Abstract

Contemporary facades of the office building typologies are either fully transparent facades or a derivative of one. Having originated in cold countries, these building facades have found their way into the skyline of the hot climatic zones of the world. Representative of progress, peace and prosperity, the transparent facades have started to replace the indigenous architecture of the hot climatic zones despite the well-known problems of the fully glazed façade. This thesis explores the fundamental problems of this type of building envelope that includes questioning of its origins, its materiality and its relevance based on energy for a hot climatic zone. The proposed solution is based on architecture that was already truly sustainable in every way (materially and energetically). This is the pre-industrial architecture, even though been in existence for centuries; it has been increasingly rejected by the developing countries on the grounds of it being visually representative of the old, obsolete and the poor. This thesis goes beyond a simple exploration of the sustainable components of the indigenous architecture to reveal a more holistic approach for the building envelope based on energy, material and form. This approach is formally organized into a potential envelope design methodology for contemporary buildings. This methodology is put to test at the end of the thesis by designing a building envelope based on it. This envelope design tests the feasibility of the methodology at present as well as demonstrates its potential to change the future of building envelope design and construction. It also proves that deriving a façade design from the concepts of pre-industrial architecture will not lead to a façade replicating the past but will be representative of the contemporary times. This thesis is meant to change the perspective towards how we approach the concept of energy and materiality in architecture and also find a better way to integrate the knowledge of the pre-industrial architecture into the contemporary world.
Lay Summary

This thesis argues the unsustainable nature of the unprecedented growth of contemporary office facades (transparent facades) in hot climatic zones. It then proposes an office façade design methodology based on historical local architecture of the location being considered. The proposed methodology is a more holistic approach to the designing the building façade and incorporates choice of façade material and geometry by considering energy flows between building and its surroundings. The proposed design approach is put to test by designing an office façade based on the principles defined in the methodology.
Preface

This dissertation is original, unpublished, independent work by the author, Rohini Rajani Nair.
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To my husband, my parents & sister.
Chapter 1: Introduction

1.1 Background

The building façade as the name suggests is the face of the building and in turn, also the face of the city or its located context. It represents both the function and the occupant while also protecting the inhabitant from harmful effects of the external environment, offering privacy and a physical boundary of one’s property (Christian Schittich, Pg 9, 2002). But the contemporary responsibility of this building component has increased to give rise to the ‘performative building façade’. This refers to an envelope that integrates many electrical and mechanical functions that are highly engineered and integrated into the fully glazed façade. But the performative aspects of the envelope essentially counter the negative effects of the glass façade to ensure that the HVAC systems that condition the internal space can function efficiently (Michelle Addington 2015). As such technology is added to mitigate the effects of glass.

The origins of this term (performative building skin) can be traced back to the 1950s and 60s with the development of the curtain wall systems. Transparency in architecture using the material glass during the pre-war era was used as a luxury and artwork and in prominent buildings such as large religious establishments or greenhouses; but this changed as a result of a mutual interest between the commercial developers and commercial curtain wall installation contractors. Their objective was to create maximum rental return against capital outlay (Hisham Elkadi 2016). This was the beginning of the office building typology which dictated maximum floor area, flexibility of use, lowest possible cost and larger window areas. This along with the advent of the HVAC systems around the same time led to hermetically sealed high rise offices with fixed glazing detached from the load bearing
structure, which depended on mechanical conditioning of the air. This is the international architectural style that saw unparalleled growth across the world.

But the 1973’s oil crisis and understanding the existence of the sick building syndrome led to the beginning of green initiatives in architecture. There was momentum toward reconsidering of the need to use extravagant quantities of natural resources for HVAC systems that also needed to balance the greenhouse effect introduced due to the design choice of having a fully transparent building envelope. People also questioned the notion of a sealed building. But instead of re-evaluating this approach, research began towards designing high performance building skins with the transparent faced in focus in order to maintain the expected levels of services (Hisham Elkadi 2016).

The curtain wall was also established as a way to counter the pre-war notion of the building façade as being the face to the architecture. But as the international style saw unprecedented growth across the world, it became “visual indicators of the level of prosperity, safety and peace” (Hisham Elkadi 2016) regardless of the existence of locally established architectural styles. Offices established in one part of the world could now became multinational with the international style of architecture as its face. The newly efficient mechanical air conditioning systems along with high performance building skin helped remove restrictions on where these offices could be located. They are now everywhere from places with very low average temperatures like Oslo to deserts like Dubai with very high temperatures.

But are these high performance building skins truly sustainable?
Gurgaon is a city in India which used to be farmlands and villages until about 2 decades ago. Temperatures here can go up to 50 degree Celsius on a hot summer afternoon. Now it has turned into a hub for multinational firms. It clearly demonstrates the popularity of the international style of architecture. New buildings such as the One horizon Center designed by Robert A.M Stern architects are marketed having LEED gold certification as of December 2016. In terms of their sustainability features for energy they list dual-pane high performance glass, efficient HVAC system that optimizes air flow and minimizes operating costs which in turn means it also uses less energy to operate.

It is misconceptions like this – that façade materials such as high performance glass lead to sustainability - that go unchecked and unnoticed. Such buildings, other than being highly energy intensive, adds to the urban heat island effect increasing the temperature of its micro climate and disrupts in the surrounding areas with glare caused due to the material glass among other things.

Jaipur (Figure 1) is also a city in north western India. It is located about 240km from Gurgaon has similar weather conditions. It is a large thriving city founded in 1726 AD and is also known as the pink city because of its main construction material which is pink sandstone. The old buildings in this city are well ventilated, naturally lit by the courtyard system & Jaali work\(^1\) and maintain favorable interior conditions without the need of artificial air conditioning systems.

\(^1\) Jaali work is like the Middle Eastern mashrabiyas, these are porous patterned screens used for sun shading and ventilation traditionally carved in wood or stone.
It is perplexing to think the international style should be so prevalent here (which is both expensive and bad for the environment) when there is already a well-established architectural system that provides comfortable habitable environments.

According to Stein and Reynolds (2000) there are two design concepts for traditional building envelopes. First one being an open frame, located in places where the external environments is very close to favorable conditions and the second being the closed shell, used in places of harsh external environments as a barrier. As the examples demonstrate the architectural performance depended on the design of the entire building design including the façade. But the introduction of the glass façade technology is questioning this categorization as transparency and protection are no longer contradictory architecture behavior and has changed the image of the façade from a space or zone into a surface.

Therefore, there is a critical need to re-think the design of the architectural façade of the office typology as a sustainable skin. We must let go of the glass façade as the only way to make this building envelope. A fresh perspective is needed towards the methodology of its design.
We are at a stage where instead of going forward with trying to solve the issues brought on by technology with more technology, we may need to look at architecture of the pre-industrial era. Preindustrial architecture is architecture at the time before mechanical system of air conditioning and HVAC systems. Buildings were carefully designed to create habitable internal conditions despite the weather conditions outside and with no energy (fuel or electricity) added. The materials and material technologies were limited but architecture from that time survived into the 21st century. Therefore, the answer to the design of sustainable façade may lie in the understanding of the past in the context of present architectural issues.

This research questions whether the contemporary approach towards the design of high performance architectural skin is in fact sustainable and looks for answers in architecture (pre-industrial) that was sustainable and green in every way.

1.2 Methodology

My personal experience in the field of architectural design of office buildings in India forms the grassroots of this thesis. As mentioned in the introduction earlier in this chapter, the unchecked growth of the international style of architecture in the hot climatic zones of the country led to my questioning of its sustainable nature for this location. The following questions were going increasing unanswered:

1. Why is there an unchecked growth of fully glazed facades in hot climatic zones?
2. In order to find a solution of the unsustainable nature of the fully glazed office envelopes, performative building skins were introduced. Are they truly sustainable?
3. Are the materials being used on the contemporary office facades truly contributing towards environmentally friendly buildings?

4. Countries such as India already has their own a fully developed traditional architecture, why isn’t this being properly studied and adapted into the contemporary world?

This thesis attempts to find the answers to the questions above in a two part methodology. Firstly, an extensive literature review was done in order to find the relevance as well as the solutions of the questions being asked. The literature review was essentially concerned with two things:

Firstly, understanding the contemporary office building envelope is order to find its strengths and weaknesses. Unfortunately, most literature on the weakness of the fully glazed building skins was correct and accurate but the solutions to cater to these weaknesses were inadequate and not fully formed. Therefore, the first part of this literature review also spreads beyond the field of architectural design into the material science world as well as thermodynamics to present a set of arguments that shows the true nature of the weakness and can lead to design solutions that are more in sync with the natural world.

Secondly, understanding architecture that is truly sustainable in every way, which is the pre-industrial architecture. In order to build contemporary architecture that is sustainable, this thesis finds it important to study the built environment of the past, which was architecture at a time when no active systems of cooling and ventilation were used. Since, this is not a unique thought; there already exist numerous papers and studies on different traditional architecture around the world. The literature review studies this and compares them in order to present an understanding of this type of architecture that goes beyond the obvious solutions/conclusions already given in the reviewed papers.

The second part of the thesis methodology is the testing. The literature review as discussed above is used to develop a strategy or methodology for the design of a contemporary office building envelope.
in hot climatic zone. This second part proposed a design approach for an envelope for a generic office building and then uses it to test the proposed methodology. This part holds importance as to visually confirm the possibility of changing our perspective on how the fully glazed façade is designed and constructed.

1.3 Thesis structure

This thesis is divided into five chapters. First being an introductory chapter, three chapters which comprises of the main thesis body and the last concluding chapter with future research scopes.

Chapter two discusses the contemporary office building envelope which is the building typology being questioned in this thesis. This chapter critically examines the history and origins of this type of building skin and presents an argument against this type of architecture in the framework of material science and energy.

Chapter three studies research (both quantitative as well as qualitative) on pre-industrial architecture (traditional/local architecture) based in some of the hot climatic zones in India. The climatic zones includes hot and humid, as well as hot and arid because both of these zones are seeing a surge in the construction of fully glazed building skins. The buildings in this research are reexamined with a different perspective using the analysis data available in the case study reports as well as its literature.

Chapter four presents a test case for the proposed methodology based on the studies from chapter two and three. This is in the form of a building skin design that provides visual confirmation of how this methodology delivers an architectural design that is in keeping with the standards of the contemporary office design.

Finally, the last chapter summarizes the whole thesis and its objectives along with the future prospects of this research.
1.4 Scope & Limitation

- This thesis is limited to office building facades that are transparent. Conceptually the same can be applied to almost any façade.

- This thesis only develops an architectural envelope design methodology for buildings located in hot climatic zones and proposes a design based in India (culturally and climatically) but can be applied to any hot climatic zone on the planet.

- The building façade is studied and designed only on the criteria of performance and because of its location based in hot climatic zones, the performance criteria is heat. The design proposal is not completely optimized for water or air movement.

- All conclusions drawn from the study of pre-industrial architecture is based on second hand research of quantitative and qualitative research reports and papers along with personal experience.
Chapter 2: The problem with the transparent façade (in hot climatic zones)

2.1 Introduction

A fully transparent façade which is essentially the contemporary curtain wall system is typically made up of a few components which are the mullions, infill panels and anchors. The mullions are typically made up of extruded aluminum due to its high strength to weight ratio and within these mullion framework is where the infill panels are set. These infill panels can be comprised of stone, glass, metal etc. The anchors are typically either rubber gaskets or silicone sealants for glass panels and secondary anchor clips for metal or stone panels.

The drawbacks of using glass panels are well known ones, the most prevalent one being its capacity as a poor thermal insulator. The solution to which is the use of various coatings on the glass panel to able to vastly affect the way the glass conducts or transmits/rejects solar energy (Murray 2009). Secondly, the use of double paned clear glass with coatings is also being extensively used to reduce its solar heat gain. The curtain wall also transmits heat into the interior space by thermal bridging. Thermal bridges are formed at the point where the curtain wall system connects to the main building structure. At this point the structure (curtain wall) that is exposed to the outside environment is easily able to transfer heat from the outside into the main building structure thus increasing the overall temperature of the building. Thermal breaks are used as solutions for this, where the metals components from the outside are physically kept separate from those exposed to the inside.

Newer solutions to the heat gain problems of the transparent façade are through the use of dynamic, responsive building envelopes. These are highly engineered facades that are capable to real time response to the changing external environmental conditions. Their key goal was the better
management of energy flows to increase the performance of the building (Kolarevic, Parlac, and Taylor & Francis eBooks A-Z 2015). Early examples of which include Jean Nouvel’s Institut du Monde Arabe (1989) and the more recent examples, include the Al Bahar towers in Abu Dhabi (2012).

But the above solutions to the problems brought on by the use of transparent facades are similar to a doctor treating the symptoms of the disease instead of the actual problem. In other words; we as architects do not seem to understand the main principles behind the issues that are brought on by the design choice of using a transparent skin like the curtain wall in hot climatic zones, instead we are only solving each of the multiple problem with one solution each as seen in the case of reducing solar heat gain by using low e coatings or using thermal breaks to solve the problem by thermal bridging. The low e coatings have high embodied energy and thermal bridging requires more detailed design of new components. Similarly, performative skin uses sensors and other forms of electronics along with a range of new and high engineered materials, all having high embodied energies to solve the same problems. All of this seems counterproductive and band aid solutions to a problem which would have never come up in the first place if the fully glazed façade was not used in the hot climatic zone. But the solution to this is not the complete abandonment of transparency which would take us back to pre-industrial times. Instead we must understand the principles behind the problems of the transparent façade.

Therefore, this chapter articulates the problems with the transparent façade to provide solution oriented explanations. It covers four principles behind the complications faced by the fully glazed building skin in terms of environmental performance in order to leave us in a better solution finding position.
Firstly, the line of origin of the performative facades can be traced back to greenhouses which are essentially a structure that was never meant for human habitation especially in hot climatic zones. Secondly, in the process of making the greenhouses fit for human habitation we have added on a large number of components within the building façade which is leading to wastage of materials as well as energy. Thirdly, the contemporary architect’s inadequate knowledge of materials to leading to the selection of unsuitable materials for the façade and finally, even though we are sincerely trying to bring down the energy usage by the buildings, in this effort we maybe increasing the energy usage elsewhere. The last part of this chapter presents the contemporary building skin as an open thermodynamic system in order to explain its inappropriateness for a hot climatic zone when compared with the local pre-industrial architecture of that location.

2.2 History and origins

Change the line of origin from plant habitable to human habitable structures

Most of the multinational office building typologies have a transparent façade. They are all fully glazed towers and look similar irrespective of what part of the world they are located in. The history of the glazed façade can be traced back to the industrial revolution.

The industrial revolution was the beginning of new ways of producing, manufacturing and distributing goods. Its results were far reaching and impacted life at all levels. Large number of rich company towns cropped up everywhere (Garner, John S. 1992). Coal and petroleum were now the new sources of energy rather than bio fuels like wood. This paved way to new ways of production and manufacturing of architectural elements like glass and steel sections. Glazed windows were
used as luxurious items during the middle ages until the industrial age. For architecture, this meant going from dark spaces with very little day lighting towards naturally illuminated spaces.

The pioneers of fully glazed structures were initially the greenhouse designers such as John Loudon and Joseph Paxton (Elkadi 2016; 2012). They designed greenhouses with the intent of allowing sunlight into the structure; hence the iron framework was kept to the minimum and rest were glass panels, for example, the Palm house (1820) in Devon, UK. This was designed as Loudon’s theory of hot houses, as a way to control and modify the climatic conditions. Greenhouses gained a lot of popularity with the developing of the great exhibitions such as the Jardin des plantes(1833) or the Munich glass palace (1834) (Elkadi 2016; 2012). The rising popularity of large glasshouses was pushed up further by the parallel development of the iron industry and thus gave rise to the iron and glass age of architecture. These structures provided an opportunity to accommodate large number of people in a naturally illuminated space. Therefore, the glass facades started being observed in large public buildings, exhibition spaces and train stations. Naturally lit interior spaces in the cities of England and France were a refreshing change to the generally low lit spaces inside heavy stone walled structures of the past in that area.

This was the beginning of the transparent building skin; that started as a utilitarian purpose of sustaining vegetation in extreme cold climates to curtain walls for tall human habitable buildings. The transformation from the green houses or conservatories into the fully glazed facades we see today was not an immediate process. It was a direct influence of the development of the frame structure in architecture. This type of structure removed the load bearing responsibility from the building envelope completely and transferred it to the beam and column structure. It became independent from the main building and became the face of the building; therefore responsible for the visual representation of the building and its occupant’s character. The development of the curtain
wall facades was a product of simultaneous growth in multiple fields which included the commercial availability of elevators, advancements in structural framing and the development of the HVAC systems (Murray 2009).

Large transparent façade did not see its use in the office buildings right away. As mentioned earlier it saw its beginning in green houses, and then was also used as shop and factory facades. For example, Gardner’s stores in Glasgow (1855 – 1856) (Richards and Gilbert 2006).

Large panes of glass were produced commercially for the first time in England by Lucas chance in 1830 A.D. (Elkadi 2016; 2012) but structural glazing saw production only after the World War II (Murray 2009). This led to the beginning of fully sealed buildings relying completely on the artificial ventilation and air conditioning systems. Such a hermetically sealed high rise with fixed glazing detached from the load bearing structure, depending on mechanical conditioning of air saw an unparalleled growth across the world.

Low energy and production costs, high downtown real estate rates, new technology such as artificial air conditioning, elevators and an economic boom led to the unchecked construction of this international style, even though they were highly energy intensive. Studies on artificial air conditioned spaces showed an increase in productivity of workers during the summer months (Kolarevic, Parlac, and Taylor & Francis eBooks A-Z 2015). With air conditioning the office building typology would have never moved into the hot climatic zones because in some cities during the summer months, the office building needed to be closed due to excess heat.

The energy crisis of the 1970s, architects and designers were forced to reevaluate the way buildings were designed (Elkadi 2016; 2012). They had to come up with innovative solutions to bring down the
energy usage and operational cost of the building without compromising on the thermal comfort standards set before the crisis.

Since the building envelope is the interface between the interior and the external environment, other than working on improving the efficiency of the HVAC system, all efforts were on improving the design of the building façade. Single skinned glass facades gave way to double glass building envelopes (Schittich 2001). Werner Lang in his essay (Schittich 2001) “Is it all just façade?” describes the role of the building façade as the part of the building responsible for all or most of the environmental controls in the building and also describes the comfort factors as parameters for building skin design which are air temperature and average surface temperatures. Air change rates, relative indoor humidity, luminance and lighting intensity. These are essentially systems that are in place to create conditions that are favorable for the working of the HVAC systems at low energy costs. The standards of this have been established by ASHRAE (American society of heating, refrigerating and air conditioning engineers) and have remained unquestioned.

Michelle Addington questions these standards, in her paper “Contingent Behaviors”. The modernist idea of the glazed skin has been as a way to enable visual contact with the external environment. It is meant to engage with the outside and create the connection between a human body and the environment as compared to the preindustrial architectural ideas of what a building envelope is. But unknowingly, we have further isolated the human body from the external environment by creating a “manufactured environment” (Addington 12-17 2009). This environment converts maximum amount of primary fuel for energy in both residential and commercial buildings. Therefore, after this energy crisis, most of the focus is on reducing the energy utilization by the built environment.
Contemporary meaning of building performance addresses the understanding that all the forces acting on the building are not fixed or static but are always in flux. Therefore, today’s building skin is given different names from being smart and intelligent envelopes to responsive and dynamic facades.

2.2.1 Conclusion

This is the fully glazed façade as we witness it today. Even though this façade now gets hidden under a second layer of responsive skin but a straight line can still be traced between the origin of greenhouses and the performative glazed façade that we see today. There is clearly a problem here, as we are still trying to compensate for the problems that are created by a structure not even meant for human habitation. Like the green houses, the origins of the curtain wall were also seen in the cold countries of Europe and America. Solar heat gain is welcomed here. But due to globalization and the symbolic power held by these buildings in the developed world, the countries of the developing world aimed to copy these structures to position themselves as progressive countries. Most of these countries are essentially located in hot climatic zones. When the curtain wall structures are built in these climatic zones the impact is manifold that includes huge solar heat gain through the façade, glare etc. this increases the operational costs of the building because energy use by the HVAC systems increased in trying to maintain comfortable internal conditions.

Therefore, once the problem is identified; which in this case is the fact that the roots of the contemporary transparent office façade lie in the green house, the solution to this also becomes very clear. The above section does not push the use of the solutions mentioned in the introduction but guides us to a solution at a more fundamental level; which is attempting to design and construct the
contemporary office façade as a derivation of a human habitable structure instead of a conservatory or a greenhouse based in the cold climatic zone.

2.3 Component based design

Going from a highly engineered and component based design methodology to a holistic façade design approach

2.3.1 Introduction

Edward Allen and Joseph Lano state that the main purpose of the exterior wall is to separate the indoor from the exterior environment to maintain favorable interior conditions. Similarly, Ajla Aksamija in her book ‘Sustainable Facades: Design methods for high performance building envelopes’ states the two functions of the building envelope as being, a barrier and the component that creates the image of the building. First section of this chapter explains the origins and the status of the contemporary transparent façade today. Maximum system efficiency has become almost the sole aim of every building today owing to the fast depleting natural resources and increasing pollution. Most of the responsibility for this falls on the building skin. It is regarded as the face of the building and a reflection of its occupants and designer. The gaining spotlight on this component (building envelope) is causing the contemporary architectural skins to use the latest technologies and materials to achieve all its tasks, but such emphasis risks superficiality.
Performance of the skin in the context of this paper is limited to adaptive envelopes, which has the key task of better management of energy flows, both from the interior and exterior (Kolarevic, Parlac, 2015). This can be achieved both with visible movement or no motion at all. Visible movement on a building facade leads to an urban spectacle, which often gets exploited for visual purposes, even if this movement may not be directly related to the environmental responsiveness. Therefore, it is required for an unbiased look at all parameters for building envelope design to single out only the most crucial ones. The growing list of building envelope design requirements leads to an overdesigned skin that is complicated and wasteful in terms of energy. In other words, it uses a component based design approach. This approach along with its limitations is explained further in this section.

Allen and Iano (Allen and Iano 2009) translate their building skin definition into the following requirements: (i) Keeping water out, (ii) Controlling light, (iii) Controlling air leakage, (iv) Controlling water vapor, (v) Controlling radiation of heat, (vi) Controlling the conduction of heat, (vii) Controlling sound. Figure 2 (next page) demonstrates how the above 7 points are addressed in a typical façade section of a contemporary curtain wall building.
4. Controlling Light
Light is controlled through the type of glazing used, in this case it is the low E glazing with silver coating. Other than this, the shingled façade are self-shading with horizontal baffles for extra shading. There are also internal blinds to control day lighting.

2. Controlling water vapour
3. Controlling conduction of heat
To avoid condensation of the moisture in the façade system or on the inside, there should be minimum temperature differential between the inside and outside of the system and avoid conduction of heat. The material aluminium used in the mullions have high thermal conductivity, therefore, to increase resistance to condensation, materials with low thermal conductivity are used as thermal breaks. For example, PVC, neoprene, polyurethane or polyester-reinforced nylon.

5. Controlling air-leakage and sound
The air leakage and sound is controlled through the gaskets, sealants and air barriers provided for controlling water.

1. Keeping Water Out
To stop water from going into the system through the joints between the glass and the mullions, protective gaskets are used; but water and vapour do end up entering the system through the corner of the gaskets, but can be channelized through the system into the weep holes/drainage points.

Figure 2: A typical curtain wall section demonstrating how the building skin requirements are addressed.
Figure 2 clearly shows that for the seven requirements mentioned, there is a separate component for each of them and as experienced architects we also understand that this is not a foolproof section. There is always going to be air or water vapor leakages into the interior. Each of the components is also made of different material assemblies. The component for lighting control, which is actually the transparent façade, is the material glass that allows light to pass through. To install the glass on the façade requires a framework of aluminum extrusions to position the glass panels as explained in the introduction of this chapter. This whole curtain wall system needs to be attached to the main building which is done through steel brackets. But the junction between the aluminum and glass is not air tight; therefore, it requires silicone sealant or gaskets in between etc. this list goes on. As seen in Figure 2 every assembly deals with one problem. This problem mostly arises due to the shortcomings of another component as described in the curtain wall example.

Unfortunately, contemporary office building envelopes in a hot climatic zone do not limit themselves to only these components. For example, under the requirement of light control, there is an added component of blinds that are required to regulate the amount of sunlight coming in (the problems of excess sunlight in the interior is discussed in the later sections in this chapter). Therefore, with new locations or criteria, the list of façade requirements also increases.

The importance of reducing the energy consumption by the building skin has led designs to be more conscious of its geographical location. The following are examples of design strategies used for sustainable facades:

(i) Solar control (ii) Reduction of external heat gains (iii) Cooling (iv) Daylight
Aksamija states the use of building form and shading devices to control the sun while using insulation to cater to the second point, using natural ventilation for cooling and using special shading devices to regulate daylighting. All of these points essentially add new set of building skin requirements to the seven points mentioned before.

Having reviewed various literature (Yu and ebrary 2013; Schittich 2001; Lovell 2010; Allen and Iano 2009; Knaack and Ebook Central Perpetual and, DDA 2007; Aksamija 2013) that lists out the requirements of a building envelope, Werner Lang’s (Schittich 2001) list summarizes the general trend of the architectural community; (a) Lighting (b) Ventilation (c) Protection from humidity (d) Insulation against heat and cold (d) Wind protection (e) Sun protection (f) glare protection (g) visual protection (h) visual contact/transparency (i) Safety/Security (j) prevention of mechanical damage (k) Noise protection (l) fire protection (m) Energy gain.

When the building façade is responsible for lighting, it refers to its access to daylight. Daylighting is easily available through the transparent façade. But even though lighting and view is available through the glazing, it needs to be controlled using blinds or screens. This same argument applies to the points on view and visual contact. Sun protection in hot climatic zone is achieved by the use of an external second layer of sun shading. It should be noted that the above list is the list of requirements for a building façade and not a list of requirements for a ‘transparent’ building façade. But most of the requirements are a function of the assumption that the building skin is going to be a transparent one. For example, glare protection and visual protection are properties arising due to a preconceived material choice that is glass. Curtain wall facades are a major cause of glare. According to a research by the Council on tall buildings and urban habitat (CTBUH) (Vicente Montes-Amoros, Curtain Wall Design and Consulting, Inc. 2015) the increased demand for skyscrapers that
maximizes views has led to an extensive use of exterior glass paneling. Due to the high reflectivity of glass, they generate a lot of heat that leads to property damage and distracting glare. The HVAC system in the building is responsible for ventilation and there may be fans or ventilator sections on the building skin. Protection from humidity is achieved by removing the moisture from the air and not allowing the moisture from the outside to come in. There exists a vapor barrier component on the façade that is responsible for this. Insulation against heat and cold is achieved by the use of insulation on the building envelope. Wind protection may not be the responsibility of the building skin but of the overall building form. The next requirement on this list is protection from mechanical damage. In the quest towards trying to attain real time responsive facade systems, designers have leaned towards using moving parts resulting in dynamic building skins. For example, Jean Nouvel’s Institut du Monde Arabe, Paris completed in 1989, has one of the first large scale dynamic façade. It contains photosensitive diaphragms that control light levels and transparency according to the sun positions. This mechanism is no longer functioning. This system is based on mechanical movement through numerous joints and as these parts undergo mechanical loading on a continuous basis, they are bound to fail due to fatigue or creep over time if not due to other reasons. Therefore, prevention of mechanical damage is in the list because it has been assumed that the building envelope will also have a moving component.

The above discussion also brings attention to the component based design, where just like there is a separate component for each requirement in Allen and lano’s list. The number of components in the above lists is more; simply because the requirement list has increased. For example, Blinds for lighting, fans for ventilation or even a second exterior sun shading layer. Additionally, each of these components also has further units, for example, the sun shading layer needs its own structural system that gets attached to the main structure. This type of design methodology is a byproduct of
the era of mass production where various components will be manufactured in bulk and assembled together to serve only one purpose. The statement below by Scott Murray summarizes this best.

“In contemporary practice, the curtain wall is typically conceived as a system – that is, as a coordinated assemblage of components designed to perform in a specified way.”

(Murray 2009)

This is not the case in pre-industrial architecture (chapter 3). Therefore, a more holistic design strategy needs to be applied demonstrating a reduced list of building envelope requirements.

The daylighting, sun protection, visual protection, transparency requirements in the interior depends on how the facade mediates the visual spectrum of the sunlight. Energy gain and insulation against heat and cold is achieved by mediation of the non-visible radiation of the sunlight. Therefore, all are a function of the sunlight on the whole. Temperature fluctuation and ventilation depends on air movement mediated through the skin. Whereas wind protection, noise protection are a function of air while protection from humidity and precipitation are achieved by water mediation. Therefore, the main aim of a building envelope is to be able to mediate between air, water and sunlight.

Jenny Lovell in her book Building Envelopes: An integrated strategy, simplifies the wide range of building skin functions from a list similar to that of Werner Lang’s to air, water, material and installation, daylight, heat and energy. She terms them as elements of a holistic approach which have possibilities of integration instead of being called as problems of mitigation. She does so by
understanding the principles behind the situations brought on by through the mitigation between the building skin and the external elements.

![Diagram of factors affecting building skin]

*Figure 3: The building skin mediates air, water and sunlight. Each is an umbrella term that comprises of the above shown factors also.*

Using the same strategy, we can make her list shorter. The elements mentioned in Lovell’s list are not mutually exclusive. As discussed earlier daylighting and heat are factors of the sunlight. And energy maximizing or minimizing is possible from either and all of the three (Air, Water and Sunlight). Therefore, there are only three parameters of mediation which are sun, water and air.
2.3.2 Conclusion

The problem identified in this section is the fact that we use an approach that compartmentalizes everything. An issue/component is identified (in this case the building façade) and it is broken down into further components for ease of resolution and manufacture. Each of these are also further broken into components, this process goes on until a unit that can easily be resolved and built. All of these components are finally brought together and assembled. In the process of resolving each building façade component, we keep it independent of the other and as explained in this section, this is not an adequate solution. Since, the industrial revolution, we have only been adding components to architecture, our building skins have become more complex and energy expensive. It is time to pause instead of adding more components to the building envelope to make it more energy efficient; we must go from a component based design approach to a more holistic design approach where nothing is considered in isolation but as part of a holistic energetic system that exists around us.
2.4 Materials selection in architecture

Informing the architectural designer towards making appropriate decisions concerning material selection for increased building performance.

2.4.1 Introduction

Materials are an innate part of the architectural façade. Its texture, color and form give the building its face. The wide range of materials and technologies available to the contemporary architect only adds to the need for every building to more different and unique than its predecessor.

Architectural history shows us that materials available in abundance, were used to construct most components of the building while the purpose of rare and expensive materials was ornamentation and symbolism. Fired brick is one of the most used building materials. It was first produced as a sun dried form, dates back at least 6000 years. It is a unit derived from readily available loose raw material in the form of clay and soil. The original concept of ancient brick makers was that the unit should not be larger than what one man could easily handle. The knowledge of brick making and construction was passed down generations and may be regarded as one of the most optimized forms of a material. This is an extremely versatile unit and has many purposes in the industry of built environment. This versatility enabled the brick to move into the 21st century without becoming obsolete.

Such intrinsic knowledge of architectural materials is not visible among designers today. For example, the transparent façade is an assembly of components as discussed in the previous section. It is also be an assembly of different types of materials. Starting with the extruded aluminum for mullions, glass and other metals for infill panels within the mullions; rubber gasket or silicone
sealant for sealing the connection between the infill panels and mullions and finally steel sections that connect the curtain wall to the main building structure. These are the bare minimum number of materials used in the construction of the curtain wall. All of these materials are unsuitable for buildings located in hot climatic zone because firstly, large panes of glass gives access to solar heat gain, secondly, the aluminum extrusions have high thermal conductivity and allow heat to easily transfer into the interior through thermal bridging. Therefore, these are clearly unsuitable material for a hot climatic zone. But they continue to be used without being questioned. There seems to be misinformation between the environmental performance criteria and the materials being used. This connection of architectural requirements to materiality can only occur when the person designing (the architectural designer in this case) understands material properties, just as the brick makers had the innate knowledge of the brick and its properties to make forms that the material does not resist.

The contemporary architect does not have full liberty to select any material he or she wants, they are influenced by several factors including the client expectation (which in most cases does not coincide with environmental performance) and whatever material or component assembly that is presented or available to them through the vendors of the same. Architects generally do not select building façade materials based on first principles nor do they have the adequate knowledge to do so. Looking at the material world for the design of the building façade based on first principles, we find ourselves with more material options as explained further in this section. But these are generally not offered as a building façade option or not very easily available. With new methods of design and fabrication at our disposal like additive manufacturing or robotic construction, we have far greater flexibility to use new materials without the need of an intermediate vendor providing us with the prefabricated components.
This chapter brings to light the third concern of transparent façade, which is its inappropriate material selection. The inadequate knowledge of the innate properties of materials is responsible for the construction of a large number of energy intensive buildings especially, in the hot climatic zones. Therefore, this chapter provides the solution to this by understanding the importance of appropriate material selection during design stage by introducing the material classes, along with pushing us to change our perspective towards conventional materials as a way towards the future of architecture.

2.4.2 Misunderstandings in contemporary material selection

For buildings located the hot climatic zone, sun shading is very important. Solar heat gain is one of the fundamental reasons for interior discomfort.

Sun shading in buildings has been fundamentally done by blocking off the direct sunlight or diverting it. For example, the horizontal overhangs on top of a window openings and ‘Brise soleil’\(^2\). This concept has given rise to venetian blinds and contemporary macro louvers as a shading system in front of the transparent glazed façade. Glass provides transparency without the physical exchange between the internal and external environment. This traps the heat (infrared radiation) coming from sunlight inside, which makes it an ideal material for green houses. But for a building with occupants, this concept of transparency creates a problem for the interior environment and the building systems. It increases the internal temperature creating an uncomfortable space and increases the load on the mechanical air conditioning systems. Instead of reducing the use of completely glazed

\( ^2 \text{brise soleil is an external wall with lattice work used to block direct sunlight.} \)
exterior walls, a second building skin is designed to reduce the amount of direct sunlight hitting the glazing and therefore, reducing solar heat gain by physically blocking the sunlight.

This second layer can be designed and constructed using various types of materials as well as geometries. For example, the King Fahad National library in Riyadh Saudi Arabia has a second skin composed of filigree textile in geometric patterns which are common in the Middle East. This translucent white membrane is stretched and propped up using a three-dimensional, tensile-stressed steel cable structure. This layer does not fully cut out the sunlight instead provides the inside with an evenly distributed diffused light. This light falls on the inner glazed layer. Similarly, The Sur Yapi offices in Turkey also have a second outer sun shading layer. This layer uses wooden horizontal slats for sun shading purposes on the southern façade of the building. The skewed angles of these wooden slated panels create a screen similar to an overhang to block of direct sunlight. Finally, this second outer skin can also be composed of bricks as seen in the South Asian Human Rights Documentation Centre in New Delhi, India to create a sun shading system. A single repeating brick module creates a visually complex pattern in the manner of traditional South Asian brise soleils on the sun facing façade of the building. The depth of the brick wall also acts as a horizontal shelf that blocks direct sunlight.

All examples above mentioned use similar geometrical approach towards the task of sun shading. They are all the second outer skin to the interior glazed façade. It is its geometry that is responsible for reducing the amount of direct sunlight hitting the inner layer. The material selected is primarily responsible for this layer’s appearance. All of them are also located in a primarily hot climatic zone where the maximum temperatures on a hot summer afternoon can be extremely high along with intense sunlight. The outer layer is able to reduce the solar heat gain and the resultant interior temperature change inside the space for all may also be similar.
The stark difference between the three is the material used to achieve this. This brings on the question of why are the materials in these examples different, even though they are meant to perform the same tasks. One could argue this case on the grounds of material availability for each location, since the most common building material in New Delhi, India is fired bricks. But this is not the case for materials used in the example shown here from both Riyadh and Turkey. The next argument comes in the form of performance; Teflon coated fibre glass membrane is translucent and provides natural daylighting other than sun shading. Wooden louvers provide acoustic shading along with the thermal barrier. All three examples have fully sealed glazed façades and depend on mechanical HVAC systems. Therefore, this outer sun shading layer helps in reducing the load on these systems. This is the objective for all performative architectural building skins. All intelligent or smart or dynamic architectural envelopes are design to reduce the load on the mechanical systems used for building operations which is directly proportional to the operational cost of the building also.

But do these materials truly add to green architecture or buildings that do not exploit or endanger the natural environment?
Figure 4: Materials property chart: Electrical resistivity vs Thermal conductivity. Source: Granta Design (Used with permission)

Figure 4 shows a materials property chart. This graph is plotted between the axes of thermal conductivity and electrical resistivity. Thermal conductivity is the rate at which heat is conducted through a solid at steady state (Ashby 2011). This is one of the important material properties to consider when selecting the material of the architectural envelope. This is especially important for buildings located in hot climatic zones where the main purpose of the envelope is to keep the heat out. Therefore, a material with low thermal conductivity is always preferred. Based on the above shown chart, wood used in the office in Turkey has one of the lowest thermal conductivity rates. But the steel framework used to support the translucent fabric in the library in Riyadh has extremely high conductivity. Meanwhile the brick façade in India falls in between but it has a higher thickness than the other two, therefore increasing thermal mass and increasing the time taken for the heat to pass through the material.
Figure 5 is the material property chart comparing the embodied energy of the different material classes. The embodied energy is the energy, excluding that from bio-fuels, that is used in making 1 kg of material from its ores and feedstock (Ashby 2011). All three materials discussed above are plotted here. It is evident from this graph that the Teflon coated fiber glass fabric has high thermal conductivity and also high embodied energy. While wood and brick have low thermal conductivity and low embodied energy and also can be recycled. Therefore, in a city such as Riyadh which has extremely high external temperatures, the geometry has been optimized well for sun shading and visual appeal but the material is unsuitable. Therefore, what would be the ideal material for the task at hand?

The three examples here clearly demonstrate the insufficient understanding of material properties by architectural designers. The material such as the steel cable structure holding up the white
translucent membrane is not only increasing the interior temperatures due to its high thermal conductivity but is also harmful to the environment in a global scale due to its high embodied energy, Therefore, it is important to understand the need for material study and optimization along with form and geometry design during the design and construction of a building today.

2.4.3 Material science and properties

Michelle Addington in her book smart materials and technologies defines materials in two ways, which are derived from smart material definitions from NASA and from the encyclopedia of chemical technology. She summaries that we can look at materials as substances such as elements, alloys and compounds but we can also refer to them as series of actions as a composite or singular or as an assembly of many materials. Either ways, there are some properties like density and strength that are intrinsic to the material and is a function of its chemical bonds which cannot be changed or altered to a large extent unless there is a change of state due to extreme temperate variation.

Material science classifies the material universe into six broad categories which are metals, ceramics, glasses, elastomers, polymers and hybrids (Ashby 2011). The following page shows a series of charts (Figure 6) on the evolution of materials and material classes through time. It shows its development over time to meet demands on strength and density. Low density and high strength materials is the most sort out because of it being strong and lightweight.
Looking at these charts we also notice that materials belonging to the same class bunch up together around the same location of the chart marked by a single colored translucent cloud. This is because these properties are dependent on the type of chemical bonding that was discussed earlier, therefore materials belonging to the same class exhibit similar materials properties. Architectural designers do not need the precise knowledge of properties for each material in question instead they need a direction to look towards while in their material selection stage. Instead of the material choices coming from a product marketing executive or a client’s preference, the decision maker (the
architect) must have in-depth knowledge of each of these classes to will help keep us at par with the growing list of materials entering the world. All the materials that exist today fall under one of the six classes, which are ceramics, metals, polymers, elastomers, glasses and hybrids. Ceramics have a high response to compressive loading, in other words they are strong under compression, and building materials such as concrete come under ceramics. Brick and different stones such as granite are also ceramics. Most metals have high tensile strength and in pure state they can be easily deformed, but they are combined with other materials to form alloys to suit different purposes. For example, steel with a certain percentage of carbon is the composition of the steel girders in skyscrapers. Glasses are non-crystalline solids (Ashby 2011). They are also brittle like ceramics. Fully glazed buildings are composed of soda-lime glass panels. Polymers as seen in the chart above have very low elastic moduli. They are not as strong as metals and incur high deformations but they have a very low thermal conductivity as compared to other material classes. Polymers are commonly seen in food packing and plastic beverage bottles like the PET bottles. Epoxy is also a form of polymer. Elastomers are long chain polymers above their glass transition temperature. They have very low moduli and with increased temperatures and show large elastic extensions. Common elastomers are synthetic rubber which is commonly used in the inner tube of tires. Hybrids are composed of two or more material classes combined in a specific way to give rise to materials that are able to display the required properties from all the used classes. For example, rigid polymer foam is used as wall insulation in buildings. Most naturally occurring materials like wood and paper also fall into this class of material. All of the properties of each class is a function of its chemical bond. Therefore, it is its intrinsic property and cannot be easily changed.

The above discussion leads to the belief that it may be impossible to manipulate the materials to suit our needs. Certain properties like stiffness (which is dependent on the shape of the component) can be increased or decreased by changing the shape of the material. For example the I-beam is stiffer
than a solid beam with the same amount of material. Shape is used regularly in mechanical design to enhance certain material properties or allows materials to overcome failures. Therefore, geometrical optimization is also important for building design.

Contemporary architecture in most case is a resultant of first choosing the form or geometry and then finding a material that best suits our needs or that which is visually pleasing. This may often lead to unsuitable choices, as is seen in the example of the sun shading systems in the beginning of this chapter.

The sound understanding of the intrinsic properties of the material universe is important along with the need to know what material properties are imperative for the design of a building. This could lead to a responsive architecture that may react in real-time to the changing environmental and structural conditions. But even if we are able to document every material property required for the performative building skin, the ideal material or materials are not available consisting of all or some of the required properties. In most cases, if there is one desirable property, the rest are contradictory for the purpose of the built environment. For example, one of the most desirable material properties is a very light and strong material.
Above is a material chart between the density and strength of materials. With a few common architectural materials labelled. It is observed from this chart that materials that have high strength are also heavy due to its high density.

A similar pattern is observed in the material property chart if transparency vs the thermal conductivity of materials is plotted. The most ideal material for architectural purpose would be one that is transparent as well as a good insulator. Soda lime, which is the glass that is used on the building façade, has a higher thermal conductivity in comparison to the extremely low thermal conductivity portrayed by the opaque materials.
This limitation of materials that shows a contradictory nature in their behavior with respect to the required material properties has resulted in excessive energy use for compensating the undesirable properties that come along with a few desirable ones as is observed in the example of using fully glazed building facades. The thin glass panels do not stand on its own and are heavy, therefore need a framing system that is strong as well as light if it needs to conceal the entire building exterior. For this aluminum extrusions are commonly used. Aluminum is a metal and has a high thermal conductivity and when used in buildings located in hot climates, they increase heat flow into the interior. This increases the air conditioning load on the building HVAC systems.

In material science, when the perfect material for the task is unavailable which the case in most designs is, then the concept of ‘trade off’ is applied to find from the pool of materials (that is proved quantitatively to satisfy all the minimum design requirements) for a material that has the best ratio of properties. Observing both these charts, there are two materials that stand out GFRP (glass fibre reinforced plastic), which is transparent and has a lower thermal conductivity in comparison to soda lime glass. The second material is CFRP (Carbon fibre reinforced plastic, which displays high strength and low density as compared to the commonly used architectural materials.

The combination of these two materials has been recently used in the ICD/ITKE Research Pavilion in 2013 that demonstrated the potential of the robotic coreless filament winding process. Due to the ideal level properties demonstrated by hybrid materials such as CFRP or GFRP, the movement towards similar engineered materials is on the rise which is also getting termed as smart materials.
2.4.4 Smart Materials

Smart materials have come to become solutions to the shortcomings displayed by the material universe. Addington in her book Smart Materials and Technologies describes the characteristics of these engineered materials as the following:

- **Immediacy**: they respond in real-time.
- **Transiency**: they respond to more than one environmental state.
- **Self-Actuation**: intelligence is internal to rather than external to the “material”.
- **Selectivity**: their response is discrete and predictable.
- **Directness**: the response is local to the activating event.

These characteristics are almost synonymous with dynamism. They define the way the material reacts to its immediate environment. Since these are engineered materials, they have been designed to provide movement at the scale visible to the human eye. Smart materials can be defined as the materials that respond to changing energy fields (what is changing energy fields). When compared with conventional materials which are static and intended to withstand building forces, it may be unfair to put these materials in two separate categories simply based on designed characteristics rather than its innate material properties. In other words, a conventional material can also respond to changing energy fields if we design them to do so. For example, hygroskin – Metrosensitive Pavilion by Achim Menges in collaboration with Oliver David Krieg and Steffen Reicher. This project makes use of the intrinsic property of wood to create a climate responsive skin. The dimensional instability of wood that takes place with changing moisture content inside to made use of cleverly to achieve a self-actuated system. Here wood is responding and reacting to energy fields, even though wood is considered a static material that withstands building forces when it is used as load bearing systems or for walls. Therefore, it may be incorrect to define the two categories of materials as done so in the
book. Instead it can be stated that the two definitions are two separate utilities of the building material and applies to all the materials in the universe. They can either respond to energy fields or withstand building forces.

2.4.5 Conclusion

This chapter provides a solution to combating the growth list of inappropriate material selection in the design of the transparent façade in hot climatic zones. It shows us that the way into the future does not lie in the invention of new materials or in trying our best to keep up with the new technologies to give rise to newer, more sophisticated and highly engineered facades.

Firstly, it lies in gaining correct information about materials for its better incorporation into the building design. Secondly, Conventional materials also have a lot of potential that we haven’t fully explored as yet. Therefore, changing our perspective on how we utilize such materials can lead us into a more sustainable future.
2.5 **Energy systems**

Understanding the architectural envelope as part of a larger energetic system for designing better performing building skins

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### 2.5.1 Introduction

Chapter 2 until now has discussed three problems with the transparent façade; its history, its design methodology (component based design) and its inappropriate material selection. Finally, this section explains the concept of the building façade (transparent building façade in hot climatic zone) as part of the larger energetic system. It introduces the concept of understanding the building envelope beyond the tangible forces around us but together with the invisible; the thermodynamic systems. This section brings together the concepts from the last three sections and explains the building skin as an open thermodynamic system. The understanding of the concept of energy by the architectural designer as a step beyond just its generic use is important to truly design and construct a building façade that is in sync with the environmental forces around it. The architect’s insufficient knowledge of this is brought out in this section when a generic building façade is analyzed with laws of thermodynamics that brings to light the inefficiency of the transparent façade in hot climatic zones.
Every energy system around us has the tendency to move towards equilibrium. This includes the building system. The building is an open thermodynamic system. This means that this system allows the free exchange of matter and energy through its boundary (systems boundary).

A systems boundary is defined as the edge of the energy system. This has been clarified here because this boundary in the case of a building does not necessarily mean the physical building envelope only. It also refers to the point where the building energy flows interact with the surroundings.

The main purpose of the building envelope is not to allow the systems equilibrium to be achieved. In other words, it helps maintain a position that is as far away from equilibrium as possible. In order to constantly keep the building system from reaching equilibrium energy needs to be provided. Therefore, there will always be a minimum amount of energy required as input; this makes the task of achieving zero energy architecture conceptually wrong. What type of energy (active or passive) we provide the building is the correct set of choice.

The open thermodynamic system of that of a building can be explained further with an example of achieving comfortable internal temperature for a building located in a hot climatic zone.

Let us assume that the temperature on the site in question is 40°C and an internal temperature of 25°C is needed to provide adequate comfort levels. The systems boundary and the building envelope need to do work, firstly to bring down the temperature from 40°C to 25°C and then maintaining this difference. The natural tendency of this building system since it is an open thermodynamic system is
to allow for constant exchange of matter and energy through its boundary until the internal and external temperatures are the same.

Therefore, according to the first law of thermodynamics, the change in internal temperature is equal to the heat going to the system minus the work done by the system.

\[ \Delta U = Q - W \]

Where, \( \Delta U \) is the change in temperature or energy

\( Q \) is the heat added to the system or the flow of mass and energy

\( W \) is the work done by the system

This equation is for a system where heat needs to be added into the system to change the internal temperature but for a system where heat needs to be removed such as the building envelope in the current example.

\( \Delta U \) becomes ‘- \( \Delta U \)’

Hence,

\[ -\Delta U = Q - W \]

\[ W = Q + \Delta U \]
For an isolated thermodynamic system, where there is no exchange of mass and energy from the boundary.

\[ W = \Delta U \]

Work done is equal to the change in temperature (energy). An isolated system is only theoretical. Such a system doesn’t exist. Theoretically, work done to bring the required change in temperature for such a system will be very high because there is no exchange of matter or energy to help in this process. Therefore, it may seem that the work done by any building system to achieve the required internal temperature should be less than this.

When applying this to a fully glazed office building occupied between 9am and 5pm (which is the scope of this thesis), a building located in a cold climatic is technically able to achieve this. For example, if the temperature outside is 15°C and an internal temperature of 25°C is required. The ample solar heat gain through the transparent facade raises the internal temperature.

The equation of this system is

\[ \Delta U = Q - W \]

Here, \( \Delta U \) is positive since heat is added into the system. Therefore, work done is

\[ W = Q - \Delta U \]
This is less than the work done by an isolated thermodynamic system.

When examining the glazed building in a hot climatic zone, to examine whether heat is getting added or removed through the building envelope, we examine the wall thickness as well as the material properties.

The material properties as well as the wall thickness along with the percentage of transparent façade shows that heat will be added into this building system between 9am to 5pm when it is imperative to maintain comfortable temperatures. Therefore, according to the thermodynamic equations discussed earlier, the amount of work done by either the active or passive building systems to maintain comfort levels inside the glazed building will be more than the building system located in an isolated system.

This is not true for buildings constructed before the industrial revolution. Studies (Dili, A.S. 2010; 20 Dili, A.S. 2011) have shown that the design of a residential unit using the local materials, technologies and knowledge are successfully able to create adequate comfort levels for human habitation. In buildings located in hot climatic zones heat will always move through the external wall towards the interior space. But studies have shown these walls are able to retard the heat movement and create a lag, therefore providing adequate comfort levels when required without the need for any mechanical system of cooling and ventilation.

Hence, for a pre-industrial building the work done by the building system is less than that of an isolated one. Hence proving that the work done by the pre-industrial building is far less than a contemporary glazed building.
2.5.3 Energy quality

Today, we are trying to bring down the energy use in a building but the knowledge of the energy aspect is not sufficient in architects to be able to make the right decisions regarding building energy usage.

Energy is a very broad term. It encompasses many aspects of the natural forces operating in the universe. Most architectural designers visualize energy mostly as the fuel that it put into the building for its operation, which means that when we design a building to bring down its energy use, the term energy here implies to the amount of electricity/fossil fuel used to power the lights, HVAC system etc. This incomplete knowledge of the term energy may be leading to unsustainable building design including wastage of time and materials as discussed in the following chapters of the thesis.

All forms of energy contain two aspects to it, the exergy and the entropy. Exergy is the actual amount of useful energy available to do work. Entropy is the amount of unusable energy in a system. Every time energy is used for converting one form of energy to another, only a small portion (exergy) of it is used for this process and the rest is lost to the environment mostly as heat. Therefore, more the number of conversion steps involved till its end use, the more the waste of energy, as loss needs to be accounted for at every step.

Electricity that is used for running the HVAC systems in buildings is very high quality energy because it undergoes a large number of conversion steps until it becomes an input into the building system. When architects are tasked with building sustainable architecture, they are concerned with bringing down the fossil fuel or electricity used in the buildings. Architects are not experts in energy analysis and therefore, precise analysis is done by trained engineers. The results of such simulations are also
interpreted by scientists or engineers helping them increase efficiency in *end-use conversion devices* (Cullen, Jonathan M. 2010) such as motors, light bulbs or engines. The architect on the other hand designs buildings to house these devices. Therefore, in most cases when the question of constructing low energy architecture is involved, it generally consists of employing the most energy efficient conversion device there is; for example, using energy efficient HVAC system or automatic light bulbs and dimmers etc.

When these devices are removed from a building, what are left behind, are the materials and the architectural form. The energy used by these systems is not precisely quantifiable because they absorb or use useful energy and low grade heat is the by-product. But this is the architect’s domain and this is exactly what the pre-industrial architecture is.

It is architecture that is in sync with the natural energetic forces around it, so as to provide the user adequate comfort levels without the use of any form of active systems of conditioning. This is why this type of architectural façade can be called as the ‘Pre-industrial synergistic building skin’. The above discussion throws light on the difference in which buildings are being designed today as compared to the pre-industrial synergetic buildings. The discussion of the quality of energy is a very important topic for architects because the impact of choosing between providing ambient vs light bulbs is more far reaching than just the operational cost of the buildings.

Comparing both the pre-industrial architecture as well as the contemporary architectural façade in the same platform is the ideal way to understand the advantages of the local architecture of the concerned site in terms of energy systems and material. A simple energy system diagram adapted from Howard Odum’s theory of emergy analysis (Brown and Ulgiati 201-2132004) helps put the architectural façade in the broader context.
Figure 8 is representative of an energy systems diagram for a typical contemporary building. The red boundary represents the building envelope and the grey dotted boundary represents the energy system boundary which has been selected as within 10km of the building envelope. The left hand side represents the natural environmental conditions or low quality energy that directly or indirectly affects the building envelope and the top right hand side elements are higher quality energy affecting the building in question. The width of the arrows represents the relative quantity of energy moving through the system. The sun and air indirectly affect the building by adding heat into the energy systems boundary and this heat directly affects the building envelope. Meanwhile, light from the sun
can be used for daylighting and air for ventilation. Natural gas and electricity are used for the building’s HVAC system. Labor and materials both coming from beyond the energy systems boundary are used for the construction of the building envelope. This diagram shows almost all of the higher quality energy coming from beyond the energy systems boundary and affecting the building more than the low quality energy received from the surrounding environment. This throws light on the fact that we make use of higher quality energy in our contemporary buildings, even if they are sustainable (with solar cells and solar water heating systems). The ideal building envelope is the one that uses minimum high quality energy, for example as shown in Figure 9.

Figure 9: Energy systems diagram for a pre-industrial building

Figure 9 represents a similar energy systems diagram as Figure 8 but with a few changes. It shows that the materials and labor come from within the systems boundary and the low quality energy from sun, air and water are only used for the functioning of the building. This is representative of an ideal building energy systems diagram. Though, it may look impossible to achieve, we already have this
type of a building system in existence. This is a typical pre-industrial building or a pre-industrial
synergistic building.

It is time to move away from the romantic or the nostalgic notion of traditional architecture or
vernacular architecture towards looking at it from the perspective of energy systems to be able to
truly take advantage of what this pre-industrial architecture has to offer us.

2.6 Conclusion

The four sections in this chapter highlight the problems posed by the extensive use of the
transparent façade. But this thesis is being critical against the concept of transparency but simply
the methodology by which it is attained. Currently, the transparent façade and the fully glazed façade
are synonymous and this chapter brings to light a new perspective towards the way we analyze the
problems of the transparent building envelope in hot climatic zone. Instead of providing solutions like
those mentioned in the chapter introduction, it is important to understand the principles behind the
issues posed by the transparent skin. This chapter presents a set of solution oriented arguments as
to why we need to reimagine the contemporary façade. Solution oriented means that the analysis of
the problem gives rise to the solution to the same.

The first section demonstrated the unreliable roots of this type of building skin. The origin of the
completely glazed facades was seen in greenhouses which were meant for growing exotic plants
and trees in the cold climate providing the interior with ample daylight and solar heat gain. This
concept was further expanded to places were large number of people gathered like the railway
stations and finally found its application in the facades of commercial buildings. But the main problem emerged when this building skin concept started getting built in the hot climatic zones, rendering the building highly energy intensive as it was never intended to function in the hot climatic zones in the first place. These were actually spaces for plants in cold climate. Therefore, the solution to this problem simply lies in deriving the contemporary office façade from a human habitable structure in a hot climatic zone.

The second section explains the contemporary methodology for the design and construction of the transparent façade. This methodology involves the breakdown of the building envelope in a large number of components to be resolved and manufactured independently and then assembled together. The section explains the draw backs of this issue that results in over design and wastage of materials. Therefore, the solution to this is in finding a holistic approach to the design and construction of the building envelope.

The third section brings to light the inappropriate material selection in architecture in terms of environmental performance. Materials such as aluminum used as mullions on the curtain walls are used on the criteria of a high strength to weight ratio but its thermal performance for the façade located in hot climatic zone is very poor due to the high thermal conductivity of the material. Therefore, rendering the building inefficient as it adds heat to the inside. Therefore, the solution is in educating the architectural designer on the innate properties of the materials in order to help him/her to make a more informed decision with respect to façade design.

Finally, the last section clarifies the term energy; the very concept that most architectural designers base their building skin design on. It explains that the term energy goes beyond the notion of simply using fossil fuels and in turn the building façade design being simply focused on the reduction of this
type of fuel. Instead this section explains the transparent building façade located in a hot climatic zone as an open thermodynamic system and concludes that we are currently building a thermodynamically inefficient building skin. Therefore, it is important for us to design a building façade by understanding all the energetic forces around that is directly or indirectly going to affect the building façade.

The problem with the transparent façade in hot climatic zone is a combination of insufficient information (material and energy) and an unchallenged methodology of its design and construction as well as its unquestioned past. It is important for us to change our perspective and question how things are done. Currently, in order to get transparency on our building skin, we use large panels of glass and the solution to decrease solar heat gain from it is by coating it or by installing sun shades. But it is important to note that the concept of transparency is not limited to the use of fully glazed building skins. Transparency and daylighting can also be achieved without the use of large panels of glass. This thesis addresses all of these issues with the proposed solution may lead to a more energy efficient building façade design.
Chapter 3: The pre-industrial synergistic building envelope

3.1 Introduction

Pre industrial building in the context of this thesis is architecture that was built before the mechanical systems were used to achieve internal comfort levels was invented. They did not have the ability to generate high quality energy such as electricity. They were optimized to the restrictions posed by the local climate and available materials. Today this form of architecture is referred as ‘vernacular architecture’ or ‘traditional architecture’ and considered an alternate school of thought than mainstream architecture. They are mostly seen in residential units or institutions.

Almost all the quantitative and qualitative research papers based on pre-industrial architecture introduce the need for the study of the past due the increasing energy consumption by contemporary architecture. They stress that to study the local architecture is to understand how to build architecture that is able to maintain adequate thermal comfort. Current issues that are clouding the 21st century such as global warming, climate change and limited resources as us to resist this vernacular typology.

It is baffling that in the 21st century, architects are urged to rediscover or study the science of built environment when this knowledge should have been engrained in us already. This was the way of our ancestors; it does not mean it is irrelevant or obsolete instead it is far more valid now than ever.

As discussed in the previous chapter we are slowly shifting our design priorities and regard new materials and technologies as the right way forward. Unfortunately this shift is more towards the
buildings such as the performative glazed facades which did not see its origins in a human habitable structure. It is such mistakes or misinformation that needs to be reevaluated and we may need to relearn the origins of architecture in order to move towards a more sustainable future.

Every system in the universe self organizes themselves to achieve maximum power for the resources available (Hau and Bakshi 215-2252004). Similarly, pre-industrial architecture is a product of generations of corrections and redesigns depending on knowledge and tool availability in the community. The self-organization is at a temporal scale which is difficult to witness in one lifetime but can be understood by what exists in front of us today. These structures respond to the immediate environment materially, geometrically and energetically. They successfully achieve habitable conditions by taking advantage of thermodynamic systems around it.

In our haste to look relevant and keep up with the changing technologies we have forgotten some of our basic tasks as an architect. Therefore, the future of sustainable architectural skins may not lay in using the most efficient machine or having a very intelligent, responsive facade instead a façade that derives itself from the roots of architecture. As discussed in the previous chapter the pre-industrial architecture represents the ideal energy systems diagram (Figure 10).
This chapter explores the potential of pre-industrial buildings as a basis for all contemporary office façade designs by understanding the holistic (materials and form) nature of this architecture. This chapter attempts to understand what is wrong with our practice of vernacular architecture today and why is it important in order to devise a more relevant design methodology for the future.
3.2 What is wrong with the way we incorporate pre-industrial architecture in today's buildings?

Pre-industrial architecture gets attached in the discourse of the past, a romantic notion of architecture that felt nostalgic or associated with good old days. When applying the learnings of vernacular architecture today, it is either to keep it exactly the same or to adapt one or more components of it. For example, the Development Alternatives office building located in New Delhi (built 2009).

This is an office building that is designed using sustainable design practices inspired by the vernacular architecture of the city. The materials of construction are brick, concrete, terracotta and wood. The exterior walls are cavity walls that have high thermal mass. The building has a courtyard in the center with a shaded corridor around it. Almost all the offices open up into this space. Therefore, this is an inward looking plan. This building maintains favorable interior conditions along with ample daylight. This type of office though favorable to the environment with a very small carbon footprint is not popular with companies that primarily use fully glazed facades in their office along with any other materials and technologies that are new and relevant. Even though the ‘Development Alternatives’ building has done everything right in terms of sustainability, it still isn’t seen as mainstream architecture. It looks like a traditional building or a small modification of vernacular architecture which tends to be synonymous with the past and the irrelevant (Asquith, Vellinga, and MyiLibrary 2006). It is difficult to imagine that commercial companies that see themselves as pioneers of promoting the most hi-tech and relevant materials and technologies will agree to associate themselves with old form, materials or technologies. When these types of companies choose to be sustainable; that is when buildings such as the Al Bahar towers or the Burj Doha in Qatar make a debut, where there is a second layer of sun shading that is inspired by the local
architecture. It’s a way to respect the traditional past of the site and also appeal to the commercial office owner.

There are two reasons why this type of architecture maybe doing more harm than good. Firstly, the Al Bahar tower has two building skins, the interior is a completely glazed façade and the second layer is the external sun shading layer. If this layer is removed, we are left with a glazed tower. This glazed tower can be said to look almost like the 30 St. Mary axe office building by Norman Foster in London. London and Abu Dhabi have drastically different climatic conditions and topography. We do not have enough information to support the fact that the addition of this extra layer is lowering the energy use by the building or making the building more sustainable. It is estimated that more than 50% of the solar heat gain is reduced with this second layer as opposed to having none.

However, an office building like the one in London which is predominantly a cold place where heating loads are the issue, is using a fully glass façade. The glass façade which has been covered in chapter two is a transparent façade that allows for maximum solar gain, which helps raise the internal temperature rapidly and thus reducing the heating load of the building.

On the other hand, the glass tower without the 2nd external skin is sitting in a place where the maximum temperature on a hot summer afternoon can reach up to 50°C as opposed to a maximum of 30°C in London. The fully transparent façade is technically increasing the internal temperature in a place where it is not desirable and then a 2nd layer is added in order to counter this problem. This layer is inspired by the Middle Eastern sun shades or the mashrabiyas.

Therefore, the problem was first created by the choice of a transparent façade and then a solution was found in the language style of local architecture. Technically and thermodynamically (explained in chapter 2) the choice of using a fully transparent façade is wrong in a climatic zone such as Abu Dhabi. Secondly, it is important to understand that the mashrabiya does not work in isolation or does
not shade a glass façade. In most cases it is a screen used in the semi covered spaces and is preceded by a very thick opaque wall.

Secondly, the materiality of the building is not ideal considering the physical and energetic environment around it. The previous chapter covered the basics of materials and what we may be doing wrong in the field of architecture. The example of Al Bahar towers demonstrates exactly this. The minimum list of materials used for the construction of only the inner/main façade of the towers is shown in figure 5.

<table>
<thead>
<tr>
<th>Material</th>
<th>Location in building</th>
<th>Density (Kg/m³)</th>
<th>Thermal conductivity (W/m.°C)</th>
<th>Embodied Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal Flashing (coated steel, stainless steel, temper steel)</td>
<td>Waterproofing in the wall</td>
<td>7600</td>
<td>14.9</td>
<td>68.7</td>
</tr>
<tr>
<td>2 PVC oem</td>
<td>Insulating the wall</td>
<td>470</td>
<td>0.057</td>
<td>68.6</td>
</tr>
<tr>
<td>3 PVC / elastomer</td>
<td>Gasket between the glass and mullions</td>
<td>1080</td>
<td>0.973</td>
<td>1.105</td>
</tr>
<tr>
<td>4 Aluminium</td>
<td>Mullions</td>
<td>2500</td>
<td>133</td>
<td>174</td>
</tr>
<tr>
<td>5 Low-emission glazing</td>
<td>Glass</td>
<td>2440</td>
<td>0.744</td>
<td>17.1</td>
</tr>
<tr>
<td>6 Silicone sealant</td>
<td>Sealant between the mullions</td>
<td>1300</td>
<td>0.3</td>
<td>118</td>
</tr>
</tbody>
</table>

Table 1: List of minimum materials used in the curtain wall / fully glazed facade

Simply by comparing the thermal conductivity and the embodied energy to a list of materials used in the construction of pre-industrial buildings, it is clear that this type of façade (fully transparent) is not a suitable choice for this climatic zone. Additionally, there is a second layer to this building to compensate for the problems brought on by material and design choice. This is a group of moving geometries set on an aluminum structure. There are sensors attached to each of them in order to react to the changing sun positions. Therefore, to the list above we can add an additional frame, sensors and the fabric of the screen itself. This adds to the embodied energy since none of the materials used in this building are indigenous and due to the high thermal conductivity of the exterior frame also (which is attached to the main building façade), there is no doubt that we are adding
more heat into the super structure and therefore, to the interior. We do not yet have enough research to show that this increased embodied energy and other hidden energy costs (like the transportation of these non-indigenous materials) equate or is much lower than the energy savings made in the operation of the building because of this.

On the other hand, a traditional mashrabiya, other than being used as part of a different layout system, uses completely indigenous materials for its construction and design. They are generally wooden or stone screens with much smaller openings. In terms of both embodied energy and thermal conductivity both of these materials sit far lower than the ones in the contemporary office tower.

Therefore, other than the basic geometry of the exterior screen on the Al Bahar towers, it may be incorrect to say that this structure is truly inspired from a middle eastern mashrabiya.

The above examples, explain the basic things we are getting wrong when we try to incorporate pre-industrial architecture into the 21st century. Its either incorrectly incorporated like in the case of the Al Bahar towers or they come out looking very similar to the vernacular of the local site. The dangers of marketing towers such as the Al Bahar’s as sustainable can be easily understood just by comparing what they are deriving their inspiration from.

3.3 Why is there disconnect between the lessons learnt from the past and its integration into the contemporary building skin?

The previous two sections clearly demonstrate the existence of disconnect between what we understand as pre-industrial architecture and its introduction into the contemporary world. There are many reasons for this disconnect. Firstly, the type of studies and analysis conducted on pre-
industrial or pre-modern or vernacular architecture is highly qualitative in nature. For example, some of the widely summarized vernacular techniques are as follows; using local materials, high ceiling heights or sun shades. It is very difficult to find literature that has done quantitative analysis on such buildings. Energy analysis on passive structures in very difficult because of the simple nature of the structure; a passive structure simple absorbs energy from the surroundings and releases heat as a byproduct. Since there does not exist any form of active systems in this type of building that use electricity, there is no way to calculate the energy used in the operation of such architecture. The operational energy calculation in a contemporary building is much easier, simply due to the fact that all of them use electricity to run all the basic functions for inhabitant comfort such as lighting, thermal regulation and ventilation.

Secondly, the building typology in question here is the office typology. The office typology is a post-World War 2 architectural type. No building equivalent to this existed during the pre-industrial era. This makes it impossible to find a readymade solution in the past for our contemporary problems. Most of the literature (especially quantitative) is found with respect to residential units. This can also be speculated as the reason for why most successful adaptations of vernacular architecture today are found in houses.

Most of the literature (Baran, Yıldırım, and Yılmaz 609-6192011; Khoukhi and Fezzioui 1-92012; Srivastava 932015; Priya et al. 502012; Radhakrishnan et al. 89-972011; Anderton 15-241989; Gupta 58-641985; Foruzanmehr 61-672015; Lall et al. 837-8491991; Mortada 383-3932016; Azadi and Haghighatbin 1335-13432016) on the pre-industrial architecture has successfully explained the buildings in their environmental settings. They clearly identify what makes these buildings environmentally responsive structures and why they need to be studied today in order to develop a more sustainable future. But there is extremely inadequate literature on how these methodologies can be applied in the contemporary world.
This leads to the component based design approach that was discussed in the previous chapter. When designs encounter a problem in their contemporary design, a solution for that problem is looked for in pre-industrial architecture or in the local designs of the site in question as seen in the case of the Al Bahar towers.

It was the problem of solar heat gain from the transparent facades that pushed for the development of the contemporary mashrabiyas. We are applying the vernacular architecture as components on today’s architecture where material and geometry are considered mutually exclusive.

Thirdly, we do not have a common language or platform for comparison of the pre-industrial architecture and the contemporary building. Both are completely different schools of thoughts with different priorities and functions. Today, we use electricity in all our buildings especially for thermal comfort, while pre-industrial architecture did not have any, but still maintain the required internal conditions. Contemporary architectural issues involve the reduction of energy use or dependence by the building but traditional or pre-industrial architecture has no form of quantifiable energy like electricity. Therefore, making it very difficult to truly incorporate the core concepts of the traditional architecture and resulting in architects just choosing appropriate components to be assembled into today’s architecture.
3.4 Case studies

3.4.1 Introduction

The following section is a literature review of pre-industrial houses in areas of hot, humid climate and hot, dry climate. It uses existing qualitative and quantitative research done on such architecture as a comparison with contemporary requirements or measures of the building façade. The parameters of comparison is adapted from the book “Fundamentals of building construction I Materials and method” 6th edition by Edward Allen and Joseph Iano. The requirements of the external wall mentioned in this book can be regarded as a basic generic model for contemporary building envelope design.

The literature review includes houses from (i) the southern part of India where the weather is predominantly hot and humid and (ii) the North West part of India where it is hot and arid. This section aims to compare this with the literature on pre-industrial houses located in other cities in the world that exhibit similar climatic conditions.

The external wall requirements are as follows:

1. Keeping water out
2. Controlling light
3. Controlling air leakage
4. Controlling water vapour
5. Controlling the radiation of heat
6. Controlling the conduction of heat
7. Controlling sound.
The following study qualitatively determines how the vernacular architecture in hot climatic zones is able to fulfill all the contemporary requirements of the external wall. This is supplemented with quantitative data wherever applicable.

The aim of this section is to make a conclusion of a holistic (geometry and material) nature (as opposed to which components to use) on how the architecture in question is able to achieve the above tasks.

### 3.4.2 Location and climatic zone

Kerala is located in the south western tip of the Indian subcontinent and has a warm humid climate because of its location. The architecture of Kerala is a derivation of climate responsive measures that are tried, tested and modified with generations. This state extends between 8 18’ and 12 4°N latitude and 74 52’ and 72 22’ E longitude (Dili, Naseer, and Varghese 917-927). It is flanked by the Arabian sea on the west and land on the east. The major source of discomfort in this region is from the high humidity in the air. Therefore, the local architecture caters to this by instigating continuous air movement throughout the building without bringing in solar heat gain. The basic form of the architecture remains the same; it has a square or rectangular plan with a courtyard in the centre and a semi open space surrounding the exterior of the house. The rooms are located around the courtyard.
The cities of Jaipur and Jaisalmer are located in the North West part of India, which has typically a hot and arid climate. It's located at 26.9124° N, 75.7873° E. The local architecture is derived from the hot and dry weather due to the presence of a desert nearby. Pink sand stone is the major construction material. The major source of discomfort in this area is the extremely high temperatures and the urban planning as well as the architecture responds to this in order to maintain habitable temperatures. The houses here also typically have a courtyard in the center but do not have a semi open patio (verandah) on the exterior of the house.

The following is a comparison of how the local architecture of both these areas of India are able to fulfill the list of contemporary requirements of the external wall.
3.4.2.1 Controlling light

The plan and section of a Kerala house drastically reduces the amount of direct sunlight entering the interior space or hitting the exterior wall as demonstrated in Figure 13.

![Figure 13: Sun angles during various times of the day in January and May.](image)

According to the latitude and longitude of the site, the above two sections demonstrate the overhang angles successfully shielding the ground floor wall against direct sunlight. Other than the visible light spectrum, we also have the infra-red radiation and the ultra violet radiation. Clay tiles provide an excellent shield from the UV rays (Ashby, 2010) and are not damaged under their exposure. Infra-red radiation is the heat that we feel. The above sections show minimum direct sun light entering the house, hence reducing the chances of the infra-red radiation heating the air inside.
The four figures (Figure 14) demonstrate how the building shades itself from direct sun light. Morning and evening sun finds its way through the overhang around south west part of the house. The south and west side of the building is protected from the harsh afternoon sun by the same overhang. Direct and indirect sunlight enter the courtyard through the day and provide ambient daylight to the interior of the house.

The haveli building type in Jaipur is a common residential unit for the climatic zone that exhibits hot and arid climate. This building also has a courtyard like the house located in the hot and humid climate but does not have a patio around the building. The walls are thicker and more opaque (less windows) than that of the Kerala house. The material is predominantly sandstone. This is an inward looking plan. Daylight is accessible through the courtyard and some windows located on the exterior wall.

Figure 14: Shading of the house during various times of the day.
3.4.2.2 Keeping water out

Allen and Iano describe the existence of five natural forces that cause the movement of water through the wall. (i) Pressure difference (ii) Capillary action (iii) Surface tension (iv) Momentum (v) Gravity. Contemporary architecture completely avoids the water from seeping in by either having hydrophobic water barrier, or maintaining a pressure difference in the case of curtain wall structures and lastly introduction of gaskets at intersections of different materials or connections. This introduces multiple materials into the equation of façade design as discussed in the previous chapter and this holds good for hot, dry and hot humid climatic zones.

On the other hand pre-industrial architecture addresses this issue differently in both these locations. In the case of hot and dry weather where rainfall is minimum; the issue of water coming inside is not there. The exterior walls are mostly thick and opaque with minimum openings. There is minimum overhang on the wall to prevent the walls from eroding in case of the occasional heavy rainfall.

![Figure 15: Architectural response of the house towards controlling water.](image)

But in the case of hot and humid climatic zones, rainfall is regular and consistent. Therefore, there exist multiple points that stop water from coming in. Firstly, the house is always made on a high plinth, in the case of the house in the quantitative report there exists a 450mm plinth. Then there is a semi covered patio called as the verandah with sloping overhangs. This structure is able to block
majority of the rainfall and a little does come in. The floor of the verandah is generally made up of stone and the walls inside are plastered with lime that act as waterproofing. Therefore, water stops at this point and does not enter the rooms inside. Apart from the geometry of the envelope, the material plays an equally important role. Located in a coastal area, the building may encounter salt water, therefore, lining the roofs with terracotta also helps in this as it has excellent resistance to salt water.

3.4.2.3 Controlling conduction and radiation of heat

This is by far one of the most point requirements for a building located in the hot climatic zone. Almost everything we design as part of the building façade is to ensure thermal comfort, whether it is to stop solar heat gain or sealing the façade to prevent the hot air from coming in.

Sunlight is also responsible for heating the air inside and outside. The exterior wall provides comfortable conditions for the user by controlling the conduction and radiation of heat.

Figure 16: Time vs Temperature in winter and summer (Source: Dilli, Naseer, and Varghese 917-9272010, used with permission)
Figure 16 shows the temperature inside the bedroom is maintained around 27 degree Celsius despite the outdoor ambient temperature ranging between 38 degrees and 24 degrees in the summer and 36 degrees and 17 degrees in the winter.

![Figure 16](image)

Looking at the plan of the building (Figure 17), we can see the location of the bedroom and that its walls are not exposed to the external air or any direct sunlight. The thickness of the wall is 350mm and is made up of laterite blocks or granite stone with lime plaster. Granite stone has thermal conductivity between 2.5 W/m. degreeC to 2.8 W/m. degreeC (Ashby 2010).

![Figure 17](image)

High thermal resistivity of the wall due to the low thermal conductivity of the blocks along with the thickness of the wall causes a 24 hour delay between the outside and inside temperature; hence no lag is detected as per the report. The veranda around the south and west part of the house ensures the external shading of the walls from direct sunlight and keep the space from heating up drastically, therefore, the temperature difference between the interior wall surface and exterior wall surface is kept to the minimum preventing condensation and controlling user discomfort due to radiation of heat.

In the case of buildings located in hot and arid climate, the same explanation of thermal mass applies. The walls are extremely thick that ensures that the transfer of heat from the surroundings is delayed. Unlike the house in Kerala that has ample open space around it, the building units in Jaipur
are all built very close together, this is to ensure that they can take advantage of the shadow of the neighbouring house falling on it. Other than this, the part of the house exterior wall that receives direct sunlight has a lot of wall articulation on it, in the form of cultural and symbolic patterns. This increases the surface area of the wall and therefore, increasing the dissipation of the heat from the walls through convection (Gupta 58-641985).

3.4.2.4 Controlling water vapour

![Graph](image)

*Figure 18: Temperature vs Relative humidity vs time (Source: Dili, Naseer, and Varghese 917-9272010, used with permission)*

The Kerala house is located in a tropical climate. Therefore, the air stays saturated with moisture (Figure 18), lower the temperature higher the relative humidity. The top most source of discomfort for an occupant in a building in this location in from the presence of high amount of moisture. This issue is resolved by the presence of a continuous stream of air around 0.5m/sec allowing for moisture present on human bodies and other objects in the space to get evaporated.
This air speed is maintained despite the continuous changes in the wind speeds outside. The geometry and the layering of the walls is responsible for this. There is ample cross ventilation between the courtyard and veranda passing through rooms like the bedroom ensuring comfortable occupant conditions.

Therefore, the second point in the list of design requirements for the external wall of controlling air leakage is not applicable in this building. The movement of air through the house plays an important role for maintaining comfort.

In the hot and arid climate, due to minimum amount of water vapour. Humidity is not the source of discomfort.
3.5 Conclusion

The examination of how the residential unit is able to fulfil the seven requirements of the contemporary external wall, revealed the following steps:

All the wall requirements are not fulfilled by one external layer as is attempted by contemporary architecture. There exist different layers in the building. Each layer having its own particular task. This system of layers also exists in all other traditional buildings studied as part of this research following is the layers and its tasks. The three layers are shown below and are later explained in detail.

Figure 21: Demonstration of different zones of mediation (layering system) in a pre-industrial house.
3.5.1 Building envelope layer 1

This is the outermost layer of the house; in this case it is the large semi covered space enveloping the south east corner of the house. Figure 23 shows the temperature of the semi covered space much lower than the ambient external temperature. Therefore, proving that this layer is able to manipulate the external environment to provide slightly lower temperature and humidity conditions before it reaches the second layer which is the thick stone wall separating the public spaces such as the semi covered space with the more private spaces such as the bedroom.

![Figure 22: Plan showing the sectional plane](image)

![Figure 23: Graph showing temperature vs time in summer](image)

(Source: Dili, Naseer, and Varghese 917-9272010, used with permission)
This space has a sloping roof at an angle of 65° with timber framing and clay tiles. The slope is able to provide ample shading from direct sunlight, therefore, heating of the space by infrared is reduced significantly. Both timber and clay tiles have very low thermal conductivity, which means they are excellent insulators; this reduces heating of this space through conduction through the roof. Clay tiles are also impermeable to UV radiation. The floor is made of stone and sometimes terracotta tiles as well. The above mentioned points together are able to help towards the lowering of the temperature. Due to its semi open nature, there is a continuous air movement that helps reduce the relative humidity in the space.

The first is almost non-existent in house located in hot and arid climate. The extreme weather makes it undesirable to have semi open spaces towards the outside of the building. But this layer exists surrounding near the courtyard.

3.5.2 Building envelope layer 2

The second layer of the building skin represented here as an abstract box is the space that is enclosed between two thick opaque walls. This layer houses the private rooms of the residential units such as the bedroom, store or the prayer rooms. These are also the rooms that require a higher level of security. Minimum temperature variation and low daylighting levels, especially the rooms such as the bedroom (occupied only at night) and the store (not meant for human occupation). Graph on the right represent the temperature variation of the bedroom of the houses that were part of this study. It shows that the bedroom temperature variation is the minimum as compared to all other spaces in the house. This is true for all of houses represented below.
The bedroom is all cases is enclosed within thick wall made of materials such as local stone and mud bricks which have very low thermal conductivity. The roof/ceiling above this space is either thick or have attics as air gaps (section AA) along with heat gain retarding materials such as timber and terracotta tiles. The floor is on a stone or earth plinth and generally covered with stone of terracotta tiles. This layer is a function of all the four or six sides of the space unlike layer one in which only three sides are crucial.

Figure 24: Air temperature vs Time in summer (Source: Dili, Naseer, and Varghese 917-9272010, used with permission)

Considering this is an enclosed space located in hot climatic zone, the biggest contributor to inhabitant discomfort is rising internal temperatures and humidity. The thickness of the wall along with its material make up is responsible for delaying the heat gain within this space during the day. The minimum punctures on the wall are responsible for maintaining a continuous stream of air to help keep the humidity low and promote radiation of heat to the outside during the night which further brings down the internal temperature.
3.5.3 Building envelope layer 3

The third layer of the vernacular building envelope involves a void. This is the courtyard of the house. Depending on the size of the building, there will be one or more of this. This void has no roof and the floor is generally untreated and is earth itself. It is surrounded by a semi open space similar to layer one. This is a piece of the surrounding that is trapped by the geometry of the house. The residential unit is able to change the micro climate of this space to help with a controlled flow of mass and energy through the entire building system. Figure 24 show that there is a variation between the temperature of the lower courtyard and the upper courtyard. This is what causes the pressure different that causes air movement throughout the building. Figure 19 shows the presence of constant air movement despite the varying wind speeds outside. The temperature difference is able to pull out the heat from the building system and throw it out initiating the stack effect.

The courtyard also provides daylighting to the inner parts of the residential unit and is also the space where the people living in the house perform their daily functions like cooking or eating. The presence of a courtyard in contemporary architecture has become associated with culture. But the study of houses from Iran, Turkey, India, China and Spain all show the presence of a courtyard, therefore, proving that there is more than a cultural need for this layer. The data presented by the articles of these houses show an essential role of this void in maintaining comfortable conditions.

3.5.4 Conclusions

The three layers discussed in this chapter are just a broad discussion. They may contain more layers within them or less number of layers depending on its geographic and climatic location. For example, in the hot and dry climate of Jaipur, India, we find that layer one is not there. The first manmade
layer in contact with the ambient outdoors is the wall similar to layer two. This is not local only to India, similar design concepts have been observed in Iran, Saudi Arabia, Turkey (Baran, Yıldırım, and Yılmaz 609-6192011; Khoukhi and Fezzioui 1-92012; Foruzanmehr 61-672015; Mortada 383-3932016; Azadi and Haghighatbin 1335-13432016) all of which are countries located in similar climatic belts. Grondzik and Kwok in their book “Mechanical and Electrical equipment for Buildings” explain the two building envelope design concepts. First is ‘the open frame’ which is generally found in the hot and humid climatic zones or places where the outside temperature is closer to desired levels. In these cases semi open spaces are regularly used. The second concept is ‘the closed shell’ which exists in locations with harsh external climate. Here the designer makes an opaque wall with selective punctures in it similar to the ones demonstrated by the houses in the hot and dry climatic zones.

This discussion throws light on the existence of these conceptual layers. For a pre industrial building, the discussion of the envelope does not end with the exterior wall, but is a combination of multiple layers both spatial in nature as well as a surface. They can also be voids like the courtyards. But all of them together are responsible for the resulting comfort levels inside while the contemporary building especially the office building typology puts all the environmental controls for the building in the outermost layer or the only exterior layer of the building.

There are two subsets to the discussion of the layers. First is its materials and geometry. The discussion of each layer in this chapter also includes the material with which it was made and its resultant geometry. Both of which are not mutually exclusive. Changing the material in one of the layers while keeping the geometry same will have completely different results and the vice versa also hold true. This is demonstrated by the selected buildings for this study all showing different results but have similar envelope concepts.
Secondly, Space planning.

Space planning may not be the first thing that we would expect to see in the list of requirements for the design of the building skin. But on examination of the houses in this study, it is observed that space planning is important if we are expected to maintain comfort levels inside. The conditions adjacent to the external wall are different from that located further from it. The traditional building is able to incorporate this with ease, eventually leading to a condition where the sleeping quarters or the bedroom has the least temperature and humidity variation and also the least daylighting. While the spaces where people interact or perform their day to day activities are sufficiently day lit and have slightly higher temperature variation to that of the bedrooms.

These conclusions provide a holistic approach to the design and construction of buildings in hot climatic zones. They define zones and boundaries within the unit instead of explaining each component. Each of these zones is responsible of multiple tasks which is the function of its positioning in the overall plan.

Limitations of pre-industrial architecture

Despite the pre-industrial architecture being a truly sustainable piece of design and construction, the reluctance to build such a building stems from its draw backs. A visit to any one of these building whether hot and humid or hot and arid, shows the insufficient daylight access to the interior rooms. Even though the plans show ample daylighting in the semi open spaces, due to the minimum number of openings in the 2nd layer of the building envelope, the inside is almost always dark. This is not generally accepted during the design of contemporary office facades which make access to sufficient daylight as one of their requirements for both energy savings in terms of artificial light and
for the health of the users of the space, as studies show access to daylight improves productivity (Al Horr et al. 369-3892016).

Secondly, Due to the small size of openings which are mostly meant for ventilation, there is also no or minimum access to outside views from the inside room.

Therefore, a contemporary design would have to incorporate these missing factors.
Chapter 4: Proposed façade design methodology

4.1 Introduction

The last three chapters gave us information on how we build office buildings today and how our ancestors have been building human habitable spaces. Just like people’s homes, a person’s work is also where he or she spends most of their day. It needs to be comfortable both physically and mentally. Currently, office spaces such as those located in fully glazed towers create their own internal environment and use mechanical systems of heating or cooling to provide thermal comfort to its inhabitants, but as discussed earlier (chapter 2), these are highly energy intensive and degrading to the environment. Since, climate change and energy costs are requiring architects to design more sustainable structures, our focus has shifted towards responsive building facades, which I believe is also not sustainable or green (see chapter 2).

Instead this thesis focuses on taking notes from an era when humans were already building sustainable building or building that did not harm the environment and have stood the test of time and exist even today. This is the pre-industrial architectural skin or the pre-industrial synergistic building envelope (chapter 3).

This chapter takes a cue from the lessons learnt from the past to design a building skin for the glazed office building typology that is sustainable and also has the visual identification of a contemporary office building for a developing country (in the scope of this thesis it is India) based on a methodology derived from the previous chapters.
4.2 Design Objectives

The objective of this thesis is to develop a methodology for the design of a sustainable office building façade based on performance. Due to the constraint of location, heat is the primary performance criteria.

1. The aim of all building facades in this climatic zone is to keep the heat outside and removing heat from the inside. Therefore, the first objective is to design a façade that is able to reduce the amount of heat transferred from the outside to the inside during the working hours of the day.

2. Chapter 2 discussed the shortcomings of using curtain wall glazing as the exterior skin during high temperatures. Which is; the increased transparency due to glass that provides the interior access to large amount of direct sunlight that gets absorbed in the interior and radiated heat gets trapped inside and therefore, increasing the internal temperature. Hence, the second objective is to reduce the percentage of transparent surface.

3. The building envelope will be self-supporting, in other words, it does not require attachment to a framing system like the curtain wall.

4. Finally, the design will strive to cater to the two major drawbacks of the pre-industrial architecture, firstly, the interior habitable space will have access to daylight and lastly, it will also have access to the outside views.

Overall, the aim of this building skin is to bring down the embodied energy of the envelope itself as well maintain comfortable internal conditions, so that there is either no use or minimum use of the mechanical system of cooling and ventilation.
4.3 Design methodology

This design methodology has been derived by addressing the problems of the transparent building skin. Chapter two discourses four issues. Firstly, the point of origin of the transparent skin; a chronological assessment of the fully transparent building skin from its beginning in the greenhouses until the curtain wall as we know it today shows us that the point of origin is the problematic issue because it is a non-human habitable structure. Therefore, the first change is to establish this origin point from a human habitable structure instead of a green house. To do this, the structures than came before the age of steel and glass (pre-industrial architecture) were studied. The study of pre-industrial architecture revealed the following points; firstly, they never considered the building envelope as a separate component, it is difficult to point out where the building skin starts and ends whereas in contemporary architecture, there is a clear demarcation of what the building envelope component is. Secondly, the variety of materials that were used in the construction of a building was much less as compared to the contemporary world, where there exist multiple building skin components, and in most cases each component was made up of a different material. Along with this the material used was local or from within a few square miles of the site, local materials were innovatively used and its purpose perfected over generations. We must not disregard this local knowledge of material and architecture. Today, they are combined into a different school of thought as art and craft or vernacular architecture. But they have potential knowledge that could aid in building truly sustainable architecture. Thirdly, energy is a term, though very commonly used today among architects, is a very misunderstood concept that maybe leading to unsustainability in architecture. When it comes to energy, architects mostly concentrate on reducing the operational energy of the building. Chapter 2 discussed a broader perspective of energy and how understanding the building envelope in the context of its energetic ecosystem is key in designing a truly sustainable façade.
Keeping in mind the above discussion, this design methodology addresses a holistic approach to the design of a building envelope. The components and requirements of the building envelope as discussed in chapter 2 are not listed, for example, if we need daylighting into the interior space, we would make a window; if we need natural ventilation we would make a ventilator elsewhere on the façade. Instead, now there is a better understanding of the first principles of the building skin. Which are; it mediates between air, water and sunlight, inside a specific systems boundary and therefore, we have to find a holistic approach to address all of the concerns simultaneously. This is done by first listing out the material properties of the building envelope. A building façade that is made up of one material (preferably local) that is able to mediate between air, water and sunlight, will be our ideal building façade. But the material discussion in chapter two demonstrated to us the world of materials and how most of them have properties of the contradictory nature, making it almost impossible for us to have one perfect material to be used on the building skin. Therefore, depending on the location of the architectural façade, the material options may vary. Geometrical patterns associated with performance are also a function of its geographic location and culture. Therefore, this methodology does not involve us listing out a generic list of building skin components and then bring it to site and finding a way to adapt the components or requirements for the climate zone in question. Instead, we list out the material properties based on the climatic zone and then find a way to modify the typology design based on the climate zone in question.

The thesis tests this methodology by proposing a façade design concept, even though the transparent façade design methodology is derived from a pre-industrial building, the visual identity is no longer the same as the traditional design and we have moved into the contemporary world from the pre-industrial world without intersecting with the old line of origin of the transparent façade.
Conceptually, there are two ways to approach this design problem. Firstly, development of building envelope layers in plan (horizontal layering) and secondly, the layers of the building envelope are segregated in terms of elevation (vertical layering).

In horizontal layering, the various performance criteria of the building envelope is addressed by multiple set of layers or zones. But unlike the contemporary layering system, where each layer is a surface, here each zone is an occupied space/zone. The vertical layering addresses the various performance criteria of the building envelope by its varying thickness and opacity along the wall section.

In both these approaches the building façade addresses the issues of thermal mass, ambient daylighting, access to view and it is self-supporting. The following sections discuss both these concepts in detail.

The design proposal of the horizontal building façade concept is not explored in this thesis. But further research on this topic can lead to more desirable office building facades and layouts. The following has been concluded based on literature of chapter 2 and 3:

1. The each layer or zone needs to be a human occupied space. This means, that having 2 or 3 such layers before arriving at the space that is able to maintain thermal comfort for long periods of time leads a large amount of space being used to something other than work space. Circulation spaces or services could become part of this space depending on how the layout gets designed.

2. This design concept is a layout design as well as a façade design problem. This type of design almost restricts the layout design for the office occupying this space.

3. Except for the option of one layer mediating all three environmental parameters. The layering design is an easier problem to deal with than the vertical segregation. The discussion in these
section beings to light the existence of precedence for this type of design, which may have been a more intuitive choice than a conscious or calculated one.

For further information on the exploration of this design concept, refer appendix A.

4.3.1 Vertical layering

This building skin design methodology is comprised of three levels of geometrical optimization. It is derived from the research in chapter 3. Almost all the exterior exposed wall of the pre-industrial architecture is neither smooth nor completely flat. All the walls are deeply articulated at multiple levels. This helps with two things; firstly, the surface area of the building envelope has been increased and therefore allowing for quicker release of heat through the process of convection (Gupta 58-641985). Secondly, the undulating façade surface results in the whole wall being shaded at some point of time or the other. The wall articulation existed in various forms: as cultural geometrical patterns or the presence of multiple walls. The last level of design is the material itself which forms the last level of defense against the undesirable external environment. This design methodology attempts to demonstrate these levels of design (Figure 25), starting with the global design (presence of a courtyard and building form), Exterior wall design, unit design and material selection.
Therefore, instead of listing out the requirements of the external wall and solving each requirement with one component and bring them all together in form of a building façade. Each consecutive layer of the proposed building skin design methodology reacts to its previous and one cannot exist without the other.

4.3.1.1 Building form design

It is observed in pre-industrial architecture that to shade the external wall from direct sunlight they have large overhangs that shade the wall during most of the day. But in the case of office towers shading the entire façade with only one overhang would mean we need an illogically large horizontal sun shade. Therefore, we need to venture into other areas of design exploration.
The overall form of the office tower is as important as the site in which it is located. Literature (Aksamija, 2013) states that one of the first steps towards sustainable design is site response, for example, orientation of the building according to optimal sun and wind directions. In the scope of this thesis, it is already assumed that this step has been followed for the design of the building form. The main building design itself will dictate the form and material decision for its external wall. One of the major lessons learnt from the study of the pre-industrial buildings is that to enable natural movement of air and for optimal access to daylight without the heat from the sun, the presence of a courtyard is important. Therefore, for the design of building envelope this thesis assumes the following:

1. The main building form is made in response to the site.
2. There is always a courtyard in the center of the building.

The form of the office building is able to give clues to the next step in the design of the building skin.

Figure 26: Solar radiation analysis of generic office towers without sunshade (left) and with sunshade (right)
For example, Figure 26 shows the difference between a tower with no articulation and one with the presence of a slight sun shade on each floor. This difference is the first step to make sure that when articulation exists, the entire wall face does not need to be considered in the same manner. The bottom portion of the façade can be completely different from the top.

![Radiation analysis of one floor with a courtyard (left) south west, (right) north east](image)

*Figure 27: Radiation analysis of one floor with a courtyard (left) south west, (right) north east*

Figure 27 shows the radiation analysis conducted on one floor of the office tower shown before. This analysis clearly shows the presence of a whole range of radiation values on each wall as well as the courtyard walls. But it can be argued that this can be made into a generic rule, because of any building located in the northern hemisphere will exhibit similar/same range of values. This means that the southern face will always receive maximum solar radiation and the north will be minimum but, this isn’t always true. For example, Figure 28 shows an office tower with slightly shifted floor plates.
It is clear from this figure that the overall geometry dictates the nature of the building façade irrespective of the orientation. In Figure 29 the south wall on the second floor receives almost the same value of radiation as the north wall.

Figure 29: Radiation analysis of the first 3 floors of the tower in figure 31
The examples above clearly describe the importance of considering the overall form of the office building before reaching the decision of the exterior wall design.

4.3.1.2 Exterior wall design

The vertical building skin layering involves the addition of ‘roughness’ to the building’s exterior wall. The fully glazed building façade as discussed in chapter 2 has a plain glass face; direct sunlight covers every part of this façade unless there is a sunshade. When the building is located in a hot climatic zone it is important to reduce the surface area of the building façade that is exposed to direct sunlight. Therefore, we require more surfaces that do not receive direct sunlight. This is demonstrated below.

Radiation analysis is performed on a simple cuboid as shown below, representing a single floor on an office tower. The analysis is done for a period of 1 year (1st January to 31st December) for the city of Trivandrum, Kerala, India (for climatic conditions, see chapter 3).
Figure 30: A simple cuboid depicting one floor on an office tower showing the total amount of radiation received by the external wall.

The radiation analysis reveals that the external walls facing south and west receive the same amount of sun radiation from top to bottom of this wall. To this wall, roughness is added in the form of small pyramidal outcrops and a radiation analysis is done on this structure on it, we observe the following.

Figure 31: Addition of pyramidal roughness and radiation analysis conducted for a year on it.

The value of radiation on the wall has reduced drastically.

Why pyramidal extrusions?
A pyramidal extrusion coming out normal to the building exterior wall, (i) increases the thickness of the wall (ii) Reduces the surface area of the exterior wall face exposed to direct sunlight to a minimum (iii) provides extra surfaces that are not exposed to solar radiation.

![Figure 32: A flat square surface transforming into a sharp pyramid.](image)

A pyramidal extrusion is only one of the many options (Figure 33) as to the type of roughness that can be introduced. This thesis uses pyramidal extrusion as an example.
Following the results of the radiation analysis, we remove the face of the pyramid that is receiving the minimum amount of solar radiation. We get the following result.

Figure 34: Elevation of south wall with the radiation analysis conducted on the south façade.

Figure 35: The south façade with the face witnessing the lowest amount of radiation has been removed.
Examples of exterior wall designs

The following are four examples of how the above concept has been applied to four different exterior wall geometries. Each design also shows the view from the interior through the north wall as well as the south wall. The view is taken using a rendering with camera positioning as shown in figure 26. Based on the image the percentage of transparency is also calculated.
Type 1

Figure 38: (left) radiation analysis done on the north east face. (center) radiation analysis done on the south west face. (right) typical section

Figure 39: View from the South wall of the unit. Transparency: 14.2%

Figure 40: View from the north wall of the unit. Transparency: 30%
Type 2

Figure 41: (left) radiation analysis done on the north east face. (center) radiation analysis done on the south west face. (right) typical section

Figure 42: View from the south wall

Figure 43: View from the north wall
Figure 44: (left) radiation analysis done on the north east face. (center) radiation analysis done on the south west face. (right) typical section

Figure 45: View from south wall

Figure 46: View from north wall
Type 4

Figure 47: (left) radiation analysis done on the north east face. (center) radiation analysis done on the south west face. (right) typical section

Transparency: 22.5%

Figure 48: View from the south wall

Transparency: 27.67%

Figure 49: View from the north wall
Conclusion

Since, the extend of extrusion of each pyramid is directly proportional to the amount of radiation received at that point, the south wall is going to be always thicker than the north as the site in question is located in the Northern hemisphere. It would be vice versa in case the site is located in the southern hemisphere. Secondly, the roughness on the southern wall also has more opaque surfaces only reducing the view to the outside and not cutting off completely. Since the north wall has shorter roughness and more transparent surfaces, it provides access to the outside view. For adequate indoor daylighting the exterior wall does not need to completely transparent, instead only 25% - 30 % transparency is required for commercial and residential buildings (Lovell 2010). The north walls of all the designs discussed, have achieved that percentage. But even though the south wall is slightly lacking, the presence of a courtyard in the center will make up for any reduced daylighting numbers.
4.3.1.3 Unit Design

The coming together of all the units on the building façade is responsible for the roughness that is required for achieving the performance design criteria. Conceptually the unit is similar to a fired brick or stone block, where it is assembled together as the external wall without the need for an alternate
support structure. Metaphorically drawing from the human skin, where conceptually it is homogenous but changes composition depending on its location and function, each unit is conceptually designed the same. For example, Figure 50 (a) and (b) are two different units in the same face of the building. The unit has a front and a back. The front is the cantilevered portion which is like a miniature sun shade for the unit opening. (a) has a shorter cantilever with more openings while (b) has a longer cantilever with the top face of the unit being opaque. This is because the amount of opening and the length of the cantilever is the function of the amount of radiation falling at that part of the building façade. Therefore, larger the amount of radiation, longer is the cantilever along with it being more opaque.

The unit design of the façade in the scope of this thesis demonstrates each unit as being unique because as explained earlier it derives its sizing from its location on the building façade and the amount of radiation that part of the envelope receives. The geometry under investigating is a pyramidal extrusion as shown in Figure 50.

The unit is comprised of two parts: the opaque and the transparent.

*Figure 51: A typical façade unit of the building envelope*
4.3.1.3.1 The opaque

The opaque portion of the unit is its visible structure. This part is the result of geometrical optimization of the building façade based on the amount of solar radiation received by the building envelope. It is responsible for giving structure to the building façade as well acts as a framework to support the material used in the transparent part of the unit. The material selection of this opaque part of the unit is discussed in detail in section 4.3.1.4 of this chapter.

The building envelope gives an opportunity to rationalize the units to a few number of repeating elements strategically placed for optimal reduction of sun radiation and maximizing view. Firstly, for example, in the case of the building envelope (Figure 50) we observe that the units in the each horizontal line are almost the same and hence they can be considered as the same unit for the convenience of design and construction. Secondly, to achieve maximum thermal mass along with views, the units up to 1100 mm can be considered opaque. This allows for access to views at the eye level of the occupants (Figure 52).

![Figure 52: An example of the proposed building façade demonstrating the opaque units until 1100 mm.](image-url)
Therefore, there are 2 or more rationalized units. Figure 53 demonstrates typical rationalized units from a fully transparent one to an opaque one.

The units further modify themselves based on the face of the building they are located. In other words if we strictly follow the amount of radiation falling on each face of the building façade, we will have different unit for every face. For example, the south and the north facades have already been discussed in the previous section and can be seen in Figure 50. The north has units with less thickness as compared to the south and all are shaded from the top. But the east and west faces of the façade get more oblique sun angles therefore, it is seen that the vertical facades of the unit also gets covered as seen in.
Unit design is an exercise in designing a three dimensional unit instead of a 2D skin. This is because as explained in chapter 2 and 3 the glazed office façade is imagined almost like a 2D surface and there exists multiple surfaces depending upon location and design brief. Therefore, the intension of the unit design was to make each unit a zone of mediation instead of a barrier. This was achieved by giving thickness to the pre-industrial traditional lattice work or jail. But simple extrusion for this lattice work restricted access to views and daylighting as shown in Figure 54. Deeper the extrusion, the more opaque the building façade; pre-industrial architecture were able to get views and daylighting from the jail due to the lower thickness of the wall (20mm) which would almost behave as a screen.

Figure 54: changing transparency of the pattern with changing thickness
Therefore, it was required to extrude asymmetrically in order for light to enter the cone of vision of the human eye. Therefore, the proposed units in this thesis behave as tiny zones of mediation between the elements of the environment and the interior (Figure 55).

![Diagram](image)

*Figure 55: A single unit is a small zone of mediation between the air, water and sunlight.*

Using parametrically design 3D self-supporting units made using materials such as clay or concrete similar to the ones demonstrated in this thesis are rare. Most parametric units are made of materials such as textiles and have their own base structure that holds them up.

Erwin Hauer in the 1950s was already designing units similar to this. He used a composite of cement and crushed marble (Barreneche 55-582012) to make his units. He cast these units in rubber lined aluminum molds. These units were exactly alike but the way they came together provided an
aesthetics that was beyond his time. But all of these units (Erwin Hauer modules) are used as a second skin due to the presence of transparent parts which are not optimized geometrically or materially. His units at most times form the external skin in front of a fully glazed façade. But the proposed unit in this thesis works with another level of geometrical optimization; a micro level which is the property of the material that can be used by strategically positioning them for performance. The discussion and design of the transparent part of the unit is as important as the opaque which is addressed in the next section.

4.3.1.3.2 The transparent

This thesis begins with addressing the problems of transparency. Therefore, it is also important to discuss it in the proposed test design. The transparent in contemporary architecture is of two types.

1. The part that has nothing, which is open to all the environmental conditions, it is a void. It does not have any materiality and is a function or a negative of the opaque portion of the unit. It allows the free exchange of matter and energy across its borders.

2. The transparent also refers to one that is open to light, views and energy but there is no physical exchange of matter across it. It is a function of the material occupying this transparent space.

In the proposed façade design unit, the transparent portion of the unit has the task of allowing views, light and ventilation but with the heat. The resistance to heat transfer of the unit is a function of the material and geometry of the opaque part as discussed earlier. Here also, the transparent façade can be of two types as above.
For example, as discussed earlier, access to view is not required from waist down therefore, these units can be completely opaque or filled with translucent materials. Translucent materials such as salt crystals ([http://www.emergingobjects.com/project/saltygloo](http://www.emergingobjects.com/project/saltygloo)) have the potential to provide diffused daylight as well as the required thermal mass. The openings on higher portions of the building façade need to stay; therefore, they are covered with micro mesh. A mesh system that is thin enough to keep the dust and other big particles out but allow air to pass through. Similar to the bug mesh used in contemporary residential units.

4.3.1.4 Material selection

Informed material selection in the design of the architectural skin is extremely important (chapter 2, section 2.4), even though it is covered last in this façade design methodology. This methodology requires this to be the first step. Contemporary material selection for architectural facades is highly formal in nature. This means most materials; especially the latest ones are used for visual purposes.

Material selection for the proposed design in this chapter is based on the performance criteria of the building envelope. First the building skin is described in terms of material properties and then the ideal material is selected. This methodology similar to that followed in mechanical design (chapter 2, section 2.4) allows for all materials to be potential candidates. It includes a large range of materials which may otherwise not be an obvious choice for an architectural skin. Therefore, this methodology goes beyond just the visual and physical characteristics of the architectural skin to select an ideal material or propose a set of material property for one hypothetical material.
The first set of material properties are a function of the geographical location of the building skin; which is the hot climatic zones. Therefore, the thermal properties of the materials take precedence. Selection of insulating materials is based on its thermal resistance while highly conductive materials such as metals use the thermal conductance as their measurable property (Aksamija, 2013). Materials used in pre-industrial synergistic facades do not use metals but use materials like stone, bricks or adobe which have high thermal resistance and are able to slow the movement of heat through the building skin.

The next are its physical properties. Lightweight materials are always preferred to be used in the construction of building facades. Therefore, there are two ways in reducing the dead load of the building skin, firstly, a material with very low density can be used and secondly, a material with intermediate density but very high strength is advisable. This is because the latter will use less material to achieve the same task as the former. This is why hollow aluminum or steel sections are preferred in curtain walls due to its high strength but due to their high thermal conductivity, these materials are not considered for the design of the building façade in this thesis, it increases the interior temperature by thermal bridging.

The geometry of the building façade unit in the proposed design also defines its mechanical properties. Figure 56 demonstrates this. Firstly, the unit affixes itself to the main façade by the thick frame at the back. When this unit comes together with the others its dead load will pass through it, making this part of the unit in compression. Therefore, the material needs a good compressive strength. On the other hand the front part of the unit that faces the exterior is small cantilevered sun shade. This part of the unit is on tension and therefore, the material needs to possess adequate tensile strength also.
Due to the building type of the proposed architectural facade, transparency to both daylight and views is required.

Interior thermal comfort took precedence over everything else in pre-industrial buildings as there was no other alternative form of maintaining thermal comfort as compared to now (HVAC systems). Daylighting was available (through the courtyard), views were almost nil but both was these are insufficient as compared to contemporary needs. Therefore, contemporary building skin requirement lists transparency as a requirement but uses a transparent material to achieve this. The thesis design proposal does not use a transparent material, instead uses the design of the opaque portion of the unit design to achieve the required daylighting and access to views. Therefore, the optical properties of the materials are not important, and it is preferred to have a completely opaque material. But the transparent part of the unit can have a material that is transparent. This material can either allow for controlled ventilation or be completely opaque air but transparent to light.
Additionally, the material or the unit must not be damaged/eroded by prolonged exposure to water. Building skin optimization with reference to water is not in the scope of this thesis but water does not enter the proposed building facades due to two reasons. Firstly, the slope of the overhang does not let the water stay on the building skin. Secondly, there is a presence of a micro mesh in all the full open parts of the building skin unit. This micro mesh is similar to a bug mesh that is used on the windows today. It is small enough to stop large water droplets and dust particles from getting inside. This material must allow reasonable permeability to water and moisture to ensure that the building structure is kept cool. If this main building envelope is cooler than the outside, any air passing through it, will also undergo temperature reduction and thus ensuring adequate thermal comfort.

Finally, one of the most important material properties after the thermal properties, are the environmental properties of the material, which is its embodied energy. *This is the amount of energy required to extract, process, transport, install and recycle or dispose of a material.* It is important to keep this value low if the building needs to truly reduce its carbon footprint. Removing even one or more steps in the final installation of material on site will bring down the overall embodied energy of the building façade.

**Transparent materials**

Based on the above discussion, the units can be made up of either only the opaque material or a combination of the opaque as well as transparent. Ironically, the ideal transparent material to be used when we do not require ventilation is glass, the regular soda lime glass used in conventional windows. As compared to all the transparent materials (Figure 58) at our disposal glass has considerably low, thermal conductivity as well as low embodied energy (Figure 57, Figure 59).
Figure 57: Materials property chart: Electrical resistivity vs Thermal conductivity showing the location of soda lime glass. Adapted from Granta Design (Used with permission)

Figure 58: Material chart showing the transparency of the common materials (source: Ashby 2011) (Used with permission)
Figure 59: Material chart showing the embodied energy of the common materials (source Ashby 2011) (used with permission)

On examining the electrical resistivity vs thermal conductivity charts, we can see that the polymers and GFRP (glass fiber reinforced polymer) have lower thermal conductivity than glass and some are also transparent (PET, PS) but when looking at these against the embodied energy chart, we see that all of these have much higher embodied energy as compared to soda lime glass. This does not imply that materials such as polymers need to be completely discounted. It only means now we know that they must be used only in strategic locations that needs them to be there to increase the performance of the building façade.

Opaque materials

Based on all of the above properties for opaque materials, it can be inferred that the earth excavated from the site can be the material that can be used for the majority of the building façades. Earth is a
powder based material like sand and concrete. The resultant unit would be similar to a brick. Figure 59 shows that the embodied energy for brick is much lower than the contemporary façade materials used for a transparent building envelope.

The earth needs to be combined with a binder to allow it to be set into the unit of desirable geometry. The binder used here is like water to cement, where the actual strength or required property of the form is the property of the material and not its binder. Therefore, the following two methodologies ensure that the energy utilization for the design, manufacturing and installation of the unit is kept to the minimum. Today powder based materials can be made into a desirable form by either casting it using a mold or additive manufacturing.
Figure 60 shows the manufacturing of the unit that is rationalized (see section 4.3.1.3). Step one is the earth that is excavated on site from the pit made for foundation. This earth is combined with the adequate binder and put into molds to set. These molds are not made on site. Due to the complicated nature of the unit, these molds can be 3D printed or milled (or any other form of cast manufacturing) off site and brought to site for use. The set earth and binder can then be fired in an onsite kiln to achieve its required strength similar to bricks. The fully formed units are then carried for installation on the building façade. Figure 61 demonstrates the manufacturing of units that all different from each other. In this case all steps remain the same as Figure 60 except for the additive manufacturing that take place onsite. Here, the earth is combined with the adequate binder and then fed into a machine like a 3D printer to manufacture the desired units. There is no vehicular movement between the mold manufacturing location and site and thus removing the fossil fuel use by transportation completely.

Both the methodologies show the use of manual labor in this process. As compared to the developed countries in the world, developing countries such as India still rely on manual labor for the majority
of the construction of its built environment. The labors are easily available and also at much lower cost than in the developed countries. It is also offers a large source of employment. Therefore, this can be easily used to the advantage of the installation and fabrication of a façade design such as this.

This section discusses individual materials from the material universe being brought together by climate responsive design and a proposed fabrication processes to create a building envelope. This building envelope is made up of one kind of unit which has been discussed in the unit section. Therefore, this unit which is a combination of different materials is a composite material. As discussed in chapter two, we are limited by the material choices available to us due to the innate nature of each material. The properties of the materials are a function of its chemical bonds. Therefore, leading us to select more than one material to achieve our tasks which led to component based design. But this proposed façade design develops one unit; different configurations of which lead to a climate responsive building façade. This unit is a combination of different materials and a definite shape, therefore, becoming a composite material; in this case this is a transparent brick. It is a unit that behaves like a brick (thermal mass, material used for its manufacture, manufacturing process) but its shape gives it extra properties of transparency and tensile strength which is otherwise missing from a typical brick, therefore, introducing a new material into the material universe. Figure 62 Figure 63 and Figure 64 show the relative positioning of the new material on different material property charts.
Figure 62: Materials property chart: Electrical resistivity vs Thermal conductivity showing the location of soda lime glass. Adapted from Granta Design (Used with permission)

Figure 63: Material chart showing the embodied energy of the common materials (source Ashby 2011) (Used with permission)
4.4 Conclusion

This chapter demonstrates a design methodology that is derived from the fundamental problems of the transparent façade (chapter 2) and the learnings from the pre-industrial synergistic building envelope (chapter 3). It introduces two concepts; the horizontal layering and the vertical layering. Both of these concepts follow the same design objectives, firstly, to maintain thermal comfort inside a building located in a hot climatic zone without or with minimum usage of the HVAC system. Secondly, reducing the overall embodied energy used for construction of this building skin and thirdly, maintaining the contemporary visual and daylighting levels through the building envelope.
The first type (horizontal layering) addressed this by introducing zones or layers of mediation in plan. This means that environment passes through multiple rooms/zones before it gets modulated to comfort level required in the work space. But in a building typology (office) where floor space is precious, this may prove ineffective as compared to its success levels when used in a residential unit.

The second type (vertical layering) is seen as the type of building facade design concept that has the potential to be used as an office façade. Here, the design makes use of the external surface treatment followed in the pre-industrial synergistic building envelope, which generally never built fully plain surfaces such as the glazed skin as external walls that were exposed to direct sunlight. Instead there was always the presence of wall articulations in terms of sculptures or cultural patterns that made sure the wall was always shaded throughout the day. In this thesis, I call this adding roughness to the wall. Therefore, in order to achieve performance criteria, the surface area of the wall was increased by the introduction of ‘roughness’. But as demonstrated in this chapter the increased surface area resulted in the decrease in the percentage of surface under direct sunlight and finally changing surfaces with the least radiation exposure to fully transparent enabled this façade to have access to both daylight (without the heat) and views.

As observed in the proposed design, this building façade is at places completely transparent to environmental elements. But the presence of a micro mesh ensures the reduction of dust and large particles from entering the work space while maintaining adequate ventilation.

But this design also has the potential to use glass instead of micromesh incase complete opacity to the outside elements are required at certain parts of the building envelope. This is because the glass used here will be smaller pieces therefore; the requirement of toughened or coated glass is not
there. Secondly, the location of the glass insertions is always in shade, discouraging the energy of direct sunlight. Even though this thesis is critical about the fully glazed building façade, it is not critical of the material glass but is cautious of the concept of abundant transparency in hot climatic zones of the world.

One major advantage of this design is the fact that this design breaks down the building façade into smaller units. One might argue that I am breaking down the building envelope into components which was discussed in chapter 2 as a disadvantage of the transparent skin. But in the case of this design, each of these units does not serve a separate function which was the case with component based design. All the units are made for the same performance criteria. The Figure 65 shows the potential of this unit based design as an aid for user control during work hours.
4.4.1 Drawbacks and future research

One of the major drawbacks of this design (introduction of surface roughness) is the issue of maintenance. The presence of a large number of small highly articulated units with lots of small nooks and crannies allows for the settlement of unwanted elements. Therefore, cleaning it with a jet of water can be an option when the façade is completely opaque for example, in the case of units with glass in them but the problem arises when there are units which are open to air. Further research in this design and methodology will help solve this type of issue in the future.

The proposed design relies on the earth excavated from the foundation pit as the main material component of the façade. But not all sites will have the soil type that is suitable for the purpose of unit fabrication. Adobe and local clay construction is very common in countries such as Iran and India but the desired soil type does not exist in every part of the country. This does not lead in a complete abandonment of the proposed design methodology. Our first step in this approach was listing of material properties; this type of hurdle (unsuitable soil type) only causes us to look for an alternate material that fulfills all the required material properties. At this point we are not compromising on the environmental performance of the building façade but we may need to transport the raw material in bulk from off the site and continue with the rest of the fabrication process on site.

Future research lies in understanding different soil types and their consequent fabrication techniques. Therefore, just as we conduct soil testing to detect the load bearing capacity of the earth, there may be a future possibility in testing the local soil for façade design capabilities. Depending on the soil constituents, future research can tell us what other materials needs to be added to it in order to make it moldable or made into units by additive manufacturing. Therefore, the
future may not be in new technologies or realization of new materials but by finding new potential in existing materials and technologies.

This thesis only demonstrates one idea generated from a proposed façade design methodology which is based on a more holistic approach. Therefore, this methodology is not limited to the proposed design in this thesis. The design follows a set of design decisions to arrive that the final façade design as shown. The proposed façade designed in this chapter is based in India, where terracotta, sun dried bricks or fried bricks have been traditionally used for generations. Using local soil for construction is very common. Therefore, the façade visually looks like this. But the same methodology can still be applied if the design decisions change. For example, in a location with abundant trees on site or even certain types of stones will result in a completely different fabrication methodology and eventually in a very different visual appeal and performance.
Chapter 5: Conclusion

5.1 Summary

A reimagining of the contemporary office façade is of utmost importance now more than ever. New technologies and materials are continuously added onto the architectural skin in the name of sustainable architecture and these are going unchecked. These are added as passive design strategies (orientation of building or opening sizes) or active component implementations (use of Photovoltaic panels). This thesis identifies that current research still insists on only making small changes and tweaks to our existing façade design strategies and argues for a complete overhaul of the building façade methodology in order to start designing and constructing truly sustainable architectural facades.

The unchecked use of contemporary glazed office facades in developing countries such as India is owing to the fact that this type of architecture found its beginnings in the developed countries of Europe and America. These countries represented progress and peace to the developing world and therefore, building the same in their respective countries symbolically gave them a global image of progress and prosperity. This building typology (the transparent office facade) arrived in India along with the multinational firms from Europe and the United States of America; it was familiar for these firms to build their work places exactly like the ones back home. Due to the highly modular and component based design of such building facades, these structures were quick and easy to replicate. This aided with mechanical systems of air conditioning and ventilation made it convenient to be replicated in any location on the planet.
The onset of the energy crisis saw through the unsustainable nature of replicating the same building type in any part of the world especially those facing extreme climate, eventually small tweaks to the design of the fully glazed facades led to the development of highly engineered building envelopes which are intelligent and had the latest technology and materials such as performative skins, dynamic facades or responsive building skin all in the name of sustainability. But all of them essentially brought down the operational cost of the building and provided a visual spectacle to its users and onlookers.

Addington (Kolarevic, Parlac 2015) in her essay “Dumb buildings, smart architecture” states that “we want our facades to be more and to do more, but we are not clear on what we need or why we want it” We are in a race with the changing and advancing technologies and are in a rush to integrate them in architecture to create structures that are full of drama and are different from its predecessors. Schittich provides a reason to this by saying that, all architectural styles that followed the curtain wall all followed the common goal of providing the building with a face which was almost non-existent with the use of monolithic glass (Schittich 2001).

But the component based design approach simply led to the addition of more and more technology as well as materials that were not suitable for the buildings climatic location. Michelle Addington questions the blinding faith of human society in technology and states that we must disassociate the need of technology for a smart design. But technology does not always result in sustainable architecture. Hathaway (Kolarevic, Parlac 2015) argues that technology and collaboration is the step towards creating an energy efficient structure.

Even though the architectural community identifies and explains the problems of the contemporary architectural façade, very little literature exists on its solutions. Most of the solutions are generally in
the form of component/device additions or subtractions from the existing facade design methodologies.

The main aim of this thesis was to help change the perspective of architects towards the way they approach the design of contemporary building envelopes. This is done by drawing their attention to the limitations existing in our facade material selection methodology and our understanding of energy efficiency.

This thesis looks to understand pre-industrial architecture as a basis for a solution. These architectures succeeded where ours fail (chapter 3). Most of the available literature on this type of architecture identifies its sustainable strategies and components. This thesis introduces the pre-industrial architectural facade as a pre-industrial synergistic architecture skin. This is because the intention was to discourage the design professional from concentrating on the indigenous or vernacular architecture purely on the basis of aesthetics or material and formal quality. The thesis shows this type of architecture on the same comparison platform as contemporary architecture. It shows how the indigenous architecture is sustainable in a holistic view of energy flows. This is one of the proposed ways in which the pre-industrial architecture can be brought into the present without compromising on the modern day comfort factors like facade transparency and ambient daylighting.

This research fills of the gaps identified both in contemporary building facade and pre-industrial architecture. It does so by questioning modern day facade design strategies at the fundamental level and proposing a building envelope design methodology based on first principles.
5.2 Lessons learned

This thesis has three important parts. Firstly, identifying the problem, secondly, analyzing the solution and finally proposing a methodology and a test design.

The context of this building envelope research is the envelope of the contemporary office buildings in hot climatic zones that was identified as one of the most energy intensive facades despite following basic sustainability measures. The majority of the building envelopes of this type of architectural typology is the transparent or the fully glazed building façade. The study of the literature available on this type of architecture skin identified four central problems posed by the transparent façade. Firstly, the origin of this type of façade was questioned. Secondly, the design methodology for the design construction of the contemporary office façade was identified as a component based design approach. Thirdly, the environmental performance of the materials used in the curtain wall was not adequate for hot climatic zones. Finally, based on all of the above problems, it was identified using the laws of thermodynamics that this type of façade is not energetically efficient and will always be energy intensive. All of the four points goes beyond tweaking the transparent façade in order to reduce the operational cost of the building. Instead it views the building façade as an open thermodynamic system in the context that goes beyond its physical site boundaries and acknowledges the invisible forces in play that directly indirectly affects the building façade as well as the buildings occupants.

Therefore, this thesis proposes a solution based on an architecture that was truly sustainable in every way. This is the pre-industrial architecture. These were buildings designed for human habitation and perfected over generations. This was architecture before the age of glass, steel and electricity and therefore, was a truly climatic responsive architecture. This thesis studied the
literature based on this type of architecture from hot climatic zones. Every paper identified the advantages of its design strategies but failed to explain its smooth integration into the contemporary world. This thesis identified the gaps existing for the failure of the correct incorporation of pre-industrial architecture into today’s world and proposed strategies of incorporation based on a holistic building envelope design methodology.

The study of the pre-industrial architecture revealed that these types of buildings had a holistic approach towards architecture that was responsible for comfortable habitable conditions. Unlike today’s architecture that is component based, even when it comes to taking inspiration from the past. The architecture of the past was a merger of its form, function and its material. All three was equally important to achieve the required thermal comfort. But this type of building was not without faults, ambient daylight and its limited access to views was its major drawbacks. Both of which are now important requirements for the design of the contemporary office façade.

This strategy was put to test by a proposing a present-day office façade that was able to fulfil the basic requirements of transparency and daylight of the office façade as well as keep to the holistic design strategies of the pre-industrial architecture.

The proposed design methodology attempts to design the office building façade based on first principles as was done in the past. There was always a close relationship between the climate responsive design and the pre-industrial architecture. Climate responsive design is not a modern day invention. It has been followed by generations of people until the time humans learnt to modify or manufacture their own climate and we lost track of climate based design.
The proposed façade design methodology encourages the designer to think locally. Instead of tapping into already existing designs or design strategy, one must question the geographical location. Its location on earth offers a vast hoard of data that includes climate, topography, material and local architecture. All of which must be the input parameters towards building envelope design. The design methodology is the introduction of roughness at every level of the façade, from the full wall, to its units until the material type. Increasing the surface area of the external wall was able to provide us with a new set of shaded surfaces that could accommodate transparency that allowed light without heat.

The proposed design is only one variant of the vast potential of this methodology. This is a way to convince the contemporary man that the past and future can work hand in hand for designing and building a more sustainable form of architecture. As the design and material maybe inherited from the past but its application is futuristic. We cannot ignore the past by shelving it as obsolete or old. There is a logical reason for its survival until now. Looking at the past does not necessarily mean that we are recreating the same buildings. It means we are using the same concept but contemporary design for contemporary requirements.

5.3 Contribution

The main contribution of the thesis comes in form of proposing a process or a methodology that a new technology to achieve its aim. It introduces the idea of using a fairly new technology of additive manufacturing to make a module such as a brick that has been in existence for centuries. Due to the nature of fabrication, it is now possible to make computer generated forms that are optimized to be climate responsive and structurally sound. This along with the old technology of passing them
through a firing kiln provides us with a building façade design and construction process that is successfully able to bring together new technology and what we already know. It is introducing the idea of 3D printing of local clay or earth as an onsite assembly line which makes use of all existing components into a new construction process that is truly sustainable. This comes at a time, as mentioned earlier where we are in a rush to find new and spectacular products and technology to be used in the field of architecture and as argued in this thesis, which may not be as sustainable as being marketed.

Secondly, this thesis locates the building façade not just in its physical context of the site but also puts a new boundary of energy systems. It locates the building façade within the various energetic forces around it that directly and indirectly affects the building façade. Graphically, we can now look at the building and how all other environmental as well as manmade forces affect it. Figure 66 shows how the proposed façade design sits in its energy systems boundary; coming to close to the ideal energy systems diagram proposed in chapter 2.

Figure 66: Energy systems diagram for the proposed façade design
Thirdly, it introduces the idea of designing the building façade on the basis of first principles. Which means material selection and the building form is not based on just what is presented to architects or the choice of the client, but on defining the physical and energetic properties based on the site and climatic zone in question. This opens up material and geometry choices that would have otherwise not been in material palette of the architect. This is adapted from the process by which the material selection is done for mechanical design by material engineers. This thesis proposes a new material which is a composite (a material made of one or more basic materials in a definite shape) that is slightly away from our normative definition of what a material is defined as. By doing this we move away from the building façade moves into a more coherent design instead of being an assembly of components and therefore, pushing the architects to a role of an architectural designer based on intrinsic properties.

5.4 Future

The main goal of this thesis was to change the perspective of the design professionals as to how they approach the design of the contemporary office façade. It introduces the problems of the transparent façade in a completely different context as previously done. This was important so as to put new questions into the design thinking of an architect. Even though the solution based on pre-industrial architecture is not a new one. Its implementation strategy is new.

This thesis is not a foolproof methodology but it is an attempt to draw attention to the gaps in architects design knowledge, or an attempt to explain the requirement for the change in perspective towards how we design or identify the building façade. This thesis is only an introduction in the direction of the possibility and feasibility towards a design methodology of the contemporary office
façade based on first principles. Future research is required in each of the three sections (chapter 2, 3, 4) for the development of the proposed design methodology.

With issues such as global warming, climate change and resource shortage haunting our world daily, research such as this holds more importance now than ever.
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Appendices

Appendix A

A.1 Introduction

Conceptually, there are two ways to approach this design problem (Figure 67). Firstly, development of building envelope layers in plan (horizontal layering) and secondly, the layers of the building envelope are segregated in terms of elevation (vertical layering).

![Building envelope Design strategy diagram]

*Figure 67: Different types of building envelope design strategies*

In horizontal layering, the various performance criteria of the building envelope is addressed by multiple set of layers or zones. But unlike the contemporary layering system, where each layer is a surface, here each zone is an occupied space/zone as shown in Figure 67. The vertical layering
addresses the various performance criteria of the building envelope by its varying thickness and opacity along the wall section.

In both these approaches the building façade addresses the issues of thermal mass, ambient daylighting, access to view and it is self-supporting. The following sections discuss both these concepts in detail.

A.2 Horizontal layering

Chapter 3 considered the pre-industrial architecture of hot climatic zones of India and concluded the existence of different building envelope layers. It demonstrates that the concept of a building envelope is very different from how we see it today. Contemporary building skin is regarded as a 2D surface that is almost stretched over the building structure and this thin layer is responsible for almost all the environmental controls for the building.

The study of the pre-industrial architecture explains that the concept of a building envelope goes beyond the external walls to the presences of occupied set of spaces or layers in the form of solids (rooms) and voids (courtyards).

The concept of number of layers in plan implies the zones of mediation or energy exchange. There can be one zone where all types of energy exchange takes place or many. It may be argued that, in increasing the number of such zones, there is more space occupied and more materials used; therefore, ideally reducing all mediation within one layer. But there are two important reasons for using multiple zones of mediation. The first reason is discussed in the material study in chapter two. The basic nature of currently available materials renders it implausible to have one material or surface mediating between the air, water and sunlight. Therefore, in addition to using the most suitable material and dynamic actuators, adding multiple surfaces or layers to the definition of the
building envelope can be seen as one of the ways to achieve this basic task. The second reason is the increase in thermal mass of the architectural envelope to maintain comfortable internal temperatures. One of the important factors of human comfort is temperature that is maintained in the interior. This temperature can be created by using mechanical air conditioning systems or through passive mediation between the interior and exterior. In both these cases, once the temperature is at the comfort level, its maintenance is very important. The building envelope is a key component in the thermal loss or gain and it depends on the temperature outside. For example, if it’s very hot, this temperature is easily conducted through the skin into the interior or in cold climates; the internal heat is lost through architectural envelope. This makes it important for the building skin to perform as a thermal lag, which is greatly minimized due to decreased mass in enclosures with only one or a very thin skin. This leads to highly fluctuating internal temperatures resulting in increased peak loads on buildings using mechanical system of air conditioning.

The study of pre-industrial architectural skin in chapter 3 reveals the existence of similar layers or zones. The first layer was one that modified the outside environmental conditions before letting it come in contact with the wall of the room adjoining the human. Next there exists a courtyard in the center of the house plan to create a pressure difference that allows for air movement from the outside, adjoining the courtyard is also a layer similar to the layer 1 which is the environmental modifier and finally the third layer is a zone that is inhabited by humans for lengthy periods of time that has minimum temperature variation which is the bedroom In a house and in case of an office building it will be the workplace. Hence, providing the occupied space with ample protection from heat gain; both by the means of thermal lag as well as protection from direct sunlight.

The following section is a small exercise in determining the number of zones of mediation required and where or in what order. This is done by using the conclusion of chapter 2, where it was established that the building envelope broadly mediates between air, water and sunlight and
everything else is a derivative of it. Parallels of the same are drawn from existing system of building façade layering in contemporary architecture.

A.3 Adequate number of layers

![Diagram key](image)

*Figure 68: Diagram key*

We have three factors of mediation. Starting with one skin mediating between all three; to one skin mediating only one parameter, we have a total of up to three layered envelope. Using the basic principles of permutations:

\[
\frac{n!}{(n-k)!}
\]

- \(n\) – Number of parameters (Air, water, sunlight)
- \(k\) – Number of skins
In the case of one skin; we have all three parameters mediated within that skin. When \( k = 2 \), that is, there are two skins, therefore 6 permutations for 3 parameters to mediate with 2 skins and finally when \( k = 3 \), there are still only 6 ways for the parameters to mediate with 3 skins.

The below shown diagrams are all the combinations that are achieved by the combinations of three parameters of mediation with one, two and three layers of building skin.

![Building skin with one layer needs to mediate all three elements](image)

![Figure 69: The different combinations of number of building envelope layers vs the environmental factors](image)

Two layered building skins are very common in the contemporary world. Type 1 is the most common that is used in hot climatic zones, examples of which include the Al Bahar towers, Abu Dhabi or the Doha tower in Qatar. Both of these have an outer layer of sun shading that regulates the sun and the inner second layer is glazing that keeps out water and air. Similarly, type 2 is observed in the Media ICT building in Spain that uses inflated ETFE panels for insulation as well as sun protection, therefore
the outer layer is able to mediate the air as well as the sun. The inner layer is glazing and prevents water from getting inside.

Type four is common observed in cold climatic zones, where the solar heat gain in welcomed to reduce the heating costs of the building. The 1st outer layer is generally glazing that is able to capture the maximum amount of sunlight but stop air and water from entering inside, while the second layer will be after the glass in the form of mechanical blinds that mediate the sunlight. For example, the KFW Westarkade in Frankfurt.

A.4 Conclusion

All of these combinations (Figure 69) are seen today but they are not used in the same spirit as the layers discussed in the pre-industrial architecture. The layers are almost considered as surfaces and when they come together they are still thinner than the walls of the pre-industrial architecture, therefore there is a presence of inadequate thermal mass. Secondly, because of the basic thickness achieved by this building envelope, it essentially behaves as one building skin trying to mediate between all three environmental factors, which as explained earlier is the most difficult type of building skin to achieve. Therefore, the materials and technologies used here are highly energy intensive which is completely opposite to the type of materials used in the pre-industrial world.