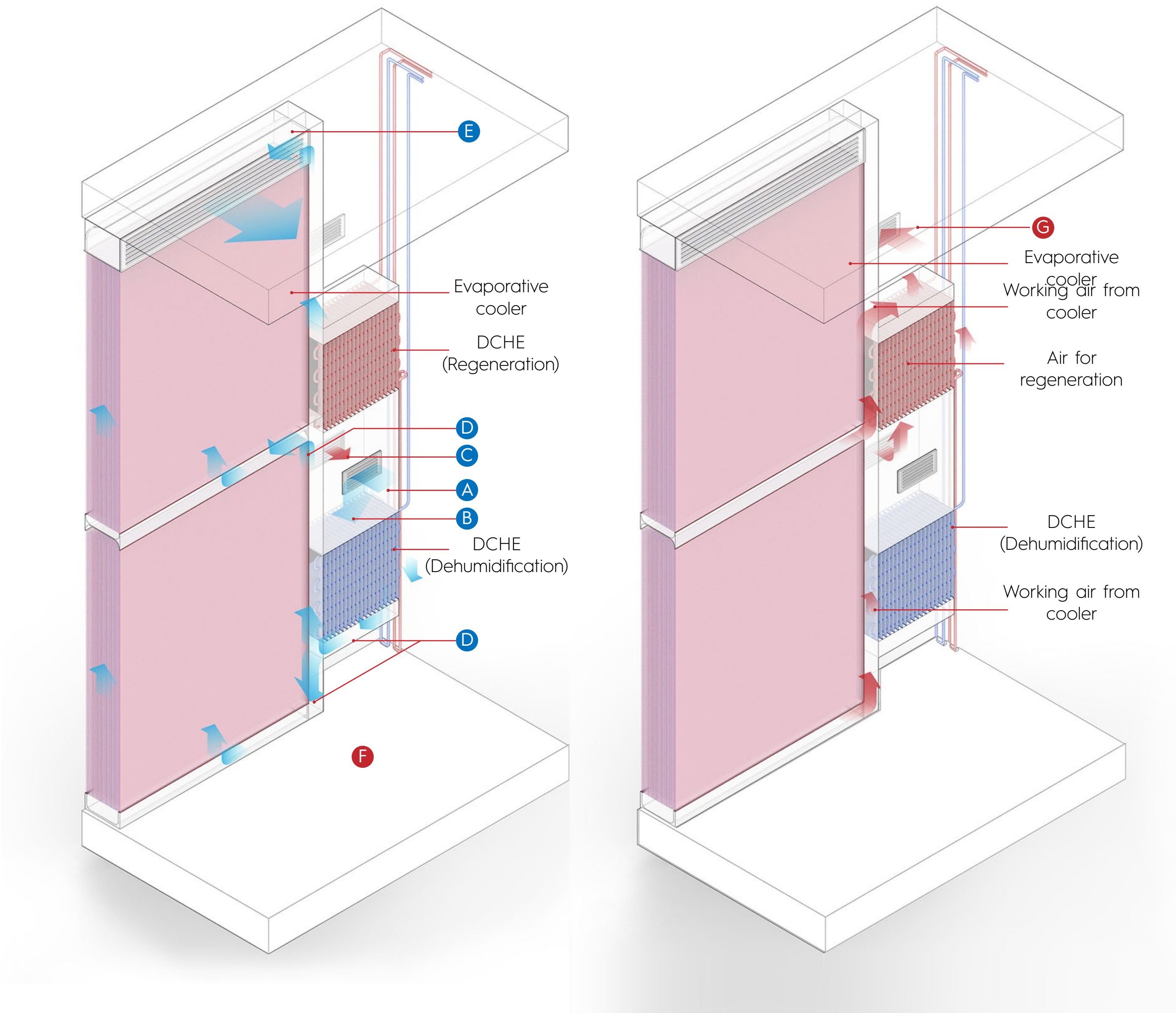


Figure 7.26: Variation 01 : Process of Supply air (left) ; Process of exhaust air (right)

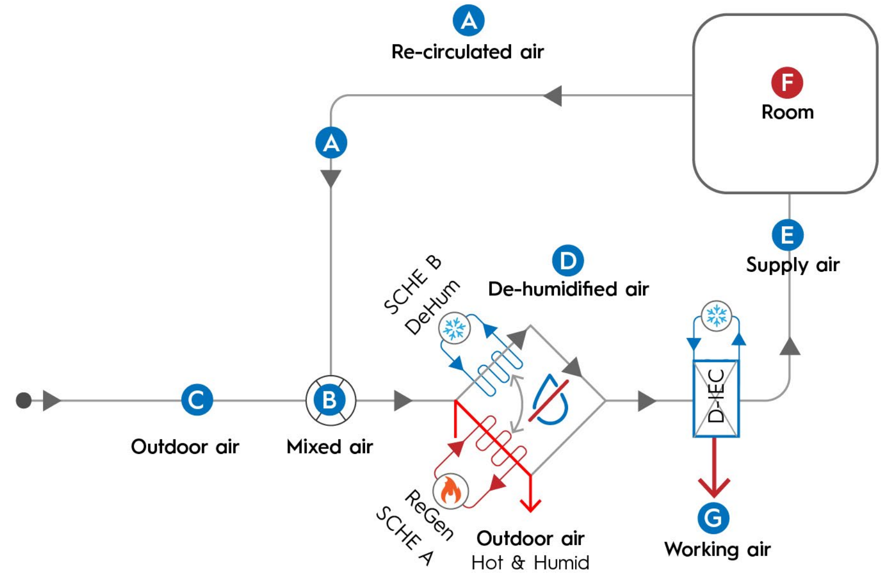


Figure 7.27: Process - Variation 02 - Wall Integrated - 2.7 m

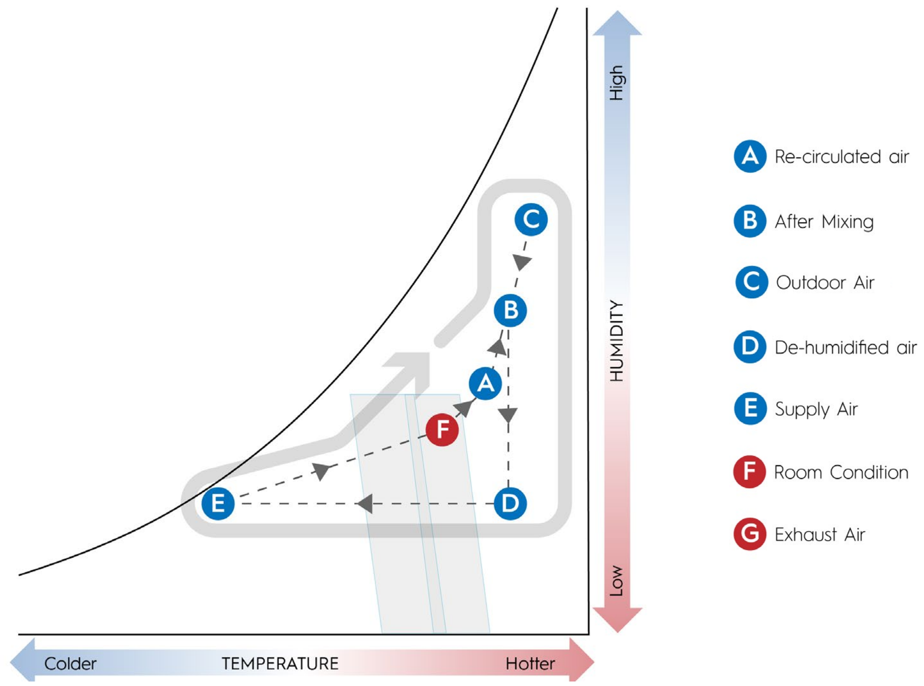
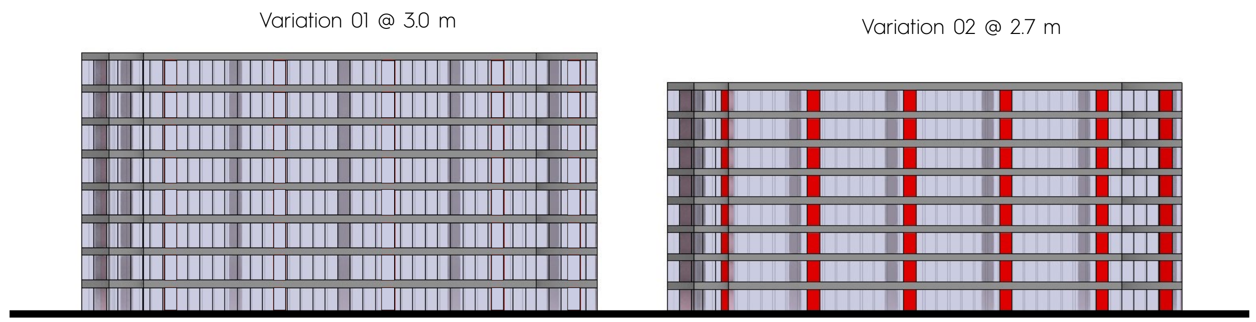


Figure 7.28: Process - Variation 02 - Wall Integrated - 2.7 m



No. of floors : 8
Height of each floor : 3.3 m
Total Height : 26.4

No. of floors : 8
Height of each floor : 3.0 m
Total Height : 24

Total Height saved : 2.4 m

Figure 7.29: Height reduction between various systems

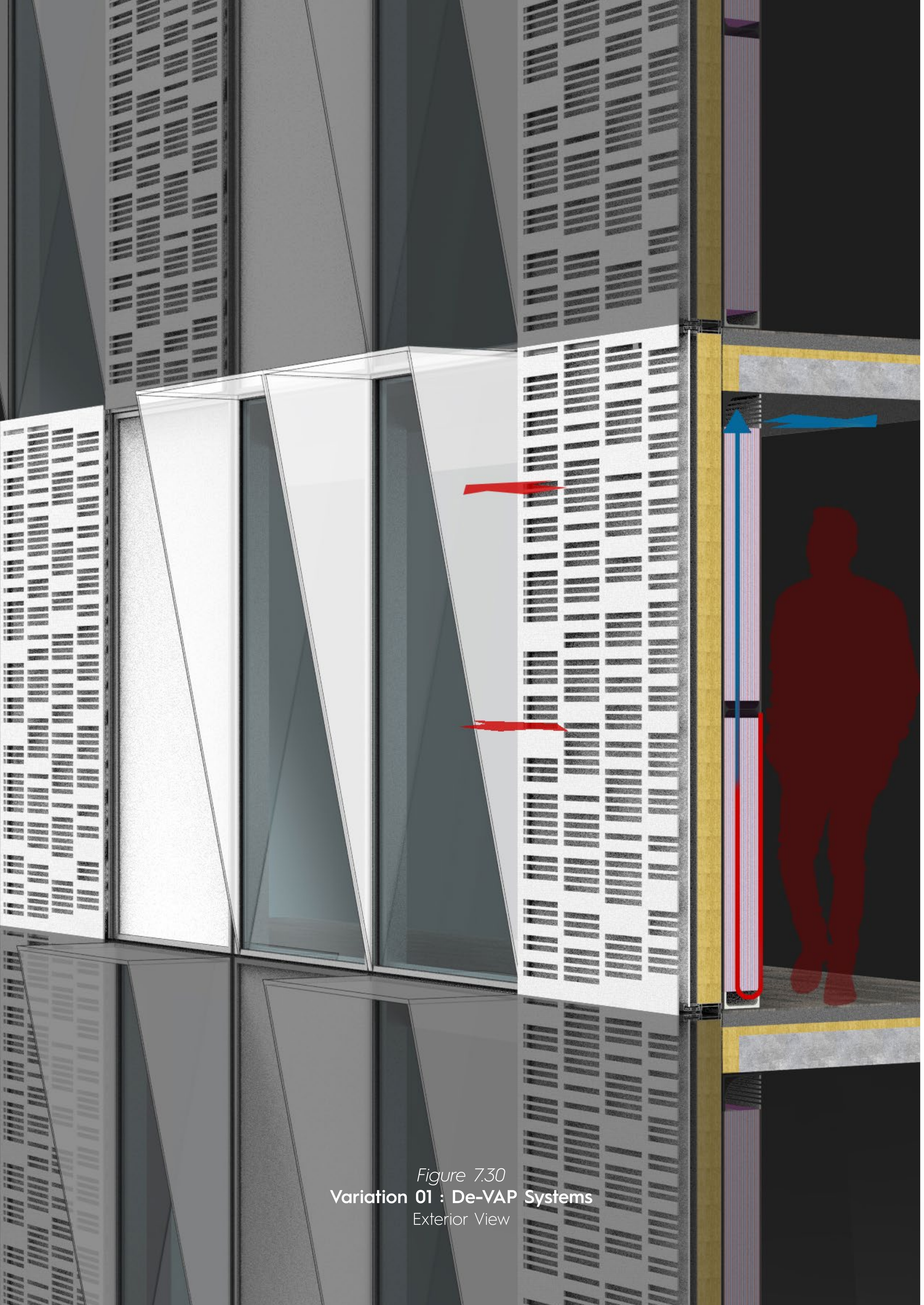


Figure 7.30
Variation 01 : De-VAP Systems
Exterior View

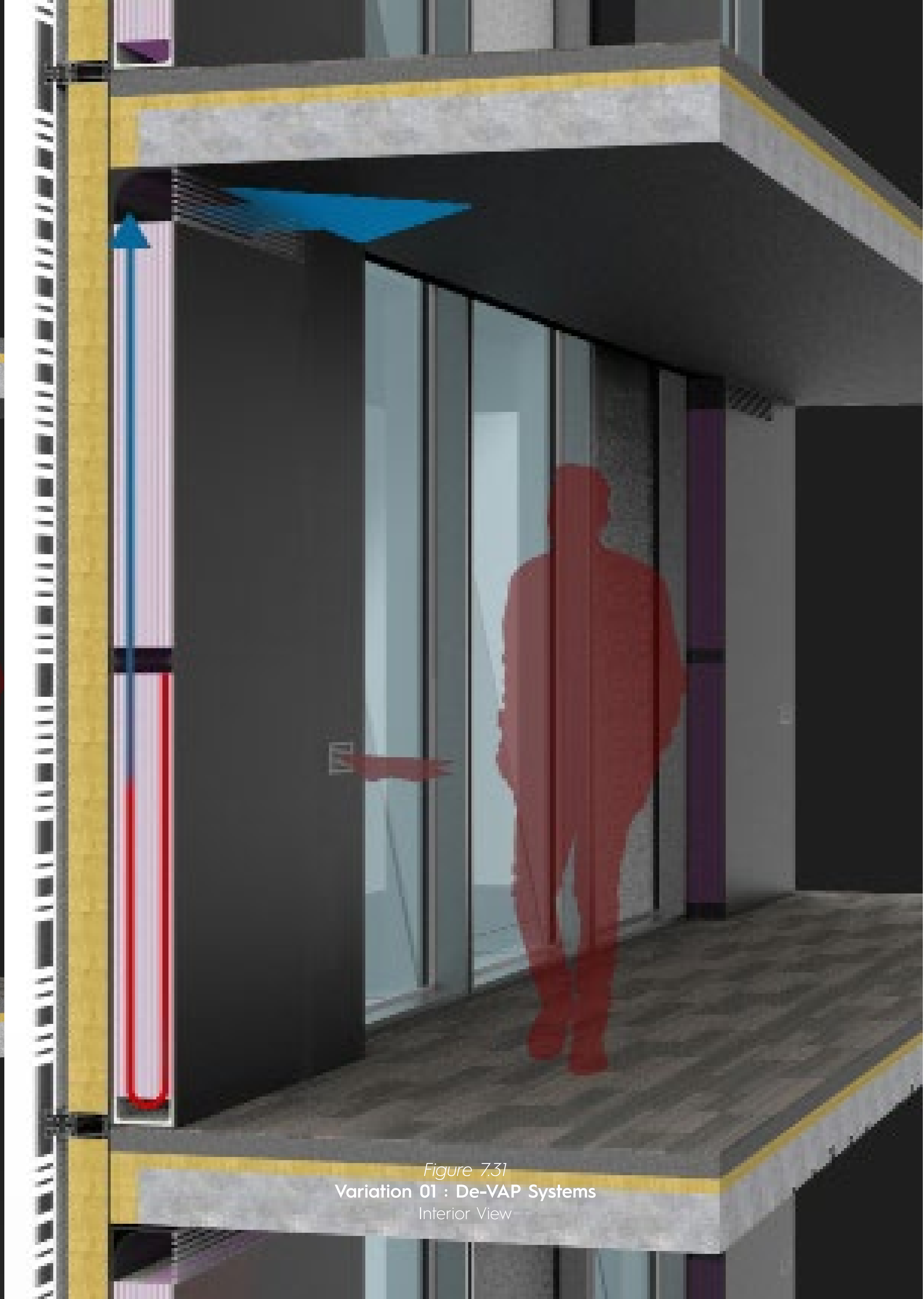
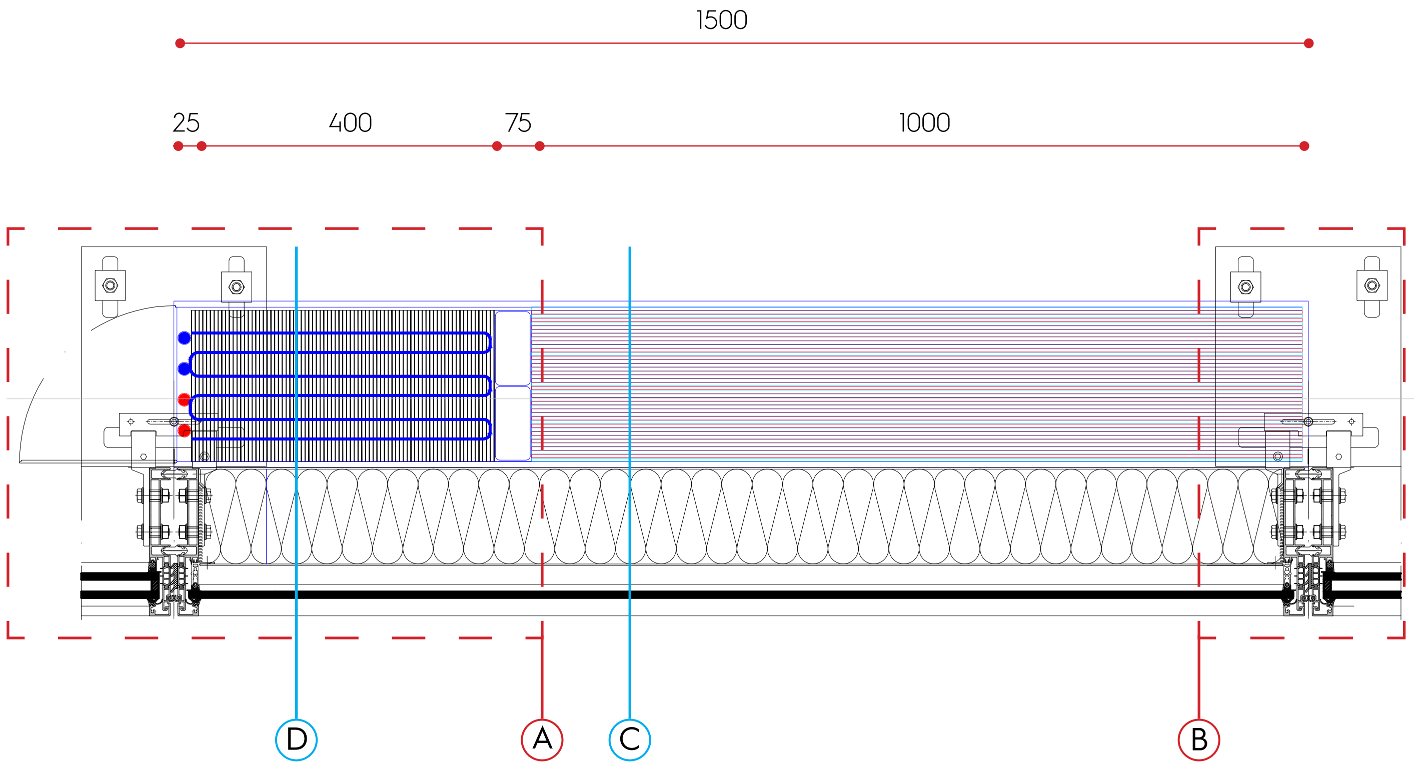


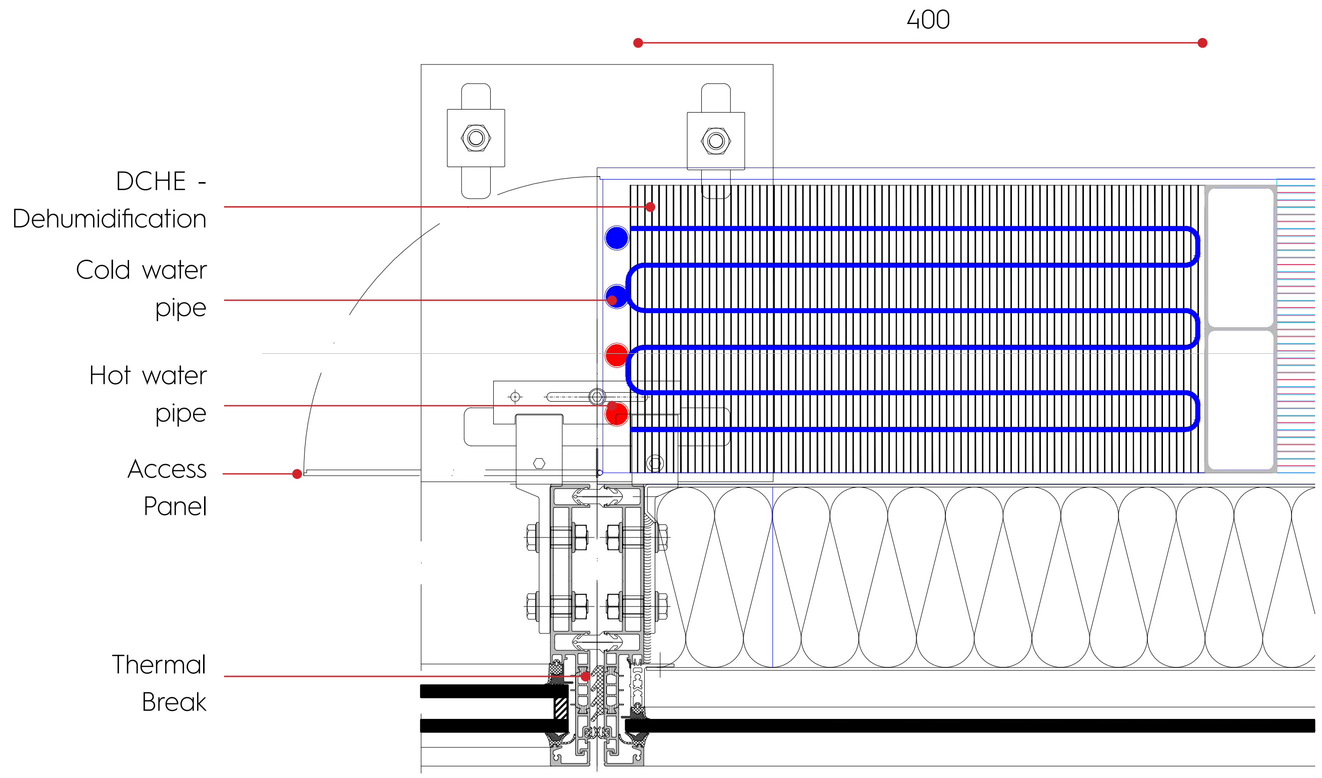
Figure 7.31
Variation 01 : De-VAP Systems
Interior View

7.8.2.1 INTEGRATION DETAILS:

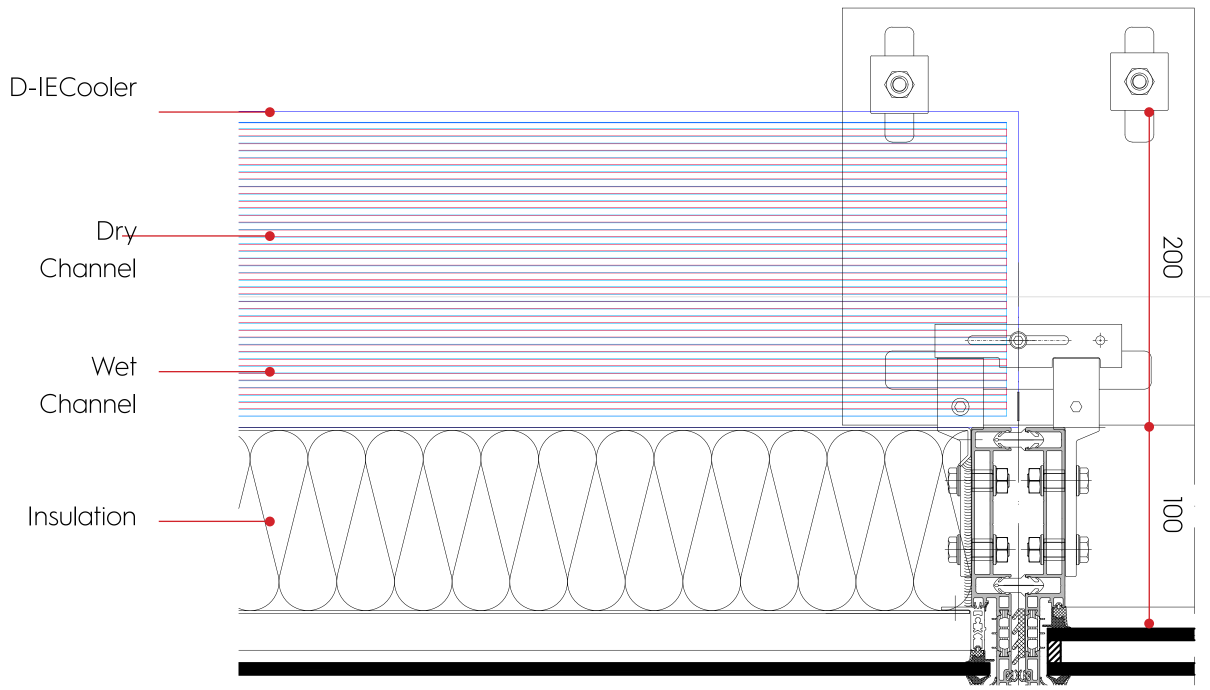


PLAN - Wall system (Variation 02)
Scale 1 : 10

Figure 7.32 : Variation 01 - Wall Integrated - 2.7 m

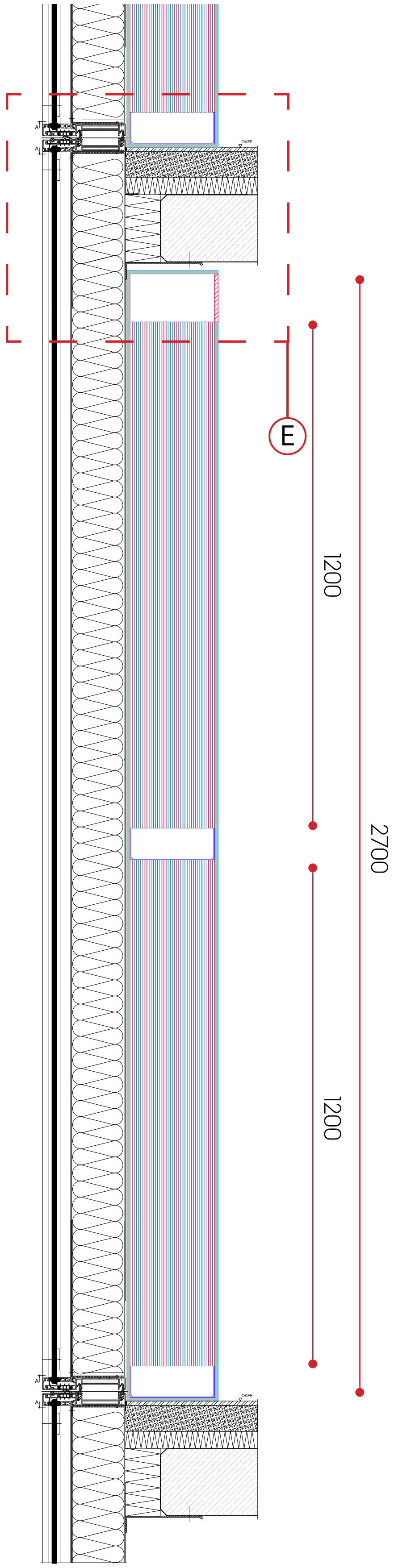


DETAIL @ A
Scale 1 : 5

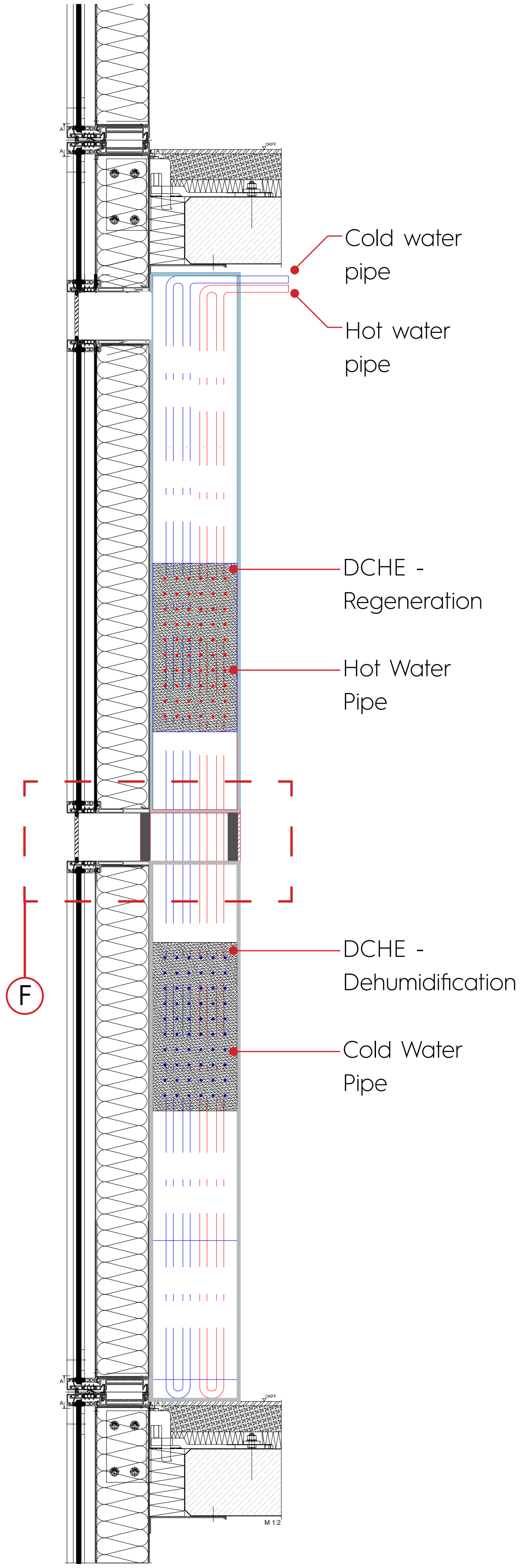


DETAIL @ B
Scale 1 : 5

Figure 7.33: Variation 01 - Wall Integrated - 2.7 m

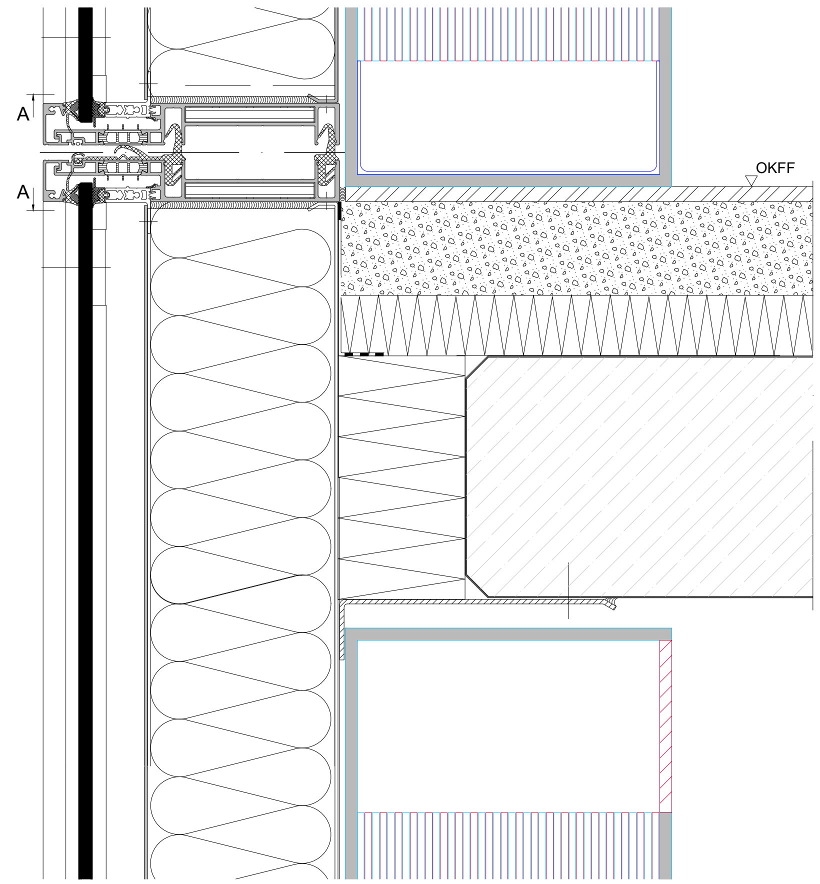


SECTION @ C
Scale 1 : 15

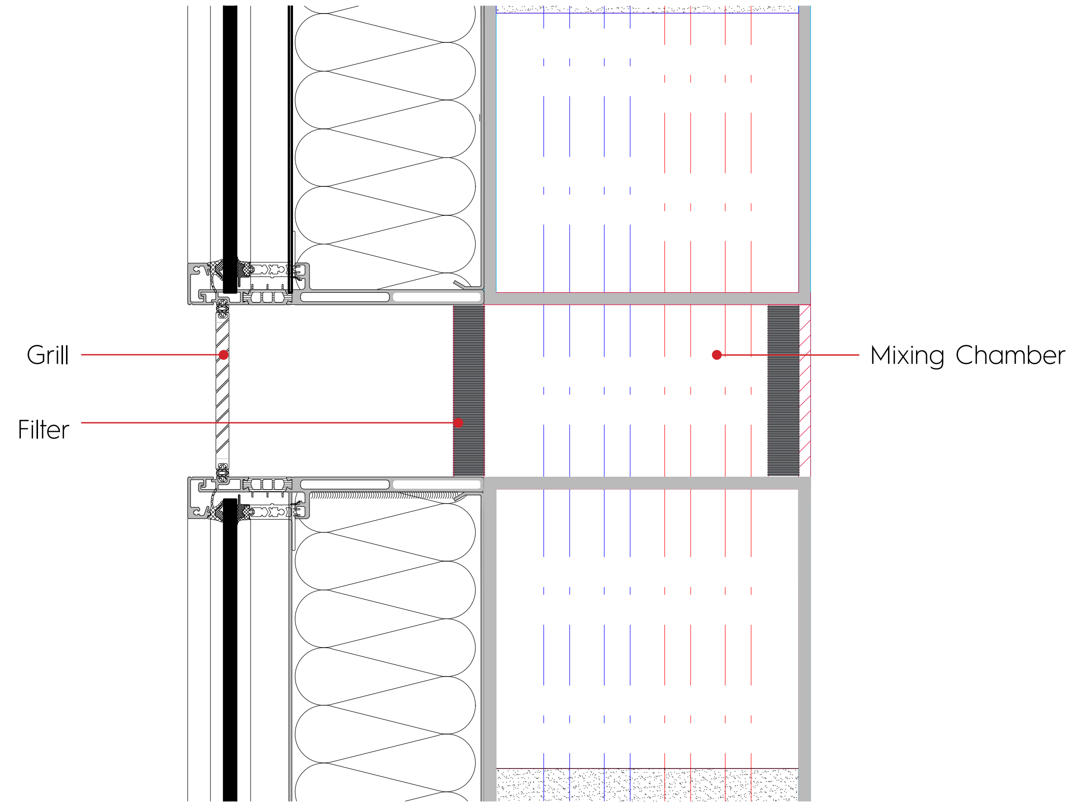


SECTION @ D
Scale 1 : 15

Figure 7.34: Variation 02 - Wall Integrated - 2.7 m



DETAIL @ E
Scale 1 : 5



DETAIL @ F
Scale 1 : 5

Figure 7.35 : Variation 02 - Wall Integrated - 2.7 m

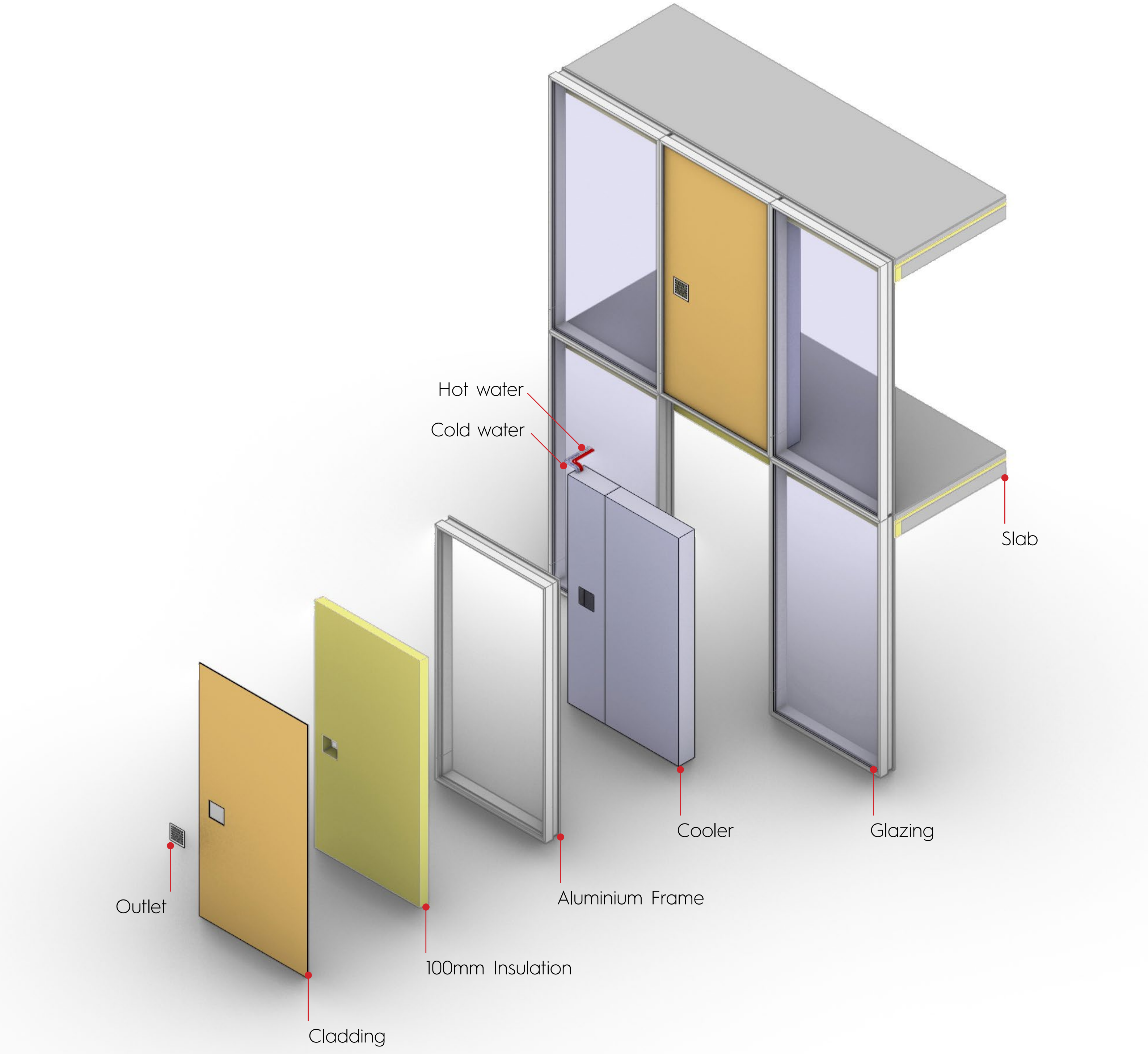


Figure 7.36 : Exploded view : Variation 02 - Wall Integrated - 2.7 m

7.8.3 VARIATION 02:

In the previous option, the cooler is placed inside, but in variation 03, the system acts as an element of the facade with a clean flushed design from the inside. This projected structure can be integrated with the shading devices and helps in creating the language for the facade. The new cooler is resized into a 0.4m*0.4m device and is covered with 100mm of insulation. The 3m high shade system has two evaporative cooler stacked upon them with desiccant coated heat exchanger in the middle. Well, the diffuser is placed on the adjacent glazed surface.

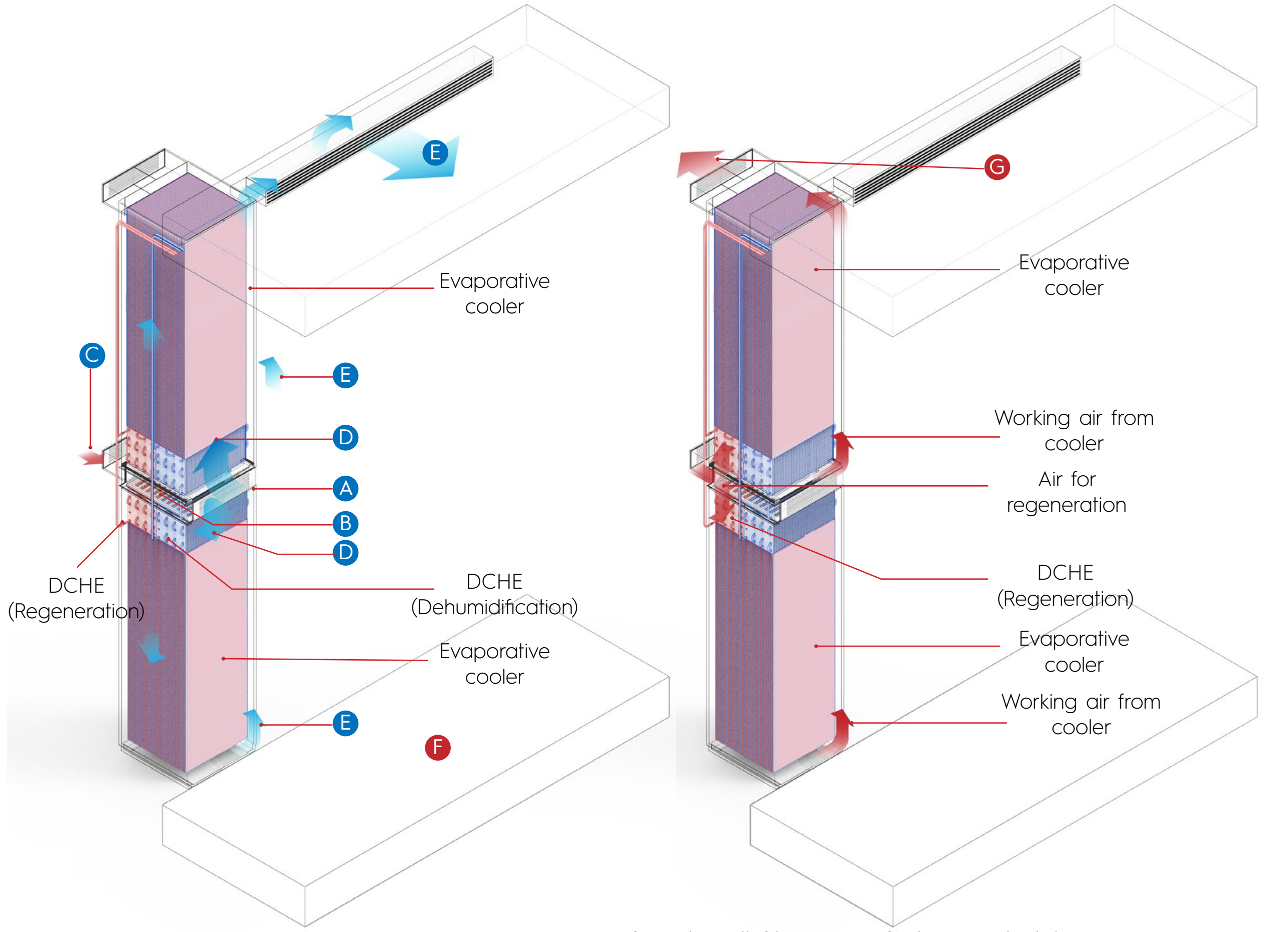


Figure 7.37: Variation 02 : Process of Supply air (left) ; Process of exhaust air (right)

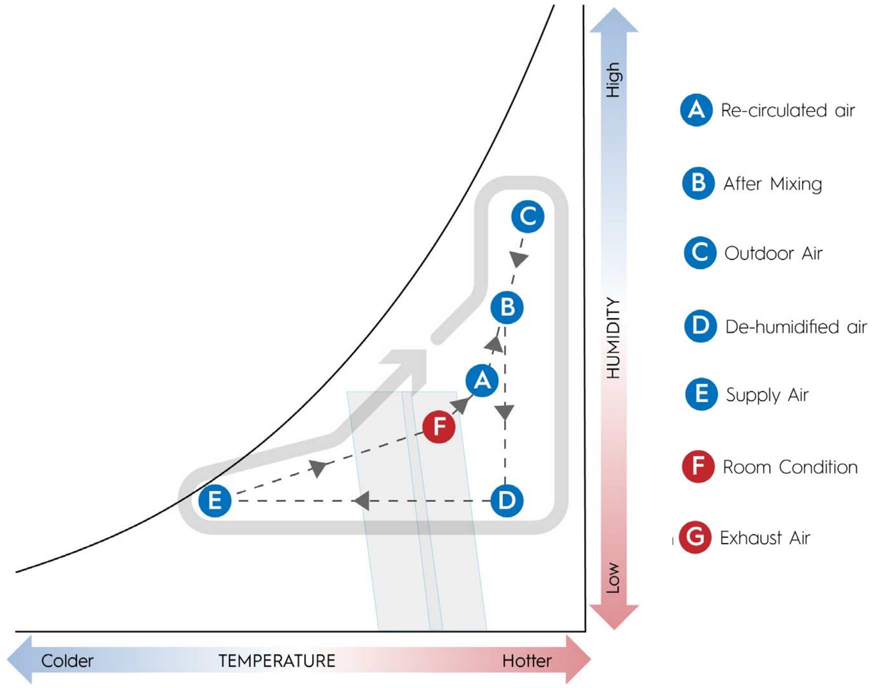


Figure 7.38: Process - Variation 02 - Wall Integrated - 3.0 m

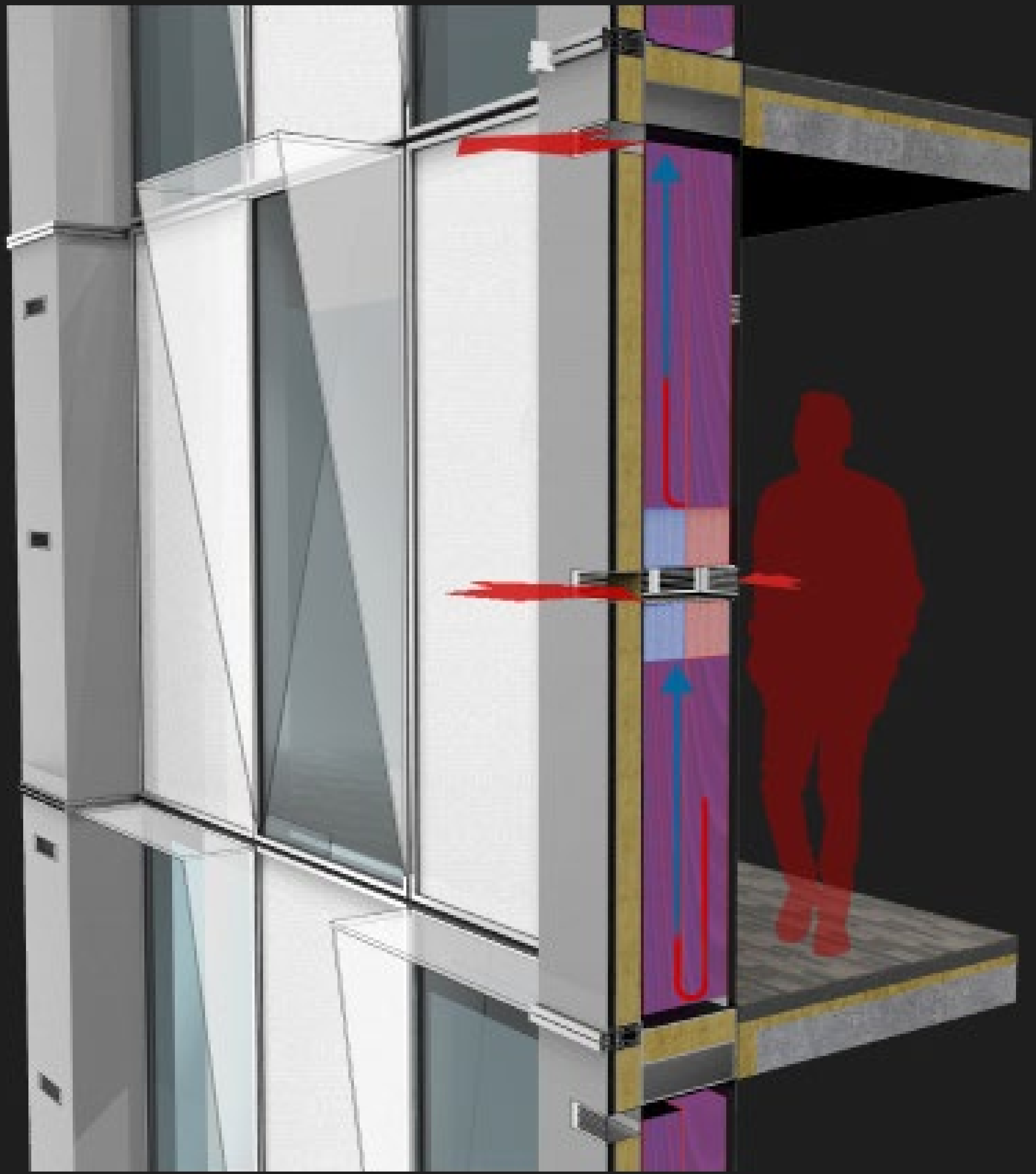


Figure 7.39
Variation 02 : De-VAP Systems
Exterior View

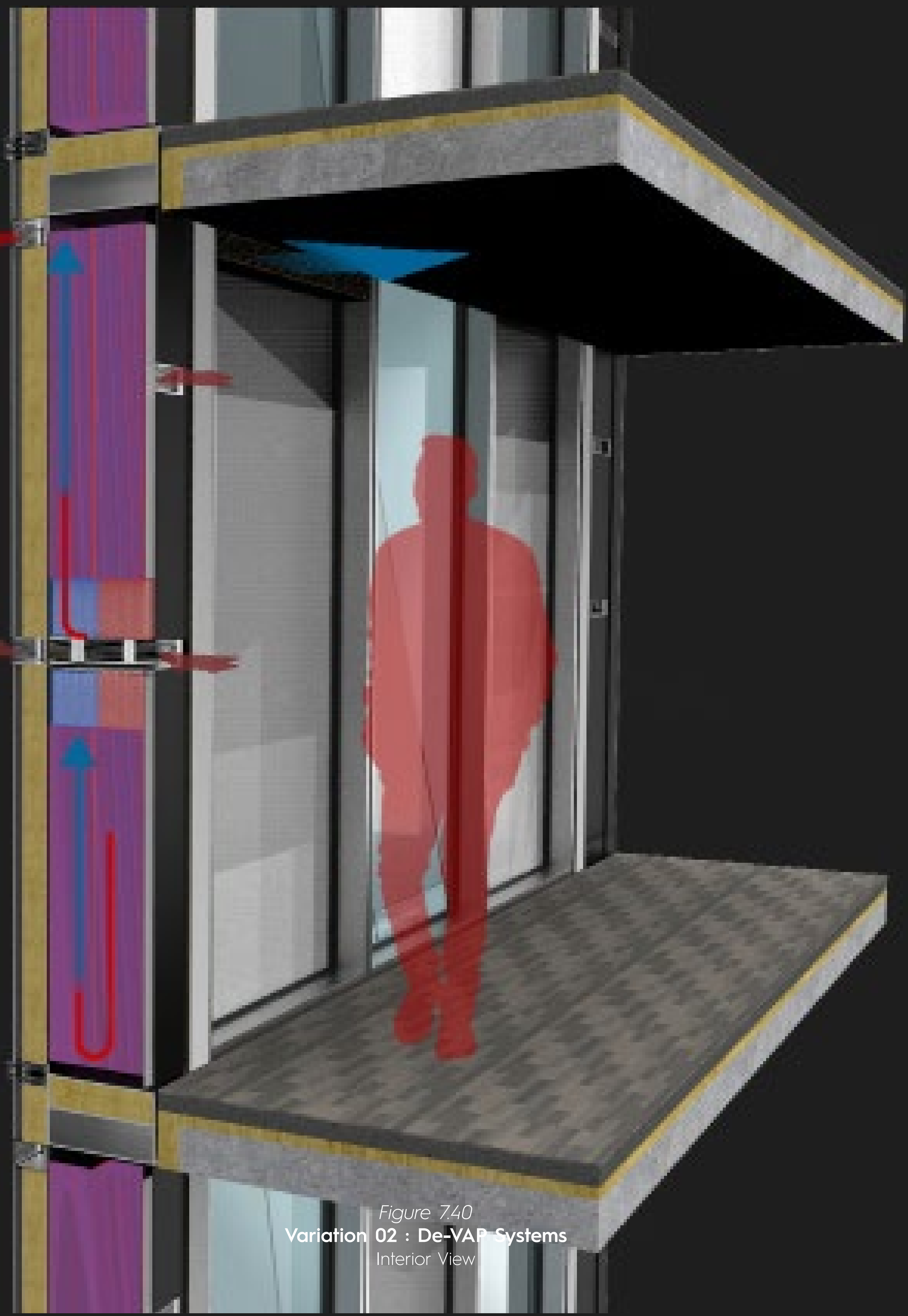
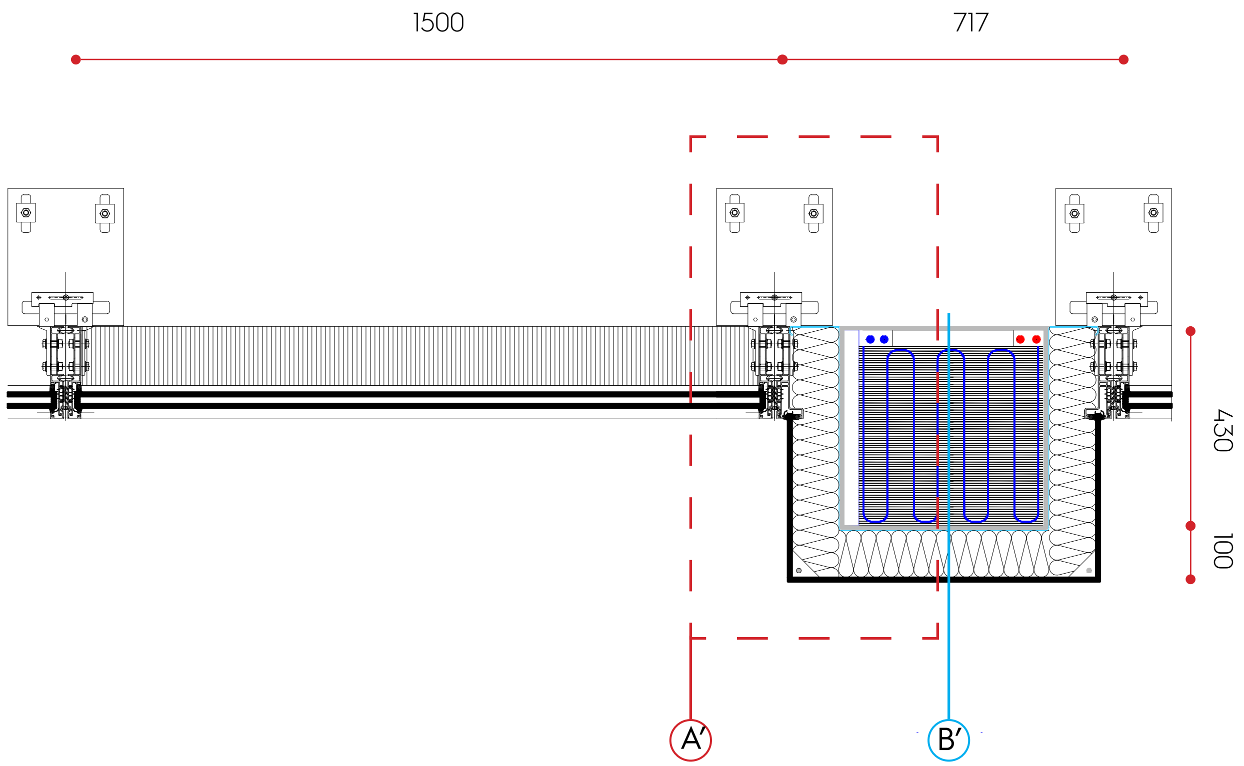


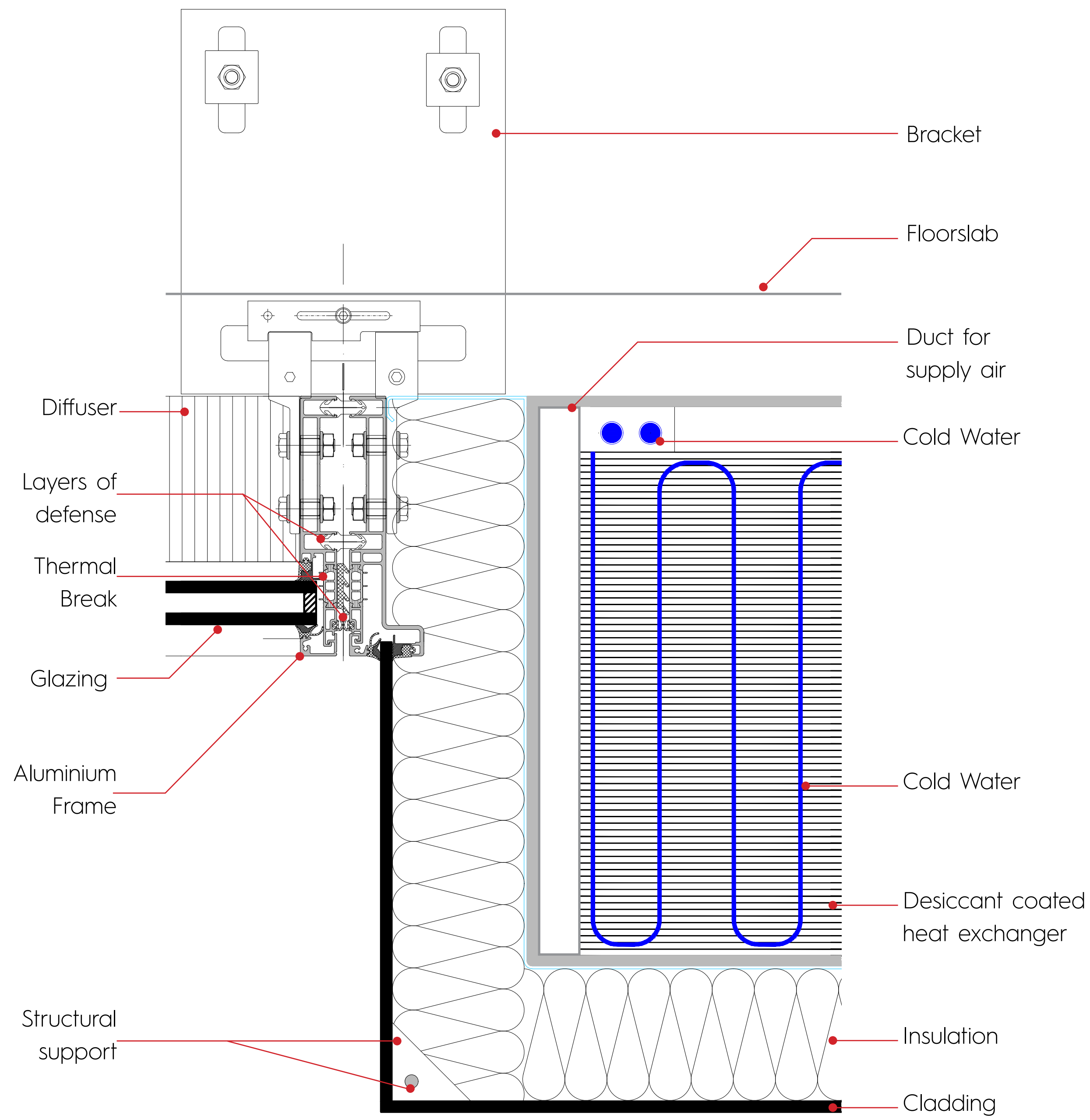
Figure 7.40
Variation 02 : De-VAP Systems
Interior View

7.8.3.1 INTEGRATION DETAILS:



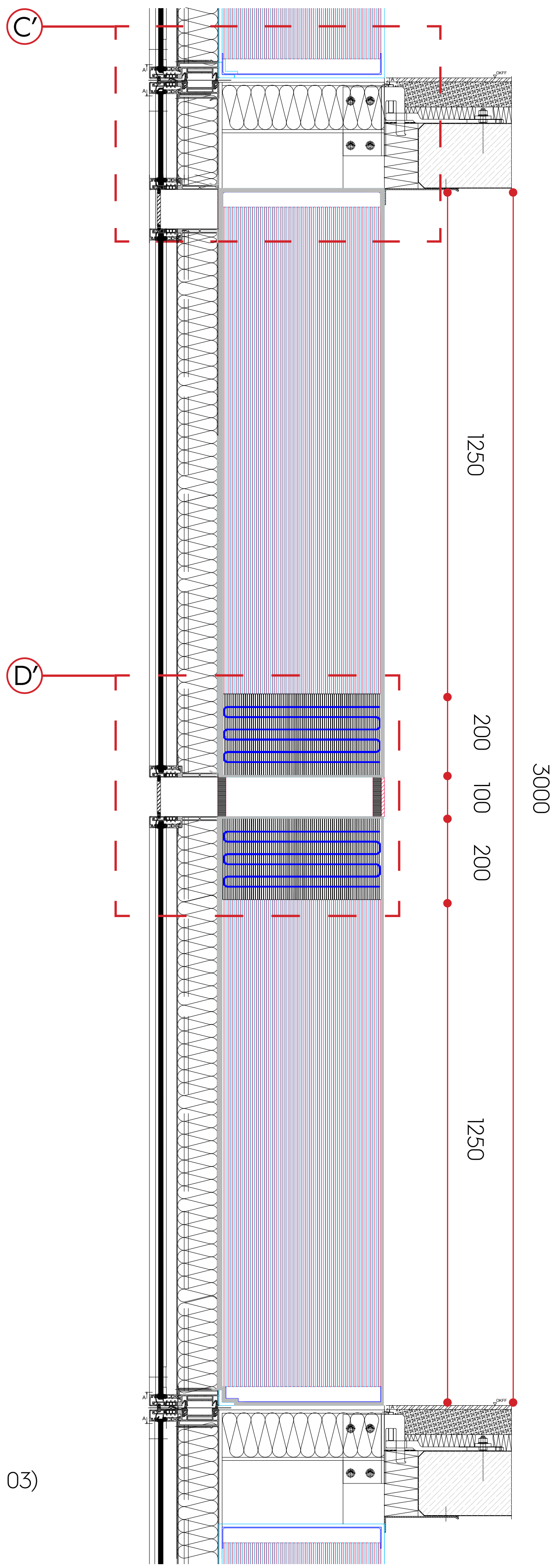
PLAN - Shading system (Variation 03)
Scale 1 : 15

Figure 7.41: Variation 03 - Shade Integrated - 3.0 m



DETAIL @ A'
Scale 1 : 5

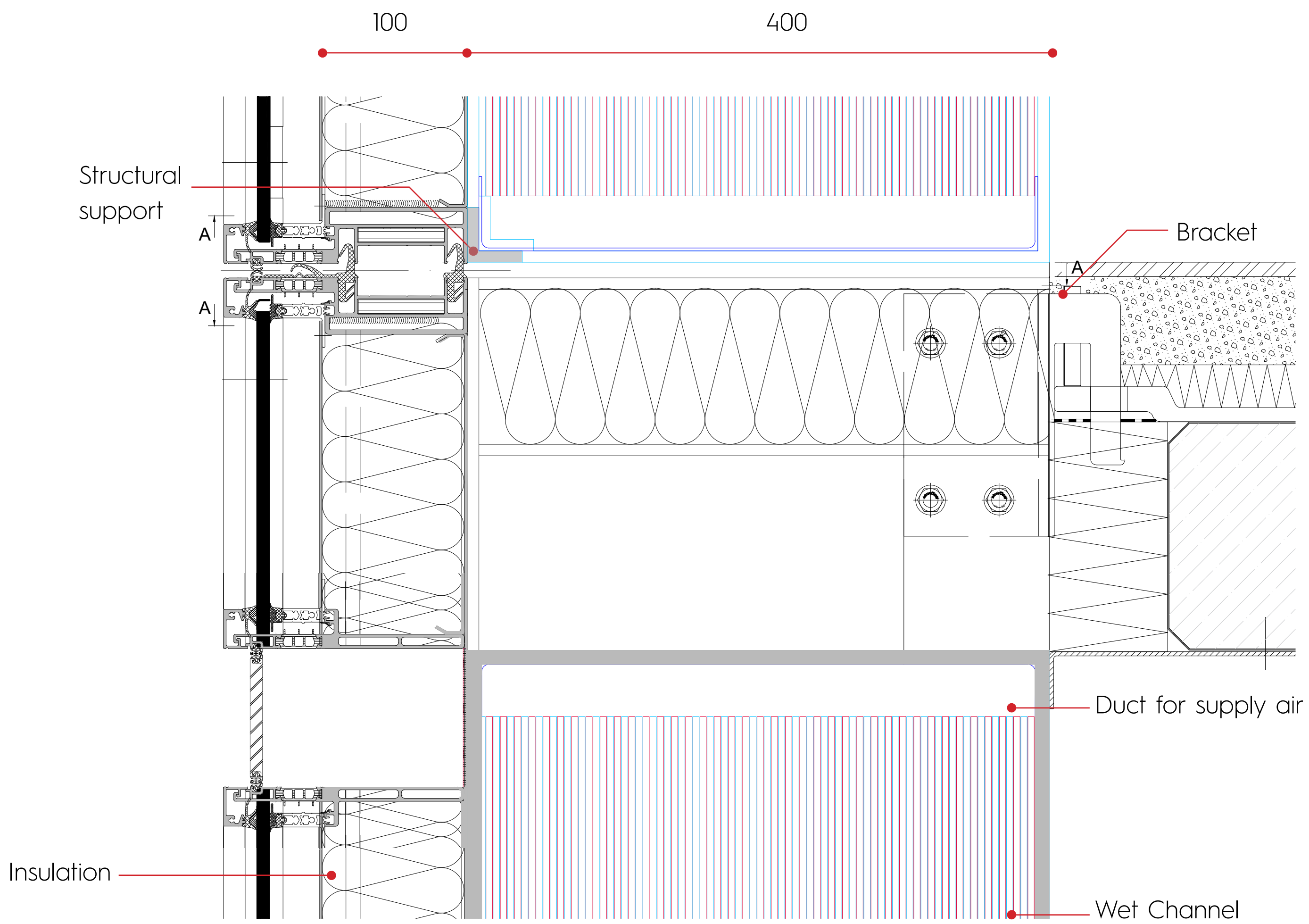
Figure 7.42: Variation 03 - Shade Integrated - 3.0 m



SECTION @ B′ - Shading system (Variation 03)

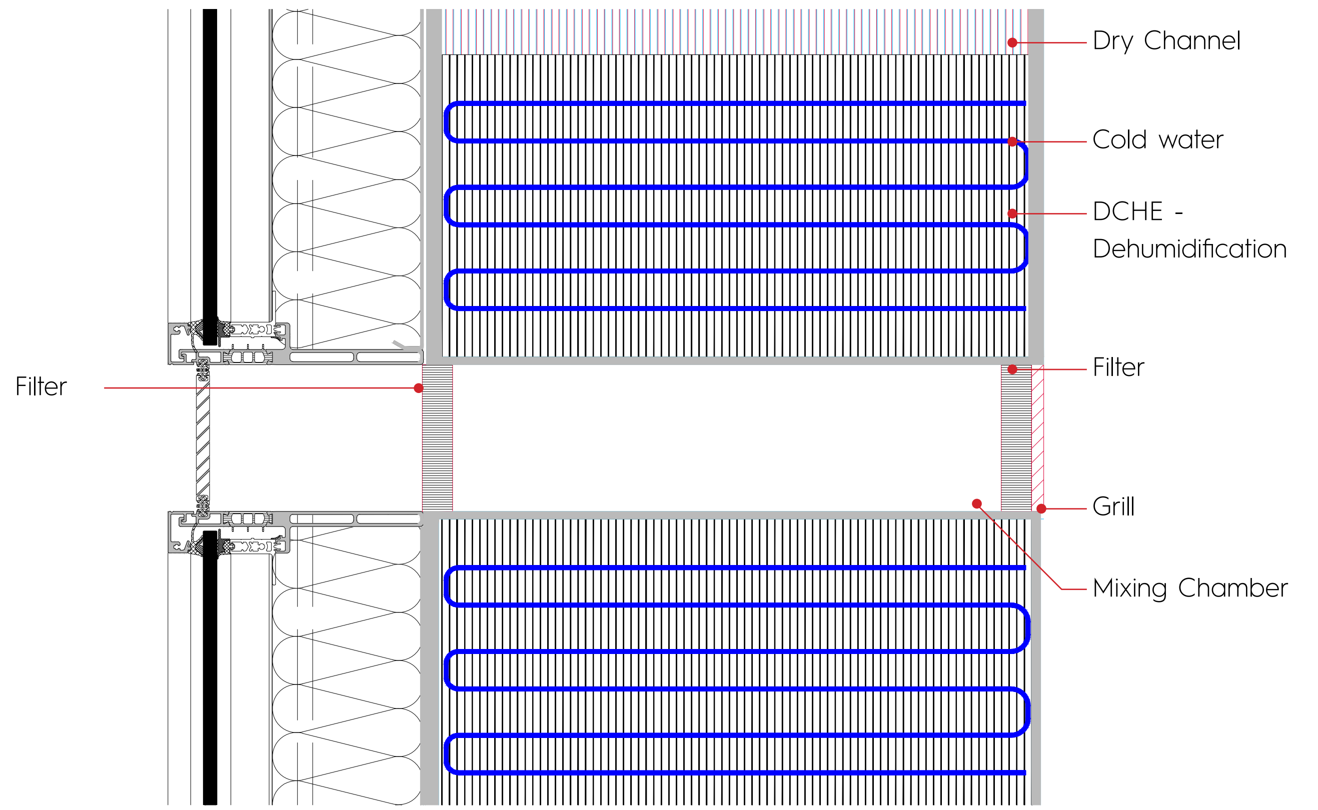
Scale 1 : 15

Figure 7.43: Variation 02 - Shade Integrated - 3.0 m



DETAIL @ C′

Scale 1 : 5



DETAIL @ D′

Scale 1 : 5

Figure 7.44: Variation 02 - Shade Integrated - 3.0 m

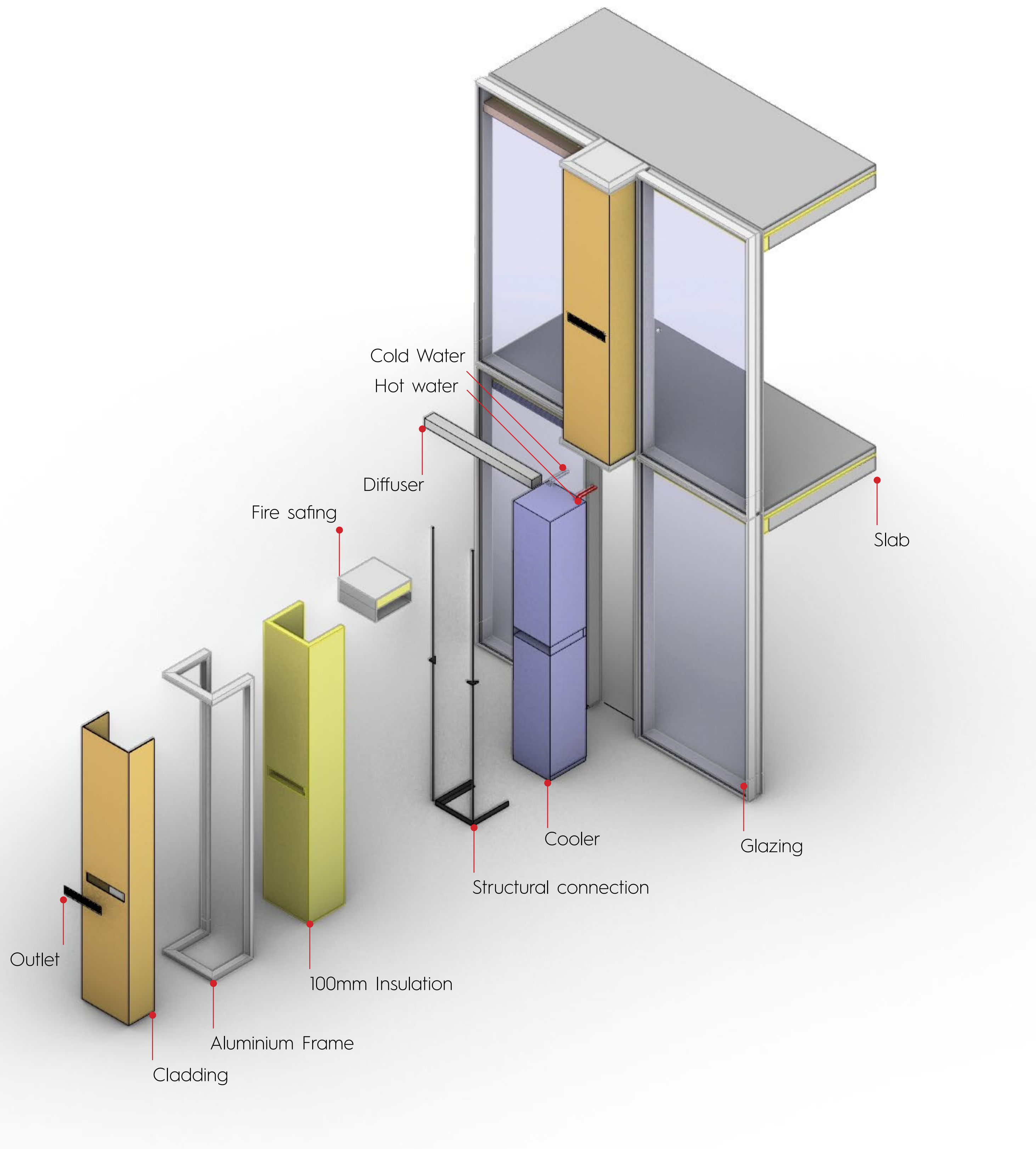


Figure 7.45 : Exploded view : Variation 02 - Shade Integrated - 3.0 m

7.9 GUIDELINES FOR INTEGRATION – NUMBER OF SYSTEMS VS COOLING LOAD :

The number of devices that are to be integrated over the facade depends on the cooling load of the space. The balance between numbers of devices over the cooling load not only plays a crucial role in maintenance but also its hinderance over the skin as a design element. Various passive strategies result in different cooling load resulting in various configurations in which the cooler can be integrated.

A series of simulation is conducted to understand the cooling loads of various passive strategies and visualization of the cooler system over the facade. The major structure for the order of simulation is by varying the WWR as 40%, 60% and 80%as it is the most influential parameter on the cooling and on the design language. Each window to wall ratio-built

Case 1: The Base case building with standard materials for construction which has poor insulation, with no shading and improved internal heat gains. see APPENDIX
Case 2: Improvised internal heat gains by using LED and calculating the required ventilation.
Case 3: Along with the heat gains and ventilation, the U values of various built structure are increased
Case 4: The final parameter includes most efficient shading strategy.

The variation 03 has been used for the visualization, as it has a more prominent impact over the facade as a projected vertical element. From the series of the design, it is up to the architect or the designer to decide on till which level they would like to incorporate passive strategies on design. This decision creates a major impact on the language of the facade.

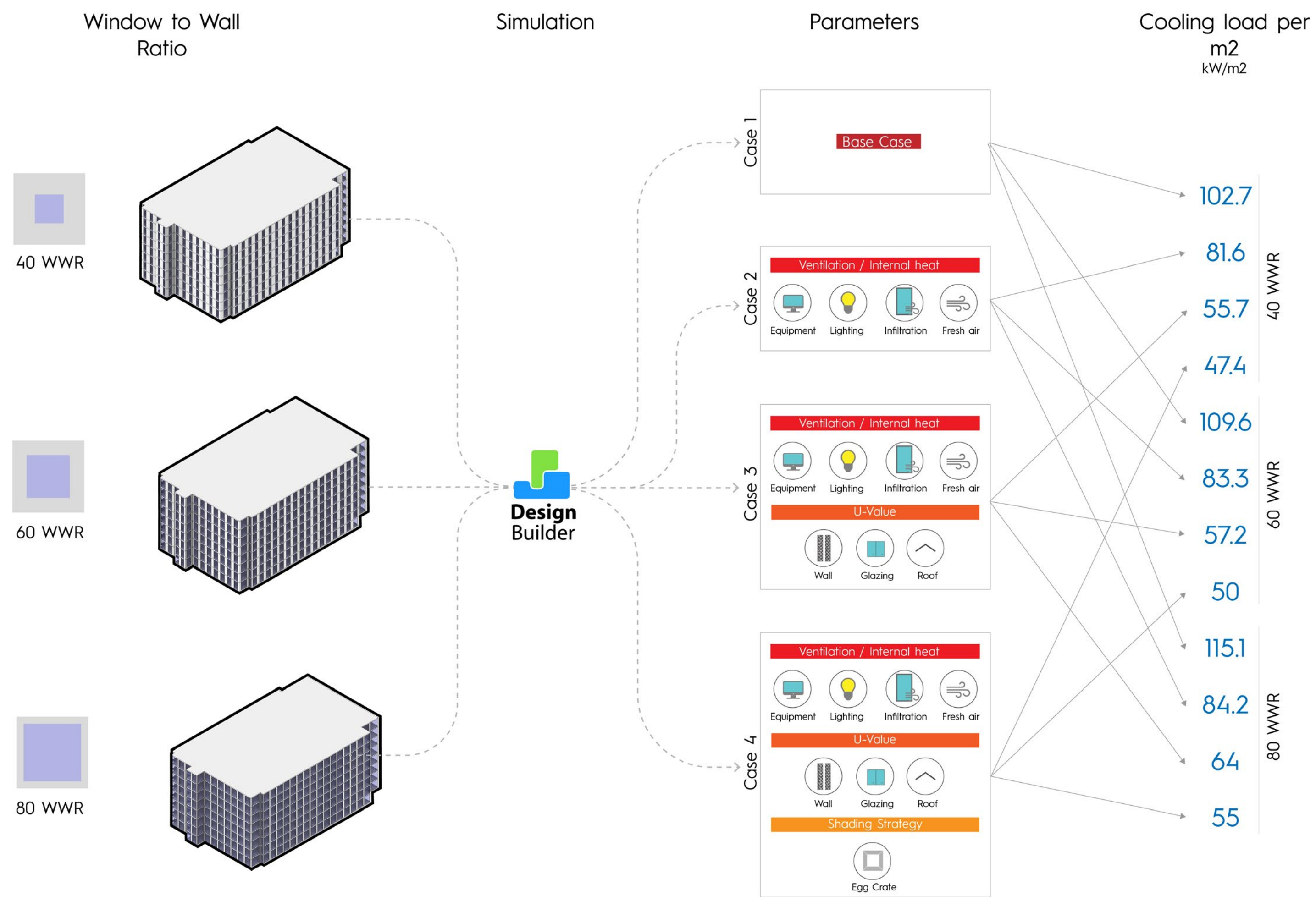
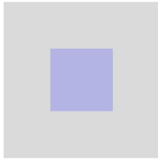


Figure 7.46 : Simulation of the built structure with varying parameters

7.9.1 40 WWR



40 WWR

Case 1

Cooling load

178 kW

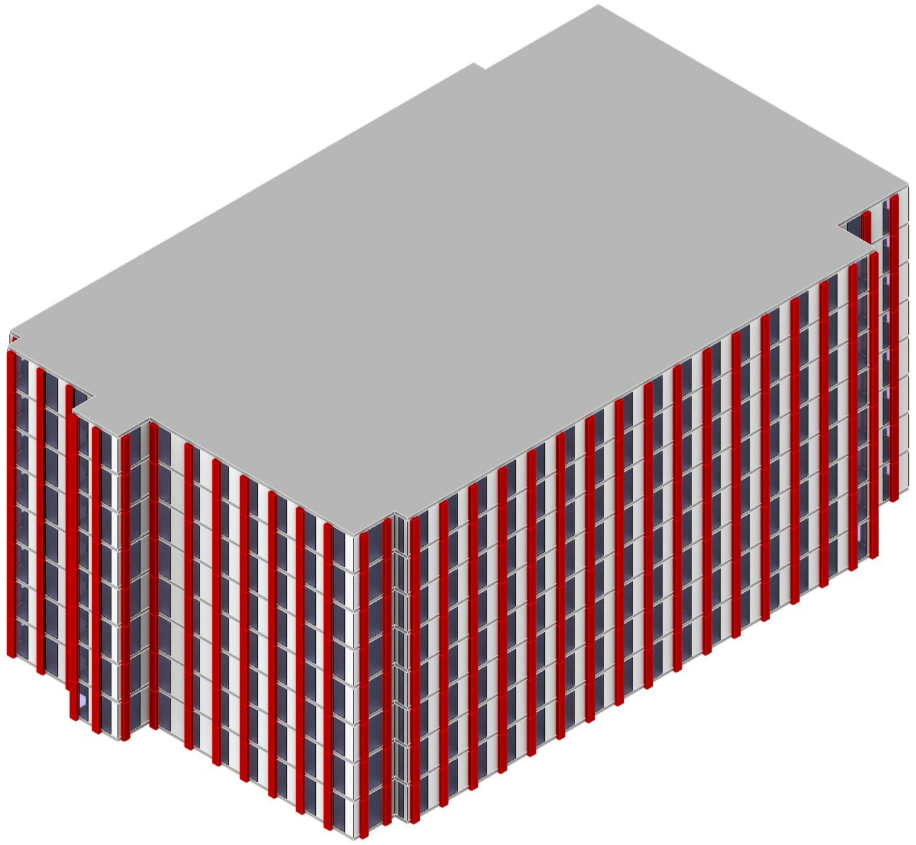
Cooling load per m2

102.7 W/m2

No. of Devices per floor

70

(Appendix 11.6)



Case 2

Cooling load

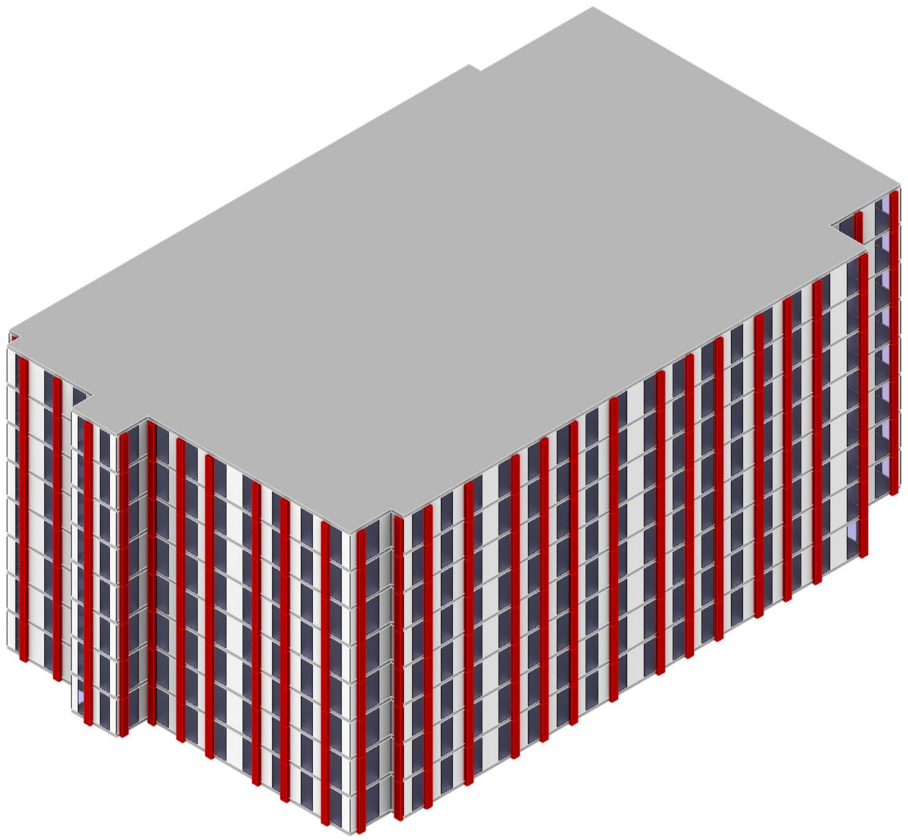
142 kW

Cooling load per m2

81.6 W/m2

No. of Devices per floor

55



Case 3

Cooling load

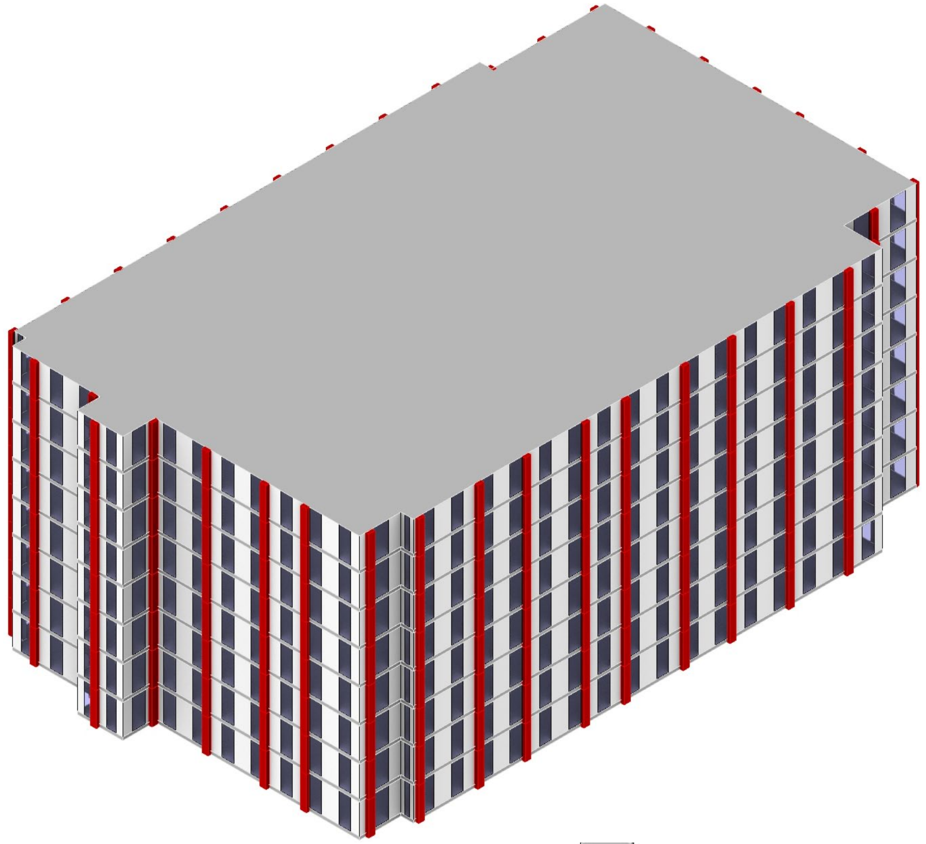
96.9 kW

Cooling load per m2

55.7 W/m2

No. of Devices per floor

37



Case 4

Cooling load

82.5 kW

Cooling load per m2

47.4 W/m2

No. of Devices per floor

32

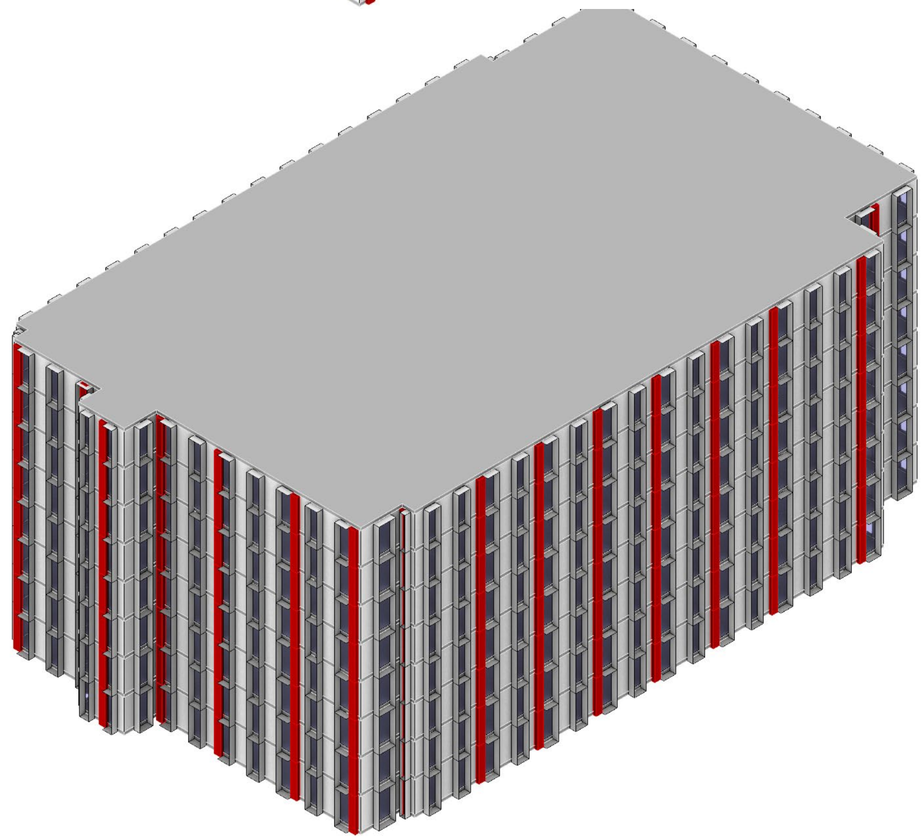
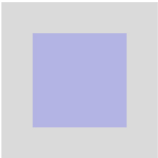


Figure 7.47 : Visualization of overall buiding facade with various cooling load at 40% WWR

7.9.2 60 WWR



60 WWR

Case 1

Cooling load

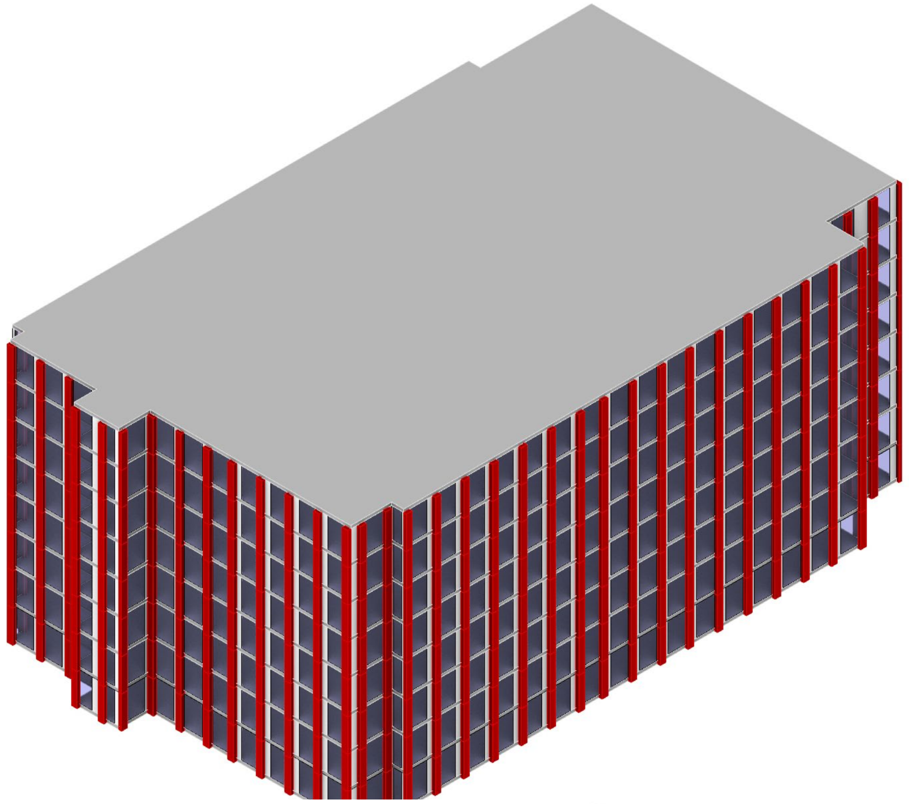
190.7 kW

Cooling load per m2

109.6 W/m2

No. of Devices per floor

75



Case 2

Cooling load

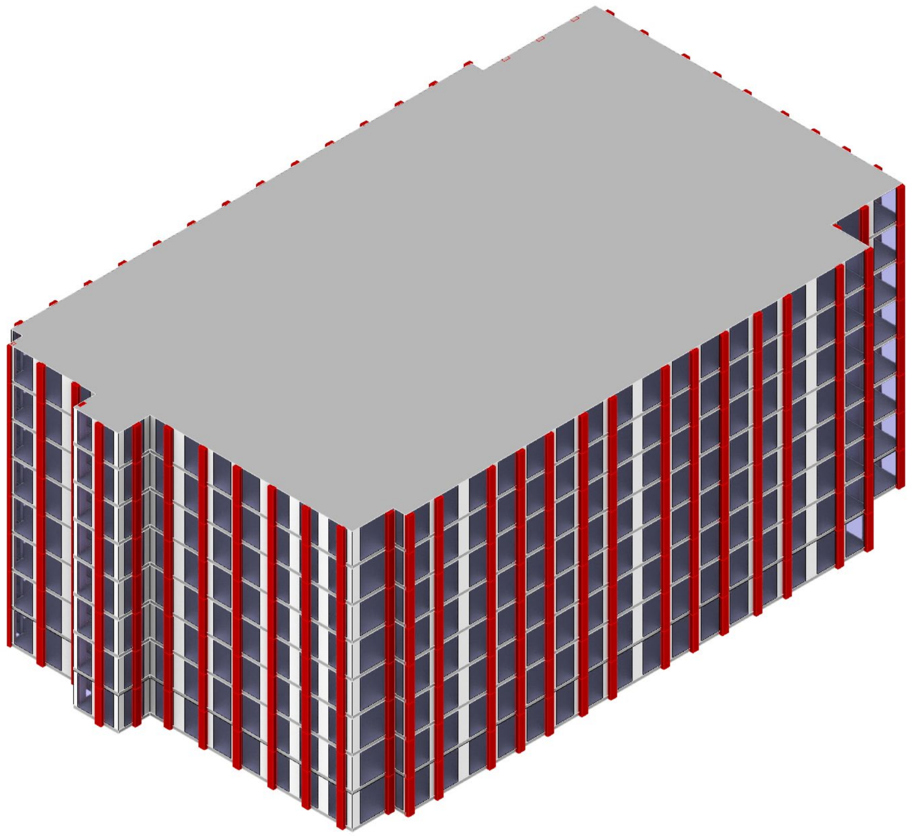
144.9 kW

Cooling load per m2

83.3 W/m2

No. of Devices per floor

56



Case 3

Cooling load

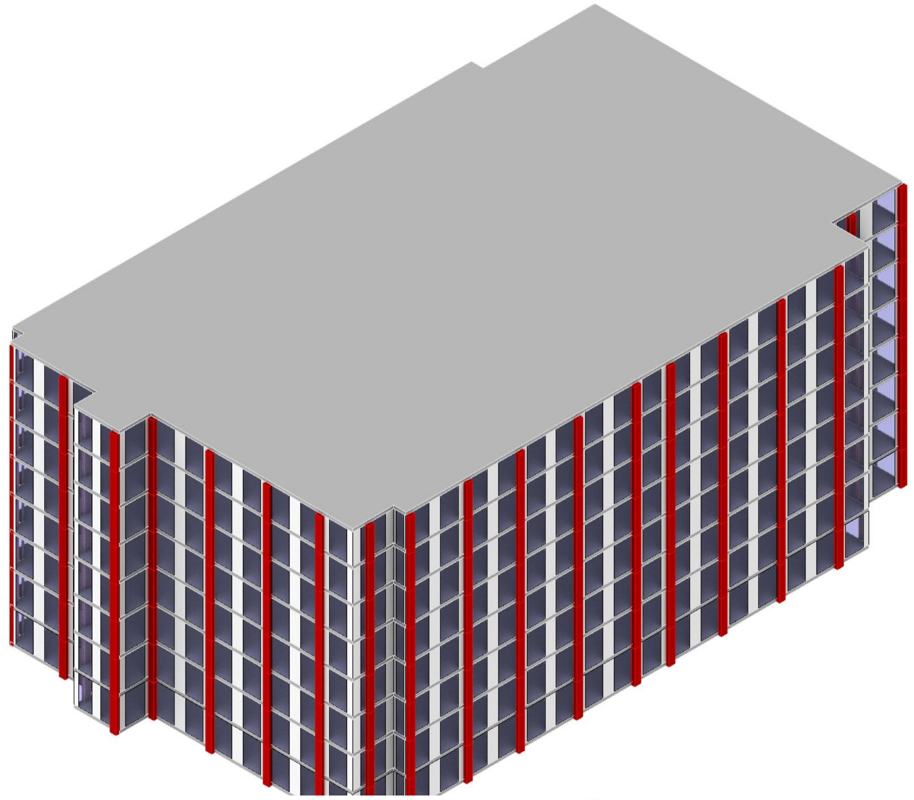
99.5 kW

Cooling load per m2

57.2 W/m2

No. of Devices per floor

38



Case 4

Cooling load

87.0 kW

Cooling load per m2

50.0 W/m2

No. of Devices per floor

33

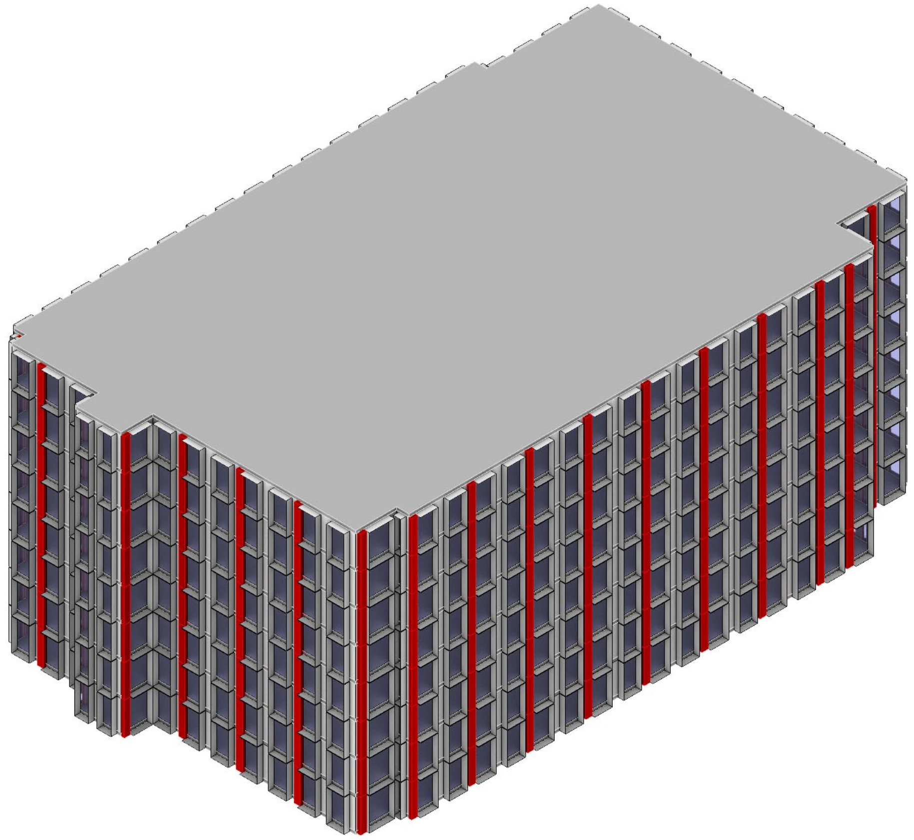


Figure 7.48 : Visualization of overall buiding facade with various cooling load at 40% WWR

80 WWR

7.9.3 80 WWR:

The recommended WWR ratio by ECBC for Indian composite climate is below 60%. But despite the fact if the design really compels for a fully glazed structure the maximum that be can be achieved is up to 80%. Since the building has higher WWR, the number of devices required to address the cooling demand is more. This devices significantly covers the building's skin resulting in lower WWR, so the building needs to be passively optimized to get less number of devices with more openings/glazing.

Case 1

Cooling load

200.3 kW

Cooling load per m2

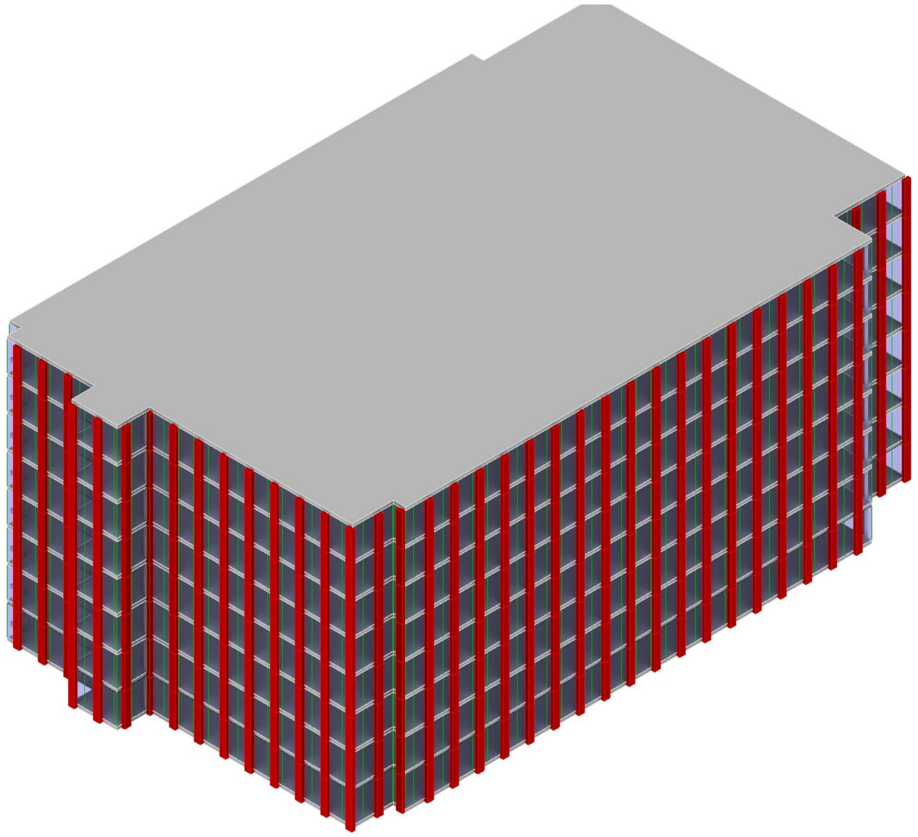
115.1 W/m2

No. of Devices per floor

77

WWR

57.8



Case 2

Cooling load

146.5 kW

Cooling load per m2

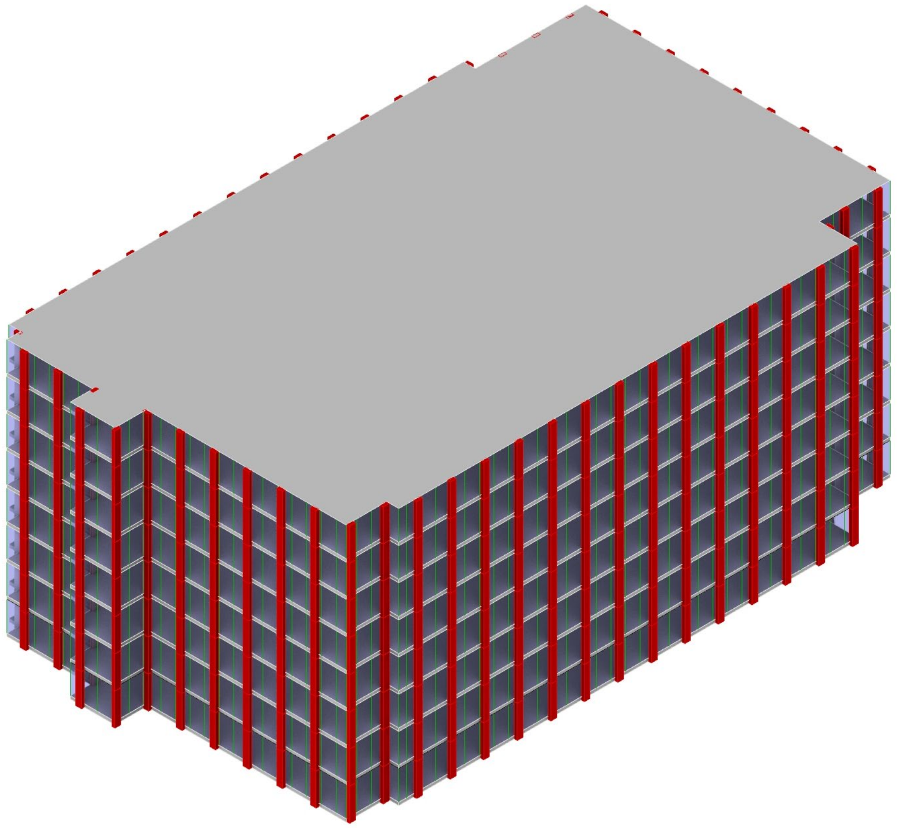
84.2 W/m2

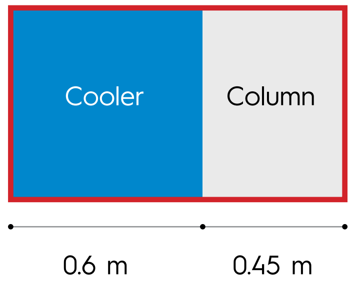
No. of Devices per floor

57

WWR

68.8





The cooler can be fixed along with the column and can be treated as a single vertical element. As the cooling load is so high in Case 1 and Case 2 the amount of opening that can be achieved is only up to 57.8 and 68.8 % respectively. In order to achieve highly glazed surface, all parameters should be incorporated like in Case 3 and Case 4 leading to WWR up to 76.4 % and 79.7 % respectively.

Case 3

Cooling load

111.4 kW

Cooling load per m2

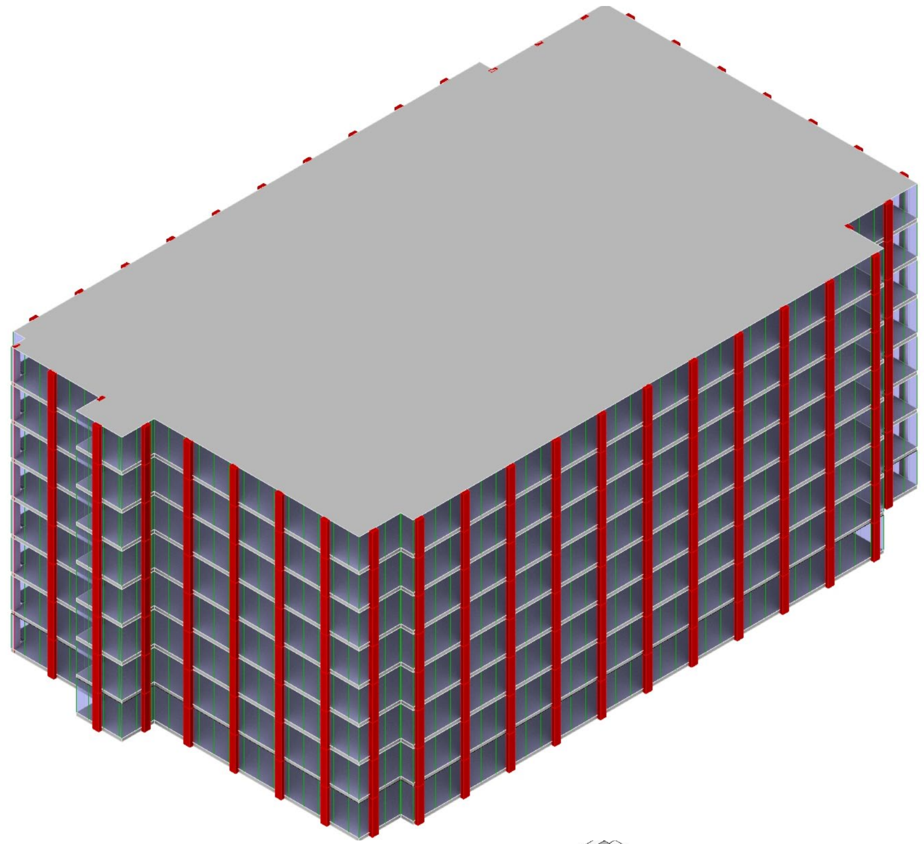
64 W/m2

No. of Devices per floor

43

WWR

76.4



Case 4

Cooling load

96.4 kW

Cooling load per m2

55 W/m2

No. of Devices per floor

37

WWR

79.7

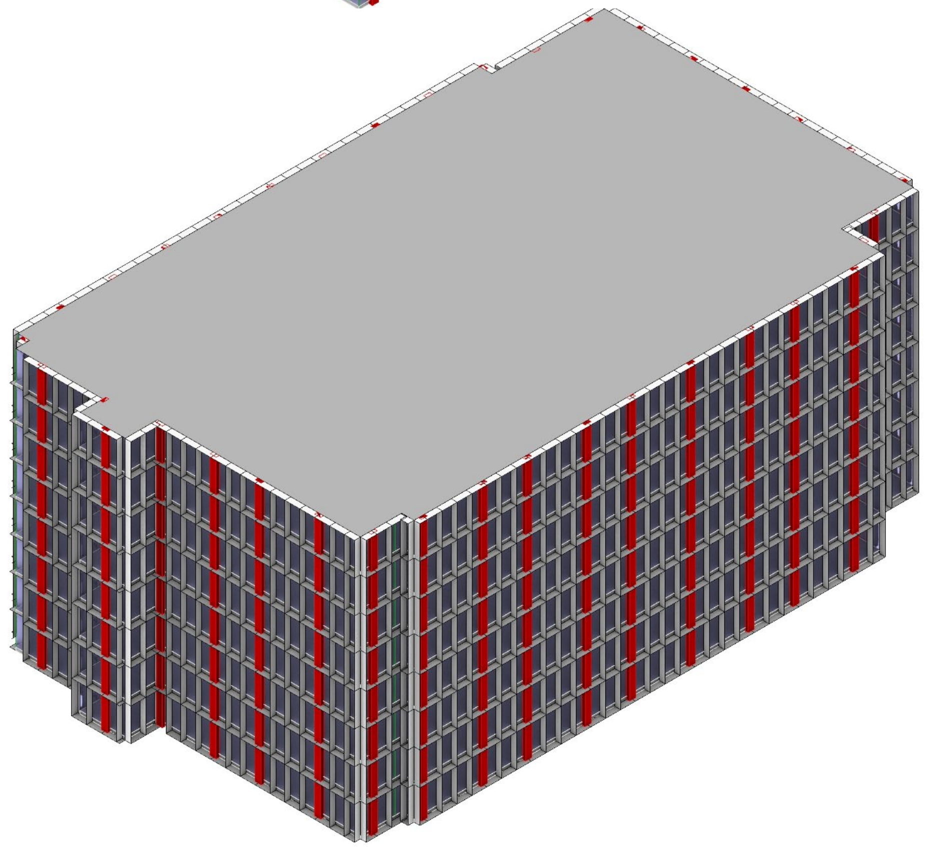


Figure 7.49 : Visualization of overall buiding facade with various cooling load at 80% WWR

8
EVALUATION

Chapter Overview

The chapter provides detailed calculations of power consumed by the decentralized dew point indirect evaporative cooler. This includes the power required by the water pump, blower, distribution system, hot and cold water for the desiccant and the evaporative cooler. The major share of the energy is spent on heating the water for the desiccant system. The chapter checks the feasibility to heat the water in a sustainable way with the combination of solar collector, heat pump and PV panels. The energy consumption between the centralized and decentralized system has been analyzed at the end.

The evaporative cooler saves significantly up to 80% of the energy when compared to the conventional water-based chiller as it only has a couple of blowers with the recirculation pump. However, the system cannot function as a standalone prototype; but needs to be coupled with the desiccant-coated heat exchanger which requires hot water and cold water for regeneration and dehumidification. The requirement for hot water is around 50°C [39] and cold water at 25°C [40]. The demand for hot water needs to be provided through a more sustainable solution. The energy required for the various components is listed below and calculated later.

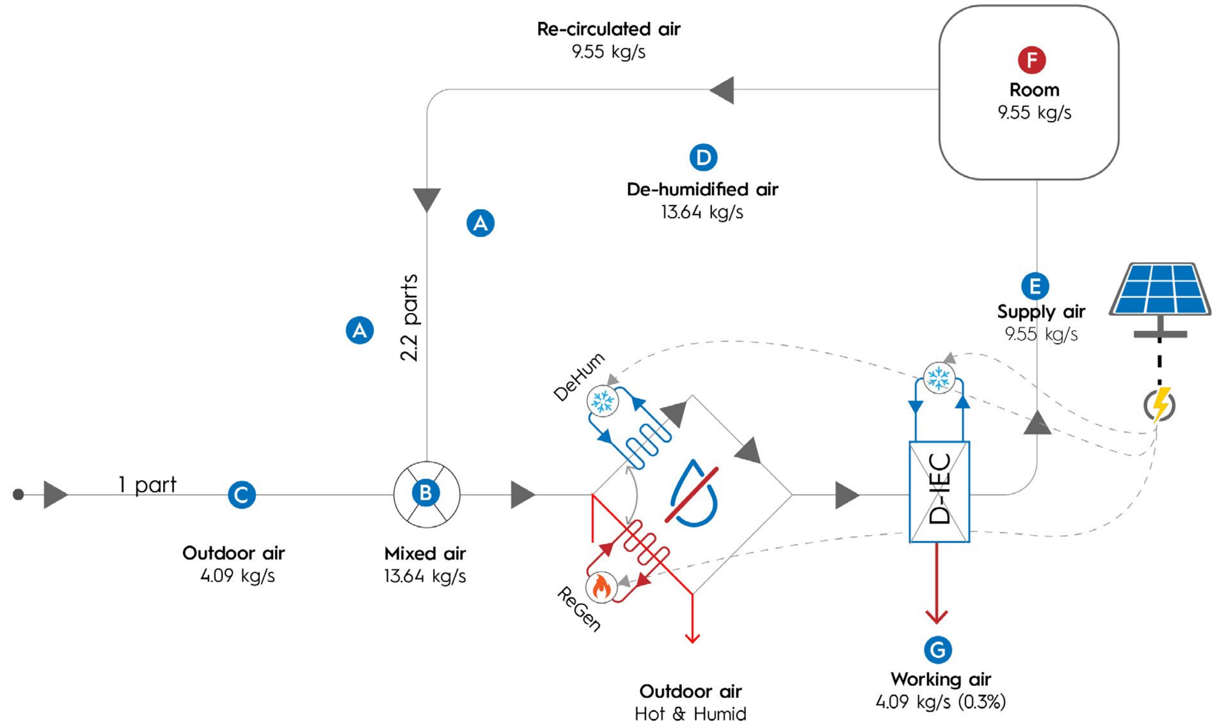


Figure 8.1: Layout of system backed by Solar power

Energy required :

1) Pumping of Water:

1) To pump the hot water required for regeneration in the desiccant heat exchanger

2) To pump the cold water requried for dehumidification in the desiccant heat exchanger

3) To pump the cold water required for the evaporative cooler.

2) Blower + Misc :

1) For air blowers to circulate primary and working air throughout the system

2) For all the other Misc including the energy required for the basic operation of flaps in diffusers and others.

3) Hot and Cold water:

1) To produce hot and cold water constantly for both the desiccant and evaporative cooler.

4) PV system:

1) Maximum power produced by the PV array and its integration to the system.

8.1 WATER PUMP:

The system has three water circulation pipelines, hot water for desiccant system, cold water for desiccant and evaporative cooler. The required amount of water can be referred from the case studies and the hydraulic power required to push the water can be calculated using the following formula [45]:

$$P_h = \frac{q * \rho * g * h}{3.6 * 10^6}$$

8.1.1 HEAD OF THE PUMP:

The head of the pump is the total equivalent height that the fluid needs to be pumped looking into the account of friction losses, length of the pipe, static elevation difference. The radius of the pipe, flow rate of the water and even the pipe material have a great influence over the head. The calculations are done using the link below with the inputs at the table 8.1.

8.1.3 CLOSED AND OPEN LOOP SYSTEM:

The pumps that are required for the desiccants and the evaporative cooler varies based on their usage. There are two types of pump systems that can be installed open loop and closed loop system.

An open loop system needs to be used when the pumped water is exposed to atmospheric pressure at any point of time in its circuit. For e.g. the water for the evaporative cooler is sprayed over the channels exposing itself to the environment (atmospheric pressure), thus open loop pumping needs to be used. On the other hand, the closed-loop system is one in which the water circulated is not at all exposed to the local environment. For. e.g. the hot and cold water required for the desiccant system can be practically heated and cooled down without exposing it via a chiller. [46]

The unique aspects of a closed loop are that the static elevation need not be considered while calculating head pressure as they are not affected by the local pressure. A closed-loop system will exhibit only friction losses. Pumps operating in a closed loops system needs to overcome dynamic friction losses. [46]

	Desiccant system Hot and cold water (Closed loop)	Evaportive cooler with cold water (Open loop)		
P_h			kW	Hydraulic power of the pump
q	145.68	0.1	m^3/h	Volume flow rate
ρ	1000	1000	Kg/m^3	Density of the fluid
g	9.81	9.81	m/s	Gravity
h	2.66	30	m	Head of the pump http://www.pumpworld.com/total-dynamic-head-calculator.htm
E	0	30	m	Differential elevation
L	65	65	m	Pipe length
D	150	150	mm	Pipe Diameter
M	New Steel	New Steel		Pipe Material

Table 8.1 : Hydraulic power and head of the pump - Calculation

Desiccant system Hot and cold water (Closed loop)

$= 145.68*1000*9.81*2.66 / 3.6 * 10^6$

$= 1.0559$

Evaportive cooler with cold water (Open loop)

$= 0.1 * 1000 *9.81* 30 / 3.6 * 10^6$

$= 0.0081$

Total Hydraulic power req. = 1.0559 + 0.0081

P_h =1.064 kW

The design has both an open loop system and closed loop pump system and they are calculated separately and added to get the total power required for the motor to pump the water.

The hydraulic power gives only the energy required for the system to push the water without considering the efficiencies of the shaft and the motor. So, the hydraulic power can be used to calculate the energy required to operate the shaft using the following equation [45] :

$$P_s = P_h / \eta_p$$

P_s		kW	Shaft power of the pump
P_h	1.064	kW	Hydraulic power of the pump
η_p	0.8	%	Pump efficiency

P_s = 1.064/0.8

P_s = 1.33 kW

From shaft power the energy required to calculate the motor can be calculated [45] :

$$P_m = P_s / \eta_m$$

P_m		kW	Motor power of the pump
P_s	1.33	kW	Shaft power of the pump
η_m	0.8	%	Motor efficiency

P_s = 1.33/0.8

P_s = 1.66 kW

Total number of devices = 291 nos

Power required per device = 1.66 kW / 291

Power required per device = 0.0057 kW

The final power required for the pump is the sum of all the three water circutes:

	Desiccant System		Cold water for evaporative cooler
	Hot Water	Cold Water	
Flow rate per device	250 l/hr	250 l/hr	0.06 l/hr
Energy req. per device	0.0028	0.0028	4.38 E-05
Total energy	0.0057 kW		
Total energy per year	20.5 kWh		
Energy consumed by all devices annually	**5.98MWh**		

Table 8.2:: Power consumption of the by for the pump

8.2 BLOWER

The major components in an evaporative cooler are the air blower and the step motors which are used to control the dampers. The energy requirement for all the components above is more complex. But in order to achieve more reliable energy requirement, existing decentralized systems are taken as a base case study. (APPENDIX 11.7)

The power requirement is calculated for both the primary and the working air.

	Primary Air	Working Air
Total CFM per floor (36 devices)	17363	5208.78
CFM per device	17363 / 36 = 476.75	5208.78 / 36 = 143.02
Energy req. per 100 CFM	0.026 kW	0.019 kW
Energy Consumption	0.126 kW	0.028 kW
Total Energy	0.153 kW	
Energy consumed by all devices throughout the year	**161.1 MWh**	

Table 8.3: Power consumption of the blower

8.3 INTEGRATING SOLAR:

The design strategies have incorporated passive and low ex strategies to reduce building energy considerably. But, the design can go beyond the basics of energy conscious building to produce high-value energy in a more renewable way. India is endowed with a rich source of solar energy. The Solar radiation that is received as heat and light can be converted into thermal energy to produce power or to heat water.

8.3.1 PHOTOVOLTAIC PANEL:

The most common solution to generate energy even with small surface area is via PV panels. Especially with subsidiaries from the government, the price of the PV panels is dropping with an increase in its efficiency the integration is much easier than before with great paybacks. The PV can be integrated either on the device itself or collectively over the roof. Both the options were explored and evaluated based on the amount of energy produced per m2 (maximum output) and total power produced. Delhi has an average irradiation of 2130 kWh/m2 and it can produce up to 351 kWh/m2. Ann. when placed at the optimum angle. The efficiency of the power production per m2 is calculated with the base value as 351 kWh/m2. [48]

The major aim of the design is to generate maximum energy addressing the requirement of the cooler. The design concepts are proposed at roof level and on the facade itself along with module. The major limitation in the integration for power is the optimal slope and orientation. The energy produced by the PV panels is calculated using the following formula for Option 01 [47]:

$$E = A * r * H * PR$$

E		kWh.ann.	Energy produced
A	4.5	m²	Area of the solar pane;
r	22	%	Solar panel yield / efficiency
H	812.17	kWh/m².ann	Annual average irradiation on tilted panels
PR	0.8	-	Performance ratio with the coefficient for losses

$$E = 4.5 * 0.22 * 812.17 * 0.8$$

Total PV Power E = 643.23 kWh.ann

Energy per m² E = 643.23 / 4.5 = 142.9 kWh/m2.ann

Efficiency = (142 / 351) * 100 = 40.4 %

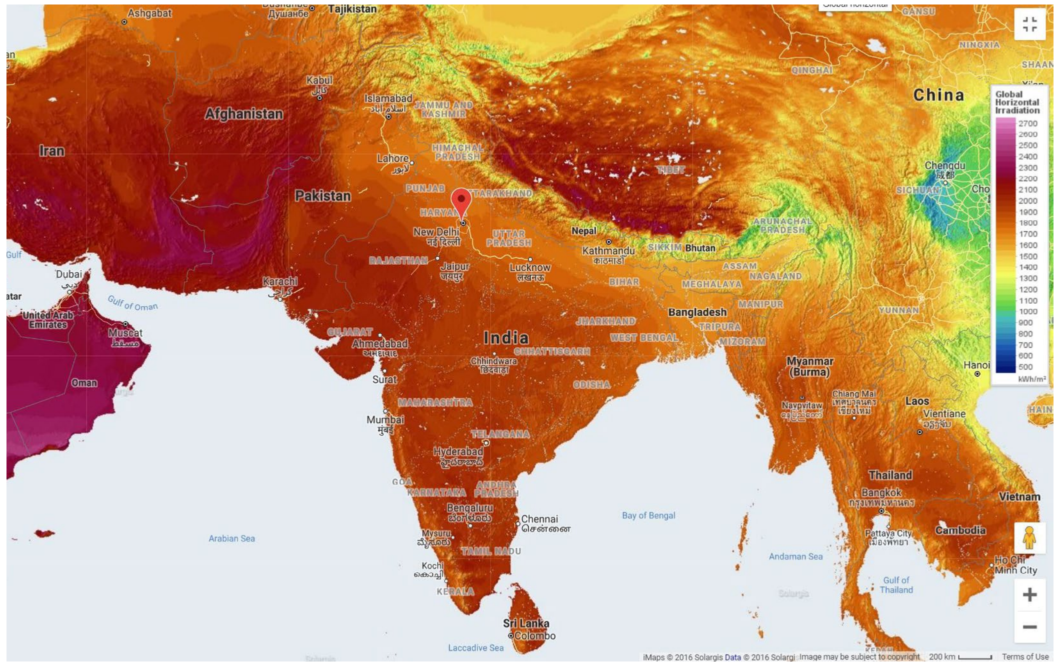


Figure 8.2: Global Horizontal Irradiation - India

8.3.2 MODULE INTEGRATED DESIGN:

The modules were designed and simulated in grasshopper to determine the radiation over the surface onto which the PV can be integrated. The solid wall integrated system and the shading system projecting out are integrated with PV panels and have been analyzed. The PV panels are has lower tilt which not only increases its efficiency but also decreases it's shading over the next row. As the cooler will be integrated on all sides of the facade, the PV panel integrated with them losses its effectiveness other than in the southern orientation. The production of energy in the east and west has a similar pattern with maximum energy produced by the PV panels facing south.

OPTION 01:

The power produced by PV panels that are flat and facing east/west is 142.8 m2 less than half of the maximum energy that can be produced. The panel facing south is relatively better but the slop places a major role in the power production in the PV system.

OPTION 01.1:

The energy from the sloped option is significantly higher with 226.2 m2 on East and west. But the panels need to be spaced out in order to avoid overcast over them. The south oriented facade is the most effective option producing up to 320 kWh/m2.

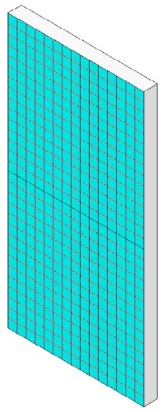
OPTION 02:

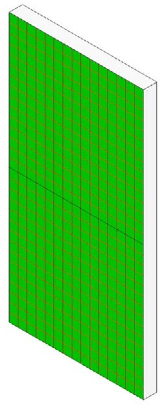
The energy trends of the flat panels on the shade integrated system is more similar to option 01.

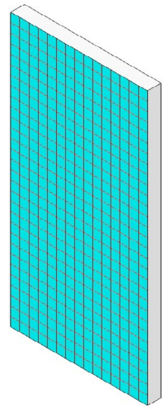
OPTION 02.1:

The PV system is integrated as a horizontal shading device. The panel is fixed between the devices and the geometry of the system is cut to avoid overcast of the shading on the panel. The energy trends of the sloped panels as shade is more similar to option 01.1.

Option 01

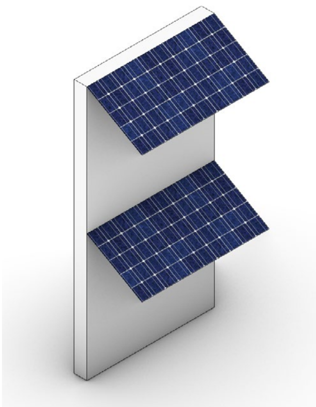


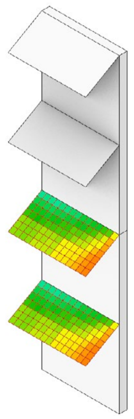


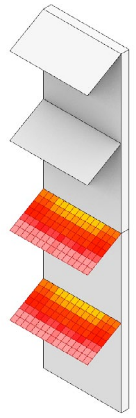


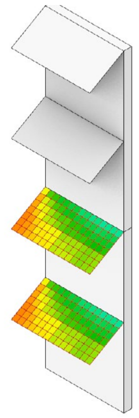
Option 01	WEST	SOUTH	EAST
Area of PV (m²)	4.5	4.5	4.5
Radiation (kWh/m2.ann)	812.17	1138.19	807.44
PV Power (kWh.ann)	643	901	639
Energy per m² (PV power / Area)	142.8	200.2	142
Efficiency %	40.7%	57%	40%

Option 01.1



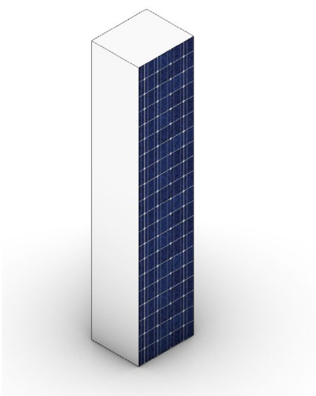


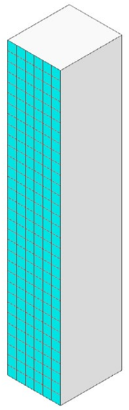


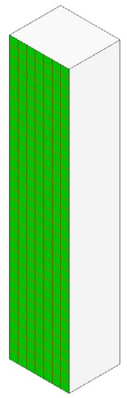


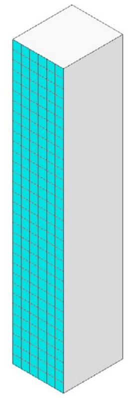
Option 01.1	WEST	SOUTH	EAST
Area of PV (m²)	2.25	2.25	2.25
Radiation (kWh/m2.ann)	1285.94	1823.61	1283.39
PV Power (kWh.ann)	509	722	508
Energy per m²	226.22	320.88	225.77
Efficiency %	64.4%	91.4%	64.3%

Option 02



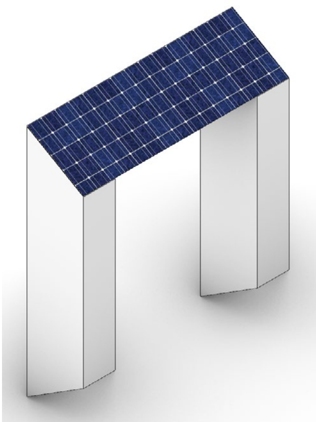


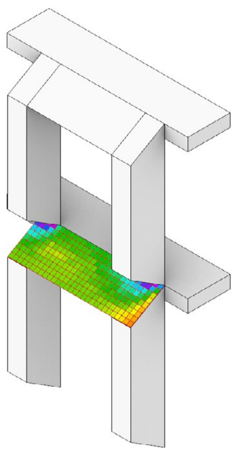


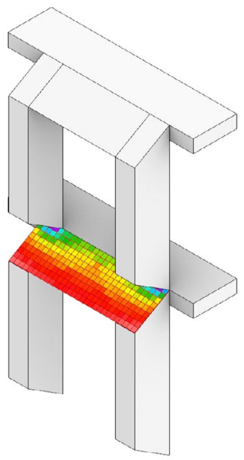


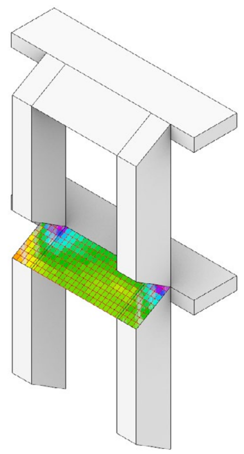
Option 02	WEST	SOUTH	EAST
Area of PV (m²)	1.98	1.98	1.98
Radiation (kWh/m2.ann)	812.16	1138.19	807.44
PV Power (kWh.ann)	283	463	281
Energy per m²	142.9	233.83	141.9
Efficiency %	40.7%	66.6%	40.4%

Option 02.1



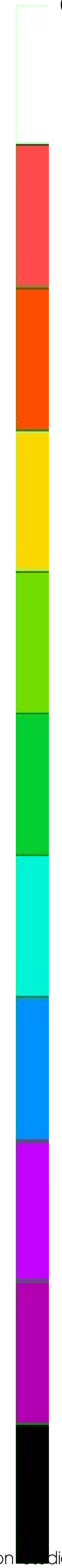






Option 02.1	WEST	SOUTH	EAST
Area of PV (m²)	2.67	2.67	2.67
Radiation (kWh/m2.ann)	1154.47	1542.00	1148
PV Power (kWh.ann)	544	727	541
Energy per m²	203.74	272.28	202.62
Efficiency %	58%	77.5%	57.7%

LEGEND (kWh/m2)



8.3.3 RESULTS:

The system performs poorly in East and west orientation reducing its performance by 60% in the flat panels and 40% in the sloped ones from the maximum output. The systems with PV panel facing south and sloped are more efficient achieving up to 90% of the maximum output. Since the coolers will be placed all over the facade, except the systems facing south, integrating PV in other orientation is going to result in low energy production with very low effective output. So, PV array over the roof is explored in the following section.

8.3.4 ROOF INTEGRATED DESIGN:

The distance between two panels to avoid mutual shading needs to be determined for maximum energy output. The distance is determined by numerical calculation and it is evaluated by a parametric model in grasshopper.

8.3.4.1 NUMERICAL CALCULATIONS FOR MINIMUM DISTANCE BETWEEN PANELS:

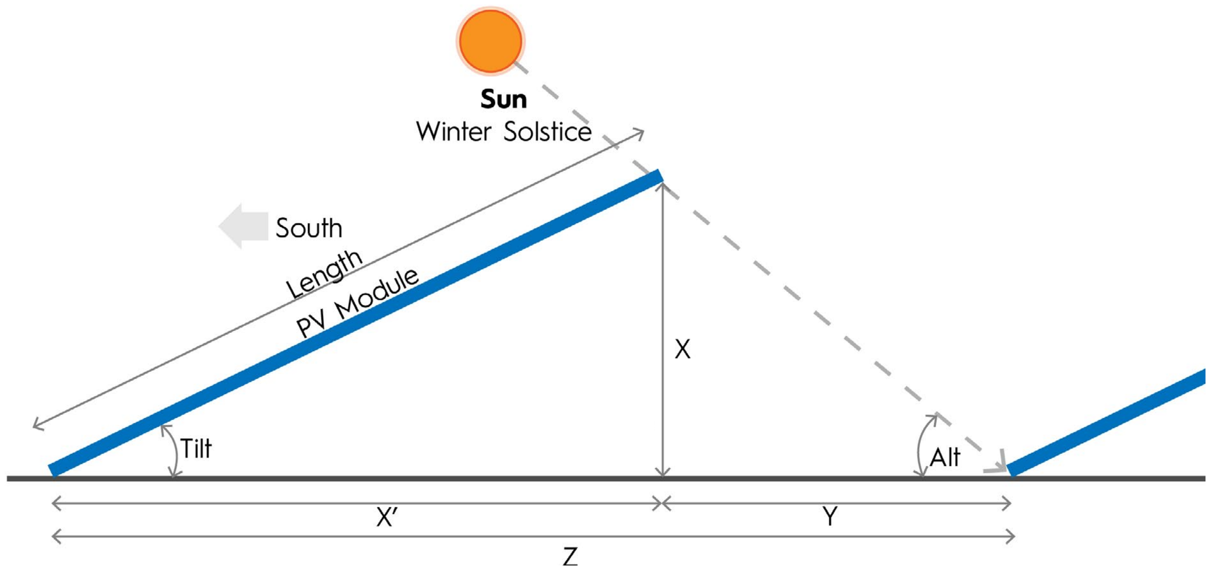


Figure 8.3: PV array placement over the roof

Numerically the altitude and azimuth angle of the sun is determined when the sun is at its lowest position typically during the winter solstice (Dec 21) for the northern hemisphere. These angles and the slope along with the length of the panel are used to determine the distance between them. [50]

The least distance between the panels to avoid mutual shading at the winter solstice is calculated using the following formula:

$$X = \sin(Tilt°) * L$$

$$Y = X * \frac{\cos(\gamma)}{\tan(\alpha)}$$

$$X' = \cos(Tilt°) * Length$$

$$Z = X' + Y$$

$$X = \sin(27°) * 2 = 0.90 \text{ m}$$

$$Y = 0.90 * \frac{\cos(143.66)}{\tan(28.43)} = 1.35 \text{ m}$$

$$X' = \cos(27°) * 2 = 1.84 \text{ m}$$

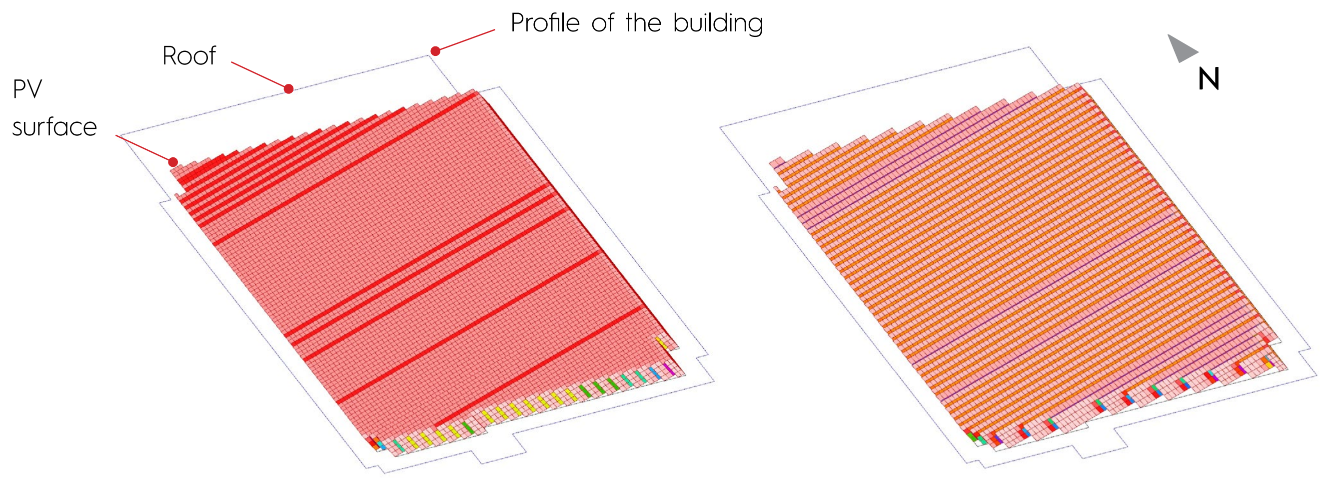
$$Z = 1.84 + 1.35 = 3.2 \text{ m}$$

Minimum Distance between panels to avoid mutual shading and maximum output per m2

Z = 3.2 m

X	m	0.90	Height of the panel due to the slope
Tilt	deg.	27	Optimum angle of PV for maximum energy production
L	m	2	Length of the PV Panel
γ	deg	143.66	Azimuth angle of the sun at winter solstice
α	deg	28.43	Altitude angle of the sun at winter solstice
Z	m	3.2	Distance between two panels at the starting point.

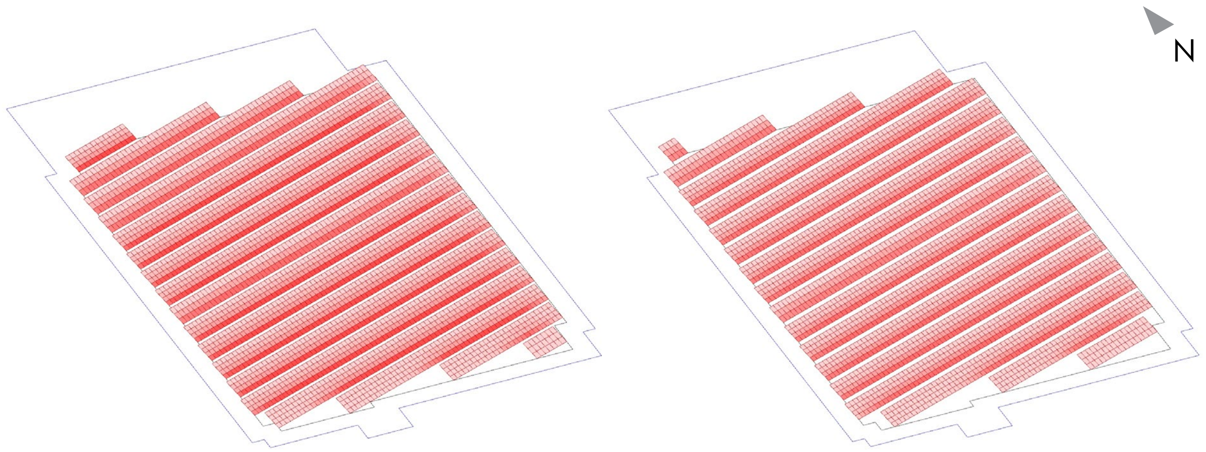
8.3.4.2 PARAMETRIC SIMULATION TO CALCULATE MINIMUM DISTANCE BETWEEN PANELS:

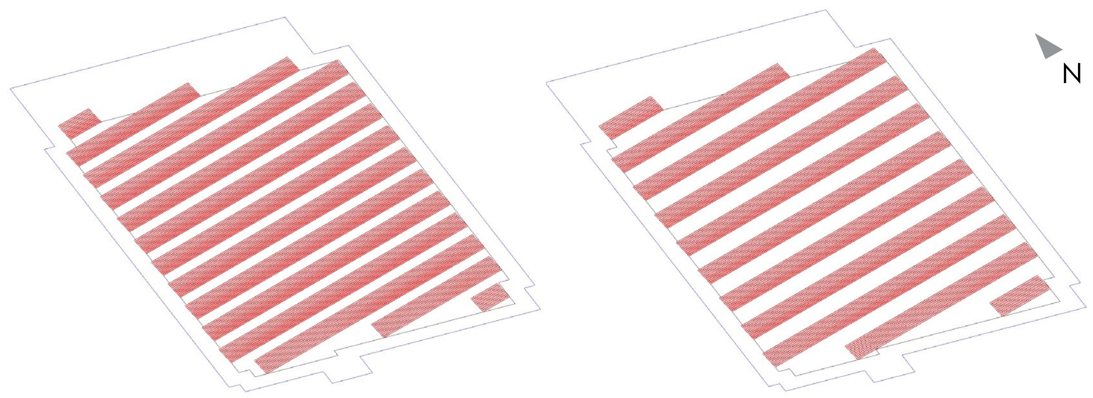


Parameter	Unit	Variation 01	Variation 02
Length of Panel	m	2	2
Distance between Panel(Z)	m	0.5	1
Azimuth	deg.	180	180
Tilt	deg.	23	23
Area of PV	m2	6102.35	3050.52
Average Irradiation	kwh/ m2	563.36	1001.03
Energy Output	kwh/ ann.	608174	537788
Energy/Area	kWh/ m2	99.66	176.29

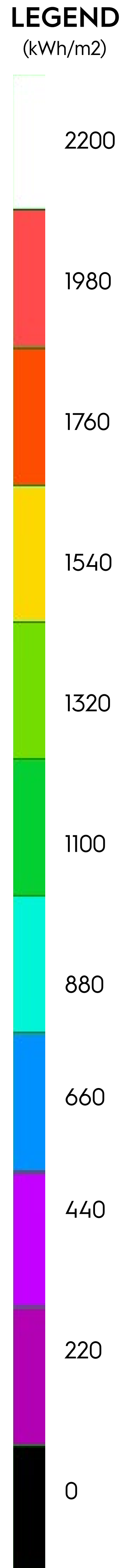
The major advantage of integrating the solar panel on the roof is that all panels can be oriented in the optimum slope and azimuth angle. Important configurations parameters of PV systems are the inclination and row distance, both leading to mutual shading which reduces the PV's performance. So, the slope, azimuth angle, distance between the panels are simulated parametrically and optimized to find the right configuration resulting in maximum power with less PV area

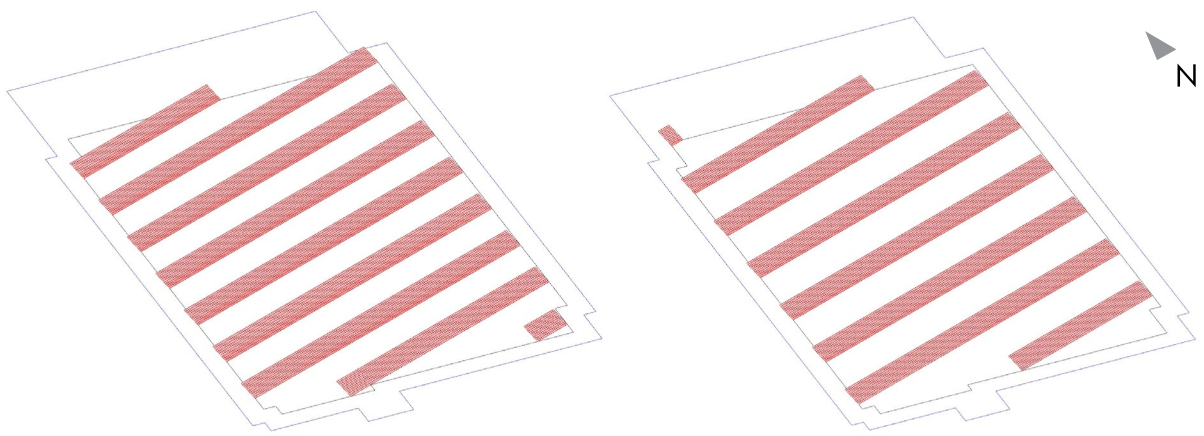
The optimum slope for the PV panels is 27 deg. with azimuth angle 180 deg. South is found using Galapagos in grasshopper. Even though many papers recommend angles over 30 deg. the result is smaller in order to avoid the mutual shading caused by higher angles. The main variable that was included for the script to manipulate to find the maximum power with less mutual shading is the distance between the panels (Z) as the other variables like slope, azimuth is already found and they are kept as constants between the variations.[49] (APPENDIX 11.10)

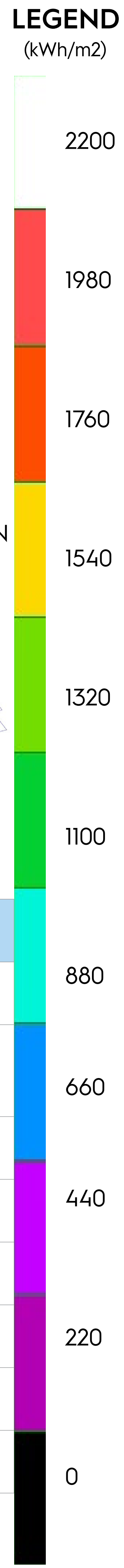




Parameter	Unit	Variation 03	Variation 04	Variation 05	Variation 06
Length of Panel	m	2	2	2	2
Distance between Panel(Z)	m	2	**3.2**	4	5
Azimuth	deg.	180	180	180	180
Tilt	deg	23	2323	23	23
Area of PV	m2	1526.05	952.31	763.82	612.46
Average Irradiation	kwh/ m2	1859.19	2103.86	2123	2130
Energy Output	kwh/ ann.	499006	352646	285407	229712
Energy/Area	kWh/ m2	326.99	370.30	373.65	375.05







Parameter	Unit	Variation 07	Variation 08
Length of Panel	m	2	2
Distance between Panel(Z)	m	6	7
Azimuth	deg.	180	180
Tilt	deg	23	23
Area of PV	m2	510.21	431.06
Average Irradiation	kwh/ m2	2138.124	2142.25
Energy Output	kwh/ ann.	191996	162524
Energy/Area	kWh/ m2	376.30	377.03

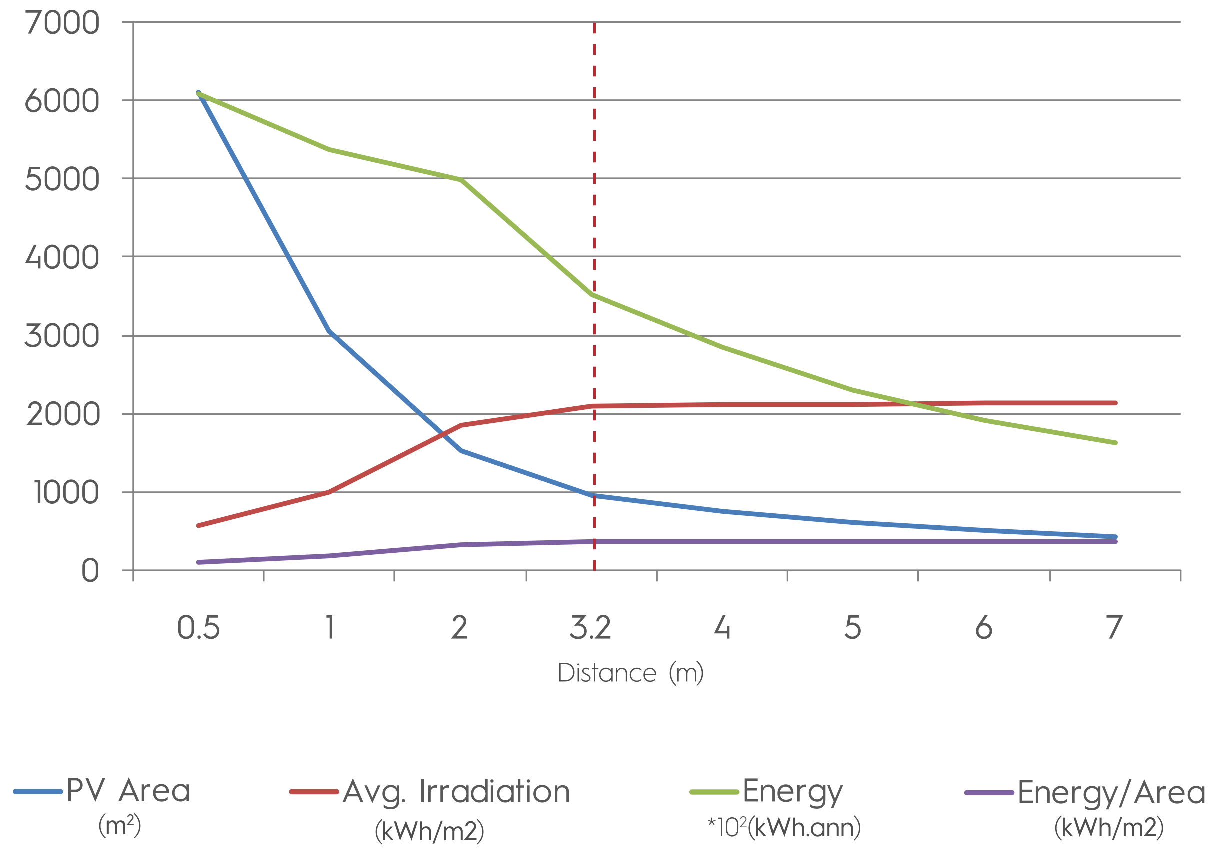


Figure 8.4: Optimum distance between PV arrays for maximum output

8.3.4.3 RESULTS:

The panel area, average irradiation from the sun, energy produced by the PV panels and the ratio of energy/area are plotted for the various distance between the panels 0.5m, 1m, 2m, 3.2m, 4m, 5m, 6m, 7m etc. in the graph above.

The PV panel area drops exponentially with an increase in the distance but the total energy produced drops gradually. Even though the area has a significant impact in energy production the increase in distance decreases the mutual shading and increases the amount of irradiation falling on the panel thus increasing its potential for energy generation. The average irradiation increases with the increase in distance initially (563 kWh/m2 to 1859.19 kWh/m2) at (0.5m to 2m) and almost reaches saturation over 3m (2103 kWh/m2). The increase in irradiation is only around 2% (2143 kWh/m2) at 7m.

The maximum power that can be produced by the PV panel / m2 is 377.03 kWh/m2 at a distance of 7m between the panels. Even though the maximum output produced is at 0.5m (608174 kWh/m2) the efficiency of the PV panel in producing the power is at its lowest (99.6 kWh/m2). This trend in the rise in power production in m2 is similar to the irradiation, it increases with distance and achieves saturation over 3m (370 kWh/m2). This balance between the distance and the maximum energy produced can be inferred from the graph that the amount of energy that is produced at 3.2 m is 352646 kWh. ann and at 7m is 16254 KWh.ann. So, the maximum irradiation/energy per m2 is achieved at 3.2 m producing maximum power with less mutual shading. This simulation also aligns with the numerical calculations calculated before.

When compared to the module integrated PV design, the roof produces significantly a lot of energy with less mutual shading. The maximum output is not possible in the modules either due to orientation or the slope, whereas the PV array over the roof overcomes these limitations.

8.3.5 SOLAR COLLECTORS:

Apart from the energy harvested from the solar power, the heat of the sun can be harvested in heating up the water which can be used for regeneration of the desiccants in the heat exchanger. The common solar collectors are flat plate collectors and evacuated tube collectors.

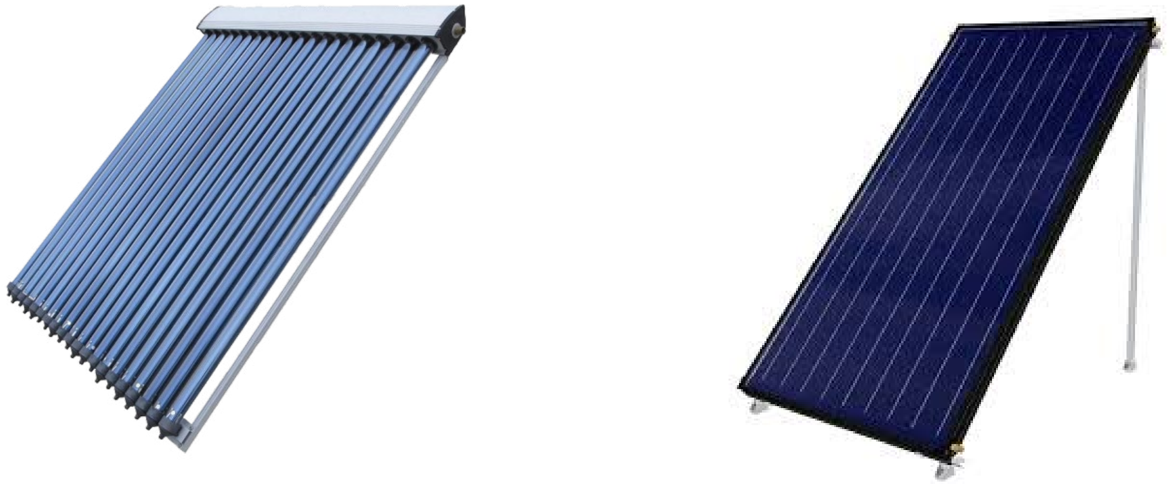


Figure 8.5: Evacuated tube collectors (left) and Flat plate collectors (right)

8.3.5.1 FLAT PLATE COLLECTOR:

Flat plate collectors have absorber panels attached to the copper pipe where the water passes through and gets heated up. They are encased in a metal frame surrounded by insulation to retain the heat and have a glazing over it which provides an insulating air space. They are sensitive to sun angle and orientation. [51]

8.3.5.2 EVACUATED TUBE COLLECTOR:

The Evacuated tube collector consists of multiple rows of parallel transparent glass tubes connected to a header pipe and which are used in place of the blackened heat absorbing plate. The liquid inside the tube gets heated up and transfers the heat to the water at the header. The air in the tube is evacuated, making it as a vacuum which helps in reducing heat loss. These glass tubes are cylindrical in shape. Therefore, the angle of the sunlight is always perpendicular to the heat absorbing. [52]

The desiccant heat exchanger requires hot water above 50°C for regeneration. The water loses its heat to the desiccant system and leaves the heat exchanger around 45°C. This additional 5°C needs to be restored in order for the system to function continuously. The solar collectors are efficient sustainable ways to heat up the water. The flow rate and difference in temperature are required to calculate the amount of heating capacity required and can be calculated using the following equation [53] :

$$\dot{Q} = \dot{m} * C_p * \Delta T \qquad \dot{Q} = 0.07 * 4.2 * (50 - 45)$$

$$\dot{Q} = \dot{m} * C_p * (T_{inlet} - T_{outlet}) \qquad \dot{Q} = 1.46$$

$\dot{Q}$		kWh	Heating capacity required per device
C_p	4.2	kJ/kg K	Specific Heat Capacity of Water
T_{inlet}	50	°C	Temperature of the water at the inlet before DCHE
T_{outlet}	45	°C	Temperature of the water at the oulet after DCHE
$\dot{m}$	0.07(250)	kg/s (l/h)	Flow rate per device

The heating capacity for a single device is 1.46kWh and with 292 devices the total heating capcity required to re-heat the water additionaly by 5°C for regeneration is 424.88 kWh.

$\dot{Q}$ = 1.46 kWh (per device)

$\dot{Q}$ = 424.8 kWh (292 devices)

A) COLLECTOR YIELD:

The collector yield calculates the amount of radiation that can be harvested in a place while considering the efficiency of the collector and the system. This can be calculated by the following [53]:

$$C_y = S_r * \eta_k * \eta_{sys}$$

C_y		Wh/m2	Collector Yield
S_r	**450**	Wh/m2	Average Solar Radiation for Delhi
η_k	**0.8**	%	Efficiency of the collector (Evacuated Tube collector)
η_{sys}	**0.85**	%	Efficiency of the system (piping, storage etc)

= 450*0.8*0.85

C_y = 306 Wh/m2

B) COLLECTOR ARRAY:

The amount of area required by the solar collector to heat up the water can be calculated by dividing the total heating capacity with the amount of radiation that the system receives [53]:

$$C_A = Q / C_y$$

C_A		m2	Collector Array
C_y	**306**	Wh/m2	Collector Yield
Q	**1.46**	kWh	Heating capacity

= 1460/306

C_A = 4.77 m2 (per device)

C_A = 1392.84 m2 (292 devices)

Each and every heat exchanger required approx. 4.77 m2 of solar collector resulting in 1400 m2 approx. for the entire building. The large area seems impractical due to the limited space available on the roof so, this system needs to be coupled with a heat pump. Further studies can be implemented on how much solar collector or PV needs to be integrated with the heat pump to produce hot water in the most efficient and sustainable way.

8.4 FEASIBILITY OF COMBINATION OF PV / SOLAR COLLECTOR / HEAT PUMP :

The solar collector cannot be the only heat source to produce the required amount of heat, a certain additional heat source (Heat pump) is required. Moreover, the PV panels are also a source of sustainable energy that can be used in operating the heat pump. In order to find out the feasibility and combination of PV, solar collector and heat pump needs to be explored. The optimized PV panel / thermal collector over roof has maximum panel area of 952.31 m2 and the following combinations were analyzed:

1) Case 1: 100 % of Solar Collector - Integrating the entire roof space 952.31 m2 with evacuated tubes

2) Case 2: 50 % PV + 50 % Solar Collector - 476 m2 for both the systems and a small heat pump to over come the additional heat required power by the PV panels.

3) Case 3: 100 % PV - The entire heating capacity is taken care by the heat pump powered by the roof full of PV panels.

8.4.1 HEAT PUMP :

Heat pumps use heat sinks to transfer heat energy from its source. The heat pump transfer heat by absorbing heat from cold space to the warmer side, the opposite direction of spontaneous heat transfer. The work of transferring energy from the heat source to heat sink consumes a small external power. Compressor, condenser, expansion valve and heat sink are the most common design components. The refrigerant is used as a heat transfer medium. The Coefficient of performance for heat pumps is 3 to 4 i.e., it can transfer heat 3 or 4 times larger than the electrical power consumed. This way more efficient than conventional electrical heater of COP 1 in which all heat produced is equal to the input electrical energy.

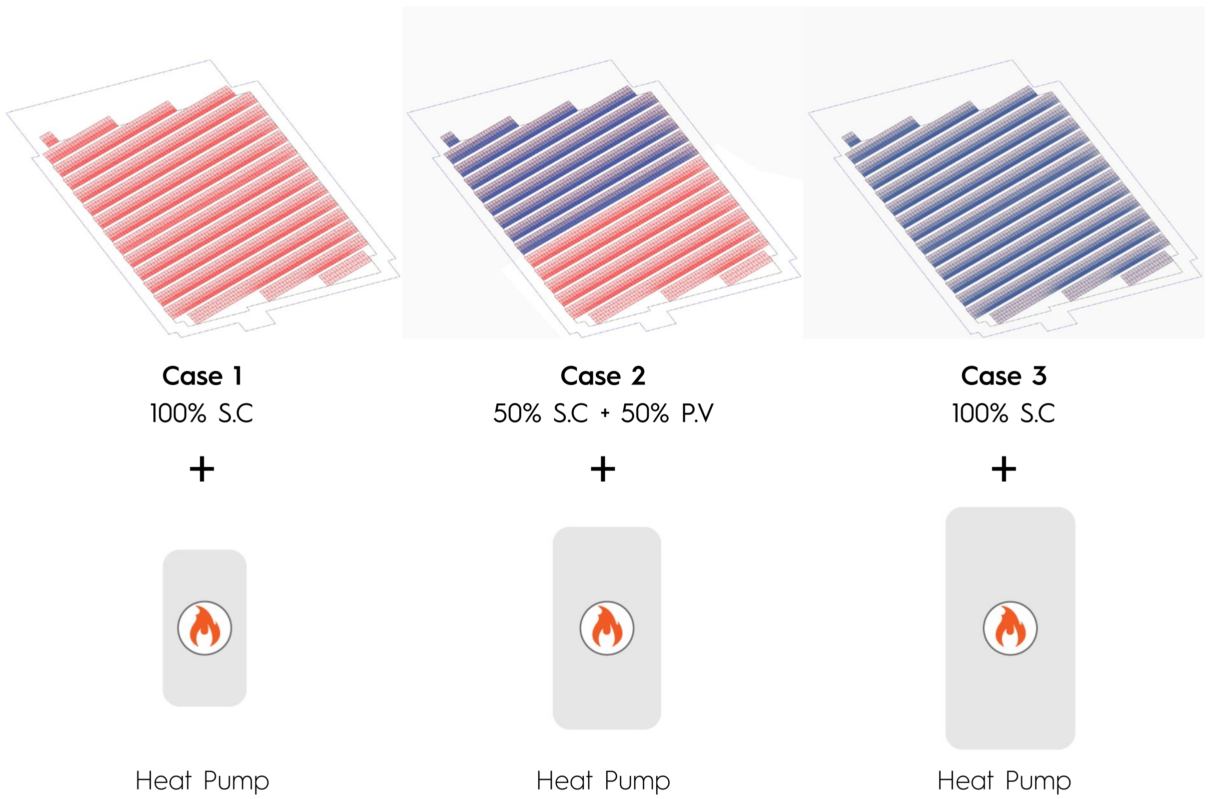


Figure 8.6: Combination of PV/ SC/ Heat Pump

Case	Heating Capacity req. (426.3kW)	Heat from Solar Collector (kWh)	Add. Heating required (kW)	Power req. for additional heating (heat pump) (kW) / (kWh)* (APPENDIX 11.8)		Power from PV (kWh.ann)	Power required (kWh.ann)
1	100% S.C + 0% PV	291.4	134.9	24.2	87,120	0	**- 87,120**
2	50% + 50% PV	145.7	280.6	62	2,23,200	1,76,323	**-46,877**
3	100% PV + 0% SC	0	426.3	90	3,24,000	3,52,646	**+ 28,646**

***heat pump operated for 12 hrs a day and for 300 days**

Table 8.4 : Combination of PV/ SC/ Heat Pump

Case 1 : 100% of SC

Panel Area : 952.31 m2
Collector yield per m2 : 306Wh/m2
Total heat produced: 952.31 * 306 = 291.4 kWh

Case 2 : 50% of SC

Panel Area : 476.15 m2
Collector yield per m2 : 306Wh/m2
Total heat produced: 476.15 * 306 = 145.7kWh

Case 3 : 0% of SC

Panel Area : 0 m2
Collector yield per m2 : 306Wh/m2
Total heat produced: 0 * 306 = 0 kWh

Case 1 : 0% of PV

Panel Area : 0 m2
Energy per m2 : 370.3 kWh/m2
Total energy produced: 0 * 370.3 = 0 kWh

Case 2 : 50% of PV

Panel Area : 476.15 m2
Energy per m2 : 370.3 kWh/m2
Total energy produced: 476.15 * 370.3 = 1,76,323 kWh

Case 3 : 100% of PV

Panel Area : 952.31 m2
Energy per m2 : 370.3 kWh/m2
Total energy produced: 952.31 * 370.3 = 3,52,649.9 kWh

8.4.2 RESULTS:

This table gives us a better understanding of the combination of solar collector, PV and heat pump. Case 1 with 100% Solar collector almost addresses 70% of the heating capacity required an additional heat of 134.9 kW needs to be supported by secondary heat. This configuration results in power consumption (-87,120 kWh.ann) per year. This drastically reduces when integrated with 50 % PV to -46,877 kWh.ann. But this negative impact significantly changes into a positive environment when integrated with 100% PV systems.

The major reason is because of the high COP of heat pump, backed by the PV on the roof. The Case 3 is the sustainable way of heating the water using PV panels all over the roof and the entire heat demand is addressed by the heat pump as +28,646 kWh.ann of additional energy can be used after supplying for the heat pump.

	Pumping water to Roof			Blower + Misc for the cooler		Heat Pump
Power required	**Hot water**	**Cold water**	**Cold water for cooler**	**Primary air**	**Working air**	
per device (kW)	0.0028	0.0028	4.38 E-05	0.13	0.03	0.3
per device for a year (kWh)	10.19	10.19	0.15	452	100	1,109
Total Power per device	1682 kWh					
Number of devices	292 nos.					
Total Power	491 Mwh					
Safety Factor 1.25	**614 Mwh**					

Table 8.1: Power consumption of the evaporative cooler

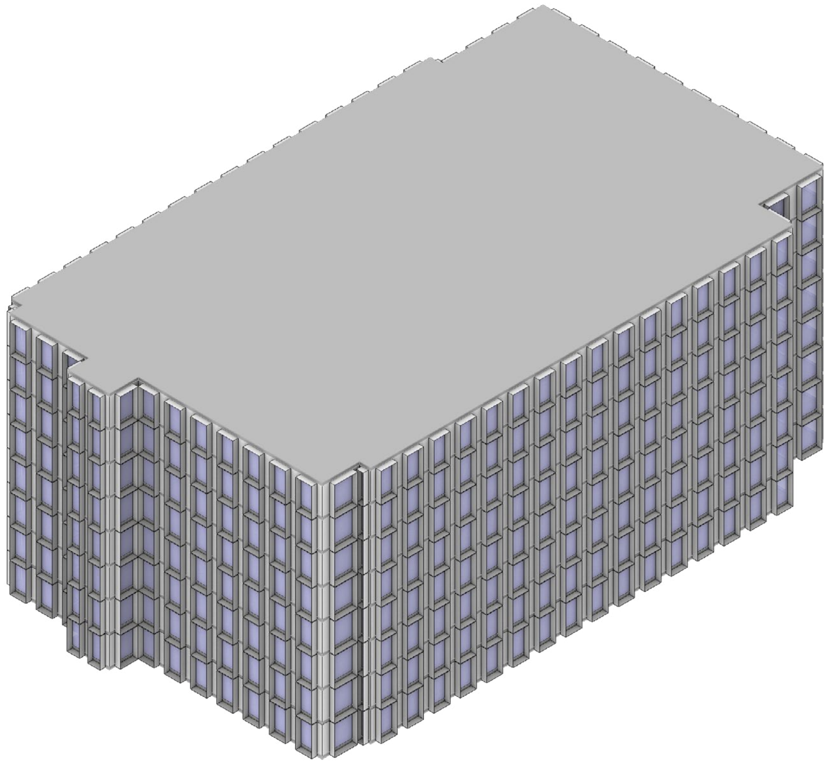


Figure 8.7: Model simulated in Design Builder for annual energy consumption

8.5 COMPARISON OF CENTRALIZED SYSTEM AND DE-CENTRALIZED SYSTEM

The 8-Storied building is modelled in the design-builder V5 with parameters (figure 6.5) and annual simulations are performed to find the annual performance. The total energy consumption and the energy required per m2 are documented below in (table 8.6) for comparison with the evaporative cooler.

With the low U values for the opaque and glazing, LED lighting and egg crate shading strategy, the EPI for the building can be brought down to 146.68 kWh/m2. The Energy Conservation Building Code sets the benchmark for office buildings in the composite climate around 180 kWh/m2 [20]. The current analysis shows a 20% reduction from the benchmark.

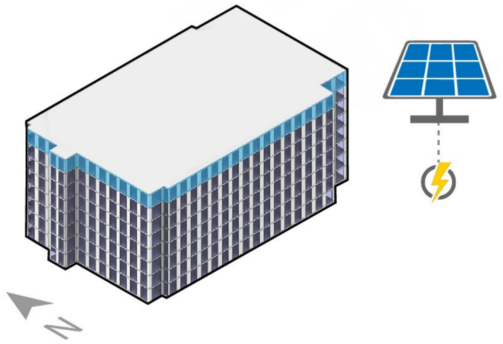
The major power consumptions for an office building is lighting, equipment and space cooling. The detailed analysis of the energy consumption these segments can be analyzed. As the design is integrated with low LPD (Lighting Power Density) - LED's energy spent on lighting is the least. Since we have 100% A.C conditioned space for the entire building the energy required to operate the chillers is significantly higher than the other consumptions. A dew point indirect evaporative cooler can significantly cut down the energy required for space cooling around 50% when compared to the 4 pipe fan coil water cooled chiller and 40% in total energy consumption. The energy consumption of the entire building drops from 146.44 kWh/m2 to 92.26 kWh/m2. The integration of an evaporative cooler has almost 50% reduction from the benchmark recommended by ECBC. [20]

Parameter	Unit	Primary Air
Area	**m2**	12501.86
Energy Consumed	**kWh**	1830812.16
EPI	**kWh/m2**	146.68

Table 8.5 : Annual energy consumption of the Model simulated in Design Builder

Parameter	Energy requirement for (kWh.ann)			Total Energy (kWh.ann)	EPI (kWh.ann/m^2)
	Lighting	Equipment	Cooling		
Dew-Point Indirect Evaporative Cooler	145886.17	393585.19	6,13,951.9	**1153423.26**	**92.26** 1153423.26/12501.86
4 pipe Fan coil water cooled chiller	145886.17	393585.19	1291340.79	**1830812.16**	**146.44** 1830812.16/12501.86

Table 8.6: Annual energy comparison between conventional chiller and evaporative cooler



WWR 60%

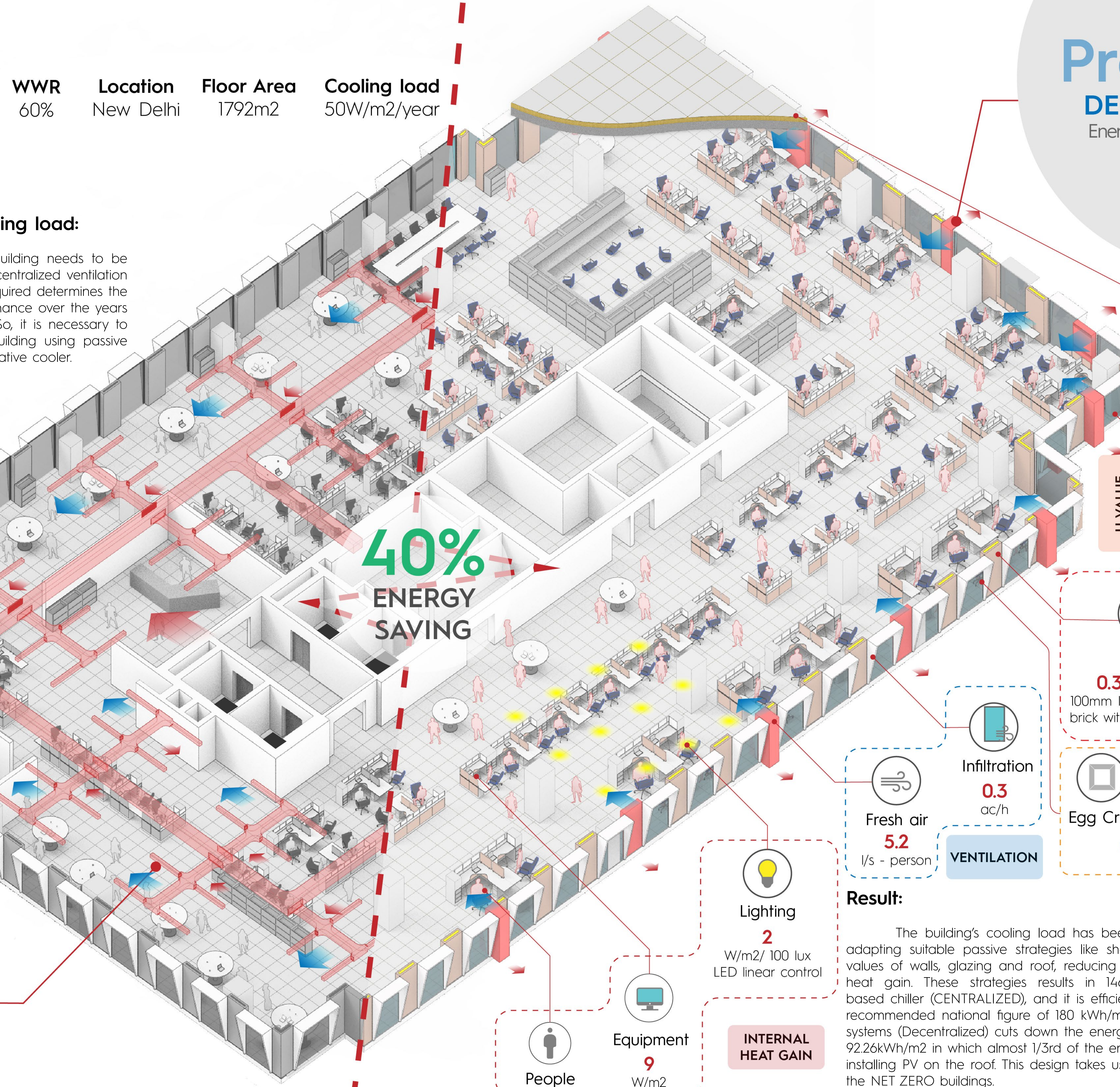
Location New Delhi

Floor Area 1792m2

Cooling load 50W/m2/year

Number of systems vs Cooling load:

The cooling demand of the building needs to be addressed by multiple devices in a decentralized ventilation system. The total number of devices required determines the cost of installation and ease of maintenance over the years and it depends on the cooling load. So, it is necessary to reduce the cooling demand of the building using passive strategies before integrating the evaporative cooler.



Proposed
DECENTRALIZED
Energy Performance Index

92.26
kWh/m2/year

U VALUE

Roof
0.2 W/m²K
150mm Insulated Roof

Glazing
1.7 W/m²K
6/13/6
LoE Double glazing with air

Wall
0.3 W/m²K
100mm Insulated Cavity brick with dense plaster

SHADING

Egg Crate

Combinative mask

0.6m by 0.6m
1.5m spacing

VENTILATION

Infiltration
0.3
ac/h

Fresh air
5.2
l/s - person

INTERNAL HEAT GAIN

Lighting
2
W/m2/ 100 lux
LED linear control

Equipment
9
W/m2

People

Result:

The building's cooling load has been reduced to 50W/m2 by adapting suitable passive strategies like shading systems, reducing U values of walls, glazing and roof, reducing infiltration and the internal heat gain. These strategies results in 146.41kWh/m2/yr with water-based chiller (CENTRALIZED), and it is efficient when compared to the recommended national figure of 180 kWh/m2/yr. But using the De-VAP systems (Decentralized) cuts down the energy by even much further to 92.26kWh/m2 in which almost 1/3rd of the energy can be generated by installing PV on the roof. This design takes us further one step closer to the NET ZERO buildings.

Existing
CENTRALIZED
Energy Performance Index

146.41
kWh/m2/year

9
CONCLUSION

Chapter Overview

The previous chapter discuss what kind of low-ex cooling will designed. Well in this chapter it describes how it will be integrated. It compares the decentralized and centralized ventilation strategies through literature and case studies. The advantages and limitations of the Decentralized systems are summarized clearly which helps to identify the scenario when the decentralized ventilation is feasible over centralized. The study also shows various DVS (Decentralized Ventilation Products) and their integration over the facade.

9.1 RESEARCH QUESTION:

1. What are the desired passive strategies that needs to be integrated in a Composite climate (Delhi) for thermal comfort and air quality requirements for Delhi?

The composite climate is characterized by heavy radiation and ambient temperature during the summers with low humidity so, it is desired to resist the heat out and with natural ventilation during the monsoons. At the same time, during winters the internal heat gain needs to be stored, to avoid the discomfort and attain maximum heat from the sun. But, natural ventilation is not possible in Delhi due to the high concentration of the pollutants. The simulation shows that using passive strategies the cooling load can be brought down by 50% from the base case load of 109.6 W/m2 to passively built design of 50 W/m2. The cooling load determines the size of the system so lower the load less number of facade integrated ventilation system over the building.

In this thesis following passive strategies were followed to attain significantly lower loads:

- Lighting has a huge demand over the cooling load and LPD needs to be kept below 2W/m2/100 lux with linear control.
- More efficient office equipments needs to be used.
- The buildings needs to be more sealed with better airtight details reducing the infiltration rate below 0.3ac/hr
- Standard construction materials needs to follow the recommendation of the energy board with U-Value for solids, glazing and roof below 0.3W/m2K, 1.56W/m2K (SHGC - 0.3 with low-e coating) and 0.2 W/m2K respectively.
- The combination of horizontal and vertical shading system proves to be more energy efficient with WWR between 40 - 60 % as recommended by ECBC.

2. Which type of evaporative cooling is more suitable for the climate of Delhi?

Delhi has significant rise in humidity during the months of monsoon during August. This reduces the performance of any evaporative cooler as it depends upon the WB temperature. Direct and Indirect evaporative cooling is not suitable for the climate of delhi as the former one increases the humidity directly in the space resulting in discomfort and later one has very low WB - effectiveness that it cannot attain low supply temperature. The Dew point indirect evaporative cooler (D-IEC) and the combination of the direct and the indirect evaporative coole has higher WB - effectiveness. Both the systems can supply really low temperature, but the D-IEC can provide with no additional increase in humidity. Moreover D-IEC has less complexity of the system interms of size, components required and water consumption when compared to combined cooler.

3. What are the advantages and limitations of de-centralized system over centralized and what are the state of the art Façade Integrated ventilation systems in the market?

The de-centralized systems can almost perform as well as an centralized system with very few limitations. The DV system cannot achieve the precision of temperature, air quality, humidity and etc, as good as a centralized system, but it can provide basic thermal comfort that an office demands. The system's performance interms of electricity consumption, heating, cooling is comparable even in a longer run, sometimes much better due to the individualized control. The space savings in terms of the vertical height and the floor area is high, as it completely eliminates the space required for ducts and false ceilings. It is going to take 1.5 times to 2 times the man hour required to maintain this system but not resulting in siginficant cost when compared to the savings in the construction and installation. One of the major disadvantage of this system is that they cannot share the load or any of the centralized control features unless they are connected via BMU.

The existing market products are integrated as sill units, wall units, under floor and over the ceiling with the air inlet/outlet via the facade. These advanced units can perform all actions like heating, cooling, dehumidification and humidification with various ventilation strategies. But, most of them are installed in the european countries esp. in germany which has more heating demand then cooling.

4. What are the components and the layout of the system that are required to supply desired air flow and temperature?

Inorder to achieve the desired temperature in the space (25°C). the supply temperature needs to be really low to overcome the internal and external heat gain. But, the dew-point indirect evaporative cooler can supply only around 26°C during August due to high humidity. This results in no cooling effectiveness. Inorder to increase the cooling effectiveness the WB temperature of the ambient air needs to be reduced using dehumidification. Multiple strategies like minimum outdoor fresh air supply, recirculating the dry return air and mixing them with the fresh air and passing the air through dehumidifier needs to be carried out inorder to remove moisture from the air before it passes through the cooler. The desiccant coated heat exchanger has been used as a dehumidifier due to its high moisture removal rate without any increase in the temperature of the air. So, the design has a mixing chamber, two desiccant coated exchanger for continous operation (dehumidification and regeneration), Dew-point Indirect evaporative cooler and a heat/cold source for the desiccant and evaporative cooler backed by PV system.

5. How this system can be designed in form of a facade that can be integrated over the built structure?

The volume flow rate calculated during the simulation can be used to design the size of the cooler. The length, width, thickness of the channel, water distribution, air velocity and working air ratio needs to be designed to keep the WB effectiveness of the cooler over 100%. The balance between the proportion of the system and WB effectiveness is the important design parameter. The design is more feasbile as a full length wall system with Mixed ventilation strategy compared to a sill integrated systems in multiple aspects. This is acheived by stacking evaporative cooler of 1.2m high over another with the desiccant coated heat exchanger at the middle or on the sides with supplpier near the ceiling and return at the middle. The height of the system can be brought down as low as 2.7m making use of the full potential of the evaporative cooler. These systems can be used as wall flushed system or as a more expressive vertical shade. The number of systems over the facade and the cooling load depends upon the architect's design concept and degree of passive strategies that he/she would like to incorporate over the design.

6. To what extent the solar energy can be used to produce heat and energy for the sustainable operation of the evaporative facade?

The solar panels were integrated over the module and over the roof to compare the maximum output of power both in total and energy per m2. It is evident from the results that the PV panel array over the roof produces more energy with less mutual shading over the other panel. The distance between the row was calculated parametrically and verified by numerical calculations. The desiccant systems requires hot and cold water for continous operation this heat can be produced using low-grade heat source. But, the amount of surface area required to produce the heat for the this large quantity of water was so high that a heat pump backed by the PV panel is more sustainable.

7. What is the saving potential in the cooling load by this façade system compared to a conventional centralized system?

From the simulation it is found that the 8 storied built structure with the passive strategies consumes 146.44 kWh/m2 ann. The Dew-point indirect evaporative cooler can save 50 % of the energy spent on space cooling when compared to a conventional fan coil water based chiller. It can save upoto 40% of the buildings energy annually 92.26 kWh/m2. The optimized PV array panel produces upto 3,52,646 kwh/m2 / 28.2 kWh/m2 further reducing the energy consumption to 64.06. kWh/m2.

9.2 FUTURE WORK :

The objective of the thesis is to reduce the cooling load of the offices in Delhi, India by integrating passive strategies and low-ex cooling (evaporative) technology through facades as a decentralized ventilation system. The following cases can be explored for future development:

- Ventilating Interiors:

The proposed design addresses only the open office floor spaces. In terms of air supply strategies, ventilating interior spaces of an office building are not considered in this scope of work and only the peripheral ventilation via the façade has been designed. But, if the system can supply ventilation for interior spaces, more typologies can be addressed and the initial design process can incorporate these as well as a design parameter.

- Refurbishment projects:

The De-VAP systems are designed as a modular system for new office buildings to gain the full potential of the system. But, they also have huge potential in refurbishment projects due to the presence of existing chiller for the De-VAP system's hot and cold water requirements. The resultant structure will be a balance of centralized and decentralized HVAC systems, with the De-VAP system reducing the load of main chiller unit.

- Coupling various low ex-cool techs:

The evaporative cooling has several classifications in terms of supplying the air with varied properties, further research on exploring alternative evaporative cooler potentials with the combination of any other cooling system to overcome its shortcomings may open up new avenues.

- Integration over design:

The role of the facades is becoming more complex than just a thermal envelope or an aesthetical element. The designers should start designing with these smart facades to create responsible change on energy footprint of the buildings. Various design possibilities can be explored.

- Cost Analysis:

More detailed cost analysis for installing the decentralized ventilation systems over the facade needs to be calculated. The analysis should also integrate cost saved by avoiding ducts, materials saved by reducing the height of the structure, maintenance of the systems and various other expenses. Such an illustration will help to actually compare the centralized and decentralized systems financially.

-Hourly simulation:

The resultant supply air is influenced by numerous parameters, especially in the everchanging composite climate of Delhi. The varying humidity and the temperature of the environment affects the performance of both the evaporative cooler and desiccant systems. So, more detailed calculations needs to be performed throughout the varying seasons to understand the potential and limitations of the De-VAP system.

- Sustainable moisture removal :

The humidity reduces the performance of the evaporative cooler. The desiccants remove moisture from the air and it requires chiller to produce hot and cold water for its continuous operation. This chiller consumes almost double the energy than the rest of the system. Either more sustainable way of heating and cooling down the water is required or any other low-ex system needs to be developed for removing the moisture from air.

- Prototyping:

The entire thesis has research and simulation based results, more practical prototyping in real life scenarios is required to identify the deviation from the numerical results.

- Market:

The results show that a significant amount of energy can be saved and may ease the construction process. More study on why these systems are not widely available in the market and main barriers for widespread production and distribution of facade integrated low ex cooling needs to be studied.

9.3 CONCLUDING REMARKS:

Almost 50% of the energy is spent on space cooling for offices in Indian climatic conditions. In order to reduce the cooling demand alternative low ex cooling technologies are being researched and implemented. The main aim of the thesis during the initial period is to completely avoid the usage of high energy intensive chillers and refrigerants. The desiccant systems are the alternatives present in the market but, for these desiccants to dehumidify the air continuously, it requires hot and cold water for regeneration and dehumidification cycle. Even though using the solar collector to heat up water seems like a sustainable solution, it requires a large area to address the quantity of heat required and making it less feasible. The heat pumps have significantly higher COP and can address this situation.

The heating demand required by the chiller to heat up the water is way less compared to the cooling demand required for the entire building. It is not possible for now to address the built structure in Delhi, India only with evaporative cooling techniques unless any other less energy intensive technology is found to dehumidify the air. But, still, from this thesis, it is found that it can reduce up to 40% of the building's energy, and with further research, it can even bring one step closer to the net-zero built structure.

The thesis in whole has to be viewed as an effort to decode the complex climatic situation of Delhi in relation to the thermal needs of office buildings in specific; with the focus maintained on developing an integrated faced system that supports and substitutes the cooling units of conventional system.

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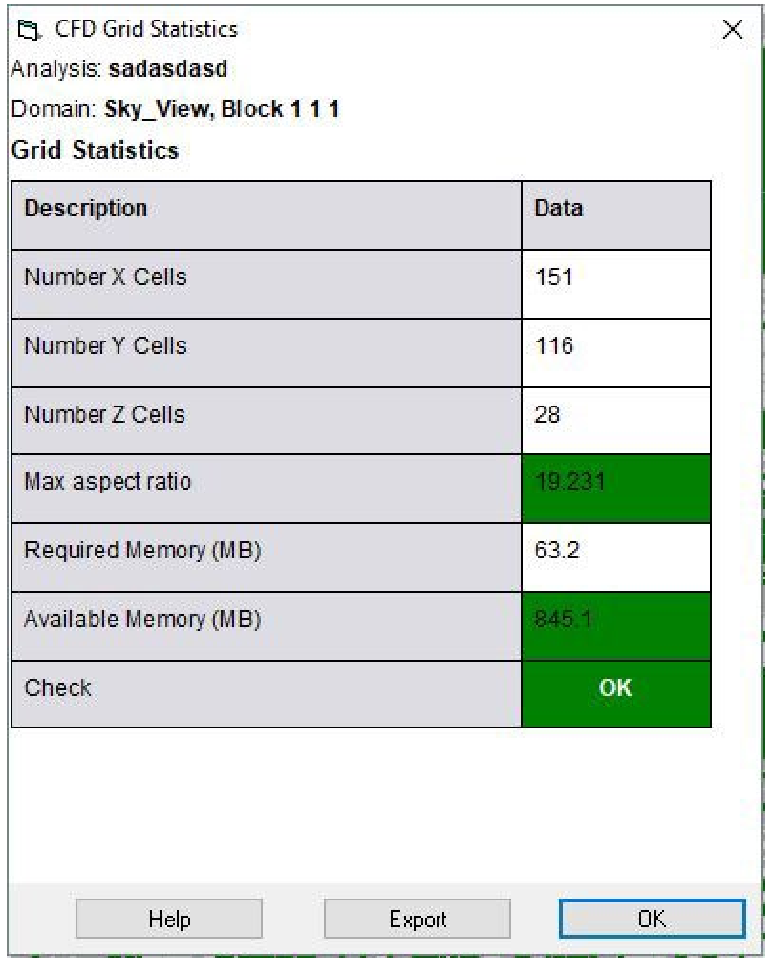
11
APPENDIX

11.1 RESULTS FROM COOLING DESIGN SIMULATION FROM DESIGN BUILDER :

Building	Block	Zone	Design Capacity (kW)	Design Flow Rate (m3/s)	Total Cooling Load (kW)	Sensible (kW)	Latent (kW)	Air Temperature (°C)	Humidity (%)	Time of Max Cooling	Max Op Temp in Day (°C)	Floor Area (m2)	Volume (m3)	Flow/Floor Area (l/s-m2)	Design Cooling Load Per Floor Area(W/m2)
Building 1	GF	GF:Zone2	14.72	0.711	12.8	9.49	3.31	25	53.2	Aug 16:00	27.9	331.2	993.7	2.15	44.4
Building 1	GF 1	GF:Zone1	84.15	4.1405	73.17	55.26	17.91	25	52.5	Aug 17:00	28.7	1752.4	5257.2	2.36	48
Building 1	MF	MF1:Zone2	15.65	0.7726	13.61	10.31	3.3	25	52.5	Aug 16:00	28.3	331.2	960.6	2.33	47.3
Building 1	MF 1	MF1:Zone1	87.65	4.3867	76.21	58.55	17.67	25	52	Aug 17:00	29.2	1752.4	5082	2.5	50
Building 1	TF	GF2:Zone2	18.31	0.9402	15.92	12.55	3.37	25	51.1	Aug 16:00	28.9	331.2	960.6	2.84	55.3
Building 1	TF 1	GF2:Zone1	102.29	5.5788	88.95	74.46	14.49	25	49.2	Jul 16:00	30.2	1752.4	5082	3.18	58.4
Building 1		Totals	322.76	16.5298	280.66	220.61	60.05	25	51.4	N/A	30.2	6250.9	18336.1	2.64	51.6

11.2 CFD GRID STATISTICS:


CFD Grid Statistics

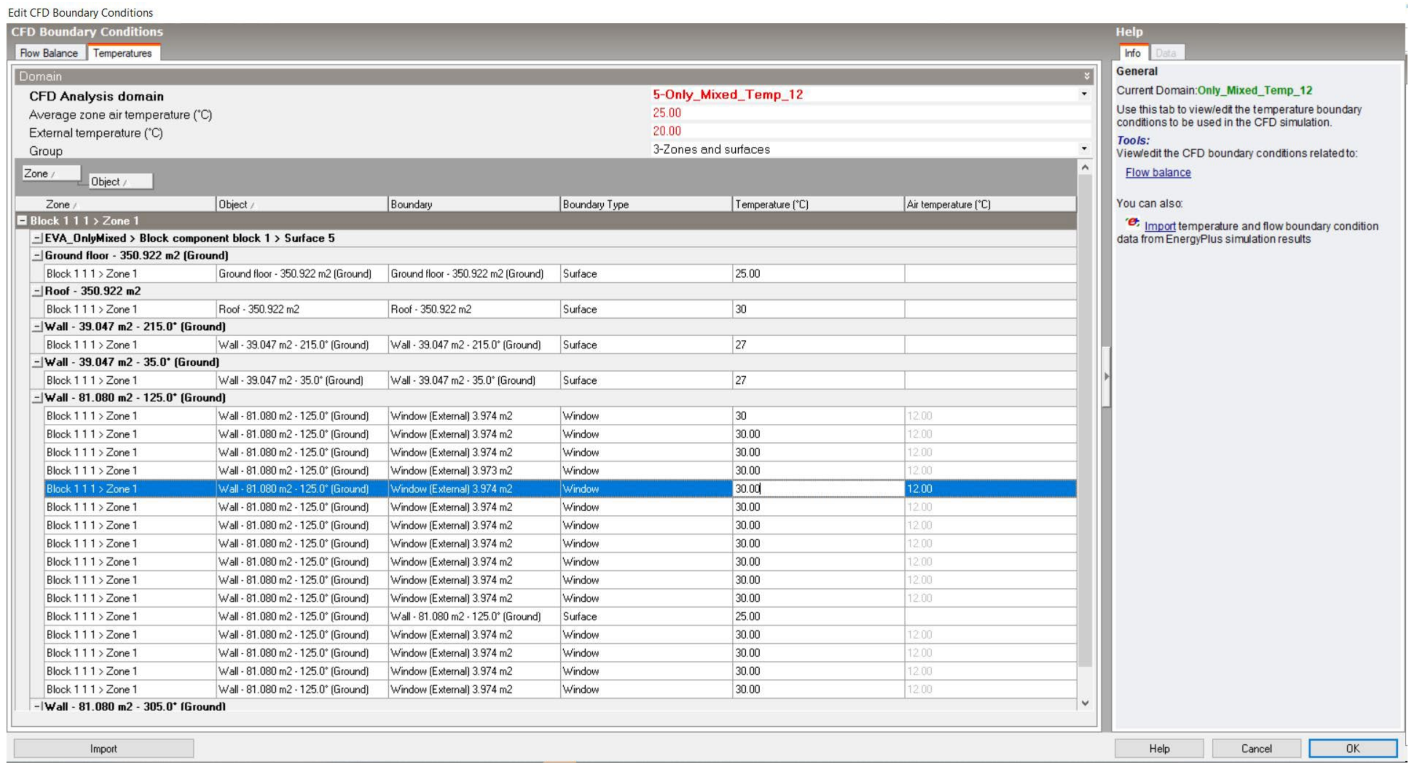
Analysis: **sadasdasd**

Domain: **Sky_View, Block 1 1 1**

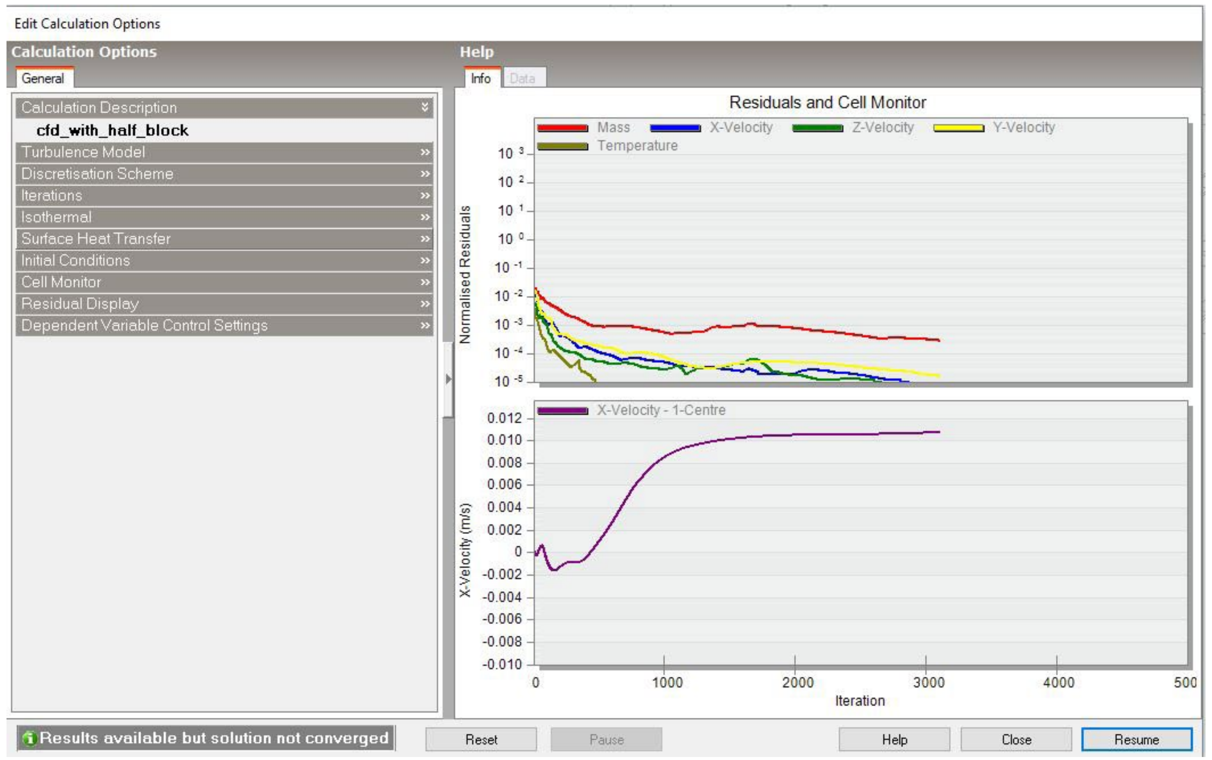
Grid Statistics

Description	Data
Number X Cells	151
Number Y Cells	116
Number Z Cells	28
Max aspect ratio	19.231
Required Memory (MB)	63.2
Available Memory (MB)	845.1
Check	OK

11.3 BOUNDARY CONDITIONS FOR CFD:

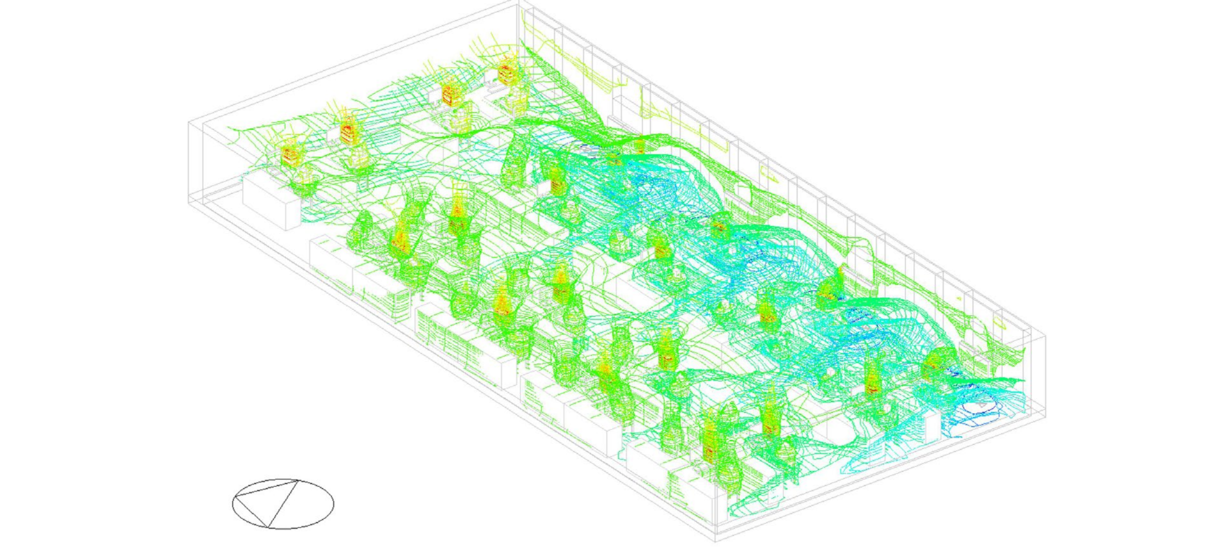


11.4 SIMULATION AFTER CONVERGING:

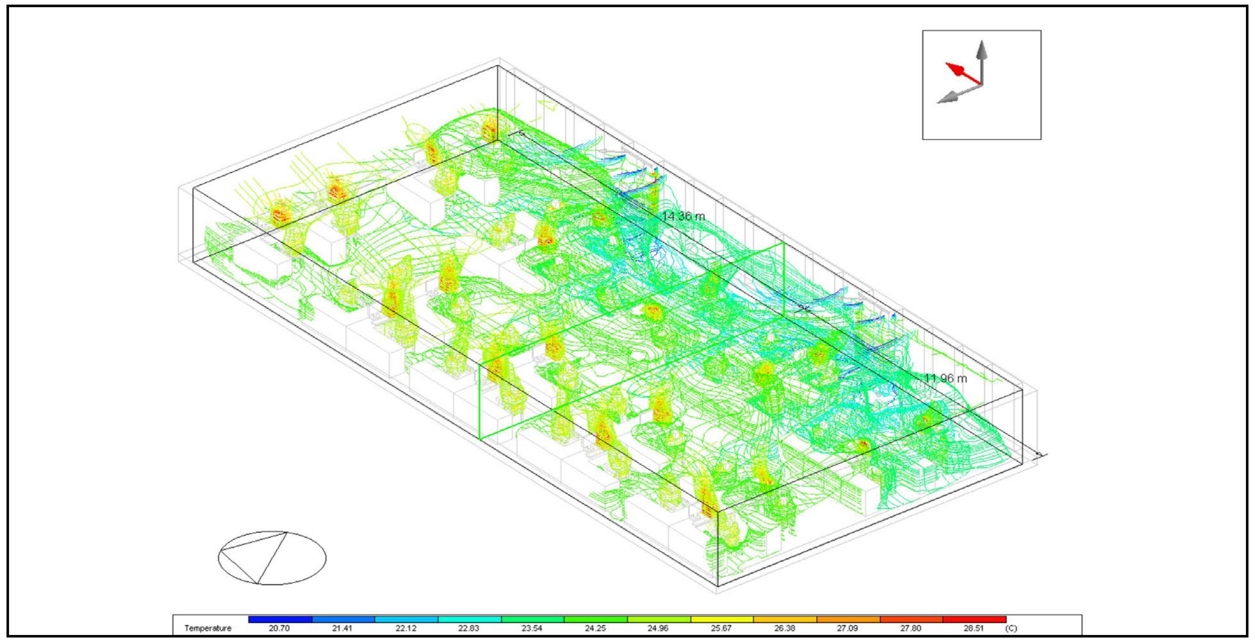


11.5 EVEN - TEMPERATURE DISTRIBUTION IN ALL VENTILATION STRATEGIES

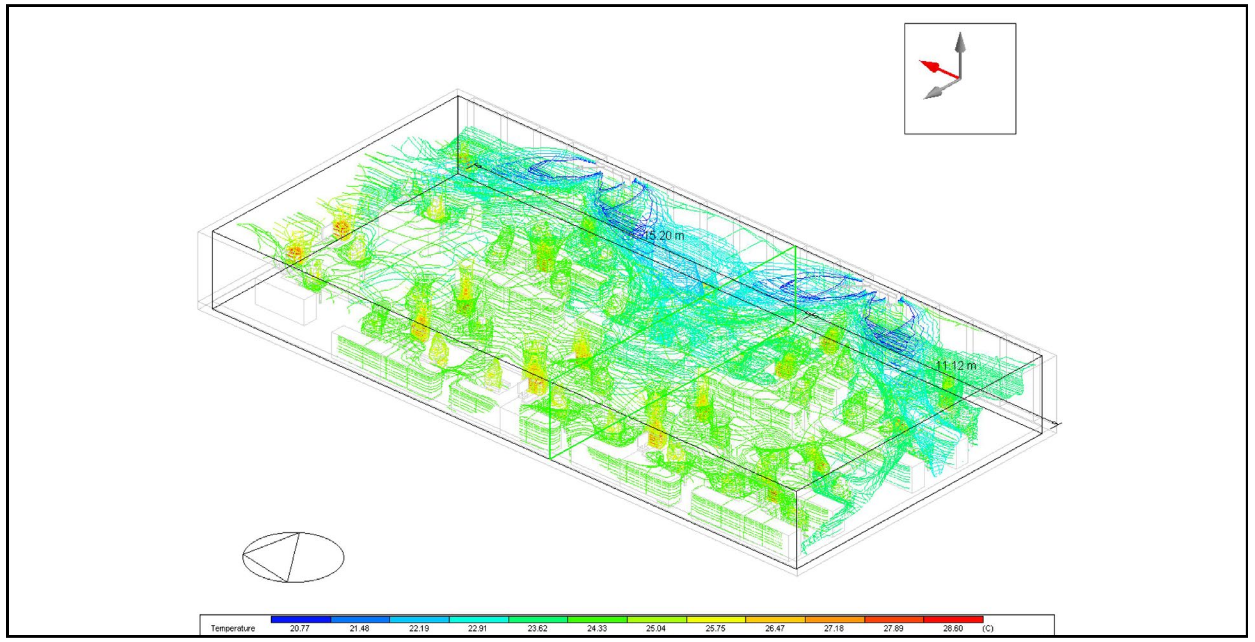
Displacement Ventilation



Mixed and Displacement Ventilation



Mixed Ventilation



11.6 NO. OF DEVICES CALCULATION - SIMILAR TO VARIOUS COOLING LOADS

Volume flow rate:

$$\dot{Q} = \dot{m} * C_p * \Delta T$$

$$\dot{m} = \dot{Q} / (C_p * (T_{set} - T_{sup}))$$

$$\dot{V} = \dot{Q} / (\rho * C_p * (T_{set} - T_{sup}))$$

$\dot{Q}$	178	kW	Design cooling capacity of one floor (From Design Builder)
ρ	1.1652	kg/m3	Density of Moist air at 25°C, 48.3% rH https://www.omnicalculator.com/physics/air-density
C_p	1.02	kJ/kg K	Specific Heat Capacity of Air
T_{set}	25 °C	°C	Indoor Temperature (Desired temperature inside the space)
T_{sup}	16 °C	°C	Supply Temperature (During the month of august)

$$\dot{Q} = \dot{m} * C_p * \Delta T$$

$$178 = \dot{m} * 1.02 * (25 - 16)$$

$$\dot{m} = 19.38 \text{ kg/s}$$

$$\dot{V} = 19.38 / 1.16 = 16.70 \text{m}^3/\text{s}$$

Area of the opening :

$$Q = v * A$$

Q	**16.70**	m^3/s	Volume flow rate
v	**1.5**	m/s	Flow velocity (v) – IEC attains WB effectiveness over 100% with velocity less than 2 m/s. [3],[4].
A		m^2	Area of opening

16.70 = 1.5 * A

Area of the opening (A) : 11.13 m²

Number of Devices:

Length	0.4 m	Based on the grid size of the facade
Width	0.4 m	Based on number of channels
Height	1.2 m	For WB effectiveness more than 100% the length needs to be 1m [42] or more. Or the length should be 200 times the channel thickness [43]
Dry channel Width	0.2 m	Width of the dry channel for supply air
Wet channel Width	0.2 m	Width of the wet channel for working air
Opening Area of Dry Channels	0.08m2	= (Length of the system x Width of dry channel) = (0.4*0.2)
Total Area	11.13 m2	Area of opening required for the flow rate
No. of systems req.	70 devices per floor	= Total opening area / Area of one system = 11.13 / 0.08 = 140 devices Since each wall systems has two coolers. 140 /2 = 70 devices

11.7 BLOWER AND OTHER MISC

Installation location	Technical details		Façade ventilation units for offices and small meeting rooms Volume flow rate range from 50 to 150 m³/h		
			Standard FSL-B-ZAB/SEK	Frame solution FSL-B-ZAB	
Under a sill (horizontal installation)	Dimensions (W x H x D)	[mm]	1085 x 630 x 320	950 x 586 x 494	Working air
	Volume flow rate range	[m³/h]	60 - 150	60 - 150	
	Total heating capacity *1)	[W]	2400	2700	
	Heating capacity per room	[W]	800	800	
	Total cooling capacity *2)	[W]	700	700	
	Cooling capacity per room	[W]	330	320	
	Heat recovery	[%]	50	50	
	Power consumption *3)	[W]	23	20	
	Sound pressure level *4)	[dB(A)]	22 - 30	27 - 37	

Installation location	Technical details		Standard FSL-V-ZAB/SEK	Project solutions FSL-V-ZAB Type I	FSL-V-ZAB Typ II	FSL-V-ZAB- Typ III
Next to a window (vertical installation)	Dimensions (W x H x D)	[mm]	400 x 1800 x 320	699 x 1700 x 313	550 x 2250 x 200	700 x 2252 x 209
	Volume flow rate range	[m³/h]	60 - 150	60 - 180	90 - 150	60 - 120
	Total heating capacity *1)	[W]	2460	2740	2650	1470
	Heating capacity per room	[W]	471	772	691	isotherm
	Total cooling capacity *2)	[W]	688	692	689	650
	Cooling capacity per room	[W]	406	406	406	321
	Heat recovery	[%]	52	60	52	52
	Power consumption *3)	[W]	27	25	38	34
	Sound pressure level *4)	[dB(A)]	19 - 36	19 - 36	14 - 32	20 - 32

Installation location	Technical details		SCHOOLAIR units for schools, kindergartens and large meeting rooms Volume flow rate range from 150 to 600 m³/h SCHOOLAIR-B	SCHOOLAIR-B-HE	SCHOOLAIR-B-HV	
Under a sill (horizontal installation)	Dimensions (W x H x D)	[mm]	1590 x 646 x 420	2090 x 750 x 420	2100 x 740 x 403	Primary Air
	Volume flow rate range	[m³/h]	150 - 320	150 - 400	250 – 600	
	Total heating capacity *1)	[W]	5800	3400	6500	
	Heating capacity per room	[W]	1700	2650	3800	
	Total cooling capacity *2)	[W]	1400	1750	1600	
	Cooling capacity per room	[W]	800	1000	1200	
	Heat recovery	[%]	55	82	75	
	Power consumption *3)	[W]	38	75	93	
	Sound pressure level *4)	[dB(A)]	21 - 35	25 - 41	19 - 42	

Installation location	Technical details		SCHOOLAIR-V-2L	SCHOOLAIR-V-4L	SCHOOLAIR-V 1800	SCHOOLAIR-V-HE	SCHOOLAIR-V-H
Next to a window (vertical installation)	Dimensions (W x H x D)	[mm]	397 x 2160 x 359	397 x 2350 x 359	600 x 1800 x 359	600 x 2000 x 408	600 x 2200 x 40
	Volume flow rate range	[m³/h]	150 - 320	150 - 320	150 - 350	150 - 360	250 - 600
	Total heating capacity *1)	[W]	5470	5760	5630	3100	6500
	Heating capacity per room	[W]	1422	1680	1005	2250	3800
	Total cooling capacity *2)	[W]	-	1440	1590	1685	1750
	Cooling capacity per room	[W]	-	850	935	965	1470
	Heat recovery	[%]	46	46	54	84	75
	Power consumption *3)	[W]	44	45	46	42	82
	Sound pressure level *4)	[dB(A)]	23 - 38	27 - 40	23 - 39	28 - 42	19 - 42

11.8 CHILLER

Vitocal 300-W Pro water/water heat pump

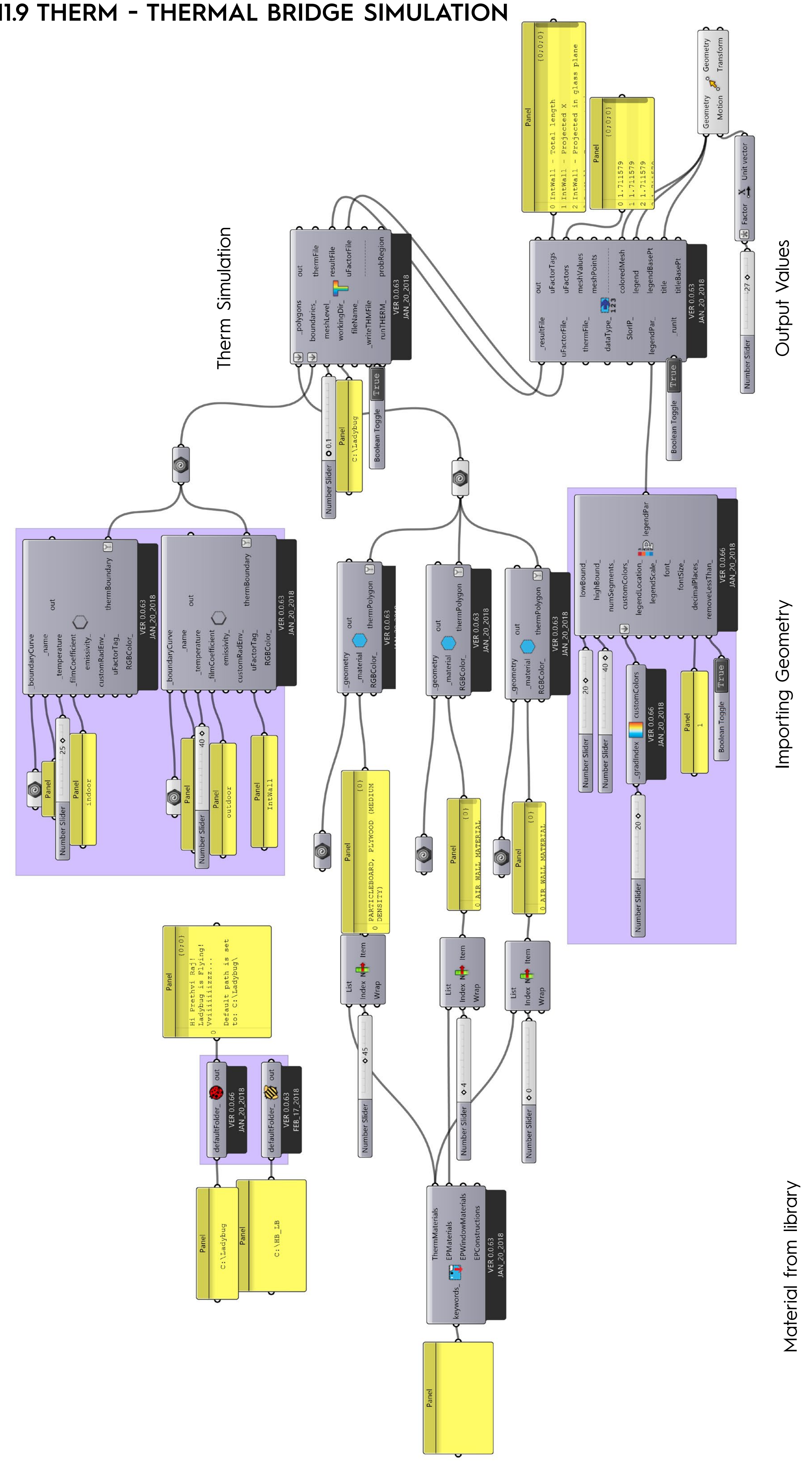
Vitocal 300-W Pro	Type	WW 301.B125	WW 301.B155	WW 302.B125
Performance data (to EN 14511, W10/W35 °C, 5 K spread)				
Rated heating output	kW	116	140.1	112.1
Cooling capacity	kW	102	120	94.2
Power consumption	kW	20.2	24.2	18.6
Coefficient of performance ε in htg mode		5.74	5.79	6.0
Dimensions				
Length	mm	1932	1932	1932
Width	mm	911	911	911
Height	mm	1650	1650	1650
Weight	kg	1015	1055	1035
Number of compressors	pce	1	1	2
Energy efficiency class LT/HT*		A++/A++	A++/A++	A++/A++

Vitocal 300-W Pro	Type	WW 302.B200	WW 302.B250	WW 302.B300
Performance data (to EN 14511, W10/W35 °C, 5 K spread)				
Rated heating output	kW	186	240	290
Cooling capacity	kW	157	199	244
Power consumption	kW	32.1	42.1	49.5
Coefficient of performance ε in htg mode		5.9	5.7	5.8
Dimensions				
Length	mm	2521	2521	2521
Width	mm	911	911	911
Height	mm	1650	1650	1650
Weight	kg	1330	1380	1425
Number of compressors	pce	2	2	2
Energy efficiency class LT/HT*		A++/A++	A++/A++	A++/A++

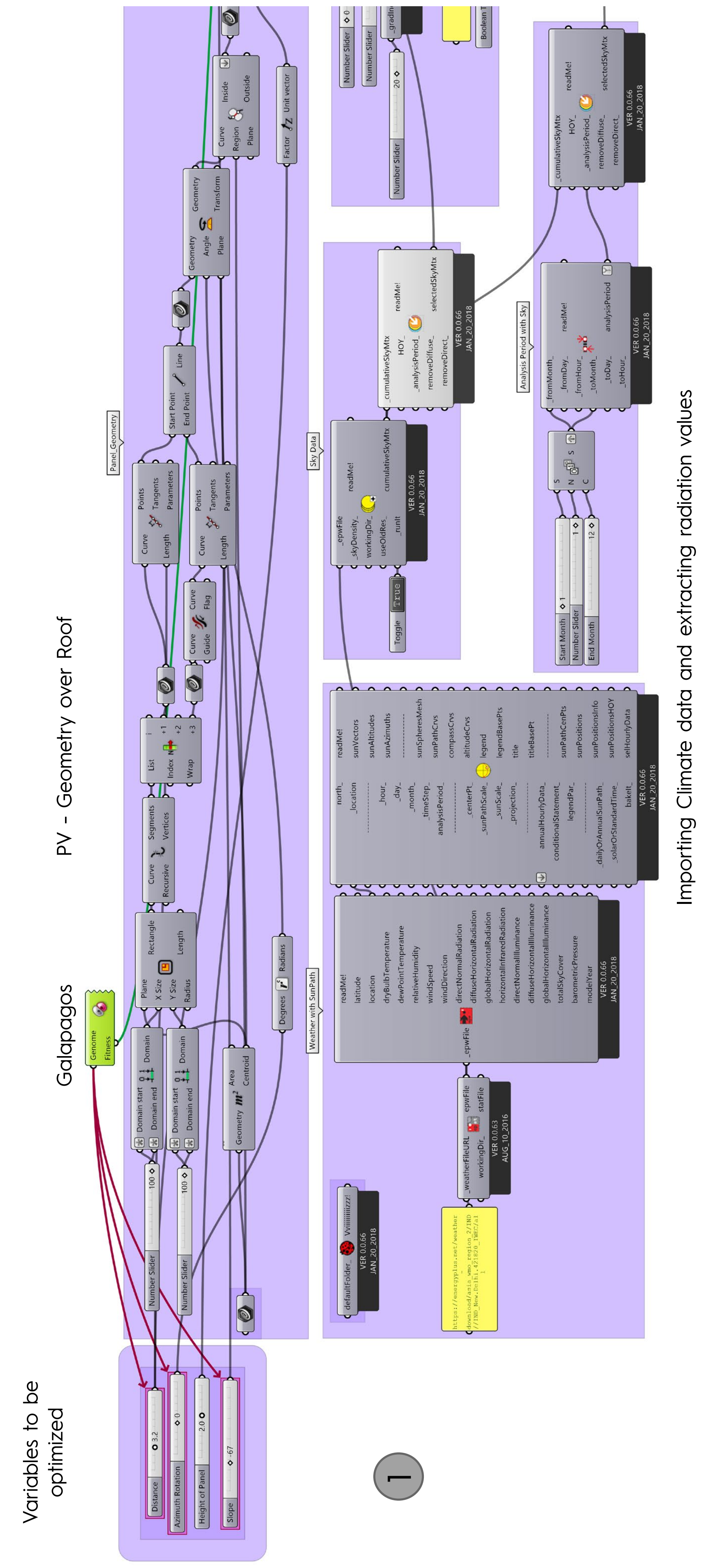
Compressor version: Hanbell	Type Type	BW 351.AS390SDH BW 351.AS390SAH	BW 351.AS440SDH BW 351.AS440SAH	BW 351.AS490SDH BW 351.AS490SAH
Performance data: heating (to EN 14511, B0/W35 °C, 5 K spread)				
Rated heating output	kW	368	422	464
Cooling capacity	kW	288	334	367
Power consumption	kW	82	91	100
Coefficient of performance ε in heating mode		4.49	4.66	4.64
Performance data: cooling (to EN 14511, W12-7/W30-35 °C)				
Rated cooling capacity	kW	426	493	541
Rated heating output	kW	513	590	648
Power consumption	kW	90	100	110
Energy efficiency ratio ε in cooling mode		4.73	4.95	4.93

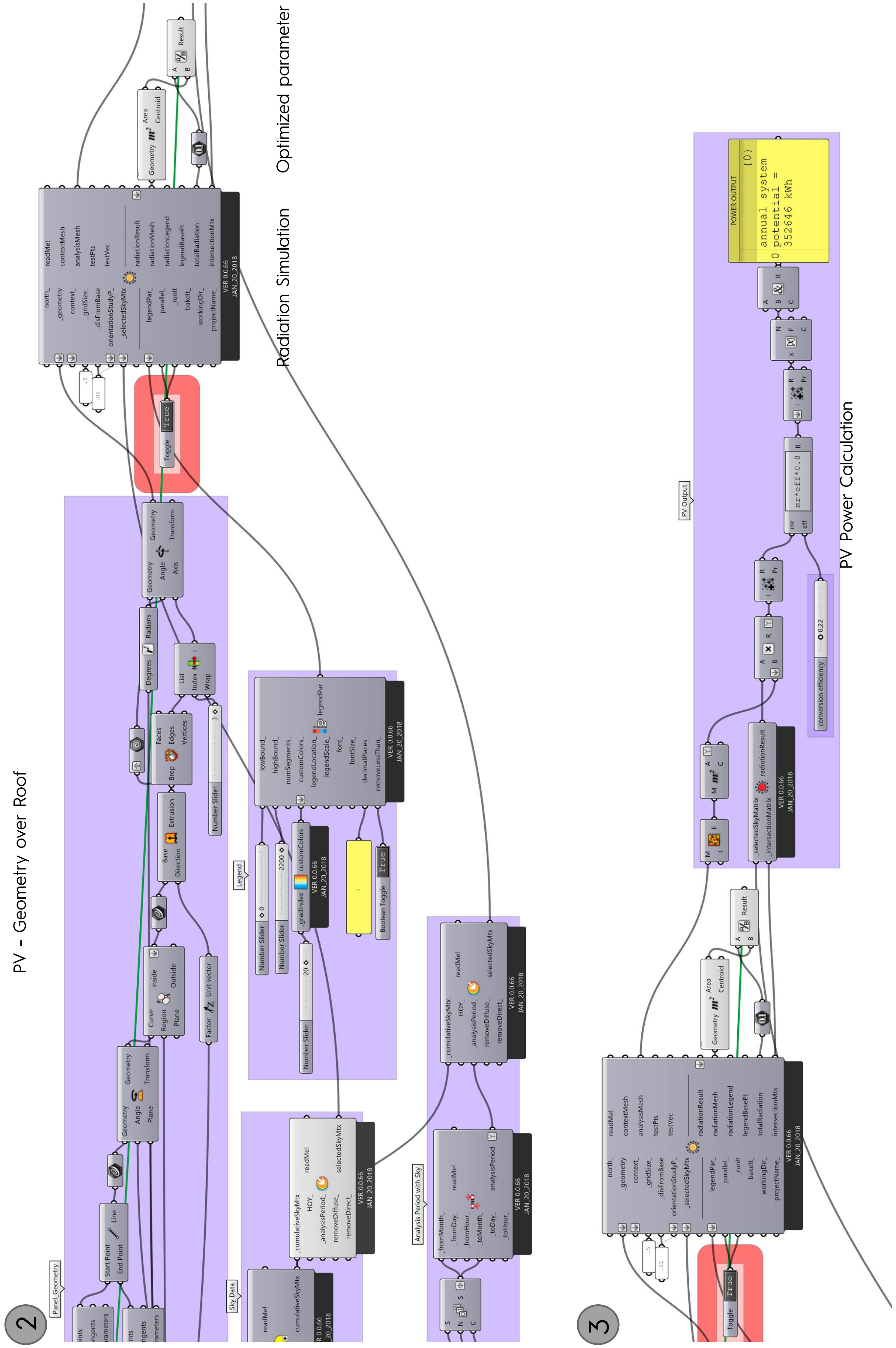
Compressor version: Bitzer	Type Type	BW 351.AS240SDB BW 351.AS240SAB	BW 351.AS260SDB BW 351.AS260SAB	BW 351.AS300SDB BW 351.AS300SAB
Performance data: heating (to EN 14511, B0/W35 °C, 5 K spread)				
Rated heating output	kW	216	245	273
Cooling capacity	kW	169	191	213

11.9 THERM - THERMAL BRIDGE SIMULATION



11.10 PV PANEL PARAMETRICAL OPTIMIZATION :




2
PV - Geometry over Roof
Radiation Simulation
Optimized parameter
3
PV Power Calculation
POWER OUTPUT
annual system potential = 352646 kWh