A DYNAMIC, CLAY DOUBLE WALL SYSTEM FOR INDOOR COOLING

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Degree of Doctor of Philosophy

Department of Civil Engineering

University of Moratuwa
Sri Lanka

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DECLARATION

I declare that this is my own work, and this thesis does not incorporate without acknowledgement any material previously submitted for a degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Name of the Supervisor: Prof. R.U.Halwatura

Signature of the supervisor: Date:

ABSTRACT

Truly, sustainable development promises environmental, social, economic, yet personal meaningfulness, beyond increasing financial wealth. The usage of clay in construction is proven sustainable in all three aspects since its usage from the very beginning of human civilization. However, the chauvinism toward clay as a nonmodern material is detrimental, and therefore novel innovations of clay, are required to fasten with modern architecture for a whole new perspective. The usage of clay for primary, heavy walling is common in hot arid climates, yet fewer studies incorporate clay for interiors and double walling in the tropics.

This gap was addressed by developing a Dynamic, Clay Double Walling (DCDW) solution for heat reduction with easy maintenance and favorable aesthetics. The cooling effect of these structures can be attributed to the resistance of heat flux to the building due to the porosity of the structure, heat absorption, and thus decline of thermal conductivity.

The research thus investigates improvements in internal porosity and air permeability of clay, for improved mechanical and chemical properties, and thermal stability upon firing. Patterns and characteristics for best indoor air temperature reduction were identified on the material mix, mix composition, firing configurations, thermal conductivity, shrinkage, panel thickness, etc.

The practicality and application potentials of the invention were tested on-site, potential improvements were tested virtually (with building simulations) for their effectiveness, and in completion, the long-term sustainability, and profitability of the DCDW system were investigated by identifying the LCC.

The innovation suggests an energy-efficient, low-cost, low maintenance and lightweight, sustainable, double walling solution for high-end to low-end, yet new construction to retrofitting for tropical interiors.

Keywords: Cooling, Dynamic, Clay, Double wall, Tropical indoors

DEDICATION

This dissertation is dedicated to my loving parents, husband, and baby 'Graahie'.

For their endless love, support, and encouragement

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Finally, I owe a huge debt of gratitude to my dear Mother, my dear husband Dimuthu, and my adorable baby Graahie for believing in me and being with me throughout the tough times.

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LIST OF ABBREVIATIONS

DCDW	Dynamic Clay Double Wall
DSF	Double Skin Facades
RH	Relative Humidity
OE	Operational Energy
EE	Embodied Energy
CFP	Carbon Footprint
GHG	Green House Gas
HVAC	Heating, Ventilation and Air Conditioning
LCC	Life Cycle costing
WLC	Whole Life Costing
WLA	Whole Life Appraisal
A/C	Air Conditioning
NPV	Net Present Value
IC	Initial cost
OC	Operational Cost
RC	Replacement Cost
MC	Maintenance Cost
DC	Direct Current
IRR	Internal Rate of Return
MCW	Mud Concrete Wall
ASTM	American Standards of Test Methods

LIST OF APPENDICES

1. CHAPTER ONE - INTRODUCTION

1.1. General

A great notice on energy efficiency for several sectors comprising the building industry has been created due to fossil fuel depletion, global climate change and an increase in CO2 emission. It is not a secret that in the current world, the building sector is accountable for 40% or more of the world's annual energy consumption, as a whole. On the other hand, under hot climatic conditions in the tropics, thus the occurrence of overheated building interiors has become common due to solar heat gain and penetration through building envelope and apertures.

Buildings are known as 'Sustainable', which are both friendly in terms of environment and resources and enjoy an increasingly higher stand for when compared to predominantly economically oriented decisions. Concepts such as bio-climatic-design [1], which involve climate responsive engineering, architectural interventions regulate the interaction of a building with its surrounding climate and contribute to promoting passive climate modification by lowering air temperature levels inside buildings than outdoor, in hot climates [2].

In hot humid climates, the late nights and the young mornings are experienced as 'comfortable', being common in the exteriors and interiors of the buildings. Even though, during the daytime, the climate normally become a level which surpasses the threshold of the human for indoor thermal comfort. 'Active cooling systems' which consume energy is observed as conventional practice all over the world for the climate modification in heating ventilation and A/C. Energy represents a notably above-average portion of the building's running cost and affects the optical and thermal comfort of the occupants, resulting in critical global environmental issues at the same time.

Therefore, a raised need is there in applying various sustainable design concepts to modify the indoor overheating condition into a favourable thermal environment. Alongside reducing energy consumption in buildings. Bio Climatic Architecture is armed with passive strategies aimed at plummeting heat gains through the involvement of building designs carry a substantial meaning and demand in this regard Environmental loads from outside and internal loads, due to internal occupancy is two topmost causes of heat gains to buildings in warm humid tropical climates [3].

To overcome the situation, it is required the understanding of thermal performance in buildings in the context of thermal load characteristics (building physics) and the bioclimatic design approach for low-energy architectural interventions. They should be a further concern with the embodied energy of materials and construction assemblies which are essential areas which cannot be neglected

The interaction between climate, occupants and building design is significant in bioclimatic design. ' Bioclimatic design approach' [2] is seen as a proper origin, which buildings involve in filtering and modifying the external climate for inhabitants' comfort, to handle with energy efficiency prospects in buildings (See Figure 1-1). They can include various forms of environmental interventions, which can seek to improve the behaviour of "internal and environmental loads" (heat generated indoors itself and at outside the building) for energy efficiency concerning the "triple bottom line principles" of minimum detrimental impacts on the natural environment, social equality and economic feasibility (See Figure 1-2).

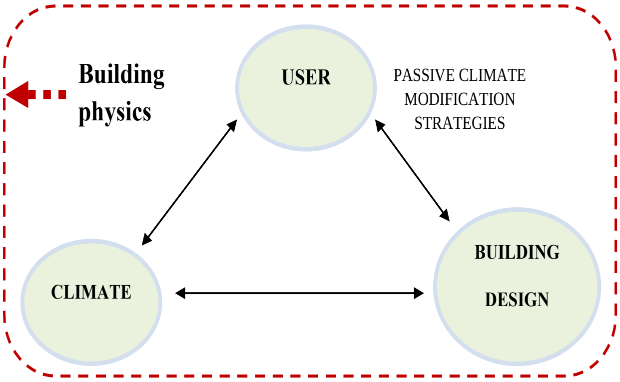


Figure 1-1: Bio-Climatic Design – An interrelation of Climate, User, Buildings

In the context of sustainability, this approach promotes less environmental impacts and cost-effectively meets social needs helping to preserve resources and biodiversity. Involvement of Building design between Climate and Occupants are two ways, they are,

1. Response to impact from outside the building (environmental loads) for maintaining thermally favourable and visually comfortable indoors.
2. Response to impact from elements and systems inside a building (internal loads) for the benefit of occupant's comfort.

1.2. **Need of Study**

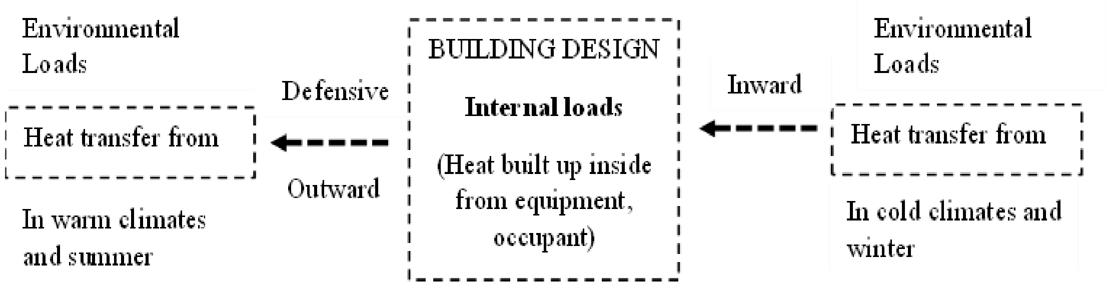


Figure 1-2: Bio-Climatic Design to moderate between climate and building interior for cooling thermal loads, defensive outward heat transfer in summers and inward promoting heat transfer in winters.

There is much research on building envelope developments: for different climates, which are separately conducted as passive cooling involvements such as structural cooling, thermal mass effect, double walls, material experiments, natural ventilation etc. But less research is found on the combined effect of such popular passive cooling strategies to increase the cooling effectiveness.

Further passive cooling strategies along show various drawbacks in their practical usage, especially when utilised in developing tropical countries such as Sri Lanka. Thus, active indoor cooling interferences have become more popular among building professionals (Architects, Engineers), and dwellers. As an example, recent research evidence, daytime natural ventilation in the tropics is less effective in cooling purposes as it carries heat indoors and has opportunities to carry dust odour as well as it limits the potential of thermal mass effect due to low and varying air velocities [4].

This research attempted in getting a holistic approach by developing a novel indoor cooling system, by amalgamating known passive indoor cooling strategies focusing on tropical climates. The focus of the invention is to develop building envelope configurations in achieving indoor thermal comfort, by investigating opportunities for low energy consumption, but highly effective hybrid ventilation systems.

Moreover, the research targets to be this novel indoor cooling system an ultra-simple, low-cost, Low energy and low-carbon intervention with uncomplicated technologies involve and even laymen can handle the complete process.

Furthermore, the experiments focus on developing the invention to become a modern alternative for tropical interiors with an enhanced aesthetic rustic look of burnt clay, making the novel application an architectural element for topical interiors.

1.3. The research gap.

There's a question that, passive cooling techniques and local materials are recommended, yet why less popular? It's proven the usage of active cooling strategies solely in indoor cooling is not recommended due to disadvantages in several aspects. Much research has evident the success of passive cooling systems in terms of energy efficiency and less environmental impact; but practical usage of passive strategies for indoor cooling in buildings can be rarely seen in all climates, whilst active cooling systems, which consume lots of energy have become the most popular indoor climate modification mode throughout the world.

There the research question is aroused why these most recommended, natural and low-cost cooling strategies are less used.

Answering the above question, the research identifies that many known passive cooling strategies have drawbacks/downsides either when they are utilized along or when utilised in particular climatic conditions. Some of them have been discussed below.

a) Thermal mass in warm humid climates – drawbacks

   'Thermal mass effect' is optimum in hot arid climates with higher 'Time-lags' where the diurnal range within a day is long. In hot arid climates even though the building interiors are considerably protected by the high mass envelopes during day times, due to the heat release, it makes more uncomfortable nights.

Comparative to hot arid climates, the thermal mass effect shows restrictions with lesser time lags in the hot humid region as a result of lesser diurnal range [32].

b) Clay and Water, for evaporative cooling - drawbacks

Use of fired or unfired clay together with water for evaporative. cooling is proven effective. in indoor heat. decrease in. hot arid climates, yet in warm humid regions, it's evident that it can course. long-. term health. impacts, for the reason of high humidity levels in the air. Also, direct evaporative cooling can have low efficiency in thermal comfort (makes discomfort due to less sweating) in warm humid climates, where the air reaches near its saturation point [31]. Further, the high humidity indoors can cause corrosion of interior iron utensils, moss, mold growth etc. can occur as long-term impacts.

c) Double walling – drawbacks

Another well-liked passive cooling approach, which is proven successful, is using Double walling. The archetypal double / multi walling is a heavy and costly construction process, bulky and everlasting wall mass thus less responsive in maintenance, especially the cavity in-between two skins. Therefore, potential health and sanitary issues, the requirement for pre-planning of the construction etc. [8].

d) Natural ventilation for indoor cooling - drawbacks

Research evidence that with an increase of global warming effect, daytime straight natural ventilation is less effective in tropics for indoor cooling, since it creates opportunities in carrying outdoor heated air to the indoors and carrying dust, odour [33][34]. Moreover, the velocity is uncertain throughout, depending on the microclimatic conditions. And indoor flows of wind generally depend on in and out pressure difference, wind direction and positioning of the openings, and the internal layout. Nevertheless, an even velocity cannot be expected for all the parts of the indoors.

e) Stack effect for indoor cooling – drawbacks

The less performance of tropical stack ventilation is due to the low-temperature differences between indoor and outdoor temperatures of a building [35], thus low air pressures. For a good, automated stack-induced wind within a tropical building, the opportunities for incoming and outgoing air should be identified and occupied correctly, which generally has limitations in building orientation depending on the context.

Due to the above-mentioned, and more issues related to reducing the tropical indoor overheating problem, the obligation arises for a better technique which provides a low energy, low cost and highly efficient opportunity.

With that knowledge gap, the research designed a holistic approach by developing a combination of proven passive cooling strategies with active cooling methods for an accelerated hybrid cooling system.

The novel cooling system is designed as a combination of selected principles of building physics such as thermal mass effect, porous material's effect as heat insulation, thermal conductivity and absorptivity effect, ventilative cooling effect, structural cooling effect etc.

The novel system is tested by focusing on the 'developing countries' of 'tropical climates', by investigating opportunities for low-cost materials and building technologies with low and easy maintenance opportunities with an aesthetically rich, thermally effective system.

1.4. **Research objectives**

a) Main objective

1. To determine innovative cooling intervention using double walling concept with dynamic clay wall panels which to be applied as secondary skin, integrating with cross ventilation, and creating effective structural cooling for indoors, thus reducing the operational energy demand, and creating fresh and healthy indoor environments.

b) Specific objectives

1. To identify the most effective mix material, material mix portion firing temperature, firing time in terms of cooling, panel thicknesses and size, panel's

hole distribution, hole angle and hole diameter in terms of better cross air passing, moreover the best fan configurations in terms of best indoor heat reduction.

2. To identify the practicality of the innovation with an application in a real-scale prototype building.
3. To identify the thermal performance improvements of the proposed system, in virtual space while identifying the potentials in mechanical engineering aspects for zero or near zero energy applications.
4. To evaluate the sustainable parameters of the invention- (Life Cycle Cost)

1.5. Limitations

Investigations have not specified the exact type of Saw dust (from a specific plant species) while developing and testing for the material mix.

Thermal performance investigation in the real scale building depends solely on the ambient weather, which the period spent is a limitation due to slightly different outdoor conditions, even though indoor temperature data were compared in the dons where similar outdoor conditions prevailed.

Energy requirement for the operation of the fans and the negligible noise generation due to the fan operation. However, there exists the possibility of integrating with alternative energy to fulfil the energy requirement since this is involved the n tropics.

1.6. Scope of the research

The system is a combination of two components, which work together for heat reduction and gaining cooling. **Component 01-** A set of thin-fired clay panels which are pounced and fixed as a second skin to the interior of the primary wall, while **Component 02-** low energy consuming mechanical air supply unit, provides ventilation to the indoors through Component 01.

The research scope limits for developing Component 01 by identifying its optimum physical and mechanical characteristics for optimum indoor air temperature reduction, and developing Component 02 for its maximum efficiency when working together with Component 01.

Moreover, the research investigates the potentials of the proposed cooling system solely for passive mode and solely active mode as well, to make comparisons for better indoor cooling.

Further, the research identifies the simplest practical casting method for Component 01 and develops the minimal fixing details of Component 01 and 02.

The invention remains possibilities for zero energy consuming operation by developing Component 01 with a Nocturnal cooling effect with night ventilation and with evaporative cooling.

The energy consumption for Component 02 will depend on the fan type availability in the local market.

1.7. Methodology

- The background knowledge will be gained by reviewing related literature, conducting observations and participating in studies within the scope to identify the key parameters to be dealt with for the proposed dynamic clay double walling (DCDW) system.
- Following the gained knowledge, design the proposed cooling system with potential components to be employed (components 01 and 02).
- Development of Component 01 –
- Identification of potential raw materials (clay types) and organic waste compound types and their mix materials (water absorption test).
- Identification of best firing temperature and time, for the best formation of dynamic inner pores in the clay body (water absorption test).
- Identification of best material mix proportion in terms of forming internal pores in. the clay body. upon firing (water absorption test).
- Identification of the effect of dynamic clay wall panels' thickness on indoor heat reduction (Chamber test)
- Improving the air permeability characteristics of the dynamic clay wall panel; Deciding the pouncing technique, identifying the best hole angle (buoyancy), best hole diameter, and best hole distribution to enhance the cross-air movements. (Chamber test)

- Developing a mass-scale targeted production method for the DCDW panel.
- Identification of the practicality of the DCDW panel with an application to a prototype real-scale building.
- Identifying the time and cost-saving best panel fixing method.
- Development of Component 02 –
- Identifying the DCDW panel's effect on indoor air temperature reduction with different negative ventilation and positive ventilation for different panel areas.
- Identifying the DCDW panel's effect on indoor air temperature reduction upon the application on different airflow patterns (same direction in /out, opposite directions in / out)
- Identifying the effect on indoor air temperature reduction with increasing the number of fans and the area of DCDW panel into selected Fan: No. of panels ratios. (1:4, 1:8, 1:12)
- Design builder simulation - Identifying the effect on indoor air temperature reduction with different air cavity distances (between the primary and secondary walls), and the effect upon application of the proposed DCDW for the different indoor facades.
- Identifying the operational energy reduction due to the proposed cooling system.
- Evaluating the sustainability of the DCDW system with LCC calculations.

1.8.Main Findings

- Dynamic Clay Double Wall indoor cooling system is promising its best indoor heat reduction when component 01 (Dynamic Clay Double Wall) and Component 02 (Mechanical ventilation supply) function together.
- Best material mix for the DCDW panel (Component 01) was confirmed as ‘Red Pottery Clay with Saw Dust (5mm particle sizing to 50:50 Clay: Saw Dust volumetric proportion.
- The DCDW should be punched with millimetre-scale holes for better air permeability, specifically with, a 2mm diameter, ½ x ½ inch distance to each with 45 degrees buoyance angle.
- DCDW panels to be cast with the tested novel technology, in a manually operating machine to compress the clay and touch the holes.

- The casted DCDW panels should be air dried, and oven-dried, and the firing temperature was confirmed as 800°C for one hour, in terms of best internal porosity and indoor air temperature reduction.
- The thermal conductivity of the finalized DCDW material is 0.05 W/mK.
- By increasing the thickness of the DCDW panel, the thermal mass effect and thus heat absorption capacity can be increased.
- In component 02, when the fans are inhausted, it gives a better indoor air temperature reduction than fan exhaustion.
- Experiments proved that the DCDW system contribute to f a significant air filtration.
- The maximum cooling capacity for $1m^2$ of DCDW with 01 fan-recorded as 1.39 m^2, with 02 fans as $2.62m^{2,}$ and with 3 fans as $3.94m^2$.
- West façade where the DCDW system is installed should be oriented to 30 degrees further om East for better indoor heat prevention.
- In LCC assessment, (NPV and Payback period) it's evident that the DCDW cooling system can contribute to significant operational energy saving, thus operational cost reduction when compared with an active mode.
- Therefore, the economic benefits and the success of the Dynamic Clay Double Wall system are strongly proven by its profitability.
- Among all three cases, the DCDW arrangement with 01 fans, is recognized as the best saving option comparably, in Energy saving, Net Percent Value and Simple payback period.

1.9. Arrangement of the dissertation

The thesis breakdowns the chapters as follows.

Chapter 01 presents the introduction and the background of the research.

Chapter 02 offers a detailed review of literature conducted for the background, methodologies, standards, and establishments of findings of each section of the research.

Chapter 03 presents the mix design development. of DCDW system. This chapter expounds on the process of developing mixed mix material, mix material composition, production process, firing temperature and time, linear shrinkage, thermal conductivity, inner porosity by Water Absorption capacity, in terms of surface and microstructure etc. for optimum indoor air temperature reduction.

Chapter 04 presents the improvements of DCDW in terms of thermal performance. This chapter particularizes the process of improving the clay panel's air permeability, development of the casting method and thermal investigation above with the test chamber.

Chapter 05 presents the actualization of the DCDW system in a real-scale prototype building. The chapter emphasizes, the practical application of the DCDW system in a real building, the impact of the DCDW system on identified parameters such as the ratio of DCDW wall panels to the number of fans, the orientation of the DCDW application, the effect of panel area expansion etc. and the impact of mechanical ventilation supply (Component 02) on indoor air temperature reduction.

Chapter 06 presents potential improvements to the dynamic clay double wall system, using thermal simulation. The chapter discusses the process of modelling the real-scale building with the Design-builder simulation tool and identification of behavioural patterns with the DCDW system, improvement potentials for better indoor air temperature reduction.

Chapter 07 presents the assessment of the long-term sustainability of the DCDW system with a life cycle cost analysis. The chapter presents the LCC with Net Percent Value (NPV) calculation method and Simple payback period method comparing with identified three cases with DCDW system, with different operational schedules, different panel area coverages, comparing to 100% active cooling case study, maximum for 60 years. Further, it identifies the best payback option of the DCDW system.

Chapter 08 presents the conclusions and recommendations. and future directions related. to this research.

2. CHAPTER TWO – LITERATURE REVIEW

2.1. General

Literature provides a basis or conviction for a fact in research. This chapter presents a comprehensive review of literature related to the research. The Literature review covers the related similar work done, related principles, standards, methodologies etc. adopted in comparable experiments. This chapter emphasizes the previous work done on climatic behaviour and issue in the tropics, Earth and clay as construction materials, Properties related to cooling in clays, Potential organic waste in clay bricks, psychometrics etc. in detail.

2.2. Climate in tropics

Countries positioned close to the equator which lies down between the Tropics of. Cancer and Capricorn. between the latitude of 15°South and 15°North is known where the tropical climatic conditions prevail in. A great deal of the equatorial belt inside the tropical climate zone comes across hot yet humid weather. The main characteristics unique to tropical climates can be shown as high-pitched humidity throughout the year combined with low 'diurnal' temperature variations.

There is ample precipitation because of the 'active vertical uplift', or air convection that occurs there. Thus, for some period thunderstorms can take place daily, Nonetheless, receiving significant sunlight, and extreme precipitation lays an excellent environment for crops. Temperatures in the tropics seldom exceed 5℃; a daytime upper limit of 32℃ is typical since a significant part of the Sun's temperateness is used for the loss of vapours and creation of the rain. Abundant cloud cover restricts heat loss, and the lowest temperatures decrease no lower than about 22℃ experienced at night. This high level of temperature is preserved with little adjustment throughout the year [5].

Uninterrupted evaporation from the human physique happens due to the high amount of solar radiation received in the equatorial region. A significant discomfort can be experienced in indoor environments in buildings, due to excessive solar radiation.

Thus, building designs should be incorporated solar control, to reduce heat surplus in the main course [5] [6].

2.3. Requirement for "Indoor climate modification" in the tropics; prevention of overheating.

A pleasant thermal environment is vital to human comfort and wellness. Since the indoor setting is closely influenced by the outdoor condition. The microclimatic factors to be determined to enhance a healthy indoor setting, which is comfortable. That means ambient air temperature, precipitation, radiation, relative humidity, wind, shadings etc. are led to variation of the indoor thermal environment [7][8].

Since the tropical region exists closer to the equator, a harsh climatic condition resulting in an overheated building interior is common, with a solar heat gain and penetration through the building envelope and apertures, [5][6] which causes excessive heating exceeding the threshold of indoor thermal comfort for the living beings. To overcome the uncomfortable situation, thermal modifications in the indoor climate need to be done (See Figure 2-1). Indoor climate modification can be done in the following three ways.

2.3.1. Passive mode (building interventions which do not consume energy)

To offer natural heating and cooling in a space, in diverse seasons, the building design should be amalgamated with ordinary rudiments on a site (including sun and wind patterns), known as passive cooling strategies. This is an energy-efficient, low-carbon, low-cost and low environmental impacting solution which can be provided as a solution, especially for tropical overheating

2.3.2. Active mode (Strategies which rely on energy in their operation)

Active cooling strategies demand 'energy' in its term, including electricity and fuel to keep buildings contented, including mechanical systems, Air-Conditioning machines, heat pumps, electric lighting, heat recovery ventilators, radiant heating etc.

2.3.3. Hybrid mode (Passive and active modes together)

Providing comfortable indoor conditions at minimum capital and running costs can be recommended in terms of prevention of overheating due to several aspects such as energy conservation, environmental impact etc.

The use of passive cooling strategies for the prevention of overheating thereby creates a good match. Broadly, the prevention of overheating is concerned with minimizing the amount of heat which gets into a building, whilst passive cooling is concerned with getting the heat out. Ventilation and air movement tend to fall into both categories[11]

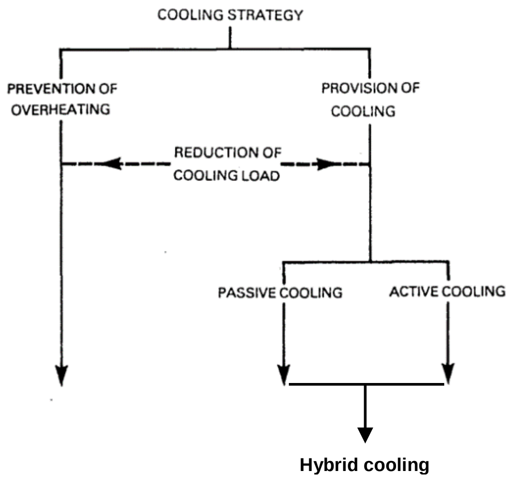


Figure 2-1: Cooling strategy diagram

2.4. Passive climate modification in tropical climates

True strategies of design in altering the indoors to refrain from overheating are immensely significant in encouraging passive cooling. The renowned researcher [9] establishes this theory by referring to the graph below which shows how the building design (passive strategies) controls the indoor air temperatures, while the ambient temperatures fluctuate with high peaks during day and night.

2.5. Building interventions for passive thermal modifications

Living beings, especially humans are used to living in shade to protect from the outdoor climate from the very beginning of human civilization. To proceed with a contented thermal environment indoors is crucial in terms of the mental and physical well-being of the dwellers. The outdoor/ambient climate is considered a parameter which is directly affecting human beings; nevertheless, something beyond the control of the human thus can remain comfortable or uncomfortable. Therefore, there should be an intermediate partner between these two parties, in which the role of "Building" often acts. The architect, as the building designer, plays the major responsibility in this case (See Figure 2-2).

The buildings are recommended to be designed at their early stages with the approach of "do-no- environmental-harm", in contrast to the 'harm and then fix later or offset' approach which is not sustainable long term. Buildings of this nature live up to true passive principles because their very basic intentions are attached to a holistically environmental philosophy that is more concerned with protecting nature, than achieving a high green rating.

Baker N.V states, [11], "We have only to look around a modern city in any developing country to see the fallacy of adopting "international style" architecture. These buildings, often produced for reasons of civic pride and prestige, soon become an embarrassment, with huge energy bills and serious maintenance problems".

Therefore, the thermal performance of buildings which are resulted from the context of thermal load characteristics (building physics) and sustainable design approaches should become a key concern in achieving low-energy buildings. On that basis, there are main factors which should be essentially focused on when designing buildings in the tropics in terms of 'passive climate modification', as discussed below in detail [3].

2.6. Building Orientation

Orientation of the building should be considered in the initial stages of a design. In building orientation, there are two main considerations. They are,

- Sun path orientation (orientating the building considering the solar axis and shadings around the building)
- Wind orientation (orientating the building considering the wind direction to catch optimum fresh air) [3] [7].

In tropical countries, orientating the building considering the solar geometry is an essential factor in terms of thermal comfort. Because the solar radiation gain in tropical equatorial regions is significantly high and it causes direct heat up in the building envelope. Therefore, facing the building facades to the solar directions also should be carefully handled. In these climates, building should be orientated to obtain maximum shadings during the day. A famous researcher supports this factor further as below.

“Shadings created on the building form and fabric depend on the type of climate. Shading is necessary not only against the direct and reflects solar tradition in warm humid climates, although against the high concentrations of diffused radiation from the sky” [13].

If the buildings are oriented in East-West directions (wider facades) when sun rises and sets the wider facades to get heated by direct solar radiation. Therefore, the building should be designed in the tropics orientating the narrower facades to the East and West directions [14][15]. When positioning the openings need to arrange them with proper shading around, then while flowing through the shading it helps to reduce the air temperature of the wind gained from outdoors. If the roof and walls get overheated in the daytime by exposure to the direct / defused solar radiation, they contribute to transfer the heat into the interiors of the building.[10] [12]. Further literature depicts the importance of correctly located openings in building design (See Figure 2-2) as follows.

“An efficacious design with natural ventilation building requires a moral understanding of the patterns in the flow of the air around it and also on the consequence of the surrounding buildings, nevertheless, the prevailing design-

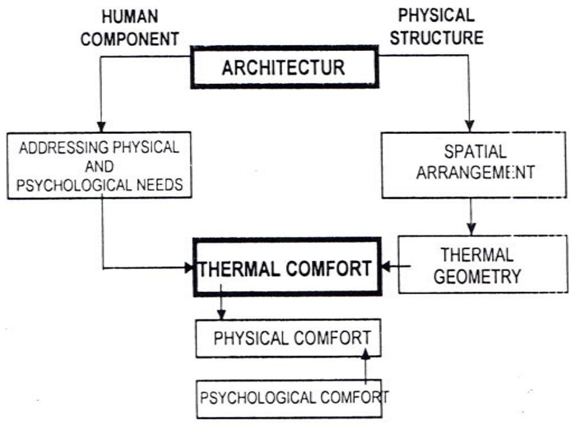


Figure 2-2: Interrelationship between building design and thermal comfort [110]

strategies to improve aeration. The aim of this is to ventilate the major probable parts of the space indoors. The approach of this impartial is contingent on the positioning of the window location, wind characteristics, interior design etc." [16]. Since building designs for optimum wind-forced ventilation are vital in the tropics,[12] courtyard buildings gain better ventilation through the internal spaces. With the courtyard, the functional depth of the plan can be kept to a minimum for better ventilation potential. But ventilation in warm climates has limitations, as they can carry heat from outsides[13] [14][5].

2.7. Cooling with Ventilation

Ventilation is used in buildings to provide satisfactory indoor air quality, especially thermal comfort (See Figure 2-3). Ventilation and air movement are considered separately. They can be categorized as follows:

- Ventilation — the substitute of indoor air. with outside air
- Air movement —the passage of air as perceived by the dweller

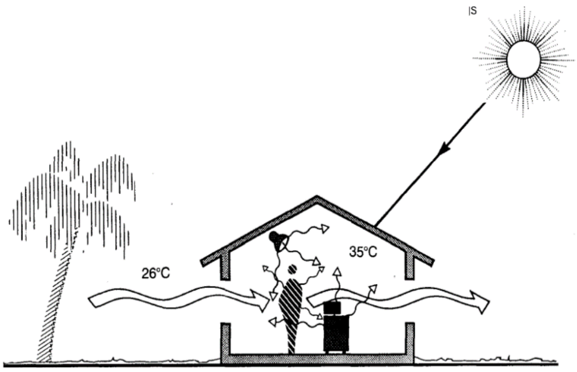


Figure 2-3: Heat Removal by ventilation [11]

The cooling effect or thermal comfort by ventilation occurs as it creates a heat loss, or heat exchange. Heat loss by ventilation is proportional to the following:

1) Air transformation frequency
2) Temperature disparity between in and out of the building.
3) Air's heat volume (capacity)

The heat The capacity of air varies a little with humidity but with sensible accuracy we can write:

$$w = 0.33\ NV\ (T_i - T_0) \qquad \text{Equation 1}$$

Where **N** is no. of air changes per hour, and **V** is the volume of the. building.

Cooling the buildings with ventilation comes under three modes as follows.

2.7.1. Passive ventilation mode

Ventilative cooling has been used historically as an effective passive cooling design strategy. The “Hawa Mahal”, is a living example of historical architecture where passive cooling is utilized in building designs. This building is also known as the "Palace of Winds" or “Palace of the Breeze”. This was built in the 18th century in Rajasthan, India and used the venturi effect to cool the entire palace passively (See Figure 2-4).

By locating the palace next to a large waterbody, where the direction in which wind passes from, the palace has formed an example of a ventilative cooling effect coupled with evaporative cooling.

Figure 2-4: Hawa Mahal, ‘The Palace of Winds’, Rajasthan, India

As a significant traditional Islamic architectural feature, the “Mashrabiya” can be highlighted as a component used for natural ventilation and cooling of buildings without demanding any energy It consists of wooden canopies or windows which provide shade and gives a shield from the sun and permits breezes to flow through into the building for cooling purposes. See Figure 2-5 for a ‘Mashrabiya’ system, attached with water-jugs which are porous, to deliver an evaporative cooling effect for the dwelling and cooling water inside jugs for water drinking as well [19].

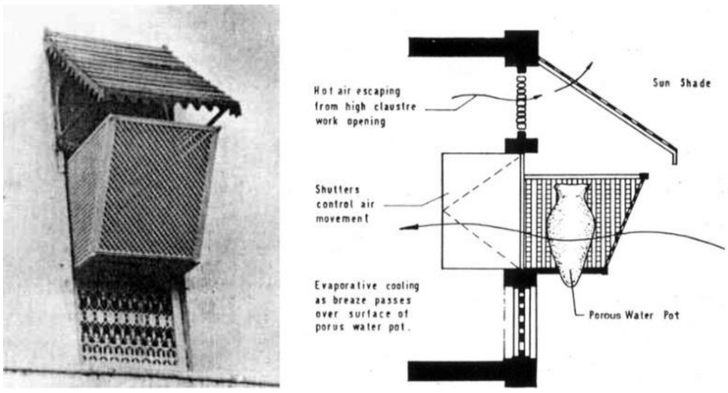


Figure 2-5: The ‘Mashrabiya’ with porous water jugs cooling system

The Middle East and South Asian countries have the most primaeval buildings in tropical climates, where they are built with excessive thermal mass and with elements for natural ventilation to preserve cooler interiors. “Wind towers” (alternatively 'catcher') are used for convection and evaporation to promote cooling (See Figure 2-6). Wind towers were popular as a convective cooling system In Egypt in 1300 B.C., [2] [20]. Olgay V. describes a chimney in reverse which was used as an evaporative cooler in an Egyptian village.

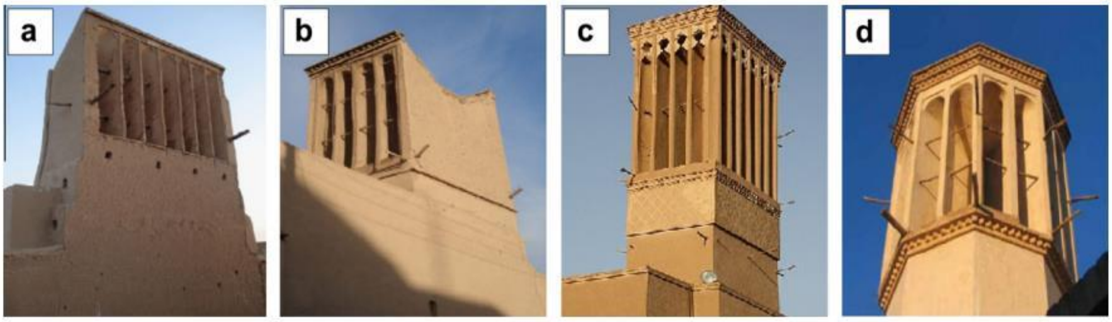


Figure 2-6: Old-style wind towers with consisting diverse quantity of openings: [112] **(a)** single-sided **(b)** two- sided **(c)** four-sided **(d)** octahedral

In these buildings, a scoop-like shape is oriented to imprisonment the passing wind, and the captured air is passed down through a shaft made of porous clay, where a water jar is located at the bottom. While passing the path, the air is subsequently chilled earlier it arrives at the room Many other examples are found in Iraq, Morocco, Iran, Turkey, and Indian cities. Hyderabad and Sindh where the same strategies have been utilized for indoor cooling [21].

Since they incorporate no outward electricity compared to others, these types of ventilation systems are classified as carbon-neutral passive cooling systems Wind towers have survived in various forms for periods, and are st as an environmentally friendly method of providing indoor ventilation. Further, opportunities are existed in integrating commercial wind towers into the designs of new buildings with no use of electrical energy [22].

Numerous studies have shown that wind-driven force is the primary strength of the wind towers, which provide 76 % extra indoor ventilation than forces that are driven on buoyancy [23]. Stack effect ventilation normally trusts the circulation of the warmer air inside the building rise and leave the building from a high outlet and get released while cooler air income to the interior through lower opening.

According to Hyde R.,[24] in warm humid climates, the recommended way is to achieve the cross-ventilation through openings, maybe the main door, windows or by a central courtyard from windward and enclosure in the leeward direction. In traditional Sri Lankan building forms, the verandah in the front or on the sides acts as a wind tunnel that directed the occurrence of wind towards the courtyard. This ‘air funnel’, in turn, ventilates the indoor spaces near the courtyards (See Figure 2-7).

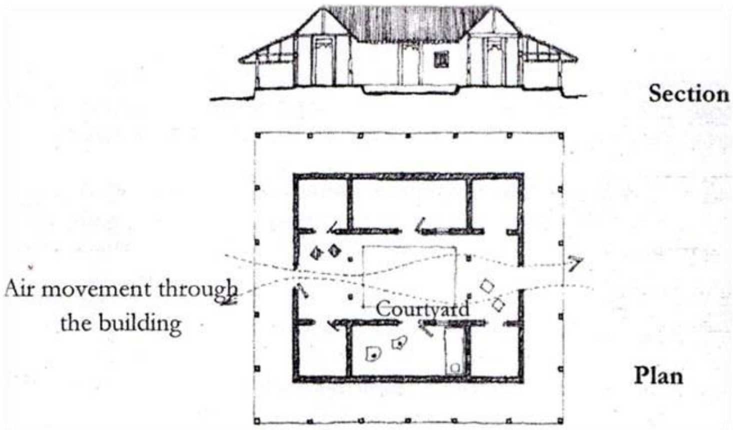


Figure 2-7: Tropical courtyard building as an ‘air funnel [104]’

To prevent the heat gained with wind-induced ventilation from entering the interior, the boundary openings are shaded with eves or with verandahs [13] [14][5].

2.7.2. Active ventilation mode

Mechanical ventilation systems which consume energy are used as “Active climate modification” strategies. Mechanical fans drive mechanical ventilation. Centrifugal fans and blowers are the turbo machines widely used for mechanical ventilation in contemporary trade and households used in the place of air conditioners [25]. It is identifiable that much research has been conducted on aerodynamics, local flow physics, and energy transfer phenomena, in terms of the performance of blowers, pumps, or fans, [26] [25] [27].

Mechanical ventilation requires regular maintenance, if using air conditioning machines, the filters should be altered frequently, since if they are getting dusted, it pollutes and directly affects the indoor air quality, which, in sequence, decreases the efficiency of the dwellers which also increases the pervasiveness of illnesses like sick building syndrome [28]. Fans such as exhaust units can either be directly fitted to walls, in air ducts to air inhaust, or exhaust.

The mechanical ventilation type and the method hinge on the climate in the surrounding in an air supply with a positive pressure, the room is in positive pressure the room air can be dripped out through envelope leakages or openings. In a system with negative pressure, the room is negative pressure and the room air are rewarded by “sucking” air from the outside.

In a system where air inhausts and exhausts are verified and accustomed to design specifications, there comes a balanced mechanical ventilation system. In these situations, either a vaguely positive or negative pressure is gained by an incapable supply or exhaust ventilation rates. As an instance, a slight negative pressure in the room is achieved by draining 10% more air than its supply [29].

2.7.3. Hybrid ventilation mode

Hybrid ventilation comes together with mechanical ventilation and passive ventilation to optimize thermal comfort, Indoor Air Quality, and energy management. These systems: ‘Hybrid cooling technologies are partially assisted by mechanical ventilation supplies when the natural ventilation is in use. The implementation of passive and hybrid ventilation provides an opportunity to lower the energy consumption taken for occupant comfort by utilizing free natural cooling as much as possible. This method optimises the indoor environment while reducing energy costs. Variations of hybrid ventilation systems do exist.

a) Combined natural and mechanical ventilation
b) Fan-assisted natural ventilation
c) Stack- and wind-assisted mechanical ventilation

Not like in passive ventilation systems along, hybrid ventilation systems can adjust for the preferred flow rate of wind. Whereas it integrates mechanical ventilation on occasions when the natural ventilation flow rate is too low [17]. In situations where natural ventilation alone is not efficient, exhaust fans (with satisfactory prior planning) can be fitted to improve the air exchanges in the rooms. Anyhow, it is identified as that simple type of hybrid ventilation needs to be used with care. The fans should be installed only if provisions are there which air can be exhausted straightaway to the outdoors through, whichever a wall or the roof. The size and number of exhaust fans depends on the targeted ventilation rate and necessity be measured and tested before use. Not like in passive ventilation systems along, hybrid ventilation systems can adjust for the preferred flow rate of wind. Whereas it integrates mechanical ventilation on occasions when the natural ventilation flow rate is too low

Moreover, hybrid ventilation can diminish the peak demand. When the outdoor climactic conditions are favourable, the hybrid ventilation mode provides more choices to minimize the fan energy [30]. If the hybrid cooling is in use, there are basic issues related to the use of exhaust fans, like installation difficulties (especially for large fans), noise (particularly from high-power fans), etc other than that, there are possibilities to install whirlybirds (whirligigs or wind turbines) that do not require electricity or provide a roof- exhaust system growing cross airflow [17].

2.8. The Building Envelope

The envelope is the skin of the building, which protects the internal spaces from the outside climatic factors. The envelope consists of Walls, Roof and Floor, literature [11] explains that the specific performance requirements of a building's envelope will depend on the climate and the building characteristics. Each element contributes to the thermal transmittance, the thermal storage, and the admission of daylight, as well as to the appearance, cost, ease of construction and maintenance, security, and many other features of the building. In terms of climate, 'the building envelope' always performs as a climate modifier, as examples; in cold climates, a building envelope is used to prevent outdoor coolness gain into the building by sealing the indoor, and in warm countries, the same building envelope is used to avoid outdoor heat gain into the building.

For both situations, there are common factors included in envelope performance as follows,

1. Solar Heat gain Factors (SHF) of the building
2. The absorptivity of the external surface
3. The insulation value of the envelope
4. Mass of the envelope

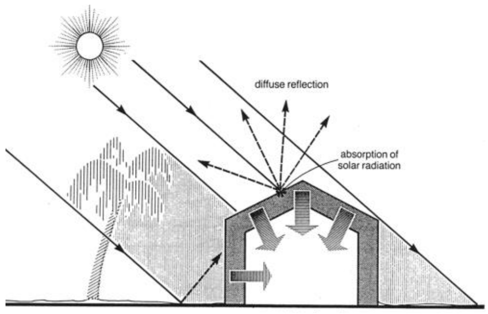


Figure 2-8: Solar heat gain through building fabric and shadings to the envelop [11]

In the tropics, the greatest concentration of solar radiation lays on the roof as well as the west walls, with slightly less on the eastern because the morning temperatures are lower (See Figure 2-8). Vernacular buildings in the tropics show way outs to diminish the direct fall of solar radiation on the internal spaces around the courtyard. A verandah, a place of transition from inside to the courtyard, is found along the courtyard perimeter in most cases. The verandah sometimes partitioned with lattices or blinds is a multi-functional connecting element used for circulation, eating, sleeping, relaxing, and entertaining as well as being a sheltering and shading space [24]. Spread-out plan forms with internal courtyards allows better integrations of switch spaces in the building arrangement than the compact one.

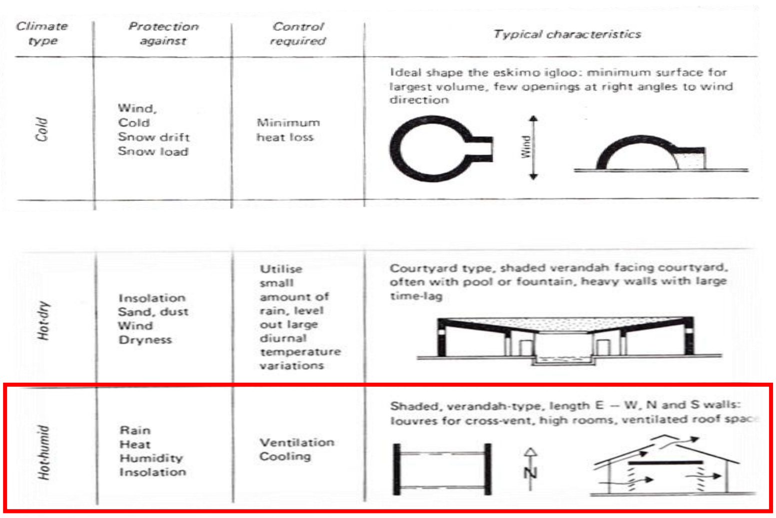


Figure 2-9: Different characteristics of buildings in different climates [32]

Solar heat gain through the building envelope occurs because of the heating of soaked up solar radiation which is conducted to the interior. To minimize it,

- Shading can be used to lessen the quantity of radiation falling on the structure (e.g., by vegetation or covering with another element)
- High reflective finishes to be used in reducing the radiation
- Expanding the insulation values of the roof and walls.

To increase the thermal performance of the envelope, it is worth identifying the thermal characteristics of the building materials which are used for the envelope. Out of the envelope thermal properties like thermal conductivity, thermal capacity, thermal resistance (*R-value*), U value, heat resistance etc., thermal reflectivity and emissivity of some building materials are mentioned in Table 2-1.

Table 2-1: Reaction of materials to solar and thermal radiation [11].

Reaction of materials to solar and thermal radiation			
surface	Percent of reflectivity		Percent of emissivity
	Solar radiation	Thermal radiation	Thermal radiation
Aluminum polished	85	92	8
White wash	80	-	-
White marble	54	5	95
limestone	43	5	95
wood	40	5	95
Asbestos	29	5	95
Red clay brick	23-30	6	94
Galvanized iron	10	72	28
Black matt	3	3	95

Solar heat gain through the building envelope occurs because the ‘Thermal mass’ is prescribed as the capability of a material to grip the radiation or heat. The thermal capacity is an important factor well-thought-out in moderate climates. When the thermal capacity is low which is also referred to as ‘quick response’ limber up easily and cool rapidly. Structures with high thermal capacity will have an extended ‘heat–up time which will conserve heat after switching off the heating.

In building design, the mass of the building (envelope and internal mass) provides "inertia" alongside temperature variations, which is known as the “Thermal flywheel effect” The principle of thermal equilibrium works in this. For an instance, a large thermal mass can help to “flatten out" the daily temperature fluctuations when outside temperatures are shifting throughout the day, as the ambient is hot than the mass, it can absorb the thermal energy and transfer bit ack when the surroundings get cooler This is different from a material's insulative value, which helps to reduce a building's thermal conductivity, allowing it to be heated or cooled relatively separate from the outside, or even just retain the occupants' thermal energy longer [3][31].

2.8.1. Thermal mass and passive cooling

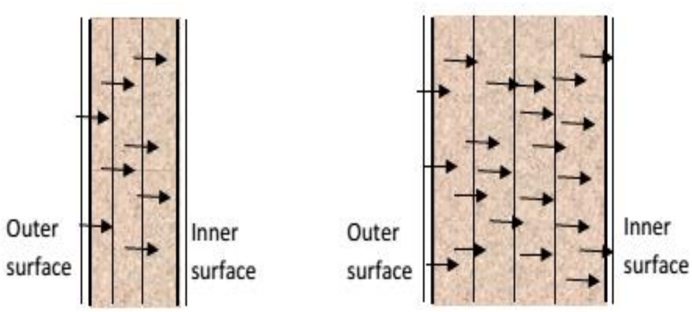


Figure 2-10: Heat transfer by conduction through mass walls; thicker walls take more time to pass the heat from outside to inside

There are several examples of hot arid climates where the diurnal range of the climate is very high, of using thermal mass for passive cooling. Its traditionally proven with trial and error that when these strategies are applied accurately, it works amazingly in these climates making outdoor uncomfortable conditions into comfortable situations throughout the day [28].

High thermal mass materials like stone, mud and adobe are used in these regions for the construction of the building envelope deliberating their high thermal capacity and heat absorbance. In hot climates, walls are constructed ‘thicker’, as they can absorb and store the outdoor direct and defuse solar heat inside them. When the wall is thick and its material has a high thermal capacity, the heat transfer from the outside to the inside becomes delayed (See Figure 2-10).

In the book “House Form and Culture”, Amos Rappoport, [33] says about high mass houses in arid climates,

“The houses there, with thick mud walls and few openings, are constructed to keep out the sun; the result is that the interiors remain cool and dark all day”

It's proven that, when an insulated high-mass building is ventilated at night, the structural mass of it gets cooled due to convection from the inside, by-passing the thermal resistance of the envelope. In the daytime, that cooled mass is adequately insulated with heat from the outdoors, which can serve as a ‘heat. sink’ [11] [13] [32].

As another method, during the daytime, the building should be closed to the maximum to control heat gain to the interior from hotter outdoors. As a result, in such buildings the indoor maximum temperature can be substantially lower than the ambient maximum, or indoor maximum temperature of a similar building which is not ventilated at night. This cooling strategy is named ‘Nocturnal cooling’. The above process “time-lag” between maximum temperatures of outdoor and indoor due to the time delay occurred by the thermal mass [34].

2.8.2. Thermal mass in hot humid climates

The low diurnal range and the small annual range of temperature are the main characteristics of the hot-humid climate. Humidifies are high and typically average about 70% RH, thereby reducing evaporative cooling from the skin. According to Baker.N.V[11], high thermal mass constructions of envelope in hot humid climates releases the absorbed heat at the night and evening hours. To avoid heating the interior by this, ventilation should be introduced at nighttime. With a diurnal temperature fluctuation of 6-10^{0}C, coolth storage in structural mass is just about worth considering.

Famous researcher, Szokolay S. [34] has researched thermal mass characteristics in warm humid climates. The results of a computer simulation of a heavyweight structure in the climate of Darwin, in Australia, were demonstrated to identify the beneficial effects of thermal mass (See Figure 2-11).

The heavyweight building is considerably warmer at night, which would probably be unacceptable for housing, but in the daytime shows a 2^0C reduction in peak temperature.

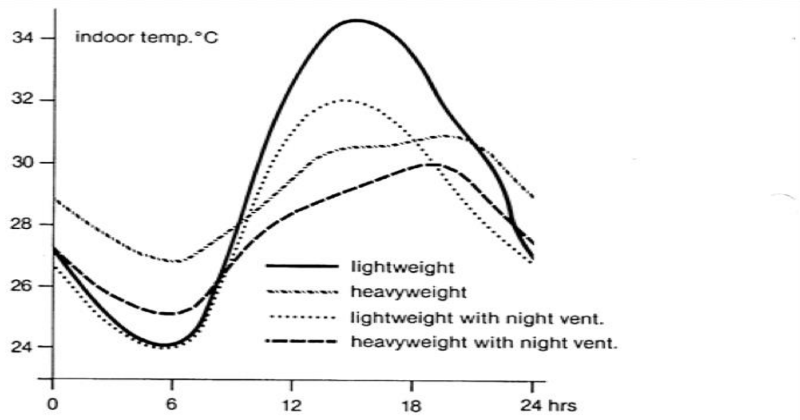


Figure 2-11: Results of night ventilation simulations for a building in Darwin Australia [11]

This performance is increased in the daytime ventilation rate is decreased to 1 air exchange per hour and the night ventilation is increased to 30 ac/h, peak day temperature is almost 4^0C lower than the lightweight case, whilst night temperature is only about 1^0C above the lightweight case.

Szokolay's [34] bio-climatic chart predicts increased air movements to provide indoor thermal comfort in warm humid climates. In addition, Giovani's [3] bio-climatic chart meant at forecasting the indoor thermal conditions of the building, recommends increased air movement to provide indoor thermal comfort. It represents that a high mass envelope coupled with nocturnal ventilation can reestablish indoor thermal comfort for the warmest period of the year.

Olay's [2] standard of "optimum shape of buildings" names for buildings. freely elongated. in the East. – West. directions yet considering solar radiation, temperature and others. climatic conditions. This provides shelter. from. Sun. for north-south faced and, apart from that, facilitates easy air. the movement inside buildings. Moreover., the directional. effects of airflow bays and building orientation. can assist to ameliorate the. indoor air movement situation. The work indicates that the pressure differences which are primarily determined by the building geometry, on the leeward sides windward and contribute to the airflow inside the building when the inlets face a high-pressure area and the outlets face a low–pressure area.

Givoni's [10] work shows that in hot dry climates, how a spread-out building form allows better natural cross ventilation than a compact one, by giving more wall areas and more directions for catching the breeze.

2.9. Time –lag in indoor thermal performance

Time – lag is a theory often used for indoor thermal comfort gain in warm climates. According to time lag theory, a delay of time between the ambient and indoor maximum air temperature is done (See Figure 2-12). Generally, the implementation of time lag theory is approached by the building envelopes.

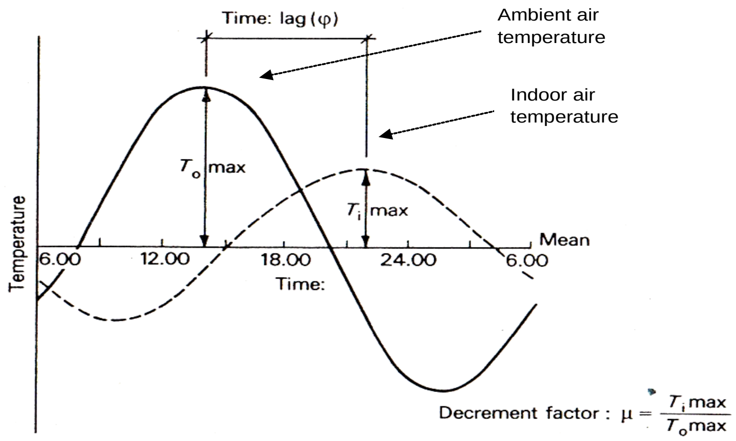


Figure 2-12: Time -Lag and Decrement factor [35]

The ambient air temperatures reach their peak around 12-1 pm times (To- max). When the envelope of the building is a high in thermal mass (heavy Construction), it engrosses heat and preserves indoors with a low-temperature rate even in the ambient peak temperature times. The outdoor temperature gradually reduces after the peak time, where the high mass begins to release the absorbed heat to the indoors while it is reaching the maximum indoors temperatures. The time delays. Between these two maximum temperatures are called Time-lag.

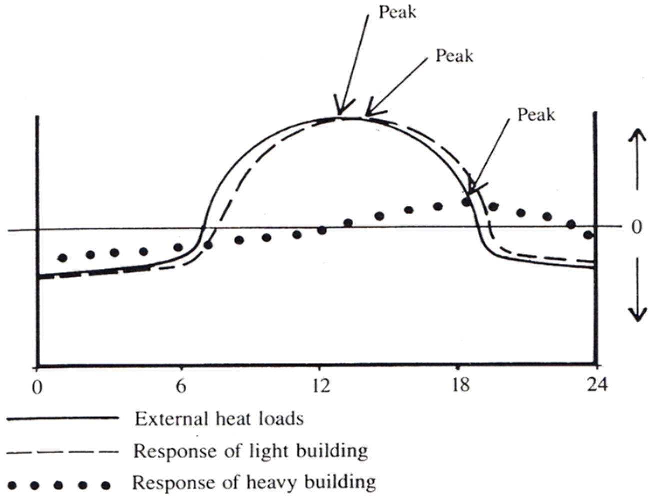


Figure 2-13: Time -Lag behavior for light building envelopes

During mornings, the heat starts entering the outer facades of the buildings when the outdoor temperature is increased. Thus, dashed lines show a delay of consistent increase of the internal temperature (See Figure 2-13). By then, the outdoor temperature has reached its peak and it started decreasing before the inner the surface temperature has grasped the same level. Meanwhile, the heat is stored in the wall will be gradually dissipated to the inside as well as outside. As the outdoor the air cools, increasing proportion of this stored heat flows outwards, and the the direction of the heat flow is complete reversed when the wall temperature falls below the indoor temperature. The two quantities characterizing this periodic change are the decrement factor (or amplitude attenuation, denoted μ) and the time–lag (or phase shift, Θ). The rate at which it will transmit heat to the next partial depends on two factors,

1) The heat transfer rate will be faster if the envelope material has high thermal conductivity.
2) The heat transfer rate will be slower if it is a dense material with high special heat it will absorb much of the incoming heat, before it can start transmitting the heat.

The graph shows the peak temperature behaviour of high mass and low mass buildings that can be referred to make the above factors clear (See Figure 2-13).

According to O.H Koenigsberger, S.V Szokolay, in “Manual of Tropical Housing and Building”,[35] the variation of climatic conditions causes a non-steady state. It happens when the diurnal ventilations harvest an approximately repetitive twenty-four-hour cycle of growing and declining temperatures.

O.H Koenigsberger, and S.V Szokolay [35] further explains that time lag (Θ) and the knowledge of the decrement factor (μ) for different materials , thicknesses , and combination of materials in various construction elements since its important factors for a designer (See Figure 2-14). Thus, the selection of construction with an appropriate time–lag is an essential factor in the design and the process could be described as ‘balancing in time’.

The time lag theory is often made used by buildings in hot humid climates. Because they have the most critical ambient solar radiation situations in their countries among warm climates.

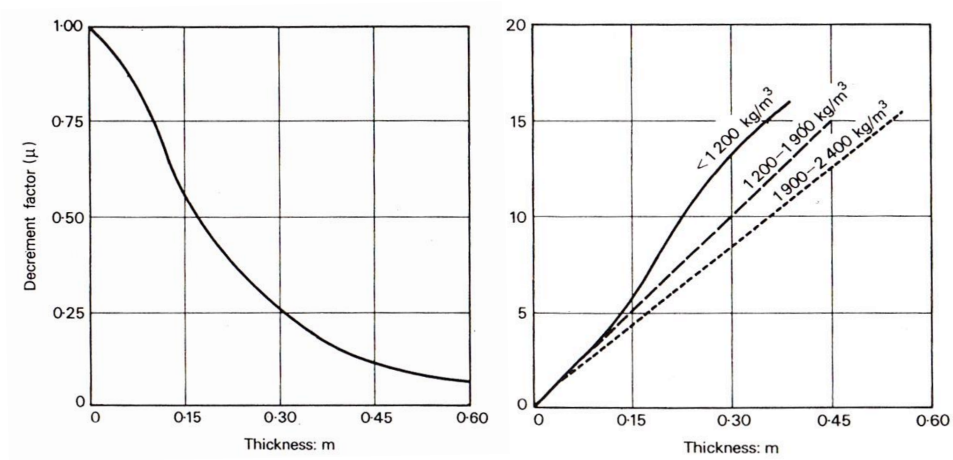


Figure 2-14: Decrement factor and time lag values for massive walls [35]

In “House form and culture”, Amos Rapoport [33] too has explained this phenomenon as follows: “Hot dry regions are considered by elevated daytime temperatures and anxiously low-slung nighttime temperatures, fluctuations to be met by suspending the admission of heat, letting it reach the interior late.

With high heat capacity materials, this can be achieved. They are stone, adobe or mud and various material combinations which provide a “heat sink”, by absorbing heat during the day and re-radiating in the night.

The below example clearly explains how time lag theory works in the architecture in hot climates for Adobe dwellings (See Figure 2-15).

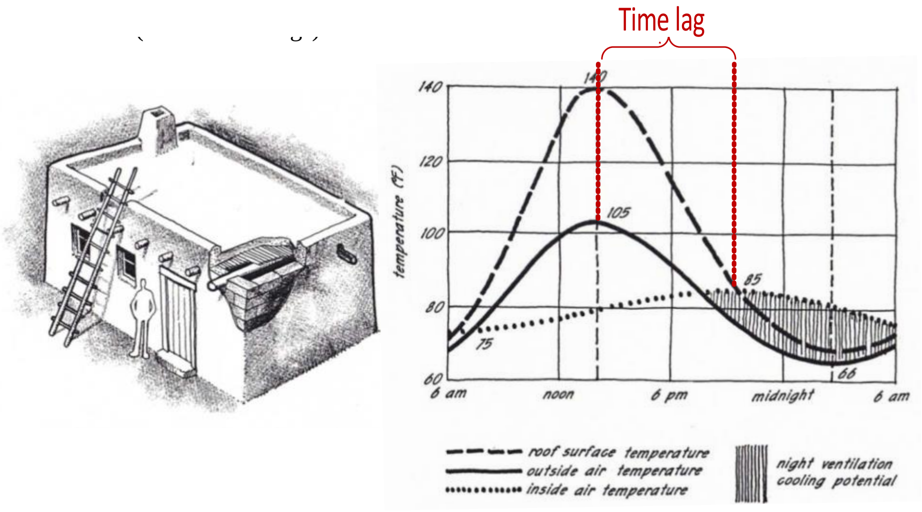


Figure 2-15: Square house form of an adobe dwelling [11]

The maximum interior temperature occurs at about 10 p.m. like Eight hours after the outside peak. By this time the outside temperature has dropped below the inside and the window can be opened for ventilative cooling. Assume that the outside temperature swing is about 105°F while the interior is only about 85°F. The difference between the indoor, and outdoor temperature has been indicated as the “Time – lag”.

Night ventilation can be introduced as a solution for the nighttime indoor heat gain as a result of heat released from the envelope thermal mass. This is especially applicable not only for hot dry climates but also for warm humid climates as well the night.

2.10. Usage of Sustainable building materials

There are different types of sustainable building materials that can be identified, as follows.

2.10.1. Natural Materials

If any material is available in nature to find, it’s called a natural material. They are inherently arising and can be disposed of safely, not like faux or man-made materials Natural materials are normally ‘grown’, such as wood or cotton, mined like stone, clay, and metals [32].

2.10.2. Renewable Materials

If the material is from a renewable source, it is called a renewable material. Normally all-natural materials do not come under renewable materials. For something to be renovated, it needs to be able to fill up naturally, allowing resources to be maintained without being depleted over time. There are many natural materials which are not renewable, but materials that can be grown and re-grown or infinitely recycled [32].

2.10.3. Harmless and Non-toxic Materials

During the manufacturing of many materials in use, either natural or synthetic, they are treated with harmful chemicals that come up with poisonous effects on people, and animals, solely on the natural environment. Certain substances can affect a long time after the initial application and can cause complications due to unsafe disposal [32]. Materials that define 'Sustainable materials' are mostly natural, renewable, harmless materials which are locally available such as timber, bamboo, clay, adobe etc. which are promising sustainability, in terms of Life Cycle Cost (LCC), Embodied Energy (EE), Carbon Footprint (CFP) and in their thermal performance as well [37].

But in general, people prejudice to use these building materials because they are in short supply and non-modern in their common form. In contrast, building materials which are costly, high-energy consuming, unsustainable and less environmentally friendly materials are widely accepted currently because of their widespread availability. Conventional common building materials such as steel, cement, and concrete are known as materials that are produced less sustainably. The production and transport of such materials create a higher level of Green House Gas (GHG) emission.

The use of local materials and technologies without sacrificing any of the building parameters such as aesthetics, strength and durability of the structures are crucial and can be done with thoughtful utilization. This century has witnessed several new construction materials which have less harmful possessions on the environment, less demand for non-renewable resources, etc. while providing maximum user-friendliness and comfortability. On the other hand, they create local employment and promote local craftsmanship, which promotes a true sense of sustainability. Traditional building technologies also can be regenerated with these innovative products. E.g., Common bricks, and face bricks [42] (See Figure 2-16).

OVERALL HEAT TRANSMISSION COEFFICIENT (U) AND TIME LAG CHARACTERISTIC DATA FOR HOMOGENEOUS WALLS[10]

Material	Thickness, Inches	U value, Btu/sq ft/hr	Time lag, Hours
Stone	8	0.67	5.5
	12	0.55	8.0
	16	0.47	10.5
	24	0.36	15.5
Solid Concrete	2	0.98	1.1
	4	0.84	2.5
	6	0.74	3.8
	8	0.66	5.1
	12	0.54	7.8
	16	0.46	10.2
Common Brick	4	0.60	2.3
	8	0.41	5.5
	12	0.31	8.5
	16	0.25	12.0
Face Brick	4	0.77	2.4
Wood	½	0.68	0.17
	1	0.48	0.45
	2	0.30	1.3
Insulating Board	½	0.42	0.08
	1	0.26	0.23
	2	0.14	0.77
	4	0.08	2.7
	6	0.05	5.0

Figure 2-16: Heat transmission coefficient and time-lag characteristics [42]

But in general, people prejudice to use these building materials because they are in short supply and non-modern in their common form. In contrast, building materials which are costly, high-energy consuming, unsustainable and less environmentally friendly materials are widely accepted currently because of their widespread availability. If the wood is used it needs to consider its transportation costs and the re-planting of trees etc. In summary, it can be recommended wood as a building material and it becomes ecologically responsible only if the trees are re-planted [39].

2.11. Earth as a sustainable construction material

For thousands of years, natural materials like ‘Soil or Clay’, has been used in the construction industry. In developing countries, the use of local materials like the earth is common due to high availability, cost efficiency, ease of construction with local laborand simple technology etc. and due to low impact on the environment [40].

Soil is a material which can be extracted immediately below the organic layer, and is commonly available [41] especially the in tropics within the close vicinity of the sites without or less transportation.

High thermal mass materials such as ‘clay’ provides various benefits in terms of energy, such as potential reduction in the requirement of the HVAC system, reduction of peak heating and cooling loads, control of indoor temperature swings etc. when clay is used as burnt clay bricks, its proven if the technology used with brick is cavity wall system, it gives more cooling effect to the building interiors. In potential interior appliances such as these, the thermal mass can be improved more as a protective layer of insulation, enhancing its ability to control the gain or release of heat [42].

High energy consumption in the production stage, transportation, as well as in operation for indoor thermal comfort is a great disadvantage of the use of conventional materials. Furthermore, minimum waste generation because of earth constructions simply can be disposed to the ground or can be reused [43] [44]. Most of the present buildings are constructing with un-natural materials which consist of a high amount of chemicals, heavy metals which are harmful to the human health as well as environment [45]. But earth construction itself does not involvee with artificial chemicals or other toxic substance; thereby does not createe adverse effects on indoor air quality providing volatile organic compounds [44].

At present, more than 50% of the world population are reported as living in earthen buildings [46]Out of them, most of the earthen construction centered around developing countries. But earth construction is increasing in developed countries, as well as countries such as Australia, UK, Germany, etc. due to the ‘sustainable construction agenda’. However, a true need is there to train and encourage building professionals: Architects, Engineers, and Artisans to use earthen construction as a day-today practice [44].

It is numerous research done by many worldwide researchers, as well in Sri Lankan context, interrelated to the soil as a construction material [47]. Though, soil has several positive properties a construction material, the literature suggests that soil can be strengthened by adding different stabilizer(s) or can be changed with many of its properties by adding different compounds to achieve the properties required [43].

Soil is considered twofold adequate as an environmentally approachable material since its capable in performing low in terms of overall embodied energy, for its manufacturing, nevertheless being a zero embodied energy as a raw material. 'Earth', and even developed as products, earthen products comparatively display a low LCC, EE, CFP and in their thermal performance as well [48][44].

F. Pacheco et.al [49], say that, according to the earth masonry design and construction guild lines, the construction material can act as a more effective indoor air relative humidity controller than that use of ventilators [50]. Earthen building material has the ability to control indoor air relative humidity. Its capability in absorbing moisture is ten times than glazed ceramic bricks. Therefore, its known as a relative humidity flywheel equalizer. The relative humidity of external environment can maintain indoor relative humidity between 40% to 60% known as the most suitable rang for human health [51].

Over the centuries, countless products and techniques have been developed with earth and in the present, it has become a core element of innovations in the field of nanotechnologies [44]. Traditional building materials such as loam and adobe are used in new ways. For example, walls made of Compressed Earth Blocks (CEB) give excellent thermal comfort, which is reducing heating and cooling costs. Buildings made with CEB can be sustainable and durable when they are built in the accurate technique. This implies that improvements of the technologies can be used small-scale and at the local level, potentially contributing to locals [52].

But the disadvantage is that the water may cause decaying earthen materials, but it can be prevented either by burning or by stabilization of earth [53] Moreover, there are several drawbacks related to pure earth construction such as less durability, labor intensive, structural limitation, require high maintenance, deterioration under climatic condition, etc. and the main deterioration due to shrinkage cracking and erosion [54].

2.12. Clay

Clay is a very fine-grained material and unconsolidated rock matter. Clay becomes plastic when mixed with water and turns out to be hard and stony when heated. Clay origins through natural processes, due to long-term complexity weathering, transported and deposited by sedimentation. in different geological periods. The composition of clay is silica (Sio2), Alumina (AbO3) and water (H2O.) plus appreciable. concentration. of oxides of iron, alkali and alkaline earth further contains groups of crystalline properties known as clay minerals like mica, quartz and feldspar [55]. Primary clay is clay minerals which gather at the same place where they are produced. If the minerals are transported to a different location and settled there, it's known as secondary clay. The secondary clay is transported usually with water, it will pick up sediment and particles along the route. As a result of this, secondary clay is less pure than primary clay. In analysis, more porous clay types such as Earthenware clay are secondary clay [56].

2.12.1. Clay as a porous material for indoor cooling

Cooling is a function of porosity, which in terms of clay, the porosity characteristics can be improved by subjecting to firing. Generally, porous ceramics exhibit excellent mechanical properties, thermal stability chemical and abrasion resistance. Further porous ceramics demonstrate properties like high surface area, high permeability, low bulk density, and low thermal conductivity. These properties depend on solid chemical composition, as well as on final pore volume fraction and structure, size, connectivity and morphology.

2.12.2. Clay for evaporative cooling

Many evaporative cooling systems use porous evaporators / porous material as their wetting media. If clay is to be used with water for better evaporation it prefers a high surface area because when the area increases potential evaporation rate becomes high.

Okada K.[57], states several advantages of porous ceramics in his review on evaporative passive cooling with porous ceramics. They are as, quality of high-and fast absorption rate, and slow water discharge rate. If used wetting porous materials as the building envelope materials, Heat absorption can be highly reduced which also will enable accelerate water evaporation too [57]. When a porous media absorbs a liquid, it carries the liquid to the next surface of the body. That capability is more comport with the clay materials, mostly red clay.

2.12.3. "Clays" in Sri Lanka

Having deposits of clay (mineral resource) can be considered one of the vital treasures in Sri Lanka. Sri Lanka owns various clay deposits around the island, yet the southwestern coastal belt carries the most important clay deposits as a whole. Mostly kaolin and types like ball clay are popular as 'Clay' and it's found that they are produced as a natural process due to tropical weathering. Jayawardena D. [58], has outlined the occurrence of these clay deposits and their general mineralogical features. Even though, detailed studies are yet to be completed.

There can be identified three clay mineral provinces in the Island according to the work of Jayawardena D. [58],

1) Montmorillonite-kaolinite clays contain slight quantities of calcareous materials limited to the dry zone of north and south -east.
2) Gibbiste -kaolinite clays stir together layer of mineral cramped to the wet zone.
3) Clays existing in the intermediate zone between (1) and (2). (See Figure 2-17)

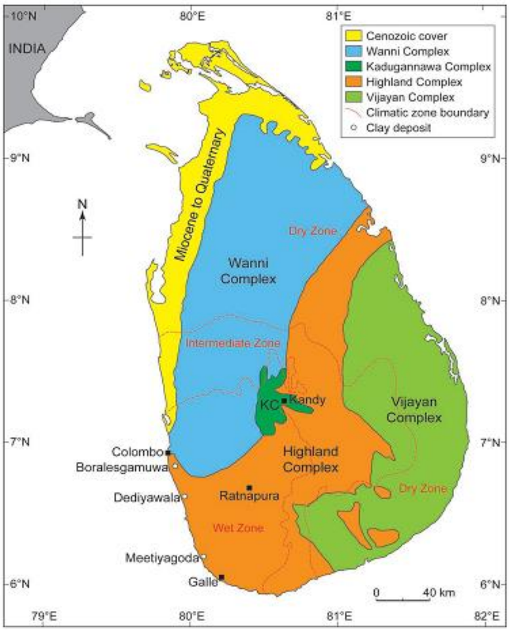


Figure 2-17: Locations of clay deposits in the geological outline of Sri Lanka. The clay deposits are indicated by open circles [59].

According to Jayawardena D. [58] , the most important ceramic raw materials employed in the industry of ceramic in Sri Lanka are,

a) Clays
b) Ball Clay
c) Kaolin
d) Feldspar
e) Vein Quartz

a) Clays

Clay mineral resource is laid in three climatic zones of the island and the clay deposits which are used for tiles and bricks are positioned mainly in the intermediate zone. Maha-Oya basin north of Negombo, Weuda, Aluthnuwara, Yatiyana and Uda-walawe are identified as regions which have commercial-scale clay. The annual requirements of clays mostly for the brick industry, tiles and pipe industry is approximately 1500-acre-feet according to the recent estimations. These statistics cover the need for both private and public sectors per year. Exploitable clay assets in the Maha-oya basin are recommended since this area upholds the major factories for brick and tile factories operated both by the public and private sectors.

b) Kaolin

The amount of China. clay or kaolin in the low-lying zone over Colombo is well known for decades. In estimation, the 'Boralasgamuwa' kaolin deposit comprise about 1 million tons of above clays. However, the neighborhood of the 'Boralasgamuwa' kaolin field has not been surveyed in detail on the presence of reserves of raw kaolin.

Kaolin deposits are reported also from the Horton-plains and few others have been identified as intensely weathered. zones of the central highlands. One of the other kaolin fields is located in 'Meetiyagoda', the south-west sector of the Island.

c) Ball Clays

Ball clays are spread over the flood plains of rivers which are confined to the southwest sector. The well-known ball-clay deposit is located at 'Dediyawala' near 'Kalutara' and the reserves as estimated at 500000 tons. These clays are classified as fire clay or refractory bond clay (Fusion point 1700°C).

d) Feldspar

Feldspar is primarily employed in the ceramic and glass industry in Sri Lanka. In different parts of the Island especially in the ‘Rattota’, ‘Kaikawela’,‘Namal-oya’,‘Talagoda’, and ‘Koslanda‘ areas the microcline feldspar (potash, feldspar) occurs. The major deposit of feldspar was discovered from ‘Owella estate’ (Kaikawela). Due to the properties of strength and high plasticity, the above-mentioned clays are employed for casts and as a refractory material. With great success, Quartz, ball clay, silica and feldspar can be used in the ceramics and glass industries [59].

In Sri Lankan context, not only as the construction material but also in domestic utensils the red clay is used, as a traditional material. Wattle and daub, clay flooring and Adobe bricks are the initial step of clay usage as condition of adobe, which means sun dried clay.

When fired clay was used for roofing tiles, bricks, and flooring tiles, it helps maintaining a good cooling condition in the house as the fired clay body absorbs the atmospheric heat. In Sri Lankan traditional day today clay utensils like ‘Guruleththuwa, Kalaya, Pilihaliya, Pinthaliya also do the same, although they are used for the storing purposes, they alternatively provide a good cooling effect.

2.12.4. Traditional casting methods for ‘Clay’- “Hand-building” methods

a) Pinch pot method

b) Coil method

c) Slab method

Figure 2-18: Clay hand building methods

a) Pinch pot method

Creating a lump of clay into a smooth sphere that matches the size of the builder's hand then begin a pinch pot. In this method, it is required to press the thumb into the centre of the ball, halfway to the bottom while holding the sphere of clay. While spinning the ball in one hand, force the walls out consistently with the thumb inside and fingers on the outside, smoothing surface is done with a damp sponge [60].

b) Coil method

To process the coil method, the fingers should keep flat on the clay lump, form the clay into a sausage shape, and then roll into ropes 1/4 to 1/2 inches. thick. With this method, interesting forms and textures can be created, by pressing the clay with fingers or a tool on both the inside and outside.

c) Slab method

Working on a textured fabric will leave interesting footprints on the clay slab. The method is to place the clay on the cloth between the strips of wood and roll it out. To trim the slab of clay to the desired size, a pointed tool can be used. Edges can be joined by rubbing a wet finger over the edges and score with a tool. The thin coil of sticky clay should roll out and place along one edge Slabs of clay may be placed around rocks, bowls, and plastic forms etc.[60] (See Figure 2-18).

2.12.5. Wheel Throwing

This method produces pieces much more quickly than in hand building, but each piece (bowl, pot, etc.) will be formed slightly different as it's an individual process (See Figure 2-19).

Figure 2-19: Clay wheel throwing method

2.12.6. Molds

In cases of generating multiple identical copies, this method is ideal for pottery are a necessary tool for sculpting or hand-building clay to achieve shapes or designs. If not molds, some of these to be done with the pottery wheel but, not easy as this method (See Figure 2-20). Other than the Press Molds, none of the Molds for Clay is functional for slip casting. All the Pottery Molds for clay are manufactured from Pottery Plaster (mostly plaster of Paris) which allows easy release of the ware Following the shaping, forming, or decorating of a simple slab of moist clay into a complex shape.

a) Press Molds (Sprig molds)

These molds are primarily used with moist clay Clay is pressed into the mold; the absorbent plaster evenly draws moisture from the clay body. This method limits cracking and sticking, and when the clay has dried to the leather hard stage the design is withdrawn for additional drying or affixing to other clay objects [60].

b) Slump and Hump molds

This method is used in forming moist clay into shapes. Huge plaster molds which are not easily accomplished on the pottery wheel are used in this method. Depending upon the design and purpose of the mold, these plaster molds for clay are collectively called slump, hump or drape molds [60]

c) Texture molds

Texture molds are also known as textured slab molds. One-piece plaster slabs that have textures across the entire face are used to mold. Slabs of moist clay are pressed and compared to the textured surface; thus, the detail of the mold is transferred to the moist clay.

d) Clay stamps

These molds are also known as ceramic stamps. The material used for the stamp is fired earthenware (ceramic) clay. Clay Stamps are designed to press. complex designs into leather hard clay surfaces [60].

a) Press molds b) Slump and hump molds c) Texture molds d) Clay stamps

Figure 2-20: Clay mold methods

2.13. Porous materials as indoor thermal insulators

n terms of thermal storage, porous materials. are of significant scientific and technological interest. Porous materials reduce the penetration of heat indoors thus energy transfer too. These materials contain a solid matrix with microstructural pores which are inter-connected [53].

Applying coal fly ash to insulate the walls of a building is a novel technology which is introduced by Zhang et al. [62]. Slip casting and foaming techniques are used as methods for this. This material exists with a very low thermal conductivity, as low as 0.0511 W. m−1K−1, thus performing good indoor cooling Zhang et al. [62] suggested coal fly as an environment-friendly material, appropriate for wall application to fulfil insulation purposes of the walls.

Another research conducted by Buratti et al. [63], examined for an insulation material using basalt fiber[64]. They reported that this material has a thermal conductivity in the range of 0.030–0.034 W m−1K−1. Further, by using this material, a decrease in heat transfer between 20% and 40% was obtained by them.

Fiberglass was identified as a good porous material by the work of Levinson et al. obtained the relationship between air velocity and the thermal conductivity of fiberglass using an inlet-to-outlet temperature drop of a duct. They found the duct's air velocity. increases from 0 to 15 m/s, when the measured conductivity of low-density inner fibre glass-blanket insulation is strengthened by about 140%.

Most relatively, the research work of Dimoudi et al. [20] on a wall fabricated by two main sub-layers containing the dynamic insulation and ventilated outer envelope sub-layers. The dynamic insulation sub-layer consisted of substrates of porous materials that insert air into the room. This helped decrease the conduction of heat losses through the wall and the results showed an improvement in the applied pressure difference between the internal and external sections of the room and cooling in the room.

2.14. Natural waste compounds to change the properties of clay

Recently, since waste management has become a global interest, different research can be found investigating the potential of sturdy trash materials that are reused in making clay bricks. Numerous researchers have been done with various types of agricultural waste such as palm oil waste, sawdust, bagasse, pineapple leaves, rice husk, vegetable matter rice husk, into stable building material. These materials are sustainable alternative materials found as an environment-friendly additive in modern construction.

Folaranmi J. [65], has conducted fruitful work on identifying the effect of sawdust additives on the properties of clay. He has assessed the Shrinkage on Firing, Bulk Density, Porosity and Permeability, Refractoriness, Cold Compressive Strength, Thermal Conductivity and Thermal Shock (Spalling) Resistance. According to the results, the bulk density, thermal conductivity, shrinkage, and cold crushing strength have decreased with an increase in the sawdust percentage, and porosity increased with an increase in saw dust percentage. Thermal shock resistance and sintering point remain constant with the increase of the saw dust percentage.

As an additional waste material Kadir A.A [66], has identified the coconut fibre and have tested clay bricks fired with General properties of Coir fibre to test the Physical and mechanical properties such as total shrinkage, dry density, porosity thus weight, and compressive strength. According to the results, by adding different percentages of coconut fibre, most of the properties conformed with the standards, except for the compressive strength of 5% of coconut fibre in clay brick. A higher number of additives has helped to increase the shrinkage and the porosity of bricks. Also, the results indicated that, incorporating 5% of coconut fibre into fired bricks has produced higher gas emissions compared to normal red clay brick.

Higher number of additives has helped to increase the shrinkage and the porosity of bricks. Also, the results indicated that, by incorporating 5% of coconut fiber into fired bricks have produced higher gas emissions compared to normal red clay brick. Kabir A. A's [66], findings show coconut fiber's high potential in incorporating with fired clay bricks as an effective, low -cost, material that produce adequate physical and mechanical properties.

Furthermore, the possibility of using coir fiber to enhance clay's sheer strength is dissolved by Maliakal S. [67], where he tested and describes on more eco-friendly materials used for construction such as bamboo, straw , linoleum , timber, grass , sheep wool, panels made from paper flakes, compressed earth block, baked earth, rammed earth, clay , vermiculite , flax linen , sisal , sea grass, cork , expanded clay grains , coconut , wood fiber plates etc. Above materials were identified as natural materials which reduces the energy demand in buildings[67].

Puppala, A.J., and Musenda, C.,[68]studied the effect of sand and basalt as substitution for clay on the physio-mechanical properties of basalt-clay bricks. It was concluded that the substitution of 10% clay or basalt by sand improves the bulk density , apparent porosity , water absorption and crushing strength of the fired brick.

2.15. Double Skin Facades (DSF) for indoor cooling

Double skin façade (DSF) has immense potential as an energy-saving option and it has become a common architectural feature across the globe. DSFs consist of a building envelope type of internal and external skins with an intermediate gap within them. They have various advantages which include the provision of natural ventilation, and natural daylight and act as a thermal and acoustic barrier for buildings.

Kim et al. have proven that the usage of DSFs can reduce the consumption of energy within buildings. during the heating and cooling. seasons by maintaining the levels of indoor comfort. According to Chen W.'s [64], studies when utilizing DSF's ventilated cavitiesin between two layers do function as a good thermal buffer and reduces thermal discomfort.

However according to studies carried out by Tascon M.H. [70] indicate that DSFs experience overheating issues during the summers. To end this aspect various methods have been explored to derive possible solutions to minimize the problems of overheating.

Jager et al. [71] prove that the problem of overheating can be prevented by the provision of a minimum distance between the internal and external panes of DSF , this is attributed due to greater stack flow and adequate flow of air within the cavities.

Wigginton et al. [72] indicate that the sizes of the openings for ventilation are necessary parameters that influence the cavity temperature as they contribute to the efficiency of the exchange between DSF and the external environment. Wigginton et al. [72] further state that the utilization of concrete slats as thermal mass in mechanically ventilated DSF can help reduce the risk of overheating.

2.16. Thermal simulations - Double Skinned Facades and energy saving potentials

Analysis and modelling study done by García et al. [18] has validated a numerical model Design Builder to identify an acceptable representative error in contrast with the source model. That model dealt with different solutions such as involving actions on both roofs and facades aiming in improving the indoor thermal conditions. Through the findings, it was identified as the most fitting orientation and demonstrated the influence of key aspects, such as roof-slab shading and a blend of both facade and roofing strategies [73].

Alibaba and Ozdeniz analyze the energy performance of a double-skin façade. Accordingly, to test as many factors as feasible in an acceptable amount of time, simulation programs were required. It is required to open and close the windows according to the weather conditions for the double-skin facade to function year-round. Furthermore, the wind's direction and velocity can have an impact on the outcome. In a hot climate, simulations demonstrate that the double-skin facade outperforms the single-skin facade. During the under-heated (cold) time, the double-skin facade helps to heat the building and aids natural ventilation during portions of the over-heated (warm) period [74].

According to Hien et al. [75] , At work, the energy consumption. of a double-skin. facade in a hot, humid region is investigated and it found that double-skinned facades use less energy compared to the single-glazed facade. Ballerini et al.[76], did another study on natural ventilation by retrofitting ancient buildings with double-skin facades. These researchers discovered that using two distinct dynamic simulation models, a double-skin facade may save a 12% of ventilation energy in a year.

Ding et al. [77] investigated the natural ventilation possibilities of a double-skin facade with an extra ventilation chimney above it using a 1/25 scale model and full-scale computational fluid dynamics model. They concluded that the additional ventilation chimney ensured natural ventilation even when there was no in the room.

Yi and Peng carried out a microclimate change simulation framework to examine the connection between outdoor and indoors, by displaying a series of numerical modelling and prognostic visualization. Also considered is the energy required to maintain indoor thermal comfort and confirm the methodological applicability of the simulation framework and integrate it into passive building adaption design. Finally, this research demonstrated how microclimate change scenarios can be combined with an outdoor-indoor coupled assessment to inform existing building adaption design [78].

Experimental and simulation study was carried out by Chen et al. [79] mentions, energy plus was used to model the quantitative electricity savings potential of day lighting, as well as the effect of decreasing artificial lighting on heating energy consumption. It was discovered that as artificial lighting was reduced, heating energy use increased.

2.17. Life Cycle Costing (LCC)

Life Cycle Costing can be defined as the total cost of an item through its life, including planning , design , acquisition , operations , maintenance , and disposal , less any residual value [80] (See Figure 2-21). There are different terms used for this, in the literature, like, “cost in use”, “Life Cycle Costs” (LCC), “Whole Life Costing” (WLC) and “Whole Life Appraisal” (WLA). The terminology has changed over the years from “cost in use” to “Life Cycle Costing” and further to “Whole Life Costing” [81] The common denominator of the analysis is to identify that the costs throughout the entire life cycle of the product or investment [82]. If it’s a material or product, the process is covered by following basic steps (See Figure 2-21).

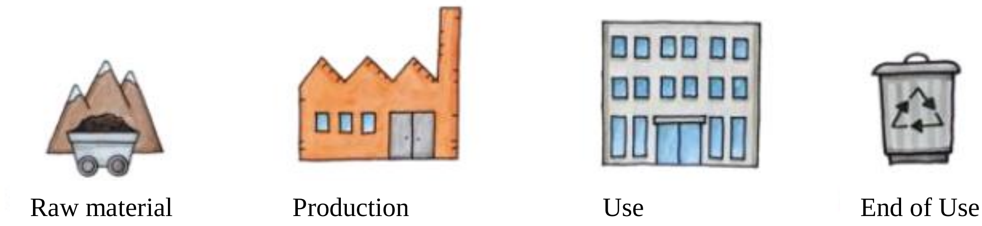


Figure 2-21: The basic stages of the Life Cycle of a building

“The total cost of both acquiring. and maintaining a building over its life” is the sum of the capital cost and the accumulated sum of maintenance costs, energy costs and other recurrent costs, less any disposal value at the end:

$$LCC = I_C + (M_c + E_c + C_c + O_c) + U_c - R_v \qquad \text{Equation 2}$$

Where,

Ic – Initial cost, **Mc** – Maintenance costs, **Ec** – Energy costs, **Cc**- Cleaning costs, **Oc**– Overhead and management costs, **Uc** – Utilization costs, **Rv** – Resale value.

Swarr T. et al.[83], point out that for construction, the initial cost can be determined easily and reliably but maintenance and operational costs are less predictable as they extend in the future. For that reason, the initial cost is used as the main base for decision-making today.

The availability of LCC data is rather limited. One reason is the lack of any framework for collecting and storing data [83]. Construction clients often give a low priority to LCC as they are not aware of the benefits from it. Extensive knowledge and experience of specialist manufacturers and suppliers are valuable sources for the life cycle.

information If the required data are not available, ‘modelling’ techniques can be used [80]

2.17.1. LCC techniques

Several methods of calculating the LCC exists in the industrial/business sectors. The three most common LCC methods are as follows [84],

1) Simple Payback
2) Net present value (NPV)
3) Internal rate of return (IRR)

Of all three methods, the most preferred LCC technique in the construction industry is the NPV method; because the simple payback is not widely used, and IRR is a more comprehensive procedure [84]. NPV is defined as the sum of money that needs to be invested today to meet all future financial requirements as they arise throughout the life of an investment.

$$\sum_{t=0}^{T} \frac{c_t}{(1+r)^t} \qquad \text{Equation 3}$$

Where,

Ct is the estimated cost in year ***t*** , ***r*** is the discount rate and ***T*** is the period of analysis in years.

2.17.2. Life Cycle Cost assessments for earth related wall materials for Sri Lanka

Many attempts to calculate. and compare LCC of different waling materials can be found as previous studies. But only a few studies have been done relating to tropical climatic conditions on earthen walling materials, achieving thermal comfort and reducing LCC [84].

C. Udawattha *et.al* [85] says Life cycle cost, is a combination of all costs incurred from construction to the end use of the building. The findings reveal that merely for walling materials, brick mud concrete blocks can be reused repeatedly for similar use. Mud concrete block is 92% reusable Its ingredient can be crushed and produce the same walling material with an addition of a cement ratio of 8%. Therefore, Mud Concrete blocks and Brick are more environmentally suitable than other walling materials such as Hollow Cement blocks and Cabook.

C. Udawattha *et.al* [85] further concludes, that most of the energy was used to construct walls are not renewable. Out of total energy consumption, a higher portion of the energy was spent on manufacturing and transportation. In this research, since the burnt clay bricks are made in coconut husk kilns, they are assumed to use more renewable energy than other walling materials, but it consumes more energy with a higher carbon footprint.

And the walling materials such as Cabook and Mud concrete blocks are eco-friendly since they are using less amount of carbon-based energy sources [85]. Its only nonrenewable energy comes from the transportation and construction of electricity such as cutting and grinding at the site. Considering all the scales given to measure the suitability of different walling. materials such as embedded energy initial cost operation cost and Life Cycle Cost; Mud concrete block is the best walling material to build affordable houses Carbon dioxide emission is another study carried out and results show that CABO earth waling materials have the lowest carbon emission because it’s extracted from the earth. And Brick is worse carbon emitting walling material.

R. Arooz *et. Al* [86] has researched an in-situ cast Mud-Concrete load-bearing walling system (MCW) which is optimized to save the LCC and EE in energy-efficient building construction. The results confirmed the lowest Embedded Energy, higher reusability, and high thermal performance of MCW as an alternative walling material for tropics. It further suggests the minimization of transportation needs and utilization of locally available resources, formwork optimization and local labour can significantly affect the environmental footprint of the Mud-Concrete production system.

2.18. Psychometric Chart and the Comfort Zone

“Psychrometric charts are graphic representations of the psychrometric properties of air. By using psychrometric charts HVAC engineers can graphically analyze different types of psychrometric processes and find a solution to many practical problems without having to carry out long and tedious mathematical calculations” [87].

Comfort within buildings is primarily controlled by four major factors: air temperature, mean radiant temperature, humidity and airflow. Each can have a dominating effect. Their effects are not necessarily additive and practically never linear. There are other factors which affect comfort including clothing, activity level and climatization. Some psychological triggers, such as certain colours, also seem to affect comfort, and "state of mind" can have major effects on individual comfort sensations. Comfort zones, therefore, are very generally defined as the zone in which 80 per cent of the population will experience the sensation of thermal comfort [88].

The recent trend in defining thermal comfort in free-running buildings was to use adaptive comfort models instead of those based on balance. In these adoption models, the outdoor thermal environment is considered as the input for the weather. and seasons exert some influence on behavioral adaptations. This is because people generally use the available weather data to decide how to respond to the conditions expected on a particular day [88].

2.18.1. Basic Psychrometry

The atmosphere is a mixture of air (oxygen and nitrogen) and water vapour The science dealing with this mixture is psychrometry (From the Greek ψυχροσ = psukhros = cold) and the graphic. Representation. of various attributes of this mixture is the psychrometric chart. The diagrams below illustrate the step-by-step build-up of this chart and the process of psychometrics [87] [89]. (See Figure 2-22).

1. Temperatures
    a. Dry Bulb – This is the temperature reading found on a typical thermometer. Measured in °C. You can find a psychrometric chart that offers these temperature ranges:
    b. Low temperatures that range from -20 degrees FDB to 50 degrees FDB
    c. Normal temperatures that range from 20 degrees FDB to 100 degrees FDB

d. High temperatures that range from 60 degrees FDB to 250 degrees FDB

e. Wet Bulb – This is a typical thermometer's standard reading if the sensing bulb is covered with a wet wick or sock and exposed to air flow.

2. Dew Point – At this temperature, moisture starts condensing from the air.

3. Specific Volume & Density – Specific volume is measured in cubic feet per pound. This refers to the amount of space air occupies per pound of weight.

4. Enthalpy – This is the measurement. of heat energy. Enthalpy is measured by 'Btu' (British thermal unit) per pound of dry air.

5. Sensible Heat Ratio – This is the total sensible heat flow divided by the total heat flow.

6. Sensible Heat Flow – 60(specific heat of air in Btu/lb. ºF (0.24 at 72ºF)) (density of air in lb./ft^3) (Air flow in ft^3/min) (| supply air temperature – conditioned room temperature)

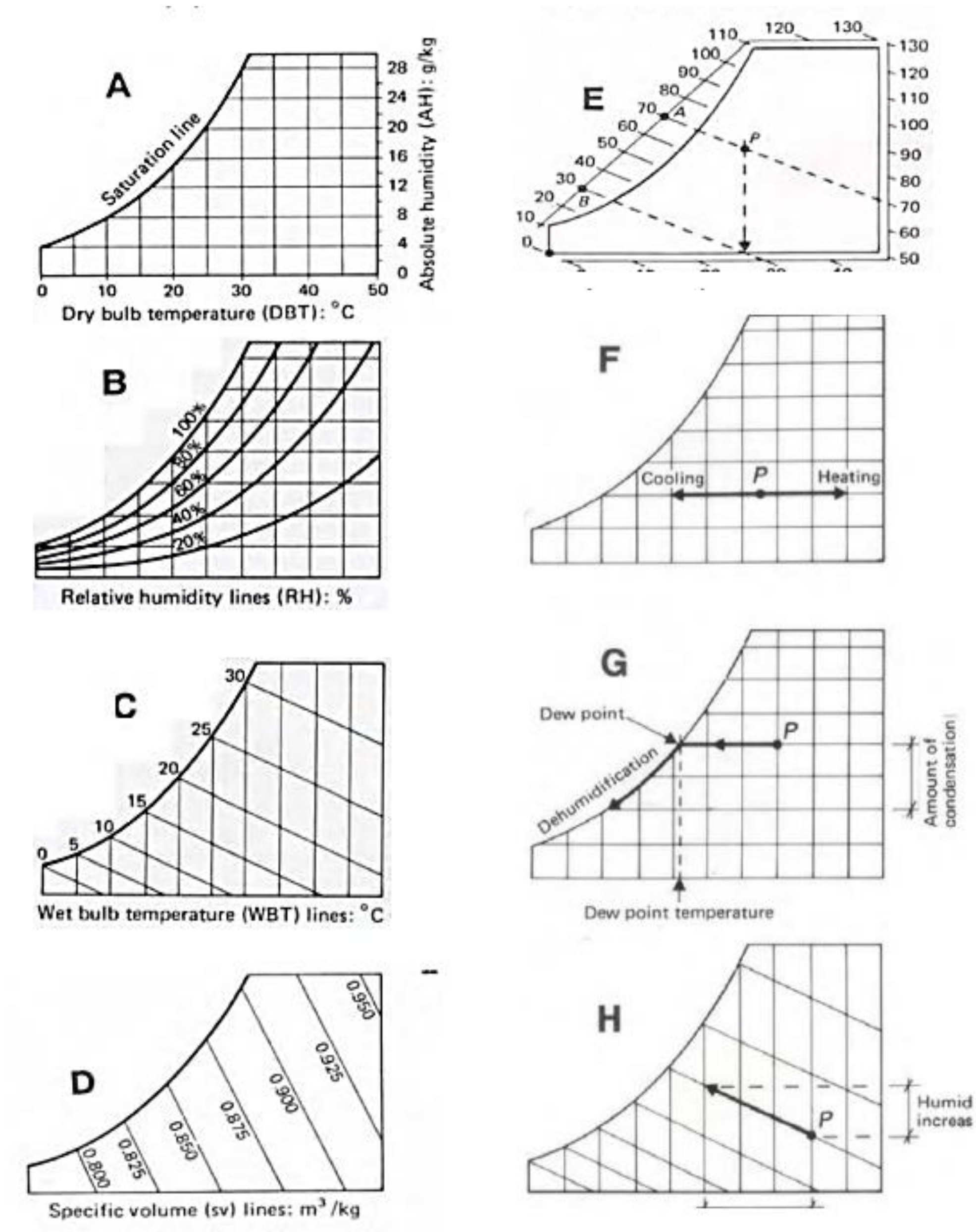
7. Latent Heat Flow – 60 (Latent heat of vaporization of water in Btu/lb (970 at sea level)) (Density of air in lb./ft^3) (air flow in ft^3/min) (humidity ratio difference in lb. water/lb. dry air)

8. Moisture Content – Also known as the humidity ratio, this is the total weight of water vapor per pound of dry air.

9. Relative Humidity – This refers to the percentage of water vapor per pound of dry air in relation to how much the air can hold at its current temperature.

10. Vapor Pressure – Vapor pressure is measured in inches of mercury and represents the pressure exerted by water vapor in air.

11. Standard Air Dot – This dot marks the measurement for standard air. Standard air is typically 70 degrees Fahrenheit with a relative humidity of 54% and 60 gr/lb. of specific humidity.



A. The basic grid with Dry Bulb Temperature

B. Relative Humidity (RH%) curves

C. Wet Bulb Temperature

D. Specific Volume (sv) Lines

E. Enthalpy (H) Lines

F. Cooling /. Heating

G. Dehumidification

H. Humidification (Evaporative Cooling)

Figure 2-22: Basics to work with the Psychometric chart

2.18.2. The comfort zone.

To establish the comfort zone in the psychometric chart, identifying the Neutrality temperature is required. The neutrality temperature (T_1) indicates the value that the mainstream of the population feels acceptable in terms of comfort in a given climatic condition. It can be obtained by the daily average temperatures (minimum and maximum values) in a given period Szokolay S. has used the below equation for that [34].

$Tn = 0.31\ T_0 + 17.6$ Equation 4

Where T_0 is the mean temperature.

The acceptance of higher temperature and humidity levels can be significantly reduced with ventilation which surges air motion along the skin. The physiological cooling sensation of air movement is considered in the psychrometric chart with subsequent adjustments which Szokolay has recommended [34]. And as per Kolokotroni [90] when there is a ventilation supply, the comfort zone can be extended up to some extent.

$dr = 6V\text{-}V^2\ (°\ C)$ Equation 5

Where, V is the air velocity.

This modification is valid up to a velocity of 3.0 m / s. Generally, internal air velocities of about 1.5 m / s are not so comfortable because they will cause disturbance to deskwork. An air velocity of 1.5 m / s can give rise to an extension of the comfort zone by about 6.75 °C. With 1.0 m / s, it is about 5°C. With a more probable average internal air velocity of about 0.6 m / s, it will be about 3.25 °C. The same procedure and values were used by Rajapaksha et al. [91] for air velocity properties under prevailing warm humid conditions for Sri Lanka.

2.19. Chapter Summary

The literature review paves the path to identify the research background, classify a similar methodology, to confirm or establish a finding. This chapter: “Literature review”, clarifies the need for the research study through facts and principles of architectural sciences and related building physics such as passive-hybrid cooling, thermal mass effect and time-lag, stack effect, ventilative cooling etc.

The cruciality of rejuvenating earth and clay as a popular building material was established and further Clay's significance for this research as a cooling material was convinced.

Clay's key qualities and potential clay casting methods were reviewed.

Potential compounding material options (including waste material) with clay, to improve certain identified properties of clay were found.

Properties of clay to improve cooling characteristics, such as microstructural porosity, continuous air permeability, thermal conductivity and insulation properties etc. were identified.

Double skin facades (DSF) were identified as an effective passive cooling strategy [92], and the potential for the DCDW cooling system as an extension of DSFs is investigated through literature.

Similar thermal simulation studies were evaluated on double skins, clay walling, and ventilative cooling.

To assess the Sustainability of buildings, the theory of Life cycle costing was reviewed with its most popular methods.

The theory of Psychometrics was assessed with basics, developing the psychometric chart including comfort zone and its extensions with ventilation was established through literature.

3. CHAPTER THREE - MIX DESIGN DEVELOPMENT

3.1. General

This chapter introduces the Dynamic Clay Double Wall cooling system, it presents the experimental design of the material mix and mix compositions, production process, experimental processes conducted, and results of physical and thermal properties related to DCDW panel's performance in terms of indoor heat reduction.

3.2. An Introduction; The Dynamic Clay Double Wall (DCDW) cooling system

An important research gap was identified with a comprehensive literature review, and in addressing the gap, the research intends in investigating an efficient indoor air temperature reduction strategy by integrating some of the proven building physics principles.

The research designs to make an effective combination of thermal mass effect (low heat conductivity and time lag effect, heat absorptivity), ventilative cooling (convection heat loss), structural cooling, heat insulation effect of porous low-density materials (self-cooling effect and heat flux due to cross air permeability) etc., concepts to accelerate the indoor cooling with low energy consumption.

The invention: "DCDW system" consists of two components which are working together to accelerate the cooling effect of tropical indoors. Component 01 is a developed, porous, air-permeable clay panel to be applied as a second skin to the interior of the primary wall. This secondary skin act as a non-load bearing light façade which is an easily fixable, removable, and maintainable element while at the same time is an environmentally friendly and sustainable construction solution (See Figure 3-1).

Clay is one of the most affordable building materials and is a traditionally used, well-established material used for indoor cooling. Clay is also a very versatile material which can be used for walls, roofs, floors, and many other building elements as well.

But with literature, it can be proven clay has not been used as a secondary wall application for indoor cooling purposes.

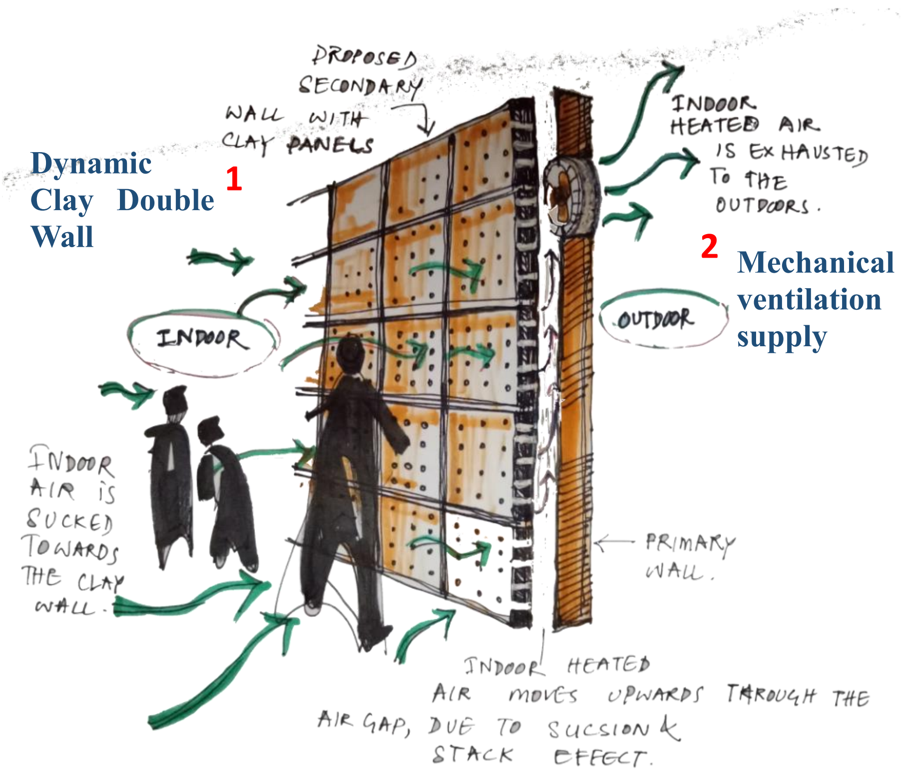


Figure 3-1: The conceptual sketch idea of manipulating Component 01 and 02 in the DCDW cooling system

Literature establishes that the cooling performance of clay can be enhanced by coupling with water or air. Using clay façades with (water) evaporative cooling techniques can course long-term health issues due to high humidity levels in the air and dampness, and the direct evaporative cooling, in a humid climate will indicate a low-efficiency value as the air will be nearer to its saturation point.

Therefore, the '*Clay with Air'* combination is given priority in this research, since less previous work has also been found in that area. When identifying the potential of coupling clay with air/ventilation, control of carrying outdoor heat, dust, or odour to the indoors with ventilation was focused on.

Further, due to low wind velocity levels and inconstant velocities throughout, the invention targeted providing low energy consuming constant mechanical air flow (Component 02) to the indoors through Component 01(Dynamic Clay Double Wall).

Relating to literature, for better insulation performance, low thermal conductivity properties and high thermal mass effect, the DCDW panel is focused to develop a highly porous microstructure.

Baked clay / fired clay/clay ceramic is a porous material compared to the unfired raw clay. Which depicts clay has the ability to create internal pores while it is subjected to high temperatures. There are 'non-natural' chemicals found which can improve internal porosity in clay such as 'polydioxanone'. But considering the sustainability of the invention, the research intended to use non-toxic cost effective and environmentally friendly materials. On this basis, attention was paid to incorporating waste materials with clay, since it helps for the 'productive waste management' concept as well.

In previous research, several studies found, which were conducted with different types of agricultural waste with the purpose of enhancing the structural, chemical, or mechanical properties of clays. Based on the prevailing literature, and considering the common availability in Sri Lanka, five types of organic wastes were selected to be tested in terms of their contribution to the formation of pores in the microstructure of clay.

The DCDW system was designed to obtain optimum structural cooling effect/ heat flux by incorporating permeable air movements crossing component 01. In addition to the developed porosity effect of the clay panel, continuous buoyancy pathways in the clay panel were created for this purpose.

A collective set of fired DCDW panels are fixed to the inside of the primary wall as a second skin, with a thin air gap in-between. Concurrently, a low energy-consuming fan is fixed to the primary wall to provide a continuous airflow through the DCDW panel, which is assumed to course a release of absorbed indoor heat from the clay wall, becoming a constant "absorber-releaser".

The two components together create "a good couple" in terms of an efficient indoor air temperature reducer thus cooling, further in reduction of health risks by maintaining good air quality. On the other hand, this technology provides a sustainable solution since it produces at a low cost and low embodied energy.

3.3. Identifying the best material mix for Component 01; DCDW panel

Clay is natural earth-type material, and it behaves as plastic and can be molded as it is mixed with water. Clay can gain its hardness once it is dried and fired. Considering the proven sustainability factors, cooling effect, low cost, and availability, “clay” is determined to be the base material for the DCDW panel. Choosing a proper type of clay is important, which highly supports indoor heat reduction by having a porous microstructure. The internal porosity of clay depends on the “mineral compositions and size of the particle.” Thus, a study about the characteristics of various clay types should be conducted to find the best suitable material.

In a broader sense, clay can be categorized into classes in accordance with its colour, porosity, absorption rates, texture, and strength [93] [94] .

There are five main types of clay. They are,

- Earthenware
- Stoneware
- Porcelain
- Ball clay
- Fire clay

The firing temperatures of earthenware are low providing it with an earthy outlook. These firing temperatures fall within the range of 112F and 2109F (604-1154 ℃) [56]. A lot of earthenware clay is red or orange. Subjected to the firing process, earthenware clay will appear to be refined and smooth due to the high levels of iron oxide, i.e.-rust. Nevertheless, the earthenware can also come in colours such as yellow, tan and buff. [56] (See Table 3-1).

Table 3-1:Identification of suitable type of clay [114]

EARTHENWARE CLAY	PORCELAIN CLAY	STONEWARE CLAY
Colour range from white to brick red	Colour range from white to brown	Colour range from Gray to dark brown
Various Texture	Various Texture	Various Texture
Porous Surface	Non-Porous	Slightly Porous
Relatively Fragile	Relatively Less Fragile	Relatively Strong

Table 3-2: Firing temperature, porosity, and absorption rates of clay types [114]

	EARTHENWARE CLAY	PORCELAIN CLAY	STONEWARE CLAY
Firing temperature	Cone06 (1,828°F)	Cone09 (2,300°F)	Cone06 (1,828°F) Cone09 (2,300°F)
Porosity	Porous	Non-porous	Slightly porous
Absorption	12-14%	0.5-2%	1.5-3%

Earthenware clay is more porous than other clay bodies. The porosity of the material is a major factor influencing its thermal conductivity, but no simple relationship can be formulated to cover the complexity of various factors. Air is a very good insulating material so a highly porous body material will have a lower conductivity than the same material with a solid body.

Clay is made up of clay particles or platelets. As clay is fired, these platelets move closer together. Different types of clay vary in how dense they become and how much glass is produced. If clay produces less glass during firing, then the gaps between the particles are more open. This is due to the higher levels of porosity, unlike most clay types. This aspect makes the clay less dense and stronger [95].

As literature previous research suggests earthenware clay as the most porous type of clay, it was selected to proceed with further stages of the research. Under the category of earthenware clay, a suitable type of clay was needed to be selected. For that, specialist knowledge and literature on commonly available earthenware clay types in Sri Lanka were referred. The following types of commonly available earthenware clay from different areas of the island were selected to be tested (See Figure 3-2).

1. Processed Red Clay (Meetiyagoda, Ground)
2. Processed White Clay (Dediyawala, Ground)
3. Brick Clay (Kadawatha - Unground, directly from sediments)
4. Red pottery clay (Kadawatha- Ground, taken directly from sediments)
5. Processed Chinese clay (Ground)

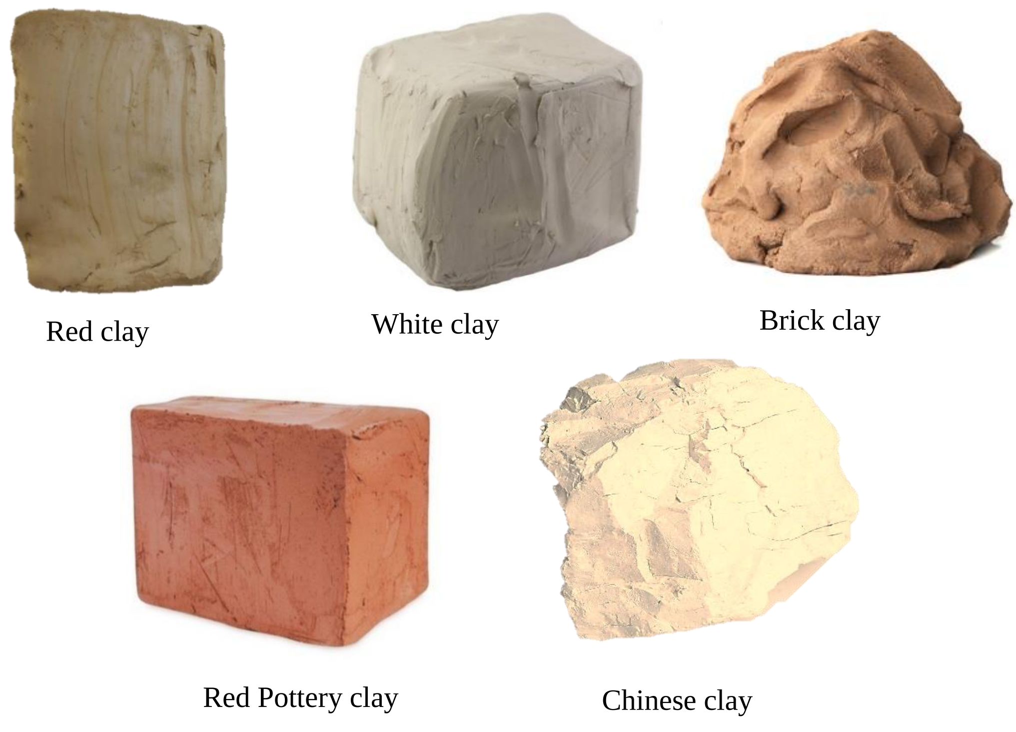


Figure 3-2: Five types of ‘Clays’ selected for testing

The collected samples obtained from deposits were soaked in water for the separation of harmful particles by the process of gravity sedimentation. Subsequently, the clay samples were dried for a period of three days and further dried for eight hours at 50°C while placing them in an oven. After the process of drying, it is crushed into smaller sizes and grounded into finer sizes using the equipment of a laboratory crusher and ball mills.

Thermal conductivity is influenced by the porosity of a material. However, a simple relationship can be derived to identify the various factors. Air can be used as an insulating material allowing a material with high porosity to have a lower level of conductivity compared to a solid body in the same material.

Therefore, different organic wastes available in Sri Lanka were identified during the pilot survey, such as pineapple leaves, palm oil waste, straw etc. Based on the literature, expertise knowledge and considering the general availability, the following five natural wastes were selected to test by mixing with selected clay types (See Figure 3-3).

1. Saw Dust (5mm particles)
2. Coconut Fiber (5mm parts)
3. Rice Husk (normal particles – 5mm)
4. Straws (5mm parts)
5. Rubber powder


Saw dust


Coconut fibre


Rice husk


Straw


Rubber powder

Figure 3-3: Five different types of organic waste compounds selected for testing

Each organic waste compound was mixed with each type of clay and cast 25 specimens and subjected to firing. The specimens were then subjected to identified tests for the properties to be determined.

During the firing processes, the compound particles are assumed burnt and trap the air within the clay body, giving the panel an excellent insulation quality and lightweight characteristic [61]. The below organic waste compounds and clays are tested for the best mix proportion to obtain the optimum indoor heat reduction (See Table 3-3).

Raw Coconut fibre was directly taken from coir producers and Saw dust was taken randomly (without considering the specific type of timber) from timber mill for the test. Dried Straw was collected from paddy fields and Rubber powder was collected from the Rubber development board as waste from the initial stages of the rubber production process, Rice husk was taken from rice mills as a waste product. All five types of compounds were dried at a temperature of 50°C in an oven for a period of eight hours [96] [55].

The additive was dry sieved through (ASTM) No.4 mesh and finally waste particle sizes were obtained as 5 mm. Rubber powder was used as it is with the original particle size (approx.500 microns), and since the next large particle size was with rice husk (approx.5mm), coconut fibre, straw, and sawdust were also taken with 5mm particle size.

Table 3-3: The casting plan, clay- compound mix specimens

	Red Clay (RC) (Meetiyagoda-Ground)	**Brick Clay (BC)** (Kaduwela-Unground)	**Red Pottery Clay (PC)** (Kaduwela-Ground)	**White Clay (WC)** (Dediyawala -Ground)	**Chinese Clay (CC)** (Ground)
Coconut Fiber (**CF**) (4 cm parts)	RC+ CF	BC+ CF	PC+ CF	WC+ CF	CC+ CF
Straws (**S**) (4cm parts)	RC+ S	BC+ S	PC+ S	WC+ S	CC+ S
Saw Dust (**SD**) (4cm Particles)	RC+ SD	BC+ SD	PC+ SD	WC+ SD	CC+ SD
Rubber Powder (**RP**)	RC+ RP	BC+ RP	PC+ RP	WC+ RP	CC+ RP
Rice Husk (**RH**)	RC+ RH	BC+ RH	PC+ RH	WC+ RH	CC+ RH

3.3.1. Fabrication of the clay panel

The primary focus of the fabrication method was to come up with quality output in terms of its cooling effectiveness and architectural appearance and to develop the production process with a simple, low-cost, practical and manually operatable technique. A series of pilot castings were conducted to confirm the required water content and linear dry shrinkage of the clay–compound mixed panels to determine the panel size and the formwork size.

All five compound types were oven dried for 24 hrs., at 50 ℃ temperature to make the moisture content a constant. Moisture content of each clay type was maintained approximately similar during the test according to the below formula,

$$MC = \frac{w-d}{w} X\ 100 \qquad \text{Equation 6}$$

w = wet weight d = weight after oven drying

Each clay type was mixed with each compound type for the ratio of 75:25 (clay: compound) volumetric proportion. Five duplicates of each clay–compounds mix panels were casted manually with timber mold in the traditional method, (See Figure 3-4).

Figure 3-4: Traditional method of casting clay bricks manually, using timber mold

3.3.2. Air drying

The casted specimens were kept at room temperature and air-dried for 24 h (See Figure 3-5). Wet clay contains a considerable amount of water. This water needs to be evaporated for the clay to become dry. The particles of clay are drawn closer together due to this condition, resulting in shrinkage. Most of the problems with clay occur because of uneven drying rates, thereby creating stresses in the clay. These stresses are occasionally indicated by cracks and warping, and sometimes they cannot be identified during or after firing. Thus, drying should be given major priority [97],[98].

Figure 3-5: Traditional method of air drying the clay bricks.

a) Typical clay bricks b) Test specimens

3.3.3. Oven drying

The literature depicts that, complete drying doesn't happen until the specimen is kept in the oven [99]. Therefore, after air drying, the samples were oven-dried at 100±5 °C to remove the water content for a period of 24 hours. Time needs to be provided for this process as the body of the clay may burst due to the formation of steam [99].

Therefore, all specimens were let dry in a laboratory oven for 24 hours at 105 °C temperature. The specimens were then cooled to room temperature before the firing (See Figure 3-6).

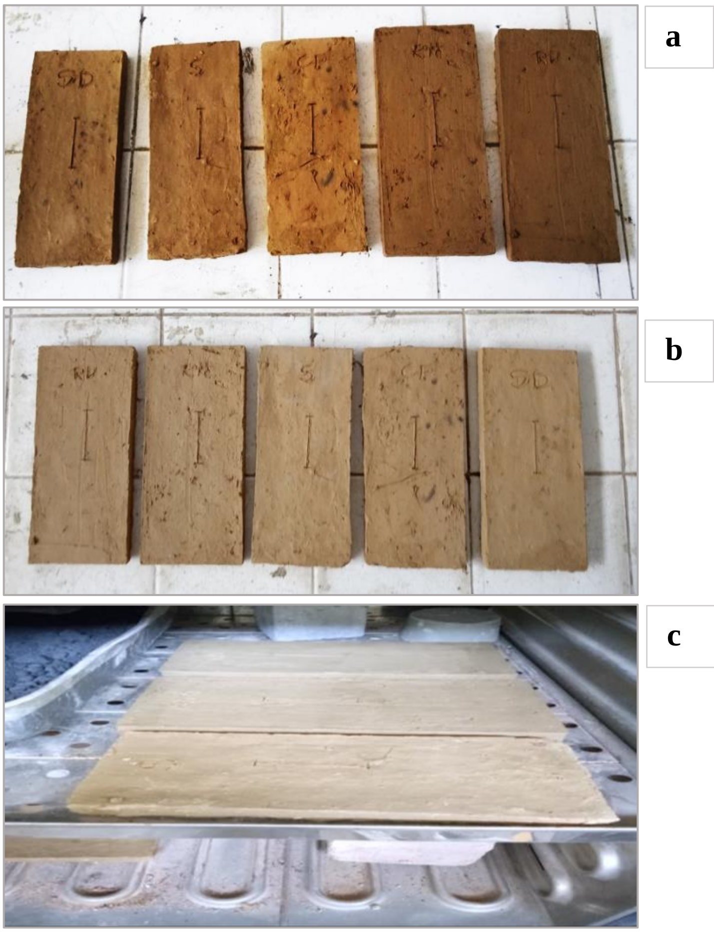


Figure 3-6: Specimens after air drying **(a)** oven drying **(b)** and loaded in the oven **(c)**

3.4. Identifying the best firing temperature and time duration.

An important factor in the clay brick-making industry is the firing temperature. As this temperature affects the texture, mineral composition and physical attributes of clay bricks [100] Oven dried samples whose moisture content is 0%, are then subjected to firing at higher temperatures.

The firing temperature and composition of the raw material influence greatly the shrinkage level while firing, microstructure, absorption of water and the conductivity of heat of the fired bricks. Existing evidence from experiments proves that the absorption rate of water, hence porosity is greatly dependent on the firing temperatures and the volume of alumina in the mixture of the raw materials.

Below SEM micrographic images shows how the microstructure (porosity) of raw clay changes with different firing temperatures (See Figure 3-7). When the firing temperature increases, the porosity of internal microstructure has decreased [99].

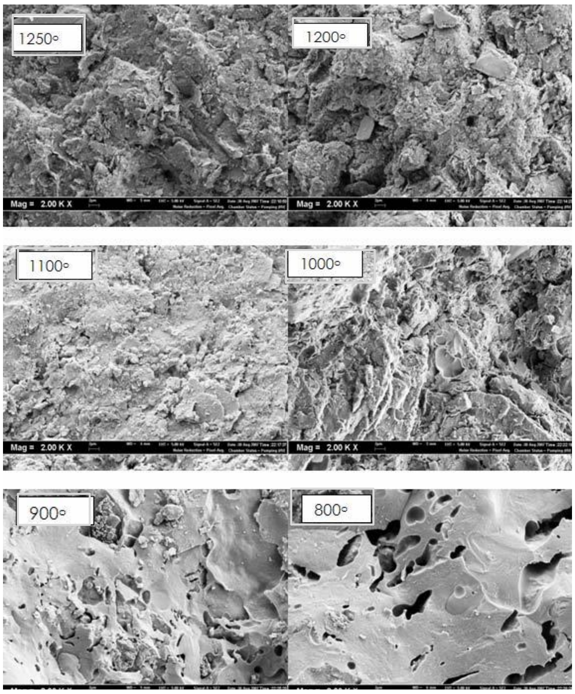


Figure 3-7: SEM micrographs for raw clay fired at different temperatures [100]

The specimens with five types of clays and five types of compounds then fired using N100, Nabertherm GmbH electric furnace (SeeFigure 2-8). The different compounds mixed with the clay are assumed to be burned to ash during the firing, creating micro-scale inner pores where they were located inside the clay panel, and once they were fired to ash the air can be optimally gathered and cross move becoming light in weight as well [101].

a) N100, Nabertherm GmbH electric furnace

b) Samples are loaded in the furnace for firing

Figure 3-8: Electric furnace used for firing of the samples

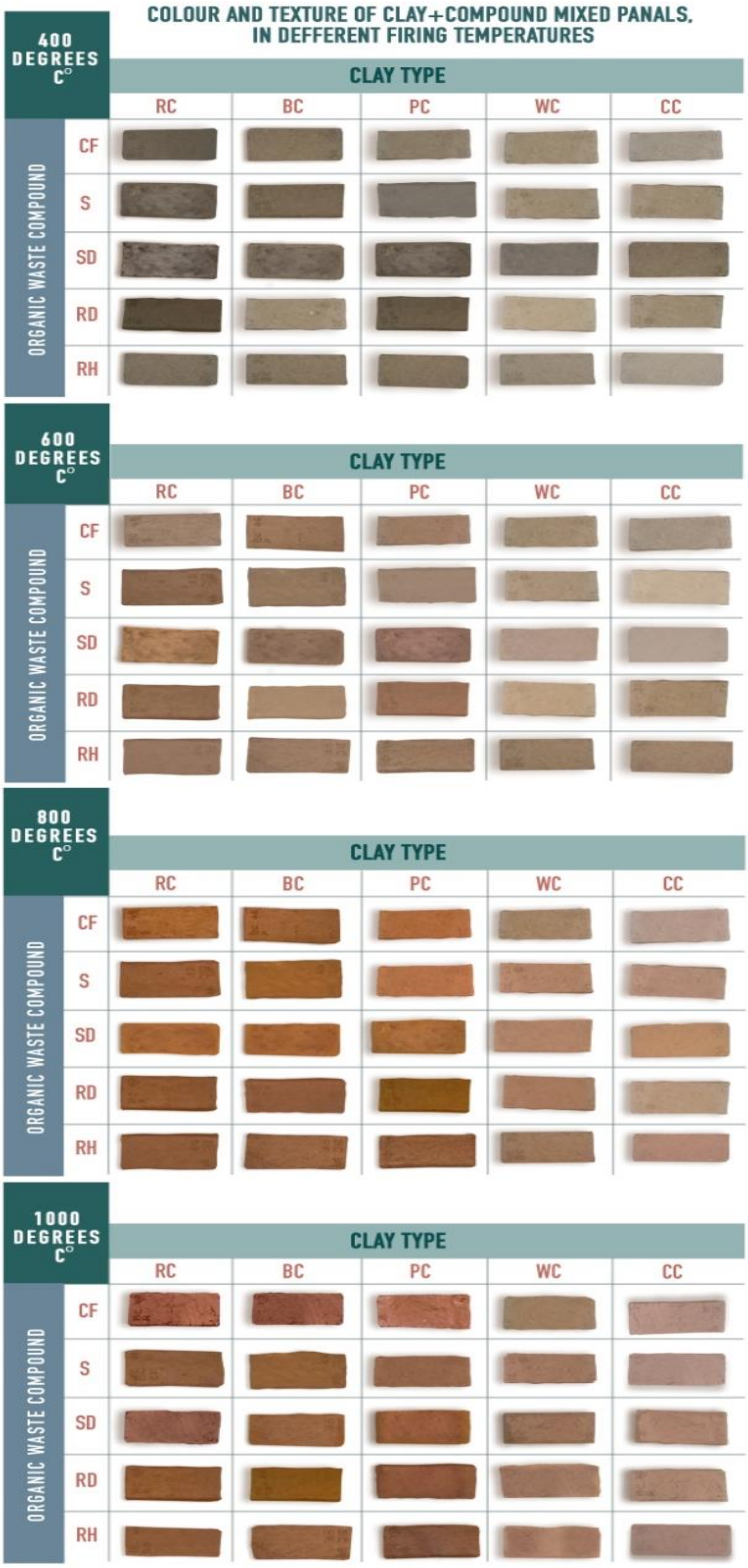
Four firing temperatures were identified by literature which are considering the firing temperature range for earthenware clay, as 400 °C, 600 °C, 800°C, 1000°C [102][103] for a 60 min peak temperature time.

Altogether 100 specimens were subjected to this experiment, counted as 5 (clay types) * 5 (Compounds) * 4 (Firing temperatures). The fired samples were categorized based on the firing temperature, to identify the firing effect on the panel's appearance (colour and texture), in terms of aesthetics. Through this categorization, it was easily identified when the specimens are fired under low firing temperatures in the range of earthenware clay like 400°C, 600°C, the colour remains Grey / Light Orange, but when the temperature increases to the 800°C-1000°C range, the colour of the clay panels become more Reddish-Orange due to activation of iron oxides (See Table 3-4). Also, it was visible that when the temperature increases, the samples tend to crack and become less fine in texture.

Referring to the samples which were fired to 800°C degrees were well-toned with a brick red-orange colour, strong and stable, and smoothly appeared with no cracks. More than 50% of the samples which were fired to 400°C either crashed, discoloured, or cracked (See Figure 3-9) Samples fired to 600°C remained in light reddish/orange colour. All the samples fired to 800°C and 1000°C remained well-toned brick red colour.

Figure 3-9: Samples fired to 400 C were either crashed, discolored, or cracked.

Table 3-4: 100 samples categorized according to the firing temperatures



According to literature, with an increase in firing temperature, internal porosity in the microstructure of clay decrees, and material density decreases thus water absorption capacity decreases, which depicts thermal insulation value decreases. Through properties like compressive strength, the thermal conductivity increases.

In that sense, refraining from lower and higher firing temperatures seems suitable, thus firing the proposed clay panels into 800C can be identified as "comparatively suitable" in terms of appearance (colour tone and texture), and strength and considering the compatibility with literature on above properties comparatively.

Colour, texture, or appearance are important factors since the DCDW system is proposed to be an interior application affecting the aesthetics of the space. Yet, more important properties to be assessed in terms of indoor air temperature reduction capacity of the proposed DCDW system.

Out of them, a few properties were identified which are as mostly involved with burned refractory brick listed as follows. Following the standards, these properties are involved in research design, development, and quality control.

- Apparent porosity
- Water absorption
- Linear shrinkage
- Bulk density
- Compressive strength

To improve the DCDW panel, it is crucial to identify the relationship between porosity and the Bulk density, as well as the Relationship between porosity and Permeability of the clay body.

Some literature shows a co-relation of water absorption Vs firing temperature of the clay [103] as follows (See Figure 3-11). According to the graph, amount of water absorbed has been decreased with the increase of firing temperature.

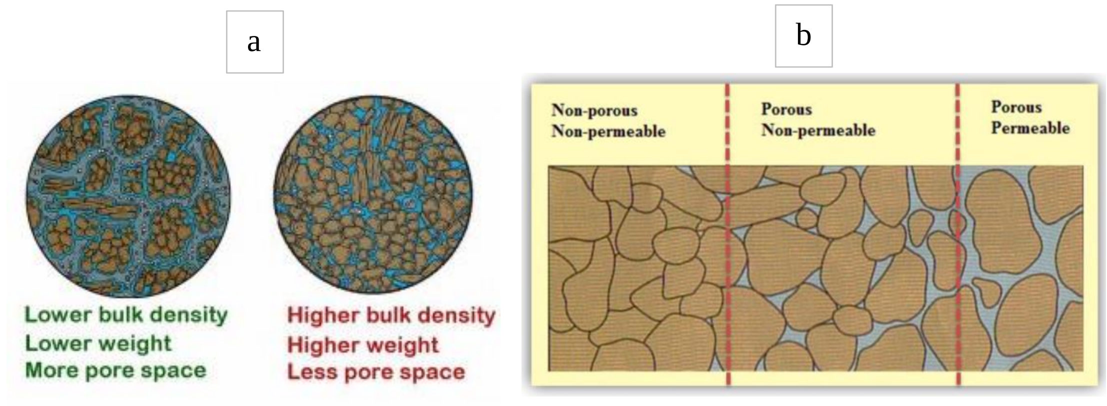


Figure 3-10: a) Relationship between porosity and the Bulk density, b) porosity, and Permeability of clay body

Considering the compressive strength of the clay specimens, the behaviour is in other way, which is, when the firing temperature increases, the compressive strength is also increased (See Figure 3-12).

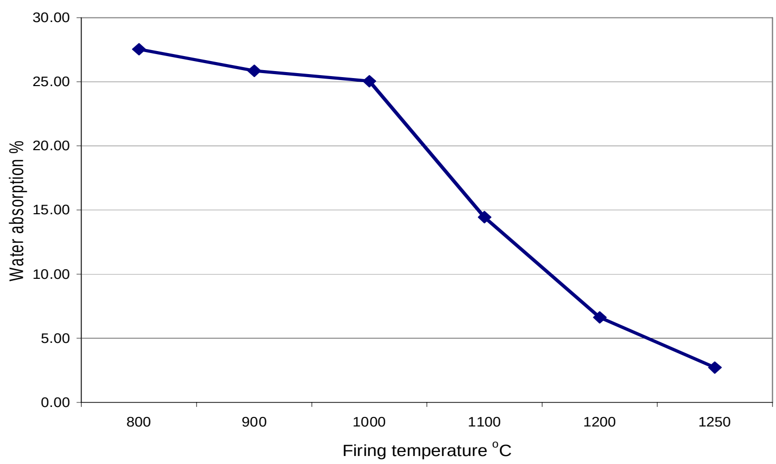


Figure 3-11: Behavior of Water Absorption Vs. Firing temperature of red clay [115]

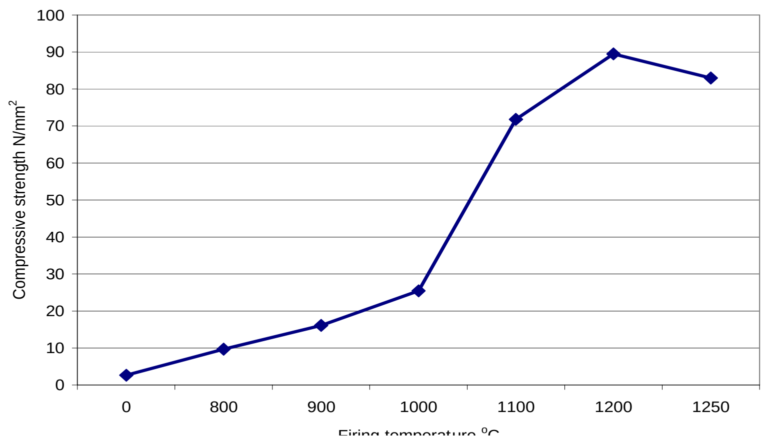


Figure 3-12:Behavior of compressive strength Vs. Firing temperature of red clay [115]

3.5. Testing for Water Absorption (WA): Configuring the optimum internal porosity

"Porosity" is identified as a key property to maintaining the insulation capacity and the thermal conductivity of a material. Based on the theory, "a high-water absorption capacity is found in certain samples; the sample contains a high number of internal pores in its microstructure" [104], the research intended to identify the water absorption behavior of 100 specimens.

ASTM C373-88(2006) standards were used to determine the water absorption for lightweight bricks [105]. In accordance with the standards, the first step was to cool the fired 100 nos. of specimens to room temperature (20 °C) and to get the weights before placing them in a water tank for 24 h. After sinking the specimens in the water for 24 hours, the surface water was wiped off, and the weights were taken again (See Figure 3-13).

The water amount absorbed by each specimen was calculated in accordance with the following equations.

$$MC = \frac{w - d}{w} X\ 100 \qquad \text{Equation 7}$$

w = wet weight d = weight after oven drying

Figure 3-13: Letting the samples for water absorption and weighting before and after soaking

$$\mathrm{WA}(\%) = \frac{\mathrm{m}_w - \mathrm{m}_d}{\mathrm{m}_d} \times 100 \qquad \text{Equation 8}$$

m_d-mass of the oven - dried specimen (g) m_w-mass of the wet specimen (g)

3.5.1. Results and Discussion

Out of the five types of selected earthenware clay used with five types of organic waste compounds, fired samples of red pottery clay (Kadawatha- Ground mixed with sawdust (5mm particles) showed the best performance in water absorption, the results confirm the literature [106][2] while Chinese clay samples with rice husk show the least water absorption within the given test time. The best suitable firing temperature was confirmed as 800°C, which substantiates that fired red pottery clay with sawdust creates optimum internal porosity while Chinese clay panels fired with rice husk create least (See Figure 3-14).

As a whole, the saw dust shows better water absorption, and the rice husk shows the lowest water absorption. Out of all clay types, Chinese clay shows the least water absorption overall. Thus, the material mix is confirmed as red pottery clay with Saw dust fired to 800 °C for 60 min.

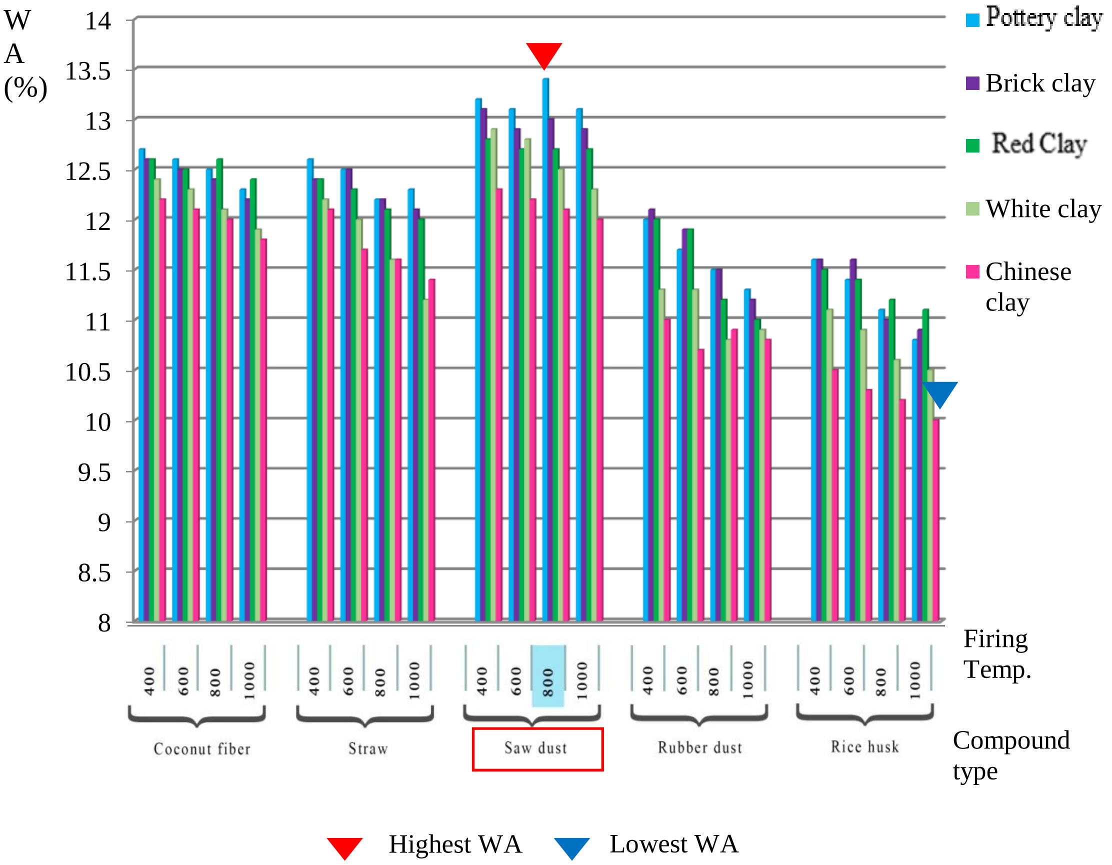


Figure 3-14: Water Absorption of the Samples

Since the water absorption results confirmed the best porous mix material as red pottery clay + Saw dust, literature was further surfed to identify the compatibility with related properties of clay when it is mixed with saw dust.

3.6. Saw dust as an additive for Clay

Numerous researches have investigated the use of saw dust to produce clay bricks, this has contributed to the aspects of environmental protection and sustainable development. The main chemical constitutes of saw dust are as follows,

C (60.8%),

H (5.2%),

O (33.8%)

N (0.9%).

Further, dry wood is primarily composed of cellulose, lignin, hemicelluloses, and minor amounts (5-10%) of extraneous materials. Therefore, saw dust remains a non-toxic natural material. The literature further shows the potential of using sawdust waste for industries or products which can contribute to waste management's point of view as well.

In Sri Lanka, sawdust is an abundantly available form of solid waste. It is available in large heaps around sawmills and environmentally sensitive areas such as river basins, estuaries and woodlands. The country produces about 112,000MT every year, this is sufficient to produce energy products [107]

Annually about 277.5MT of saw dust is available around a major sawmill. A majority of the sawmills are situated in Moratuwa, within proximity to Colombo, the capital of Sri Lanka [107] But there is no proper industry involved with sawdust waste in Sri Lanka other than using them for burning purposes in several production processes, such as for furnaces in clay brick burning and bakery industry.

According to Shyamalee D., Sawdust waste can be used with clay as a pore-forming agent in the process of making clay brick technology. These products combined, provide the clay with a microstructure with higher porosity levels".[100]

Folaranmi, [65] has investigated the Effect of Sawdust Additive on the Properties of Clay (See Figure 3-15). In his experiments, he increased the % of Saw dust from 0% to 30% and investigated the effect on different properties of clay. The investigated properties are Bulk density, Porosity, Linear shrinkage, Cold crushing strength, sintering point, and thermal shock resistance. The findings are summarized below.

↓ Property Decreases

↑ Property increases

Table 3. Variation of bulk density with sawdust.

Sawdust (%)	0	1	5	10	20	30
Bulk Density (g/m^3)	1.518	1.515	1.511	1.507	1.504	1.500

↓

Table 4. Variation of porosity with sawdust.

Sawdust (%)	0	1	5	10	20	30
Porosity	0.37	0.39	0.43	0.48	0.57	0.61

↑

Table 5. Variation of linear shrinkage with sawdust.

Sawdust (%)	0	1	5	10	20	30
Linear Shrinkage (%)	2.47	2.46	2.43	2.40	2.36	2.30

↓

Table 6. Variation of cold crushing strength with sawdust.

Sawdust (%)	0	1	5	10	20	30
CCS (Kg/m^2)	487	455	405	388	344	207

↓

Table 7. Variation of sintering point with sawdust.

Sawdust (%)	0	1	5	10	20	30
Sintering Point (^oC)	1430	1430	1430	1430	1430	1430

→

Table 8. Variation of thermal shock resistance with sawdust.

Sawdust (%)	0	1	5	10	20	30
Thermal Shock Resistance (cycles)	10	10	10	10	10	10

→

Figure 3-15: Literature on clay's properties with different saw dust percentages [98].

With the above basis of literature, research intended to identify the suitable “Material mix composition”, for optimum indoor air temperature reduction.

3.7. Identifying the best mix-composition of the best material-mix

In the Red pottery clay+ Saw dust mix material, the optimally performing mix composition (in terms of indoor air temperature reduction) was required to be confirmed. Thus, five specimens in the size of 6 inches. x 3 inches. were cast adding five different red pottery clay: saw dust compositions, as follows: Red pottery clay 80%: saw dust 20%

1. Red pottery clay 65%: saw dust 35%
2. Red pottery clay 50%: saw dust 50%
3. Red pottery clay 35%: saw dust 65%
4. Red pottery clay 20%: saw dust 80%

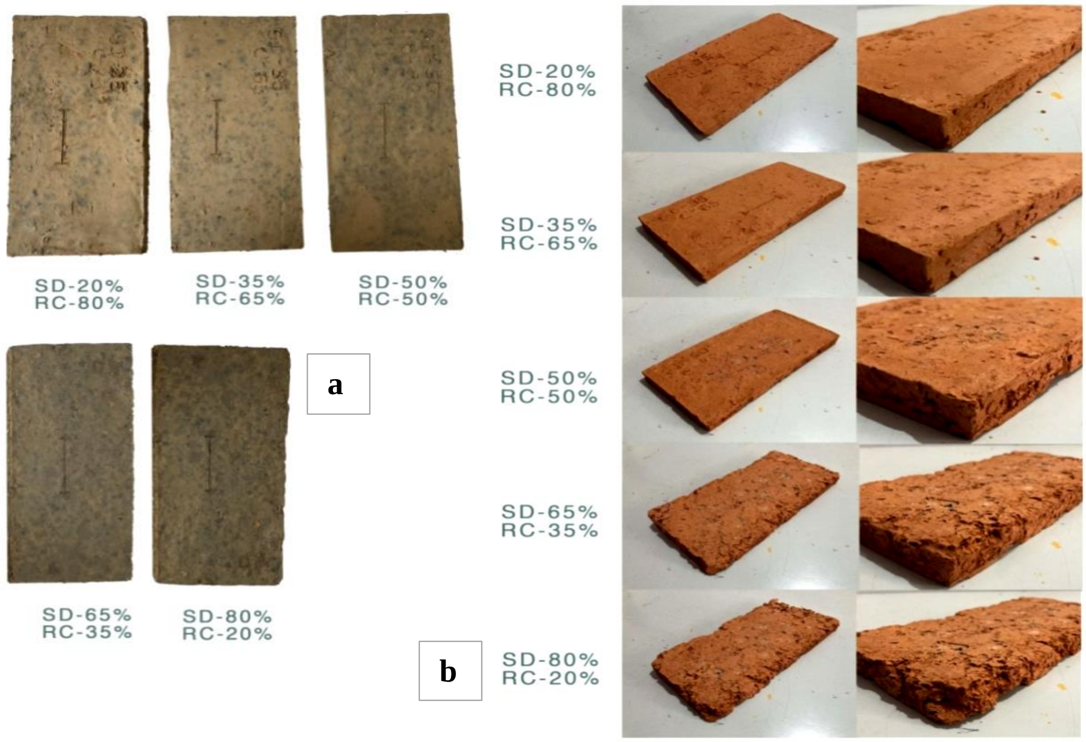


Figure 3-16: **a-** Specimens with different Saw dust percentages - before firing **b** - Texture variation of the specimens with different Sawdust percentages (fired to 800 C degrees for 60 min.)

Different saw dust percentages to be mixed with clay were decided based on related previous research [65]. The samples were fired to 800 °C for 60 min. In accordance with ASTM C 373-88 standards, [105] , the above five clay bricks were dried to a constant mass (air dried, oven dried), cooled to room temperature (20 °C), and took the dry weight, before fully covering with water for 24 h. The specimens were removed from the water container, the surface water was removed, and their wet weights were taken again (See Figure 3-17).

Figure 3-17: Testing the water absorption - red clay panels with different compositions of Saw dust

The water amount absorbed by each specimen with different saw dust percentages was calculated using Equations 7, and 8 to identify the patterns. The results are presented in the graph (See Figure 3-19).

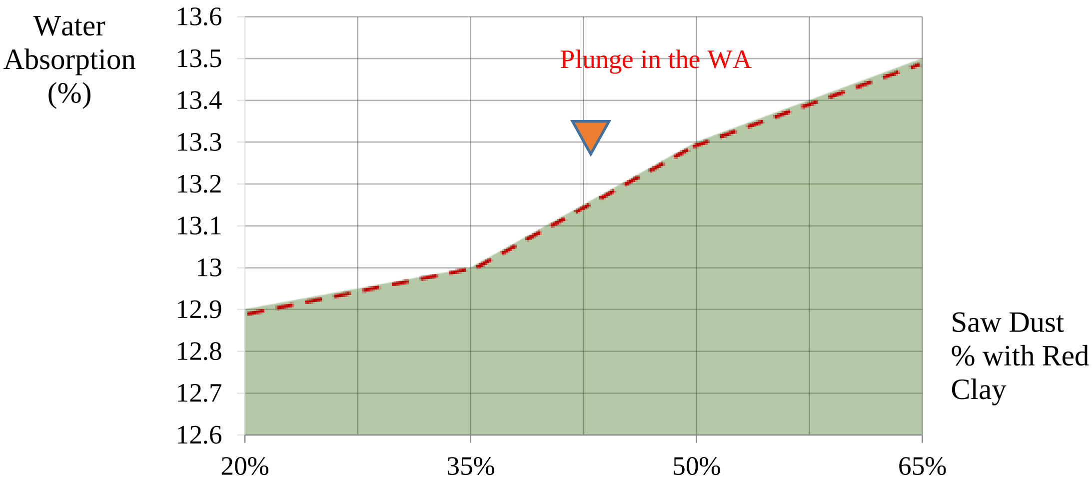


Figure 3-18: Water Absorption of specimens with different Saw dust percentages.

The results indicate, that when the percentage of sawdust increases the percentage of water absorption of the specimens' also increases. The finding of Nigay P.M, which mentioned "A high-water absorption capacity is found in certain samples; the sample contains a high number of internal pores in its microstructure" [102] is confirmed by the test results.

The results show, that out of four Saw dust percentages added to red pottery clay specimens, the lowest air temperature reduction is recorded by the specimen which contained the lowest Saw dust percentage (See Figure 3-18).

The water absorption capacity of the specimens was investigated to identify the formation of internal pores in the microstructure, in order to identify the heat insulative capacity or heat absorption capacity of the DCDW panels. Therefore, in the next step, the specimens with different saw dust percentages were inserted in a developed test chamber to identify their effect on indoor air temperature reduction due to the DCDW system.

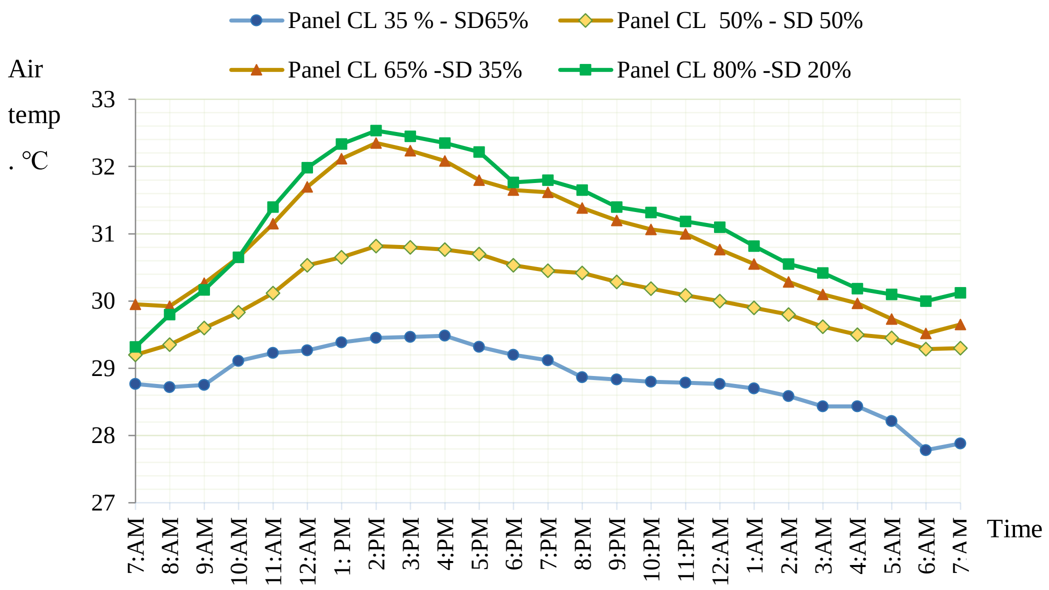


Figure 3-20: Behavior of air temperature, with DCDW panels containing different Saw dust percentages

A special test chamber was built for this test, and it was fully insulated to control and maintain the indoor thermal condition at a similar level. Indoor Air Temperature measurements were taken with New Graphtec GL840M midi Logger for 24 hours for each panel (every panel was tested for the same time period of the day) with a constant airflow (See p. 96).

When the percentage of Saw dust is increasing in the specimen, the indoor air temperature reduction has increased, nevertheless the air temperature reduction rate has also increased accordingly. Thereby, out of for specimens, the highest indoor air temperature reduction has been recorded with the specimen which contained the highest Saw dust percentage, which is 65% of saw dust with 35% of clay (See Figure 3-20Figure 3-20: Behavior of air temperature, with DCDW panels containing different Saw dust percentages).

The result depicts, when the internal porosity of the DCDW panel increased by increasing the % of saw dust added, it has given a good thermal insulation property as well as a good heat absorption capacity to the clay panels, which contribute to reduce the air temperatures of indoors (See Figure 3-20).

3.7.1. Compatibility of the results obtained, with existing literature

Phonphuak N. [100] has investigated the impact of sawdust waste on the thermal conductivity of fired clay bricks, as he states

“A porosity of 32.40% for 10% sawdust, is the highest level which was obtained after firing the bricks at 900°C. Whilst, the lowest porosity level of 22.80% with 2.5% of sawdust waste fired at 1100°C.

The obtained result confirms the above literature, in terms of the most efficient saw dust percentage and confirms the firing temperature adopted in the test methodology [100].

3.8. Assessing the ‘Surface texture’ of DCDW material

Phonphuak N. [100] has tried to identify the variations of the texture of the surface of the clay with a different waste form of sawdust on the physical properties and thermal conductivity of fired clay brick” which the outcome is presented (cross-sectional view) below (See Figure 3-21).

The results of the above-mentioned research indicate when the sawdust waste is mixed, it affects the water absorption rate, porosity levels and density of the fired clay bricks.

There is a large number of visible pores in these fired clay bricks. Moreover, the method of firing, the composition of the chemicals of the clay and firing temperature affected the colour of the fired clay bricks.

3.9. Assessing the Microstructural Porosity of DCDW material

Considering literature, the research attempted to identify the visible pores in the micro-structure of specimens fired with different percentages of Sawdust. For this, a photographic survey was conducted, 5mm Micro lens was used to photograph the specimens with *2 x zoom*. The photographs of each specimen are presented in consecutive order of their sawdust percentage (See Figure 3-22).

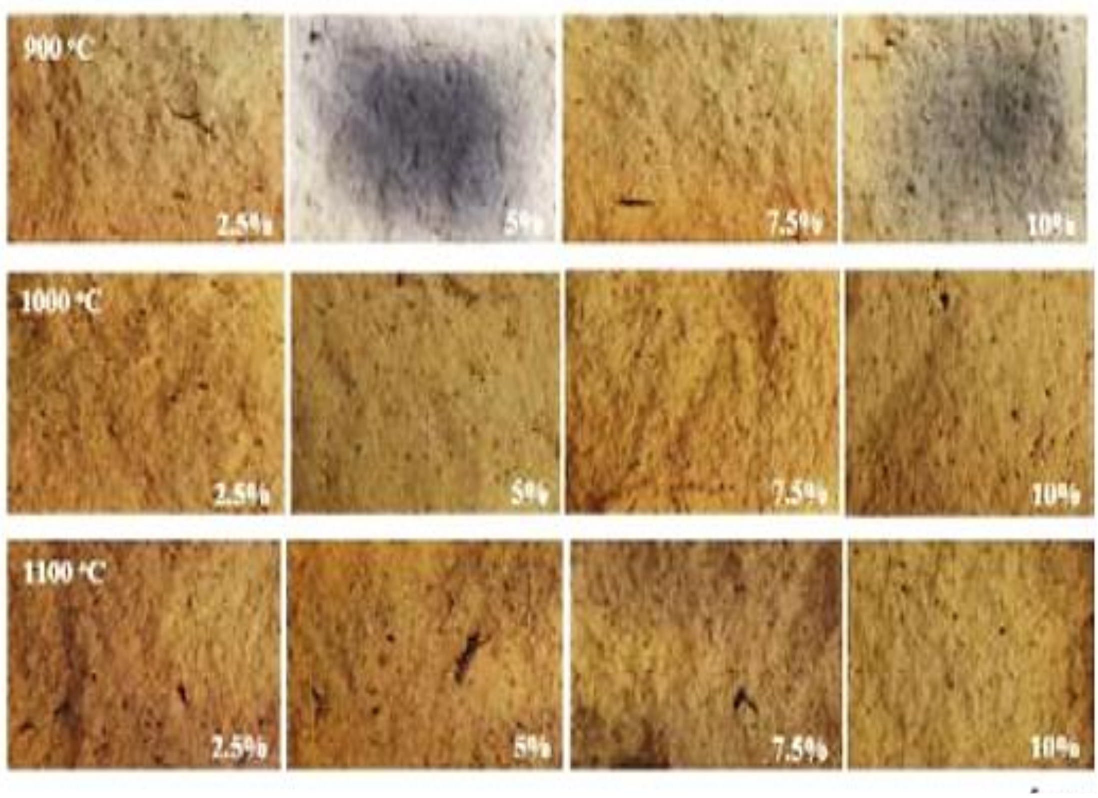


Figure 3-21:Surface texture of fired clay bricks specimens fired 900 to 1100 ℃ with different percentages of saw dust waste. (2.5%, 5%,7.5%,10%) [98]

It is clearly visible that, when the percentage of sawdust in the specimen is increasing, the internal porosity increases. This depicts, that when the percentage of sawdust in the specimen increases, it carries more capacity to contain air in its microstructure, thus it increases heat insulation capacity.

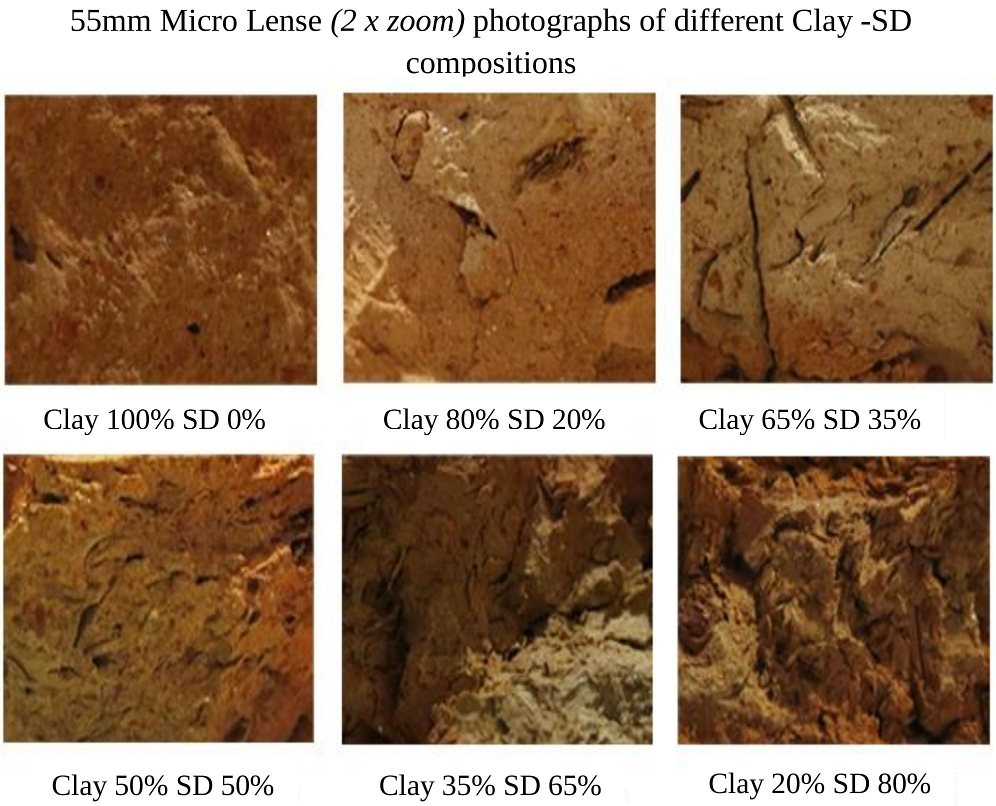


Figure 3-22: Photographic survey of visible porosity in the microstructures of DCDW panels, fired with different saw dust percentages

In summary, in terms of low thermal conductivity, its suitable to increase the percentage of sawdust in the DCDW panel, but, since high internal porosity; low material density decrease the structural strength of the panel, it is recommended to utilize an average saw dust percentage for the DCDW panel which would be preferred by many other aspects too.

3.10. Identifying the thermal conductivity of DCDW panel

Phonphuak N. et al, [100] in their research on the effect of using sawdust waste on the physical and thermal conductivity properties of fired clay bricks, these bricks used sawdust waste of 0 to 10% in weight and these were fired at 1000°C. The results prove that the specimens which constituted higher percentages of sawdust were provided with low thermal conductivity. The ratio of 10% wt% provides the lowest thermal conductivity. It can be inferred that thermal conductivity is related to the density and porosity of the fired clay bricks (ie- the thermal conductivity reduces with a decrease in density and rise in porosity). Thermal conductivity is directly proportional to density and inversely proportional to the porosity of the fired clay bricks. The heat conduction process includes the porosity of the clay bricks directly relates to their density [100].

Folaranmi J. has investigated the thermal conductivity behavior of fired clay with different saw dust percentages (See Figure 3-23). He has determined the thermal conductivity values of the specimens using Lees' apparatus the following results have been obtained [108]

Sawdust (%)	0	1	5	10	20	30
K(W/m K)	0.250	0.230	0.190	0.130	0.090	0.060

Figure 3-23: Variation of thermal conductivity with clay and different saw dust % [98]

According to Folaranmi J.'s results the thermal conductivity values decrease rapidly with increase in the amount of sawdust.

Thermal conductivity ('k value') is a property of a material that determines how much heat is conducted through it for a given temperature difference. It is measured in watt per meter kelvin [W/ (m · K)] and given by the following formula

$$k = QL / A\Delta T \qquad \text{Equation 9}$$

where,

Q is the amount of heat transfer through the material in watt [W]

L is the thickness of the material [m]

A is the area of the specimen in square meters [m^2]

ΔT is the differential temperature across the specimen in kelvin [K]

Based on the literature, this research used 50%: 50% clay: saw dust DCDW specimens fired to 800°C. To identify the thermal conductivity. 'Transient Hot Bridge - Thermal Conductivity Meter', which complies with ASTM D 5930-01, ASTM C1113 was used for the test (See Figure 3-24, Figure 3-25).

Figure 3-24: Testing the thermal conductivity of the DCDW specimen with Transient Hot Bridge - Thermal Conductivity Meter

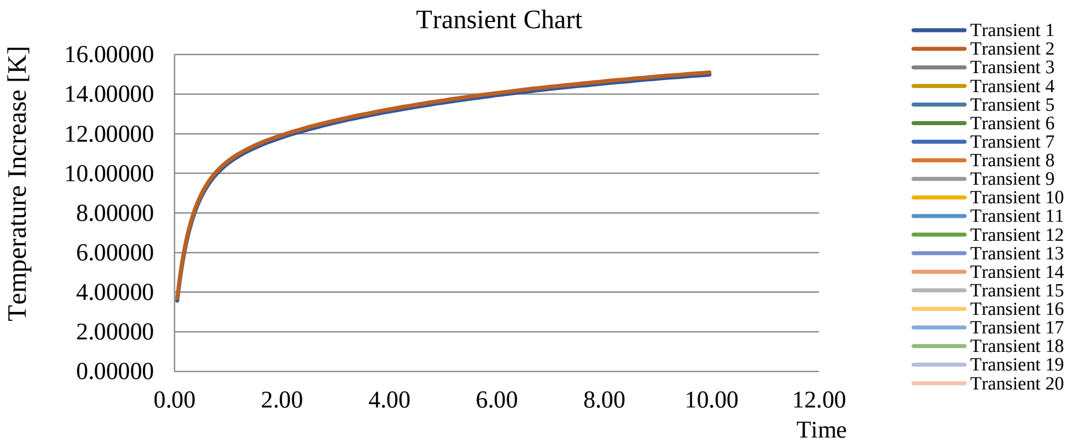


Figure 3-25:Transient chart for the tested DCDW specimen

The thermal conductivity value for the finalized DCDW panel specimen was recorded as 0.05 W/mK. The obtained result can be justified, by comparing it with the conductivity value obtained in literature [108] for 30% of sawdust with clay which is 0.06 W/mK. and when the percentage of sawdust added is 50% the thermal conductivity has become lower.

3.11. **Weight loss and Firing shrinkage, in different firing temperatures**

How the weight of specimens' loss with increasing firing temperature is shown Figure 3-26. Generally, good quality fired clay bricks exhibit shrinkage below 8% [11].

According to literature, the firing shrinkage increases when the firing temperature increases (See Figure 3-27).

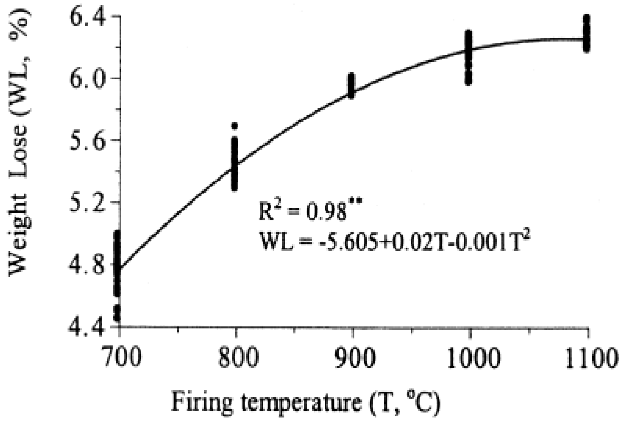


Figure 3-27:Behavior of weight loss Vs firing temperature of clay [116]

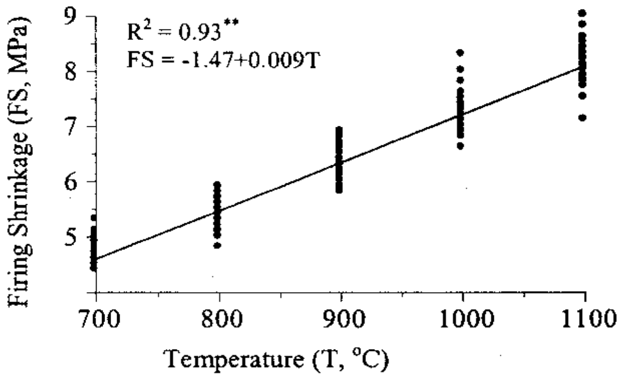


Figure 3-27:Behavior of firing shrinkage of clay, upon different firing [116]

3.11.1. Identifying the linear shrinkage

British Standard BS 1377:1990. was used to measure the linear shrinkage of clays. This bar linear shrinkage test was found to be the most reliable method.

Linear shrinkage test only describes the change in length. The shrinkage is assumed to be uniform in all three directions when calculating 3D shrinkages (volumetric shrinkage).

Six sample panels were cast for this test, five with red pottery clay and five different saw dust percentages (SD 65%,50%,35%,20%) and one with no added compounds. 5 cm bar was marked in each panel before they are sent for firing (See Figure 3-28). The sample was allowed to air dry for four hours. Then they were placed in an oven at 105˚C for 18 hours. The samples were fired to 800 °C for 60 minutes, the new length of the marked 5cm bar was measured three times with a Digital Calliper and the average was used to calculate linear shrinkage using the following equation:

$$LS = \left(1 - \frac{L_{avg}}{L_o}\right) \times 100 \qquad \text{Equation 10}$$

where:
LS = Linear Shrinkage (%)
L_{avg} = Average Length (mm)
L_o = Original Length (mm)

Before firing

After firing

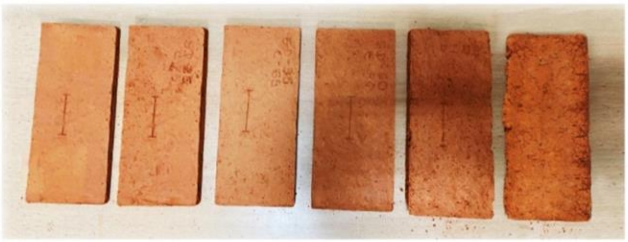


Figure 3-28:Red clay samples with five different Saw Dust compositions and with no compounds, Before and After Firing to 800°C

3.11.2. Results of the linear shrinkage test

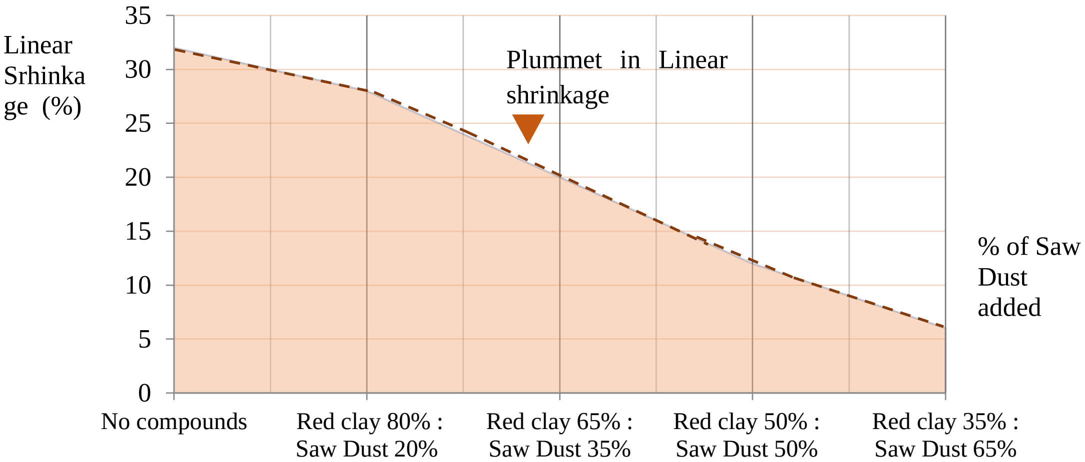


Figure 3-29: Linear Shrinkage of Red with Different Saw Dust %

The results show that red pottery clay with no saw dust shrinks more than it is mixed with saw dust. Moreover, the linear shrinkage rapidly decreases with the increase in Saw dust percentage in the clay pane (See Figure 3-29). This result agrees with Folaranmi's finding in [108].

3.12. Identifying the effect of the panel thickness

The thickness of an interior wall panel can be identified as important in many general aspects such as space management, weight, ease of production and transportation etc. in addition to the above aspects, the thickness of a DCDW panel can be affected by indoor air temperature reduction too, as with thickness it increases its thermal mass capacity. Therefore, this test intended to identify the patterns of the behaviour of panel thickness on indoor air temperature reduction.

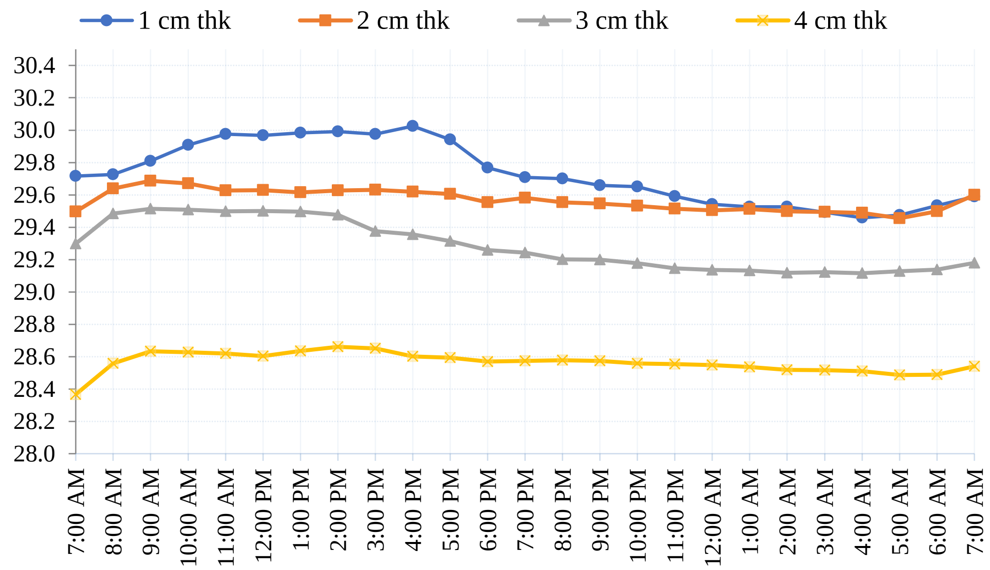


Figure 3-30: Indoor air temperature behavior with different DCDW panel thickness

Considering the practical casting and testing possibility, as well as space utilization capabilities in average building interiors, four-panel thicknesses are decided to be tested. They are 1cm thick, 2cm thick, 3cm thick, and 4cm thick DCDW panels with 50%: 50% clay: saw dust mixed and burnt to 800℃.

The thickness of the panel is consecutive to the amount of indoor temperature reduced. 4cm thick panel shows the highest indoor temperature reduction while the lowest indoor temperature reduction records with the 1cm thick panel. When the thickness increases, the temperature reduction rate also increases (See Figure 3-30). (This result agrees with the theory of thermal mass effect and decrement factor by S. Koenigsberger [34]) With gained results, it can be recommended that, if the effectiveness of the DCDW system is increased in the practical context where space utilization is not a limitation, the thickness of the DCDW panel can be increased.

3.13. Chapter summary

The chapter initially introduced the DCDW system which consists of two Components, and its conceptual idea of working together for indoor air temperature reduction.

The chapter involved presenting the experiments processed to improve the identified properties of Component 01 (Dynamic Clay Double Wall panel), which are listed as follows,

1) The material mixes
2) Material mix composition (On internal porosity and indoor air temperature reduction)
3) Production process of DCDW panel (From material mixing to firing the DCDW panel)
4) Firing temperature and time (trial and error process of identifying the best firing temperature and time)
5) Water Absorption (to assess the internal Porosity)
6) Visibility of Microstructural Porosity (photographic survey)
7) Visibility of Surface Texture (photographic survey)
8) Linear shrinkage
9) Thermal conductivity (of the DCDW panel with finalized material mix and properties)
10) Effect of panel's thickness on indoor air temperature reduction

In summary of each experiment results, the best material mix was confirmed as ‘Red Pottery Clay with Saw Dust’ into 50:50 Clay: Saw Dust composition, air dried, oven dried and then fired to 800°C for one hour will result from the best DCDW panel in terms of Indoor air temperature reduction. It was clearly visible, that when the percentage of Saw Dust increases in the clay body, both in surface texture and in the microstructure, an increase of porosity can be seen clearly.

Water Absorption capacity is also increased with the increase of Saw Dust % in clay while the linear shrinkage decreases.

The thermal conductivity of the finalized DCDW material was recorded as **0.05 W/mK.** Further to the results depicted, when the thickness of the panels increases, it increases the heat absorption capacity thus, it increases the indoor air temperature reduction due to the DCDW solution.

4. CHAPTER FOUR – SYSTEM DELOPEMENT AND THERMAL INVESTIGATION

4.1. General

The best material mixes and best compositions, best firing temperature and time, some other important parameters in terms of best indoor air temperature reduction were identified via testing done in the previous chapter.

Component 01 is thereby developed for its optimum thermal insulation properties. Then the research intended to incorporate the ventilative cooling effect with component 01 by further improving the DCDW panel with air permeability performances. For this, it was required to improve the cross-air movement capability of the DCDW panel with additional buoyance pathways across the DCDW panel to accelerate the area of the surface to touch the ventilation.

4.2. Improving the DCDW panel's cross air permeability

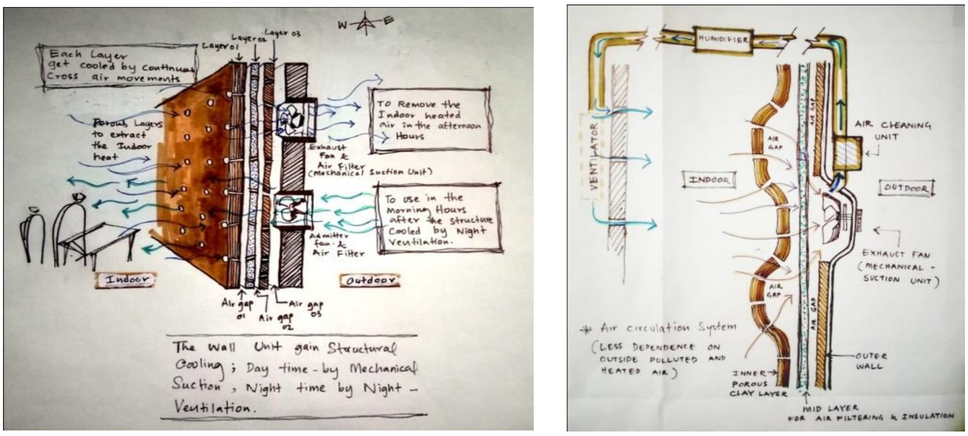


Figure 4-1: The conceptual idea developed for cross air movement of the proposed clay wall.

Possibilities in improving internal porosity characteristics of clay were tested already and this experiment involves in improving the cross-air penetration characteristics of the clay panel to a further level (See Figure 4-1). In addition to the micro-scale pores inside, it was attempted to improve the cooling capacity / decrease the thermal conductivity of the -DCDW panel together with an increased ventilative cooling effect. The focus was to try the impact upon the application of millimetre scale pores to the proposed clay panel to identify the optimum characteristics for indoor air temperature reduction.

4.2.1. Developing the form of DCDW panel

Air cooler pad

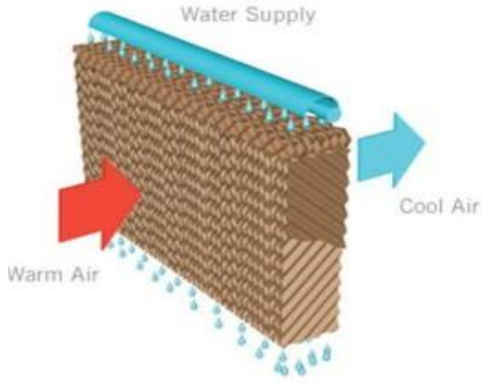


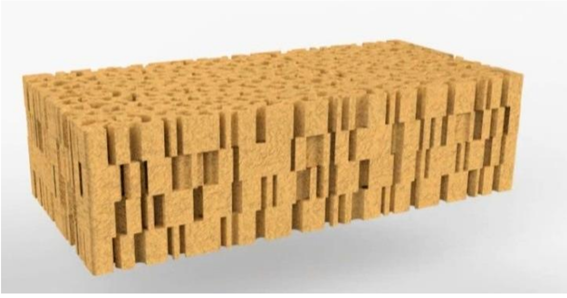
Figure 4-2: Inspiration for the DCDW panel – Air cooler pad

4.2.2. Precedents studied to develop the form of the panel

Figure 4-3: 3D printed components developed by Ronald Rael and Virginia San Fratello

4.3. Form development with 3D modelling

With the literature and precedent background, the research tried developing the conceptual form (See Figure 4-2, Figure 4-3) for the DCDW panel as a 3D model using Google SketchUp software. The developments were focused on making the clay body/microstructure of the DCDW panel optimally porous and interconnectedly permeable with maximum buoyance pathways (See Figure 4-4 to Figure 4-8).



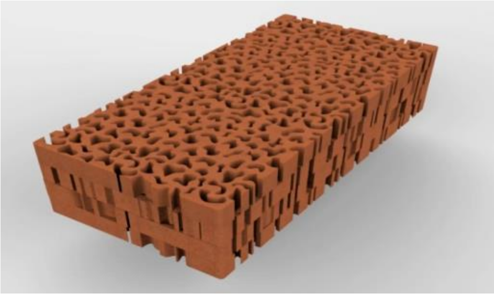


Figure 4-4: 3D Model of proposed DCDW panel before and after firing.

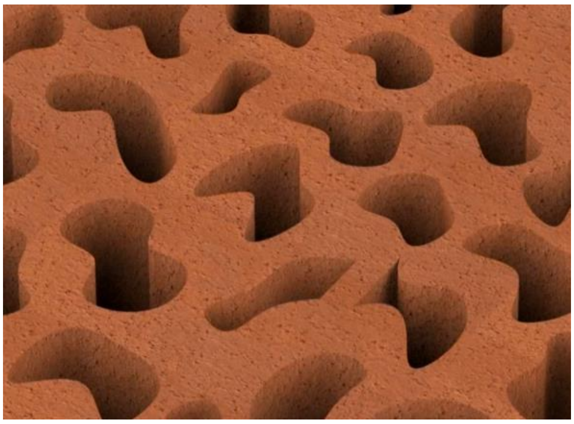


Figure 4-5: The porous microstructure: Micro scale pores in the clay body, in addition to the millimeter scale buoyance holes

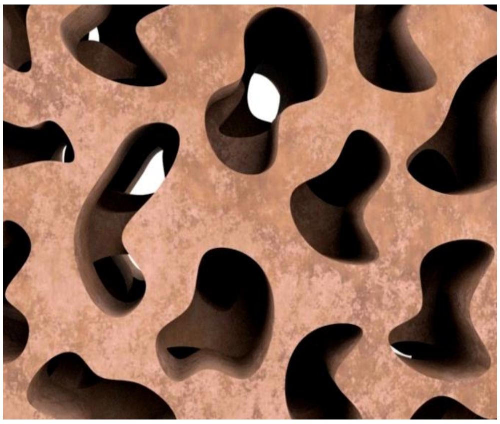


Figure 4-6: 3D view of the see-through (interconnected) buoyance holes punched in the clay panel for cross air movements.

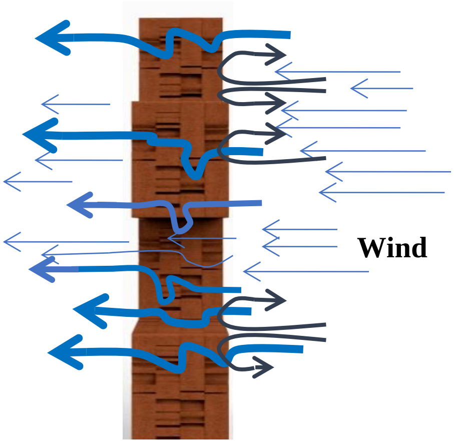


Figure 4-7: A cross section of the proposed DCDW panel which shows cross-air movements through the clay panel along buoyance pathways

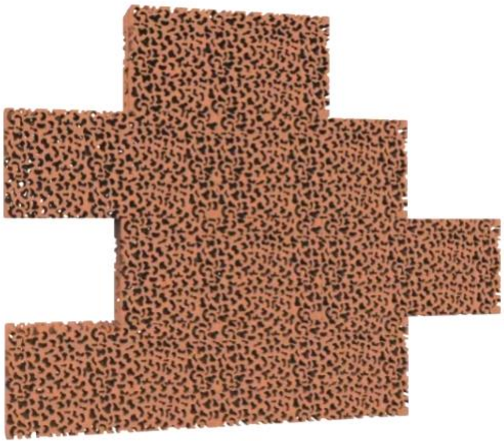


Figure 4-8: 3D Appearance predicted for the DCDW panel upon application

To test the potential in actualizing the developed 3D form of the DCDW panel, specimens were required to be cast and thereby, a suitable fabrication method was required to be identified. Since clay is selected as the main material for DCDW panel, basic clay casting methods were studied (See 2.12.4) to figure out a suitable method to cast the proposed panel. Out of many methods, some popular methods, ‘hand building methods’ and ‘moulding methods’ were given priority since they showed potential in casting the clay panel as a porous, continuously permeable structure as required.

4.4. Finding the potentials to improve the air permeability of DCDW Panel

Traditional clay casting methods individually did not fit fully or cannot be used as it is in casting the DCDW panel as porous and permeable as required, but their influence and experience were used to develop a suitable novel casting method for the DCDW panel. To identify its own method of casting, a few pilot castings were done. Since increasing the porosity in microstructure was proven with sawdust, a method for continuous permeability of the DCDW panel was required to ensure.

For this, 6” x 1ft x ½ inch thick compressed clay veneers from the identified material mix and composition were built as pilot casting. The specimens were built in a timber formwork and the clay lumps were compressed into the frame by hand until it become stable, and the excess clay was removed by cutting with a thread. Initially the punching the clay panel was done manually to a random pattern with an iron nail (See Figure 4-9).

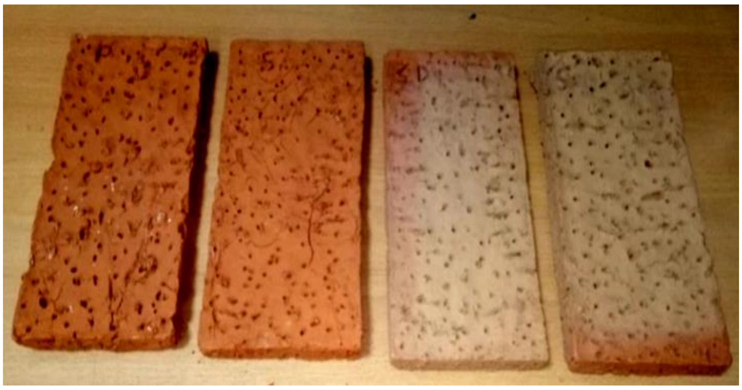


Figure 4-9: Specimens made for pilot casting; compressed by hand in timber frame, punched randomly with a nail and fired to 800°C for 60 min.

In this stage, it was required to confirm a size for the DCDW panel, and with a series of pilot castings, taking the dry shrinkage and firing shrinkage of the clay–compound mixed panel into account, 1x1 ft x 1inch specimen size was confirmed to carry out considering the ease of handling, application, and testing during further indoor heat reduction experiments.

With pilot castings and outcomes, the requirement was aroused to identify the proper configurations of the holes to be introduced to the DCDW panel to identify its potential in improving the cooling characteristics. For better identification of its cooling effect, it was decided to introduce millimetre scale holes to the clay panel. Moreover, these holes were expected to be as buoyance as they can be, to improve the area of the clay surface which can touch the air, while the cross ventilation occurs through the clay panel, to increase the structural cooling effect of the proposed clay panel due to ventilative cooling (See Figure 4-10). When applying the mm scale holes in the clay panel, attention was paid to Four main parameters which can involve in increasing the indoor cooling effect.

They are as following,

1. Diameter of the holes
2. Hole distribution (distance between each hole)
3. Buoyancy of the hole (Hole angle)
4. Thickness of the panel

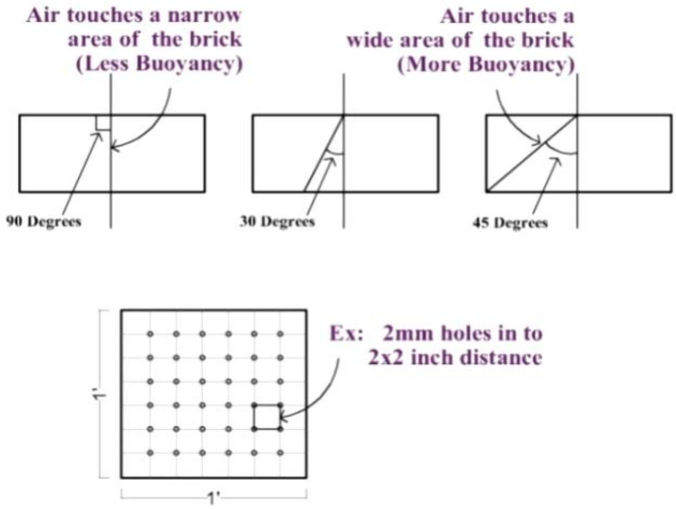


Figure 4-10: Punching the clay panels; creating buoyancy pathways through the brick for better air movements.

To test the application and performance of the above parameters, 1inch thick, 1ft x 1ft clay panels (12 nos.) were cast and each set of clay panels was punched as per the following plan (See Table 4-1).

Table 4-1: Punching plan with different hole distribution, hole diameter and hole angles

Hole Distance	Hole Diameter	Hole Angle
1x1 inch	2mm (S)	90 degrees
		30 degrees
		45 degrees
	5mm (L)	90 degrees
		30 degrees
		45 degrees
2x2 inch	2mm (S)	90 degrees
		30 degrees
		45 degrees
	5mm (L)	90 degrees
		30 degrees
		45 degrees

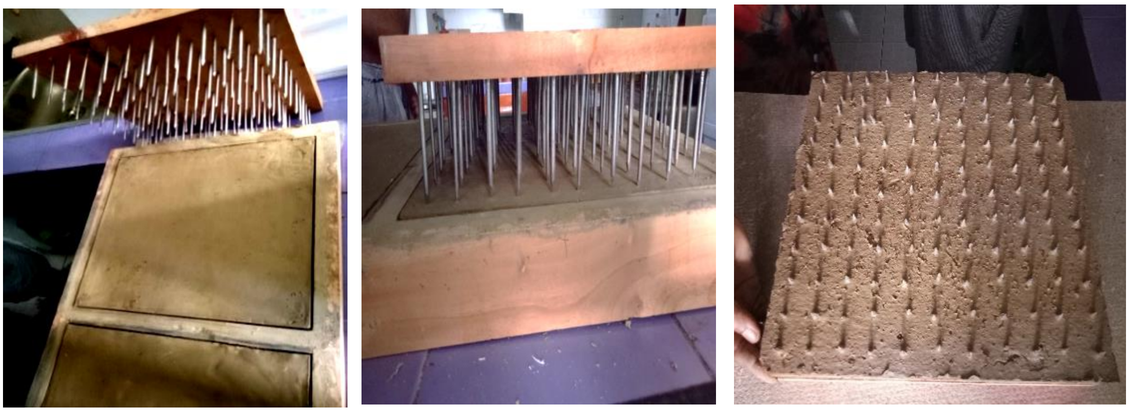


Figure 4-11: Clay samples compressed by hand in timber frame and pounced with a nail plate into a regular pouncing pattern

A suitable casting method was yet to be finalise to test the above parameters and as another pilot method the panel was compressed and cast in a timber frame and punching was done manually with a nailed timber plate as it gives the impression easy to punch the panel at ones (See Figure 4-11).

When casting using this method, it was identified this method is not practical and easy when the exactly required water content of the clay–sawdust mix, drying method and the duration of the clay type is not pre-identified. When the clay lump is too dry or too wet, manually punching with a nailed plate is very difficult/impossible.

For the above reasons and due to these techniques being less practical in mass production it was decided to test an appropriate technique of casting the clay panel targeting mass production. The research focused on developing a manually operatable machine with simple technology in casting DCDW panel, which compresses the clay lumps into a flat slab and is capable in punching it with the required hole size and distance with the same machine (See Figure 4-12).

During the test castings in developments of the machine, it was identified that clay lumps tend to stick to the steel surfaces of the machine, due to the compression. If so, it will be very difficult to remove the compressed panel to the required shape and finish, as it refrains staying stable due to wetness.

To prevent this, applying a light layer of oil was applied on the steel surfaces before putting the clay lumps in it, which is a common method involved even with Calicut clay tile production and inveterate success.

By casting the DCDW panels with the machine, all the panels can be produced with a uniform compression (which helps to maintain a uniform internal porosity level) and with even punching characteristics. Also, it has made the casting of clay panels quick and easy. Due to the simple technology of the machine, the required labour is less as well there's no requirement for well-trained /experienced labour for the casting process. The process of compressing, and punching the clay panel with the machine, is shown in the following series of images (See Figure 4-12).

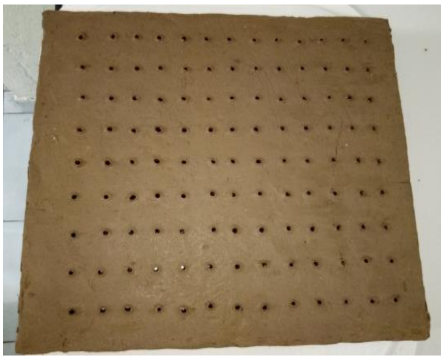
Clay lump is loaded in the steel frame

Steel frame loaded with clay is placed under the compression surface.

Clay lump, flattened by the compression

The clay lump is compressed manually with hydraulic power.

Punching the compressed clay panel



Compressed, punched clay panel taken out from the stell frame and ready for air drying.

Figure 4-12: Process of casting and punching the DCDW panel with the machine

Figure 4-13: Punched and fired clay panels, the final product

Punched panels are air dried (See 3.3.2),oven dried (See 3.3.3) and fired to 800C degrees for 60 minutes. For the final appearance of the fired DCDW (See Figure 4-13).

4.5. Thermal investigation; Assessing the effectiveness of DCDW with the test chamber

A 3ft long x1ft wide x1ft high glass chamber was built for this test as per the sketch of Figure 4-15. The chamber was insulated with 1-inch-thick polystyrene to avoid the transfer of outside heat to the inside. In one narrow façade, low energy consuming DC fan was fixed to one narrow façade to maintain a continuous air suction through the clay panels.

4.5.1. Identifying the hole configurations for optimum indoor heat reduction

The test was conducted totally under passive conditions. Each fired clay panel was inserted to the chamber and Graphtec GL840M midi logger (See Figure 4-14) was used to record the required temperature data. Surface temperature and air temperature were recorded for each panel for 24 h. For every panel, the data collection was conducted during the same time duration of the day, with a constant negative airflow of the same velocity.

Figure 4-14: Graphtec GL840M midi logger,

Figure 4-15: During the Chamber Test; Investigating the Indoor air temperature reduction **a)** Sketch plan form of the test chamber. **b)** Insulated outer look of the test chamber. **c)** DCSW panel is installed to the test chamber and ready to investigate the thermal performance

Indoor temperature results with each panel, is analyzed in the following graphs.

4.5.2. The chamber test – Results and analysis

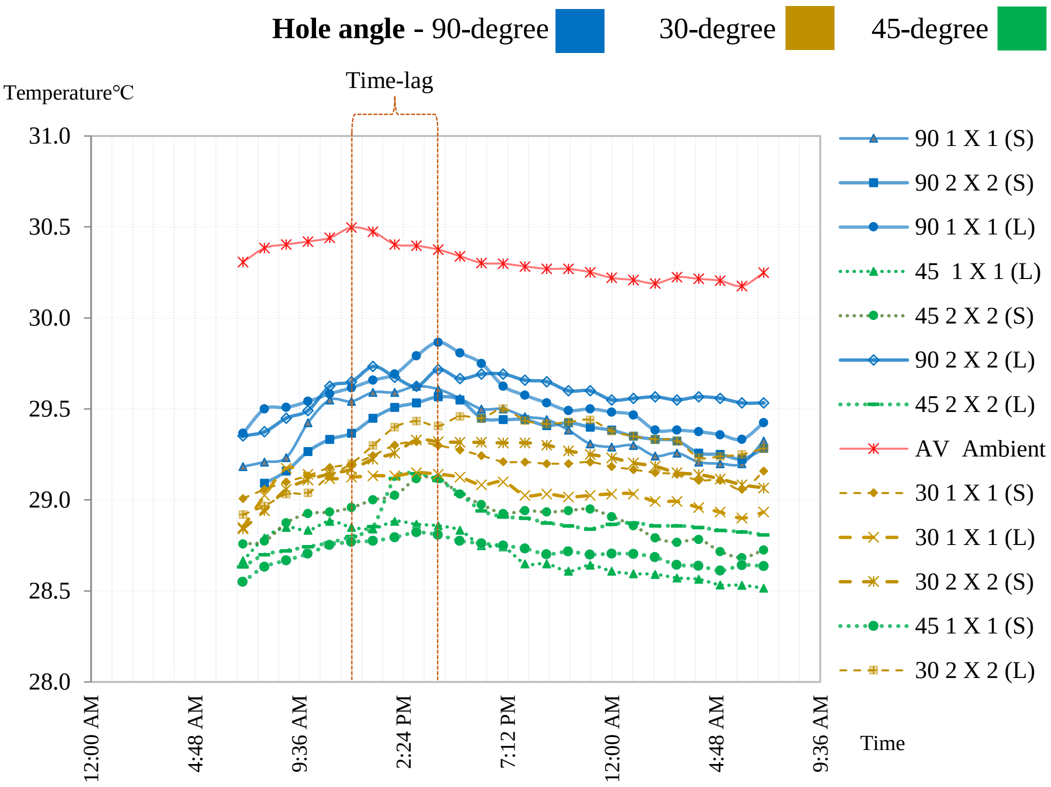


Figure 4-16: The impact of hole angle (45, 30, 90 degrees) on indoor heat reduction

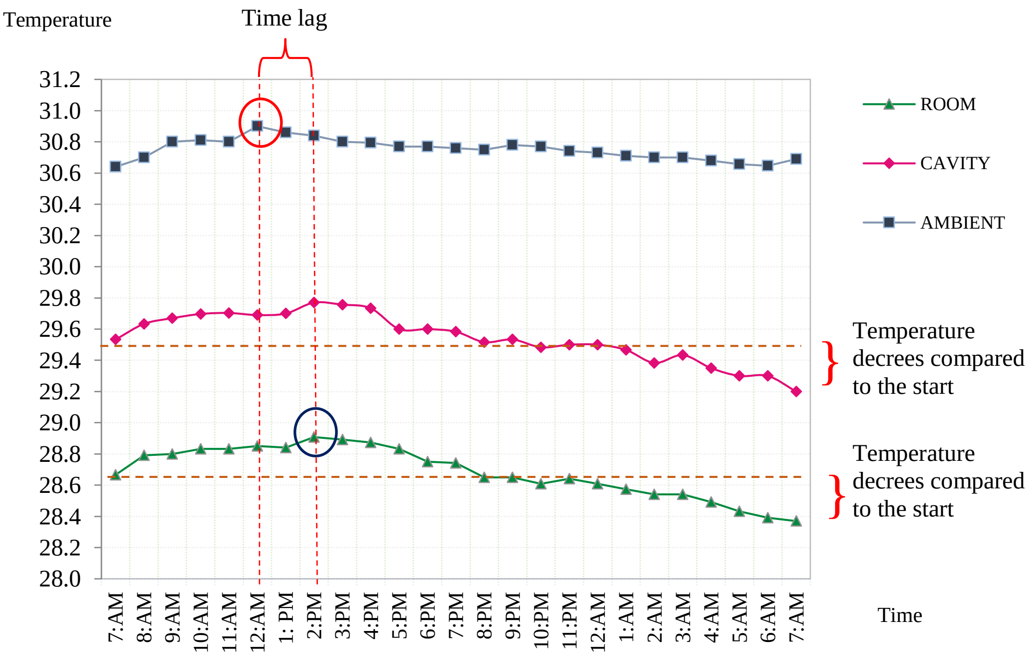


Figure 4-17: Indoor air temperature reduction comparative to the Ambient in the 'Best case'

The results show a considerable air temperature reduction compared to the ambient temperatures of the test dates. A decrease of more than 1 1/2 to 2 C degrees in the indoor air temperature can be identified upon the application of the clay wall panels, which is a constructive indoor heat reduction in a tropical climate. In addition, a good drop in air temperature after 24 hours compared to their starting air temperature was also identified. On the other hand, a clear time lag (approx. 1- 1 ½ hrs.) is observed (See Figure 4-17) compared to the ambient peak temperature Vs indoor peak temperature time, which agrees with the theory of S. Koenigsberger et.al. These results can be justified caused because of the increased thermal mass effect occurred by the application of clay secondary wall panels, which also act as a heat buffer and a heat store, which impacts directly on the indoor air temperature.

Nevertheless, a significant pattern and a relationship were identified between the indoor temperature reduction Vs. the angle of the holes (buoyancy) punched in the panels. A consecutive reduction of the indoor temperature with an increase of the hole angles is clearly identifiable. Whereas, the highest temperature reduction was gained with the panels punched to 45-degree angle holes, while the least temperature reduction was gained with panels punched to a 90-degree angle (See Figure 4-16).

However, a clear pattern cannot be observed between the reduction in indoor air temperature with the hole size and the distance between the holes, as indicated by the hole angles. Thus, a repeat test was conducted to find the optimally performing hole distribution and the hole size (See Figure 4-18).

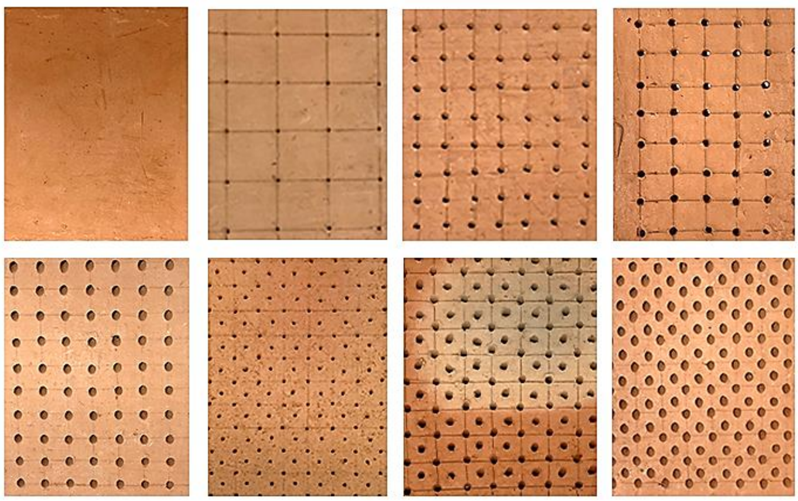


Figure 4-18: Casted panels with different 'hole sizes' and 'hole distances' for the repeat test

Since the best hole angle was identified as 45°, with the different hole distances were selected as 1/2, 1x1, and 2x2 inches for the repeat test. Since each parameter has three variations, the outcome was comparative and justifiable (See Table 4-2).

Table 4-2: Testing plan for the best 'hole distance'

Hole angle	Hole size	Hole distance
45	2mm	½ x ½ inch
45	5mm	1x1 inch
45	8mm	2x2 inch

The results of the repeated test came up with a clearly identifiable pattern, with different hole distributions and hole sizes on the indoor air temperature.

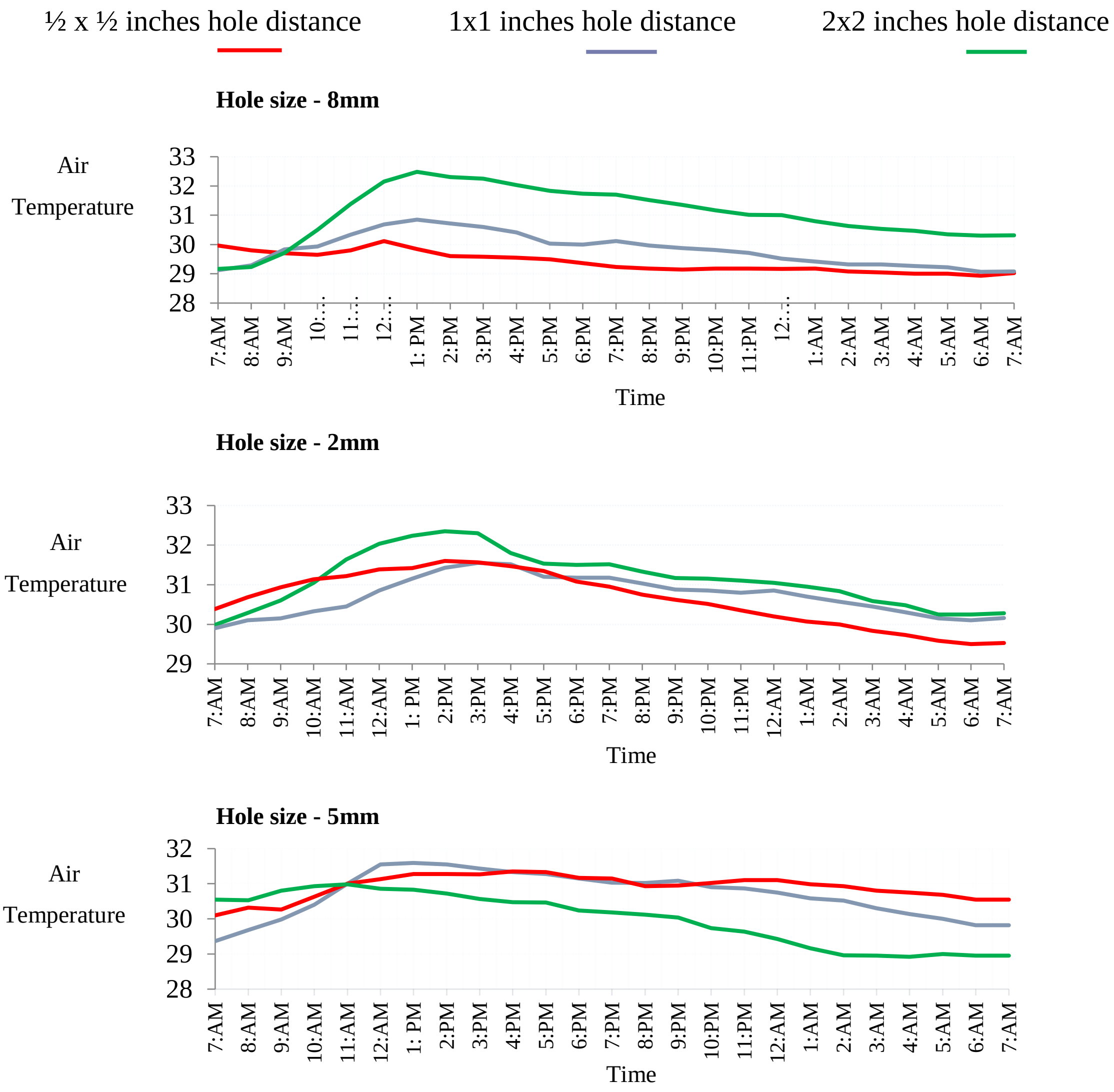


Figure 4-19- Results of the test – Best 'hole distance' in the DCDW panel

From the above results, ½ x ½ inch hole distance was identified as best in terms of indoor air temperature reduction. With this result, the best hole angle was 45 degrees and the best hole distribution of ½ x ½ inch for optimum indoor air temperature reduction was confirmed (See Figure 4-19).

Next, the different hole sizes were selected as 2mm, 5mm, and 8mm to teat repeatedly.

Table 4-3 - Testing for best 'hole size'

Hole angle	Hole size	Hole distance
45	2mm	½ x ½ inch
45	5mm	½ x ½ inch
45	8mm	½ x ½ inch

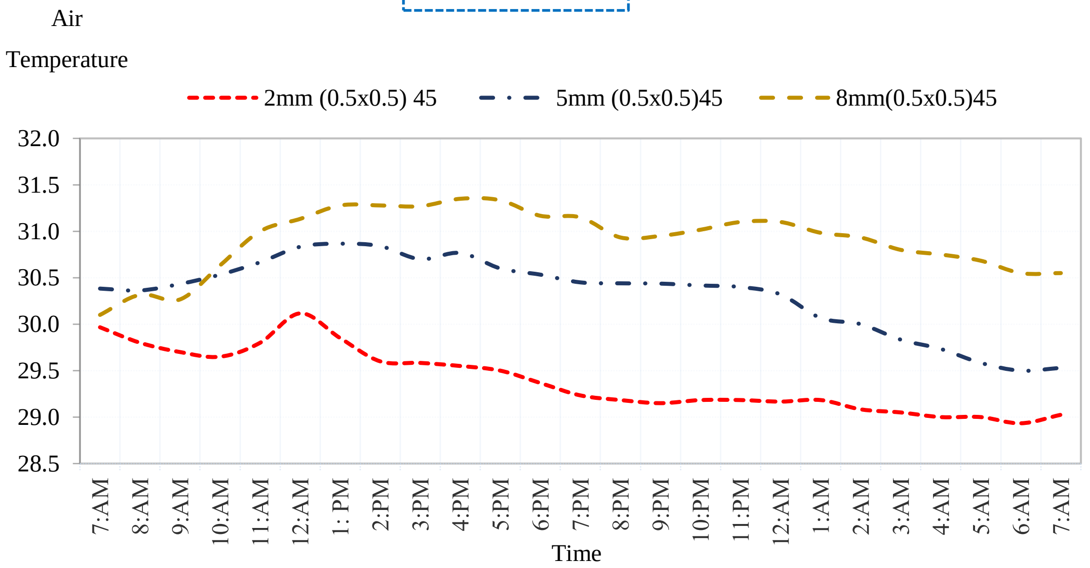


Figure 4-20:Results of the test – Best 'hole size' for the DCDW panel

Through the repeated test, it was confirmed that the pore distribution to be ½ x ½ inch distance and the pore size to be 2mm diameter pores are optimally performing in terms of indoor air temperature reduction.

4.6. Chapter summary

After finalizing the best material and related properties for the DCDW panel which are targeted at improving the microstructural porosity of the DCDW panel, in the next stage the experiments involved improving the DCDW panel (Component 01), with its air permeability characteristics for better structural cooling. It was decided to create holes across the DCDW panel, allowing cross-air movements. Based on precedents on potential practical methods to improve cross-air permeability, pilot castings were tried out, and as a result, the following parameters were identified and tested to get the optimum results in indoor air temperature reduction.

Each parameter involved with at least three sub-parameters, in order to identify the best,

1) Diameter of the holes – 2mm, 5mm, 8mm
2) Hole distribution (distance between each hole) – ½ inch, 1inch, 2inch
3) Buoyancy of the hole (Hole angle) - (30, 45, 90 degrees)
4) Impact of the thickness of the panel (1cm, 2cm, 3cm, 4cm)

To test the identified parameters, specimens were cast with a specially designed mass scale method for DCDW, which is a manually operating clay panel-making machine.

DCDW specimens were cast to test all the parameters, and as per each sub parameter too.

To assess the impact of each parameter, on indoor air temperature reduction, each DCDW panel was tested in a special test chamber.

As the results, out of the three-hole diameters tested, the lesser diameter (2mm) performed best in terms of indoor air temperature reduction.

Out of three-hole distances tested, holes with the shortest distance (½ inch) to each performed best in terms of indoor air temperature reduction.

Out of the three-hole diameters tested, 45 degrees angle creates the highest bounce and the same performed the best in terms of indoor air temperature reduction too.

Out of the four-panel thicknesses tested 4 cm panel contributed the best indoor air temperature reduction, which depicts that when the panel thickness increases, due to higher thermal mass, it increases the heat absorption capacity, thus cooling in spaces.

5. CHAPTER FIVE – ACTUALIZATION OF THE COOLING SYSTEM; THE PRACTICAL APPLICATION OF DYNAMIC CLAY DOUBLE WALL (DCDW) SYSTEM

5.1. General

Objectives 01 is covered in chapters 03 and 04, by identifying and confirming the DCDW panel's (component 01's) improved properties, such as the optimally performing material mix, material mix composition for optimum porosity in the microstructure, best firing temperature and time, best linear shrinkage, thermal conductivity, the effectiveness of the thickness of DCDW panel, best hole configurations for optimum air permeability etc.

Furthermore, its practical application and performance in terms of real indoor air temperature reduction are required to be investigated under objective 03, and this chapter involves fulfilling that.

5.2. The real scale protype for application of DCDW system.

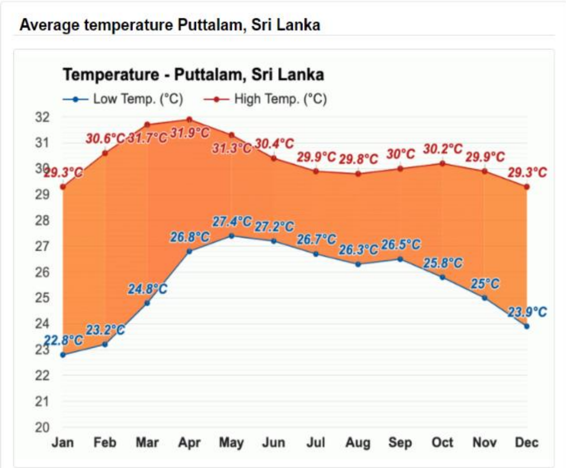
To test the cooling performance of the novel DCDW system, there were provisions to apply it in an existing room in a building. Yet, the research intended to build a new actual scale prototype building, especially for this research, as thereby the suitable climate, location and microclimate, correct orientation of the building, suitable building materials, effective building elements and proportions, opening types and sizes etc. can be used specifically as required for the research to obtain most accurate results.

Moreover, using a separate specialized building for the investigations provide the advantage of preventing the data measurements affect by unnecessary influences such as occupancy heat, operational heat, heat generated from objects and machinery etc.

5.2.1. Location of the prototype building

The prototype building for the application of the DCDW system was selected to be located in an open space of a coconut estate located at 'Keeriyankalli', in Puttalam district, Sri Lanka, where Hot and Dry extreme weather exists.

The key climatic data of 'Puttalam', such as Av. Annual temperature, Wind speed, Rainfall, Humidity, Cloud cover, UV Index and Sunshine days have illustrated below for an overall idea of the general climatic behaviour of the case study area (See Figure 5-1).



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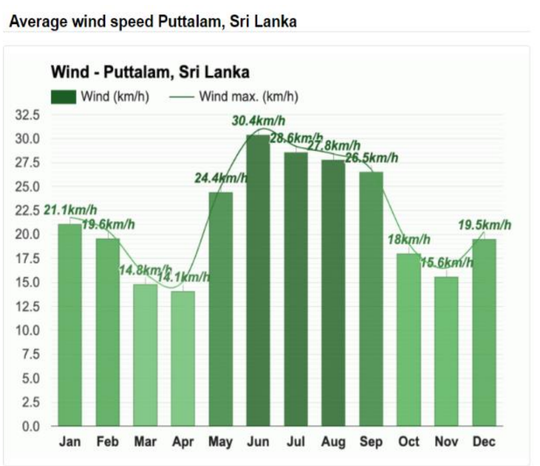

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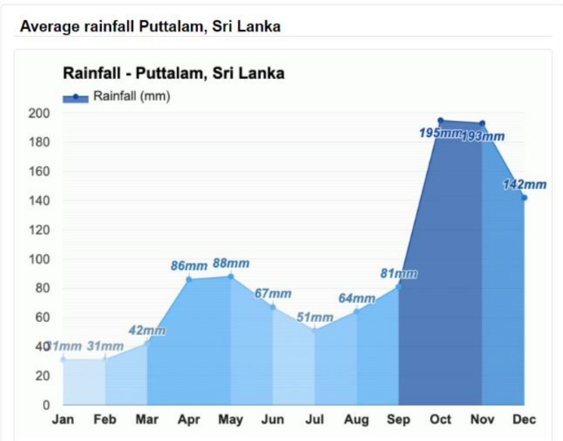

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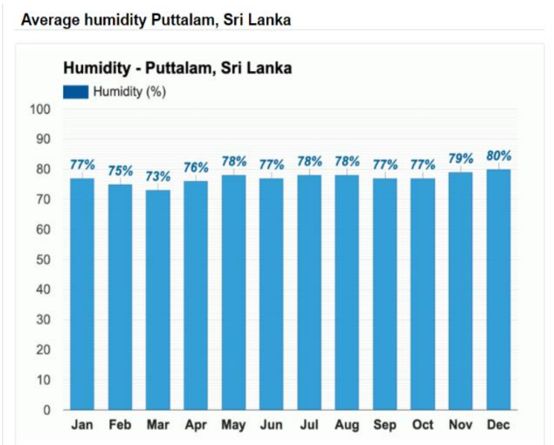

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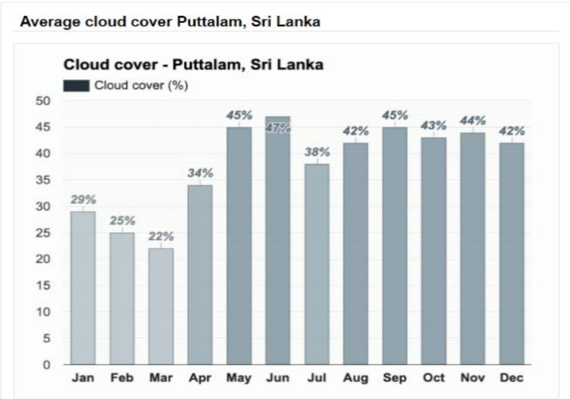

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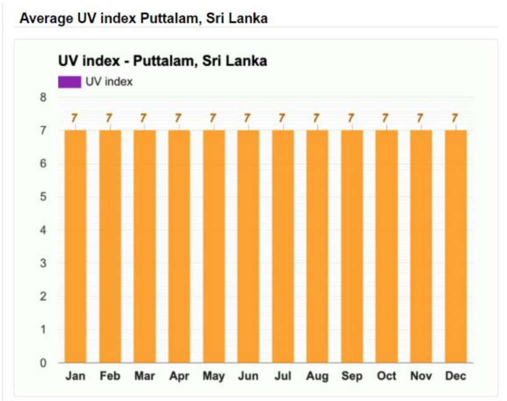

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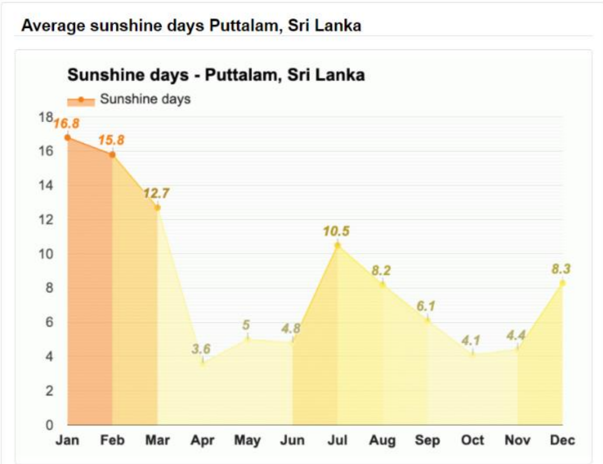


g

Figure 5-1: Key climatic data of 'Puttalam'. **a)** Avg temp. **b)** Avg Wind speed. **c)** Avg rain. **d)** Avg humidity **e)** Avg cloud cover. **f)** UV index. **g)** Avg sunshine days

5.2.1.1 Justification of the selection of case study area.

- High annual temperature and radiation
- High diurnal range in air temperature peaks
- Average law annual precipitation
- Low annual cloud cover (clear sky)

Referring to the weather data, the months of January, February and March 2022 were selected for data collection based on high and low average temperatures (diurnal range), low rainfall, low cloud cover, high sunshine days etc.

5.2.2. The real scale model house for thermal investigation

The following parameters were taken to consideration during designing and locating the prototype building on the site (Figure 5-2).

- 'Perfect orientation' principle was adopted – Narrow facades facing East and West directions for minimum heat gain
- Shadings in the microclimate - No natural or artificial shadings within 50m of the close proximity around the building, thus receiving enough direct solar radiation.
- Openings – Openings (locations, sizes and types) were decided in the design stage itself as the thermal investigation requirements. The floor area to widows area ratio was considered during design.
- Materials - Typical building materials, technologies and finishes were used, were used considering the ease of generalizing the results.

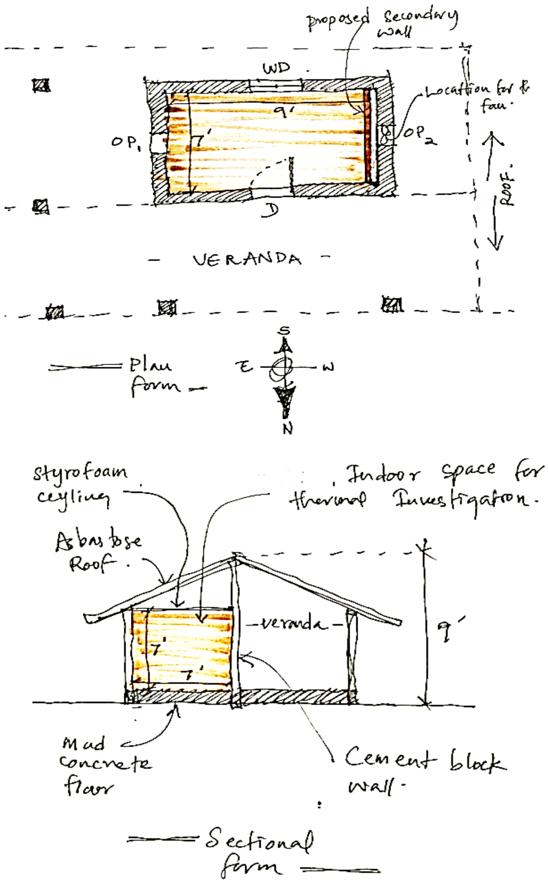


Figure 5-2: Sketch plan form and the sectional form of the prototype house

5.2.2.1 The dimensions of effective area for thermal investigation

Width -**7ft** (2.13m)

Length -**9ft** (2.74m)

Height -**7ft** (2.13m)

5.2.2.2 Materials and finishes used for the prototype building-(See Figure 5-3, Figure 5-4)

- Primary Walls – 4.5” (11.5cm) Cement block wall with 10mm cement plastering, Earth putty finishing either side of the wall.
- Roof – 0.24” Asbestos roofing sheet
- Floor – 3.9” (100mm) Mud Concrete floor
- Ceiling – 1” Polystyrene ceiling on timber frame
- Door – (3’x 6’) Class 01 timber door frame and door sash
- Windows – (1.5’ x 2’) Glazed (clear float glass, 3mm) window sashes with timber frame
- Other Openings – 6” x 6” Fixed glazed (clear float glass, 3mm) openings with no frames

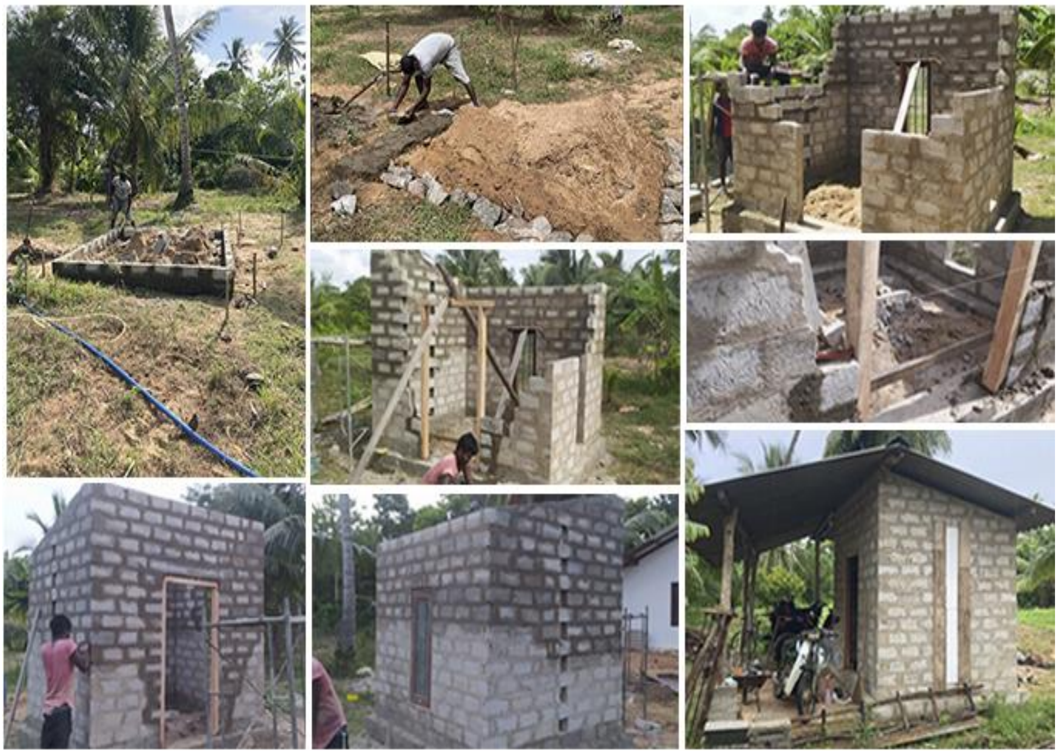


Figure 5-3: During construction of the prototype building

Figure 5-4: Outdoor and Indoor appearance of the real scale building with final finishes.

5.2.3. Casting the finalized DCDW panels for the application.

The ‘dynamic clay secondary wall’ was decided to be applied for the inner façade of the West facing wall. It is proven that in tropical countries, the west façade receives the highest direct solar radiation during the noon and evening times and has the highest potential in transferring heat to the interiors, thus it requires the highest protection to prevent the heat transfer. West facing façade has 49sqft and considering the practical application possibilities, 36 DCDW panels were decided to cast for the thermal investigation.

As confirmed in chapter 03 and 04, all the panels were cast using ground red pottery clay with sawdust into 50:50 volumetric proportion, applied with 45 degrees, 2mm diameter holes, in ½ x ½ inches distance to each hole and fired to 800℃ for 1 hour.

The DCDW panels were cast into the size of 1ft x1ft x 1-inch thickness with the aid of the panel casting machine. The following photograph shows the process of preparing the 36 DCDW panels for the application test (See Figure 5-5).

Figure 5-5: The casting process of DCDW panel; Raw materials, material mixing, compressing, punching, drying, and firing

As discussed in detail in chapter 03, the mixed material and the panels was produced manually (for mass production, an electric mixer can be utilized). The required DCDW panels were produced using the machine letting to contain the finalized characteristics. Following the finalized process; air drying, oven drying, and firing, the DCDW panels were fired, and the final panels are shown in Figure 5-8.

5.3. Identifying a suitable fixing method for DCDW system.

Fixing methods, specifications related to Component 01 and 02 is identified as below.

5.3.1. Component 01 – The fixing method

Once the panels are ready for the application, a non-complicated, cost-effective, maintenance-friendly fixing detail was required to be finalized.

This novel indoor cooling system: Dynamic Clay Double Wall (DCDW) was aimed at a panel fixing method to be minimum labour consuming, less practiced labour required (A non-complicated technology), with a minimum requirement for materials and tools/overheads, yet optimum in effectiveness in terms of indoor cooling.

Several potential fixing details were tried out, considering the above parameters, as shown in Figure 5-6

For the finalized fixing method, horizontal timber poles were fixed to the primary wall at a distance of 11” to each. The 1’x1’, 1” thick DCDW panels were added fit to each of the timber poles using screw nails. The gaps in between the DCDW panels were sealed and finished with earth putty Figure 5-7.

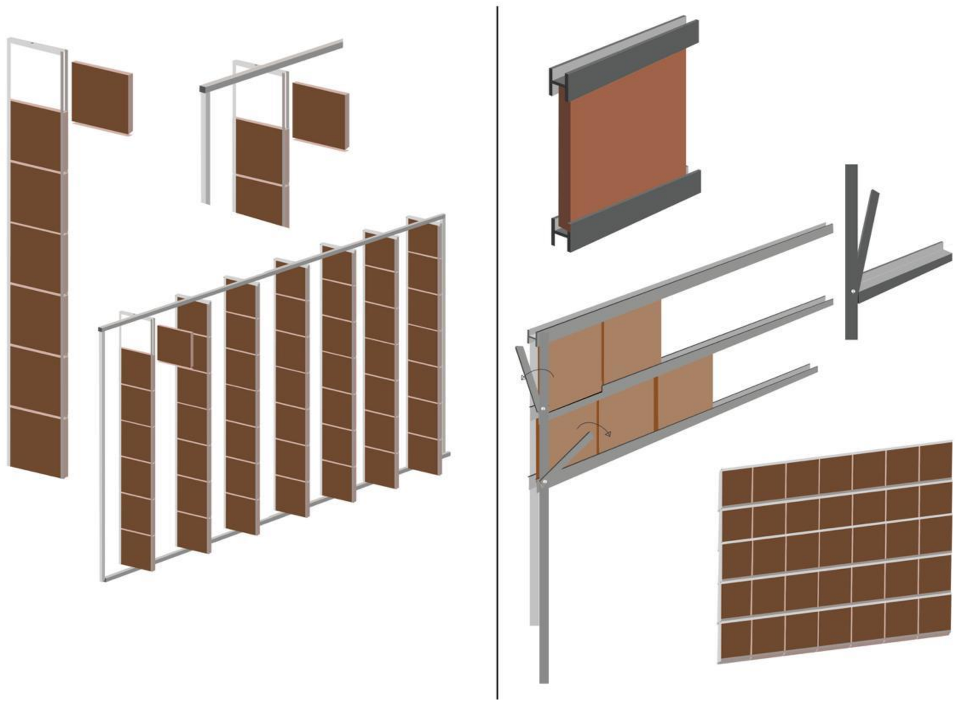


Figure 5-6:Different panel fixing details tried out though the process

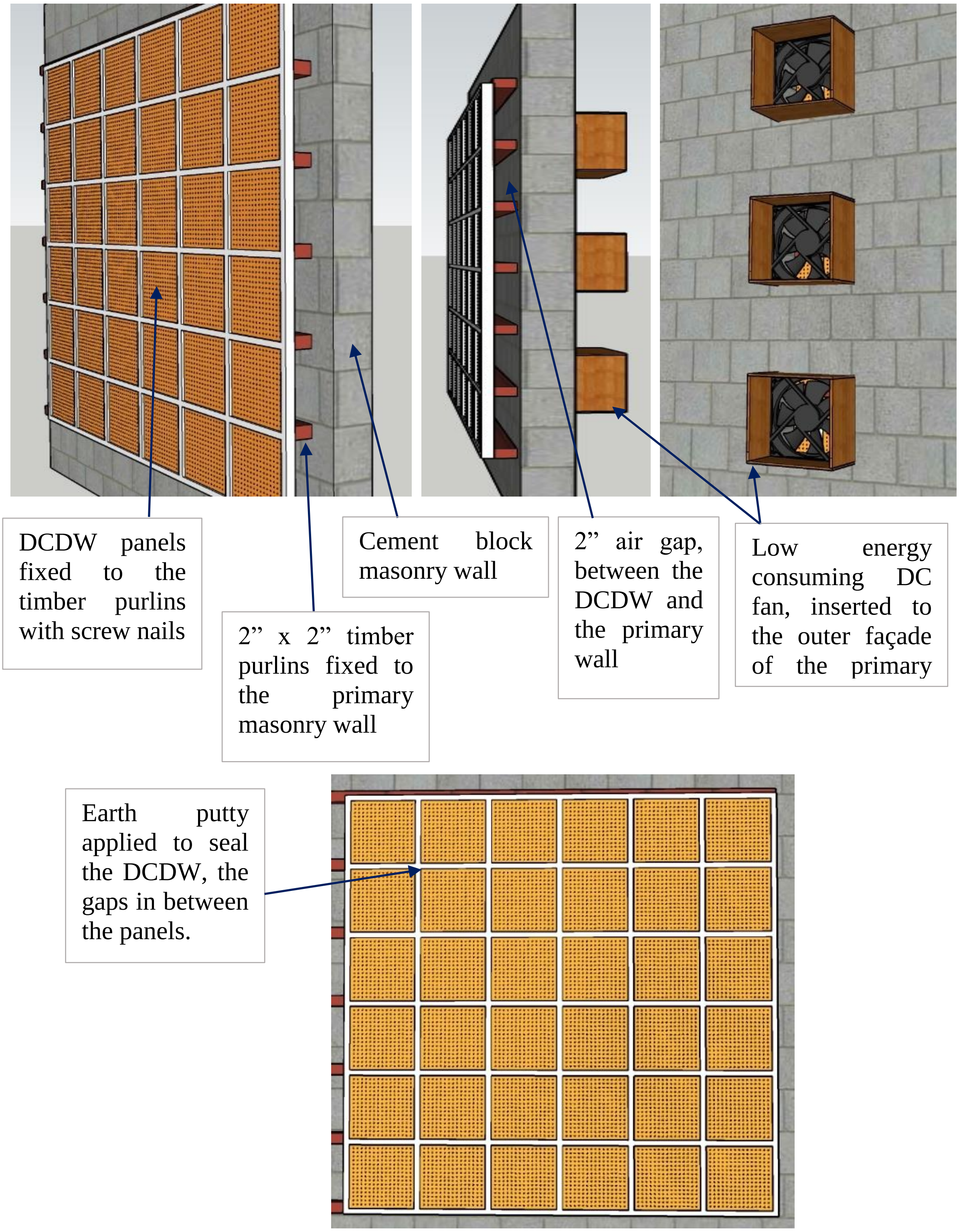


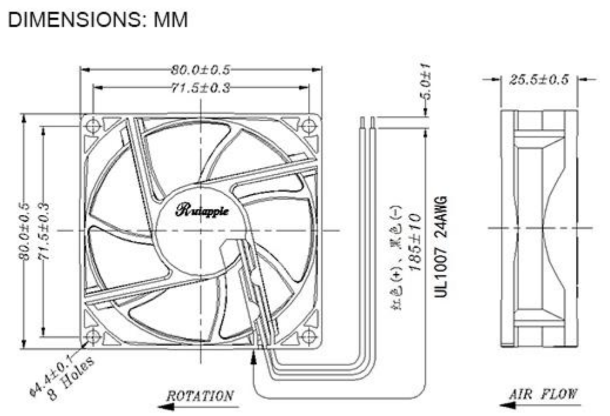
Figure 5-7:Finalized fixing method of the clay double wall and the fan unit to the primary wall; fired clay Panels are screw-nailed to the horizontal timber poles fixed to the primary wall

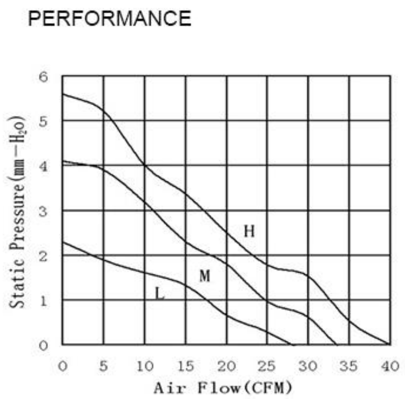
Figure 5-8:Installation of the DCDW panel; fixing the timber frame, drilling the panels, screwing, sealing, and finishing

5.3.2. Component 02 – Specifications

Component 02 is a low energy consuming mechanical ventilation method to couple with DCDW to optimize the indoor cooling effect. The direction of the air pressure (negative air pressure (exhaust), positive air pressure (Inhaust)) to provides should be confirmed by the tests. Specifications of the DC fan used for thermal investigation of the Prototype building (See Figure 5-9).

Model - RA-DC8025 - DC Axial Fans (80x80x25mm)





MODEL NO.	VOLTAGE (V)	CURRENT (A)	POWER (W)	SPEED (RPM)	MAX AIR FLOW (CFM)	MAX Sq. (mm-H2O)
RA-DC8025L	12 24	0.08 0.06	0.96 1.44	2200	20.92	1.97
RA-DC8025M	12 24	0.12 0.08	1.44 1.92	2600	26.89	2.66
RA-DC8025H	12 24	0.18 0.10	2.16 2.40	3200	31.80	3.97

Figure 5-9: Specifications of the DC Fan which was used for Component 02

5.3.3. Component 02 - Fixing detail

RA-DC8025 - DC Axial fan is covered with a 1ft x 1ft timber box, and hooks were attached at the top corners (See Figure 5-10). The fan was covered for weather protection, for the ease of handling and changing the direction of the fan and moreover for the ease of calculating the *ac/h* value of the fan.

Figure 5-10: boxed DC fan is fixed to the primary wall from the outside, positive ventilation will be provided from outdoors to indoors

The DC fan was fixed at a centre strip of the wall and the panels were fixed to a timber frame immediately inner the fan with an air gap of 2 inches.

5.4. Collection of the data to identify the effectiveness of DCDW system

It is required to maintain a controlled indoor thermal environment to conduct the thermal investigation, thus, not only the gaps between the DCDW, but the ceiling, door, window, and other openings were also fully air sealed before the data collection (See Figure 5-11).

Figure 5-11: Preparing the interior for data collection – Air sealing the building interior

In this experiment, mainly, indoor air temperature behaviour throughout the day and night (for 24 hrs.) was measured. In addition, the surface temperature of selected surfaces (DCSW inner and outer surfaces, west side primary wall inner and outer surfaces, ceiling lower surface, floor surface, other walls inner and outer surface), air temperature of the gap between primary and secondary walls were recorded (See Figure 5-12).

Figure 5-12: Preparation of the Prototype building for thermal investigation

5.4.1. Thermal investigation for best practical, application of the DCDW system, for optimum indoor air temperature reduction.

The parameters to be identified by the practical application test.

- To identify the ambient thermal condition of the case study location and the indoor thermal behaviour without the application of the system.

- To identify the patterns in indoor air temperature reduction with and without fans, with different numbers of fans, with different fan directions (positive/negative pressures), with different fan locations (East façade / West facade)
- To identify the patterns in indoor air temperature reduction with the expansion of the square area of the DCDW.

5.4.1.1 Experiment with parameter 01

First, a thermal investigation was conducted to identify the behaviour of ambient air temperature. Probs of the Data logger were located independently at 1m away from the outside wall surface, 1.5m above the floor level in all four directions (North, South, East, West) and covered from the top to avoid the radiant heat effect. Temperature readings were recorded for 72 h and considered the 24 hours with the highest average. To record the air temperature readings, a Graphtec GL840M midi logger was used for each day, with outdoor air temperature readings, indoor air temperature reading was also recorded in the closed/sealed indoor environment to compare the outdoor – indoor thermal behaviour for 24 hours.

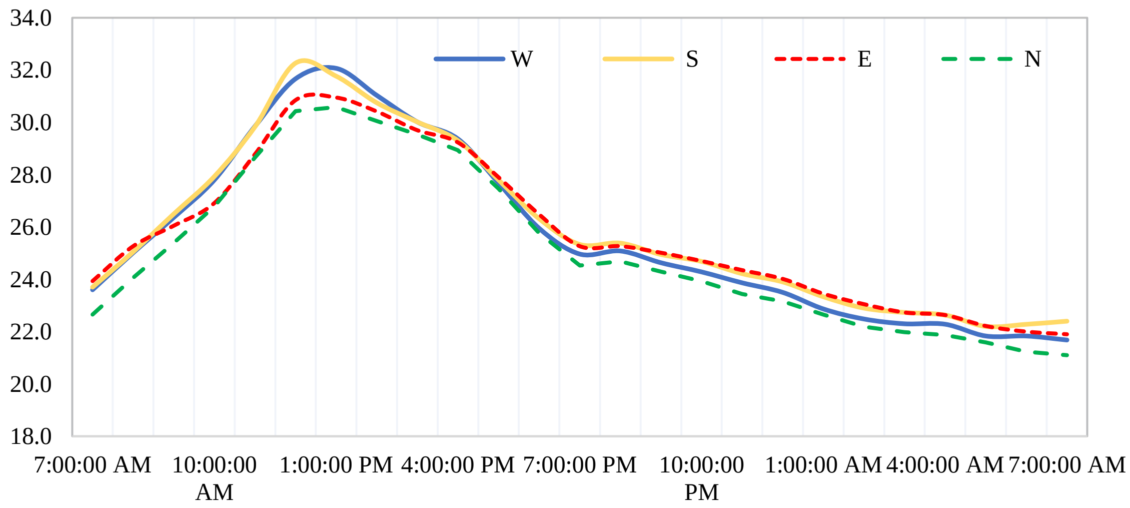


Figure 5-13:Ambient air temperature behavior of near proximity of the prototype test building

The results depicted that, ambient air temperature of each 04 sides behave approximately similar in pattern, but, during day peak temperature time East and North facades show less temperature in air, comparative to West and South facades. These results could be affected by the East and North side verandahs in the building (See Figure 5-13).

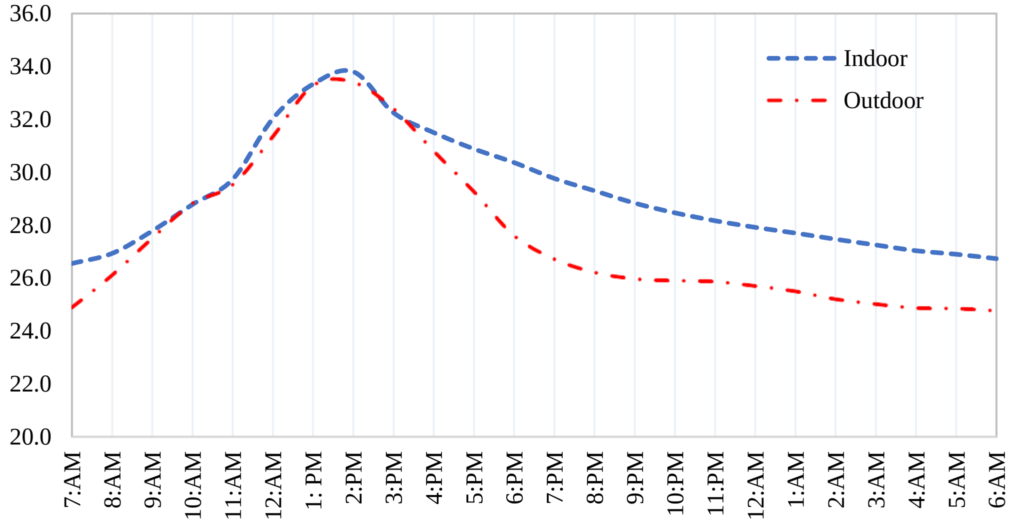


Figure 5-14: Indoor (sealed) air temperature with No system Vs Av. Ambient air temperature

When comparing the Indoor air temperature behaviour Vs. average ambient air temperature for 24 hours, throughout the hours, the indoor air temperature remains high than the Av. ambient. This result could be justified as when the building is fully air sealed, and when there's no way of releasing the heat gained from the building envelope to the outsides, it stagnates the indoors and remain till evenings until the ambient gradually becomes cool and capable in absorbing the emitted heat from the indoors.

5.4.1.2 Experiment with parameter 02 and 03

After assessing the controlled indoor thermal environment before applying the DCDW system, the research then moved to investigate the thermal behaviour, with the application of the dynamic clay double wall (DCDW) system.

The interior of the prototype building was fully air sealed, and the investigation was conducted in the following 10 steps,

1) Indoor and Outdoor air temperature readings for 72 hours were recorded, before applying the DCDW system

2) Similarly, indoor and outdoor air temperature readings were taken for another 72 hours, with 01 DC fan fixed to the centre of West wall and inhausted air with a 31.8 CFM air flow which has a 4.32 ac/h.

$$ACH = \frac{60\ Q}{Vol} \quad \text{Equation 11}$$

ACH = Number of air changes per hour

Q = Volumetric flow rate of air in cubic feet per minute (cfm)

Vol = Space volume L x W x H, in cubic feet

3) Indoor and outdoor air temperature readings were taken for the next 72 hours with the same DC fan exhausting the air with a capacity of 4.32 ac/h.
4) Next, the DC fan was switched off, 4 panels were applied as the DCDW and sealed, and then Indoor and outdoor air temperature readings were taken for another 72 hours.
5) With the same 4 panels, the DC fan was switched on to exhaust the air and temperature readings were taken for another 72 hours.
6) Similarly, with 4 panels, the DC fan was turned inhaust and temperature readings were taken for another 72 hours.
7) Next, with 02 DC fans, the number of panels was increased to 08, all 08 panels were applied in the West wall and two fans were utilized 01 inhaust and 01 exhaust (every 4 panels affected with 01 DC fan). Temperature readings were taken for another 72 hours.
8) Next, all 08 panels were utilized with 02 DC fans which are running exhaust and the readings were taken for 72 hours.
9) Next, on the other way around, all 08 panels were utilized with 02 DC fans running inhaust and the temperature readings were taken for 72 hours.
10) Lastly, 04 panels were utilized in the West façade, parallelly another 04 panels were utilized at the East façade and 01 DC fan for every 04 panels were utilized at the West and East walls, the temperature readings were taken for 72 hours.

Summary of the selected 10 cases for investigation is shown in Table 5-1.

Table 5-1: Summary of the thermal investigation with 10 cases

Case	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
Fans	NO	← **in**	→ **out**	NO	← **in**	→ **out**	⇄ **In/out**	→ **out**	← **in**	⇄ **In/out**
Panels	NO	NO	NO	4	4	4	8	8	8	8
System applied façade	-	W	W	W	W	W	W	W	W `	E4-in W4-out

Figure 5-15: Measuring the indoor temperature reduction; Locating the thermal probes to capture the temperatures for 24 hours, for each identified case

Figure 5-16: Testing different parameters, Eg: a) Fan inhaust from East side. b) no fan, four panels. c) no panels, fan-out. d) 8 panels, two fans etc.

5.5. Air temperature results of the ten cases investigated-

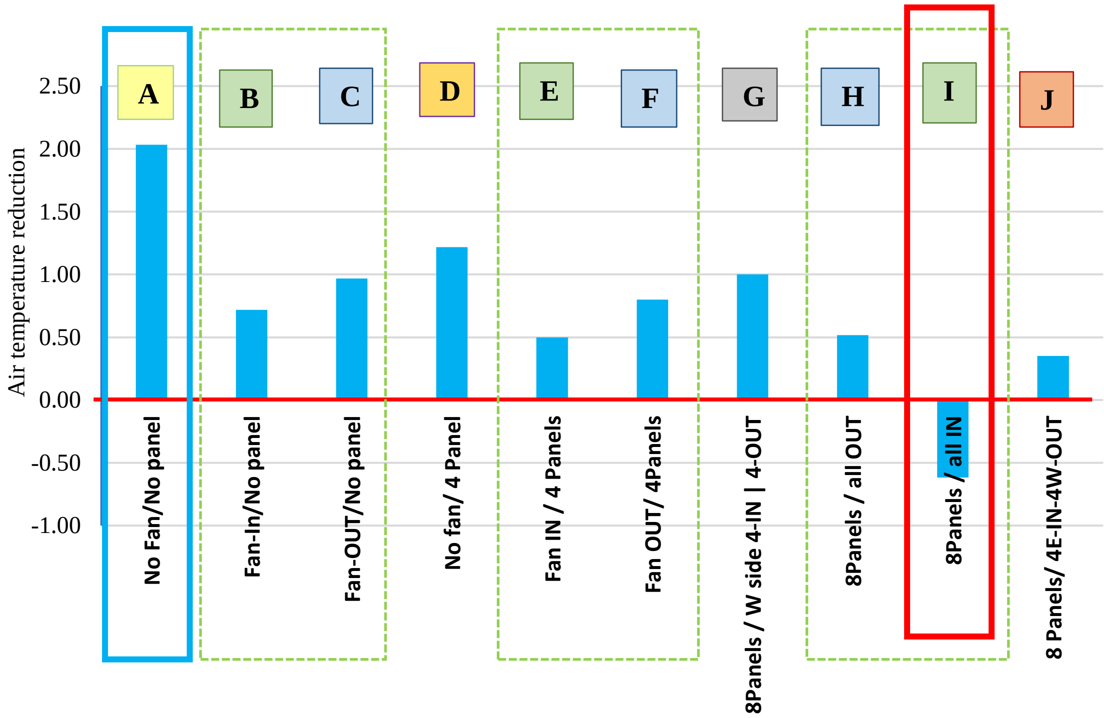


Figure 5-17: Air temperature reduction with selected ten cases

5.5.1. The analysis of the results depicts,

1. After applying the DCDW system, all situations have performed a better indoor air temperature reduction compared to the No panels / No fans (without the proposed system) situation – which depicts, that the proposed DCDW panel system can make a significant positive impact on peak time indoor air temperature reduction. (Refer the bar A,of Figure 5-17.

2. Rather supplying positive or negative ventilation without panels is far better in terms of air temperature reduction, compared to no fan with panels. (Refer the bars B, C, and D in the Figure 5-17.

3. It’s clear that out of negative and positive ventilation for the indoor, positive ventilation performs better compared to negative ventilation in terms of indoor air temperature reduction during the outdoor peak time. (Refer the bars B, E, and I in the Figure 5-17.

4. Out of the positive ventilation supplies (fan-in/no panels, fan-in/4panels, 2fans-in/8panels), fan-in 8 panels have performed best in terms of peak time indoor air temperature reduction. (Refer to the bar I in the Figure 5-17.
5. Further, the “8 panels 2 fans-in same sides” situation remains more effective than the “8 panels - 4 East side 1 fan-in”, and “4-West side 1 fan-out” situation. (Refer to the bar I, J in the Figure 5-17.
6. Moreover, “8 panels 4 East side fan-in, 4 West side fan-out” situation have performed better than “8 panels fan-in and fan-out from the same West side (Refer the bars G, J in the Figure 5-17.

With this analysis, it can be concluded that when providing more “positive” ventilation to the indoors, consecutively by increasing the DCDW panel area, the room indoor air temperature can be reduced more effectively, thus more thermal comfort can be gained during the daytime ambient peak temperature time.

5.6. Thermal investigation to identify the impact of the “DCDW panel’s area” Vs. “Number of fans” ratio, on indoor air temperature

From the previous experiment, it was identified that a significant positive influence can be done on indoor thermal comfort, by increasing the number of panels and fans in the DCDW system. Yet, to identify a pattern between these two parameters, three panels to fan ratios were selected. Therefore, the behaviour of indoor air temperature with 09 panels: fan ratios as **4:1, 8:1, and 12:1** was tested (See Table 5-2).

Table 5-2: 09 sets of panels to fans compositions to test the panel area expansion

4:1		8:1		12:1	
Panels	Fans	Panels	Fans	Panels	Fans
4	1	8	1	12	1
8	2	16	2	24	2
12	3	24	3	36	3

Figure 5-18: Different progressive stages of DCDW panel area expansion

Accordingly, the number of DCDW panels was increased as shown in Figures 5-18. The number of panels was decided under the ratios decided previously. A maximum number of panels was decided to set as 36 and DCDW was fixed to the interior of the West wall with an air gap of 2 inches.

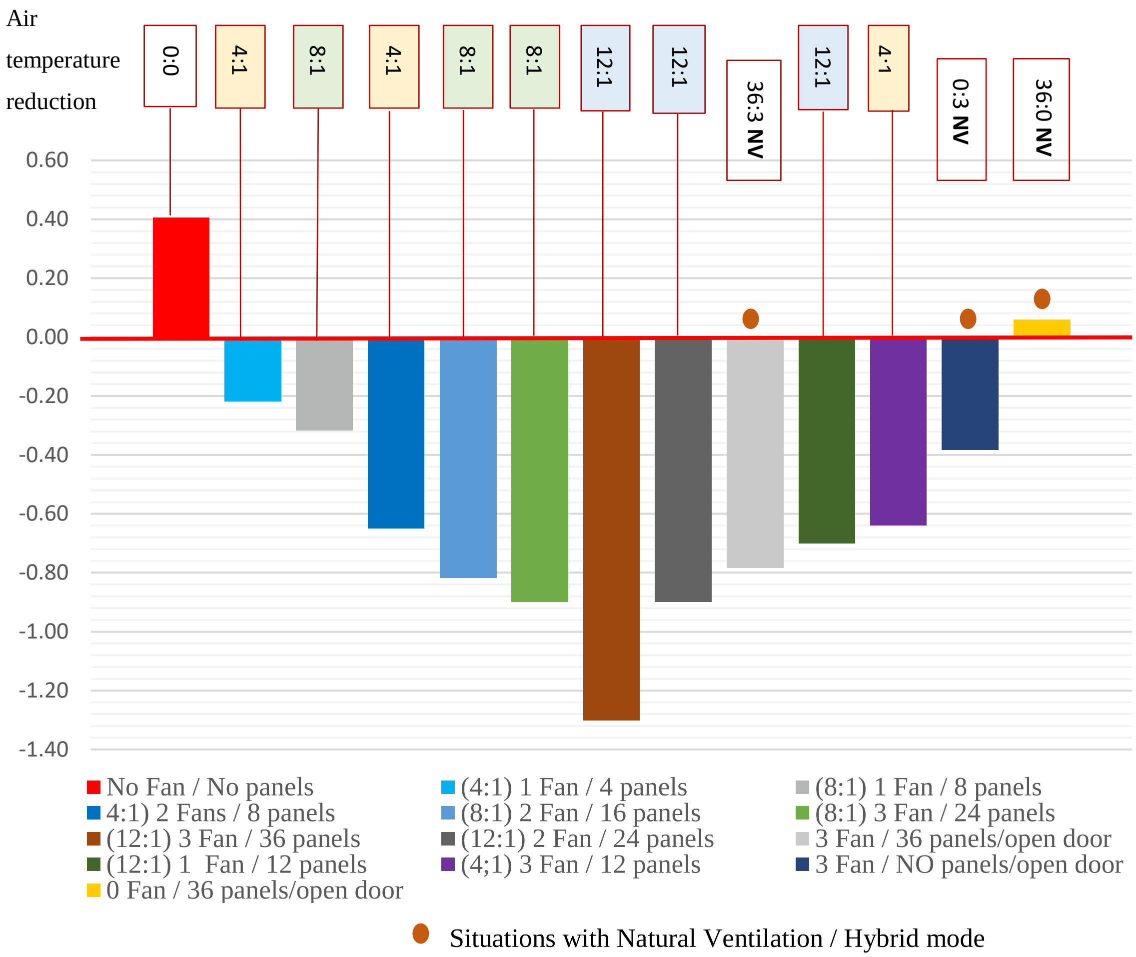


Figure 5-19: Air temperature reduction results of each, panels to fans ratio

5.6.1. Results and analysis

The above Figure 5-19 analyzes results with the indicated 13 situations, 09 with different panels: fans situations and one with No panels: No fans and another 03 situations with passive ventilation mode. According to the results,

- All the situations that the components of the system exist have performed better than the situation with no panels and no fans.
- When the number of panels increases, the cooling effect has been increased accordingly.
- In terms of the number of fans, when the number of fans decreases, the effectiveness of indoor air temperature reduction also reduced gradually.

- 36 panels with 03 fans show the highest indoor air temperature reduction. Which consists of the panels: fans ratio of 12:1.
- When both the number of panels and the number of fans increased together, the indoor cooling effect increased optimally.
- In a comparison of the results gained, a pattern can be identified as the air temperature reduction has reduced from 12:1 to 4:1.

5.7. Thermal investigation to identify the impact of the DCDW cooling system with hybrid ventilation. (Providing provisions for natural ventilation + mechanical ventilation)

Until this point, all the experiments in the prototype building were done in an internally air-sealed environment and, in this experiment, the potential of the DCDW system with hybrid ventilation (Passive + Active) was investigated. Optimum cooling performance was confirmed with the optimum number of panels (36) and the optimum number of fans (03) by the previous test; thus 36 panels Vs 03 fans were only considered in this experiment. It was planned to utilize existing natural ventilation together with panels and fans to identify how the indoor air temperature behaves. First, the standard 'floor area to opening area' ratio was calculated. 1/7th of the floor area according to the building regulation of the Urban Development Authority (UDA).

9 ft x 7 ft = 63 ft^2 (Total floor area of prototype building)

1/7 x 63 = $\underline{\underline{9\ ft^2}}$ (The minimum area of openings to be applied to the prototype building)

According to the calculation, the required area of windows was opened and provided provisions for natural cross air movements between indoors and outdoors while the DCDW cooling system function with panels + fans and the air temperature readings (indoor and ambient) were recorded for 72 hours. The experiment was conducted for three selected situations as follows (see Figure 5-20)

1. 36 panels applied, 03 fans in operation, with Natural Ventilation (NV)
2. 0 panels applied, 03 fans in operation, with Natural Ventilation (NV)
3. 36 panels applied,0 fans in operation, with Natural Ventilation (NV)

5.7.1. Results and discussion

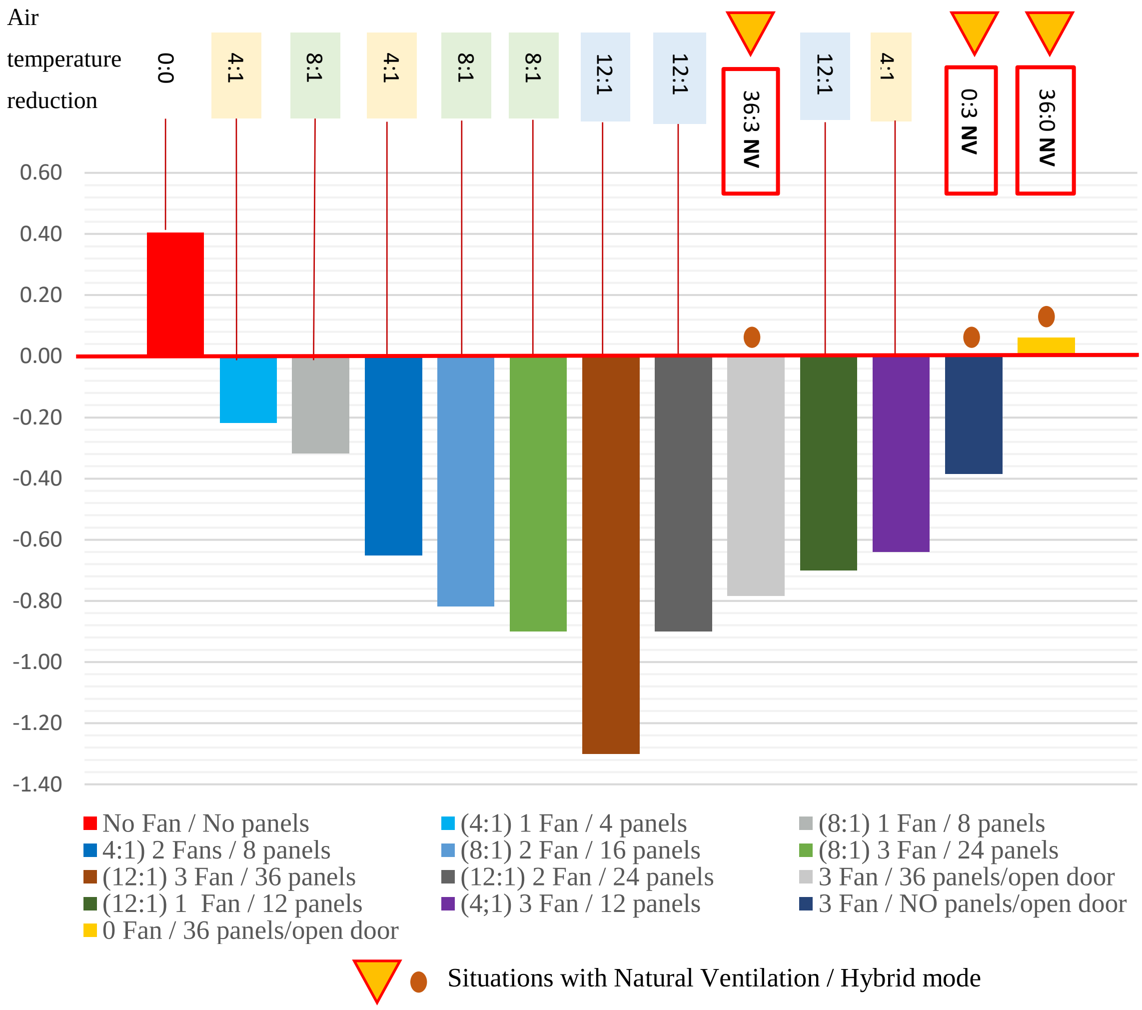


Figure 5-20: Air temperature reduction results of each case together with hybrid ventilation situations.

- According to the results obtained, the situation with 36 panels applied, 03 fans in operation with ventilation supply from the outdoor towards the indoor, and the door opened for air movements between outdoor and indoor have shown the best indoor air temperature reduction compared to the employed three cases.
- And when there are no DCDW panels applied, 03 fans in operation for inward air supply, with opened doors for natural ventilation showed the second highest indoor air temperature reduction.

- Further, when there are 36 DCDW panels applied, no fan is in operation, and the opened door showed the least indoor air temperature reduction compared to the selected three cases.
- The analysis of the results depicts, that if the hybrid mode is to be utilized, the best performance can be obtained when component 01 and component 02 of the DCDW system work together, and if each component is individually taken, utilization of fans for air supply have contributed for indoor air temperature reduction better than the panel's contribution individually.

5.8. Psychometric chart; Identifying the potential for hybrid ventilation

A psychometric chart was used to present the potential of the DCDW system as a hybrid ventilation mode. The comfort zone for Puttalam was developed, the Extended comfort zones with three air velocities were developed and physical indoor air temperature data of the best case were inserted into it. The results showed the potential of incorporating natural ventilation with the DCDW system.

Mean Annual Temperature (To) for Puttalam = **30.66 °C**

Neutrality temperature for Puttalam,

(Tn) = 0.31 * TO +17.6 Equation 12

(Tn) = 0.31 * 30.66 +17.6 = **<u>27.41°C</u>**

$T_{INTERCEPT}$ = T+23(T-14) HRT Equation 13

=25.4+23(25.4-14)0.011 = <u>28</u>

$T_{INTERCEPT}$ = 29.4+23(29.4-14) 0.014 = <u>34.3</u>

For different Wind Velocities,

dT = 6V – V 2 (°C) Equation 14

For 0.3 m/s

dT = 6 *0.3 – 0.3*0.3 * (°C) = **<u>1.71 °C</u>**

For 0.4 m/s

dT = 6 *0.4 – 0.4*0.4 * (°C) = **<u>2.24 °C</u>**

For 0.5 m/s

dT = 6 *0.5 – 0.5*0.5 * (°C) = **<u>2.75 °C</u>**

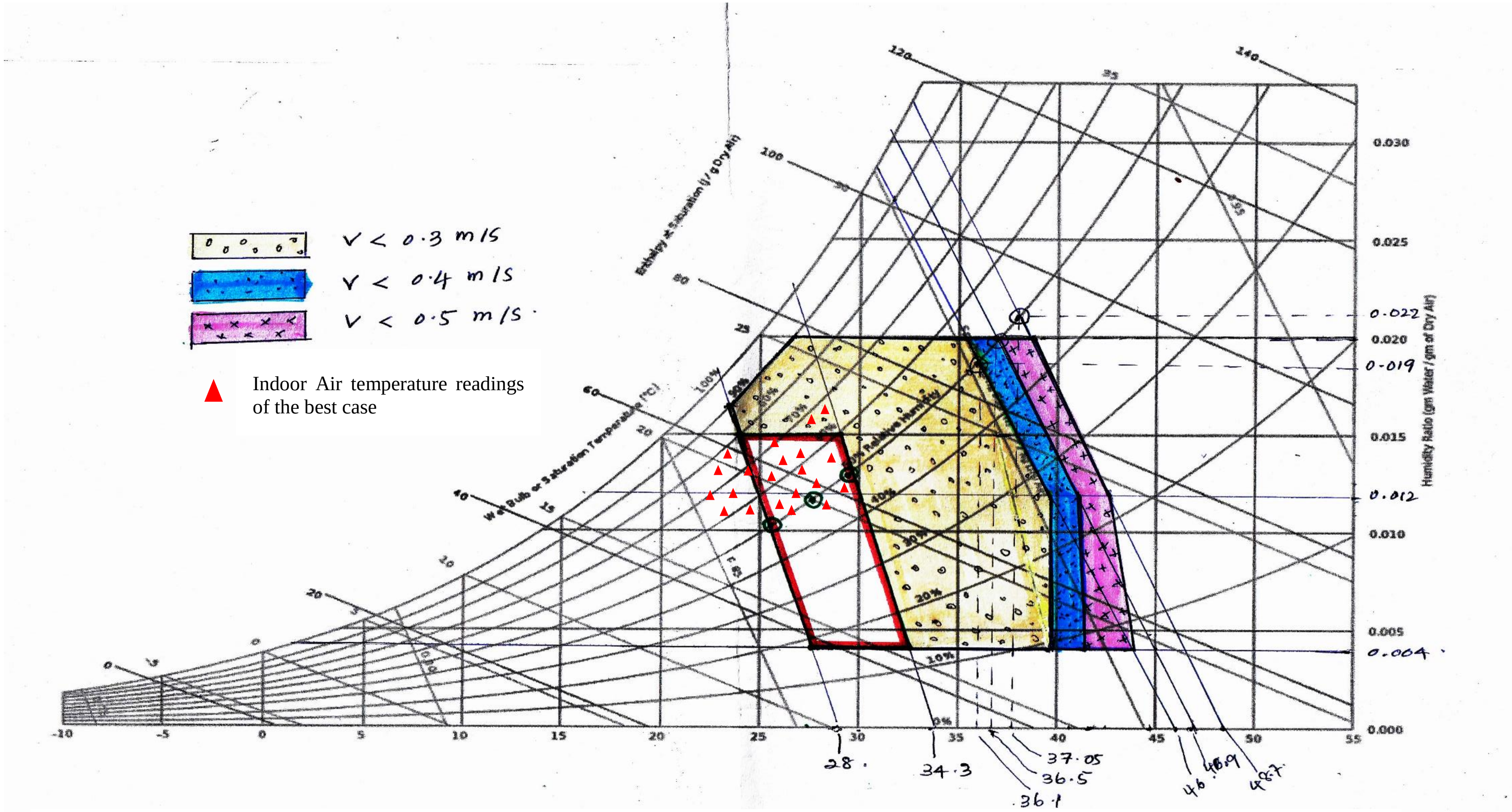


Figure 5-21:Psychometric chart developed for Puttalam with comfort zone and the extended comfort zones due to three different air velocity rates

5.9. Identifying the air filtration capacity of DCDW system

The literature emphasizes when the buildings (especially in the tropics) are naturally ventilated, it tends to carry not only the heat, but also unhealthy fumes, dust, and different particles the outdoors to the indoors [109], [110]. Based on this, and since an inhaust air supply from outdoors to indoors is occurring in the operation of the DCDW system, the research intended to identify the air filtration capacity of this novel invention; the DCDW system. In this experiment, penetration of the following unhealthy gases and particle matter through the DCDW system was tested.

- CO_2
- HCHO (Formaldehyde)
- VOC's
- CO
- H_2S
- PM (Particle Matter)

5.9.1. Equipment used

Table 5-3: Equipment used for air filtration capacity test

Name of the Instrument	Features	Appearance
Carbon Dioxide (CO2) Data Logger with Temperature and Humidity	Measure the level of CO_2, Air Temperature, RH	
BR SMART – 126 Data Logger	Measure the level of Particulate Matter PM_{10}, $PM_{1.0}$ and $PM_{2.5}$, VOC, HCHO	
Portable Multi-Gas Detector BH 4M Model BSA 20150710001 with data Logger	Measure the level of H_2S, O_2, CO, CH_4	

5.9.2. **Methodology of air filtration capacity**

The existence of each type of gas in the outdoor and the indoor is measured separately using the above standard equipment (See Table 5-3). To identify the filtration performance of the DCDW system in the normal situation Vs an extreme situation, the readings were taken with and without an artificially generated fume (See Figure 5-22).

Figure 5-22: Data collection for air filtration capacity test

Further, the DCDW system was operated with and without the operation of fans to identify the effect of air inhaust on gases and particle penetration indoors. Both indoor and outdoor measurements were taken within same 05 minutes for each gas. The results obtained are presented as follows (See Figure 5-23, Figure 5-26, Table 5-4).

5.9.3. Results of the air filtration capacity test

Table 5-4 : Results analysis of the air filtration capacity test

			CO_2 (ppm)	HCHO (mg/m^3)	VOC's (mg/m^3)	PM 10 (ug/m^3)	O_2	CO	H_2S
OUT	With artificial fume	With fan	1489	0.284	484	999	22.7	0	0
		No fan	1430	0.190	388	903	22.7	0	0
	No artificial fume	With fan	433	0.093	301	214	22.7	0	0
		No fan	435	0.088	294	150	22.7	0	0
IN	With artificial fume	With fan	723	0.154	440	74	22.7	0	0
		No fan	482	0.114	376	65	22.7	0	0
	No artificial fume	With fan	420	0.090	298	30	22.7	0	0
		No fan	400	0.078	292	22	22.7	0	0

Highlighted – within the 'Good' range

Highlighted - within the 'Normal' range

Highlighted – In Danger

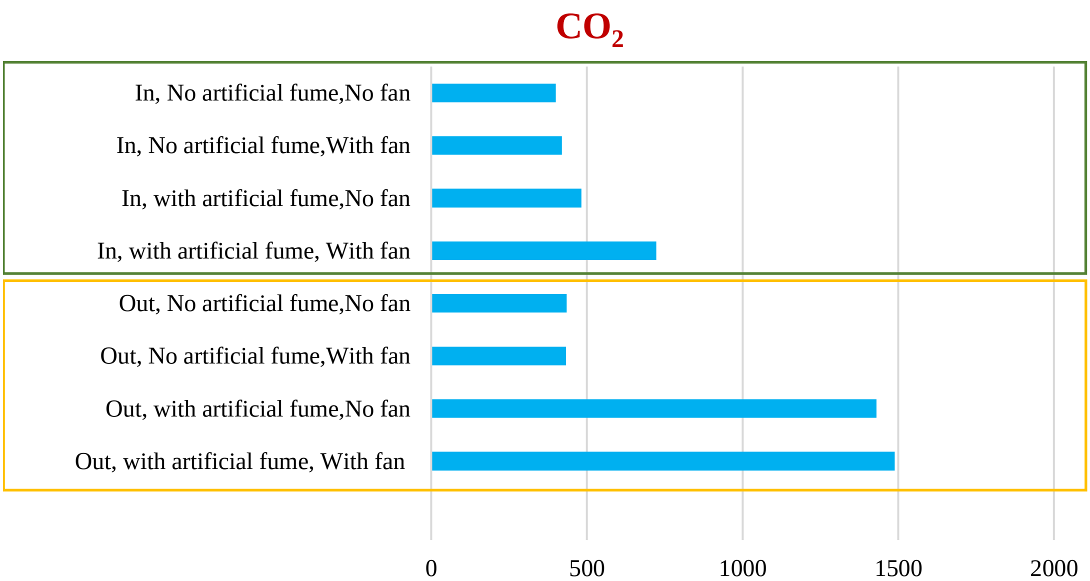


Figure 5-23: Behavior of CO_2- Outdoor-Indoor, with and no artificial fume, with and

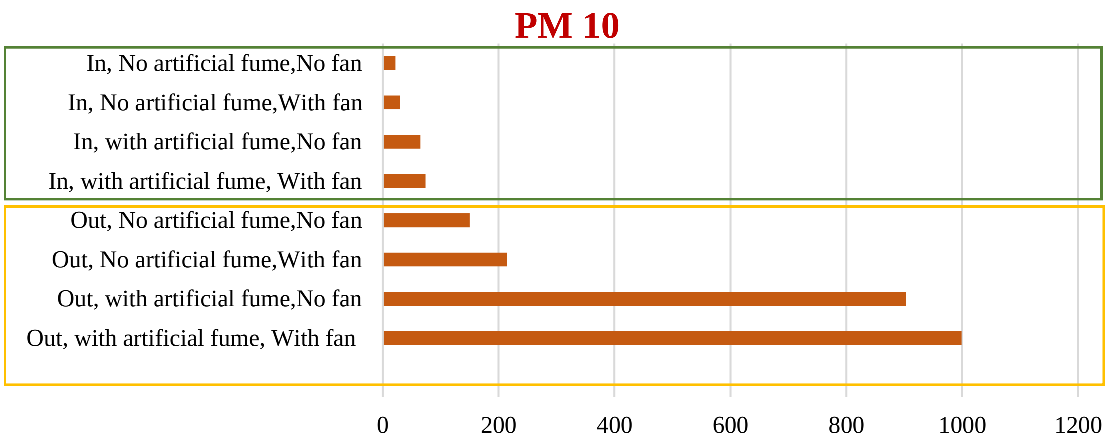


Figure 5-25: Behavior of PM 10- Outdoor-Indoor, with and no artificial fume, with and no fan

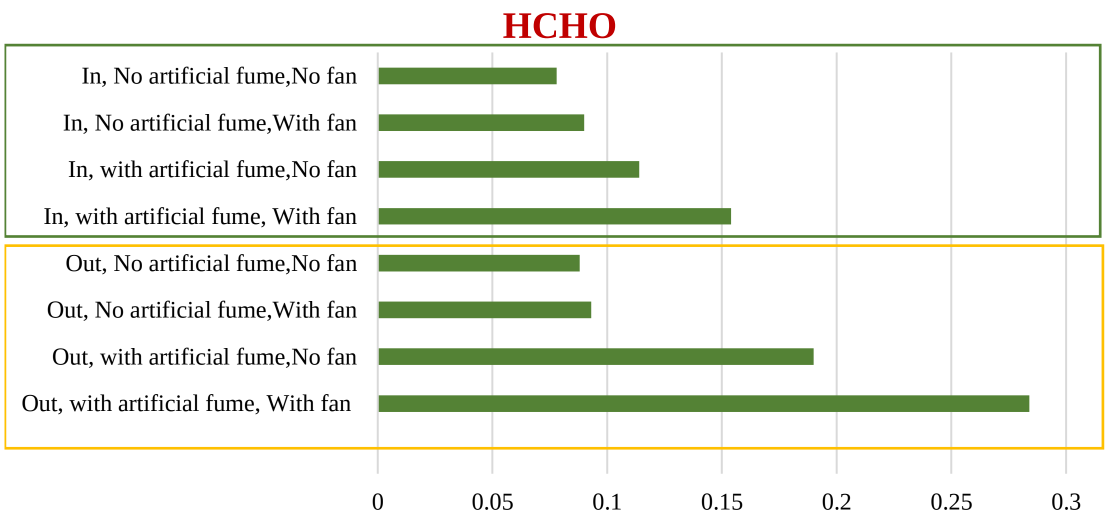


Figure 5-26: Behavior of HCHO- Outdoor-Indoor, with and no artificial fume, with and no fan

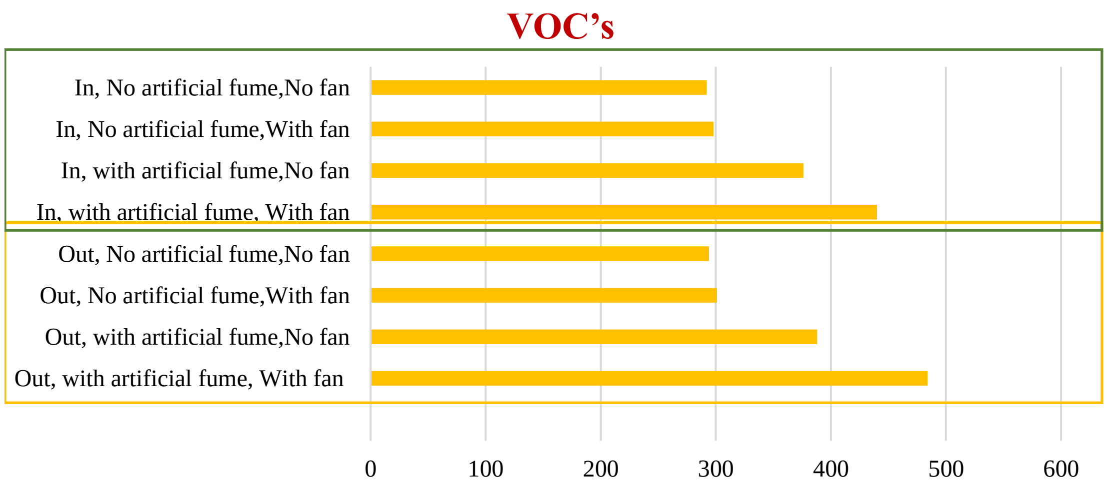


Figure 5-24:Behavior of VOC- Outdoor-Indoor, with and no artificial fume, with and no fan

5.9.4. Analysis

The results show a significant filtration with all the gases when they are moved through the DCDW system. A significant reduction can be seen in the amount of CO_2 and HCHO and VOCs that penetrated the indoors compared to the amounts that existed outdoors.

The particle matter (PM) indoors is found significantly low compared to the outdoors.

Both Outdoor and Indoor, CO_2, HCHO, VOC and PM report a high amount of existence when the fumes are artificially generated which is expected. But advantageously, the difference (filtration) of fume density between indoors and outdoors is clearly visible when the fumes are artificially generated.

Variations of the amount of O_2, CO and H_2S were slightly varied based on the location.

5.10. Chapter summary

This chapter presents the series of experiments conducted to identify the practical application and on-site effectiveness of the DCDW cooling system.

The chapter describes the climatic behaviour of the location, which was selected for the thermal investigations, the processes of building the prototype building, fixing details of the DCDW system, preparing the interior of the prototype building for the thermal investigations and the application process of the DCDW system (component 01 and 02).

The chapter thereafter presents initial data collections conducted to identify the exact microclimatic behaviour of the selected site, indoor thermal behaviour without the DCDW system, and then, the indoor thermal behaviour upon application of the DCDW system and how it varies with some of the identified parameters related to options in the application.

Under the above sections, it was identified that the microclimate around the prototype building behaves almost similarly, but in daytime peaks, the North and East directions show a lesser outdoor temperature compared to West and South directions.

When the building is fully air sealed, and with no DCDW system installed, the indoor peak time temperature exceeds the outdoor peak, due to heat stagnation.

The indoor thermal situation was further tested by inhausting and exhausting the fans without applying DCDW panels, fans in both directions with the DCDW (in two stages as with 4 panels and 8 panels) and applying the panels and fans on opposite walls (E-inhaust and W-exhaust) of the prototype building and creating a cross air movement.

The results depicted when the fans are inhausted, with the increased number of DCDW panels giving a better indoor air temperature reduction.

Next, the impact of an increase in the panel area Vs the number of fans was identified, for this, three panels: fans ratios were (4:1, 8:1, 12:1) used. The number of panels and number of fans was increased according to the above ratios, the results showed the indoor air temperature reduction is better consecutively when the ratios are 12;1, 8:1, and then 4:1.

Next, the potential of indoor air temperature reduction with hybrid ventilation was investigated by utilizing the DCDW system together with natural ventilation.

03 cases, as 36 panels, 3 fans / 0 panels, 3 fans /and 36 panels with 0 fans were integrated with natural ventilation supply from the surrounding. 36 panels and 3 fans with Natural Ventilation showed the best indoor air temperature reduction.

Moreover, physical indoor air temperature data of the best case were inserted into a psychometric chart developed with a comfort zone for Puttalam, comprising extended comfort zones with three increasing air velocities, 0.3 m/s, 0.4 m/s, and 0.5 m/s.

Lastly, the chapter presents the experiment conducted to identify the air filtration capacity of the DCDW system. Four types of gases (CO_2, HCHO, VOC’s, O_2, H_2S) and particular matter (PM) were considered during the test. The results showed that DCDW system contributes to a significant air filtration when compared to the amounts that exist the indoors with outdoors at a similar time.

6. CHAPTER SIX– POTENTIAL IMPROVEMENTS TO THE DYNAMIC CLAY DOUBLE WALL SYSTEM; A THERMAL SIMULATION

6.1. General

This chapter covers objective 04 of the research. The parameters related to the Application of Component 01 and Component 02 of the DCDW system; the fixing method of the DCDW system, their best characteristics for optimum indoor air temperature reduction (direction of the fan, ratio of panels to fans, potential for hybrid ventilation with the DCDW system) was identified in the previous chapter.

This chapter presents how a building simulation was carried out using Design Builder software to identify further potentials in improving the indoor cooling effect by integrating the DCDW system with identified parameters, in order to confirm the obtained results.

6.2. Modeling the real scale building with Design-Builder (DB) simulation tool.

It's known that the use of building simulations lays opportunities to explore the effects of various parameters with the help of a virtual interface. Therefore, to identify the potential improvements of the DCDW system, to improve its effectiveness and efficiency, the Design-Builder version 6.1.0.006 computer simulation tool is used in this research.

'Design Builder' simulation software is a vastly used and trusted building modelling and simulation tool with capacities in building modelling, evaluation, optimization, energy analysis and analysis of environmental impacts. It is useful in the efficient analysis of the building envelope thermal performances under dynamic weather conditions and allows us to predict its effects on indoor thermal comfort and energy balance. It allows an Effective, cost-saving and ideal solution for testing the vast range of data within a reasonable time period. Therefore, the real-scale prototype building which was utilized for onsite data collection was modelled (See Figure 6-1, Figure 6-2) in detail in Design Builder software with all its important elements. The actual building characteristics were modelled, and onsite temperature measurements were inserted into the model to achieve an agreement with the actual building performance in all aspects. The adjacent zones of the building model were assumed to be naturally ventilated. The hourly weather data file of the Puttalam district was inputted and calibrated to the actual weather data. Initially, the model of the building was validated without the DCDW cooling system remaining provisions in making comparisons (See Figure 6-3).

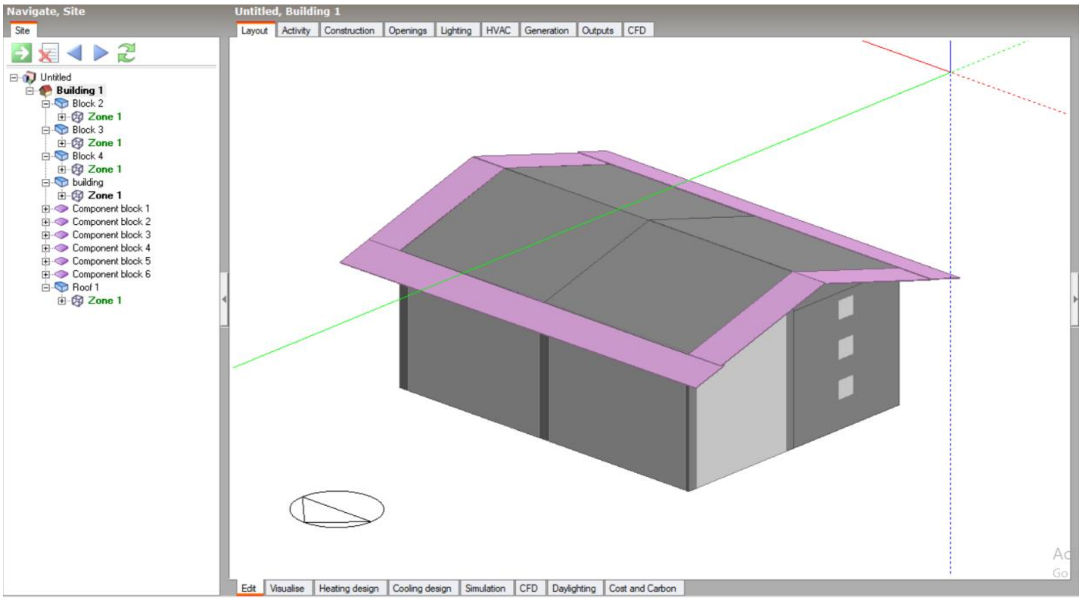


Figure 6-1: Modeled prototype building in Design Builder software

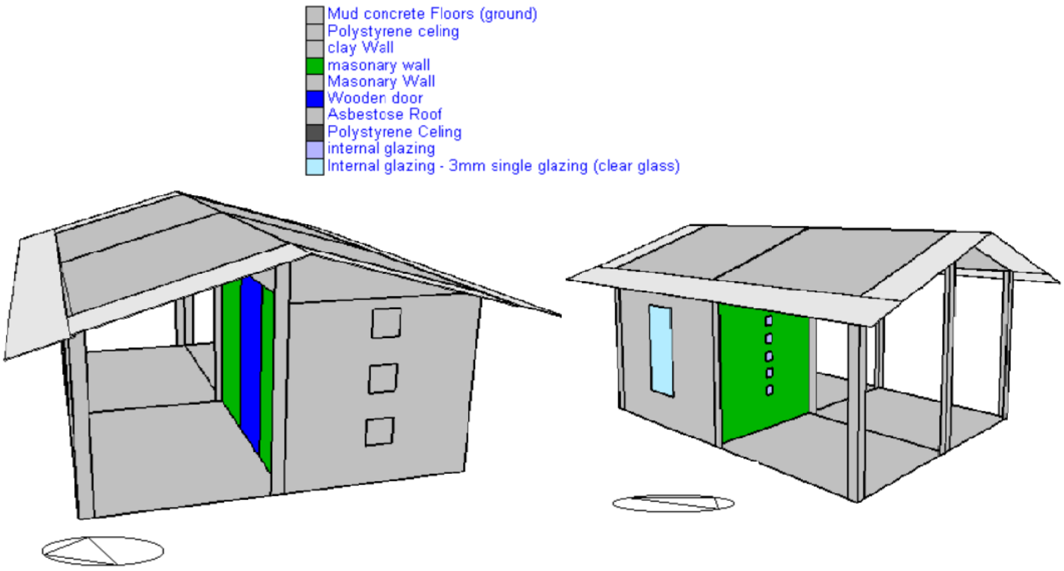


Figure 6-2: The same model of prototype building, Visualized with material usage

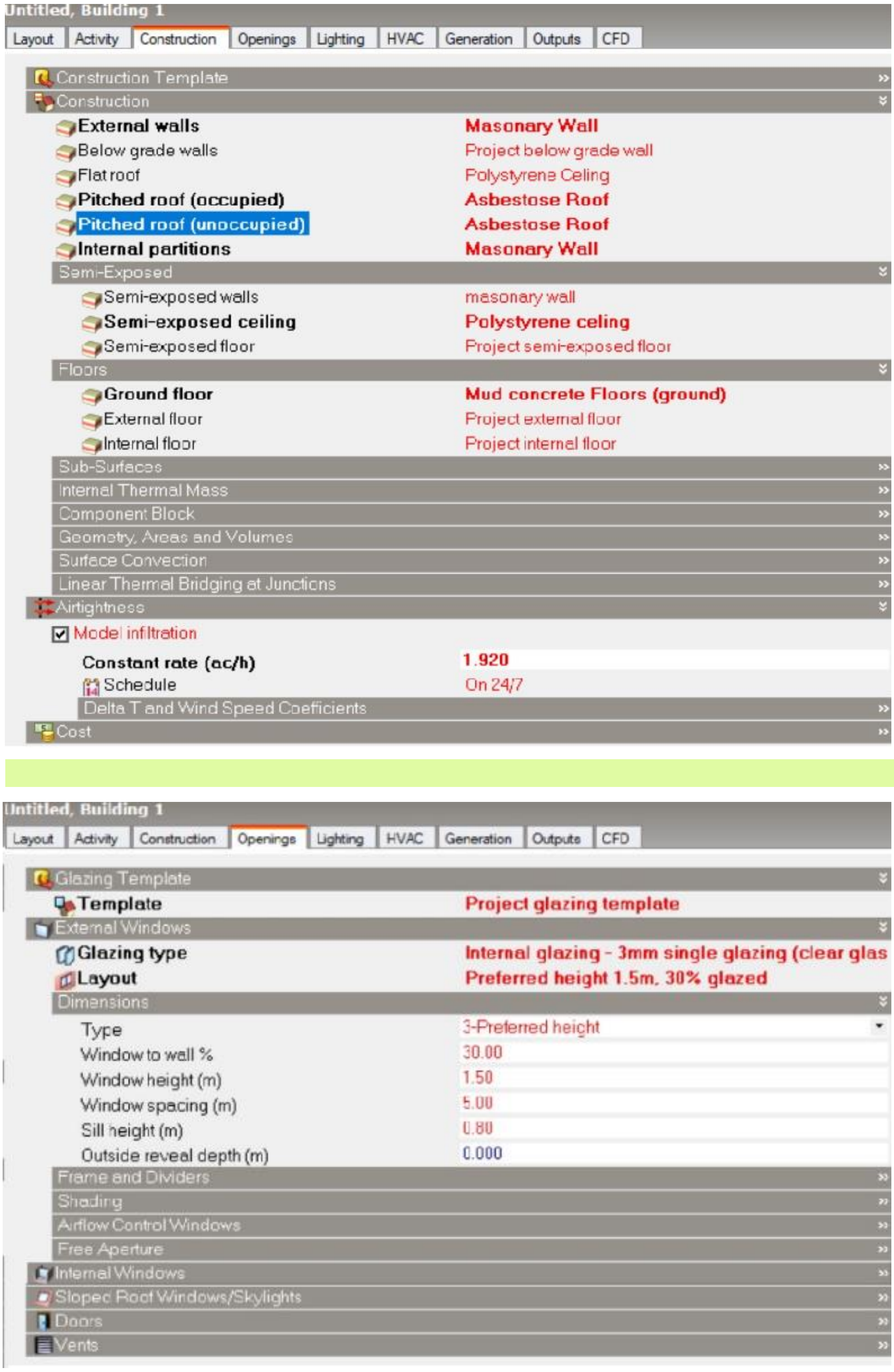


Figure 6-3: Construction details and other basic data inputted for the simulation model.

6.3. Calibration of the Design Builder model

Then, the air temperature data collected from the Graphtec GL840M midi Logger of the building without installing the panels and fan were inputted and calibrated with the actual air temperature data. The simulation results are almost in accord with the measurements, validating that both model behaviour and indoor conditions of the real building correlate with each other (See Figure 6-4).

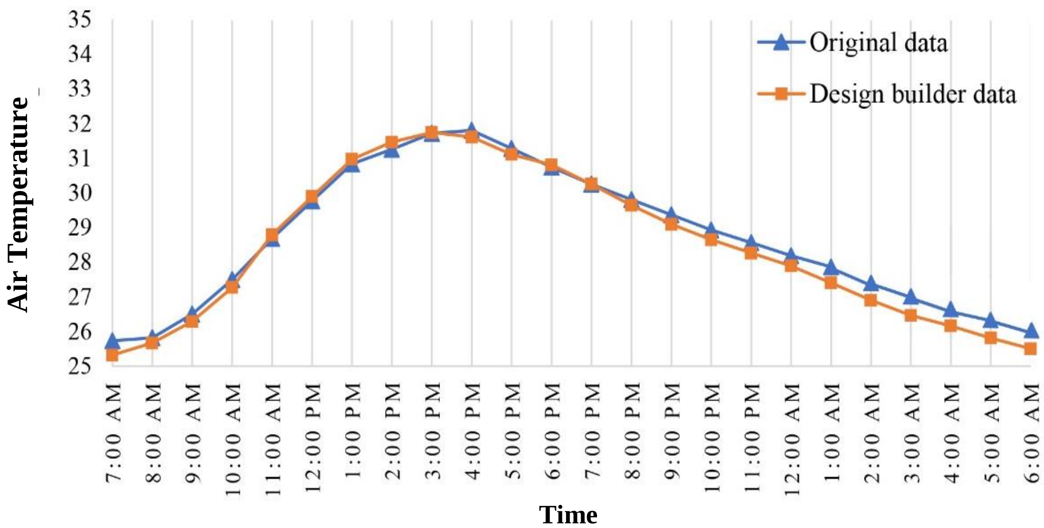


Figure 6-4: Calibration of the DB model for 'with no DCDW cooling system' situation

To the same extent, the model was further developed by adding the clay secondary wall together with the wind supply with fans. When the clay wall is inserted, the main zone was divided into two zones which are indoor (zone 1) and cavity (zone 2), (See Figure 6-5).

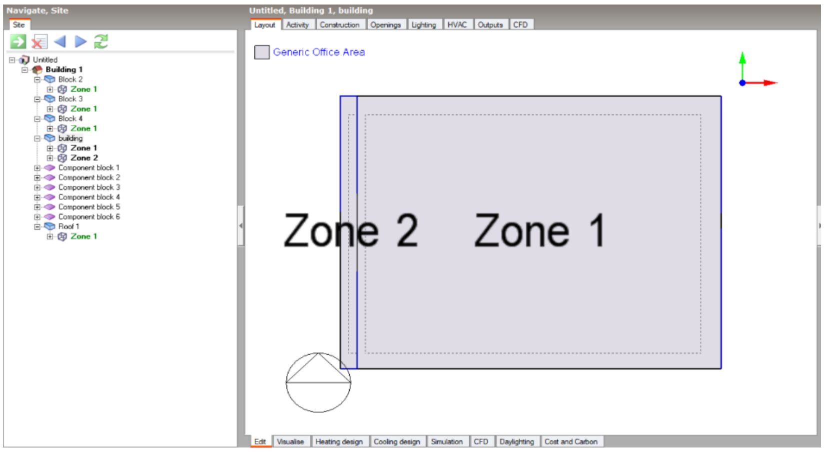


Figure 6-5: Developing the DCDW in Design Builder model

The model was developed by adding the clay secondary wall, a cavity in between (As in the separate zones) with ventilation supply from the fans, similar to Figure 6-6. Construction data were modified and edited after the application of secondary wall panels for 8- panels, and 2- fans scenario in the design builder model.

Figure 6-6: Application of the DCDW with 8- panels, 2- fans

The physical data and the modelled data after applying the system for 8- panels, and 2- fans were calibrated to match each other (See Figure 6-7).

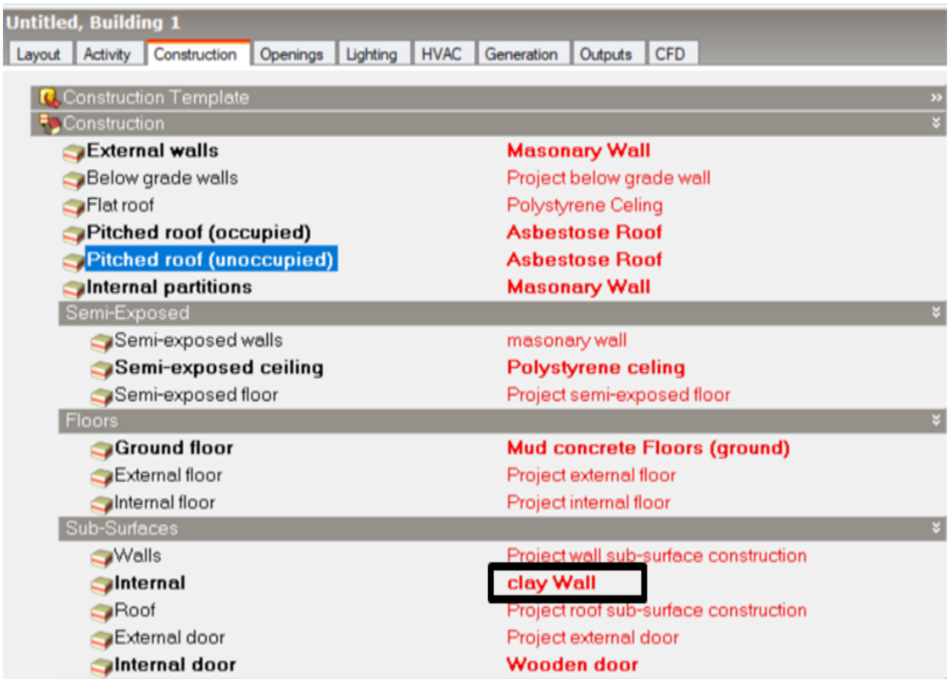


Figure 6-7: Construction data input after application of secondary wall panels in design builder

6.4. Identifying the parameters to improve the DCDW cooling system

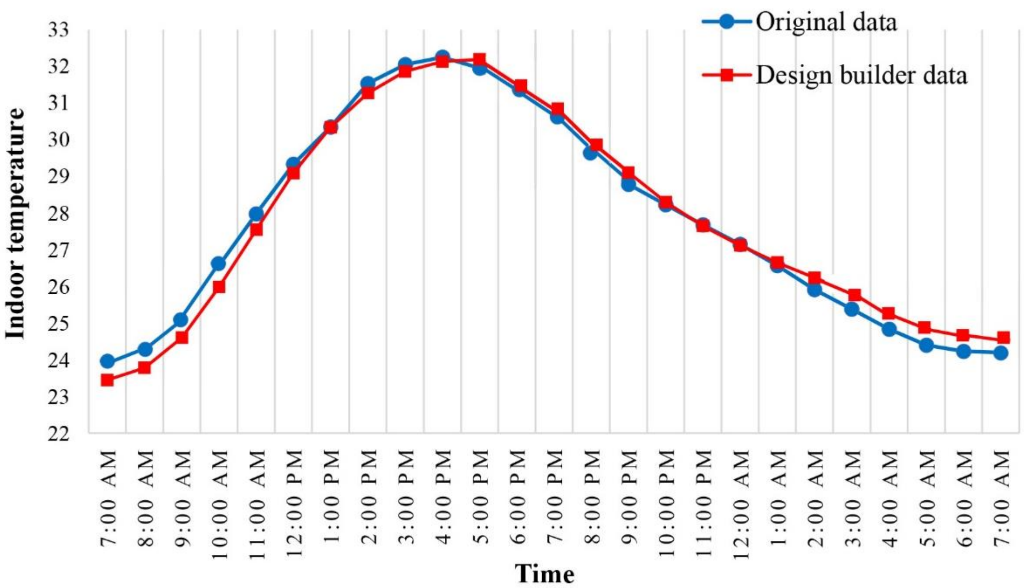


Figure 6-8: Calibration of the DB model for 'with the DCDW cooling system' situation

Due to the calibrations, the model was assured to perform similar to the real scale prototype building, thus it is considered ready for simulations (See Figure 6-8). With the calibrated building model, the following parameters were tested through simulations and confirmed.

1) The impact of the DCDW system on indoor air temperature, with a different number of panels together with a constant number of fans, comparative to no DCDW system, or only with one component of it.
2) Cooling load required for 1m2 with a constant number of fans and different panel areas.
3) Cooling capacity required for 1m2 with a different number of fans.
4) Best orientation of the prototype building for optimum indoor air temperature reduction with the DCDW system.

6.5. Experiment with parameter 1 – DCDW system with different number of panels and constant number of fans, comparative to no or only with one DCDW component.

Under the point 1, the scenarios of concern were as follows.

- 12 panels with 3 fans (4:1)
- 24 panels with 3 fans (8:1)
- 36 panels with 3 fans (12:1)
- Without panels without the fans
- With panels without the fans
- Without panels with the fans

The results obtained were presented in the graph below (See Figure 6-9).

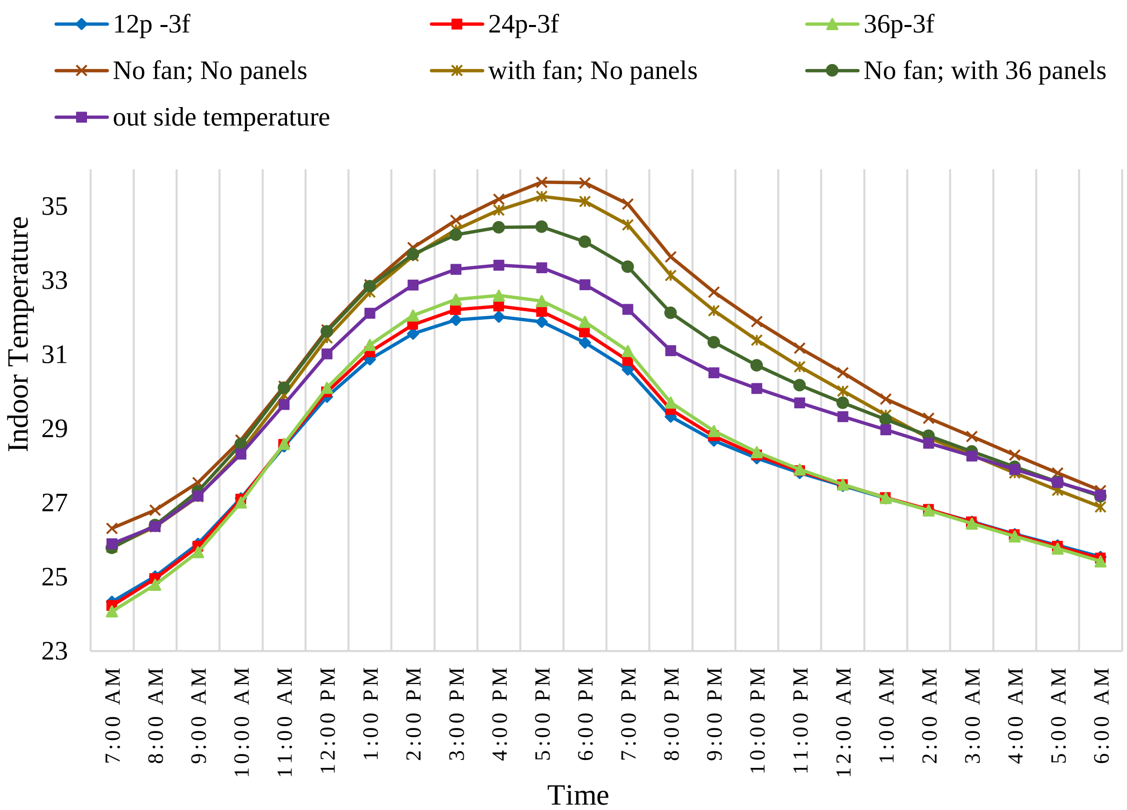


Figure 6-9: Indoor Air Temperature reduction 'with', 'partially' and 'without' DCDW system

The DCDW system has a great potential of reducing the indoor air temperature of buildings. The effect of thermal mass, insulation and structural cooling with positive ventilation created by the fans have supported to reduce of the building's indoor heat from its normal level.

The indoor air temperature is greater than the outdoor temperature condition with no panel; no fan situation when the indoor is fully air sealed, and when at least components of the DCDW system (panels or fans) are available, it has created a notable reduction in the indoor temperature comparatively, which is still remain higher than the outdoor temperature.

However, when both of the components (panels and fans) are involved together as a complete cooling system, it creates a significant reduction in the indoor temperature, which is less than the outdoor air temperatures.

Figure 6-9 shows that all three curves run below the ambient curve indicating the situations where all two components of the DCDW cooling system work together. Out of those three curves too, lesser numbers of panels with a high lesser number of fans have performed best due to the higher wind velocity effect.

As per the requirement of the DCDW system to be tangled with the actual situation, a Cooling Load was associated with the system inside the 'cavity zone' of the simulation model while providing a steady-state condition for the cooling requirement in different ratios.

The indoor 'heat absorption capacity by the DCDW system can be interpreted as the rite opposite of the 'cooling load required by the DCDW system. Higher the indoor heat absorbed; the lesser cooling load is required.

6.5.1. Experiment with parameter 02 - Cooling load required for 1m^2 with constant number of fans and different panel areas.

Under the point 2, the cooling load requirement for 1m^2 was identified as follows (Table 6-1, Figure 6-10).

Table 6-1 – Cooling load requirement for 1m^2 with different number of panels and constant number of fans

	Cooling load for different scenarios		
	12-panels; 3-fans	24-panels; 3-fans	36-panels; 3-fans
Panel Area (m^2)	1.12	2.23	3.34
Cooling load (kW)	0.85	0.86	0.86
Cooling load for kW/ 1m^2	0.76	0.39	0.26

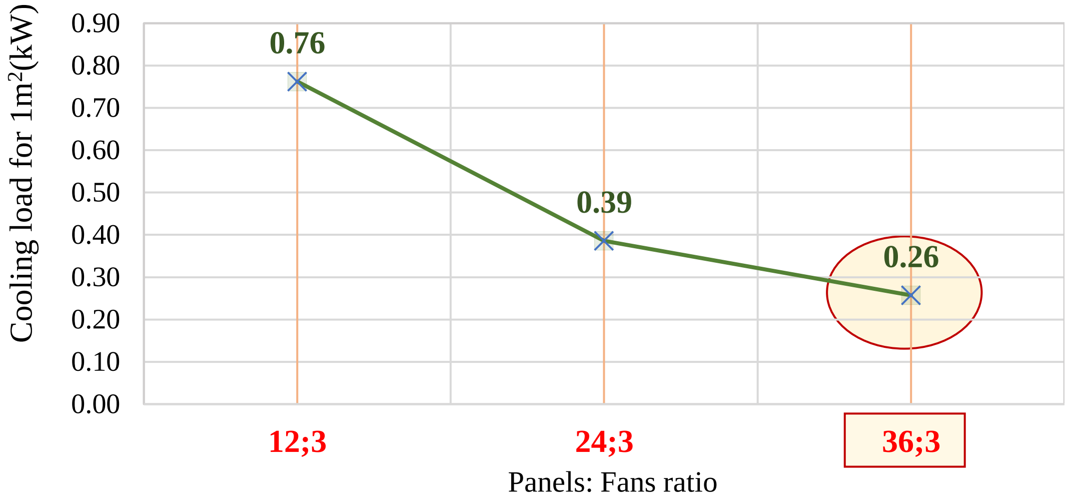


Figure 6-10: The cooling load requirement for 1 sqm

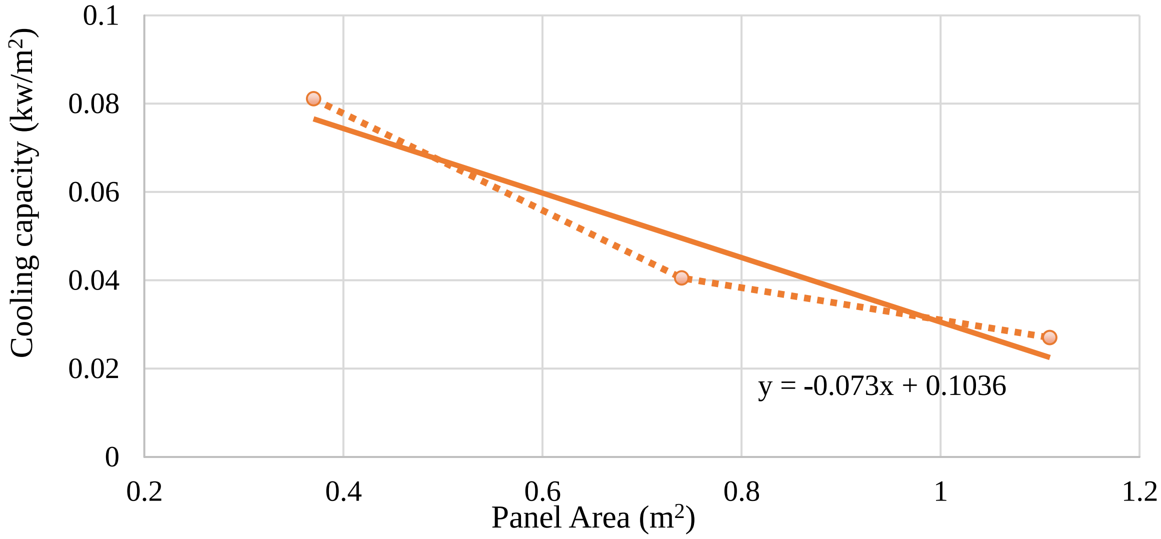
6.5.2. Experiment with parameter 03 –Cooling capacity for 1m^2 with different number of fans.

Under point 3, Cooling capacity for 1m2 with different number of fans was found,

For each number of fans, similar panel area ratios were taken and cooling capacity requirements for 1m2 with a different number of fans were calculated. The simulations were performed to find the maximum panel area and cooling capacity patterns as follows.

Table 6-2: Cooling capacity (KW/m2) – **1 fan**

	4:1	**8:1**	**12:1**
Panel area(m^2)	0.37	0.74	1.11
Cooling capacity(kw)	0.03	0.03	0.03
Cooling capacity for $1m^2$ (kw)	0.08	0.04	0.02



Optimal effective area of DCDW panels with 1 fan,

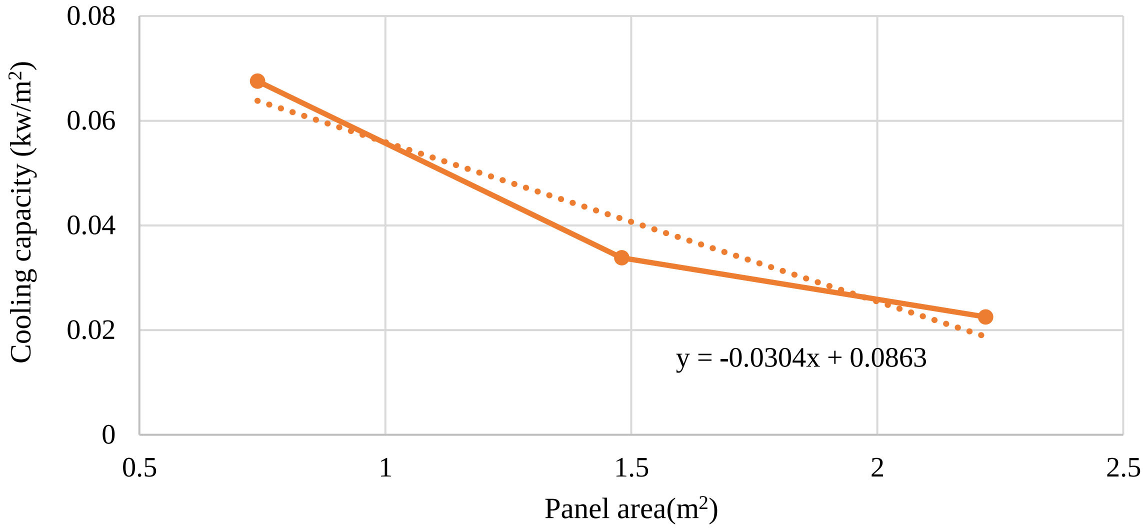
$y = -0.073x + 0.1036$

$y = 0.002$kw

x= 1.39 m²

Table 6-3: Cooling capacity (KW/m2) - **2 fans**

	8:2	**16:2**	**24:2**
Panel area(m^2)	0.74	1.48	2.22
Cooling capacity(kw)	0.05	0.05	0.05
Cooling capacity for $1m^2$ (kw)	0.07	0.03	0.02



Optimal effective area of DCDW panels with 2 fans,

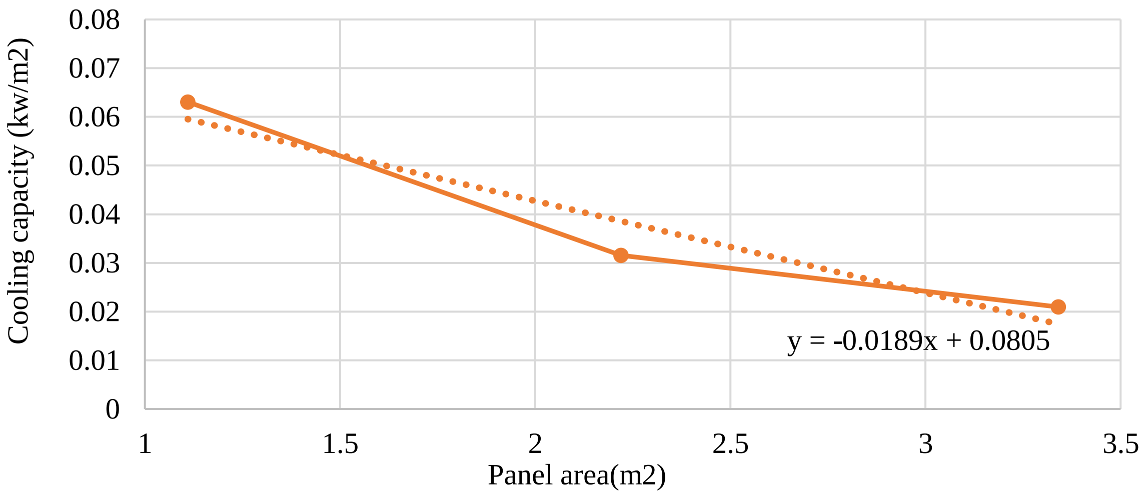
y = -0.0304x + 0.0863

y =0.004kw

x= 2.62m²

Table 6-4: Cooling capacity (KW/m2) - **3 fans**

	12:3	**24:3**	**36:3**
Panel area(m^2)	1.11	2.22	3.34
Cooling capacity(kw)	0.07	0.07	0.07
Cooling capacity for 1m^2(kw)	0.06	0.03	0.02

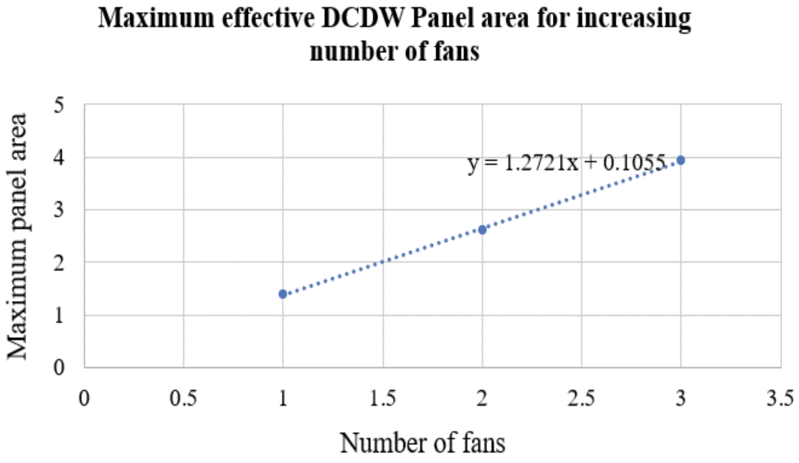


Optimal effective area of DCDW panels with 3 fans,

y = -0.0189x +0.0805

y =0.006kw

x= 3.94m²



Number of Fans	Max. Panel area
1	1.391781
2	2.6213
3	3.936
4	5.1939
5	6.466
6	7.7381

Figure 6-11: Maximum effective DCDW area, when increasing the number of fans

While increasing the area of DCDW, without changing the number of fans, a reduction can be seen in the cooling load required per square meter (See Table 6-2, to Table 6-4). As the area of DCDW increases, it increases the opportunity for indoor heat absorption. Moreover, the cooling capacity values are increasing when the number of fan increase (See Figure 6-11)

6.6. Heat absorption by the DCDW cooling system

With the cooling capacity values, the system absorption for 1m2 in kWh s per annum, with a different number of fans and for different time schedules, were identified and presented below. When the DCDW system with 3 fans, it has contributed to Highest annual heat absorption (See Table 6-5).

Table 6-5: Heat absorption by the DCDW cooling system

1 fan		
system absorption (kw/m2)	8:00 to 17:00	24 hours
kw h /m2	0.45	1.19
kwh/m2 annual	160.54	428.11
2 fans		
system absorption (kw/m2)	8:00 to 17:00	24 hours
kw h /m2	0.37	0.99
kwh/m2 annual	133.78	356.76
3 fans		
system absorption (kw/m2)	8:00 to 17:00	24 hours
kw h /m2	0.346	0.92
kwh/m2 annual	124.79	332.79

6.7. Experiment with parameter 04 – Best orientation of the prototype building for optimum indoor air temperature reduction with the DCDW system.

Under the 4th parameter, the best orientation of the prototype building for optimum indoor air temperature reduction with the DCDW system was identified.

The Design Building model was assessed with its capability of creating non-site-specific shadings hourly for approximately 24 hours, with the prototype building form (See Table 6-7).

Further, the DCDW system was set up on the West wall of the prototype building and system absorption, and temperature reductions were simulated in a steady state condition. With the rotation of the building facing different directions, the solar heat gain is varied. Therefore, to identify the best direction for the DCDW panel to be oriented, the building was rotated on an axis and the indoor air temperature was recorded (Table 6-8).

6.8. Results

When analyzing the shadings pattern around the building, especially towards the West wall of the prototype building, it shows that good shading is available during the morning hours, till noon time of the day and afterwards the West façade has been exposed to direct solar radiation from the exterior, it changes the sun exposure and intensity with different solar angles. It gives opportunities of absorbing more heat and penetrate the absorbed heat to the indoors. In terms of West wall facing direction, while rotating the building in one axis, the results show, the least indoor air temperature results have been obtained when the West façade of the model is facing the anticlockwise 150^{o} direction, which is 30^{o} from East (See Figure 6-12 , Figure 6-).

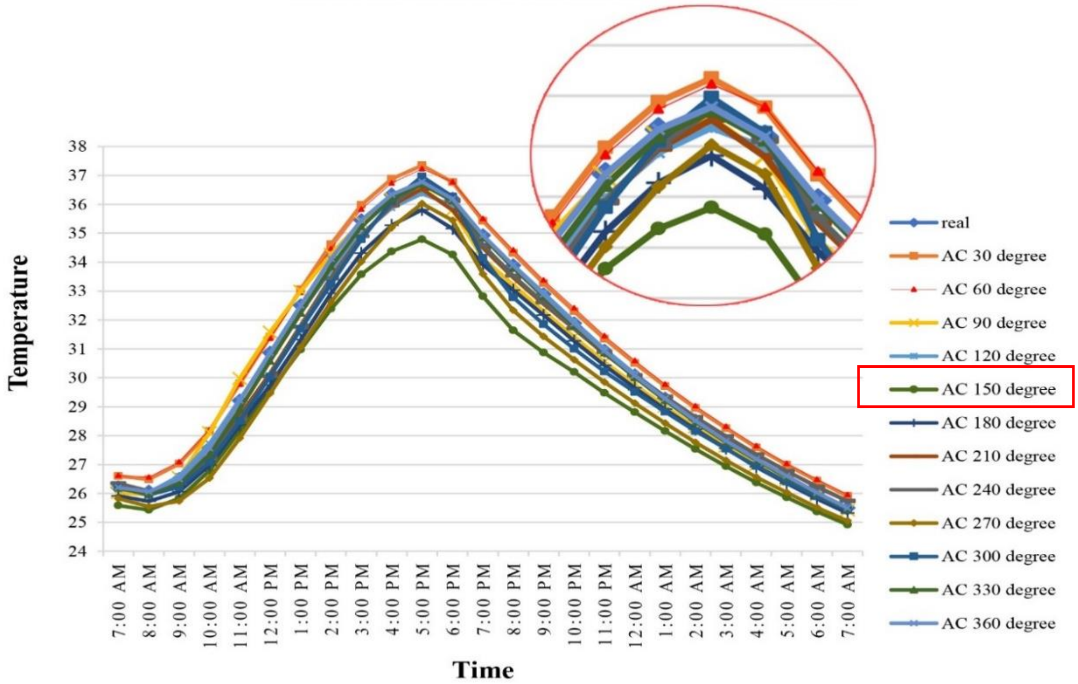


Figure 6-12: Results of the indoor air temperature when the prototype building is in different orientations

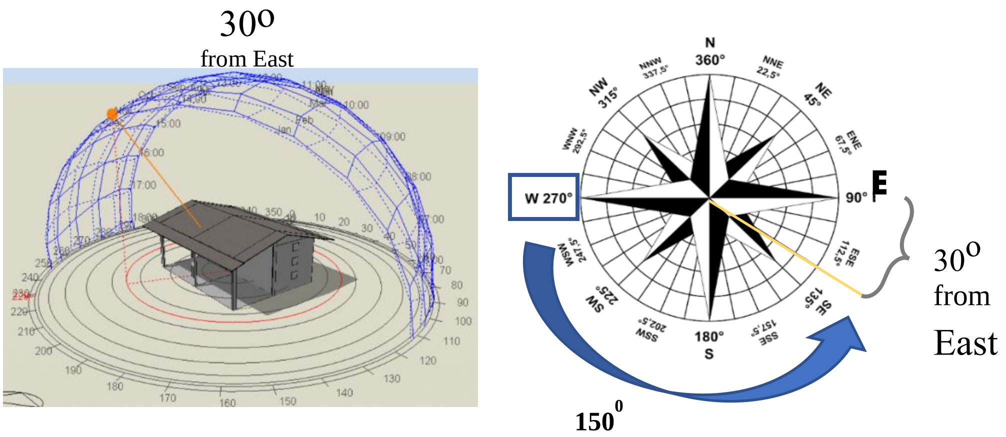
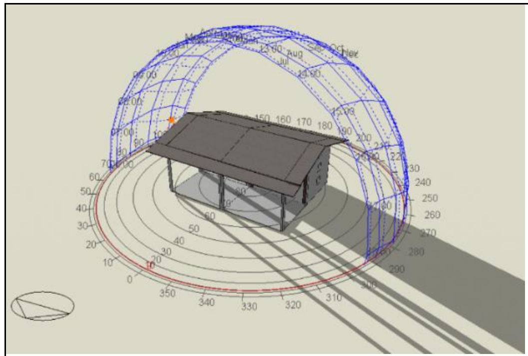
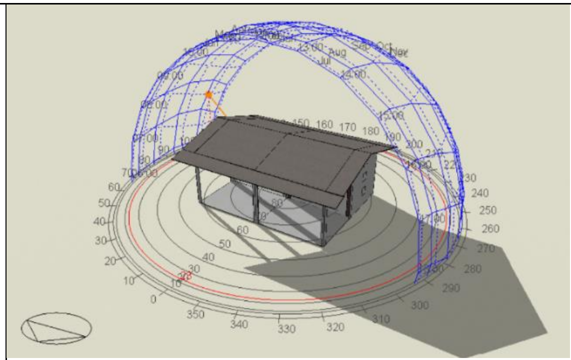
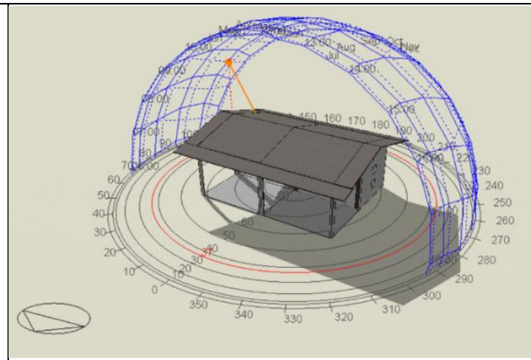
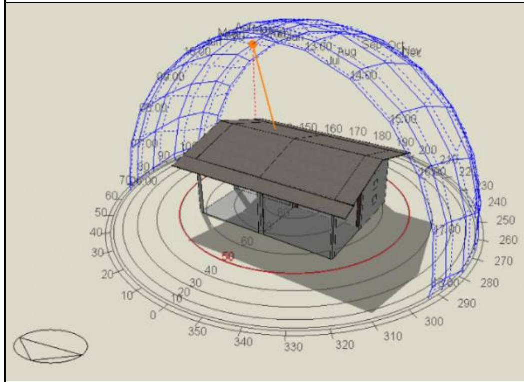
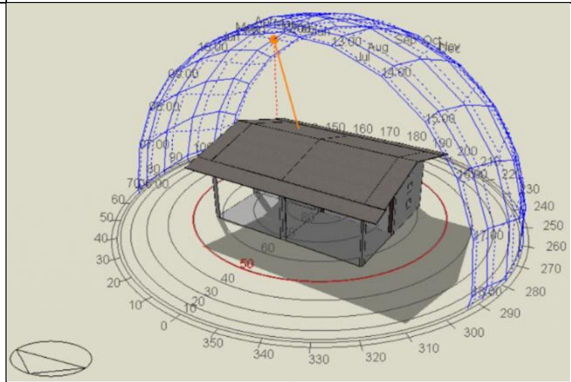
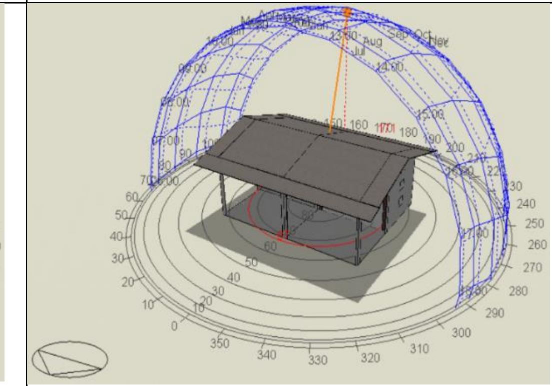


Figure 6-13:The best solar orientation of the prototype building – 30 degrees from the East

Table 6-7: Hourly variation of the self-shadow of the prototype building

 7 am	 8 am	 9am
 10 am	 11 am	 12 pm

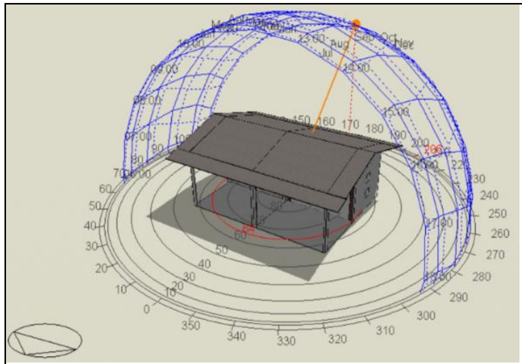
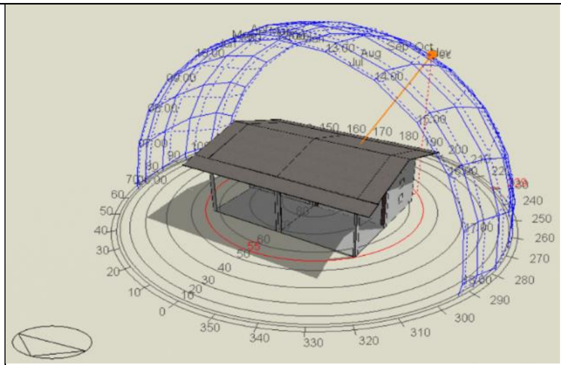
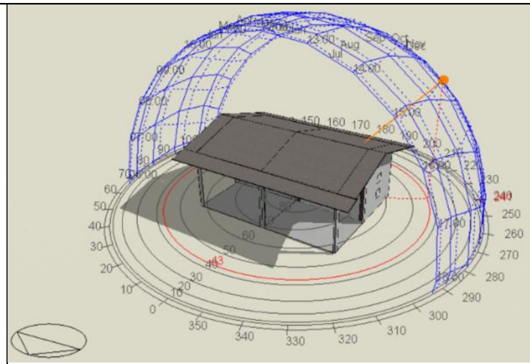
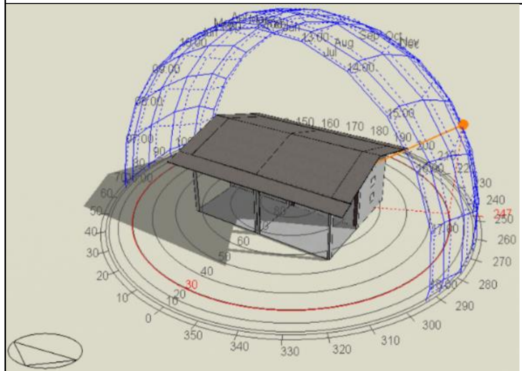
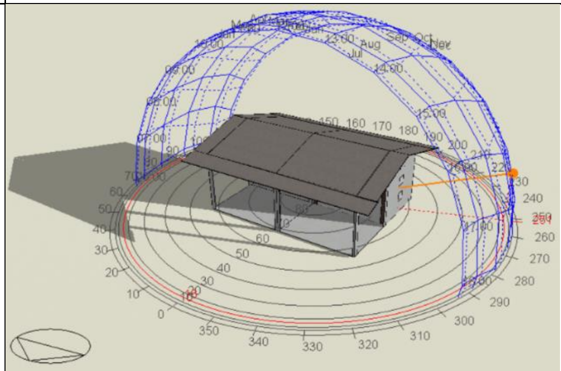
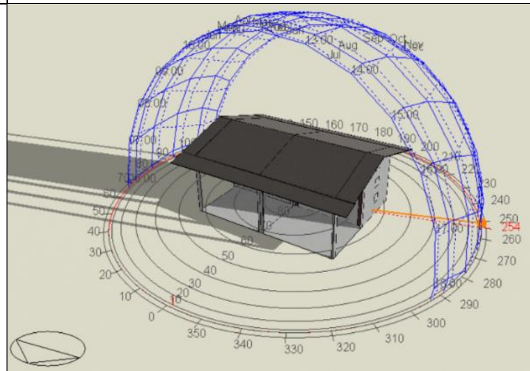
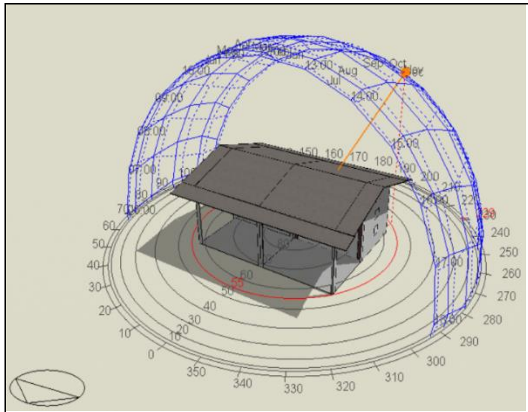
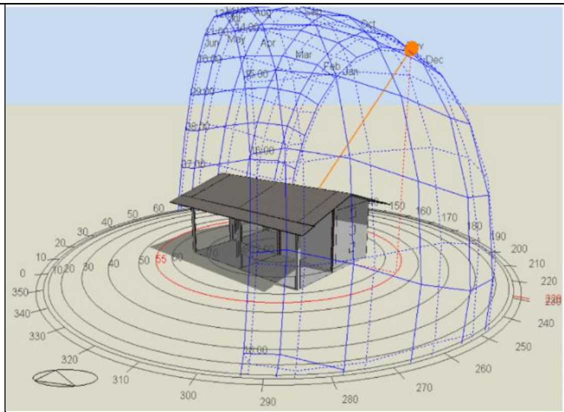
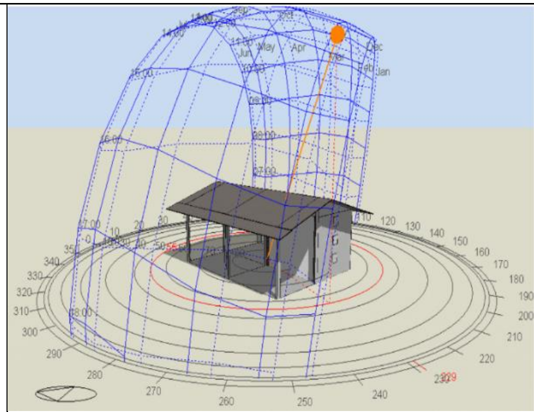
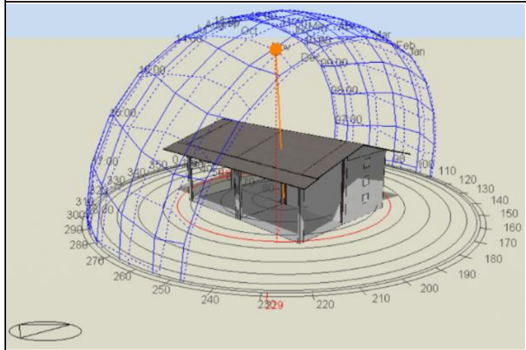
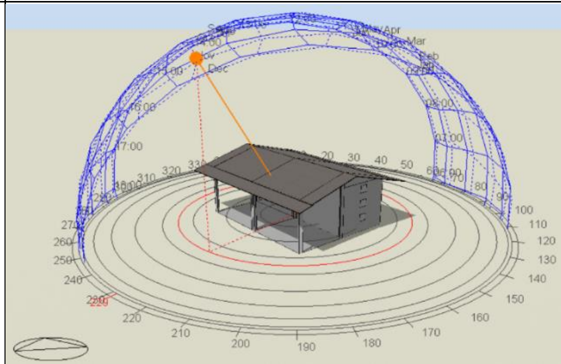
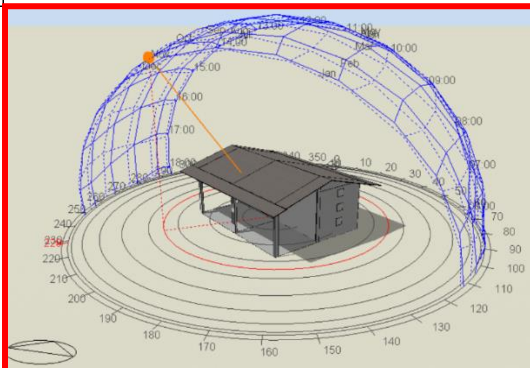
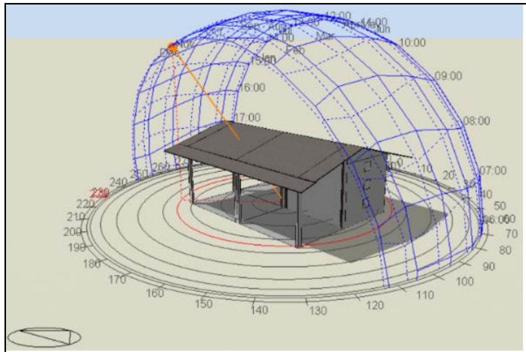
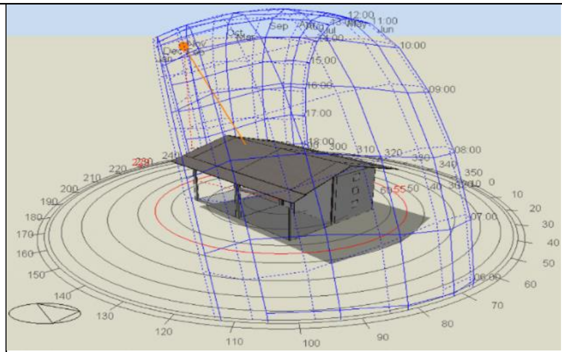
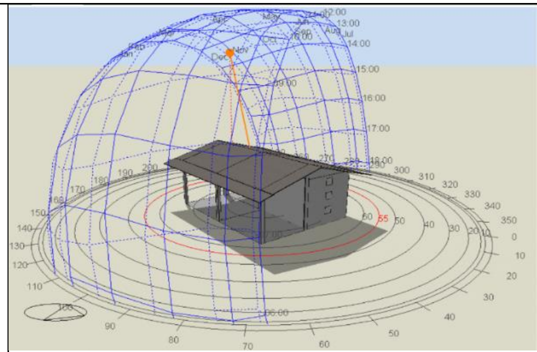
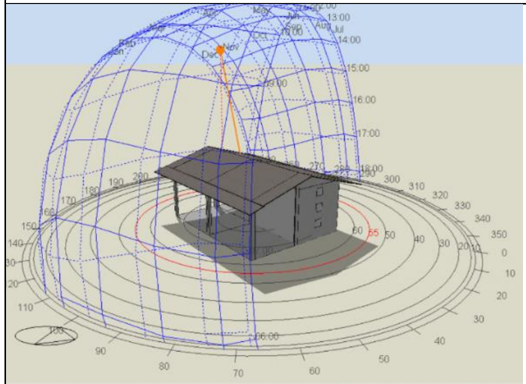
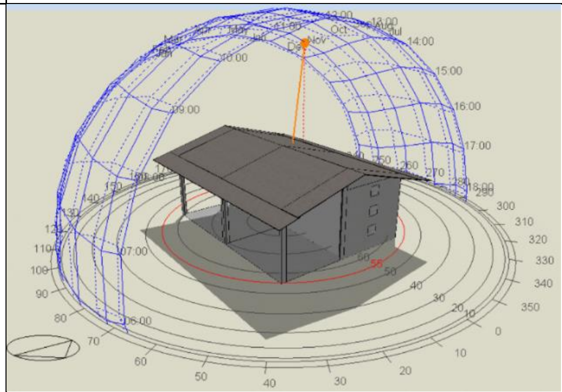
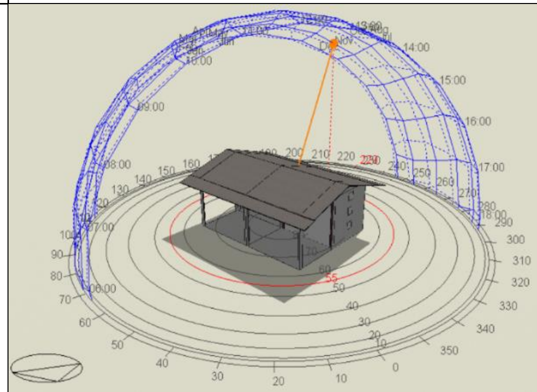
 1 pm	 2 pm	 3 pm
 4 pm	 5 pm	 6 pm

Table 6-8: Identifying the impact for indoor air temperature by rotating the West façade

 AC 0^0	 AC 30^0	 AC 60^0
 AC 90^0	 AC 120^0	 AC 150^0

 AC 180^0	 AC 210^0	 AC 240^0
 AC 270^0	 AC 300^0	 AC 330^0

6.9. Chapter summary

Indoor air temperature reduction and improvement potentials of the DCDW system are tested further with a Design Builder computer simulation program. A Design Builder model was developed validating the characteristics of the real prototype building built at Puttalam, Sri Lanka.

The model calibrated with and without the DCDW system was used to test four identified parameters for improvements in Indoor air temperature reduction.

1) The investigation results of parameter 01 depicted, that the DCDW system has a clear potential for indoor air temperature reduction compared to when there's no DCDW system applied to the same interior. Also, consecutively, when the number of DCDW panels decreases with 3 fans the heat reduction has increased.
2) The investigation results of parameter 02 depicted, Cooling load requirement for 1m2 with a constant number of fans decreases when the number of DCDW panels increases, since it increases the heat absorption capacity of the system.
3) To investigate parameter 03, selected three panels to fans ratios (4:1, 8:1, 12:1) were assessed for maximum cooling capacity for 1m2 with a different number of fans. The results depicted, the maximum cooling capacity for 1m2 with 01 fans as 1.39 m2, with 02 fans as 2.62m2, and with 3 fans as 3.94m2. Further, with the identified trends, the maximum cooling capacity of 1m2 with any number of fans can be obtained easily.
4) The results of the test; Best orientation of the prototype building for optimum indoor air temperature reduction, with the DCDW system depicted, for the best reduction of heat penetration to the indoors the building's West façade should be oriented to 30o from East, if its morning hours, the indoor heat penetration is further controlled.

7. CHAPTER SEVEN – EVALUATING THE SUSTAINABILITY AND PROFITABILITY OF THE DYNAMIC CLAY DOUBLE WALL SYSTEM

7.1. General

This chapter covers objective 5 of the research. Potential improvements to the DCDW cooling system which were identified by computer simulations were presented in the previous chapter, lastly this chapter will evaluate the long-term sustainability and profitability of the DCDW cooling system, the novel invention. The appraisals will be done based on life cycle cost calculations, mainly, with Net Percent Value calculations and Simple payback period calculations.

7.2. Calculating the Life Cycle Cost (LCC) of the DCDW system

LCC can be defined as a combination of all the costs incurred from construction to the end use of the building [111]**.** While constructing a building the significant considerations are the building environment and the cost of the construction. Any owner of a building will inquire about the economics of its initial, maintenance and operational cost over the life span of the building and these should be addressed from future perspectives too. Therefore, LCC analysis, the combination of economic theory and computer technology has allowed a more sophisticated approach to the design and construction of a facility than ever.

7.3. Service life

The service life of the materials and equipment may vary with the location, environmental factors, construction techniques and etc. Anyhow, as a norm the replacement of the fan will be at an interval of 10 years and for the air conditioner an interval of 20 years, as per the system specification. The panel is considered a part of building construction and could be sustainable throughout the building's lifespan. The sixty-year (60 yrs.) life span of the affordable house was defined by using British standards [112] and the sixty-year definition helps the research omit unnecessary calculations.

7.4. Assumptions for LCC

Life cycle costing calculations were based on the following assumptions.

- Unit cost (LKR 12.20) and other electricity tariffs remain constant throughout the lifespan of the building. (ceb.lk/commercial tariff)
- Climate conditions remain constant throughout the lifespan of the building.
- All electrical appliances shall have constant energy consumption.
- Occupancy levels remain constant.
- No inflation in the economy.
- All costs accounted by converting it to dollar value (LKR 1 = $360)

7.5. The Design Builder model for LCC

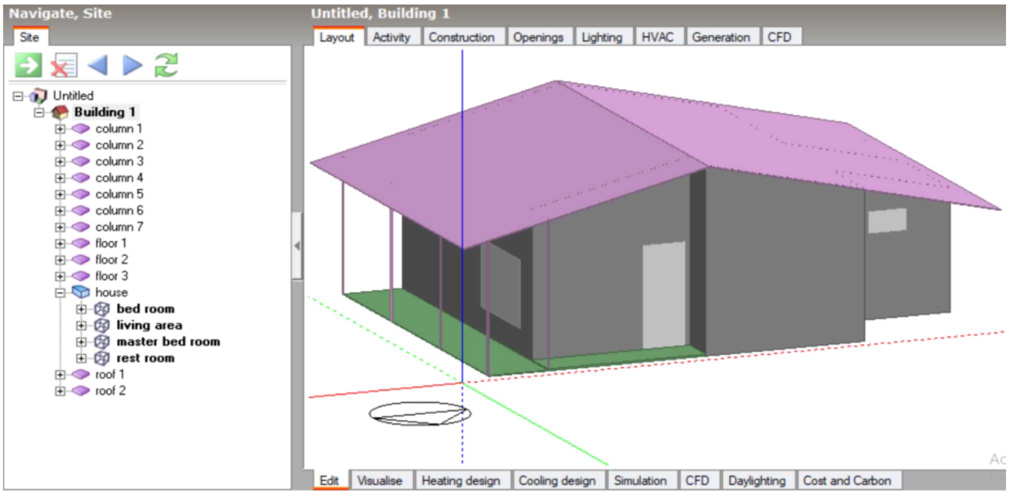


Figure 7-1: Design Builder model of the selected residence

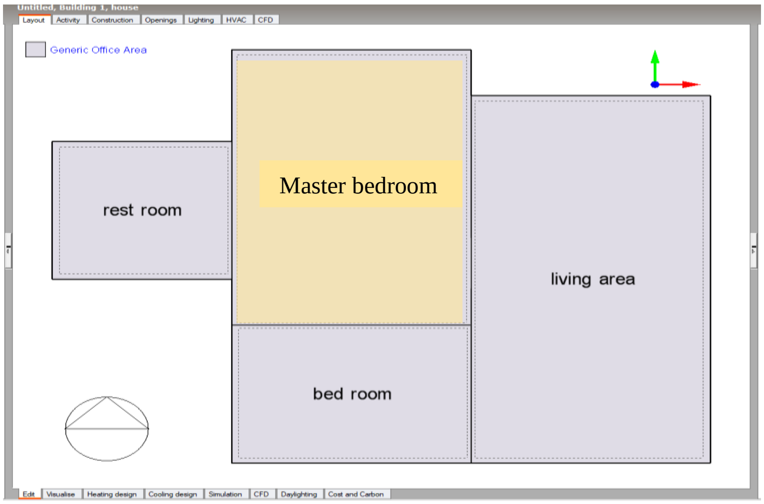


Figure 7-2: Plan form of the modeled actual residence, effective area for the LCC calculations, (master bedroom) is highlighted in yellow

The Design Builder model was developed (See Figure 7-1, Figure 7-2) as above, and the relevant construction and opening details were inserted below. With concern to LCC,

- A real residential building located next to the previous data collected prototype building was selected to assess the LCC and assumed that the system was installed in one room – A master bedroom (6x4m2 area 4m Hight) with an Air Conditioner.
- The DCDW system was installed, covering one selected wall (4x4 m2) of the selected room, increasing the DCDW area to 20%, 40%, 60%, 80% & 100%.
- Different comfort arrangements were considered for the simulation as follows,
- Three different temperature set points were considered which are nominally thermally comfortable in tropics - 25oC, 26oC & 27oC.

Fordham, in his research, has classified buildings into two broad categories concerning their operation:

i. Buildings where people live (Residential)
ii. Buildings where people work (Commercial)

Based on the above facts, two different operating schedules were selected for the investigations, from 08:00 am to 05:00 pm (Commercial) & 24 hours (Residential).

The energy requirement was found in hourly basis with Design Builder software. To identify the best DCDW proportions for minimum LCC, the following 4 cases were used,

Case A - without the panels & fans
Case B - with panels & one fan
Case C - with panels & two fans
Case D - with panels & three fans

7.6. The basic LCC comes with three different stages.

Life Cycle Cost of a building is decided to assess with the following basic stages.

- Initial cost
- Maintenance cost
- Replacement cost

7.6.1. Initial Cost (IC)

The initial cost details for the construction of a particular room, panels, fans and air conditioner were collected from the pricing specifications for the year 2022 (See Table 7-1).

Table 7-1: The basic Initial cost of materials for the selected case

Material option		Initial cost/ $	
Construction		$. /m^2	150.97
Panel			13.89
Fan	1		7.79
	2		8.27
	3		8.25
Air conditioner			619.42

The initial cost values were converted from SL Rupees to US Dollars and continued for further stages. The initial cost for each case (including the construction cost, cost due to A/C, and DCDW system) for each DCDW coverage percentage, for the selected four cases are in total shown in Table 7-3.

Table 7-3: Initial cost details for case A, B, C and D

	Covered Area of wall	Construction	Air conditioner	Panels + fans	Total
Case A		$ 3,623.19	$ 619.42	-	**$ 4,242.61**
Case B	20%	$ 3,623.19	$ 619.42	$ 69.38	**$ 4,311.99**
	40%	$ 3,623.19	$ 619.42	$ 138.77	**$ 4,381.37**
	60%	$ 3,623.19	$ 619.42	$ 208.15	**$ 4,450.76**
	80%	$ 3,623.19	$ 619.42	$ 277.54	**$ 4,520.14**
	100%	$ 3,623.19	$ 619.42	$ 346.92	**$ 4,589.53**
Case C	20%	$ 3,623.19	$ 619.42	$ 70.91	**$ 4,313.51**
	40%	$ 3,623.19	$ 619.42	$ 141.82	**$ 4,384.42**
	60%	$ 3,623.19	$ 619.42	$ 212.72	**$ 4,455.33**
	80%	$ 3,623.19	$ 619.42	$ 283.63	**$ 4,526.24**
	100%	$ 3,623.19	$ 619.42	$ 54.54	**$ 4,597.14**
Case D	20%	$ 3,623.19	$ 619.42	$ 70.84	**$ 4,313.45**
	40%	$ 3,623.19	$ 619.42	$ 141.68	**$ 4,384.29**
	60%	$ 3,623.19	$ 619.42	$ 212.52	**$ 4,455.13**
	80%	$ 3,623.19	$ 619.42	$ 283.36	**$ 4,525.97**
	100%	$ 3,623.19	$ 619.42	$ 354.20	**$ 4,596.81**

7.7. Air Conditioning cost

Since Design builder software is able in evaluating and analyzing the energy trends with reasonable accuracy, using the models developed in Design Builder software, the cooling capacity was found on an hourly basis. Diverse air conditioning arrangements were considered for the simulation.

Operational cost for air conditioning was calculated by taking the cost of one electricity unit as Rs. 12.20, which is recommended for the commercial sector (ceb.lk/commercial tariff) (See appendix B).

7.8. Energy requirement

Despite using air conditioners totally for a comfortable living atmosphere, the integration of the DCDW system together paves the way to reduce energy demand. With the expansion of panel area and the number of fans, the saving (efficiency) can be achieved by the DCDW system increases. Thus, the energy required for each set of selections could be reduced.

Table 7-4: Annual Energy Requirement with fully active mode (Case A), with the different DCDW system scenarios.

Annual Energy Requirement for the selected cases

Energy required (kwh/yr)	Area of coverage	25^0c 8:00 to 17:00	25^0c 24 hours	26^0c 8:00 to 17:00	26^0c 24 hours	27^0c 8:00 to 17:00	27^0c 24 hours
Case A		3806.22	8276.61	2845.23	5701.02	1961.84	3540.43
Case B	20%	3292.49	6906.66	2331.50	4331.07	1448.11	2170.48
	40%	2778.76	5536.72	1817.77	2961.13	934.38	800.54
	60%	2265.03	4166.77	1304.04	1591.18	420.65	-569.41
	80%	1751.30	2796.83	790.31	221.24	-93.08	-1939.35
	100%	1237.57	1426.88	276.58	-1148.71	-606.81	-3309.30
Case C	20%	3378.11	7134.99	2417.12	4559.40	1533.73	2398.81
	40%	2950.00	5993.37	1989.01	3417.78	1105.62	1257.19
	60%	2521.90	4851.75	1560.91	2276.16	677.52	115.57
	80%	2093.79	3710.12	1132.80	1134.53	249.41	-1026.06
	100%	1665.68	2568.50	704.69	-7.09	-178.70	-2167.68
Case D	20%	3406.87	211.68	2445.88	4636.09	1562.49	2475.50
	40%	3007.52	6146.74	2046.53	3571.15	1163.14	1410.56
	60%	2608.17	5081.81	1647.18	2506.22	763.79	345.63
	80%	2208.82	4016.88	1247.83	1441.29	364.44	-719.30
	100%	1809.47	2951.94	848.48	376.35	-34.91	-1784.24

Relating to the above results; energy values, its visible that from some points on the energy values have become minus (-), which indicates the energy requirement has become minus. This depicts that no more energy is required to obtain the expected cooling by assisting the air conditioner, but the DCDW system alone can fulfil the cooling requirement from that stage on. Therefore, a lifetime of Energy saving starts from that point on.

7.9. Identifying the best case for minimum LCC.

To identify the best proportions for minimum LCC, the following methods were utilized.

1) NPV (Net Present Value)

   NPV Is the number of years when money saved after the renovation will cover the investment? It was calculated by dividing the amount of the investment by the annual cash flow

2) Payback period (for cases A, B, C & D)

   A simple payback period is the number of years when money saved after the renovation will cover the investment. It was calculated by dividing the amount of the investment by the annual cash flow[85]

7.10. Identifying the NPV for 60 years with DCDW system

The research assessed NPV (Net present value) and Payback period for each case (A, B, C & D) to calculate energy consumption and cost of electricity for a 100% active, and for a hybrid system incorporating the DCDW as the two scenarios.

An Air Conditioning load was introduced to a Design Builder model (Only the Master Bedroom was considered for thermal simulations), and a DCDW system was introduced with different covering % of the DCDW and with different time schedules.

During NPV calculations, all cost details were considered in US Dollar values. The consideration was taken as $1 is equal to LKR 360.

As in Table 7-3, energy requirement for annum, for each case with different DCDW coverage percentages for two selected time schedules, were identified with aid of the Design Builder simulation summary and values for 60 years were also calculated thereby. Progressive NPV calculations for every 10 years of each case are attached with Appendix C, D, E, and F.

Table 7-5: Net Percent Values of each case, for 60 years

Case		NPV for 60 years					
		25ºc 8:00 to 17:00	**25ºc 24 hours**	**26ºc 8:00 to 17:00**	**26ºc 24 hours**	**27⁰c 8:00 to 17:00**	**27⁰c 24 hours**
A	0%	$ 13,220.75	$ 22,310.55	$ 11,266.74	$ 17,073.51	$ 9,470.51	$ 12,680.31
B	20%	$ 12,406.65	$ 19,816.14	$ 10,452.64	$ 14,579.11	$ 8,656.41	$ 10,185.91
	40%	$ 11,592.55	$ 17,321.73	$ 9,638.54	$ 13,170.43	$ 7,842.31	$ 7,691.50
	60%	$ 10,778.45	$ 14,827.33	$ 8,824.44	$ 9,590.30	$ 7,028.22	$ 4,496.64
	80%	$ 9,964.36	$ 12,332.92	$ 8,010.34	$ 7,095.89	$ 4,545.13	$ 4,787.79
	100%	$ 9,150.26	$ 9,838.52	$ 7,196.24	$ 5,078.94	$ 4,775.61	$ 5,078.94
C	20%	$ 12,592.11	$ 20,295.47	$ 10,638.10	$ 15,058.43	$ 8,841.87	$ 10,665.23
	40%	$ 11,963.47	$ 18,280.39	$ 10,009.46	$ 13,043.35	$ 8,213.23	$ 8,650.15
	60%	$ 11,334.83	$ 16,265.30	$ 9,376.25	$ 11,028.27	$ 7,584.59	$ 6,635.07
	80%	$ 10,706.19	$ 14,250.22	$ 8,752.18	$ 9,013.19	$ 6,955.95	$ 4,848.06
	100%	$ 10,077.55	$ 12,235.14	$ 8,123.54	$ 4,063.55	$ 4,832.42	$ 5,154.27
D	20%	$ 12,650.09	$ 20,450.73	$10,696.07	$ 15,213.70	$ 8,899.85	$ 10,820.50
	40%	$ 12,079.42	$ 18,590.92	$ 10,125.41	$ 13,353.89	$ 8,329.18	$ 8,960.69
	60%	$ 11,508.75	$ 16,731.11	$ 9,554.74	$ 11,494.08	$ 7,754.14	$ 7,100.88
	80%	$ 10,938.08	$ 14,871.30	$ 8,984.07	$ 9,634.26	$ 7,187.85	$ 4,845.40
	100%	$ 10,367.42	$ 13,011.49	$ 8,413.40	$ 7,774.45	$ 4,829.91	$ 5,150.95

7.10.1. Results of NPV calculations

- The study reveals the effectiveness of making use of the DCDW system for indoor heat reduction of space with a nominal lifespan and the results show that, in terms of NPV, **Case B performs best**, when it's used with maximum panel coverage (See Figure 7-3).
- The NPV values for each case under a different area of coverages are shown in the above table and with comparative to Case A, which is pure with an active

cooling system(A/C), all the other cases (B, C, D- with hybrid cooling) have shown less requirement for operational energy, thus cost.

- The shaded values indicate the points that the DCDW system can manage the required indoor cooling itself, without the use of air conditioning, where the system is sufficient in heat absorption.
- The calculations included running and renovation costs, which were considered in the NPV of each situation.
- The above findings are compared to arrive at a justification for the economic benefits of each scenario.
- Therefore, with NPV values, the cases that included the DCDW system shows a good reduction in operational cost, compared to the case with no DCDW system, and in active mode (See Figure 7-3).

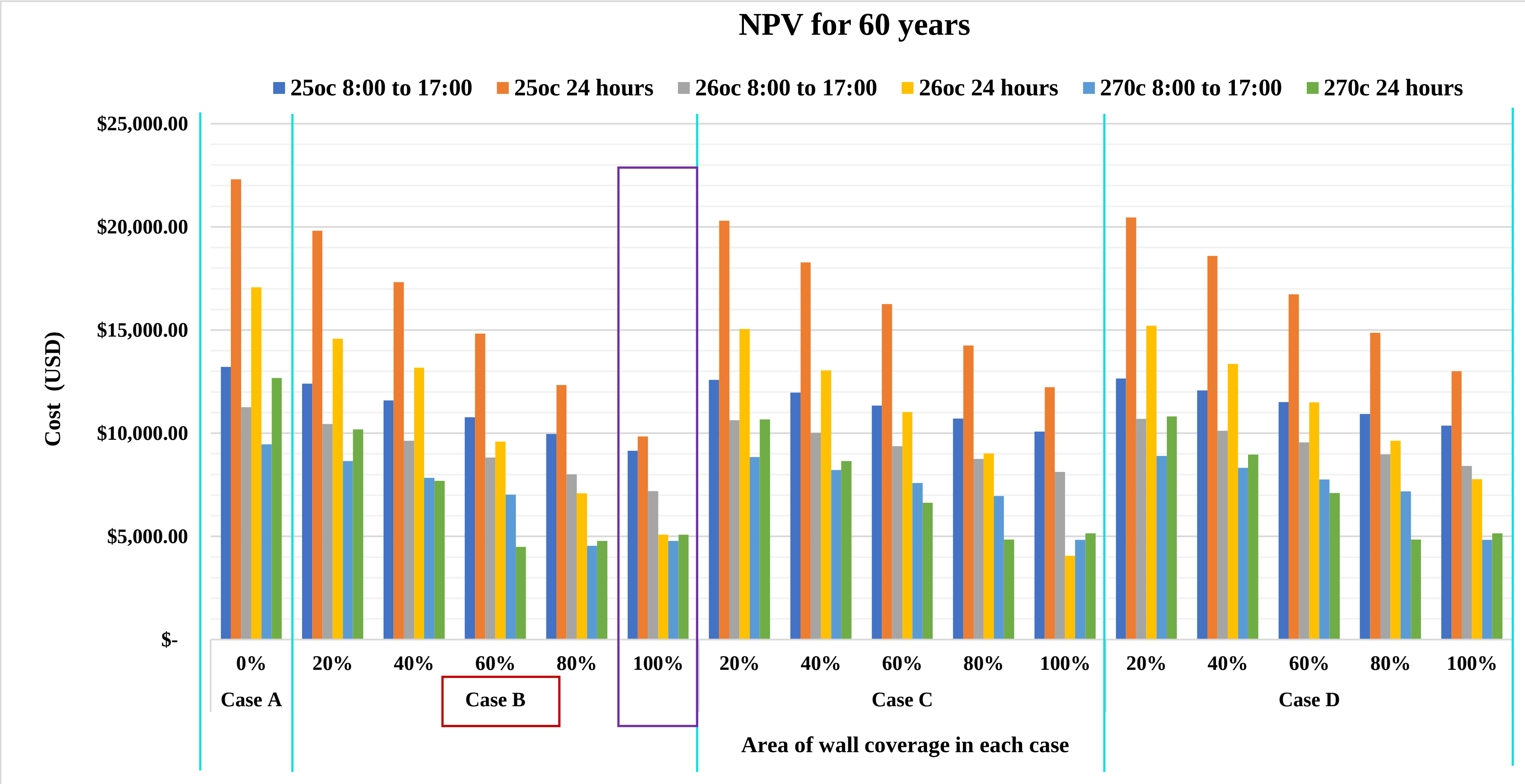


Figure 7-3: Analysis of NPV calculations of each case for 60 years

7.11. Identifying the annual cost saving due to DCDW system, and the simple payback period

The payback period is dependent on the cost saving that can be achieved with the DCDW system, higher the saving shorter the payback period. In this section, only cases B, C, and D were compared since Case A is energy-consuming and has already proven ineffective in terms of NPV.

Both time schedules were considered in terms of Annual savings and payback period.

The calculations for annual savings and payback period are in detail attached with Appendix G.

7.12. Results

		Panel + Fan	Saving/year		Pay back year	
			8:00 to 17:00	24hrs	8:00 to 17:00	24hrs
Case B						
panel	$ 222.22					
fan	$ 124.70	$ 346.92	$ 17.41	$ 46.43	4.0	1.5
Case C						
panel	$ 222.22					
fan	$ 132.32	$ 354.54	$ 72.54	$ 193.44	4.9	1.8
Case D						
panel	$ 222.22					
fan	$ 131.98	$ 354.20	$ 67.67	$ 180.45	5.2	2.0

Figure 7-4: Cost saving due to DCDW system and the payback period for each case with each time schedule

In terms of the Simple Payback Period, Case B have a short-term achievement than case C, or D, for both schedules- 24 hours and 8 to 17 hours. (Suitable both for residential and commercial use).

If the Case B option of the DCDW system is selected and proceeded with 24 hours operational schedule (for a residence), within 1.5 years the total cost for the DCDW system will be paid off, and thereafter the system will still make the interior cool yet make profits in each minute.

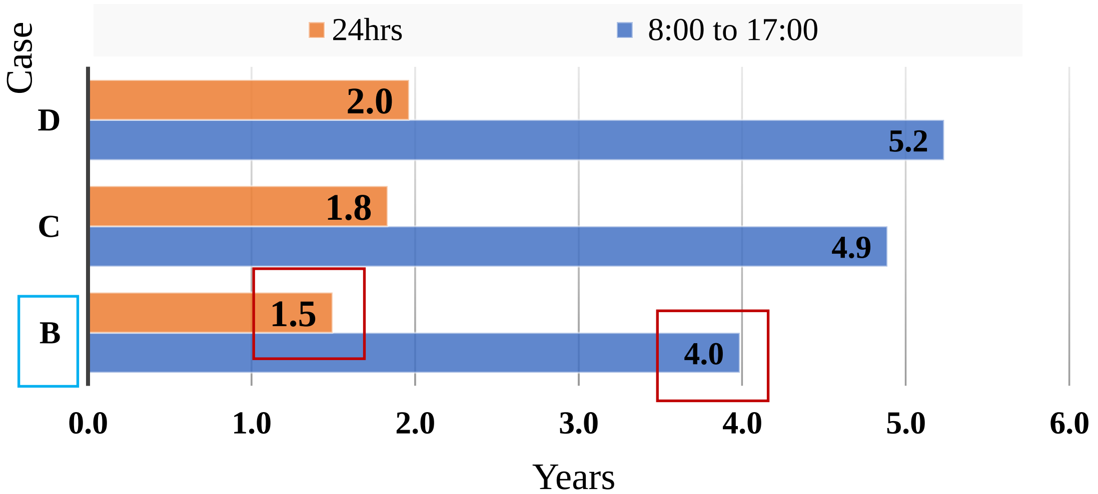


Figure 7-5: Pay back periods of Case A, B, C and D for selected two time schedules

With the above findings, it is proven that the DCDW system is profitable, more profitable with case B (with 01 fan option) (See Figure 7-5).

Therefore, even in harsh climatic conditions of the dry zone, the system will grant higher economic benefits and lesser environmental impacts throughout its lifespan.

7.13. Chapter summary

The sustainability and the profitability of the Novel DCDW cooling system were assessed using popular LCC assessment methods which are NPV calculations and Simple Pay Back period calculations. A real residential building located within near proximity of the Prototype building was modelled in Design Builder for LCC calculations. The Master bedroom of the said model with an area of 6x4m2 area 4m height was utilized for LCC assessment with an Air Conditioning load added.

The DCDW system was installed, on the narrow North facing wall of the selected room, which is 4 x 4 m2, increasing the DCDW area to 20%, 40%, 60%, 80% & 100%.

Three different temperature set points which are marginally thermally comfortable in the tropics were selected to investigate which are, 25oc, 26oc & 27oc.

Two operational schedules have also participated in the investigation, 24 hours and 8.00 am to 5.00 pm. In four cases with different panels: fan proportions were selected to identify the best proportion for minimum LCC. They are as,

- Case A - without the panels & fans
- Case B - with panels & one fan
- Case C - with panels & two fans
- Case D - with panels & three fans

NPV for selected cases were considered a maximum 60 of years of the building's nominal lifetime. For NPV calculations, Initial costs, with construction, air conditioning, and system installation were calculated and Operational costs such as Energy consumption and electricity costs were calculated in different situations and were obtained through DB simulation results.

Annual Energy consumption results for selected cases showed that, when utilizing the DCDW system, after some point the energy requirement becomes minus, the DCDW system starts providing indoor cooling its system along and starts the lifetime energy cost saving thereon. The results depicted in terms of energy saving, case B performs best.

Results of the NPV calculations depicted when the Case B Option is used with a 100% panel covering an area, in terms of Net Percent Value for 60yers it costs the least, comparative to the two other cases (case C, D).

In terms of cost saving and payback period, again Case B performed best not for a single time schedule, but for both schedules. (Residential and commercial schedules)

Both methods (NPV and Payback period) are evidence that the DCDW cooling system can contribute to a significant operational energy saving, thus operational cost reduction, when compared to space, cooled fully with an active mode. Therefore, the economic benefits and the success of the Dynamic Clay Double Wall system are strongly proven in its profitability.

In conclusion, among all three cases, case B (system with one fan) is recognized as the better saving option comparably, in Energy saving, Net Percent Value and Simple payback period.

8. CHAPTER EIGHT – CONCLUSIONS, RECOMMENDATIONS AND FUTURE DIRECTIONS

8.1. Conclusions

- Climate-responsive Architectural, Engineering, and technological interventions can promote thermal comfort in building interiors, thus cutting the operational energy demands. The research investigated the possibility of developing a cooling system amalgamating the known principles of thermal comfort, within the practical context to obtain better indoor heat reduction for tropical climates.
- The possibility of Indoor heat discharge and gaining cool, concurrently via two integrated components were experimented through the research.

- The literature review paved the path to identifying the research background, classifying a similar methodology, to confirm or establishing a finding.
- It initially clarified the need for the research study through facts and principles of architectural sciences and related building physics such as passive-hybrid cooling, thermal mass effect and time-lag, stack effect, ventilative cooling etc.
- The Cruciality of rejuvenated earth and clay as popular building materials was established and further Clay's significance for this research as a cooling material was convinced.
- Clay's key qualities and potential clay casting methods were reviewed.
- Potential compounding material options (including waste material) with clay, to improve certain identified properties of clay were found.
- Properties of clay to improve cooling characteristics, such as microstructural porosity, continuous air permeability, thermal conductivity and insulation properties etc. were identified.
- Double skin facades (DSF) were identified as an effective passive cooling strategy, and the potential for a DCDW cooling system as an extension of DSFs is investigated through literature.
- Similar thermal simulation studies were evaluated on double skins, clay walling, and ventilative cooling.

- To assess the Sustainability of buildings, the theory of Life cycle costing was reviewed with its most popular methods.
- The theory of Psychometrics was assessed with basics, developing the psychometric chart including comfort zone and its extensions with ventilation was established through literature.

- The following experiments processed to improve the identified properties of Component 01 (Dynamic Clay Double Wall panel),
  1) The material mixes
  2) Material mix composition (On internal porosity and indoor air temperature reduction)
  3) Production process of DCDW panel (From material mixing to firing the DCDW panel)
  4) Firing temperature and time (trial and error process of identifying the best firing temperature and time)
  5) Water Absorption (to assess the internal Porosity)
  6) Visibility of Microstructural Porosity (photographic survey)
  7) Visibility of Surface Texture (photographic survey)
  8) Linear shrinkage
  9) Thermal conductivity (of the DCDW panel with finalized material mix and properties)
  10) Effect of panel's thickness on indoor air temperature reduction
- In summary, according to each experiment results, the best material mix was confirmed as 'Red Pottery Clay with Saw Dust' into 50:50 Clay: Saw Dust composition, air dried, oven dried and then fired to 800℃ for one hour will result from the best DCDW panel in terms of Indoor air temperature reduction.
- It was visible, that when the percentage of Saw Dust increases in the clay body, both in surface texture and in the microstructure, an increase of porosity can be seen clearly.
- Water Absorption capacity is also increased with the increase of Saw Dust % in clay while the linear shrinkage decreases.

- The thermal conductivity of the finalized DCDW material was recorded as 0.05 W/mK.
- Further to the results depicted, when the thickness of the panels increases, it increases the heat absorption capacity thus, it increases the indoor air temperature reduction due to the DCDW solution.

- Once finalizing the best material and related properties for the DCDW panel which are targeted at improving the microstructural porosity of the DCDW panel, in Chapter 03, the experiments involved improving the DCDW panel (Component 01), with its air permeability characteristics for better structural cooling.
- It was decided to create holes across the DCDW panel, allowing cross-air movements. Based on precedents on potential practical methods to improve cross-air permeability, pilot castings were tried out, and as a result, the following parameters were identified and tested to get the optimum results in indoor air temperature reduction.
- Each parameter involved at least three sub-parameters, in order to identify the best,
    - Diameter of the holes – 2mm, 5mm, 8mm
    - Hole distribution (distance between each hole) – ½ inch, 1inch, 2inch
    - Buoyancy of the hole (Hole angle) - (30, 45, 90 degrees)
    - Impact of the thickness of the panel (1cm, 2cm, 3cm, 4cm)
- To test the identified parameters, specimens were cast with a specially designed mass scale method for DCDW, which is a manually operating clay panel-making machine.
- DCDW specimens were cast to test all the parameters, and as per each sub parameter too.
- To assess the impact of each parameter, on indoor air temperature reduction, each DCDW panel was tested in a special test chamber.
- As the results, out of the three-hole diameters tested, the lesser diameter (2mm) performed best in terms of indoor air temperature reduction.
- Out of three-hole distances tested, holes with the shortest distance (½ inch) to each performed best in terms of indoor air temperature reduction.

- Out of the three-hole diameters tested, 45 degrees angle creates the highest buoyancy and the same performed the best in terms of indoor air temperature reduction too.
- Out of the four-panel thicknesses tested 4 cm panel contributed the best indoor air temperature reduction, which depicts that when the panel thickness increases, due to higher thermal mass, it increases the heat absorption capacity, thus cooling in spaces.

- Then experiments were conducted to identify the practical application and on-site effectiveness of the DCDW cooling system was assessed through a series of experiments.
- Climatic behaviour of the selected location, for the thermal investigations, the processes of building the prototype building, fixing details of the DCDW system, preparing the interior of the prototype building for thermal investigations and application process of the DCDW system (components 01 and 02) were discussed.
- Next, the initial data collections were conducted to identify the exact microclimatic behaviour of the selected site, indoor thermal behaviour without the DCDW system, and then, the indoor thermal behaviour upon application of the DCDW system and how it varies with some of the identified parameters related to options in the application.
- With the results, it was identified that the microclimate around the prototype building behaves almost similarly, but in daytime peaks, the North and East directions show a lesser outdoor temperature compared to the West and South directions.
- When the building is fully air sealed, and with no DCDW system installed, the indoor peak time temperature exceeds the outdoor peak, due to heat stagnation.
- The indoor thermal situation was further tested by inhausting and exhausting the fans without applying DCDW panels, fans in both directions with the DCDW (in two stages as with 4 panels and 8 panels) and applying the panels and fans on opposite walls (E-inhaust and W-exhaust) of the prototype building and creating a cross air movement.

- The results depicted, that when the fans are inhausted, with an increased number of DCDW panels gives a better indoor air temperature reduction.

- Next, the impact of increasing the panel area Vs the number of fans was identified, for this, three panels: fans ratios were (4:1, 8:1, 12:1) used. The number of panels and number of fans were increased according to the above ratios, the results showed the indoor air temperature reduction is better consecutively when the ratios are 12;1, 8:1, and then 4:1.
- Later, the potential of indoor air temperature reduction with hybrid ventilation was investigated by utilizing the DCDW system together with natural ventilation. 03 cases, as 36 panels, 3 fans / 0 panels, 3 fans /and 36 panels with 0 fans were integrated with natural ventilation supply from the surrounding. 36 panels and 3 fans with natural ventilation showed the best indoor air temperature reduction.
- Moreover, physical indoor air temperature data of the best case were inserted into a psychometric chart developed with a comfort zone for Puttalam, comprising extended comfort zones with three increasing air velocities, 0.3 m/s, 0.4 m/s, and 0.5 m/s.
- Lastly, the chapter presents the experiment conducted to identify the air filtration capacity of the DCDW system.
- Four types of gases (CO2, HCHO, VOCs, O2, H2S) and Particular Matter (PM) were considered during the test.
- The results showed that the DCDW system contributes to significant air filtration when compared to the amounts that exist indoors with outdoors at a similar time.

- Indoor air temperature reduction improvement potentials of the DCDW system were tested further, with a Design Builder computer simulation program.
- A Design Builder model was developed validating the characteristics of the real prototype building built at Puttalam, Sri Lanka.
- The model calibrated with and without the DCDW system was used to test four identified parameters for improvements in Indoor air temperature reduction.

- The investigation results of parameter 01 depicted, that the DCDW system has a clear potential for indoor air temperature reduction compared to when there's no DCDW system applied to the same interior.
- Also, consecutively, when the number of DCDW panels decreases with 3 fans the heat reduction observed increases.
- The investigation results of parameter 02 depicted, Cooling load requirement for 1m2 with the constant number of fans decreases when the number of DCDW panels increases, since it increases the heat absorption capacity of the system.
- To investigate parameter 03, selected three panels to fans ratios (4:1, 8:1, 12:1) were assessed for maximum cooling capacity for 1m2 with a different number of fans.
- The results depicted, the maximum cooling capacity for 1m2 with 01 fans as 1.39 m2, with 02 fans as 2.62m2, and with 3 fans as 3.94m2.
- Further, with the identified trends, the maximum cooling capacity for 1m2 with any number of fans was obtained.
- According to the results of identifying parameter 04, it was identified that for the optimum prevention of heat in the indoors of the prototype building, the building's West façade should be oriented to 30 degrees from the East.
- If it's morning hours, the indoor heat penetration is further controlled due to shadings.

- The sustainability and the profitability of the Novel DCDW cooling system were assessed using popular LCC assessment methods which are NPV calculations and Simple Pay Back period calculations.
- A real residential building located within near proximity of the Prototype building was modelled in Design Builder for LCC calculations.
- The Master bedroom of the said model with an area of 6x4m2 area 4m height was utilized for LCC assessment with an Air Conditioning load added.
- The DCDW system was installed, on the narrow North facing wall of the selected room, which is 4 x 4 m2, increasing the DCDW area to 20%, 40%, 60%, 80% & 100%.
- Three different temperature set points which are nominally thermally comfortable in the tropics were selected to investigate which are, 25oc, 26oc & 27oc.

- Two operational schedules have also participated in the investigation, 24 hours and 8.00 am to 5.00 pm.
- In four cases with different panels: fan proportions were selected to identify the best proportion for minimum LCC. They are as,
  - Case A - without the panels & fans
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  - Case C - with panels & two fans
  - Case D - with panels & three fans
- NPV for selected cases were considered a maximum of 60 years of the building's nominal lifetime.
- For NPV calculations, Initial costs, with construction, air conditioning, and system installation were calculated and Operational costs such as Energy consumption and electricity costs were calculated in different situations and were obtained through DB simulation results.
- Annual Energy consumption results for selected cases showed that, when utilizing the DCDW system, after some point the energy requirement becomes minus, the DCDW system starts providing indoor cooling its system along and starts the lifetime energy cost saving thereon.
- The results depicted in terms of energy saving, case B performs best.
- Results of the NPV calculations depicted when the Case B Option is used with a 100% panel covering an area, in terms of Net Percent Value for 60yers it costs the least, comparative to the two other cases (case C, D).
- In terms of cost saving and payback period, again Case B performed best not for a single time schedule, but for both schedules. (Residential and commercial schedules)
- Both methods (NPV and Payback period) are evidence that the DCDW cooling system can contribute to a significant operational energy saving, thus operational cost reduction, when compared to space, cooled fully with an active mode.
- Therefore, the economic benefits and the success of the Dynamic Clay Double Wall system are strongly proven in its profitability.

- In conclusion, among all three cases, **case B (system with one fan) is recognized as the best saving option** comparably, **in Energy saving, Net Percent Value and Simple payback period**.
- In conclusion, the invention Dynamic Clay Double Wall system provides a functionally effective, sustainable, energy-efficient, low maintenance, cost-effective, healthy indoor heat reduction solution for the tropics.
- The invention further provides opportunities in popularizing the abundantly available clay material, together with the organic waste-sawdust, as an aesthetically exciting, thermally pleasing, innovative, technologically noncomplex, building intervention, that even the layman can handle.

8.2. Recommendations

- The research recommends using random Saw Dust from sawmills, even with a mixture of different types of timber, yet a future research direction can be opened by studying the impact of the type of timber used as sawdust and the impact of their chemical compositions as an interior material and for heat reduction.
- Research recommends using thicker DCDW panels for better heat absorption in interiors where the area of space is not a restriction.
- Moreover, the invention: The dynamic Clay Double Wall system shows compatibility in utilization from high-end to low-end tropical interiors, as well as from new constructions to energy retrofitting.

8.3. Future directions

- The future direction of the research can pivot towards interior designing or architecture; aesthetical improvements for the DCDW invention, application and utilization potentials of DCDW, as an interior element can be researched.
- Potentials of amalgamating the DCDW system with ‘evaporative cooling’ can be studied in terms of heat reduction, filtration for dust, unhealthy fumes, odour, external noise etc. as a future direction.
- This research involved thermal investigations at an extremely hot dry climate in Sri Lanka to identify its optimum effectiveness, DCDW system further can be evaluated relating to other tropical climates as well.

REFERENCES

[1] R. Hyde, *Climate Responsive Design: A Study of Buildings in Moderate and Hot Humid Climates*. 2000.

[2] V. Olgyay, *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Elsevier Ltd, 1963. doi: 10.1016/j.jenvman.2014.05.006.

[3] B. Givoni, *Man, climate, and architecture*, vol. 6, no. 8. 1969. [Online]. Available: https://www.researchgate.net/profile/Kovo_Akpomie/publication/312611250_Effect_of_cassava_peel_on_the_insulating_properties_of_ogugu_clay_deposit/links/59613084a6fdccc9b114927a/Effect-of-cassava-peel-on-the-insulating-properties-of-ogugu-clay-deposit.pdf

[4] M. Rajapaksha, U. Rajapaksha, and I.-K. Rajapaksha, "Passive climate modification in compact house forms in Galle fort, A case of thermal mass integration," 2013.

[5] N. Jamaludin, M. Faris Khamidi, S. Ngah, A. Wahab, and M. M. A. Klufallah, "Indoor Thermal Environment in Tropical Climate Residential Building", doi: 10.1051/C.

[6] O. K. Akande and M. A. Adebamowo, "Indoor Thermal Comfort for Residential Buildings in Hot-Dry Climate of Nigeria." [Online]. Available: http://nceub.org.uk

[7] N. Jamaludin, M. Faris Khamidi, S. Ngah, A. Wahab, and M. M. A. Klufallah, "Indoor Thermal Environment in Tropical Climate Residential Building", doi: 10.1051/C.

[8] B. C. M. Rodriguez and M. D. Alessandro, "Indoor thermal comfort in the tropics," no. October, 2019.

[9] Baruch.Givoni, E. M. González-cruz, E. Gonzalez, and U. Zulia, "Thermal Performance of Indirect Evaporative Cooling in a Tropical Climate thermal performance of indirect evaporative cooling in a tropical," no. May 2009, 2009, doi: 10.13140/RG.2.1.3813.4486.

[10] B. Givoni and E. Gonzalez, "Thermal performance of indirect evaporative cooling in a tropical climate," *38th ASES National Solar Conference 2009, SOLAR 2009*, vol. 3, no. May 2009, pp. 1734–1769, 2009, doi: 10.13140/RG.2.1.3813.4486.

[11] N. V. Baker, *Passive and low energy building design for tropical island climates*, vol. 35, no. 4. 1987.

[12] P. O. Akadiri, E. A. Chinyio, and P. O. Olomolaiye, “Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector,” *Buildings*, vol. 2, no. 2, pp. 126–152, 2012, doi: 10.3390/buildings2020126.

[13] B. Givoni, *Man, Climate and Architecture*, no. October 2012. 1976. doi: 10.4236/jmmce.2012.1110097.

[14] A. Dimoudi, “Passive cooling of buildings,” *Passive Cooling of Buildings*, no. January 2005, pp. 35–55, 2013, doi: 10.4324/9781315073668.

[15] A. Ragheb, H. El-Shimy, and G. Ragheb, “Green Architecture: A Concept of Sustainability,” *Procedia - Social and Behavioral Sciences*, vol. 216, pp. 778–787, Jan. 2016, doi: 10.1016/j.sbspro.2015.12.075.

[16] D. Asimakopoulos and M. Santamouris, *Passive Cooling of Buildings*, no. August 2016. 1996.

[17] S. J. Emmerich, “Simulated performance of natural and hybrid ventilation systems in an office building,” *HVAC and R Research*, vol. 12, no. 4, pp. 975–1004, 2006, doi: 10.1080/10789669.2006.10391447.

[18] S. Omrani, V. Garcia-Hansen, B. Capra, and R. Drogemuller, “Effect of natural ventilation mode on thermal comfort and ventilation performance: Full-scale measurement,” *Energy and Buildings*, vol. 156, no. 4, pp. 340–351, 2017, doi: 10.1520/gtj10248j.

[19] O. Amer, R. Boukhanouf, and H. G. Ibrahim, “A Review of Evaporative Cooling Technologies,” *International Journal of Environmental Science and Development*, vol. 6, no. 2, pp. 111–117, 2015, doi: 10.7763/IJESD. 2015.V6.571.

[20] L. S. DimoudiA, Androutsopoulos A, “Experimental work on a linked, dynamic and ventilated, wall component.,” *Energy and Buildings*, vol. 122, pp. 386–396, 2004, doi: 10.1016/j.buildenv.2017.06.026.

[21] EBC Annex 62, “Ventilative cooling,” *EBC Annex 62*. pp. 1–5, 2018.

[22] G. Gan, “Interaction Between Wind and Buoyancy Effects in Natural Ventilation of Buildings,” *The Open Construction and Building Technology Journal*, vol. 4, no. 1, pp. 134–145, Dec. 2010, doi: 10.2174/1874836801004010134.

[23] R. Barbosa, M. Barták, J. L. M. Hensen, and M. G. L. C. Loomans, “Ventilative cooling control strategies applied to passive house in order to avoid indoor overheating,” *14th*

International Conference of IBPSA - Building Simulation 2015, BS 2015, Conference Proceedings, no. 2015, pp. 1142–1148, 2015.

[24] R. Hyde *et al.*, “Design Solution Sets for Bioclimatic Retrofit,” *Sustainable Retrofitting of Commercial Buildings*, no. February, pp. 61–88, 2019, doi: 10.4324/9780203119846-7.

[25] T. Standard and I. Ministry, “Engineering Standard for Process Design of Fans and Blowers Original Edition,” 1998.

[26] S. S. Cunha I, Strack T, “‘Fans and Blowers ; Energy efficiency reference guide’, CEATI International Inc.,” *Building and Environment*, vol. 139, no. May, pp. 134–145, 2008, doi: 10.1016/j.buildenv.2018.05.025.

[27] A. G. Kwok, “Thermal Comfort in Naturally-Ventilated and Air-Conditioned Classrooms in the Tropics,” 1990. [Online]. Available: https://escholarship.org/uc/item/65d3k1jt

[28] A. G. Kwok, “Thermal Comfort in Naturally-Ventilated and Air-Conditioned Classrooms in the Tropics,” 1990. [Online]. Available: https://escholarship.org/uc/item/65d3k1jt

[29] J. F. Straube and E. F. P. Burnett, “Vents, Ventilation and Masonry Veneer Wall Systems,” *In Proceedings of the Eighth Canadian Masonry Symposium. Jasper, Alta., Canada*, no. December, p. (pp.-194-207), 1998, [Online]. Available: https://www.researchgate.net/publication/237552112_Vents_ventilation_and_masonry_veneer_wall_systems

[30] S. Boddy and J. Krigger, “Cooling Your Home with Fans and Ventilation.”

[31] B. Givoni, *Passive and Low Energy Cooling of Buildings*, vol. 34, no. 1. 1994. doi: 10.17221/1846-hortsci.

[32] B. Givoni, “Comfort, climate analysis and building design guidelines,” *Energy and Buildings*, vol. 18, no. 1, pp. 11–23, 1992, doi: 10.1016/0378-7788(92)90047-K.

[33] Amos Rapoport, *House form and culture*. 1969.

[34] S. V. Szokolay, *Introduction to Architectural Science: The Basis of Sustainable Design*, vol. 11, no. 2. 2012. doi: 10.3130/jaabe.11.407.

[35] O. H Koenigsberger, *Manual of tropical housing building*, vol. 7, no. November. 1973. doi: 10.3126/jsce.v7i0.26786.

[36] “Green building materials-a Way towards Sustainable Construction Editor IJAIEM I nternational Journal of Application or I nnovation in E ngineering & M anagement (I JAI E M) Web Site: www.ijaiem.org Email: editor@ijaiem.org Volume 4, Issue 4,” 2015. [Online]. Available: www.ijaiem.org

[37] B. Venkatarama Reddy, “Sustainable materials for low carbon buildings,” *International Journal of Low-Carbon Technologies*, vol. 4, no. 3, pp. 175–181, Jul. 2009, doi: 10.1093/ijlct/ctp025.

[38] G. H. Galabada, M. Rajapaksha, F. R. Arooz, and R. Halwatura, “Identifying the Impact of Concrete Specimens Size and Shape on Compressive Strength A Case Study of Mud Concrete,” 2019. [Online]. Available: www.etasr.com

[39] T. A. G. L. J. Glover, D. O. White, “Wood versus Concrete and Steel in House Construction: A Life Cycle Assessment,”,” *Building and Environment*, vol. 100, pp. 104–114, doi: 10.1016/j.buildenv.2016.10.003.

[40] J. C. Morel, A. Mesbah, M. Oggero, and P. Walker, “‘Building houses with local materials: means to drastically reduce the environmental impact of construction,’” *Building and Environment*, vol. 36, no. 5, pp. 2141–2149, 2001, doi: 10.1016/j.buildenv.2006.04.005.

[41] B. H. Rojero, J. N. S. Cuizon, R. L. Menchavez, and S. A. Nawang, “Porous Red Clay-Based Ceramics Fabricated by Pore Self-Forming Technique Porous Red Clay-Based Ceramics Fabricated by Pore Self-Forming Technique,” no. December 2018, 2019.

[42] P. B. Lourenço, F. M. Fernandes, and F. Castro, “Handmade clay bricks: Chemical, physical and mechanical properties,” *International Journal of Architectural Heritage*, vol. 4, no. 1. Routledge, pp. 38–58, 2010. doi: 10.1080/15583050902871092.

[43] G. E. Christidis, “Industrial clays,” *European Mineralogical Union Notes in Mineralogy*, vol. 9, no. 1, pp. 341–414, 2011, doi: 10.1180/EMU-notes.9.9.

[44] M. la Noce, A. lo Faro, and G. Sciuto, “Clay-Based Products Sustainable Development: Some Applications,” 2021, doi: 10.3390/su13031364.

[45] G. Reboux, A. P. Bellanger, S. Roussel, F. Grenouillet, and L. Millon, “‘Moulds in dwellings: Health risks and involved species,’” *material and environment*, vol. 42, no. 10, pp. 3540–3546, 2011, doi: 10.1016/j.buildenv.2006.10.016.

[46] A. Bouchair, "'Terra Literature Review: An Overview of Research in Earthen Architecture Conservation,'" *Building and Environment*, vol. 43, no. 10, p. 174., 2008, doi: 10.1016/j.buildenv.2007.10.005.

[47] P. J. Khedari, Watsanasathaporn, and J. Hirunlabh, "'Development of fibre-based soil–cement block with low thermal conductivity,'" *Building and Environment*, vol. 38, no. 1, pp. 185–193, 2004, doi: 10.1016/S0360-1323(02)00012-4.

[48] M. C. Jiménez Delgado and I. C. Guerrero, "'The selection of soils for unstabilised earth building: A normative review,'" *Construction and Building Materials*, vol. 40, no. 12, pp. 1591–1601, 2007, doi: 10.1016/j.buildenv.2004.12.004.

[49] A. A. Raheem, O. A. Bello, and O. A. Makinde, "'A comparative study of cement and lime stabilized lateritic interlocking blocks,'" *Building and Environment*, vol. 11, no. 1, pp. 25–54, 2010, doi: 10.1016/j.buildenv.2005.07.030.

[50] F. Pacheco-Torgal and S. Jalali, "'Earth construction: Lessons from the past for future eco-efficient construction,'" *Construction and Building Materials*, vol. 44, no. 2, pp. 431–436, 2012, doi: 10.1016/j.buildenv.2008.02.011.

[51] B. Berge, "The Ecology of Building Materials.," *Building and Environment*, vol. 44, no. 4, pp. 826–838, 2009, doi: 10.1016/j.buildenv.2008.05.020.

[52] S. Deboucha and R. Hashim, "'A review on bricks and stabilized compressed earth blocks,'" *Building and Environment*, vol. 42, no. 2, pp. 926–932, 2011, doi: 10.1016/j.buildenv.2005.10.017.

[53] A. Ramos, M. P. Sáez, M. A. Rodríguez, M. N. Antón, J. Gómez, and P. Piloto, "Thermal properties of fired clay bricks from waste recycling. A review of studies," *Fire Research*, vol. 3, no. 1, Oct. 2019, doi: 10.4081/fire.2019.71.

[54] K. A. Heathcote, "'Durability of earthwall buildings,'" *Construction and Building Materials*, vol. 45, no. 6, pp. 1422–1433, 1995, doi: 10.1016/j.buildenv.2009.12.005.

[55] J. Folaranmi, "Effect of Sawdust Additive on the Properties of Clay," 2009. [Online]. Available: http://ljs.academicdirect.org/

[56] Lesley, "3 Stages of Firing Clay – A Beginners Guide to Firing Pottery Beginner info," *https://thepotterywheel.com/stages-of-firing-clay/*.

[57] T. Okada, K., Uchiyama, S., Isobe, Kameshima, Y., Nakajima,, N., & Kurata, "Capillary rise properties of porous mullite ceramics prepared by an extrusion method

using organic fibers as the pore former.," *Building and Environment*, vol. 55, pp. 110–116, 2009, doi: 10.1016/j.buildenv.2011.12.018.

[58] Jayawardena D., "The Present Status of the Development of Mineral Resources in Sri Lanka," 1984.

[59] M. Nakagawa, K. v Wilbert Kehelpannala B, T. Manabe, L. Ranaweera, and A. Nasu, "Kaolin deposit at meetiyagoda, southwestern sri lanka," *Clay Science*, vol. 21, pp. 29–34, 2017, doi: 10.11362/jcssjclayscience.21.2_29.

[60] "Four Methods: The Very Basics Wheel Throwing Hand Building Glazing." [Online]. Available: http://www.wikihow.com/Make-Ceramics

[61] V. K., "Principles of heat transfer in porous media.," *Building and Environment*, vol. 57, pp. 362–369, 2015, doi: 10.1016/j.buildenv.2012.06.006.

[62] Z. H. Zhang R, Feng J, Cheng X, Gong L, Li Y, "Porous thermal insulation materials derived fromfly ash using a foaming and slip casting method.," *Energy and Buildings*, vol. 84, pp. 105–113, 2014, doi: 10.1016/j.buildenv.2014.11.001.

[63] A. F. Buratti C, Moretti E, Belloni E, "Thermal and acoustic performance evaluation of new basalt fiber insulation panels for buildings.," *Energy Procedia*, vol. 97, pp. 69–81, 2015, doi: 10.1016/j.buildenv.2015.12.004.

[64] C. W., "Thermal analysis on the cooling performance of a wet porous evaporative plate for building.," *energy conseration and management*, vol. 114, pp. 257–266, 2017, doi: 10.1016/j.buildenv.2016.12.028.

[65] J. Folaranmi, "Effect of Additives on the Thermal Conductivity of Clay", [Online]. Available: http://ljs.academicdirect.org

[66] S. NA. Kadir A, Zulkifly SNM, Abdullah MMAB, *"The Utilization of Coconut Fibre into Fired Clay Brick", Trans Tech Publications, Switzerland*, vol. 123. Elsevier Ltd, 2016. doi: 10.1016/j.buildenv.2017.07.023.

[67] S. Maliakal, T and Thiyyakkandi, "'Influence of randomly distributed coir fibers on shear strength of clay,'" *otechnical and Geological Engineering*, vol. 135, no. December 2017, pp. 194–201, 2013, doi: 10.1016/j.buildenv.2018.03.012.

[68] C. Puppala, A.J., and Musenda, "'Effect of fibre reinforcement on strength and volume change in expansive soils'," *Transportation Research Record*, vol. 132, no. January, pp. 83–95, 2002, doi: 10.1016/j.buildenv.2018.01.029.

[69] S. M. K. Y.M. Kim, J.H. Lee, “Effects of double skin envelopes on natural ventilation and heating loads in office buildings,” *Energy and Buildings*, vol. 142, pp. 34–46, 2013, doi: 10.1016/j.buildenv.2018.05.051.

[70] M.H. Tascon, “Experimental and Computational Evaluation of Thermal Performance and Overheating in Double Skin Facades,” *International Journal of Advances in Engineering & Technology*, vol. 6, no. 4, pp. 1524–1534, 2008.

[71] W. Jager, “‘Double Skin Facades-sustainable Concepts’, Malmo, Sweden,” *Building and Environment*, vol. 140, no. January, pp. 184–193, doi: 10.1016/j.buildenv.2018.05.033.

[72] B. M. Wigginton, “Architectural Research Quarterly, Intelligent Glass Facades by Andrea Compagno,” *Bhumi, The Planning Research Journal*, vol. 3, no. 1, p. 25, 2008, doi: 10.4038/bhumi. V 3i1.12.

[73] Y. García, J. Cuadrado, J. M. Blanco, and E. Roji, “Optimizing the indoor thermal behaviour of housing units in hot humid climates: Analysis and modelling of sustainable constructive alternatives,” *Indoor and Built Environment*, vol. 28, no. 6, pp. 772–789, 2019, doi: 10.1177/1420326X18793965.

[74] H. Z. Alibaba and M. B. Ozdeniz, “Energy performance and thermal comfort of double-skin and single-skin facades in warm-climate offices,” *Journal of Asian Architecture and Building Engineering*, vol. 15, no. 3, pp. 635–642, 2016, doi: 10.3130/jaabe.15.635.

[75] W. N. Hien, W. Liping, A. N. Chandra, A. R. Pandey, and W. Xiaolin, “Effects of double-glazed facade on energy consumption, thermal comfort and condensation for a typical office building in Singapore,” *Energy and Buildings*, vol. 37, no. 6, pp. 563–572, 2005, doi: 10.1016/j.enbuild.2004.08.004.

[76] G. Ballestini, M. De Carli, N. Masiero, and G. Tombola, “Possibilities and limitations of natural ventilation in restored industrial archaeology buildings with a double-skin façade in Mediterranean climates,” *Building and Environment*, vol. 40, no. 7, pp. 983–995, 2005, doi: 10.1016/j.buildenv.2004.09.015.

[77] W. Ding, Y. Hasemi, and T. Yamada, “Natural ventilation performance of a double-skin façade with a solar chimney,” *Energy and Buildings*, vol. 37, no. 4, pp. 411–418, 2005, doi: 10.1016/j.enbuild.2004.08.002.

[78] C. Y. Yi and C. Peng, "Microclimate change outdoor and indoor coupled simulation for passive building adaptation design," *Procedia Computer Science*, vol. 32, no. 0, pp. 691–698, 2014, doi: 10.1016/j.procs.2014.05.478.

[79] Y. Chen, J. Liu, J. Pei, X. Cao, Q. Chen, and Y. Jiang, "Experimental and simulation study on the performance of daylighting in an industrial building and its energy saving potential," *Energy and Buildings*, vol. 73, pp. 184–191, 2014, doi: 10.1016/j.enbuild.2014.01.030.

[80] E. M. Schau, M. Traverso, A. Lehmannann, and M. Finkbeiner, "Life cycle costing in sustainability assessment-A case study of remanufactured alternators," *Sustainability*, vol. 3, no. 11, pp. 2268–2288, 2011, doi: 10.3390/su3112268.

[81] J. Schade, "Life cycle cost calculation models for buildings."

[82] "Life-cycle costing of new processes, materials, and products Executive summary fostering industrial symbiosis for a sustainable resource intensive industry across the extended construction value chain," 2017.

[83] T. E. Swarr *et al.*, "Environmental life-cycle costing: A code of practice," *International Journal of Life Cycle Assessment*, vol. 16, no. 5. pp. 389–391, Jun. 2011. doi: 10.1007/s11367-011-0287-5.

[84] R. Emmanuel, "Estimating the environmental suitability of wall materials: Preliminary results from Sri Lanka," *Building and Environment*, vol. 39, no. 10, pp. 1253–1261, Oct. 2004, doi: 10.1016/j.buildenv.2004.02.012.

[85] C. Udawattha and R. Halwatura, "Life cycle cost of different Walling material used for affordable housing in tropics," *Case Studies in Construction Materials*, vol. 7, pp. 15–29, Dec. 2017, doi: 10.1016/j.cscm.2017.04.005.

[86] R. Arooz and R. Halwatura, "Prague Decision-Support Tools and Assessment Methods for Sustainable Built Environment Life Cycle Costing And Embodied Energy Analysis Of Self-Compacting In-Situ Cast Mud-Concrete Load Bearing Walling System (MCW)-An Innovative Earth Based Walling Material Application For Energy Efficient Buildings."

[87] "https://www.brighthubengineering.com/hvac/41262-what-is-psychrometric-chart-components-of-psychrometric-chart/."

[88] J. F. Nicol and M. A. Humphreys, “Adaptive thermal comfort and sustainable thermal standards for buildings,” in *Energy and Buildings*, Jul. 2002, vol. 34, no. 6, pp. 563–572. doi: 10.1016/S0378-7788(02)00006-3.

[89] “https://humiditycontrol.com/psychrometric-chart/.”

[90] M. Kolokotroni and P. Heiselberg, “IEA-EBC Programme-Annex 62 Ventilative Cooling Ventilative Cooling state-of-the-art review.”

[91] U. Rajapaksha, “Heat stress pattern in conditioned office buildings with shallow plan forms in Metropolitan Colombo,” *Buildings*, vol. 9, no. 2, Jan. 2019, doi: 10.3390/buildings9020035.

[92] G. Hu, S. Hassanli, K. C. S. Kwok, and K. T. Tse, “Wind-induced responses of a tall building with a double-skin façade system,” *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 168, pp. 91–100, Sep. 2017, doi: 10.1016/j.jweia.2017.05.008.

[93] “Types of Clay Bodies - Kiln Arts.” https://kilnarts.org/education/ceramic-pottery/the-basics-of-clay/types-of-clay/ (accessed Jan. 16, 2022).

[94] Daniel Rhodes, *Clay and Glazes for the Potter*.

[95] Lesley, “https://thepotterywheel.com/types-of-clay-for-pottery/#earthenware”.

[96] B. Berge, “The Ecology of Building Materials.,” *Building and Environment*, vol. 44, no. 4, pp. 826–838, 2009, doi: 10.1016/j.buildenv.2008.05.020.

[97] K. A. Heathcote, “Durability of earthwall buildings,” *Construction and Building Materials*, vol. 9, no. 3, pp. 185–189, Jun. 1995, doi: 10.1016/0950-0618(95)00035-E.

[98] C. W., “Thermal analysis on the cooling performance of a wet porous evaporative plate for building.,” *energy conseration and management*, vol. 114, pp. 257–266, 2017, doi: 10.1016/j.buildenv.2016.12.028.

[99] “Clay Shrinkage During Drying and Firing | Preventing Defects.” [Online]. Available: http://www.lakesidepottery.com/HTML Text/Tips/Clay drying and firing process.htm

[100] N. Phonphuak, M. Teerakun, A. Srisuwan, P. Ruenruangrit, and P. Saraphirom, “The use of sawdust waste on physical properties and thermal conductivity of fired clay brick production,” *International Journal of GEOMATE*, vol. 18, no. 69, pp. 24–29, 2020, doi: 10.21660/2020.69.5706.

[101] "Goodbye to the cavity wall - Guten Tag! to the fired clay block - Renovate Green."

[102] P. M. Nigay, T. Cutard, and A. Nzihou, "The impact of heat treatment on the microstructure of a clay ceramic and its thermal and mechanical properties," *Ceramics International*, vol. 43, no. 2, pp. 1747–1754, 2017, doi: 10.1016/j.ceramint.2016.10.084.

[103] L. C. Haw, "Empirical study of a wind-induced natural ventilation tower under hot and humid climatic conditions," *Energy and Buildings*, vol. 65, no. 2, pp. 153–159, 2012.

[104] P. M. Nigay, T. Cutard, and A. Nzihou, "The impact of heat treatment on the microstructure of a clay ceramic and its thermal and mechanical properties," *Ceramics International*, vol. 43, no. 2, pp. 1747–1754, 2017, doi: 10.1016/j.ceramint.2016.10.084.

[105] ASTM C20-00, "Standard Test Methods for Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick and Shapes by Boiling Water," *American Society for Testing and Materials*, vol. 00, no. Reapproved 2015, pp. 1–3, 2015, doi: 10.1520/C0020-00R10.2.

[106] R. Hyde, *Climate Responsive Design: A Study of Buildings in Moderate and Hot Humid Climates*, vol. 8, no. 15. 2000. doi: 10.5897/SRE12.608.

[107] N. S. Senanayake, D. Shyamalee, A. D. U. S. Amarasinghe, and N. S. Senanayaka, "Evaluation of different binding materials in forming biomass briquettes with saw dust Power Generation from MSW in Sri Lanka View project Hackathon on Digital Education View Project Evaluation of different binding materials in forming biomass briquettes with saw dust," *International Journal of Scientific and Research Publications*, vol. 5, no. 3, 2015, [Online]. Available: https://www.researchgate.net/publication/284534867

[108] J. Folaranmi, "Effect of Additives on the Thermal Conductivity of Clay", [Online]. Available: http://ljs.academicdirect.org

[109] M. Rajapaksha and R. U. Halwatura, "'Clay', for tropical interiors."

[110] M. Rajapaksha and R. U. Halwatura, "Poro-therm clay wall panel system for indoor cooling," *2020 From Innovation to Impact, FITI 2020*, 2020, doi: 10.1109/FITI52050.2020.9424896.

[111] Z. Alwan and P. Jones, “The importance of embodied energy in carbon footprint assessment,” *Structural Survey*, vol. 32, no. 1, pp. 49–60, 2014, doi: 10.1108/SS-01-2013-0012.

[112] R. Arooz and R. Halwatura, “Prague Decision-Support Tools and Assessment Methods for Sustainable Built Environment Life Cycle Costing and Embodied Energy Analysis of Self-Compacting In-Situ Cast Mud-Concrete Load Bearing Walling System (MCW)-An Innovative Earth Based Walling Material Application For Energy Efficient Buildings.”

APPENDICES

Appendix A

building dimension(m)

hight	4
lengh	6
width	4
area	24
wall area (m^2)	16
20%	3.2
40%	6.4
60%	9.6
80%	12.8
100%	16

		20%	40%	60%	80%	100%
m2	1	3.2	6.4	9.6	12.8	16
panel (1m2)						
cost	$ 5,000.00	$16,000.00	$32,000.00	$48,000.00	$64,000.00	$80,000.00

Construction

1 m2	$ 54,347.83
24 m2	$1,304,347.83

air conditioner 10,527 BTU Required

initial	$ 214,990.00
installation	$ 8,000.00
total	**$ 222,990.00**

fan initial cost

fan 1 — intial cost

	for 1m2	$ 2,805.76
20%	3.2	$ 8,978.42
40%	6.4	$17,956.83
60%	9.6	$26,935.25
80%	12.8	$35,913.67
100%	16	$44,892.09

fan 2 — intial cost

	for 1m2	$ 2,977.10
20%	3.2	$ 9,526.72
40%	6.4	$19,053.44
60%	9.6	$28,580.15
80%	12.8	$38,106.87
100%	16	$47,633.59

fan 3 — intial cost

	for 1m2	$ 2,969.54
20%	3.2	$ 9,502.54
40%	6.4	$19,005.08
60%	9.6	$28,507.61
80%	12.8	$38,010.15
100%	16	$47,512.69

A

costruction	$ 1,304,347.83
AC	$ 222,990.00
Total	**$ 1,527,337.83**

B

costruction	$ 1,304,347.83
AC	$ 222,990.00
Total	$ 1,527,337.83

case B

		panel	$ 16,000.00	
20%	3.20	fan	$ 8,978.42	$ 24,978.42
		panel	$ 32,000.00	
40%	6.40	fan	$ 17,956.83	$ 49,956.83
		panel	$ 48,000.00	
60%	9.60	fan	$ 26,935.25	$ 74,935.25
		panel	$ 64,000.00	
80%	12.80	fan	$ 35,913.67	$ 99,913.67
		panel	$ 80,000.00	
100%	16.00	fan	$ 44,892.09	$ 124,892.09

with AC

	20%	40%	60%	80%	100%
con+AC	$ 1,527,337.83	$ 1,527,337.83	$ 1,527,337.83	$ 1,527,337.83	$ 1,527,337.83
panel+fan	$ 24,978.42	$ 49,956.83	$ 74,935.25	$ 99,913.67	$ 124,892.09
total	**$ 1,552,316.24**	**$ 1,577,294.66**	**$ 1,602,273.08**	**$ 1,627,251.50**	**$ 1,652,229.91**

Without AC

	20%	40%	60%	80%	100%
con	$ 1,304,347.83	$ 1,304,347.83	$ 1,304,347.83	$ 1,304,347.83	$ 1,304,347.83
panel+fan	$ 24,978.42	$ 49,956.83	$ 74,935.25	$ 99,913.67	$ 124,892.09
total	**$ 1,329,326.24**	**$ 1,354,304.66**	**$ 1,379,283.08**	**$ 1,404,261.50**	**$ 1,429,239.91**

case C

		panel	$ 16,000.00	
20%	3.20	fan	$ 9,526.72	$ 25,526.72
		panel	$ 32,000.00	
40%	6.40	fan	$ 19,053.44	$ 51,053.44
		panel	$ 48,000.00	
60%	9.60	fan	$ 28,580.15	$ 76,580.15
		panel	$ 64,000.00	
80%	12.80	fan	$ 38,106.87	$ 102,106.87
		panel	$ 80,000.00	
100%	16.00	fan	$ 47,633.59	$ 127,633.59

with AC

	20%	40%	60%	80%	100%
con+AC	$ 1,527,337.83	$ 1,527,337.83	$ 1,527,337.83	$ 1,527,337.83	$ 1,527,337.83
panel+fan	$ 25,526.72	$ 51,053.44	$ 76,580.15	$ 102,106.87	$ 127,633.59
total	**$ 1,552,864.54**	**$ 1,578,391.26**	**$ 1,603,917.98**	**$ 1,629,444.70**	**$ 1,654,971.41**

Without AC

	20%	40%	60%	80%	100%
con	$ 1,304,347.83	$ 1,304,347.83	$ 1,304,347.83	$ 1,304,347.83	$ 1,304,347.83
panel+fan	$ 25,526.72	$ 51,053.44	$ 76,580.15	$ 102,106.87	$ 127,633.59
total	**$ 1,329,874.54**	**$ 1,355,401.26**	**$ 1,380,927.98**	**$ 1,406,454.70**	**$ 1,431,981.41**

case D

		panel	$ 16,000.00	
20%	3.20	fan	$ 9,502.54	$ 25,502.54
		panel	$ 32,000.00	
40%	6.40	fan	$ 19,005.08	$ 51,005.08
		panel	$ 48,000.00	
60%	9.60	fan	$ 28,507.61	$ 76,507.61
		panel	$ 64,000.00	
80%	12.80	fan	$ 38,010.15	$ 102,010.15
		panel	$ 80,000.00	
100%	16.00	fan	$ 47,512.69	$ 127,512.69

with AC

	20%	40%	60%	80%	100%
con+AC	$ 1,527,337.83	$ 1,527,337.83	$ 1,527,337.83	$ 1,527,337.83	$ 1,527,337.83
panel+fan	$ 25,502.54	$ 51,005.08	$ 76,507.61	$ 102,010.15	$ 127,512.69
total	**$ 1,552,840.36**	**$ 1,578,342.90**	**$ 1,603,845.44**	**$ 1,629,347.98**	**$ 1,654,850.52**

Without AC

	20%	40%	60%	80%	100%
con	$ 1,304,347.83	$ 1,304,347.83	$ 1,304,347.83	$ 1,304,347.83	$ 1,304,347.83
panel+fan	$ 25,502.54	$ 51,005.08	$ 76,507.61	$ 102,010.15	$ 127,512.69
total	**$ 1,329,850.36**	**$ 1,355,352.90**	**$ 1,380,855.44**	**$ 1,406,357.98**	**$ 1,431,860.52**

Appendix B

fan power (w) 2.4 kWh = (watts × hrs) ÷ 1,000

	hours	wh	kWh	kwh/ annum
for 8:00 to 17:00	9	21.6	0.0216	7.78
for 24hrs	24	57.6	0.0576	20.74

Energy Charge (LKR/kWh) 12.2

fan 1	intial cost	operational cost	
		for 8:00 to 17:00	for 24hrs
for (1.39m^2)	$ 3,900.00	$ 94.87	$ 252.98
for 1m2	$ 2,805.76	$ 68.25	$ 182.00

fan 2	intial cost	operational cost	
		for 8:00 to 17:00	for 24hrs
for (2.62m2)	$ 7,800.00	$ 189.73	$ 505.96
for 1m2	$ 2,977.10	$ 72.42	$ 193.11

fan 3	intial cost	operational cost	
		for 8:00 to 17:00	for 24hrs
for (3.94m2)	$11,700.00	$ 284.60	$ 758.94
for 1m2	$ 2,969.54	$ 72.23	$ 192.62

fan 1		intial cost	operational cost/ annum			operational cost for 10 years	
			for 8:00 to 17:	for 24hrs		for 8:00 to 17:00	for 24hrs
	for 1m2	$ 2,805.76	$ 68.25	$ 182.00			
20%	3.2	$ 8,978.42	$ 218.40	$ 582.40	20%	$ 2,183.99	$ 5,823.98
40%	6.4	$ 17,956.83	$ 436.80	$ 1,164.80	40%	$ 4,367.99	$ 11,647.96
60%	9.6	$ 26,935.25	$ 655.20	$ 1,747.19	60%	$ 6,551.98	$ 17,471.94
80%	12.8	$ 35,913.67	$ 873.60	$ 2,329.59	80%	$ 8,735.97	$ 23,295.93
100%	16	$ 44,892.09	$ 1,092.00	$ 2,911.99	100%	$ 10,919.97	$ 29,119.91

fan 2		intial cost	operational cost/ annum			operational cost for 10 years	
			for 8:00 to 17:	for 24hrs		for 8:00 to 17:00	for 24hrs
	for 1m2	$ 2,977.10	$ 72.42	$ 193.11			
20%	3.2	$ 9,526.72	$ 231.74	$ 617.96	20%	$ 2,317.37	$ 6,179.64
40%	6.4	$ 19,053.44	$ 463.47	$ 1,235.93	40%	$ 4,634.73	$ 12,359.29
60%	9.6	$ 28,580.15	$ 695.21	$ 1,853.89	60%	$ 6,952.10	$ 18,538.93
80%	12.8	$ 38,106.87	$ 926.95	$ 2,471.86	80%	$ 9,269.47	$ 24,718.58
100%	16	$ 47,633.59	$ 1,158.68	$ 3,089.82	100%	$ 11,586.83	$ 30,898.22

fan 3		intial cost	operational cost/ annum			operational cost for 10 years	
			for 8:00 to 17:	for 24hrs		for 8:00 to 17:00	for 24hrs
	for 1m2	$ 2,969.54	$ 72.23	$ 192.62			
20%	3.2	$ 9,502.54	$ 231.15	$ 616.40	20%	$ 2,311.49	$ 6,163.96
40%	6.4	$ 19,005.08	$ 462.30	$ 1,232.79	40%	$ 4,622.97	$ 12,327.92
60%	9.6	$ 28,507.61	$ 693.45	$ 1,849.19	60%	$ 6,934.46	$ 18,491.88
80%	12.8	$ 38,010.15	$ 924.59	$ 2,465.58	80%	$ 9,245.94	$ 24,655.84
100%	16	$ 47,512.69	$ 1,155.74	$ 3,081.98	100%	$ 11,557.43	$ 30,819.80

Appendix C

CASE A

250c 8:00 to 17:00

YEAR	RENOVATION COST (AC)	ELECRTRICITY COST (AC)	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 464,358.84	$ 464,358.84	$ 464,358.84
20	$ 222,990.00	$ 464,358.84	$ 687,348.84	$ 1,151,707.68
30		$ 464,358.84	$ 464,358.84	$ 1,616,066.52
40	$ 222,990.00	$ 464,358.84	$ 687,348.84	$ 2,303,415.36
50		$ 464,358.84	$ 464,358.84	$ 2,767,774.20
60		$ 464,358.84	$ 464,358.84	**$ 3,232,133.04**
		initial cost		$ 1,527,337.83
	total			**$ 4,759,470.87**

250c 24 hours

YEAR	RENOVATION COST (AC)	ELECRTRICITY COST (AC)	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 1,009,746.42	$ 1,009,746.42	$ 1,009,746.42
20	$ 222,990.00	$ 1,009,746.42	$ 1,232,736.42	$ 2,242,482.84
30		$ 1,009,746.42	$ 1,009,746.42	$ 3,252,229.26
40	$ 222,990.00	$ 1,009,746.42	$ 1,232,736.42	$ 4,484,965.68
50		$ 1,009,746.42	$ 1,009,746.42	$ 5,494,712.10
60		$ 1,009,746.42	$ 1,009,746.42	**$ 6,504,458.52**
		initial cost		$ 1,527,337.83
	total			**$ 8,031,796.35**

260c 8:00 to 17:00

YEAR	RENOVATION COST (AC)	ELECRTRICITY COST (AC)	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 347,118.06	$ 347,118.06	$ 347,118.06
20	$ 222,990.00	$ 347,118.06	$ 570,108.06	$ 917,226.12
30		$ 347,118.06	$ 347,118.06	$ 1,264,344.18
40	$ 222,990.00	$ 347,118.06	$ 570,108.06	$ 1,834,452.24
50		$ 347,118.06	$ 347,118.06	$ 2,181,570.30
60		$ 347,118.06	$ 347,118.06	**$ 2,528,688.36**
		initial cost		$ 1,527,337.83
	total			**$ 4,056,026.19**

260c 24 hours

YEAR	RENOVATION COST (AC)	ELECRTRICITY COST (AC)	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 695,524.44	$ 695,524.44	$ 695,524.44
20	$ 222,990.00	$ 695,524.44	$ 918,514.44	$ 1,614,038.88
30		$ 695,524.44	$ 695,524.44	$ 2,309,563.32
40	$ 222,990.00	$ 695,524.44	$ 918,514.44	$ 3,228,077.76
50		$ 695,524.44	$ 695,524.44	$ 3,923,602.20
60		$ 695,524.44	$ 695,524.44	**$ 4,619,126.64**
		initial cost		$ 1,527,337.83
	total			**$ 6,146,464.47**

270c 8:00 to 17:00

YEAR	RENOVATION COST (AC)	ELECRTRICITY COST (AC)	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 239,344.48	$ 239,344.48	$ 239,344.48
20	$ 222,990.00	$ 239,344.48	$ 462,334.48	$ 701,678.96
30		$ 239,344.48	$ 239,344.48	$ 941,023.44
40	$ 222,990.00	$ 239,344.48	$ 462,334.48	$ 1,403,357.92
50		$ 239,344.48	$ 239,344.48	$ 1,642,702.40
60		$ 239,344.48	$ 239,344.48	**$ 1,882,046.88**
		initial cost		$ 1,527,337.83
	total			**$ 3,409,384.71**

270c 24 hours

YEAR	RENOVATION COST (AC)	ELECRTRICITY COST (AC)	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 431,932.46	$ 431,932.46	$ 431,932.46
20	$ 222,990.00	$ 431,932.46	$ 654,922.46	$ 1,086,854.92
30		$ 431,932.46	$ 431,932.46	$ 1,518,787.38
40	$ 222,990.00	$ 431,932.46	$ 654,922.46	$ 2,173,709.84
50		$ 431,932.46	$ 431,932.46	$ 2,605,642.30
60		$ 431,932.46	$ 431,932.46	**$ 3,037,574.76**
		initial cost		$ 1,527,337.83
	total			**$ 4,564,912.59**

Appendix D

CASE B

250c 8:00 to 17:00

20%

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN
	AC	Fan	AC	Fan		
10		$ 8,978.42	$ 401,683.81	$ 2,183.99	$ 412,846.22	$ 412,846.22
20	$222,990.00	$ 8,978.42	$ 401,683.81	$ 2,183.99	$ 635,836.22	$ 1,048,682.45
30		$ 8,978.42	$ 401,683.81	$ 2,183.99	$ 412,846.22	$ 1,461,528.67
40	$222,990.00	$ 8,978.42	$ 401,683.81	$ 2,183.99	$ 635,836.22	$ 2,097,364.89
50		$ 8,978.42	$ 401,683.81	$ 2,183.99	$ 412,846.22	$ 2,510,211.12
60			$ 401,683.81	$ 2,183.99	$ 403,867.81	**$ 2,914,078.92**
			initial cost			$ 1,552,316.24
	total					**$ 4,466,395.17**

20%

250c 24 hours

YEAR	NOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF
	AC	Fan	AC	Fan		
10		$ 8,978.42	$ 842,613.01	$ 5,823.98	$ 857,415.41	$ 857,415.41
20	$222,990.00	$ 8,978.42	$ 842,613.01	$ 5,823.98	###########	$ 1,937,820.83
30		$ 8,978.42	$ 842,613.01	$ 5,823.98	$ 857,415.41	$ 2,795,236.24
40	$222,990.00	$ 8,978.42	$ 842,613.01	$ 5,823.98	###########	$ 3,875,641.65
50		$ 8,978.42	$ 842,613.01	$ 5,823.98	$ 857,415.41	$ 4,733,057.07
60			$ 842,613.01	$ 5,823.98	$ 848,437.00	**$ 5,581,494.06**
initial cost						$ 1,552,316.24
	total					**$ 7,133,810.31**

20%

260c 8:00 to 17:00

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF
	AC	Fan	AC	Fan		
10		$ 8,978.42	$ 284,443.03	$ 2,183.99	$ 295,605.44	$ 295,605.44
20	$ 222,990.00	$ 8,978.42	$ 284,443.03	$ 2,183.99	$ 518,595.44	$ 814,200.89
30		$ 8,978.42	$ 284,443.03	$ 2,183.99	$ 295,605.44	$ 1,109,806.33
40	$ 222,990.00	$ 8,978.42	$ 284,443.03	$ 2,183.99	$ 518,595.44	$ 1,628,401.77
50		$ 8,978.42	$ 284,443.03	$ 2,183.99	$ 295,605.44	$ 1,924,007.22
60			$ 284,443.03	$ 2,183.99	$ 286,627.03	**$ 2,210,634.24**
			initial cost			$ 1,552,316.24
	total					**$ 3,762,950.49**

40%

250c 8:00 to 17:00

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 17,956.83	$ 339,008.79	$ 4,367.99	$ 361,333.61	$ 361,333.61
20	$222,990.00	$ 17,956.83	$ 339,008.79	$ 4,367.99	$ 584,323.61	$ 945,657.21
30		$ 17,956.83	$ 339,008.79	$ 4,367.99	$ 361,333.61	$ 1,306,990.82
40	$222,990.00	$ 17,956.83	$ 339,008.79	$ 4,367.99	$ 584,323.61	$ 1,891,314.43
50		$ 17,956.83	$ 339,008.79	$ 4,367.99	$ 361,333.61	$ 2,252,648.03
60			$ 339,008.79	$ 4,367.99	$ 343,376.77	**$ 2,596,024.81**
			initial cost			$ 1,577,294.66
	total					**$ 4,173,319.47**

40%

250c 24 hours

YEAR	NOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 17,956.83	$ 675,479.61	$ 11,647.96	$ 705,084.41	$ 705,084.41
20	$222,990.00	$ 17,956.83	$ 675,479.61	$ 11,647.96	$ 928,074.41	$ 1,633,158.81
30		$ 17,956.83	$ 675,479.61	$ 11,647.96	$ 705,084.41	$ 2,338,243.22
40	$222,990.00	$ 17,956.83	$ 675,479.61	$ 11,647.96	$ 928,074.41	$ 3,266,317.63
50		$ 17,956.83	$ 675,479.61	$ 11,647.96	$ 705,084.41	$ 3,971,402.03
60			$ 675,479.61	$ 11,647.96	$ 687,127.57	**$ 4,658,529.61**
initial cost						$ 1,577,294.66
	total					**$ 6,235,824.27**

40%

260c 8:00 to 17:00

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 17,956.83	$ 221,768.01	$ 4,367.99	$ 244,092.83	$ 244,092.83
20	$ 222,990.00	$ 17,956.83	$ 221,768.01	$ 4,367.99	$ 467,082.83	$ 711,175.65
30		$ 17,956.83	$ 221,768.01	$ 4,367.99	$ 244,092.83	$ 955,268.48
40	$ 222,990.00	$ 17,956.83	$ 221,768.01	$ 4,367.99	$ 467,082.83	$ 1,422,351.31
50		$ 17,956.83	$ 221,768.01	$ 4,367.99	$ 244,092.83	$ 1,666,444.13
60			$ 221,768.01	$ 4,367.99	$ 226,135.99	**$ 1,892,580.13**
			initial cost			$ 1,577,294.66
	total					**$ 3,469,874.79**

60%

250c 8:00 to 17:00

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 26,935.25	$ 276,333.76	$ 6,551.98	$ 309,820.99	$ 309,820.99
20	$222,990.00	$ 26,935.25	$ 276,333.76	$ 6,551.98	$ 532,810.99	$ 842,631.98
30		$ 26,935.25	$ 276,333.76	$ 6,551.98	$ 309,820.99	$ 1,152,452.97
40	$222,990.00	$ 26,935.25	$ 276,333.76	$ 6,551.98	$ 532,810.99	$ 1,685,263.96
50		$ 26,935.25	$ 276,333.76	$ 6,551.98	$ 309,820.99	$ 1,995,084.95
60			$ 276,333.76	$ 6,551.98	$ 282,885.74	**$ 2,277,970.69**
			initial cost			$ 1,602,273.08
	total					**$ 3,880,243.77**

60%

250c 24 hours

YEAR	NOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 26,935.25	$ 508,346.20	$ 17,471.94	$ 552,753.40	$ 552,753.40
20	$222,990.00	$ 26,935.25	$ 508,346.20	$ 17,471.94	$ 775,743.40	$ 1,328,496.80
30		$ 26,935.25	$ 508,346.20	$ 17,471.94	$ 552,753.40	$ 1,881,250.20
40	$222,990.00	$ 26,935.25	$ 508,346.20	$ 17,471.94	$ 775,743.40	$ 2,656,993.60
50		$ 26,935.25	$ 508,346.20	$ 17,471.94	$ 552,753.40	$ 3,209,747.00
60			$ 508,346.20	$ 17,471.94	$ 525,818.15	**$ 3,735,565.15**
initial cost						$ 1,602,273.08
	total					**$ 5,337,838.23**

60%

260c 8:00 to 17:00

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 26,935.25	$ 159,092.98	$ 6,551.98	$ 192,580.21	$ 192,580.21
20	$ 222,990.00	$ 26,935.25	$ 159,092.98	$ 6,551.98	$ 415,570.21	$ 608,150.42
30		$ 26,935.25	$ 159,092.98	$ 6,551.98	$ 192,580.21	$ 800,730.63
40	$ 222,990.00	$ 26,935.25	$ 159,092.98	$ 6,551.98	$ 415,570.21	$ 1,216,300.84
50		$ 26,935.25	$ 159,092.98	$ 6,551.98	$ 192,580.21	$ 1,408,881.05
60			$ 159,092.98	$ 6,551.98	$ 165,644.96	**$ 1,574,526.01**
			initial cost			$ 1,602,273.08
	total					**$ 3,176,799.09**

80%

250c 8:00 to 17:00

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 35,913.67	$ 213,658.73	$ 8,735.97	$ 258,308.37	$ 258,308.37
20	$222,990.00	$ 35,913.67	$ 213,658.73	$ 8,735.97	$ 481,298.37	$ 739,606.75
30		$ 35,913.67	$ 213,658.73	$ 8,735.97	$ 258,308.37	$ 997,915.12
40	$222,990.00	$ 35,913.67	$ 213,658.73	$ 8,735.97	$ 481,298.37	$ 1,479,213.49
50		$ 35,913.67	$ 213,658.73	$ 8,735.97	$ 258,308.37	$ 1,737,521.87
60			$ 213,658.73	$ 8,735.97	$ 222,394.70	**$ 1,959,916.57**
			initial cost			$ 1,627,251.50
	total					**$ 3,587,168.07**

80% 250c 24 hours

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 35,913.67	$ 341,212.80	$ 23,295.93	$ 400,422.39	$ 400,422.39
20	$222,990.00	$ 35,913.67	$ 341,212.80	$ 23,295.93	$ 623,412.39	$ 1,023,834.79
30		$ 35,913.67	$ 341,212.80	$ 23,295.93	$ 400,422.39	$ 1,424,257.18
40	$222,990.00	$ 35,913.67	$ 341,212.80	$ 23,295.93	$ 623,412.39	$ 2,047,669.58
50		$ 35,913.67	$ 341,212.80	$ 23,295.93	$ 400,422.39	$ 2,448,091.97
60			$ 341,212.80	$ 23,295.93	$ 364,508.72	**$ 2,812,600.69**
			initial cost			$ 1,627,251.50
	total					**$ 4,439,852.19**

80% 260c 8:00 to 17:00

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 35,913.67	$ 96,417.95	$ 8,735.97	$ 141,067.59	$ 141,067.59
20	$ 222,990.00	$ 35,913.67	$ 96,417.95	$ 8,735.97	$ 364,057.59	$ 505,125.19
30		$ 35,913.67	$ 96,417.95	$ 8,735.97	$ 141,067.59	$ 646,192.78
40	$ 222,990.00	$ 35,913.67	$ 96,417.95	$ 8,735.97	$ 364,057.59	$ 1,010,250.37
50		$ 35,913.67	$ 96,417.95	$ 8,735.97	$ 141,067.59	$ 1,151,317.97
60			$ 96,417.95	$ 8,735.97	$ 105,153.92	**$ 1,256,471.89**
			initial cost			$ 1,627,251.50
	total					**$ 2,883,723.39**

100%

250c 8:00 to 17:00

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 44,892.09	$ 150,983.70	$ 10,919.97	$ 206,795.76	$ 206,795.76
20	$222,990.00	$ 44,892.09	$ 150,983.70	$ 10,919.97	$ 429,785.76	$ 636,581.51
30		$ 44,892.09	$ 150,983.70	$ 10,919.97	$ 206,795.76	$ 843,377.27
40	$222,990.00	$ 44,892.09	$ 150,983.70	$ 10,919.97	$ 429,785.76	$ 1,273,163.03
50		$ 44,892.09	$ 150,983.70	$ 10,919.97	$ 206,795.76	$ 1,479,958.78
60			$ 150,983.70	$ 10,919.97	$ 161,903.67	**$ 1,641,862.45**
			initial cost			$ 1,652,229.91
	total					**$ 3,294,092.37**

100% 250c 24 hours

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 44,892.09	$ 174,079.39	$ 29,119.91	$ 248,091.39	$ 248,091.39
20	$222,990.00	$ 44,892.09	$ 174,079.39	$ 29,119.91	$ 471,081.39	$ 719,172.77
30		$ 44,892.09	$ 174,079.39	$ 29,119.91	$ 248,091.39	$ 967,264.16
40	$222,990.00	$ 44,892.09	$ 174,079.39	$ 29,119.91	$ 471,081.39	$ 1,438,345.55
50		$ 44,892.09	$ 174,079.39	$ 29,119.91	$ 248,091.39	$ 1,686,436.94
60			$ 174,079.39	$ 29,119.91	$ 203,199.30	**$ 1,889,636.24**
			initial cost			$ 1,652,229.91
	total					**$ 3,541,866.15**

100% 260c 8:00 to 17:00

YEAR	RENOVATION COST		ELECRTRICITY COST		TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
	AC	Fan	AC	Fan		
10		$ 44,892.09	$ 33,742.92	$ 10,919.97	$ 89,554.98	$ 89,554.98
20	$ 222,990.00	$ 44,892.09	$ 33,742.92	$ 10,919.97	$ 312,544.98	$ 402,099.95
30		$ 44,892.09	$ 33,742.92	$ 10,919.97	$ 89,554.98	$ 491,654.93
40	$ 222,990.00	$ 44,892.09	$ 33,742.92	$ 10,919.97	$ 312,544.98	$ 804,199.91
50		$ 44,892.09	$ 33,742.92	$ 10,919.97	$ 89,554.98	$ 893,754.88
60			$ 33,742.92	$ 10,919.97	$ 44,662.89	**$ 938,417.77**
			initial cost			$ 1,652,229.91
	total					**$ 2,590,647.69**

20% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN
10		$ 8,978.42	$ 528,391.03	$ 5,823.98	$ 543,193.43	$ 543,193.43
20	$ 222,990.00	$ 8,978.42	$ 528,391.03	$ 5,823.98	$ 766,183.43	$ 1,309,376.87
30		$ 8,978.42	$ 528,391.03	$ 5,823.98	$ 543,193.43	$ 1,852,570.30
40	$ 222,990.00	$ 8,978.42	$ 528,391.03	$ 5,823.98	$ 766,183.43	$ 2,618,753.73
50		$ 8,978.42	$ 528,391.03	$ 5,823.98	$ 543,193.43	$ 3,161,947.17
60			$ 528,391.03	$ 5,823.98	$ 534,215.02	**$ 3,696,162.18**
			initial cost			$ 1,552,316.24
			total			**$ 5,248,478.43**

20% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 8,978.42	$ 176,669.45	$ 2,183.99	$ 187,831.86	$ 187,831.86
20	$ 222,990.00	$ 8,978.42	$ 176,669.45	$ 2,183.99	$ 410,821.86	$ 598,653.73
30		$ 8,978.42	$ 176,669.45	$ 2,183.99	$ 187,831.86	$ 786,485.59
40	$ 222,990.00	$ 8,978.42	$ 176,669.45	$ 2,183.99	$ 410,821.86	$ 1,197,307.45
50		$ 8,978.42	$ 176,669.45	$ 2,183.99	$ 187,831.86	$ 1,385,139.32
60			$ 176,669.45	$ 2,183.99	$ 178,853.45	**$ 1,563,992.76**
			initial cost			$ 1,552,316.24
			total			**$ 3,116,309.01**

20% 270c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 8,978.42	$ 264,799.05	$ 5,823.98	$ 279,601.45	$ 279,601.45
20	$ 222,990.00	$ 8,978.42	$ 264,799.05	$ 5,823.98	$ 502,591.45	$ 782,192.91
30		$ 8,978.42	$ 264,799.05	$ 5,823.98	$ 279,601.45	$ 1,061,794.36
40	$ 222,990.00	$ 8,978.42	$ 264,799.05	$ 5,823.98	$ 502,591.45	$ 1,564,385.81
50		$ 8,978.42	$ 264,799.05	$ 5,823.98	$ 279,601.45	$ 1,843,987.27
60			$ 264,799.05	$ 5,823.98	$ 270,623.04	**$ 2,114,610.30**
			initial cost			$ 1,552,316.24
			total			**$ 3,666,926.55**

40% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 17,956.83	$ 361,257.63	$ 11,647.96	$ 390,862.43	$ 781,724.85
20	$ 222,990.00	$ 17,956.83	$ 361,257.63	$ 11,647.96	$ 613,852.43	$ 1,395,577.28
30		$ 17,956.83	$ 361,257.63	$ 11,647.96	$ 390,862.43	$ 1,786,439.71
40	$ 222,990.00	$ 17,956.83	$ 361,257.63	$ 11,647.96	$ 613,852.43	$ 2,400,292.13
50		$ 17,956.83	$ 361,257.63	$ 11,647.96	$ 390,862.43	$ 2,791,154.56
60			$ 361,257.63	$ 11,647.96	$ 372,905.59	**$ 3,164,060.15**
			initial cost			$ 1,577,294.66
			total			**$ 4,741,354.81**

40% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 17,956.83	$ 113,994.43	$ 4,367.99	$ 136,319.25	$ 136,319.25
20	$ 222,990.00	$ 17,956.83	$ 113,994.43	$ 4,367.99	$ 359,309.25	$ 495,628.49
30		$ 17,956.83	$ 113,994.43	$ 4,367.99	$ 136,319.25	$ 631,947.74
40	$ 222,990.00	$ 17,956.83	$ 113,994.43	$ 4,367.99	$ 359,309.25	$ 991,256.99
50		$ 17,956.83	$ 113,994.43	$ 4,367.99	$ 136,319.25	$ 1,127,576.23
60			$ 113,994.43	$ 4,367.99	$ 118,362.41	**$ 1,245,938.65**
			initial cost			$ 1,577,294.66
			total			**$ 2,823,233.31**

40% 270c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 17,956.83	$ 97,665.65	$ 11,647.96	$ 127,270.45	$ 127,270.45
20	$ 222,990.00	$ 17,956.83	$ 97,665.65	$ 11,647.96	$ 350,260.45	$ 477,530.89
30		$ 17,956.83	$ 97,665.65	$ 11,647.96	$ 127,270.45	$ 604,801.34
40	$ 222,990.00	$ 17,956.83	$ 97,665.65	$ 11,647.96	$ 350,260.45	$ 955,061.79
50		$ 17,956.83	$ 97,665.65	$ 11,647.96	$ 127,270.45	$ 1,082,332.23
60			$ 97,665.65	$ 11,647.96	$ 109,313.61	**$ 1,191,645.85**
			initial cost			$ 1,577,294.66
			total			**$ 2,768,940.51**

60% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 26,935.25	$ 194,124.22	$ 17,471.94	$ 238,531.42	$ 238,531.42
20	$ 222,990.00	$ 26,935.25	$ 194,124.22	$ 17,471.94	$ 461,521.42	$ 700,052.84
30		$ 26,935.25	$ 194,124.22	$ 17,471.94	$ 238,531.42	$ 938,584.26
40	$ 222,990.00	$ 26,935.25	$ 194,124.22	$ 17,471.94	$ 461,521.42	$ 1,400,105.68
50		$ 26,935.25	$ 194,124.22	$ 17,471.94	$ 238,531.42	$ 1,638,637.10
60			$ 194,124.22	$ 17,471.94	$ 211,596.17	**$ 1,850,233.27**
			initial cost			$ 1,602,273.08
			total			**$ 3,452,506.35**

60% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 26,935.25	$ 51,319.40	$ 6,551.98	$ 84,806.63	$ 84,806.63
20	$ 222,990.00	$ 26,935.25	$ 51,319.40	$ 6,551.98	$ 307,796.63	$ 392,603.26
30		$ 26,935.25	$ 51,319.40	$ 6,551.98	$ 84,806.63	$ 477,409.89
40	$ 222,990.00	$ 26,935.25	$ 51,319.40	$ 6,551.98	$ 307,796.63	$ 785,206.52
50		$ 26,935.25	$ 51,319.40	$ 6,551.98	$ 84,806.63	$ 870,013.15
60			$ 51,319.40	$ 6,551.98	$ 57,871.38	**$ 927,884.53**
			initial cost			$ 1,602,273.08
			total			**$ 2,530,157.61**

60% energy value is negetive so no need for AC -569.41

270c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 26,935.25		$ 17,471.94	$ 44,407.20	$ 44,407.20
20		$ 26,935.25		$ 17,471.94	$ 44,407.20	$ 88,814.39
30		$ 26,935.25		$ 17,471.94	$ 44,407.20	$ 133,221.59
40		$ 26,935.25		$ 17,471.94	$ 44,407.20	$ 177,628.79
50		$ 26,935.25		$ 17,471.94	$ 44,407.20	$ 222,035.98
60				$ 17,471.94	$ 17,471.94	**$ 239,507.93**
			initial cost			$ 1,379,283.08
			total			**$ 1,618,791.01**

80% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 35,913.67	$ 26,990.82	$ 23,295.93	$ 86,200.41	$ 86,200.41
20	$ 222,990.00	$ 35,913.67	$ 26,990.82	$ 23,295.93	$ 309,190.41	$ 395,390.83
30		$ 35,913.67	$ 26,990.82	$ 23,295.93	$ 86,200.41	$ 481,591.24
40	$ 222,990.00	$ 35,913.67	$ 26,990.82	$ 23,295.93	$ 309,190.41	$ 790,781.66
50		$ 35,913.67	$ 26,990.82	$ 23,295.93	$ 86,200.41	$ 876,982.07
60			$ 26,990.82	$ 23,295.93	$ 50,286.74	**$ 927,268.81**
			initial cost			$ 1,627,251.50
			total			**$ 2,554,520.31**

80% 270c 8:00 to 17:00 energy value is negetive so no need for AC -93.08

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 35,913.67		$ 8,735.97	$ 44,649.64	$ 44,649.64
20		$ 35,913.67		$ 8,735.97	$ 44,649.64	$ 89,299.28
30		$ 35,913.67		$ 8,735.97	$ 44,649.64	$ 133,948.92
40		$ 35,913.67		$ 8,735.97	$ 44,649.64	$ 178,598.57
50		$ 35,913.67		$ 8,735.97	$ 44,649.64	$ 223,248.21
60				$ 8,735.97	$ 8,735.97	**$ 231,984.18**
			initial cost			$ 1,404,261.50
			total			**$ 1,636,245.67**

80% 270c 24 hours energy value is negetive so no need for AC -1939.35

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 35,913.67		$ 23,295.93	$ 59,209.60	$ 59,209.60
20		$ 35,913.67		$ 23,295.93	$ 59,209.60	$ 118,419.19
30		$ 35,913.67		$ 23,295.93	$ 59,209.60	$ 177,628.79
40		$ 35,913.67		$ 23,295.93	$ 59,209.60	$ 236,838.38
50		$ 35,913.67		$ 23,295.93	$ 59,209.60	$ 296,047.98
60				$ 23,295.93	$ 23,295.93	**$ 319,343.90**
			initial cost			$ 1,404,261.50
			total			**$ 1,723,605.40**

100% 260c 24 hours energy value is negetive so no need for AC -1148.71

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 74,011.99
20		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 148,023.99
30		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 222,035.98
40		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 296,047.98
50		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 370,059.97
60				$ 29,119.91	$ 29,119.91	**$ 399,179.88**
			initial cost			$ 1,429,239.91
			total			**$ 1,828,419.79**

100% 270c 8:00 to 17:00 energy value is negetive so no need for AC -606.81

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 44,892.09		$ 10,919.97	$ 55,812.05	$ 55,812.05
20		$ 44,892.09		$ 10,919.97	$ 55,812.05	$ 111,624.10
30		$ 44,892.09		$ 10,919.97	$ 55,812.05	$ 167,436.16
40		$ 44,892.09		$ 10,919.97	$ 55,812.05	$ 223,248.21
50		$ 44,892.09		$ 10,919.97	$ 55,812.05	$ 279,060.26
60				$ 10,919.97	$ 10,919.97	**$ 289,980.22**
			initial cost			$ 1,429,239.91
			total			**$ 1,719,220.14**

100% 270c 24 hours energy value is negetive so no need for AC -3309.30

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 74,011.99
20		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 148,023.99
30		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 222,035.98
40		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 296,047.98
50		$ 44,892.09		$ 29,119.91	$ 74,011.99	$ 370,059.97
60				$ 29,119.91	$ 29,119.91	**$ 399,179.88**
			initial cost			$ 1,429,239.91
			total			**$ 1,828,419.79**

Appendix E

CASE C

250c 8:00 to 17:00

20%

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 9,526.72	$ 412,129.65	$ 2,317.37	$ 423,973.74	$ 423,973.74
20	$ 222,990.00	$ 9,526.72	$ 412,129.65	$ 2,317.37	$ 646,963.74	$ 1,070,937.47
30		$ 9,526.72	$ 412,129.65	$ 2,317.37	$ 423,973.74	$ 1,494,911.21
40	$ 222,990.00	$ 9,526.72	$ 412,129.65	$ 2,317.37	$ 646,963.74	$ 2,141,874.94
50		$ 9,526.72	$ 412,129.65	$ 2,317.37	$ 423,973.74	$ 2,565,848.68
60			$ 412,129.65	$ 2,317.37	$ 414,447.02	**$ 2,980,295.69**
			initial cost			$ 1,552,864.54
			total			**$ 4,533,160.24**

40%

250c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 19,053.44	$ 359,900.46	$ 4,634.73	$ 383,588.63	$ 383,588.63
20	$ 222,990.00	$ 19,053.44	$ 359,900.46	$ 4,634.73	$ 606,578.63	$ 990,167.26
30		$ 19,053.44	$ 359,900.46	$ 4,634.73	$ 383,588.63	$ 1,373,755.89
40	$ 222,990.00	$ 19,053.44	$ 359,900.46	$ 4,634.73	$ 606,578.63	$ 1,980,334.52
50		$ 19,053.44	$ 359,900.46	$ 4,634.73	$ 383,588.63	$ 2,363,923.15
60			$ 359,900.46	$ 4,634.73	$ 364,535.20	**$ 2,728,458.35**
			initial cost			$ 1,578,391.26
			total			**$ 4,306,849.61**

60%

250c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 28,580.15	$ 307,671.27	$ 6,952.10	$ 343,203.53	$ 343,203.53
20	$ 222,990.00	$ 28,580.15	$ 307,671.27	$ 6,952.10	$ 566,193.53	$ 909,397.05
30		$ 28,580.15	$ 307,671.27	$ 6,952.10	$ 343,203.53	$ 1,252,600.58
40	$ 222,990.00	$ 28,580.15	$ 307,671.27	$ 6,952.10	$ 566,193.53	$ 1,818,794.10
50		$ 28,580.15	$ 307,671.27	$ 6,952.10	$ 343,203.53	$ 2,161,997.63
60			$ 307,671.27	$ 6,952.10	$ 314,623.37	**$ 2,476,621.00**
			initial cost			$ 1,603,917.98
			total			**$ 4,080,538.98**

80%

250c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 38,106.87	$ 255,442.08	$ 9,269.47	$ 302,818.42	$ 302,818.42
20	$ 222,990.00	$ 38,106.87	$ 255,442.08	$ 9,269.47	$ 525,808.42	$ 828,626.84
30		$ 38,106.87	$ 255,442.08	$ 9,269.47	$ 302,818.42	$ 1,131,445.26
40	$ 222,990.00	$ 38,106.87	$ 255,442.08	$ 9,269.47	$ 525,808.42	$ 1,657,253.68
50		$ 38,106.87	$ 255,442.08	$ 9,269.47	$ 302,818.42	$ 1,960,072.10
60			$ 255,442.08	$ 9,269.47	$ 264,711.55	**$ 2,224,783.65**
			initial cost			$ 1,629,444.70
			total			**$ 3,854,228.35**

100%

250c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,633.59	$ 203,212.89	$ 11,586.83	$ 262,433.32	$ 262,433.32
20	$ 222,990.00	$ 47,633.59	$ 203,212.89	$ 11,586.83	$ 485,423.32	$ 747,856.63
30		$ 47,633.59	$ 203,212.89	$ 11,586.83	$ 262,433.32	$ 1,010,289.95
40	$ 222,990.00	$ 47,633.59	$ 203,212.89	$ 11,586.83	$ 485,423.32	$ 1,495,713.26
50		$ 47,633.59	$ 203,212.89	$ 11,586.83	$ 262,433.32	$ 1,758,146.58
60			$ 203,212.89	$ 11,586.83	$ 214,799.73	**$ 1,972,946.30**
			initial cost			$ 1,654,971.41
			total			**$ 3,627,917.72**

250c 24 hours

20%

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 9,526.72	$ 870,468.58	$ 6,179.64	$ 886,174.94	$ 886,174.94
20	$ 222,990.00	$ 9,526.72	$ 870,468.58	$ 6,179.64	$ 1,109,164.94	$ 1,995,339.89
30		$ 9,526.72	$ 870,468.58	$ 6,179.64	$ 886,174.94	$ 2,881,514.83
40	$ 222,990.00	$ 9,526.72	$ 870,468.58	$ 6,179.64	$ 1,109,164.94	$ 3,990,679.78
50		$ 9,526.72	$ 870,468.58	$ 6,179.64	$ 886,174.94	$ 4,876,854.72
60			$ 870,468.58	$ 6,179.64	$ 876,648.23	**$ 5,753,502.95**
			initial cost			$ 1,552,864.54
			total			**$ 7,306,367.49**

40%

250c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 19,053.44	$ 731,190.74	$ 12,359.29	$ 762,603.47	$ 762,603.47
20	$ 222,990.00	$ 19,053.44	$ 731,190.74	$ 12,359.29	$ 985,593.47	$ 1,748,196.94
30		$ 19,053.44	$ 731,190.74	$ 12,359.29	$ 762,603.47	$ 2,510,800.41
40	$ 222,990.00	$ 19,053.44	$ 731,190.74	$ 12,359.29	$ 985,593.47	$ 3,496,393.87
50		$ 19,053.44	$ 731,190.74	$ 12,359.29	$ 762,603.47	$ 4,258,997.34
60			$ 731,190.74	$ 12,359.29	$ 743,550.03	**$ 5,002,547.38**
			initial cost			$ 1,578,391.26
			total			**$ 6,580,938.64**

60%

250c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 28,580.15	$ 591,912.91	$ 18,538.93	$ 639,031.99	$ 639,031.99
20	$ 222,990.00	$ 28,580.15	$ 591,912.91	$ 18,538.93	$ 862,021.99	$ 1,501,053.99
30		$ 28,580.15	$ 591,912.91	$ 18,538.93	$ 639,031.99	$ 2,140,085.98
40	$ 222,990.00	$ 28,580.15	$ 591,912.91	$ 18,538.93	$ 862,021.99	$ 3,002,107.97
50		$ 28,580.15	$ 591,912.91	$ 18,538.93	$ 639,031.99	$ 3,641,139.96
60			$ 591,912.91	$ 18,538.93	$ 610,451.84	**$ 4,251,591.80**
			initial cost			$ 1,603,917.98
			total			**$ 5,855,509.78**

80%

250c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN
10		$ 38,106.87	$ 452,635.07	$ 24,718.58	$ 515,460.52	$ 515,460.52
20	$ 222,990.00	$ 38,106.87	$ 452,635.07	$ 24,718.58	$ 738,450.52	$ 1,253,911.03
30		$ 38,106.87	$ 452,635.07	$ 24,718.58	$ 515,460.52	$ 1,769,371.55
40	$ 222,990.00	$ 38,106.87	$ 452,635.07	$ 24,718.58	$ 738,450.52	$ 2,507,822.07
50		$ 38,106.87	$ 452,635.07	$ 24,718.58	$ 515,460.52	$ 3,023,282.59
60			$ 452,635.07	$ 24,718.58	$ 477,353.65	**$ 3,500,636.23**
			initial cost			$ 1,629,444.70
			total			**$ 5,130,080.93**

100%

250c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,633.59	$ 313,357.23	$ 30,898.22	$ 391,889.04	$ 391,889.04
20	$ 222,990.00	$ 47,633.59	$ 313,357.23	$ 30,898.22	$ 614,879.04	$ 1,006,768.08
30		$ 47,633.59	$ 313,357.23	$ 30,898.22	$ 391,889.04	$ 1,398,657.12
40	$ 222,990.00	$ 47,633.59	$ 313,357.23	$ 30,898.22	$ 614,879.04	$ 2,013,536.17
50		$ 47,633.59	$ 313,357.23	$ 30,898.22	$ 391,889.04	$ 2,405,425.21
60			$ 313,357.23	$ 30,898.22	$ 344,255.45	**$ 2,749,680.66**
			initial cost			$ 1,654,971.41
			total			**$ 4,404,652.08**

Case C

260c 8:00 to 17:00

20%

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 9,526.72	$ 294,888.87	$ 2,317.37	$ 306,732.96	$ 306,732.96
20	$ 222,990.00	$ 9,526.72	$ 294,888.87	$ 2,317.37	$ 529,722.96	$ 836,455.91
30		$ 9,526.72	$ 294,888.87	$ 2,317.37	$ 306,732.96	$ 1,143,188.87
40	$ 222,990.00	$ 9,526.72	$ 294,888.87	$ 2,317.37	$ 529,722.96	$ 1,672,911.82
50		$ 9,526.72	$ 294,888.87	$ 2,317.37	$ 306,732.96	$ 1,979,644.78
60			$ 294,888.87	$ 2,317.37	$ 297,206.24	**$ 2,276,851.01**
			initial cost			$ 1,552,864.54
			total			**$ 3,829,715.56**

40%

260c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 19,053.44	$ 242,659.68	$ 4,634.73	$ 266,347.85	$ 266,347.85
20	$ 222,990.00	$ 19,053.44	$ 242,659.68	$ 4,634.73	$ 489,337.85	$ 755,685.70
30		$ 19,053.44	$ 242,659.68	$ 4,634.73	$ 266,347.85	$ 1,022,033.55
40	$ 222,990.00	$ 19,053.44	$ 242,659.68	$ 4,634.73	$ 489,337.85	$ 1,511,371.40
50		$ 19,053.44	$ 242,659.68	$ 4,634.73	$ 266,347.85	$ 1,777,719.25
60			$ 242,659.68	$ 4,634.73	$ 247,294.42	**$ 2,025,013.67**
			initial cost			$ 1,578,391.26
			total			**$ 3,603,404.93**

60%

260c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 28,580.15	$ 190,430.49	$ 6,952.10	$ 225,962.75	$ 225,962.75
20	$ 222,990.00	$ 28,580.15	$ 190,430.49	$ 6,952.10	$ 448,952.75	$ 674,915.49
30		$ 28,580.15	$ 190,430.49	$ 6,952.10	$ 225,962.75	$ 900,878.24
40	$ 222,990.00	$ 28,580.15	$ 190,430.49	$ 6,952.10	$ 448,952.75	$ 1,349,830.98
50		$ 28,580.15	$ 190,430.49	$ 6,952.10	$ 225,962.75	$ 1,575,793.73
60			$ 190,430.49	$ 6,952.10	$ 197,382.59	**$ 1,773,176.32**
			initial cost			$ 1,602,273.08
			total			**$ 3,375,449.40**

80% 260c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN
10		$ 38,106.87	$ 138,201.30	$ 9,269.47	$ 185,577.64	$ 185,577.64
20	$ 222,990.00	$ 38,106.87	$ 138,201.30	$ 9,269.47	$ 408,567.64	$ 594,145.28
30		$ 38,106.87	$ 138,201.30	$ 9,269.47	$ 185,577.64	$ 779,722.92
40	$ 222,990.00	$ 38,106.87	$ 138,201.30	$ 9,269.47	$ 408,567.64	$ 1,188,290.56
50		$ 38,106.87	$ 138,201.30	$ 9,269.47	$ 185,577.64	$ 1,373,868.20
60			$ 138,201.30	$ 9,269.47	$ 147,470.77	**$ 1,521,338.97**
			initial cost			$ 1,629,444.70
			total			**$ 3,150,783.67**

100% 260c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,633.59	$ 85,972.11	$ 11,586.83	$ 145,192.54	$ 145,192.54
20	$ 222,990.00	$ 47,633.59	$ 85,972.11	$ 11,586.83	$ 368,182.54	$ 513,375.07
30		$ 47,633.59	$ 85,972.11	$ 11,586.83	$ 145,192.54	$ 658,567.61
40	$ 222,990.00	$ 47,633.59	$ 85,972.11	$ 11,586.83	$ 368,182.54	$ 1,026,750.14
50		$ 47,633.59	$ 85,972.11	$ 11,586.83	$ 145,192.54	$ 1,171,942.68
60			$ 85,972.11	$ 11,586.83	$ 97,558.95	**$ 1,269,501.62**
			initial cost			$ 1,654,971.41
			total			**$ 2,924,473.04**

20% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 9,526.72	$ 556,246.60	$ 6,179.64	$ 571,952.96	$ 571,952.96
20	$ 222,990.00	$ 9,526.72	$ 556,246.60	$ 6,179.64	$ 794,942.96	$ 1,366,895.93
30		$ 9,526.72	$ 556,246.60	$ 6,179.64	$ 571,952.96	$ 1,938,848.89
40	$ 222,990.00	$ 9,526.72	$ 556,246.60	$ 6,179.64	$ 794,942.96	$ 2,733,791.86
50		$ 9,526.72	$ 556,246.60	$ 6,179.64	$ 571,952.96	$ 3,305,744.82
60			$ 556,246.60	$ 6,179.64	$ 562,426.25	**$ 3,868,171.07**
		initial cost				$ 1,552,864.54
		total				**$ 5,421,035.61**

40% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 19,053.44	$ 416,968.76	$ 12,359.29	$ 448,381.49	$ 448,381.49
20	$ 222,990.00	$ 19,053.44	$ 416,968.76	$ 12,359.29	$ 671,371.49	$ 1,119,752.98
30		$ 19,053.44	$ 416,968.76	$ 12,359.29	$ 448,381.49	$ 1,568,134.47
40	$ 222,990.00	$ 19,053.44	$ 416,968.76	$ 12,359.29	$ 671,371.49	$ 2,239,505.95
50		$ 19,053.44	$ 416,968.76	$ 12,359.29	$ 448,381.49	$ 2,687,887.44
60			$ 416,968.76	$ 12,359.29	$ 429,328.05	**$ 3,117,215.50**
		initial cost				$ 1,578,391.26
		total				**$ 4,695,606.76**

60% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 28,580.15	$ 277,690.93	$ 18,538.93	$ 324,810.01	$ 324,810.01
20	$ 222,990.00	$ 28,580.15	$ 277,690.93	$ 18,538.93	$ 547,800.01	$ 872,610.03
30		$ 28,580.15	$ 277,690.93	$ 18,538.93	$ 324,810.01	$ 1,197,420.04
40	$ 222,990.00	$ 28,580.15	$ 277,690.93	$ 18,538.93	$ 547,800.01	$ 1,745,220.05
50		$ 28,580.15	$ 277,690.93	$ 18,538.93	$ 324,810.01	$ 2,070,030.06
60			$ 277,690.93	$ 18,538.93	$ 296,229.86	**$ 2,366,259.92**
		initial cost				$ 1,603,917.98
		total				**$ 3,970,177.90**

80% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN
10		$ 38,106.87	$ 138,413.09	$ 24,718.58	$ 201,238.54	$ 201,238.54
20	$ 222,990.00	$ 38,106.87	$ 138,413.09	$ 24,718.58	$ 424,228.54	$ 625,467.07
30		$ 38,106.87	$ 138,413.09	$ 24,718.58	$ 201,238.54	$ 826,705.61
40	$ 222,990.00	$ 38,106.87	$ 138,413.09	$ 24,718.58	$ 424,228.54	$ 1,250,934.15
50		$ 38,106.87	$ 138,413.09	$ 24,718.58	$ 201,238.54	$ 1,452,172.69
60			$ 138,413.09	$ 24,718.58	$ 163,131.67	**$ 1,615,304.35**
		initial cost				$ 1,629,444.70
		total				**$ 3,244,749.05**

100% 260c 24 hours — energy value is negetive so no need for AC -7.09

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 78,531.81
20		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 78,531.81
30		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 78,531.81
40		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 78,531.81
50		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 78,531.81
60				$ 30,898.22	$ 30,898.22	**$ 30,898.22**
		initial cost				$ 1,431,981.41
		total				**$ 1,462,879.64**

20% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 9,526.72	$ 187,115.29	$ 2,317.37	$ 198,959.38	$ 198,959.38
20	$ 222,990.00	$ 9,526.72	$ 187,115.29	$ 2,317.37	$ 421,949.38	$ 620,908.75
30		$ 9,526.72	$ 187,115.29	$ 2,317.37	$ 198,959.38	$ 819,868.13
40	$ 222,990.00	$ 9,526.72	$ 187,115.29	$ 2,317.37	$ 421,949.38	$ 1,241,817.50
50		$ 9,526.72	$ 187,115.29	$ 2,317.37	$ 198,959.38	$ 1,440,776.88
60			$ 187,115.29	$ 2,317.37	$ 189,432.66	**$ 1,630,209.53**
		initial cost				$ 1,552,864.54
		total				**$ 3,183,074.08**

40% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 19,053.44	$ 134,886.10	$ 4,634.73	$ 158,574.27	$ 158,574.27
20	$ 222,990.00	$ 19,053.44	$ 134,886.10	$ 4,634.73	$ 381,564.27	$ 540,138.54
30		$ 19,053.44	$ 134,886.10	$ 4,634.73	$ 158,574.27	$ 698,712.81
40	$ 222,990.00	$ 19,053.44	$ 134,886.10	$ 4,634.73	$ 381,564.27	$ 1,080,277.08
50		$ 19,053.44	$ 134,886.10	$ 4,634.73	$ 158,574.27	$ 1,238,851.35
60			$ 134,886.10	$ 4,634.73	$ 139,520.84	**$ 1,378,372.19**
		initial cost				$ 1,578,391.26
		total				**$ 2,956,763.45**

60% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 28,580.15	$ 82,656.91	$ 6,952.10	$ 118,189.17	$ 118,189.17
20	$ 222,990.00	$ 28,580.15	$ 82,656.91	$ 6,952.10	$ 341,179.17	$ 459,368.33
30		$ 28,580.15	$ 82,656.91	$ 6,952.10	$ 118,189.17	$ 577,557.50
40	$ 222,990.00	$ 28,580.15	$ 82,656.91	$ 6,952.10	$ 341,179.17	$ 918,736.66
50		$ 28,580.15	$ 82,656.91	$ 6,952.10	$ 118,189.17	$ 1,036,925.83
60			$ 82,656.91	$ 6,952.10	$ 89,609.01	**$ 1,126,534.84**
		initial cost				$ 1,603,917.98
		total				**$ 2,730,452.82**

80% 270c 8:00 to 17:0

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN
10		$ 38,106.87	$ 30,427.72	$ 9,269.47	$ 77,804.06	$ 77,804.06
20	$ 222,990.00	$ 38,106.87	$ 30,427.72	$ 9,269.47	$ 300,794.06	$ 378,598.12
30		$ 38,106.87	$ 30,427.72	$ 9,269.47	$ 77,804.06	$ 456,402.18
40	$ 222,990.00	$ 38,106.87	$ 30,427.72	$ 9,269.47	$ 300,794.06	$ 757,196.24
50		$ 38,106.87	$ 30,427.72	$ 9,269.47	$ 77,804.06	$ 835,000.30
60			$ 30,427.72	$ 9,269.47	$ 39,697.19	**$ 874,697.49**
		initial cost				$ 1,629,444.70
		total				**$ 2,504,142.19**

100% 270c 8:00 to 17:00 — energy value is negetive so no need for AC -178.70

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,633.59		$ 11,586.83	$ 59,220.42	$ 59,220.42
20		$ 47,633.59		$ 11,586.83	$ 59,220.42	$ 118,440.84
30		$ 47,633.59		$ 11,586.83	$ 59,220.42	$ 177,661.26
40		$ 47,633.59		$ 11,586.83	$ 59,220.42	$ 236,881.69
50		$ 47,633.59		$ 11,586.83	$ 59,220.42	$ 296,102.11
60				$ 11,586.83	$ 11,586.83	**$ 307,688.94**
		initial cost				$ 1,431,981.41
		total				**$ 1,739,670.35**

20% 270c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 9,526.72	$ 292,654.62	$ 6,179.64	$ 308,360.98	$ 308,360.98
20	$ 222,990.00	$ 9,526.72	$ 292,654.62	$ 6,179.64	$ 531,350.98	$ 839,711.97
30		$ 9,526.72	$ 292,654.62	$ 6,179.64	$ 308,360.98	$ 1,148,072.95
40	$ 222,990.00	$ 9,526.72	$ 292,654.62	$ 6,179.64	$ 531,350.98	$ 1,679,423.94
50		$ 9,526.72	$ 292,654.62	$ 6,179.64	$ 308,360.98	$ 1,987,784.92
60			$ 292,654.62	$ 6,179.64	$ 298,834.27	**$ 2,286,619.19**
		initial cost				$ 1,552,864.54
		total				**$ 3,839,483.73**

40% 270c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 19,053.44	$ 153,376.78	$ 12,359.29	$ 184,789.51	$ 184,789.51
20	$ 222,990.00	$ 19,053.44	$ 153,376.78	$ 12,359.29	$ 407,779.51	$ 592,569.02
30		$ 19,053.44	$ 153,376.78	$ 12,359.29	$ 184,789.51	$ 777,358.53
40	$ 222,990.00	$ 19,053.44	$ 153,376.78	$ 12,359.29	$ 407,779.51	$ 1,185,138.03
50		$ 19,053.44	$ 153,376.78	$ 12,359.29	$ 184,789.51	$ 1,369,927.54
60			$ 153,376.78	$ 12,359.29	$ 165,736.07	**$ 1,535,663.62**
		initial cost				$ 1,578,391.26
		total				**$ 3,114,054.88**

60% 270c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 28,580.15	$ 14,098.95	$ 18,538.93	$ 61,218.03	$ 61,218.03
20	$ 222,990.00	$ 28,580.15	$ 14,098.95	$ 18,538.93	$ 284,208.03	$ 345,426.07
30		$ 28,580.15	$ 14,098.95	$ 18,538.93	$ 61,218.03	$ 406,644.10
40	$ 222,990.00	$ 28,580.15	$ 14,098.95	$ 18,538.93	$ 284,208.03	$ 690,852.13
50		$ 28,580.15	$ 14,098.95	$ 18,538.93	$ 61,218.03	$ 752,070.16
60			$ 14,098.95	$ 18,538.93	$ 32,637.88	**$ 784,708.04**
		initial cost				$ 1,603,917.98
		total				**$ 2,388,626.02**

80% 270c 24 hours — energy value is negetive so no need for AC -1026.06

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN
10		$ 38,106.87		$ 24,718.58	$ 62,825.45	$ 62,825.45
20		$ 38,106.87		$ 24,718.58	$ 62,825.45	$ 125,650.90
30		$ 38,106.87		$ 24,718.58	$ 62,825.45	$ 188,476.35
40		$ 38,106.87		$ 24,718.58	$ 62,825.45	$ 251,301.79
50		$ 38,106.87		$ 24,718.58	$ 62,825.45	$ 314,127.24
60				$ 24,718.58	$ 24,718.58	**$ 338,845.82**
		initial cost				$ 1,406,454.70
		total				**$ 1,745,300.52**

100% 270c 24 hours — energy value is negetive so no need for AC -2167.68

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 78,531.81
20		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 157,063.62
30		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 235,595.43
40		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 314,127.24
50		$ 47,633.59		$ 30,898.22	$ 78,531.81	$ 392,659.05
60				$ 30,898.22	$ 30,898.22	**$ 423,557.28**
		initial cost				$ 1,431,981.41
		total				**$ 1,855,538.69**

Appendix F

CASE D

20% — 250c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 9,502.54	$ 415,638.13	$ 2,311.49	$ 427,452.16	$ 427,452.16
20	$222,990.00	$ 9,502.54	$ 415,638.13	$ 2,311.49	$ 650,442.16	$ 1,077,894.31
30		$ 9,502.54	$ 415,638.13	$ 2,311.49	$ 427,452.16	$ 1,505,346.47
40	$222,990.00	$ 9,502.54	$ 415,638.13	$ 2,311.49	$ 650,442.16	$ 2,155,788.62
50		$ 9,502.54	$ 415,638.13	$ 2,311.49	$ 427,452.16	$ 2,583,240.78
60			$ 415,638.13	$ 2,311.49	$ 417,949.62	**$ 3,001,190.40**
		initial cost				$ 1,552,840.36
		total				**$ 4,554,030.76**

20% — 250c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 9,502.54	$ 879,824.53	$ 6,163.96	$ 895,491.03	$ 895,491.03
20	$ 222,990.00	$ 9,502.54	$ 879,824.53	$ 6,163.96	$ 1,118,481.03	$ 2,013,972.07
30		$ 9,502.54	$ 879,824.53	$ 6,163.96	$ 895,491.03	$ 2,909,463.10
40	$ 222,990.00	$ 9,502.54	$ 879,824.53	$ 6,163.96	$ 1,118,481.03	$ 4,027,944.13
50		$ 9,502.54	$ 879,824.53	$ 6,163.96	$ 895,491.03	$ 4,923,435.17
60			$ 879,824.53	$ 6,163.96	$ 885,988.50	**$ 5,809,423.66**
		initial cost				$ 1,552,840.36
		total				**$ 7,362,264.03**

20% — 260c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 9,502.54	$ 298,397.35	$ 2,311.49	$ 310,211.38	$ 310,211.38
20	$ 222,990.00	$ 9,502.54	$ 298,397.35	$ 2,311.49	$ 533,201.38	$ 843,412.75
30		$ 9,502.54	$ 298,397.35	$ 2,311.49	$ 310,211.38	$ 1,153,624.13
40	$ 222,990.00	$ 9,502.54	$ 298,397.35	$ 2,311.49	$ 533,201.38	$ 1,686,825.50
50		$ 9,502.54	$ 298,397.35	$ 2,311.49	$ 310,211.38	$ 1,997,036.88
60			$ 298,397.35	$ 2,311.49	$ 300,708.84	**$ 2,297,745.72**
		initial cost				$ 1,552,840.36
		total				**$ 3,850,586.08**

40% — 250c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN
10		$ 19,005.08	$ 366,917.43	$ 4,622.97	$ 390,545.47	$ 390,545.47
20	$222,990.00	$ 19,005.08	$ 366,917.43	$ 4,622.97	$ 613,535.47	$ 1,004,080.94
30		$ 19,005.08	$ 366,917.43	$ 4,622.97	$ 390,545.47	$ 1,394,626.42
40	$222,990.00	$ 19,005.08	$ 366,917.43	$ 4,622.97	$ 613,535.47	$ 2,008,161.89
50		$ 19,005.08	$ 366,917.43	$ 4,622.97	$ 390,545.47	$ 2,398,707.36
60			$ 366,917.43	$ 4,622.97	$ 371,540.40	**$ 2,770,247.76**
		initial cost				$ 1,578,342.90
		total				**$ 4,348,590.66**

40% — 250c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 19,005.08	$ 749,902.65	$ 12,327.92	$ 781,235.65	$ 781,235.65
20	$ 222,990.00	$ 19,005.08	$ 749,902.65	$ 12,327.92	$ 1,004,225.65	$ 1,785,461.29
30		$ 19,005.08	$ 749,902.65	$ 12,327.92	$ 781,235.65	$ 2,566,696.94
40	$ 222,990.00	$ 19,005.08	$ 749,902.65	$ 12,327.92	$ 1,004,225.65	$ 3,570,922.59
50		$ 19,005.08	$ 749,902.65	$ 12,327.92	$ 781,235.65	$ 4,352,158.23
60			$ 749,902.65	$ 12,327.92	$ 762,230.57	**$ 5,114,388.80**
		initial cost				$ 1,578,342.90
		total				**$ 6,692,731.70**

40% — 260c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF
10		$ 19,005.08	$ 249,676.65	$ 4,622.97	$ 273,304.69	$ 273,304.69
20	$ 222,990.00	$ 19,005.08	$ 249,676.65	$ 4,622.97	$ 496,294.69	$ 769,599.38
30		$ 19,005.08	$ 249,676.65	$ 4,622.97	$ 273,304.69	$ 1,042,904.08
40	$ 222,990.00	$ 19,005.08	$ 249,676.65	$ 4,622.97	$ 496,294.69	$ 1,539,198.77
50		$ 19,005.08	$ 249,676.65	$ 4,622.97	$ 273,304.69	$ 1,812,503.46
60			$ 249,676.65	$ 4,622.97	$ 254,299.62	**$ 2,066,803.08**
		initial cost				$ 1,578,342.90
		total				**$ 3,645,145.98**

60% — 250c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 28,507.61	$ 318,196.72	$ 6,934.46	$ 353,638.79	$ 353,638.79
20	$222,990.00	$ 28,507.61	$ 318,196.72	$ 6,934.46	$ 576,628.79	$ 930,267.58
30		$ 28,507.61	$ 318,196.72	$ 6,934.46	$ 353,638.79	$ 1,283,906.37
40	$222,990.00	$ 28,507.61	$ 318,196.72	$ 6,934.46	$ 576,628.79	$ 1,860,535.15
50		$ 28,507.61	$ 318,196.72	$ 6,934.46	$ 353,638.79	$ 2,214,173.94
60			$ 318,196.72	$ 6,934.46	$ 325,131.17	**$ 2,539,305.12**
		initial cost				$ 1,603,845.44
		total				**$ 4,143,150.56**

60% — 250c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 28,507.61	$ 619,980.76	$ 18,491.88	$ 666,980.26	$ 666,980.26
20	$ 222,990.00	$ 28,507.61	$ 619,980.76	$ 18,491.88	$ 889,970.26	$ 1,556,950.52
30		$ 28,507.61	$ 619,980.76	$ 18,491.88	$ 666,980.26	$ 2,223,930.78
40	$ 222,990.00	$ 28,507.61	$ 619,980.76	$ 18,491.88	$ 889,970.26	$ 3,113,901.04
50		$ 28,507.61	$ 619,980.76	$ 18,491.88	$ 666,980.26	$ 3,780,881.30
60			$ 619,980.76	$ 18,491.88	$ 638,472.65	**$ 4,419,353.94**
		initial cost				$ 1,603,845.44
		total				**$ 6,023,199.38**

60% — 260c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 28,507.61	$ 200,955.94	$ 6,934.46	$ 236,398.01	$ 236,398.01
20	$ 222,990.00	$ 28,507.61	$ 200,955.94	$ 6,934.46	$ 459,388.01	$ 695,786.02
30		$ 28,507.61	$ 200,955.94	$ 6,934.46	$ 236,398.01	$ 932,184.03
40	$ 222,990.00	$ 28,507.61	$ 200,955.94	$ 6,934.46	$ 459,388.01	$ 1,391,572.03
50		$ 28,507.61	$ 200,955.94	$ 6,934.46	$ 236,398.01	$ 1,627,970.04
60			$ 200,955.94	$ 6,934.46	$ 207,890.39	**$ 1,835,860.44**
		initial cost				$ 1,603,845.44
		total				**$ 3,439,705.88**

80% — 250c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 38,010.15	$ 269,476.01	$ 9,245.94	$ 316,732.10	$ 316,732.10
20	$222,990.00	$ 38,010.15	$ 269,476.01	$ 9,245.94	$ 539,722.10	$ 856,454.21
30		$ 38,010.15	$ 269,476.01	$ 9,245.94	$ 316,732.10	$ 1,173,186.31
40	$222,990.00	$ 38,010.15	$ 269,476.01	$ 9,245.94	$ 539,722.10	$ 1,712,908.42
50		$ 38,010.15	$ 269,476.01	$ 9,245.94	$ 316,732.10	$ 2,029,640.52
60			$ 269,476.01	$ 9,245.94	$ 278,721.95	**$ 2,308,362.48**
		initial cost				$ 1,629,347.98
		total				**$ 3,937,710.46**

80% — 250c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 38,010.15	$ 490,058.88	$ 24,655.84	$ 552,724.87	$ 552,724.87
20	$ 222,990.00	$ 38,010.15	$ 490,058.88	$ 24,655.84	$ 775,714.87	$ 1,328,439.75
30		$ 38,010.15	$ 490,058.88	$ 24,655.84	$ 552,724.87	$ 1,881,164.62
40	$ 222,990.00	$ 38,010.15	$ 490,058.88	$ 24,655.84	$ 775,714.87	$ 2,656,879.49
50		$ 38,010.15	$ 490,058.88	$ 24,655.84	$ 552,724.87	$ 3,209,604.36
60			$ 490,058.88	$ 24,655.84	$ 514,714.72	**$ 3,724,319.08**
		initial cost				$ 1,629,347.98
		total				**$ 5,353,667.06**

80% — 260c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 38,010.15	$ 152,235.23	$ 9,245.94	$ 199,491.32	$ 199,491.32
20	$ 222,990.00	$ 38,010.15	$ 152,235.23	$ 9,245.94	$ 422,481.32	$ 621,972.65
30		$ 38,010.15	$ 152,235.23	$ 9,245.94	$ 199,491.32	$ 821,463.97
40	$ 222,990.00	$ 38,010.15	$ 152,235.23	$ 9,245.94	$ 422,481.32	$ 1,243,945.30
50		$ 38,010.15	$ 152,235.23	$ 9,245.94	$ 199,491.32	$ 1,443,436.62
60			$ 152,235.23	$ 9,245.94	$ 161,481.17	**$ 1,604,917.80**
		initial cost				$ 1,629,347.98
		total				**$ 3,234,265.78**

100% — 250c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,512.69	$ 220,755.31	$ 11,557.43	$ 279,825.42	$ 279,825.42
20	$222,990.00	$ 47,512.69	$ 220,755.31	$ 11,557.43	$ 502,815.42	$ 782,640.84
30		$ 47,512.69	$ 220,755.31	$ 11,557.43	$ 279,825.42	$ 1,062,466.26
40	$222,990.00	$ 47,512.69	$ 220,755.31	$ 11,557.43	$ 502,815.42	$ 1,565,281.68
50		$ 47,512.69	$ 220,755.31	$ 11,557.43	$ 279,825.42	$ 1,845,107.11
60			$ 220,755.31	$ 11,557.43	$ 232,312.73	**$ 2,077,419.84**
		initial cost				$ 1,654,850.52
		total				**$ 3,732,270.35**

100% — 250c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,512.69	$ 360,136.99	$ 30,819.80	$ 438,469.49	$ 438,469.49
20	$ 222,990.00	$ 47,512.69	$ 360,136.99	$ 30,819.80	$ 661,459.49	$ 1,099,928.97
30		$ 47,512.69	$ 360,136.99	$ 30,819.80	$ 438,469.49	$ 1,538,398.46
40	$ 222,990.00	$ 47,512.69	$ 360,136.99	$ 30,819.80	$ 661,459.49	$ 2,199,857.94
50		$ 47,512.69	$ 360,136.99	$ 30,819.80	$ 438,469.49	$ 2,638,327.43
60			$ 360,136.99	$ 30,819.80	$ 390,956.80	**$ 3,029,284.23**
		initial cost				$ 1,654,850.52
		total				**$ 4,684,134.74**

100% — 260c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,512.69	$ 103,514.53	$ 11,557.43	$ 162,584.64	$ 162,584.64
20	$ 222,990.00	$ 47,512.69	$ 103,514.53	$ 11,557.43	$ 385,574.64	$ 548,159.28
30		$ 47,512.69	$ 103,514.53	$ 11,557.43	$ 162,584.64	$ 710,743.92
40	$ 222,990.00	$ 47,512.69	$ 103,514.53	$ 11,557.43	$ 385,574.64	$ 1,096,318.56
50		$ 47,512.69	$ 103,514.53	$ 11,557.43	$ 162,584.64	$ 1,258,903.21
60			$ 103,514.53	$ 11,557.43	$ 115,071.95	**$ 1,373,975.16**
		initial cost				$ 1,654,850.52
		total				**$ 3,028,825.67**

20% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 9,502.54	$ 565,602.55	$ 6,163.96	$ 581,269.05	$ 581,269.05
20	$ 222,990.00	$ 9,502.54	$ 565,602.55	$ 6,163.96	$ 804,259.05	$ 1,385,528.11
30		$ 9,502.54	$ 565,602.55	$ 6,163.96	$ 581,269.05	$ 1,966,797.16
40	$ 222,990.00	$ 9,502.54	$ 565,602.55	$ 6,163.96	$ 804,259.05	$ 2,771,056.21
50		$ 9,502.54	$ 565,602.55	$ 6,163.96	$ 581,269.05	$ 3,352,325.27
60			$ 565,602.55	$ 6,163.96	$ 571,766.52	**$ 3,924,091.78**
		initial cost				$ 1,552,840.36
		total				**$ 5,476,932.15**

40% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN
10		$ 19,005.08	$ 435,680.67	$ 12,327.92	$ 467,013.67	$ 467,013.67
20	$ 222,990.00	$ 19,005.08	$ 435,680.67	$ 12,327.92	$ 690,003.67	$ 1,157,017.33
30		$ 19,005.08	$ 435,680.67	$ 12,327.92	$ 467,013.67	$ 1,624,031.00
40	$ 222,990.00	$ 19,005.08	$ 435,680.67	$ 12,327.92	$ 690,003.67	$ 2,314,034.67
50		$ 19,005.08	$ 435,680.67	$ 12,327.92	$ 467,013.67	$ 2,781,048.33
60			$ 435,680.67	$ 12,327.92	$ 448,008.59	**$ 3,229,056.92**
		initial cost				$ 1,578,342.90
		total				**$ 4,807,399.82**

60% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 28,507.61	$ 305,758.78	$ 18,491.88	$ 352,758.28	$ 352,758.28
20	$ 222,990.00	$ 28,507.61	$ 305,758.78	$ 18,491.88	$ 575,748.28	$ 928,506.56
30		$ 28,507.61	$ 305,758.78	$ 18,491.88	$ 352,758.28	$ 1,281,264.84
40	$ 222,990.00	$ 28,507.61	$ 305,758.78	$ 18,491.88	$ 575,748.28	$ 1,857,013.12
50		$ 28,507.61	$ 305,758.78	$ 18,491.88	$ 352,758.28	$ 2,209,771.40
60			$ 305,758.78	$ 18,491.88	$ 324,250.67	**$ 2,534,022.06**
		initial cost				$ 1,603,845.44
		total				**$ 4,137,867.50**

80% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	TOTAL COST IN THE END OF TEN YEARS
10		$ 38,010.15	$ 175,836.90	$ 24,655.84	$ 238,502.89	$ 238,502.89
20	$ 222,990.00	$ 38,010.15	$ 175,836.90	$ 24,655.84	$ 461,492.89	$ 699,995.79
30		$ 38,010.15	$ 175,836.90	$ 24,655.84	$ 238,502.89	$ 938,498.68
40	$ 222,990.00	$ 38,010.15	$ 175,836.90	$ 24,655.84	$ 461,492.89	$ 1,399,991.57
50		$ 38,010.15	$ 175,836.90	$ 24,655.84	$ 238,502.89	$ 1,638,494.46
60			$ 175,836.90	$ 24,655.84	$ 200,492.74	**$ 1,838,987.20**
		initial cost				$ 1,629,347.98
		total				**$ 3,468,335.18**

100% 260c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,512.69	$ 45,915.01	$ 30,819.80	$ 124,247.51	$ 124,247.51
20	$ 222,990.00	$ 47,512.69	$ 45,915.01	$ 30,819.80	$ 347,237.51	$ 471,485.01
30		$ 47,512.69	$ 45,915.01	$ 30,819.80	$ 124,247.51	$ 595,732.52
40	$ 222,990.00	$ 47,512.69	$ 45,915.01	$ 30,819.80	$ 347,237.51	$ 942,970.02
50		$ 47,512.69	$ 45,915.01	$ 30,819.80	$ 124,247.51	$ 1,067,217.53
60			$ 45,915.01	$ 30,819.80	$ 76,734.82	**$ 1,143,952.35**
		initial cost				$ 1,654,850.52
		total				**$ 2,798,802.86**

20% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 9,502.54	$ 190,623.77	$ 2,311.49	$ 202,437.80	$ 202,437.80
20	$ 222,990.00	$ 9,502.54	$ 190,623.77	$ 2,311.49	$ 425,427.80	$ 627,865.59
30		$ 9,502.54	$ 190,623.77	$ 2,311.49	$ 202,437.80	$ 830,303.39
40	$ 222,990.00	$ 9,502.54	$ 190,623.77	$ 2,311.49	$ 425,427.80	$ 1,255,731.18
50		$ 9,502.54	$ 190,623.77	$ 2,311.49	$ 202,437.80	$ 1,458,168.98
60			$ 190,623.77	$ 2,311.49	$ 192,935.26	**$ 1,651,104.24**
		initial cost				$ 1,552,840.36
		total				**$ 3,203,944.60**

40% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 19,005.08	$ 141,903.07	$ 4,622.97	$ 165,531.11	$ 165,531.11
20	$ 222,990.00	$ 19,005.08	$ 141,903.07	$ 4,622.97	$ 388,521.11	$ 554,052.22
30		$ 19,005.08	$ 141,903.07	$ 4,622.97	$ 165,531.11	$ 719,583.34
40	$ 222,990.00	$ 19,005.08	$ 141,903.07	$ 4,622.97	$ 388,521.11	$ 1,108,104.45
50		$ 19,005.08	$ 141,903.07	$ 4,622.97	$ 165,531.11	$ 1,273,635.56
60			$ 141,903.07	$ 4,622.97	$ 146,526.04	**$ 1,420,161.60**
		initial cost				$ 1,578,342.90
		total				**$ 2,998,504.50**

60% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 28,507.61	$ 93,182.36	$ 6,934.46	$ 128,624.43	$ 128,624.43
20	$ 222,990.00	$ 28,507.61	$ 93,182.36	$ 6,934.46	$ 351,614.43	$ 480,238.86
30		$ 28,507.61	$ 93,182.36	$ 6,934.46	$ 128,624.43	$ 608,863.29
40	$ 222,990.00	$ 28,507.61	$ 93,182.36	$ 6,934.46	$ 351,614.43	$ 960,477.71
50		$ 28,507.61	$ 93,182.36	$ 6,934.46	$ 128,624.43	$ 1,089,102.14
60			$ 93,182.36	$ 6,934.46	$ 100,116.81	**$ 1,189,218.96**
		initial cost				$ 1,602,273.08
		total				**$ 2,791,492.04**

80% 270c 8:00 to 17:00

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 38,010.15	$ 44,461.65	$ 9,245.94	$ 91,717.74	$ 91,717.74
20	$ 222,990.00	$ 38,010.15	$ 44,461.65	$ 9,245.94	$ 314,707.74	$ 406,425.49
30		$ 38,010.15	$ 44,461.65	$ 9,245.94	$ 91,717.74	$ 498,143.23
40	$ 222,990.00	$ 38,010.15	$ 44,461.65	$ 9,245.94	$ 314,707.74	$ 812,850.98
50		$ 38,010.15	$ 44,461.65	$ 9,245.94	$ 91,717.74	$ 904,568.72
60			$ 44,461.65	$ 9,245.94	$ 53,707.59	**$ 958,276.32**
		initial cost				$ 1,629,347.98
		total				**$ 2,587,624.30**

100% 270c 8:00 to 17:00 — energy value is negetive so no need for AC -34.91

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,512.69		$ 11,557.43	$ 59,070.12	$ 59,070.12
20		$ 47,512.69		$ 11,557.43	$ 59,070.12	$ 118,140.23
30		$ 47,512.69		$ 11,557.43	$ 59,070.12	$ 177,210.35
40		$ 47,512.69		$ 11,557.43	$ 59,070.12	$ 236,280.46
50		$ 47,512.69		$ 11,557.43	$ 59,070.12	$ 295,350.58
60				$ 11,557.43	$ 11,557.43	**$ 306,908.00**
		initial cost				$ 1,431,860.52
		total				**$ 1,738,768.52**

20% 270c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 9,502.54	$ 302,010.57	$ 6,163.96	$ 317,677.07	$ 317,677.07
20	$ 222,990.00	$ 9,502.54	$ 302,010.57	$ 6,163.96	$ 540,667.07	$ 858,344.15
30		$ 9,502.54	$ 302,010.57	$ 6,163.96	$ 317,677.07	$ 1,176,021.22
40	$ 222,990.00	$ 9,502.54	$ 302,010.57	$ 6,163.96	$ 540,667.07	$ 1,716,688.29
50		$ 9,502.54	$ 302,010.57	$ 6,163.96	$ 317,677.07	$ 2,034,365.37
60			$ 302,010.57	$ 6,163.96	$ 308,174.54	**$ 2,342,539.90**
		initial cost				$ 1,552,840.36
		total				**$ 3,895,380.27**

40% 270c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 19,005.08	$ 172,088.69	$ 12,327.92	$ 203,421.69	$ 203,421.69
20	$ 222,990.00	$ 19,005.08	$ 172,088.69	$ 12,327.92	$ 426,411.69	$ 629,833.37
30		$ 19,005.08	$ 172,088.69	$ 12,327.92	$ 203,421.69	$ 833,255.06
40	$ 222,990.00	$ 19,005.08	$ 172,088.69	$ 12,327.92	$ 426,411.69	$ 1,259,666.75
50		$ 19,005.08	$ 172,088.69	$ 12,327.92	$ 203,421.69	$ 1,463,088.43
60			$ 172,088.69	$ 12,327.92	$ 184,416.61	**$ 1,647,505.04**
		initial cost				$ 1,578,342.90
		total				**$ 3,225,847.94**

60% 270c 24 hours

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 28,507.61	$ 42,166.80	$ 18,491.88	$ 89,166.30	$ 89,166.30
20	$ 222,990.00	$ 28,507.61	$ 42,166.80	$ 18,491.88	$ 312,156.30	$ 401,322.60
30		$ 28,507.61	$ 42,166.80	$ 18,491.88	$ 89,166.30	$ 490,488.90
40	$ 222,990.00	$ 28,507.61	$ 42,166.80	$ 18,491.88	$ 312,156.30	$ 802,645.20
50		$ 28,507.61	$ 42,166.80	$ 18,491.88	$ 89,166.30	$ 891,811.50
60			$ 42,166.80	$ 18,491.88	$ 60,658.69	**$ 952,470.18**
		initial cost				$ 1,603,845.44
		total				**$ 2,556,315.62**

80% 270c 24 hours — energy value is negetive so no need for AC -719.30

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 38,010.15		$ 24,655.84	$ 62,665.99	$ 62,665.99
20		$ 38,010.15		$ 24,655.84	$ 62,665.99	$ 125,331.99
30		$ 38,010.15		$ 24,655.84	$ 62,665.99	$ 187,997.98
40		$ 38,010.15		$ 24,655.84	$ 62,665.99	$ 250,663.97
50		$ 38,010.15		$ 24,655.84	$ 62,665.99	$ 313,329.97
60				$ 24,655.84	$ 24,655.84	**$ 337,985.81**
		initial cost				$ 1,406,357.98
		total				**$ 1,744,343.78**

100% 270c 24 hours — energy value is negetive so no need for AC -1784.24

YEAR	RENOVATION COST AC	RENOVATION COST Fan	ELECRTRICITY COST AC	ELECRTRICITY COST Fan	TOTAL COST IN THE END OF TEN YEARS	CUMULATIVE TOTAL COST IN THE END OF TEN YEARS
10		$ 47,512.69		$ 30,819.80	$ 78,332.49	$ 78,332.49
20		$ 47,512.69		$ 30,819.80	$ 78,332.49	$ 156,664.98
30		$ 47,512.69		$ 30,819.80	$ 78,332.49	$ 234,997.47
40		$ 47,512.69		$ 30,819.80	$ 78,332.49	$ 313,329.97
50		$ 47,512.69		$ 30,819.80	$ 78,332.49	$ 391,662.46
60				$ 30,819.80	$ 30,819.80	**$ 422,482.26**
		initial cost				$ 1,431,860.52
		total				**$ 1,854,342.77**

Appendix G

				total p+f	saving/yr		Pay back year	
case B					8:00 to 17:00	24hrs	8:00 to 17:00	24hrs
		panel	$ 16,000.00					
20%	3.2	fan	$ 8,978.42	$ 24,978.42	$ 6,267.50	$ 16,713.34	4.0	1.5
		panel	$ 32,000.00					
40%	6.4	fan	$ 17,956.83	$ 49,956.83	$ 12,535.01	$ 33,426.68	4.0	1.5
		panel	$ 48,000.00					
60%	9.6	fan	$ 26,935.25	$ 74,935.25	$ 18,802.51	$ 50,140.02	4.0	1.5
		panel	$ 64,000.00					
80%	12.8	fan	$ 35,913.67	$ 99,913.67	$ 25,070.01	$ 66,853.36	4.0	1.5
		panel	$ 80,000.00					
100%	16	fan	$ 44,892.09	$ 124,892.09	$ 31,337.51	$ 83,566.70	4.0	1.5
case C								
20%	3.2	panel	$ 16,000.00					
		fan	$ 9,526.72	$ 25,526.72	$ 5,222.92	$ 13,927.78	4.9	1.8
40%	6.4	panel	$ 32,000.00					
		fan	$ 19,053.44	$ 51,053.44	$ 10,445.84	$ 27,855.57	4.9	1.8
60%	9.6	panel	$ 48,000.00					
		fan	$ 28,580.15	$ 76,580.15	$ 15,668.76	$ 41,783.35	4.9	1.8
80%	12.8	panel	$ 64,000.00					
		fan	$ 38,106.87	$ 102,106.87	$ 20,891.68	$ 55,711.14	4.9	1.8
100%	16	panel	$ 80,000.00					
		fan	$ 47,633.59	$ 127,633.59	$ 26,114.59	$ 69,638.92	4.9	1.8
case D								
20%	3.2	panel	$ 16,000.00					
		fan	$ 9,502.54	$ 25,502.54	$ 4,872.07	$ 12,992.19	5.2	2.0
40%	6.4	panel	$ 32,000.00					
		fan	$ 19,005.08	$ 51,005.08	$ 9,744.14	$ 25,984.38	5.2	2.0
60%	9.6	panel	$ 48,000.00					
		fan	$ 28,507.61	$ 76,507.61	$ 14,616.21	$ 38,976.57	5.2	2.0
80%	12.8	panel	$ 64,000.00					
		fan	$ 38,010.15	$ 102,010.15	$ 19,488.28	$ 51,968.75	5.2	2.0
100%	16	panel	$ 80,000.00					
		fan	$ 47,512.69	$ 127,512.69	$ 24,360.35	$ 64,960.94	5.2	2.0