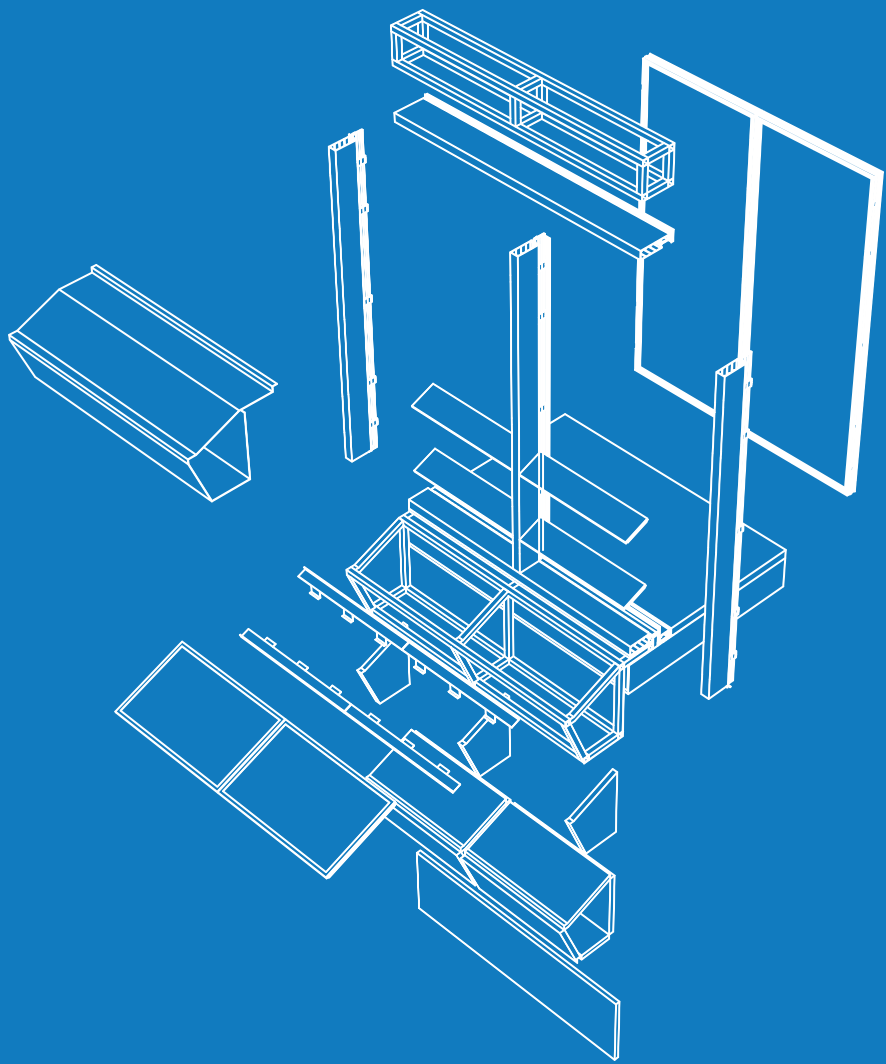
Plug & Play Facades



Sustainable Facade Refurbishment of Existing Tall Buildings in UAE using Plug & Play approach

GRADUATIONSTUDIO

2018-2019

Plug & Play Facades

Sustainable facade refurbishment of existing tall buildings in UAE to reduce energy consumption and extend effective facade service life using plug&play approach

Delft University of Technology
Architecture Engineering & Technology
Facade and Climate Design

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Delft, June 2019.

Abstract

The thesis aims to offer a review of a modern conceptual facade focusing on one more possible solution to sustainable facade refurbishment for existing tall buildings. There are thousands of highrise buildings in the world and almost all of them over time will require some degree of refurbishment. The premise of this thesis is based on the rising ecological concern of human-made climate change, and the role building industry has in its effects. The thesis only focuses on a smaller part of the whole sector, namely "curtain wall facades". But, data suggests that the demand of curtain wall systems is rising when they age or the buildings which already have deteriorated curtain walls for over 30 years will require some degree of intervention to improve the facade quality and the performance of the building using the facade. Alternatively, the increase in maintenance costs and utility costs will render the building undesirable and hence cause premature demolition of the facade or the building itself. Although this thesis only focuses on a specific region, the postulation of this research applies to any location based on region-specific analysis and design solution. The solution will mostly concentrate on feasibility aspects of design for disassembly and integrated functionality (BIPV) into one system, namely Plug & Play facades.

Contents

“We should perhaps thus be thinking of tall buildings as perpetual entities with lifecycles potentially exceeding 100 or 200 years while designing them in such a way that they can be creatively adapted for potential future uses.”

- Barrington, 2018

01
INTRODUCTION

1.1. Introduction

The thesis “Plug & Play Facades - Sustainable facade refurbishment of existing tall buildings in UAE to reduce energy consumption and extend effective facade service life using plug&play approach” aims to offer one more possible solution to refurbishment challenges posed to most of the existing tall buildings around the world. Where due to ageing facades, the performance of the buildings may reduce. Alternatively, the increase in maintenance costs and utility costs will render the building undesirable and hence cause premature demolition of the facade or the building itself. Although this thesis only focuses on a specific region, as stated in the thesis title, the postulation of this research applies to any location based on region-specific research and design solution. However, the principle guidelines for the proposed solution will remain the same, irrespective of the location or circumstances.

This chapter will briefly discuss the overall premise of the thesis and arguments which lead to the main research question, using the information to formulate the aim and focus of the overall research. Based on the interpretation of the research question, successive strategies and methods will be used to provide relevant results to answer the defined questions and the sub-questions in this chapter. Social and scientific relevance will also be discussed in this chapter to assess the feasibility and expectations of the research. The relevance section will focus on the ability of the proposal to address in future of buildings based on healthy sustainability perspective.

1.2. Background

There is no point to beat around the bush, Climate change is happening, and the threats are real. The problem is going to affect all of us. Recent reports by large institutions such as Intergovernmental Panel on Climate Change (IPCC) indicated the seriousness of climate change and damages that carbon emissions have brought upon us and considering the projections of this data in the future. The consequences of growing carbon dioxide emissions is going to be devastating.

Research suggests that the building industry consumes about 1/3rd of the energy produced and contributes to around 1/3rd as much as global carbon emissions to the environment (International Energy Agency, 2017). Moreover, efforts must be taken to minimise the impact as much as possible. Recent studies show that Residential and Commercial Building typologies account for 40% of overall energy consumption in the United States (“Energy Efficiency Trends in Residential and Commercial Buildings,” 2008). The situation urges for possible opportunities to improve the effect caused by these typologies as much as possible.

Almost all contemporary buildings require a mechanical ventilation system, and especially for middle-east, the demand for cooling is expected to increase by three folds in the next 30 years. Most if not all, buildings in the warm, arid regions need to drastically improve their external surfaces to reduce the cooling requirements (Transition to Sustainable Buildings, 2013). The quality of the envelope of the building determines the overall energy to be used for heating or cooling the volume. A well designed high-performance envelope based on climatic conditions can save up to 20 to 30% of overall energy required for heating in areas with cold climates and about 10 to 40% of cooling for areas with hot climates.

Moreover, when we consider this along with an average service life span of building facades for such types of buildings which approximately ranges from 30 to 60 years (Kakolyri, T. A, 2015). We then know that there is a definite need for a sustainable energy refurbishment. Where the refurbishment of the old facades of the existing building stock not only improves the energy efficiency of the building but also extends the service life of the facade itself to near the end of the service life of the building. Consideration of service-life aspect during design will make sure that all the materials used in the facade reaches its maximum service limit, and reduce material wastage. Hence, saving valuble usable materials from a sustainability perspective.

A sustainable refurbishment is an issue at hand, although it is relatively easy to create new buildings with raised standards and technology, Often the existing ubiquitous building stock is neglected for improvement, and this paradigm has to change. Existing buildings must be improved to newer standards, and it must be possible to improve their condition and extend their life and their components life as much as possible.

The most ubiquitous approach for energy neutrality followed at the moment is to create newer buildings with tried and tested more modern sustainable construction practices and technology. Governments are starting to realize that it is essential to sustainably renovate the existing stock of buildings than to raise standards of the new buildings and developments. They are coming up with grants and other support systems to help promote sustainable refurbishment.

The significance of the existing buildings is that they are already here. The rate of refurbishment is slow. Konstantinou, 2014, on her research, observed that the condition of the current set of buildings quite problematic. The research states that the existing buildings not only have physical issues, but they also performed poorly in energy and sustainability standards. Also, observed in the study was that most of the national building regulations were old and obsolete.

There is a call for environmentally friendly design, and this thesis will aim to understand and develop ways to reduce the impact of the existing buildings.

As shown in the Figure 1.2.1 below a comparison data chart from CTBUH, 2019 suggests that around 3,738 tall buildings (above the height of +150 meters) have been recorded to have been constructed from 1950 to present worldwide out of which 1,873 building was before 2010, which means that all these tall buildings are at a stage where would require an intervention refurbishments. Failing which the energy performance of the building would have reduced significantly and hence, making them consume more energy to keep them operational. A natural alternative is to demolish the old one and build a new one. But, this brings us to the core of this thesis, which is to keep the existing buildings intact but use sustainable refurbishment, design for disassembly and plug and play systems strategies to reduce the wastage of materials by avoiding demolition, and use circularity concepts to re-use the building components by carefully changing the materials which wear out over time and improve the energy performance of the building over time as we do it.

To focus on a specific case, we can efficiently study the effects of ageing buildings from a controlled study of a sample city. Figure 1.2.b. shows the skyline of Dubai, United Arab Emirates has drastically changed over the years with expedited construction activity happening between the 1990s to 2010s and now all these buildings in coming 5 to 10 years will be at a stage where their facade would have matured well past the end of service life of its components. This ageing of the facade would mean that its performance would decrease exponentially both structurally and energy wise.

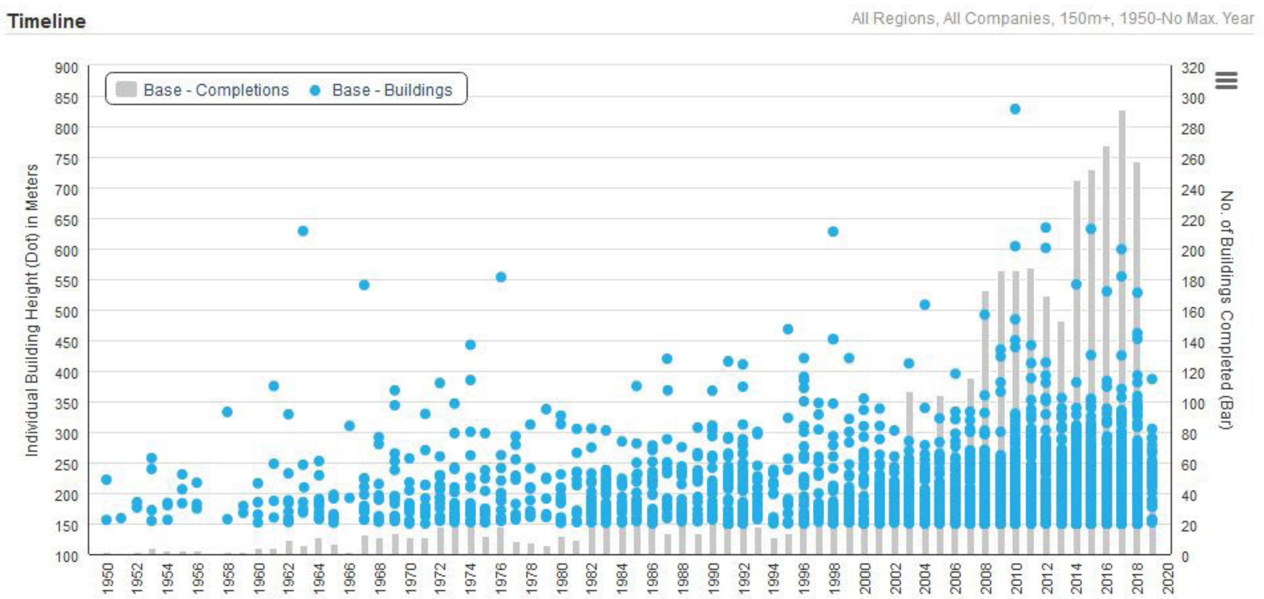


Figure 1.2.1: Distribution of currently standing recorded tall buildings (+150m) around the world after 1950's
(Source – http://www.skyscrapercenter.com/compare-data/)

Dilapidation of the facade can occur due to the natural course of things when materials such as vapour barrier, waterproofing, EPDM, Neoprene, Glass and other relevant materials will deteriorate due to seasonal curing, maturity and UV radiation of the sun whereas most of the built structure can ideally last up to another 100 or more years before it fails. It would be unfortunate to demolish the entire building or even the whole façade when only a few components need replacing. A prudently refurbished façade which incorporates the aspects of disassembly, maintenance feasibility, energy generation and many more considerations will prolong the effective life and performance of the buildings.

In this thesis, careful elaboration of plug & play system along with a systematic approach for sustainable refurbishment intends to solve just that. Not only will it focus on improving the energy performance of the building over time by using systems that can reduce cooling demands and use techniques to reduce the energy required from the grid to help achieve greater energy efficiency and low-carbon cooling supply. It will also provide an opportunity to extend the life of the façade until the end of the service life of the building itself. This innovation will hopefully help designers create adaptable buildings which will suit the requirements of the future.

Figure 1.2.2: Skyline of Dubai over the years
(Source - https://kitchendecor.club/files/dubai-20-years-ago-today.html)

1.3. Premise

A London based study by Synovate, a market research company, reported that requirements of global curtain wall systems have increased by 10% in compound annual growth rate (CAGR) from USD 12.6 Billion to USD 18.7 Billion in the year of 2009 (See Figure 1.3.1.). Data suggests that the demand from Middle-Eastern countries is the largest accounting to 26.5% (See Figure 1.3.2.) of the overall global demand (CSI, 2012). With such large requirements in consideration with data from almost a decade ago, one can determine that many buildings with curtain wall systems as façades are approaching their end-of-life expectancy and will soon require refurbishment.

Figure 1.3.1: Size of global curtain wall industry as on 2009 in USD (Source - CSI, 2012)

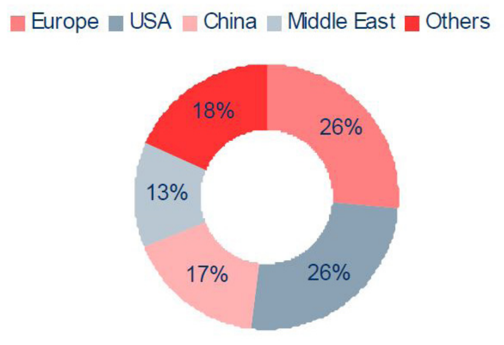


Figure 1.3.2: Peak demands per location of global curtain wall industry as on 2009 (Source - CSI, 2012)

Most of the existing building stock today is designed to be mountable, but it is not demountable. It is for the same reason that construction process requires a significant amount of time, planning, and assembly of complex building components and materials in a pre-assigned manner, which require hundreds of construction workers if not thousands (depending on the scale of the project), and various advanced machines. Contrary to assembly, disassembly of a building is quick with either stripping out of the façade or a demolition process (Durmisevic, 2006). This practice causes wastage of energy and materials introduced into the building through the construction.

End-of-life of building and potential to reuse its materials in a circular approach is discussed more commonly now than before. Although, the specific niche which will be discussed here regarding the curtain wall is alarming. As discussed in chapter 1.2 above the amount of existing ageing tall buildings is rising. However, when looked closely we can understand that curtain wall systems have been quite popular over the last two decades and because of its high standardization and modularity curtain wall systems have become a natural choice of the facade to specify in design, as it is easy to install and reduces the construction time significantly for large structures. Curtain walls capacity to customize any panel based on design requirements while maintaining the profile details have also been a perk heavily exploited by architects and contractors today.

1.3.1. Percentage of Materials in Typical Curtain Walls

The Appendix 7.1 indicates the typical components used in a conventional unitized system and the breakdown of materials arranged compositely, which contributes to the construction of each component

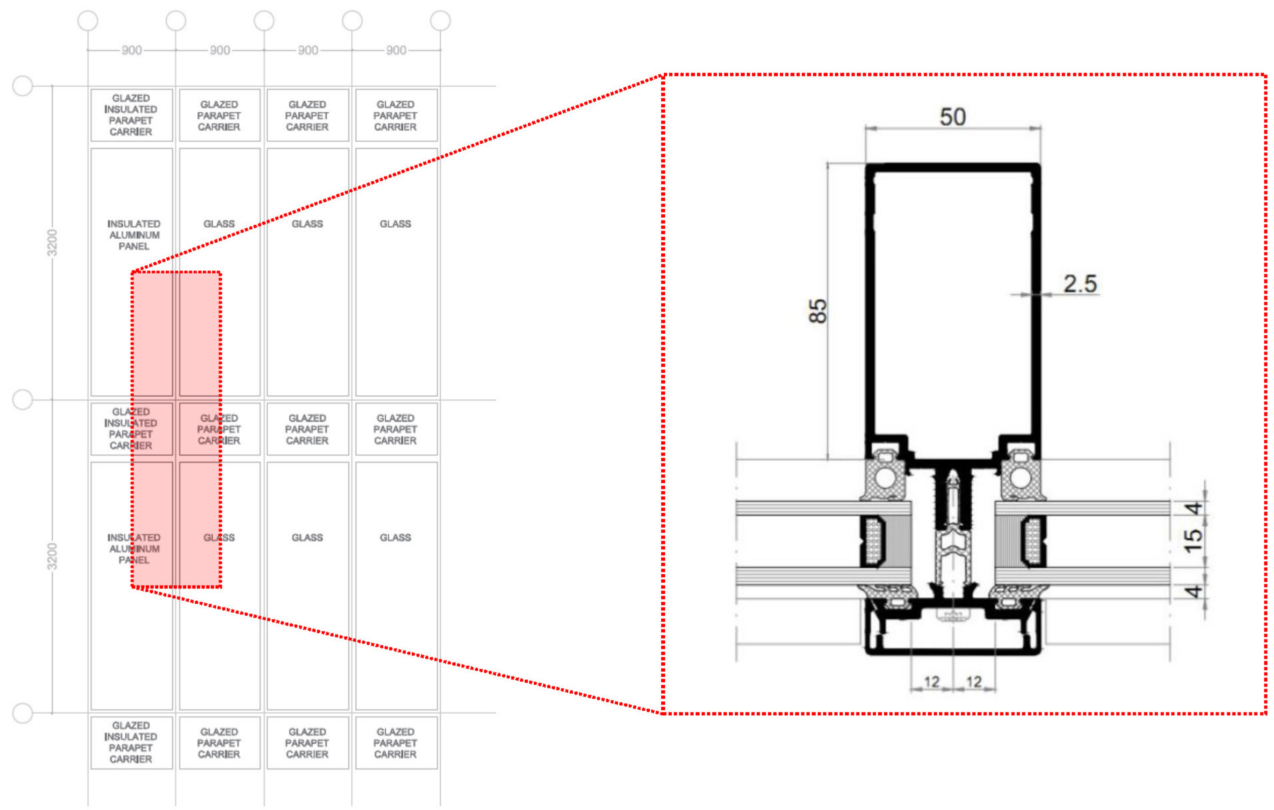


Figure 1.3.1: Standard curtain wall elevation for study (Source - Author)

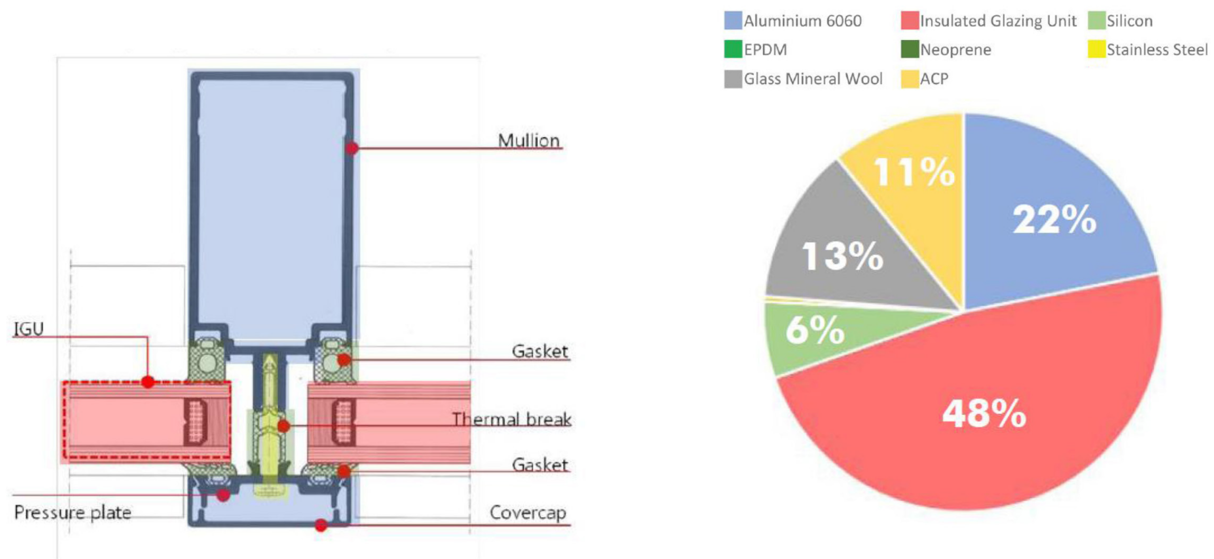


Figure 1.3.2: Typical curtain wall profile horizontal section indicating % of consisting materials (Source - Author)

and the coatings used wherever necessary. Each material was studied carefully to understand its average service life to help identify when a component starts failing. The related data for the surface area and cross-sectional area is extracted from the drawing, as indicated in Figure 1.3.1, and the material properties were extracted from the CES Edu pack 2018 software (Material Library). The quantities of each material were identified, and then the percentage of materials per selected panel was determined. Summary of results is shown in Figure 1.3.2.

Figure 1.3.1. shows a standard elevation of a typical curtain wall facade with a cross-section of the curtain wall through the aluminium profile as indicated in the elevation. After carefully analyzing all the components of a typical curtain wall façade can be broken down to the elements elaborated in Figure 1.3.2. breakdown of materials in a typical curtain wall system and the approximate percentage of those materials in usage.

Hence, it is concluded that the Integrated Glazing Unit (IGU) consists of the most material in the facade panel. Which is around half of all the material in the panel (ranging up to 48%), and then the metal profiles constitute the next most common materials in the facade panel which is about 1/4th of all the material in the panel which falls within the range of 22% to 25% of all the material. All other materials based on the area of study will constitute up to the remaining 25% of the overall materials in the panel. These materials include mixed plastics for sealants and gaskets, metal such as stainless steel screws, nuts, bolts and other brackets for connection, the opaque facade panel which may vary based on type of facade, use, or location where it is placed is likely to have Insulation panels with aluminium cover over it or an Aluminum composite panel (ACP) in it.

1.3.2. End-of-Service Life (ESL) of components in Typical Curtain Walls

While comparing the average service life of the materials, the study reveals that different materials have different end of service life. Mixed plastics such as silicone sealant and thermal breaks tend to have a service life of 20 to 30 years as per specifications of Dow Corning Corporation, 2016 a leading silicon sealant manufacturing company and studies conducted by Yu, Wen, Zhu, & Wei, 2011 about service life predictions of Neoprene at a regular temperature of 25oC. Materials such as Insulated glazing units have an end-of-service-life of about 25 years as determined by a study by T.Wolf, 1992. Aluminium profiles as such have an ESL period of up to 60 years (Y. Kim & Azari, 2012) whereas the cladding materials due to the plastic composites inside tend to last to 25 years (Llinares-Millán et al., 2014). To determine the service life of anchor bolts which are predominantly stainless steel the product catalogue of HILTI (a famous anchor bolt and construction material producer) was verified, and the results seem to inform that the bolts tend to perform according to the location where the product is installed. Since, here, the case is a mostly coastal area, the service life of the bolts drops to 25 years at most (HILTI, 2015). Similarly the product catalogue of Rockwool (a leading mineral wool insulation manufacturer in the region) was verified to extract 60 years (Rockwool, 2017) and finally, the EPDM gaskets have various life capacity based on application. Two papers researched in this particular aspect suggested that EPDM will tend to last up to 86 years in ideal lad conditions (Liu, Li, Xu, & He, 2017) whereas in practice the data suggests that the gaskets tend to last to only up to 30 years at the most before the need to replacement (Y. Kim & Azari, 2012).

Table 1.3.4 shows the ESL per component with references for ease of perusal, meanwhile Figure 1.3.5. Shows

Material	Service Life	References	Authors
Silicon	20 years	• Silicone Sealants Dow Corning ® 756 Sealant	• Dow Corning Corporation, 2016
	21 years	• Warrantee Issues and Sealant Service Life Warrantee Issues and Sealant Service Life	• UNIPRO, n.d.
Neoprene	30 years	• Service Life Prediction for the Neoprene Based on Tearing Strength	• Yu, Wen, Zhu, & Wei, 2011
Insulated Glazing Unit	25 years	• Studies into the Life-Expectancy of Insulating Glass Units	• T.Wolf, 1992
Stainless Steel	25 years	• Corrosion Handbook	• HILTI, 2015
Aluminum Composite Panel	25 years	• Construction and Building Research	• Llinares-Millán et al., 2014
Aluminum	60 years	• Comparative Assessment of Life Cycle Impacts of Curtain Wall Mullions	• Y. Kim & Azari, 2012
Glass Mineral Wool	60 years	• ProRox Product Catalogue	• Rockwool, 2017
EPDM Gasket	30 years	• Comparative Assessment of Life Cycle Impacts of Curtain Wall Mullions	• Y. Kim & Azari, 2012
	86 years	• Service Lifetime Estimation of EPDM Rubber Based on Accelerated Aging Tests	• Liu, Li, Xu, & He, 2017

Table 1.3.4: Materail based end of service life references
(Source - Author)

a graphical comparison of all the materials which with respective available service life in years. This chart is useful to determine the materials which need replacing constantly. As highlighted with red in the graphs, all materials which mature by the age of 30 years will cause a considerable reduction in the performance of the building envelope. The effects of which will be studied in later chapters.

Various studies from (Du, Wood, Stephens, & Song, 2015), (Barrington, 2018), (Durmisevic, 2006) predict that average service life of a building varies based on materials, local by-laws, type of construction and the expectations of the local government for the future of the neighbourhood where the building resides, although most studies confirm an average of 100 years-150 years of life of the building. Durmisevic, 2006 also went ahead to elaborate that the cladding of the building tends to last to up to 20 years and the interior fit-out tends to be changed every three years at an average. However, for the scope of this study, Kakolyri, 2015 has defined the average service period of the façade as 30 years.

This study hence urges an overview in the area of disassembly to allow future building operational teams to be able to access these selected materials and replace or service them as necessary.

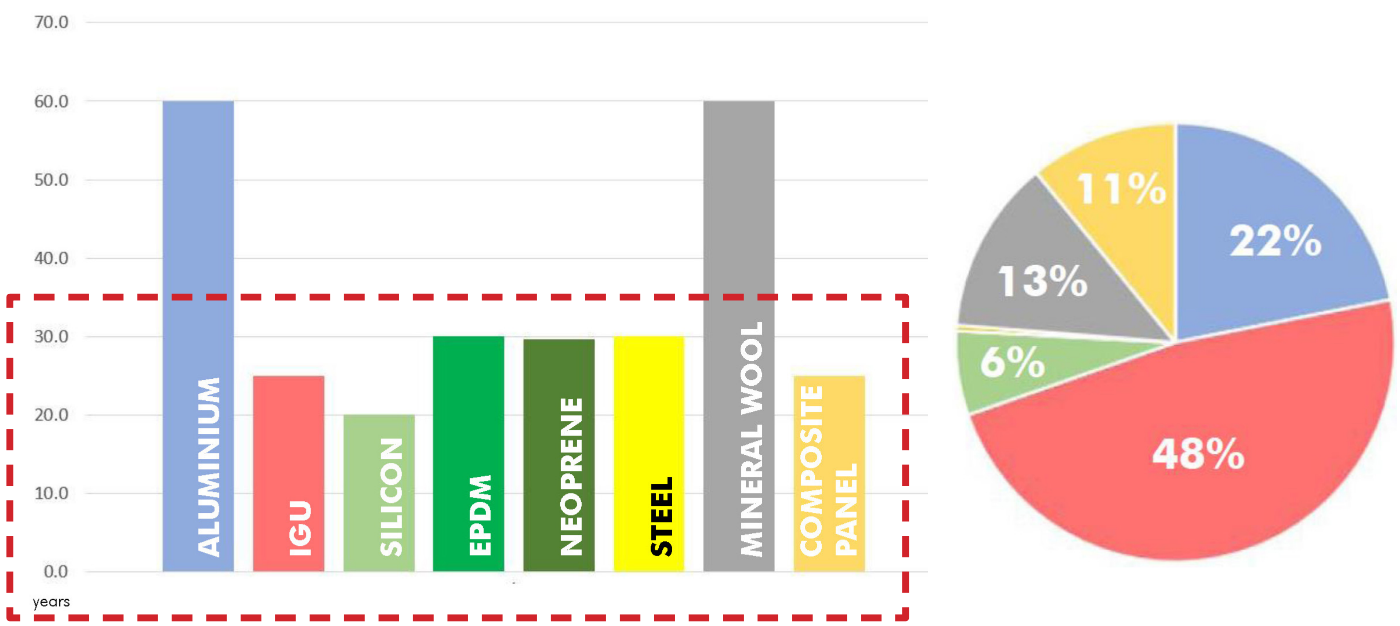


Figure 1.3.5: Material based end of service life references
(Source - Author)

The comparison of curtain wall facade system and its components with the average service life of building reveals the dissonance in expected functionality. An average curtain wall facade tends to last up to 30 years in its best performance, as stated above. However, with the building itself, the facade tends to only last to up to 1/5th of the entire life of the building. The causes of failure will be explored in later chapters. However, the premise remains that due to early failure of the facade and its components, the performance of the building is affected. An interview with a middle eastern representative from a popular aluminum extrusion company TECHNAL confirms that some aspects of curtain wall fail even before the standard ESL limit due to adverse weather condition (such as extreme temperatures differences between inside and outside, high salt content in the air, and high solar UV radiation which expedites the deterioration process overtime). Figure 1.3.6 shows a graphical comparison of the discussion above.

To conclude, due to the lesser ESL of the curtain wall in the proportion of the building (See Figure 1.3.7), Three main shortcomings can be identified:

- Firstly, the curtain wall facade needs to be replaced every twenty to thirty years based on the condition of its elements.
- Secondly, not all components (Such as aluminium, mineral wool and few others based on the design specifications) will reach its physical limit of failure and hence will be replaced before the expected ESL, causing significant material wastage. (Blue dots in Figure 1.3.7)
- Thirdly, The facade is mostly replaced at intervals when specific components may have already been dilapidated for a few years and could not have been accessed due to the composition of the construction. Hence, those components would contribute to the reduced energy performance of the building by increasing cooling loads, for example. (Red dots in Figure 1.3.7)

This study hence urges an overview in the area of disassembly to allow future building operational teams to be able to access these selected materials and replace or service them as necessary.

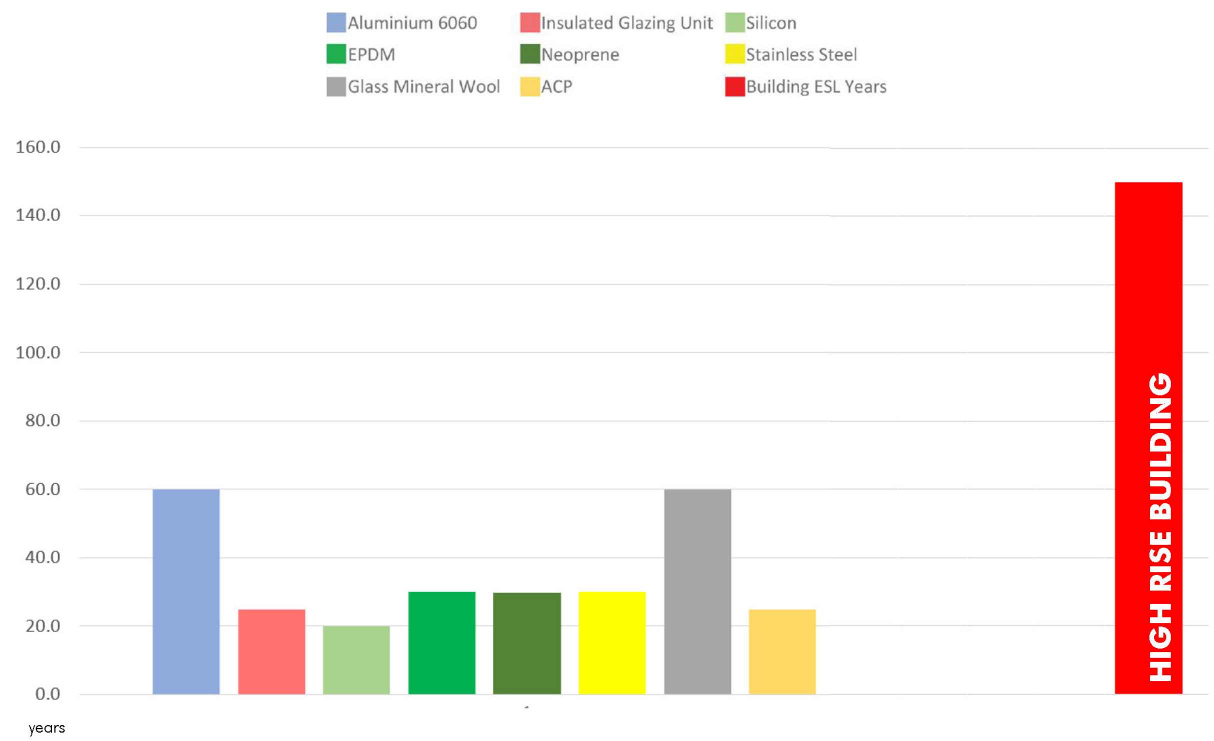


Figure 1.3.6: Material based end of service life references with comparison to a typical concrete highrise building (Source - Author)

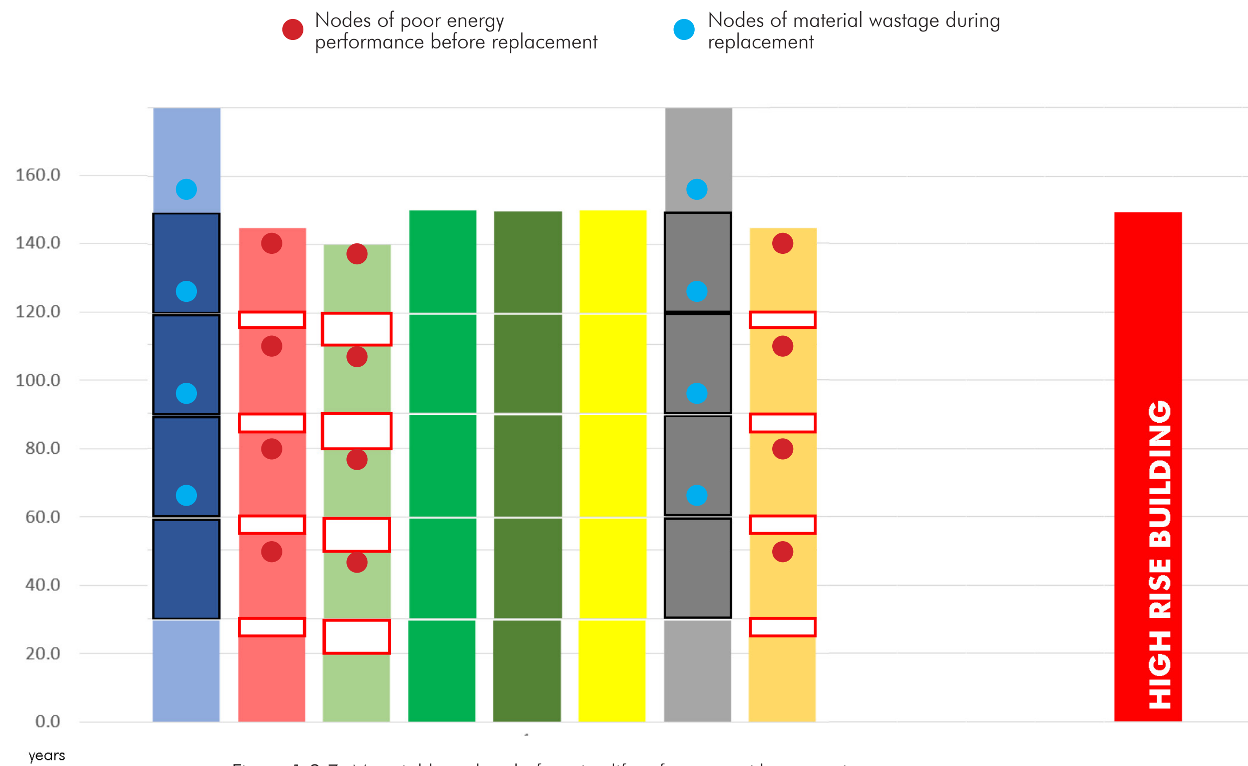


Figure 1.3.7: Material based end of service life references with comparison to a typical concrete highrise building (Source - Author)

1.4. Research Framework

1.4.1. Problem Statement

This research focuses mainly on identifying opportunities for the refurbishment of existing buildings using design for disassembly via the integration of various technologies/functionality.

The location this research mainly focuses on the city of Dubai, UAE, with too many tall buildings built during the developmental frenetic in the last two decades. The expedited development of the region was a direct result of a strategic decision taken by the rulers of the region to make the city an international quality tourism destination. (Smart Dubai Government, 2018). Many of the buildings constructed during this developmental boom have matured enough to about 20 to 30 years and with each passing day more and more buildings will age sufficienlty that their components will start to fail.

With sustainability in mind, the designed refurbishment must be able to solve aspects such as deterioration, material wastage, energy performances and many more. In term of energy performances, the demand for cooling is expected to increase by three folds in next 30 years, most if not all buildings in the warm, arid regions need to drastically improve their external surfaces to reduce the cooling requirements (Transition to Sustainable Buildings, 2013). Middle-eastern cities such as Dubai have a large number of buildings which are at a stage where their façade will reduce structural and energy performance in the coming decade.

These shortcomings give an excellent opportunity for introducing the Plug & Play façade system along with refurbishment strategies. These two strategies combined calls for a design for disassembly and can help reduce material wastage over the life of the building, improve energy efficiency, reduce the consumption of fossil fuels for powering the buildings.

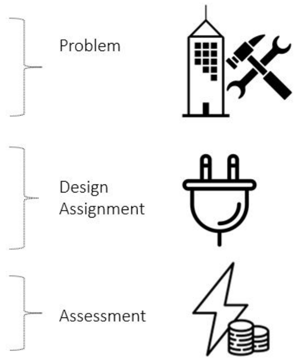
1.4.2. Research Question

A systematic approach for retrofitting and upgrading the existing envelops with systems that can reduce energy demands and use techniques to provide energy for operations will help to achieve greater energy efficiency and low-carbon emissions due to the facade. The research henceforth is based on a hypothesis that most if not all existing tall buildings in warm, arid areas need facade refurbishment. Moreover, the focus will be to investigate strategies to reduce the energy consumption of the building with a curtain wall facade system, using various passive and active strategies. Hence, the entire research is formulated to the following question;

How to sustainably refurbish facades of existing tall building

by creating a plug & play façade system which has integrated functionality

as part of value engineering



1.4.3. Sub Questions

The main research question will be answered through the following sub-questions:

1. How can we design panels which contain electrical components, that can be assembled and disassembled?
2. What amount of curtain wall material can be saved from wastage with the design for disassembly?
3. How to create a facade system which allows for access to different components with different service life for easy maintenance?
4. Identify strategies to improve the energy performance of the building and ensure that they are integrated along with the disassembly system and also estimate the amount of energy saving through integrated passive strategies.
5. How to integrate the BIPV system on the disassemblable and accessible facade system and what percentage of energy will the BIPV be able to contribute?
6. What materials, components, construction, and assembly system will help with the refurbishment?
7. When will the proposed facade system be able to break-even from an economic perspective? Is it possible that the proposed facade system pay off its own cost?

1.4.4. Methodology

To begin with the research, a specific case has to be identidied. The whole thesis is divided into five caregories literature study, evaluation, design phase, analysis and societal & scientific relevance.

1.4.4.1 Literature Study

This chapter consists of results from literature research identifying various parameters necessary for a prudent design. The literature research mainly helps in identifying the boundary conditons required for essential design practice in facade design, this characteristic can be assessed by identifying the current situation, systems and parts available in the market, performnce of each component, identifying the potentials tried and tested before, and ofcourse establishing a basecase. Literature study also explores concepts relevant to the research such as "Design for Disassembly"& "Plug and Play facade system". The study focuses on the key principles necessary to design such systems.

Apart from the relevant researches, literature study also covers market study and interview with market experts to understand the monetary aspetcs of the curtain wall facade system and the problems within the industry in various stages of the facades service life.

1.4.4.2 Evaluation

Post the data and knowledge collected from the research papers and surveys, the evaluation of the results is used to set the boundary conditions for the next stages of the research, Here in this section the premise is to tailor the boundary conditions to suit the project time frame and only focus on the main research question of the thesis. The evaluation phaze will identify the design brief, which will form the basis of design in the next stage.

1.4.4.3 Design Phase

After acquiring essential data from the literature study and the evalaution phase the formulated design brief will govern the final output. The design will be based on funtamental pre-requsites, the adopted strategies for innovation (essence of this thesis), and calculations (hand calculations and simulations) to predict the performance and the behavior of the design.

The next stage will be to intergrate the design back into the intervention case which will be explained in the coming chapter 1.6. Intervention Case. The design is mostly based in simulations and not on real time measurements and the softwares used for this study will be Design Builder and Grasshopper. In the conclusion cost, end-of-service life and energy performance aspects will govern the quality of the design.

1.4.4.5 Analysis

It is necessary to evaluate the design on pre-selected charasteristics, hence a classification is prepared of the aspects that will heavily influence the design output and its relevance in the industry. Since, the general background of this thesis revolves around sustainable refurbishment cost, end-of-service life and energy performance aspects were selected to evaluate the old and new design. These aspects will prove useful to determine if the proposed facade concept in this thesis will be relevant or not. Figure 1.4.1 oversees the proposed analysis method which is termed as the plug&play logic gate. The idea in a sentence is "If" "Refurbishment" is of "Curtain Wall Type" facade system, then "check" "Cost, End-of-Service Life, Energy Performence" markers to determine, "Yes or No" "Plug and Play System".

For the purpose of comparison a reference project was taken from the location where this investigation is held as mentioned above. The selected project was based on the parameters of availability of maximum solar radiation, availability of data, and refurbishment opportunity.

1.4.4.6 Societal and Scientific Relevance

As stated in the introduction, buildings account for 1/3rd of the carbon emissions, which is a big amount. This condition is aggravated in arid areas with warm climates. With large cooling demands for maintaining sufficient thermal comfort levels, almost all the buildings in this region require excessive mechanical ventilation, mostly throughout the year (Brittle, Eftekhari, & Firth, 2016). Moreover, according to a study by the United Nations, almost 60-70% of the people are going to live in cities, and most of the fastest-growing cities are in arid regions. (University of Georgia, 2006) moreover, the growing urbanisation trends project that high-rises will be the most ubiquitous

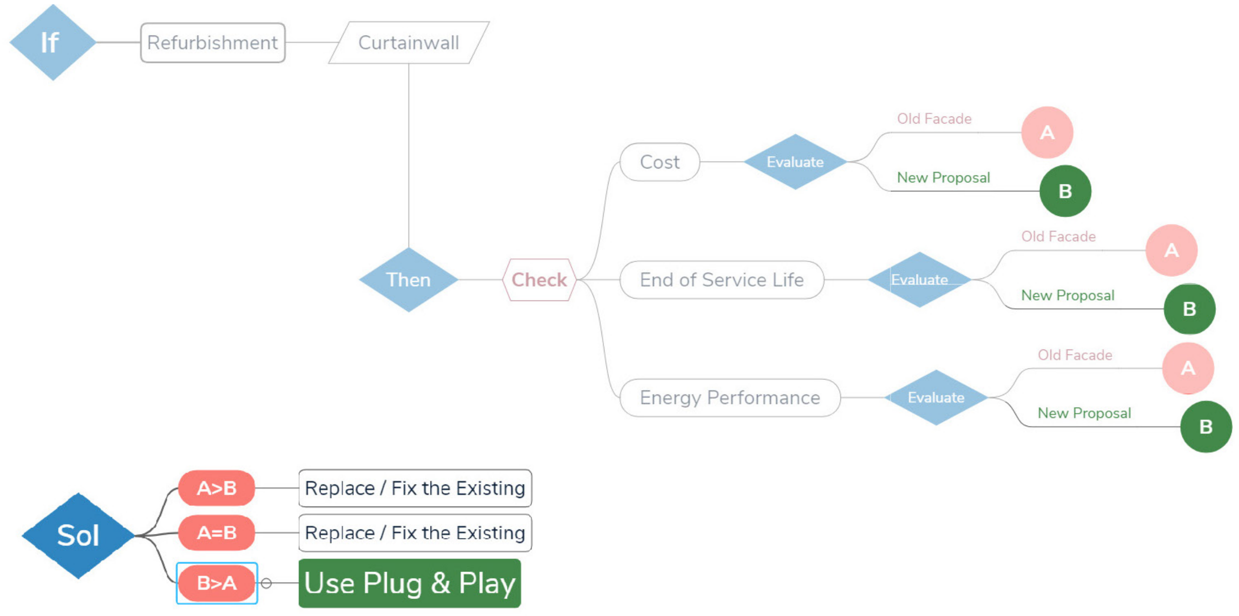
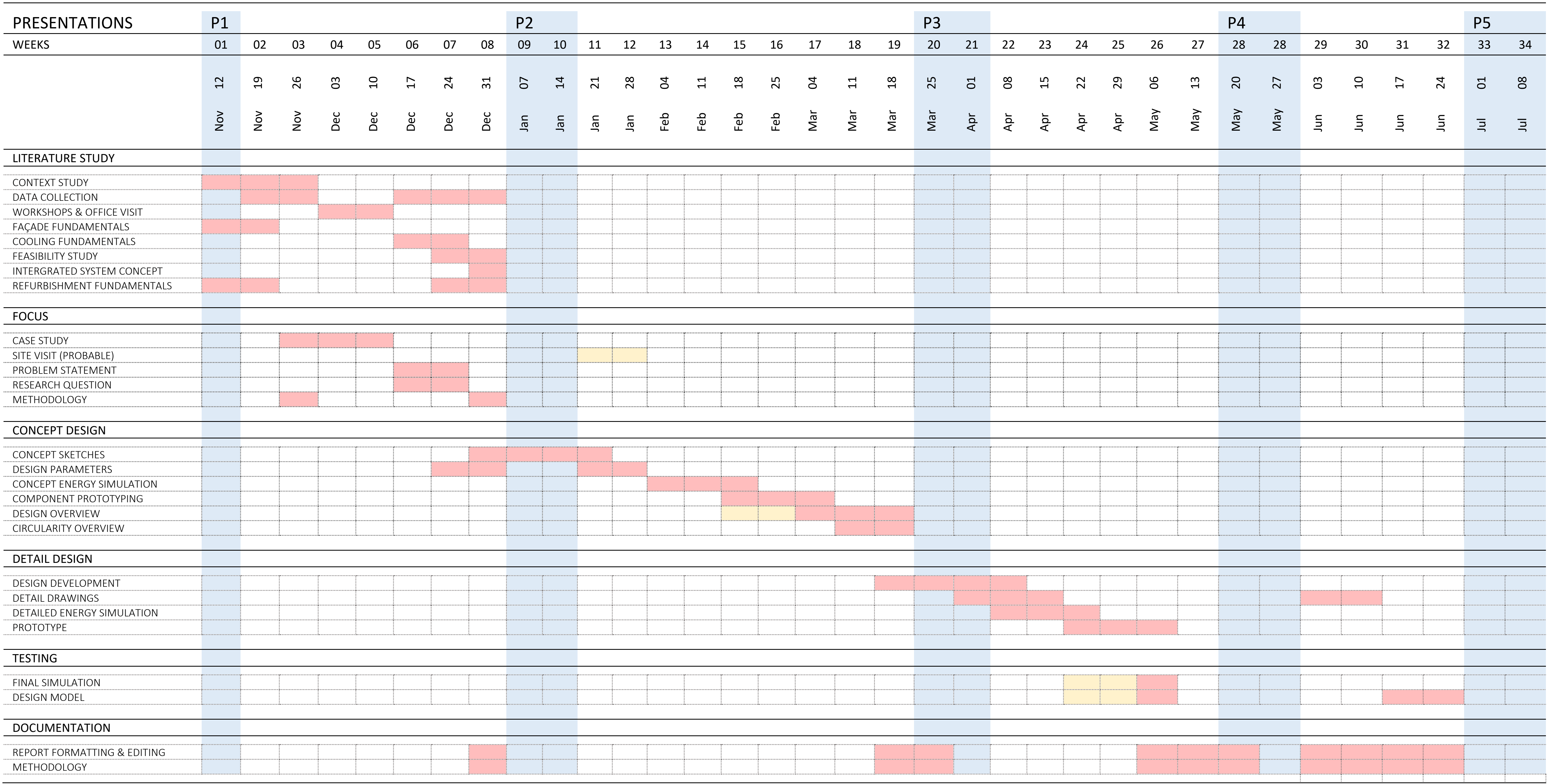


Figure 1.4.1: Research Overview (Source - Author)

choice since they occupy more people in smaller areas thus reducing the proximity to amenities and increasing the use of automobile ownership. This suggests that there is a definite niche in this area of study which needs to be explored.

The key goal of this research is to ensure a solution an ever-increasing climate change problem and test an idea of an innovative facade, which tries to solve most common shortcomings of a typical curtain wall facade. And, tries to improve the performance of the building and ensuring the factor of sustainability. The additional benefit of improving the envelope is that it will also reduce the number of materials wastage and equipment required for air-conditioning in the first place.

1.4.5. Graduation Project Timeplan



1.5. Methodology

The method followed in this thesis is to first evaluate the existing curtain wall system, understand the areas of improvement potential, then propose a system which addresses the identified shortcomings in the existing system. The deliverable of this research will consist of the design concept for a detachable/demountable façade plug & play systems (panel) which will contain contains Shading Devices, PV panels and exploration of various technologies which can be integrated as per the identified potentials. The thesis will elaborate on an existing case and tailor a Plug and Play facade design to be an alternative on an existing structure for replacing the existing curtain wall system. This document also comprises various necessary calculations, to evaluate the cost of facades (installation, seasonal maintenance and replacement), energy evaluation in comparison to the old and new facade to determine if the new proposal is feasible, and the end of service life. Evaluation of facade components will determine the possibilities of future refurbishments and bolster the argument towards a complete demountable.

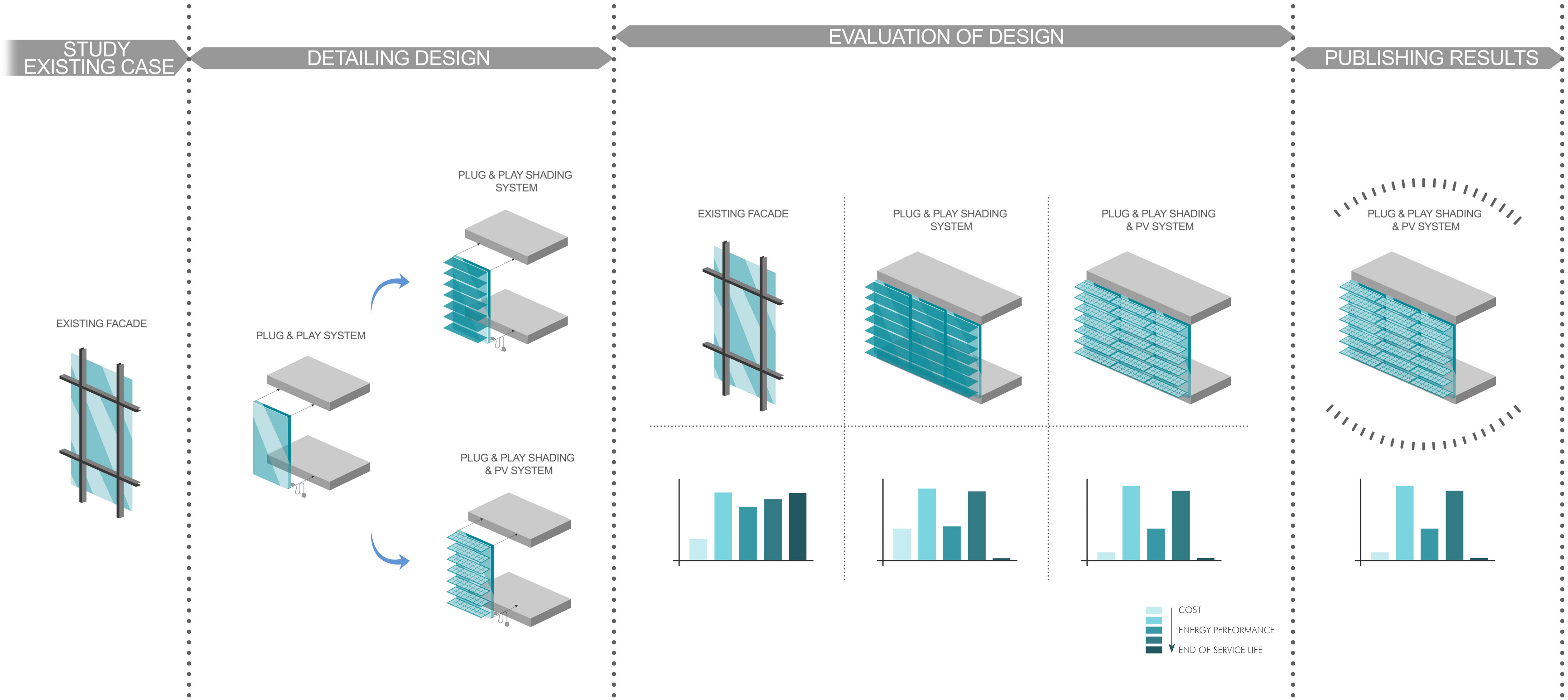


Figure 1.5.1: Research objective (Source - Self)

Figure 1.5.1: Research objective (Source - Self)

1.6. Intervention Case

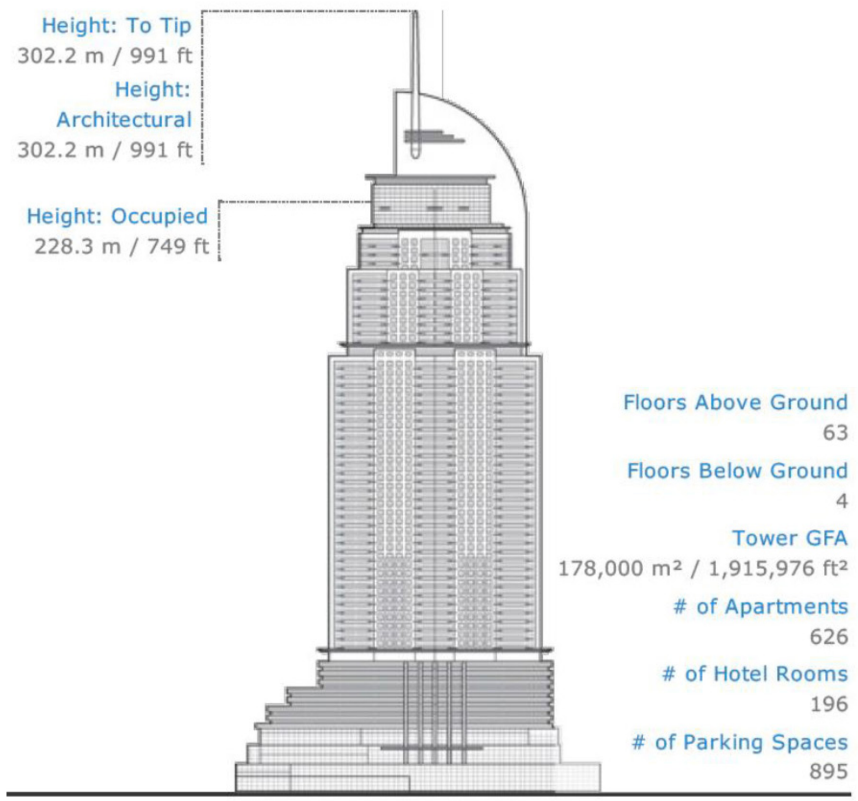
After contacting various companies for the data for studies, at present, the currently available data for the retrofit belongs to the Address Hotel, Dubai. The building is ideally located to the Burj Khalifa which is currently the tallest building the world as on January 2019, and it is adjacent to a major highway, a metro station nearby and predominantly would be serving and posh hotel for the tourists of Dubai in the downtown area. The building is oriented to the East-West direction, and the dominant side of the facade is facing the predominant wind direction (North-East). A large amount of Urban Heat Island effect is expected with all the hard surfaces, although the adjacent sizeable artificial lake of Dubai Fountains will provide a modicum amount of humidity in the air due to its microclimate.

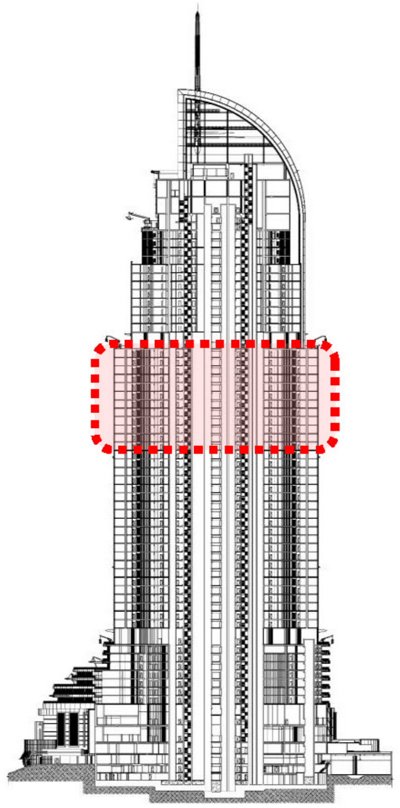
The available data for the Address Hotel Downtown Dubai, UAE, come from various property realestate websites and from the subcontractors website for the Project.

As for the case study, A typical floor plan and its section will be studied (See Chapter 3.3). The study suggests that the current facade system is a Curtain Wall hung from the edge of each floor slab. This gives sufficient information supporting Plug&Play refurbishment. Since almost all unitized pannels are wrapped over each other then its going to be difficult to sustainably remove few of them and maintain it. Hence, we may have to remove all the Curtain wall system during intervention and then the Plug & Play system can take over.

Figure 1.6.1: Location of the Address Downtown building Dubai, United Arab Emirates (Source - self)

Figure 1.6.2: Photograph of Dubai from top
(Source - Source – https://unsplash.com/photos/Fr6zexbmjmc)





Official Name	The Address
Other Names	The Address Downtown Dubai, The Address Downtown Burj Dubai, Burj Dubai Lake Hotel & Serviced Apartments
Structure Type	Building
Status	Completed
Country	United Arab Emirates
City	Dubai
Street Address & Map	The Address Downtown Dubai
Building Function	residential / hotel
Structural Material	concrete
Proposed	2004
Construction Start	2005
Completion	2008
Retrofit Start	2016
Retrofit End	2018
Rankings	Click arrows to view the next taller/shorter buildings
Global Ranking	#135 Tallest in the World
Regional Ranking	#30 Tallest in Middle East
National Ranking	#26 Tallest in United Arab Emirates
City Ranking	#22 Tallest in Dubai

Table 1.6.3: The address downtown building data dubai, united arab emirates (Source - http://www.skyscrapercenter.com/building/the-address/468) .

Floor Range		Number	Floor Type	Function	Service Area	Functional Area	Service Area Total	Functional Area Total
	63	1	Service Floor	Service	650	0	650	0
62	61	2			550	0	1100	0
60	58	3	Typical Floor Type 3	Standard Guest Rooms	250	950	750	2850
	57	1	57th Floor		250	950	250	950
56	49	8	Typical Floor Type 2		300	1100	2400	8800
	48	1	Service Floor	Service	1800	0	1800	0
47	15	33	Typical Floor Type 1	Residentail Apartments	450	1450	14850	47850
	14	1	Service Floor	Service	1800	0	1800	0
	13	1	13th Floor	Fitness + Spa	500	2200	500	2200
	12	1	12th Floor	Standard Guest Rooms	900	1800	900	1800
	11	1	11th Floor		900	1800	900	1800
	10	1	10th Floor		950	2350	950	2350
	9	1	09th Floor		950	2350	950	2350
	8	1	08th Floor		950	2750	950	2750
	7	1	07th Floor		950	3400	950	3400
	6	1	06th Floor	Lounge + Restaurant	700	2900	700	2900
	5	1	05th Floor	Lobby	700	4300	700	4300
	4	1	04th Floor	Car Park & Services	7100	2300	7100	2300
	3	1	Basement 1		6200	3900	6200	3900
	2	1	Basement 1		6900	3200	6900	3200
	1	1	Basement 2		6900	3200	6900	3200
		63			40650	40900	58200	96900

Table 1.6.4: Distribution of floor area per function with tentative approximation of functional areas (Source - self)

The hotel building itself is a 10 year old building, which requires a sustainable facade replacement due to the fire. The Table 1.6.4 shows the breakdown of all the floors of the building into functional floor space. It is noted that all the requirement here will be limited to only power the functional areas of the building and the results published in the future will only be based in percentage of power produced to the functionl floor area. On the other hand the overall surface area of the facade was extracted from a based model produced by the author based on the data collected as mentioned in this chapter above. The funtional area per floor is now known to be 2,745 sq.m and an approximate 7000 to 9000 panels (based in the facade panel width) will be used in the facade. Summary of results is shown in the Table 1.6.5. below:

Building Data	Typical Floor Area	2745	m^2
	Overall Floor Area	137250	m^2
	Surface Area of the Building	28,540,555,050.00	mm^2
		28,540.56	m^2
	Number of Panels (if Width is 0.9m)	9,910	nos
	Number of Panels (if Width is 1.2m)	7,432	nos

Table 1.6.5: Measurements from the building (Source - self)

1.7. Focus

Since the focus is on refurbishment, and the domain of the research still revolves around improving the energy performance of the existing building stock in Dubai, United Arab Emirates. Since we are going specifically to the context of tall buildings in Dubai, the focus will be particular to the range of refurbishment possible within this domain. The premise of refurbishment particular to this context will be because, as discussed before almost all tall buildings have a structural life of 120 years and this service life of the buildings can be pushed furthermore depending on maintenance and regular refurbishment. This process becomes quite necessary because just like anything else in the world, buildings are subjected to natural ageing and due to that all components dilapidate overtime. This natural ageing process is inevitable and over time causes materials and components to perform poorly in tasks they are supposed to do for the building. The performance decrease can occur in various ways, such as structural failure. When concrete, or the metal bars or the fixtures corrode or break due to thermal expansion and contraction, UV radiation from the sun, humidity, salt deposition, dust or debris, accidental damages caused by the occupants during use over time and many more such damages (see Figure 1.7.6). Apart from structural failure almost all soft materials such as gaskets and joints and sealers eventually fail aggravating air leakage, moisture penetration, acoustical apertures which are all considerable inconveniences and will directly affect the energy performance of the building. Because in order to compromise these damages, the occupants will ideally increase their reliance on air conditioning, lighting and maintenance systems. As a result of this depreciation of structural integrity and increased energy use, the regular maintenance cycles will also have to be increased, which can turn out to be an expensive process in general.

Newer codes are also a good cause in favour of sustainable refurbishment. As the building's age and society progresses, there is always newer codes or regulations which are stricter and aligned towards a sustainable future. And not to mention the vast amount of technological progress which comes in every year. If we

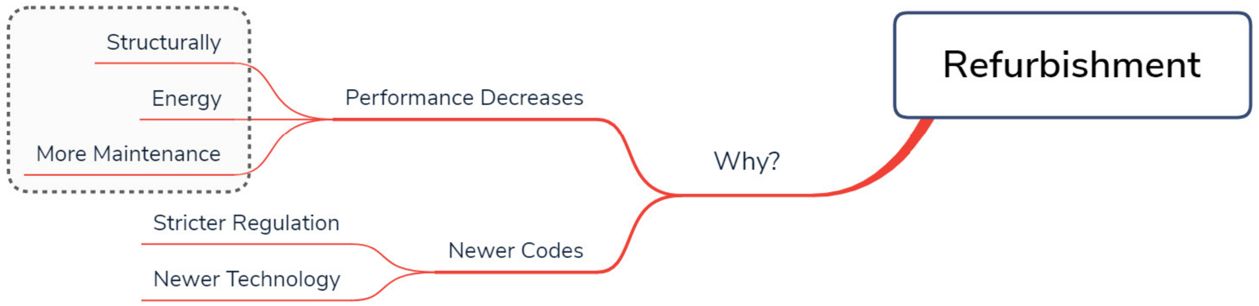


Figure 1.7.1: Mindmap - Refurbishment (Source - Self)

compare, This means that it would be ideal if the building can adapt to these changes (See Figure 1.7.1.) while saving energy and providing opportunities for easily upgraded refurbishment in the future.

As mentioned in Chapter 1.6. Intervention Case, we can already determine that the facade of the Address hotel is going to be refurbished. Also, the scope of refurbishment will be elaborated based on the situation of the facade and the design of the building.

As shown in Figure 1.7.3., the building which is going to be intervened for the scope of design of this thesis caught fire in the New Years Eve of the Year 2016. This fire was a great tragedy for the city, although there was no-one killed due to the accident, a couple of the occupants were injured. Anyhow, after the accident, the Government of Dubai had strict policies against the use of Aluminum Composite Panels (ACP) for the buildings in the region. This regulation meant that many developers, architects and contractors had to redesign facades to eliminate or remove ACP panels from their buildings.

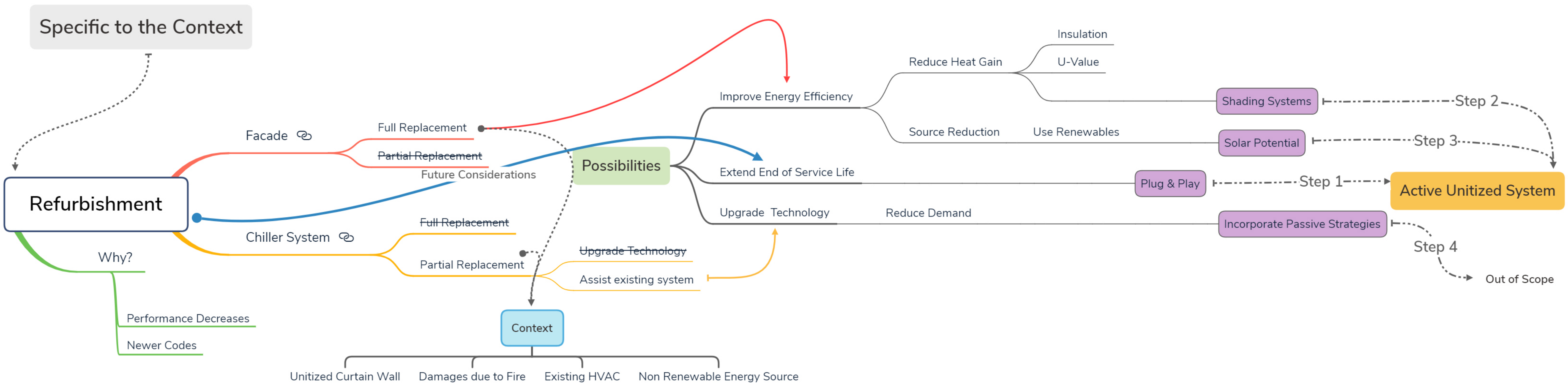


Figure 1.7.2: Research Storyline - Mindmap (Source - Self)

The case mentioned above can be a keystone project for an era of the sustainable redevelopment as the action required is immediate. However, a building does not have to wait for fire or any other accident to help trigger a mandatory refurbishment regime. The mind map shown in Figure 1.7.2. shows an overview of how this particular case can be refurbished. The refurbishment for this case or for any existing building in terms of improving energy performance can happen either in Upgrading the existing chiller system or by Improving the facade system.

Figure 1.7.3: Fire in Address Hotel Downtown, Dubai
(Source - https://giphy.com/gifs/fire-dubai-lapse-Jst1zdjaoUEDK)

1.7.1 Chiller System

Let us consider the chiller system first for this case or for any existing tall building. Full replacement of the entire system is not a very feasible option. Because, the whole building is designed to have an HVAC system of a certain kind as part of an air distribution system. This means that the rooms as per the floor plan are rigid and the central air distribution system can only ventilate them as intended through an MEP design. This is also an expensive infrastructure and removing them is an larger headache due to its complexity. The whole system is merged with the architecture of the building by design and share many connected programmes related to fire and smoke strategies. Its only wise to keep the system and maintain it to upgrade the equipment rather than to just remove the whole thing. The best option at the moment is to reduce its energy consumption by either upgrading the equipments to greener more efficient devices or by reducing the energy load on the system itself.

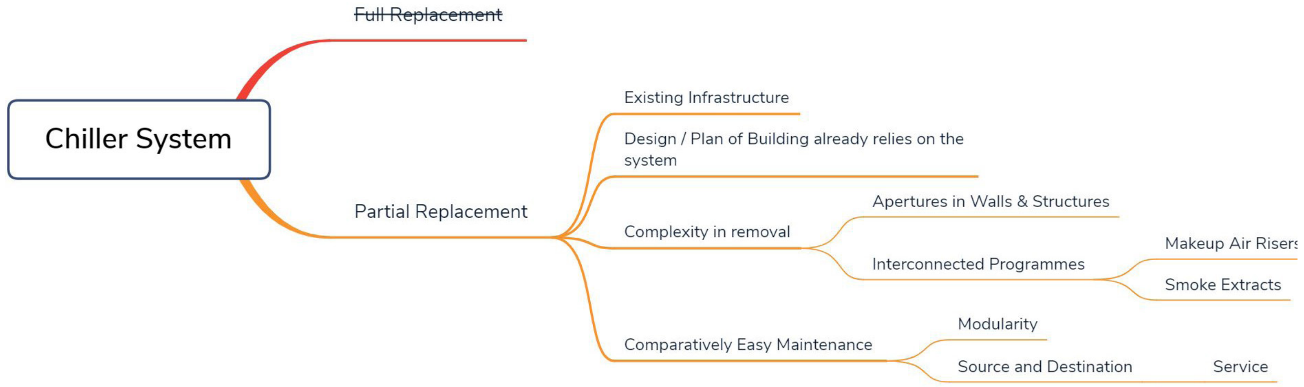


Figure 1.7.4: Mindmap - Chiller System Refurbishment Options (Source - Self)

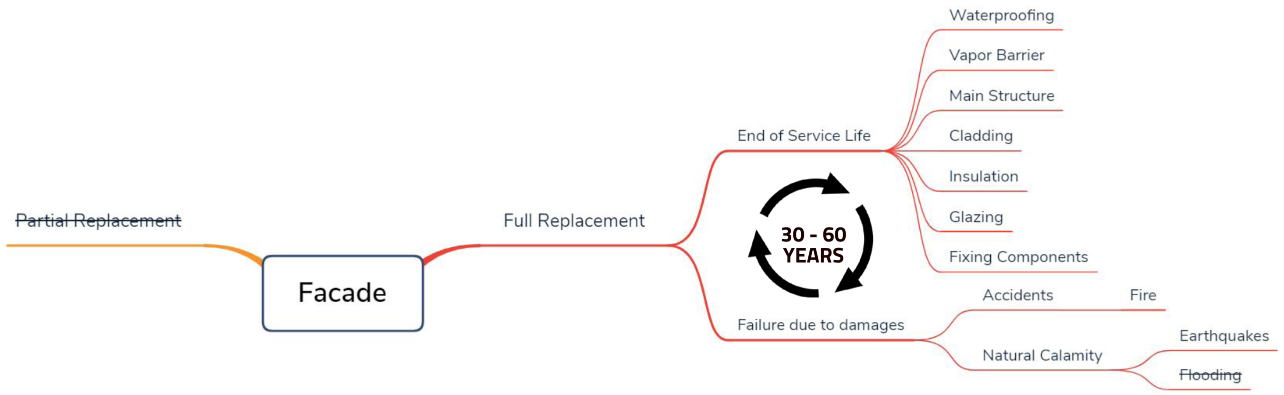


Figure 1.7.5: Mindmap - Facade System Refurbishment Options (Source - Self)

1.7.2. Facade System

As for the Facade of the particular case of Address hotel or an existing building with curtain wall system a Full replacement seems more viable due to the End of Service life limit explained in Chapter 1. Life of Facades. The facade either when it is damaged or when it is nearing the end of service life of its components will definitely perform poorly. A full replacement is an opportunity to improve its existing condtion and then use that opportunity to actually create a system which will reduce the burden of constant refurbishment every 30 years. Ideally curtin walls are very hard to refurbish as they have to be stripped out and then re-assembled completely during the time of refurbishment. Which not only is expensive but also quite unsustainable. Hence, the opportunity here is to once refurbish with a modular facade system which after the intervention can be maintained individually, and without heavy scaffolding, or Building Maintenence Units (BMU's) and also use an system which can possibly improve the energy performance of the building. Hence this is not just about making the refurbishment easy in future but also prolonging the Life of the facade and improving the energy performance of the building over time.

Image 1: Chalikng and molding

Image 2: Dried and damaged butyl on IGUs

Image 3: Dried and damages gaskets

Image 4: Damaged vapor barrier

Image 5: Condensation

Image 6: Salt Deposits

Figure 1.7.6: Causes of curtain wall facade failures (Composition - Self)

(Source - Image 1 - https://www.constructioncanada.net/condensation-on-curtain-wall-surfaces-an-investigation/
Image 2 - https://www.pladurbilbao.com/es/producto/placa-de-seguridad-carga/
Image 3 - https://glassmagazine.com/article/commercial/curtain-wall-cautions
Image 4 - McFarquar, 2012
Image 5 - https://curtain.tunder.org/curtain-wall-spandrel-insulation/
Image 6 - http://lugezi.com/images/)

1.6. Restrictions

The most common discussion with related to energy refurbishment of existing buildings is that the methodologies and simulations can only predict the results. The actual results can only be achieved with an iterative process of re-evaluation of the applied strategies. Buildings do not perform in real life in comparison to when it is simulated in computer models and calculations. Even after using very precise tools and measurements and modelling the structure to the finest detail still, there will be various anomalies which cannot be foreseen currently. This is referred to as 'performance gap' by the scientists. One of such examples is performance failure due to the ageing of materials and constructed elements; another one could be the influence of human behaviour within the building (Motuziene & Vilutiene, 2013) (Konstantinou, 2014).

Based on a study by Haas, Auer, & Biermayr, 1998 and as explained in the doctoral thesis by Konstantinou, 2014 it has been observed the service demand is higher, and that refurbished buildings show a performance gap of 15 to 30% which concludes to an interpretation that the energy savings achieved is lesser from predictions to practice.

02
FRAMEWORK

"How to sustainably refurbish existing tall buildings in UAE by creating a plug & play façade system which has integrated passive cooling and energy production strategies – specifically shading devices & PV panels - to reduce energy consumption required for cooling?"

~Research Question
-Author

2.1. Sustainable Refurbishment

Sustainable refurbishment is an intervention to improve existing building stock and reduce their environmental impact using sustainable materials and refurbishment methods. Sustainable refurbishment is equivalent to sustainable development for new cities and industries. (Various, 2018b)

The premise of sustainable development revolves around the following;

1. reducing the energy consumption of the existing buildings,
2. installing renewable energy sources,
3. measures to reduce utility consumption,
4. reducing waste and recycling,
5. reduce the overall carbon footprint caused due to activities during the refurbishment.

The relevance of sustainable refurbishment is that most of the world is built, and the majority of the buildings are being used. Newer standards with stringent environmental regulations are, of course driving the developers and designers to comply with the code for new buildings. But, for the buildings from almost around half a decade ago and older, who are not designed to meet these standards, sustainable refurbishment is the ideal way to improve their situation. (Various, 2018b)

Sustainable refurbishment is becoming more popular because of current concerns due to high energy use and related carbon emissions, which is leading to global climate change. This strategy becomes quite relevant when discussed in the context of the posed construction boom in middle-east and the ageing buildings. The focus of the research hence is to use this concept to refurbish existing facade systems sustainably. By, not just improving the energy efficiency of the building but also extend its life span as much as possible to reduce its impact on the environment and lower the expenses. (Various, 2018b)

2.2. Facade Refurbishment

Building envelopes are the primary source of air-ingress any building. Moreover, the older the building, the higher the possibility of air ingress through the envelope. Large amounts of cooling-load can be reduced efficiently by improving the façade elements of any existing building envelope. Figures 2.2.1 and 2.2.2 shows how a curtain wall facade is constructed by placing unitized panels carefully, but it is not the same during demolition. The pieces are stripped apart for quick and easy demolition, which causes heavy material wastage and is not a sustainable practice to begin with.

To get to a point where we have a sustainable existing building stock, this thesis proposes a refurbishment design strategy, which is analyzed, evaluated, and an integration strategy is proposed. The result of the proposal will allow designers to make prudent refurbishment decisions by comparing the Cost, End of Service life of materials and Energy Performance of the building.

Building envelope refurbishment if executed, must be able to improve the energy usage, comfort, safety, health and durability of the building (Jha & Bhattacharjee, 2018). Now, apart from these essential functional prerequisite aspects, the function of façade refurbishment can also be extended to improve the energy performance of the building and in turn the neighbourhood by integrating technical building components such as BIPV (Building Integrated Photo Voltic's), Air Conditioning Systems, Shading Systems, Functional Feedback Systems, Maintenance Reduction Design, and use of design based circular construction concepts.

Figure 2.2.1: Curtain wall assembly during construction
(Source - https://www.maedausa.com/mini-crane/mc285-2-curtain-wall-installation-13433570753-o/)

Figure 2.2.2: Curtain wall demolition
(Source - https://glazingrefurbishments.co.uk/services/demolition-glass-removal/)

2.3. Curtain Wall Systems

Curtain wall systems consist of many materials and components which come together to form the whole system. Although this research is limited to understanding unitized curtain wall systems, it is essential to understand all the standard components in the system.

The system ideally consists of the following components:

Aluminum Profile: Although there are many variant alloys of aluminium available, the most commonly used aluminium alloy for evaluation as per this research is Aluminum 6066. They are manufactured through an extrusion process.

Figure 1.4.a: Sample aluminium extruded profile
(Source - http://www.aluminumextrusion-profiles.com/sale-9916717-aluminum-window-extrusion-profiles-sliding-glass-door-channel-door-bottom-twin-track.html)

Insulated Glazing Unit: IGU's occupies the most material used in the curtain wall system. Is familiar and preferred because of its transparent optical quality, weather and abrasion resistance. A specific arrangement of glass panels with spacers and specialist gas can also provide thermal comfort. The arrangement of IGU's mostly consists of two or more panes of glass varying from the thickness of 3mm to 12mm, and in some instances, two pieces of glass are stuck together with an interlayer for improved structural capacity.

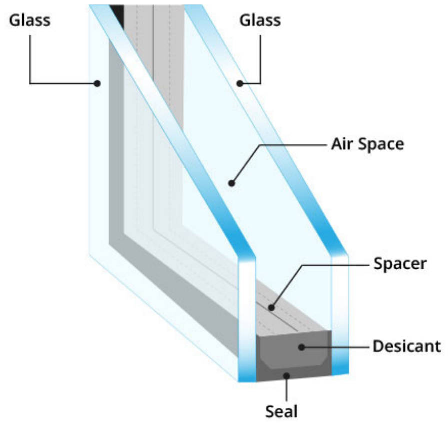


Figure 1.4.b: Component breakdown in an Double Glazed Unit
(Source - https://odg.onedayglass.com/windows/insulated-glass-unit)

Mixed Plastics: Mixed plastics vary in function based on the location where they are used, some are used for sealants others as gaskets, and some serve a primary function of thermal barriers to avoid the heat from flowing from the hot part of the facade to the colder part. All together are essential for making the envelope air-tight, watertight, vapour proof, and reduce the heat transfer.

Figure 1.4.c: Sample image of EPDM gasket
(Source - https://www.wis-ltd.co.uk/dry-glazing-epdm-gasket-688-p.asp)

Metal Connectors: Metal connectors include screws, bolts nuts, anchor units and many more. These units connect the facade structure to the edge of the building and sometimes are used to connect panels to the profiles. It is considered safe design when metals are not mixed or have minimum to less contact with different metals due to stray current corrosion. This problem can again be solved by introducing plastic gaskets between the areas where the metals may meet. The metals used here are preferred to have high corrosion resistance and can withstand shear failure.

Figure 1.4.d: Sample image SS anchor bolt
(Source - https://www.amazon.in/Plated-Anchors-Threaded-Expansion-Variable/dp/B07BXHFRZQ)

Insulation: Insulation materials such as mineral wool, extruded polystyrene, vacuum insulated panels, aerogel insulation etc... are all available in the market. They are used based on location, availability and cost aspects. The most commonly used insulation material in the industry at the moment is rockwool or extruded polystyrene, rock wool is more preferred in the facade area due to its capacity to withstand fire longer than usual having a melting point to up to 1177°C (Rockwool, 2017).

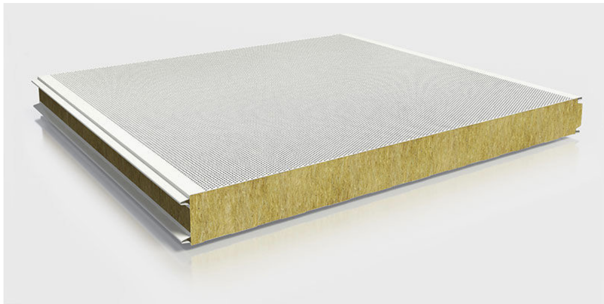


Figure 1.4.d: Sample image SS anchor bolt
(Source - http://www.archiexpo.com/prod/roma-daemmsysteme/product-146077-1555749.html)

Cladding: Cladding materials are opaque panels made of composite materials which could consist of aluminium composites, stone laminates, durable wooden panels or any opaque sheet material as required by the specifications of the design. Although, it is common in practice to use materials which are not combustible and can withstand fire propagation and must comply with fire classification ranging from A1 to D in accordance with European Standards EN-13501-1 and the requirements of the local fire protection code by the concerning municipality.

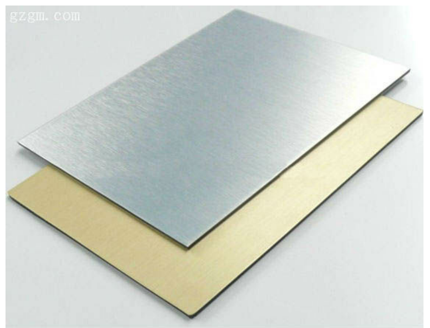


Figure 1.4.e: Sample image of ACP
(Source - https://www.okorder.com/p/size-5mm-aluminium-composite-panel-acp-sheet_399641.html)

2.3.1. Stick Curtain Walls

A stick built curtain wall is a curtain wall system which is assembled on site. The manufacturing factory delivers individual components; such as glass panes, mullions, spandrels and cladding. The construction workers then assemble the façade directly on the naked building. This system requires skilled construction workers and has higher installation construction costs. Sometimes this coordination causes quality control issues. ("Glass Curtain Wall Installation," n.d.) (Knaack et al., 2007)

2.3.2. Unitized Curtain Walls

A Unitized curtain wall system is a modular system which is made of large panels of glass, spandrels, and mullions. The panels are assembled in the factory and hence, reduce the construction time on site and which means fewer skilled laborers can get the job done. Each panel is typically almost a story high and are lifted to their intended position and fixed to the slab edge by the construction workers. ("Glass Curtain Wall Installation," n.d.) (Knaack et al., 2007)

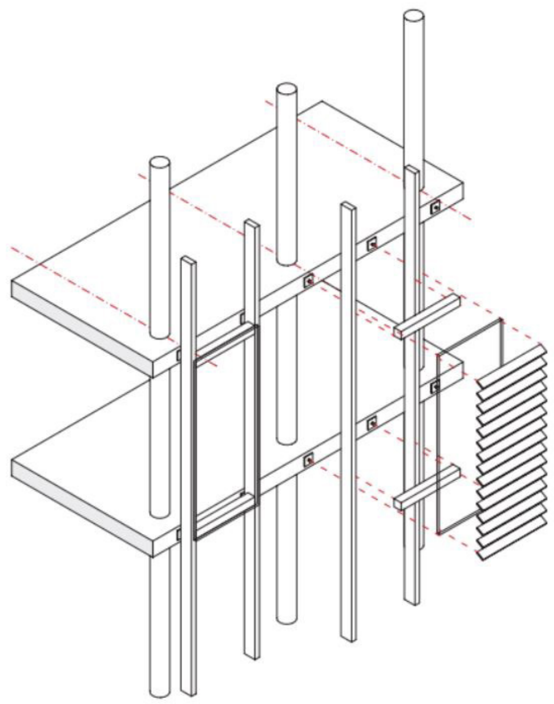


Figure 1.4.g: Diagram of Stick Curtain Wall System (Source - Knaack et al., 2007)

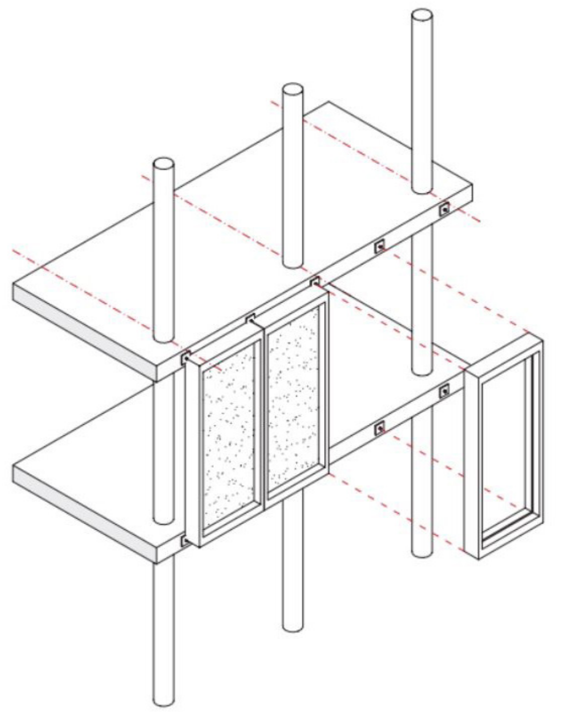


Figure 1.4.g: Diagram of Unitized Curtain Wall System (Source - Knaack et al., 2007)

2.4. Multifunctionality

Curtain wall facades usually do not have any load bearing capacity and are mostly designed to as a protective membrane separating the inside and the outside along with heat protection and acoustic insulation. The significant advantage of curtain wall facade system, as discussed in Chapter 1.3 is that it allows for pre-fabrication in comparison to other conventional facades and dramatically reduces the installation time.

As is the case with any building envelope, the primary function of the facade is to protect from the weather and climate-related elements. However, as technology progresses, the discipline of facade engineering also has to a greater extent improved and now allows for fire protection, humidity control, glare protection, daylighting and overtime has a vast array of increasing functions. The multifunctionality aspect enables facades to assume newer technologies within its domain and hence either reduce the complexity of separate building integrated systems. Facades have over the years adopted an ample amount of strategies to reduced materials in construction, and careful facade design can help abate just that.

Energy supply to existing building till date comes from non-renewable sources of energy (Mach, Grobbauer, Streicher, & Müller, 2015). As a result of climate change cost of fuel and material have increased and the resulting environmental factors such as carbon emissions, material wastage etc… are a force to reckon with at the moment. Studies from (J. J. Kim, Jung, Choi, & Kim, 2010), (Roberts & Guariento, 2009) have confirmed that BIPV technology can hold the key to sustainable renewable energy for buildings of the future. The opaque areas of façade surfaces which are mostly unused can be used to harness massive amounts of energy from renewable sources such as thermal energy, photovoltaic energy and maybe even wind energy (depending on the scale and size of the building), these sources when connected to the power grid can offer solutions making the building more self-sufficient (Mach et al., 2015).

A noticeable requirement of the building envelopes is to mitigate indoor environment to comfort levels of the occupants living inside the designated space. Space needs to be air-conditioned (cooled or heated/humidified or dehumidified), illuminated, monitored, powered etc… with each requirement comes an ancillary system to perform the required function. Such as HVAC system, Lighting system and controllers, security cameras, and even solar collectors. Each function is performed by a different system all coordinated by specialists of each industry and then built on site by the designated contractors and sub-contractors. A multifunctional façade may be able to incorporate few if not all the above-mentioned aspects within its capacity to shift the technical building facilities from indoors to outdoors. (Mach et al., 2015)

Figure 2.4.2. by Mach, Grobbauer, Streicher, & Müller, 2015 elaborates on functions which conventional facades can do and also proposes potential function which a proposed facade system could do. The extended functionality will increase the interactions a built environment could have with a building envelope, but it also means that the technical complexity of the construction of the facade will also increase.

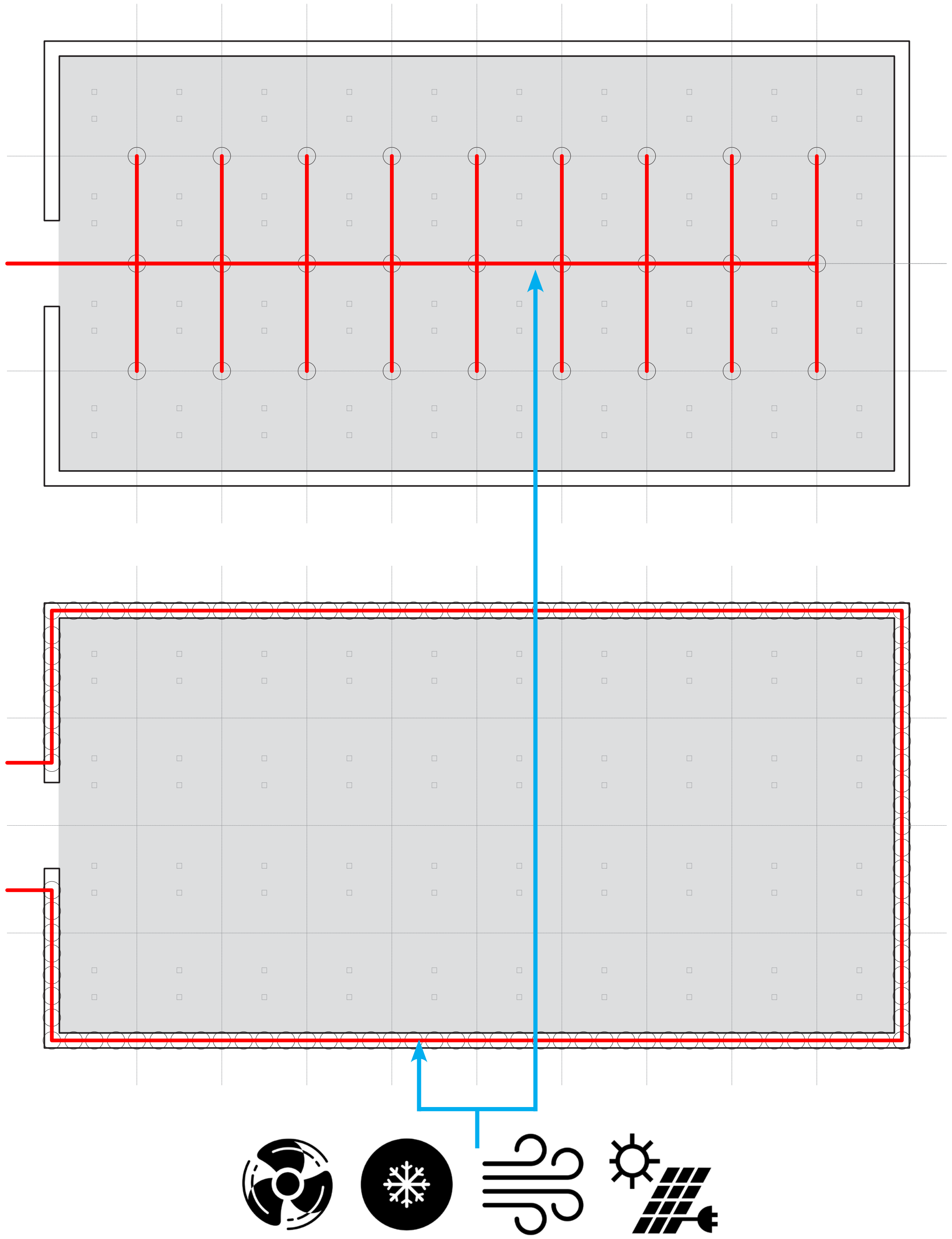


Figure 2.4.1. Shift of technologies from inside to the envelope
(Remake source - Author) (Original extract from: Mach, Grobbauer, Streicher, & Müller, 2015)

basic function		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
structural	1	■	●	●	●	●	●	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○
illumination	2		■	●	●	●	●	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○
thermal insulation	3			■	●	●	●	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○
acoustic protection	4				■	●	●	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○
humidity protection	5					■	●	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○
fire safety	6						■	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○
surge protection	7							■	●	●	●	○	○	○	○	○	○	○	○	○	○	○
fresh air – supply/return	8								■	●	●	○	○	○	○	○	○	○	○	○	○	○
glare protection	9									■	●	○	○	○	○	○	○	○	○	○	○	○
visual communication	10										■	○	○	○	○	○	○	○	○	○	○	○
energy gaining												○	○	○	○	○	○	○	○	○	○	○
solar thermal	11											■	○	○	○	○	○	○	○	○	○	○
photovoltaic	12												■	○	○	○	○	○	○	○	○	○
supply function														○	○	○	○	○	○	○	○	○
mechanical ventilation	13													■	○	○	○	○	○	○	○	○
heating	14														■	○	○	○	○	○	○	○
cooling	15															■	○	○	○	○	○	○
humidification	16																■	○	○	○	○	○
dehumidification	17																	■	○	○	○	○
electricity	18																		■	○	○	○
artificial light	19																			■	○	○
communication	20																				■	○
safety monitoring	21																					■

● interdependencies ○ added interdependencies

Figure 2.4.2. Consistancy matrix for facade functions and potentials for multifunctional facades
(Source - Mach, Grobbauer, Streicher, & Müller, 2015)

Mach, Grobbauer, Streicher, & Müller, 2015 also elaborate that few of the functions may have small negligible effect incorporating some of these technologies may crucially impact the performance of the building or its impact to its surroundings. The research also states the reciprocal factor where functions such as cooling, heating, will have an inverse effect when linked with thermal insulation systems. As the better the insulation the lesser the demand for cooling/heating systems. Similarly, the ideal combination of the window to wall ratio (WWR) can provide sufficient illumination to reduce the lighting. This means that it is considered ideal for pairing up the functions to avoid redundancy in the design of systems. This superimposition will be a primary premise during the design stages of the system.

2.5. Plug & Play Facade Systems

Plug & play is a term which is quite popular in the computing industry, which ideally means that specific devices or updates can be added to an existing system, without the need for manual intervention. PnP offers a high level of prefabrication compared to conventional façade system.

Plug & play in simplest terms can be defined as a feature of a system that allows an electronic device to be used as soon as it is connected. This technology is mostly used in the IT industry where access and performance of modern computers can be enhanced by adding additional devices to the existing system (See Figure 2.5.2)

The benefit of this system is that the designer or manufacturer does not always have to design and integrate all the components into the device during its development. Instead, they tend to make provisions for future own or third-party enhancements to be added to the system during its life in use. Another benefit of this system apart from easy attach-ability or detach-ability is that the owner gets an option to customize the devices they want for their use instead of taking a package tool which they may not use at all.

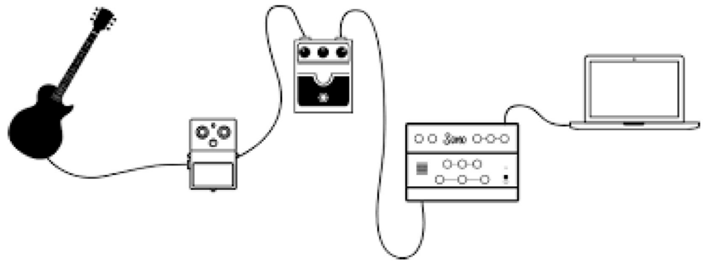


Figure 2.5.1: Analogy of Plug & Play
(Source - https://www.taiwanaccess.com.tw/products/audient-sono)

Figure 2.5.2: Logo of USB devices, But universally known as Plug&Play icon
(Source - https://www.brandsoftheworld.com/logo/usb)

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Keeping this in mind many research facilities and organizations in the world are testing if this technology can be used in the building industry (especially facades). One such system is the MPPF system under development by researches in TU Graz called as the K-Projektes Multifunctional Plug&Play Facade (Streicher, W., 2008). This research focuses to develop and test intelligent facade systems with multifunctional components such as shading system, Building Integrated Photovoltaic (BIPV), Services and Building Maintenance Systems (BMS) etc... The benefit of this system is that it has high prefabrication rate and can provide improved energy

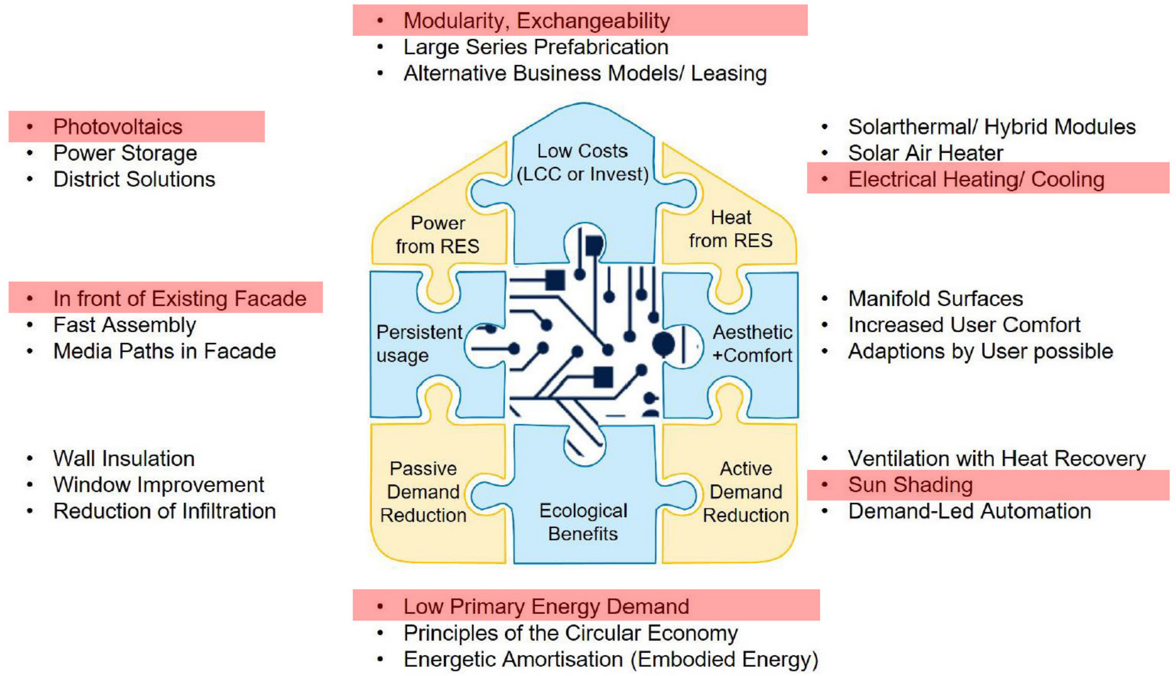


Figure 2.5.3 Elaboration of Plug-N-Harvest approach (Source - Dannapfel, Osterhage, & Klein, 2018)

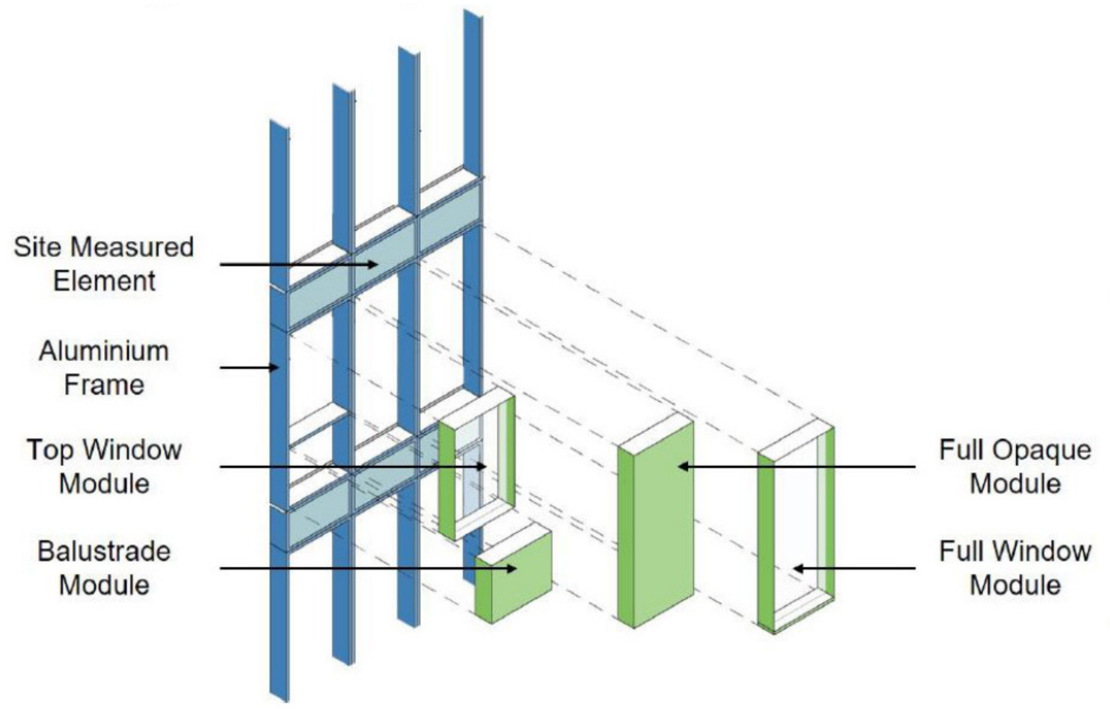


Figure 2.5.4: Construction of Plug-N-Harvest modu (Source - Dannapfel, Osterhage, & Klein, 2018)

performance for both old and new buildings. The research is still young and the researches are still trying to solve engineering aspects such as static, humidity, transport, energy, acoustics, shading, cost etc...

Another popular concept under development is called Plug-N-Harvest: A modular facade system, which is funded by EU and the main focus is also to refurbish or retrofit existing facade (Dannapfel, Osterhage, & Klein, 2018). Plug-N-Harvest and MPPF both have similar goals and try to use the same set of technology to improve the modularity, replicability and improve the energy performance of the building. These studies will a strong basis for the development of this thesis.

The primary ability of any plug and play is that each functional construction can be attached a detached non-destructively (See concept Figure 2.5.5) This allows for complete removal and replacement of panels during the utilization phase (See Figure 2.5.6). Another nomenclature for the same concept could be "unplug & replay " (Mach, Grobbauer, Streicher, & Müller, 2015. Which as it sounds means that facade panel can be removed from a grid of panels and replaced whenever the requirement arises. The need to replace could be determined by technical failure, poor performance, seasonal maintenance, or replacement of components which have reached their service life maturity.

Plug&Play does not necessarily need to be defined by the entire facade panel, it could be a functional part or even parts of the construction of the panels. The benefit of this system is that failed or matured components can be exchanged for a practical alternative.

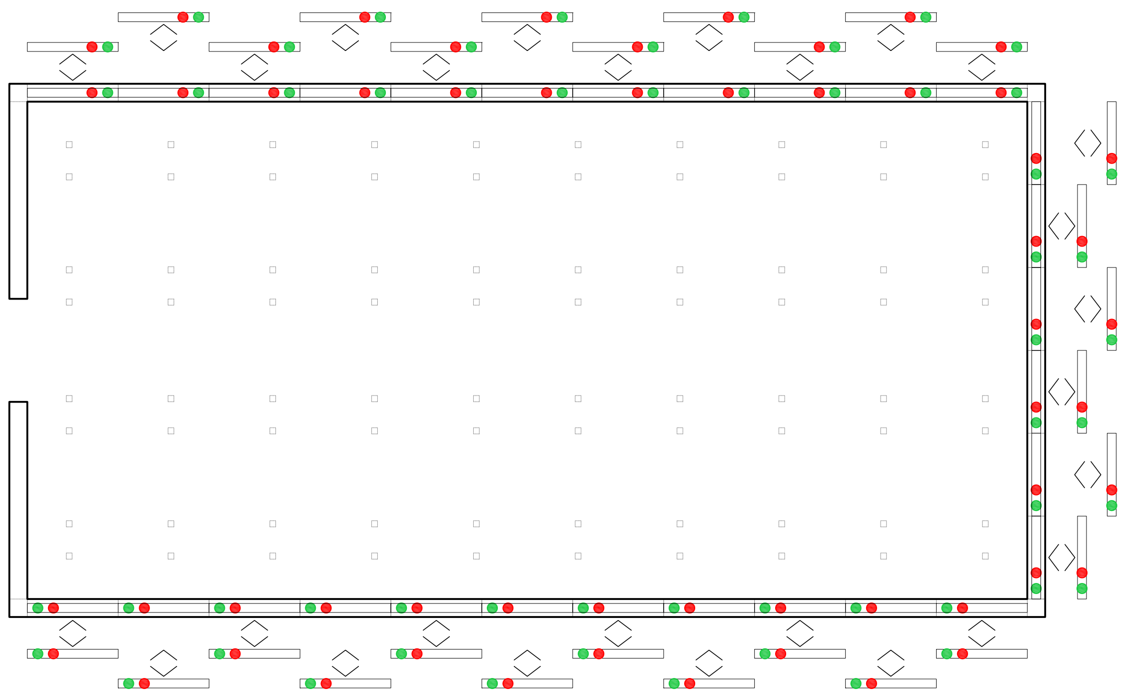


Figure 2.5.5: Plug&Play in utilization
(Remake source - Author) (Original extract from: Mach, Grobbauer, Streicher, & Müller, 2015)

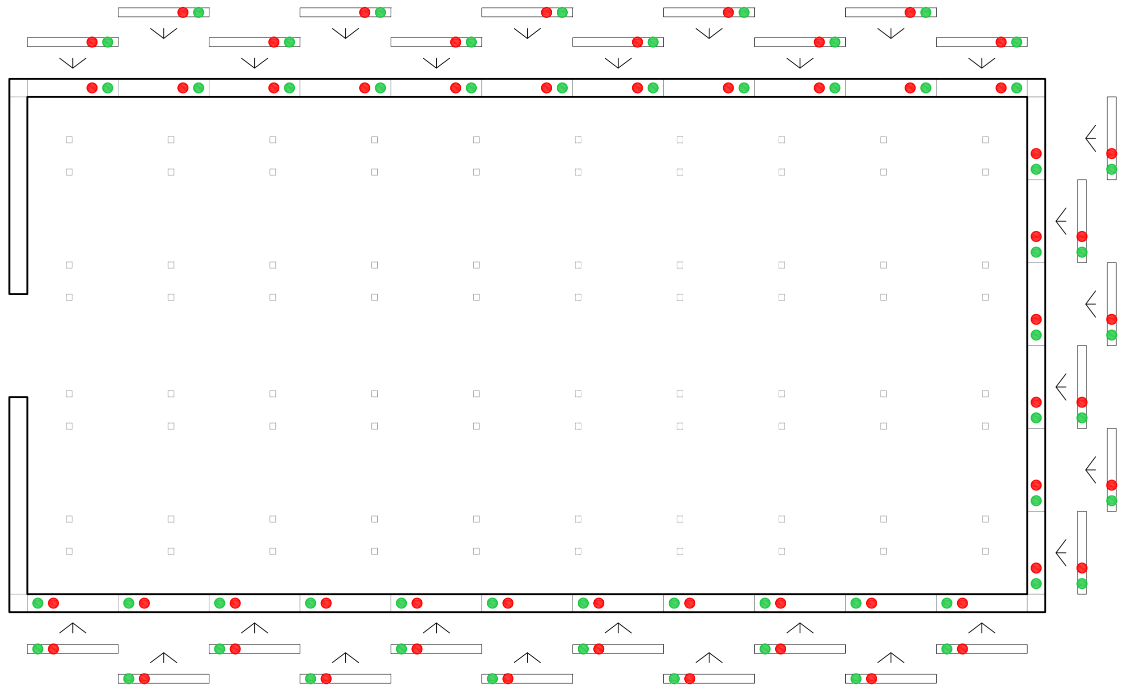


Figure 2.5.6: Plug&Play in construction
(Remake source - Author) (Original extract from: Mach, Grobbauer, Streicher, & Müller, 2015)

2.6. Evaluation of Responsibilities

2.6.1. Energy Performance

Figure 2.6.1. shows the study conducted by Al-sallal, 2016 for various office tower buildings in the United Arab Emirates. The study suggests that the energy consumption is alarming and measures must be taken to alleviate them. The study also recommends that more shading, ideal window to wall ratio and efficient cooling strategies should be introduced to future buildings. As shown in the highlighted region the study suggests that Buildings such as Dubai World Trade centre or Emirates tower use 278 kWh/m2/year and 560 kWh/m2/year respectively. These are all high energy consuming buildings and are quite strong examples of the way most of the tall buildings in Dubai would be consuming energy.

EmiratesGBC, 2017 report for Defining Nearly Zero Energy Buildings in the UAE state that a building can be a nearly Zero Energy Building (nZEB) if the Energy Performance Index or Energy Usage Index value is below 90 kWh/m2/year and the building relies more on renewable energy sources. This would be the criteria of design for the thesis and the goal would be to try and improve the facade as much as possible to reduce the EPI of the building and nudge the intervention to achieve a nZEB.

NAME OF BUILDING	DUBAI WORLD TRADE CENTRE	EMIRATES TOWER OFFICE BUILDING	NATIONAL BANK OF ABU DHABI HEAD QUARTERS
TOTAL ENERGY CONSUMPTION	278 KwH/m2/year	560 KwH/m2/year	NA
REFRIGERATION COOLING	1600 tons	NA	1500 tons
NATURAL VENTILATION % FLOOR AREA	20%	NA	NA
SOLAR CONTROL SYSTEMS	EXTERNAL SHADING	INTERNAL BLINDS	INTERNAL BLINDS
GLAZING TYPE	DGU	DGU, non tinted, low-e	DGU, reflective SS color

Figure 2.6.1: Summary of Energy Audit of 3 Buildings in United Arab Emirates (Source – Research Paper by Al-sallal, 2016)

2.6.2. Cooling Demand Evaluation

As studied before the average external air temperature for the United Arab Emirates is quite high. Based on a study by Shanks, Kirk; Nezamifar, 2013 we could understand that annually the air temperature stays above 25 degrees for about 75% of the time, the relative humidity stays above 60% for about 20% of the year and the solar radiation stays above 893 W/m2 for more than 15% of the year. Also, most of the new tall buildings follow a contemporary design style to have a maximum glazed area to increase visibility. All this means that cooling by air conditioning is required for almost throughout the year.

Studies from Radhi, 2010 show that air conditioning consumes about 65-80% of total energy of the buildings, a projection calculation from Hassan Radhi, 2009 also states that the cooling load on residential buildings will increase from 10% in 2020 to 35% by 2050. This data provides an alarming figure and efforts must be done to mitigate these values.

For the data of the energy consumed by a typical building in the United Arab Emirates, studies done Shanks, Kirk; Nezamifar, 2013 for the Al Kazim Towers, Dubai was used. The following simulation boundary conditions were established by their study:

Figure 2.6.2: Photograph of Al Kazim Towers, Dubai (Source – http://www.skyscrapercenter.com/building/business-central-tower-2/716)

- The cooling system modelled had constant volume ac with an open top unlimited cooling capacity.
- Adiabatic flooring and ceiling
- No shading or overshadowing.
-

The Figure 2.6.3. below shows the energy required for cooling of single typical floor of the above mentioned case of Al Kazim Towers, Dubai for current situation and the projections made by the researches for every 10 year interval till 2050: (See highlighted Region)

Year	External conduction gain (MWh/yr)	Infiltration gain (MWh/yr)	Total air system input / Ratio sensible:latent (MWh/yr)	Solar gain (MWh/yr)	Internal gains (MWh/yr)	Cooling + dehumidification demand (MWh/yr)
Current	3.0	3.6	31.6 / 2:1	30.6	80.0	172.9
2020	4.0	6.1	40.5 / 2:1	30.7	80.0	191.7
2050	4.9	8.5	50.6 / 1.3:1	30.6	80.0	211.3
2080	6.3	11.8	67.0 / 1:1	30.5	80.0	242.0

Note: Internal gains include those due to people, lighting and equipment. Air system input includes both sensible and latent demands of conditioning incoming fresh air to 20°C.

Figure 2.6.3: Basecase Heat Gains data (Source – Shanks, Kirk; Nezamifar, 2013)

2.6.3. Shading Potential Evaluation

Rabczak & Bukowska, 2016 conducted a study to identify different shading types per orientation of the façade as shown in Figure 2.6.6. Based on this evaluation further literature study introduced a a simulation study conducted by Yassine, 2013 for Shading devices in Dubai, United Arab Emirates in her MSc Thesis analysed how various types of shading structures perform differently and provide different levels of energy savings. For the study average weather conditions were tested in Computer Simulation – IES VS simulation. The types of shading devices are shown in Figure 2.6.4. below; (which mainly contains four typologies namely Overhangs, Side Fins, Horizontal Louvers and Vertical Louvers).

The study concluded that all the shading devices performed most effectively for the South Façade and the most effective shading was found to be the horizontal louvers, with an average energy saving of about 14.58% and about 10% saving on West and East Facades. The most reveling part of this study was that in optimum conditions the energy savings increased to up to 33%. (Results in Figure 2.6.5) The optimum condition here is a function of Horizontal Shadow Angle (HSA) and Vertical Shadow Angle (VSA) is specific to the location and the orientation. For example, another study conducted by Hammad & Abu-Hijleh, 2010 found that the optimum angle for the south orientation is -20 degrees which provides and energy saving of 31.20%.

The results in this study can be used as a parameter for the design for the shading devices. Since Horizontal louvers seem to be performing well in all orientations the design in thesis will focus only on horizontal louver shading.

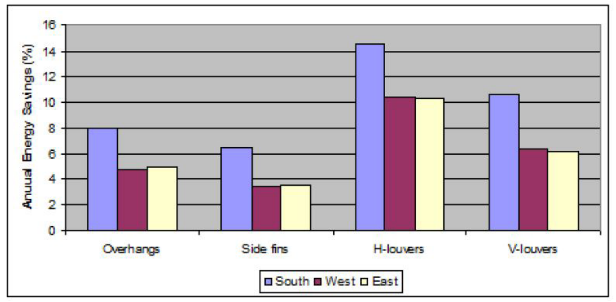


Figure 2.6.5: Performance of various Shading Devices based on Orientation (Source – Yassine, 2013)

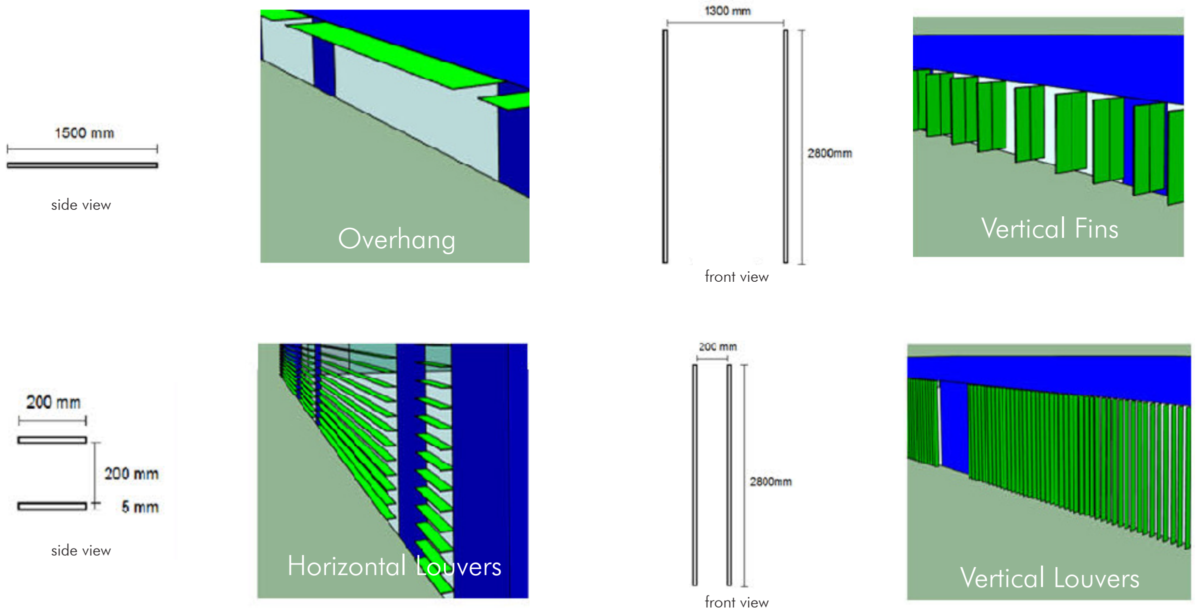


Figure 2.6.4: Performance of various Shading Devices based on Orientation (Source – Yassine, 2013)

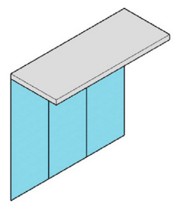
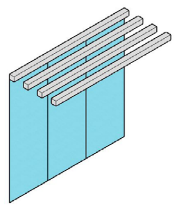
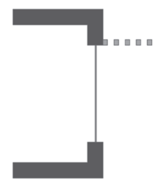
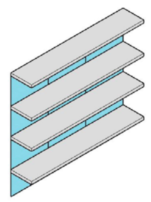
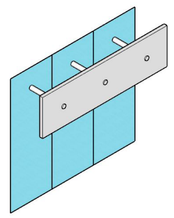
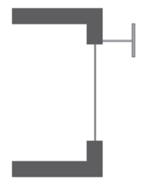
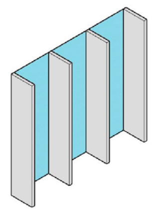
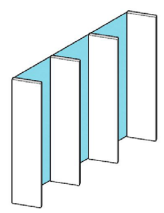
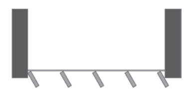
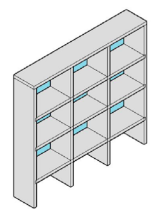
View	Description	Design	Best Orientation
	Overhang		South | West | East
	Overhang Louvers		South | West | East
	Horizontal Louvers		South | West | East
	Vertical Panel		North | West | East
	Vertical Fin		West | East
	Slanted Vertical Fin		West | East
	Eggcrate		West | East

Figure 2.6.6: External shading devices based on orientation (Rabczak & Bukowska, 2016)

2.6.4. Solar Potential Evaluation

As discussed in Chapter 2.6.3. shading devices seem to have a discernable impact in the energy performance of the building. Moreover, to be discussed in 2.6.5 solar radiation is quite ubiquitous to be harvested for electricity requirements.

It is only logical to think then to combine both of these aspects as the component which ought to protect the façade from radiation would be the one receiving most of it. Hence, comes the idea of “Photovoltaic Integrated Solar Shading devices” which falls under the domain of Building Integrated Photo Voltaic (BIPV).

This technology is quite a new area of research and has only a few companies in the market who have any product related to this requirement. Hence it would be an exciting area to explore. One such company is Colt; this young company is from South of England in the United Kingdom from a place called Hampshire, the line of products in for this technology is called Shadovoltaic. (Colt International Licensing Limited, 2012).

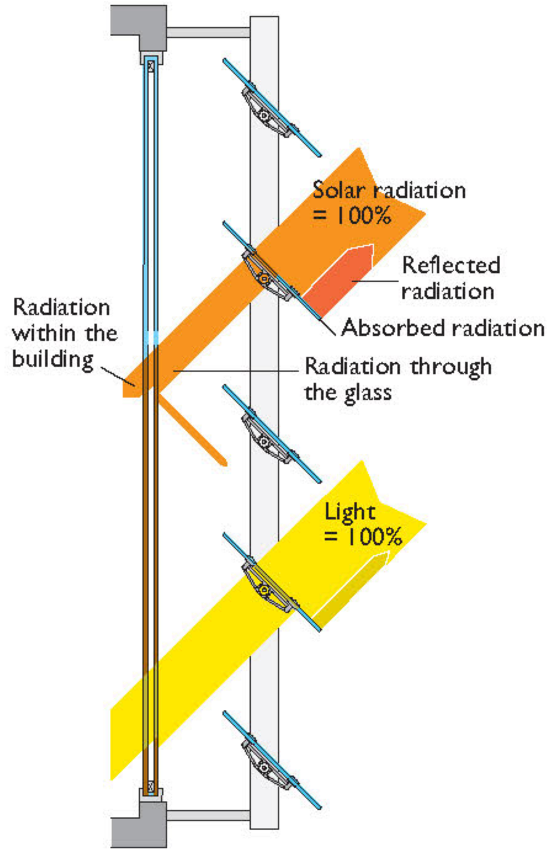


Figure 2.6.7. Diagram showing section of Colt Shading System (Source – Colt International Licensing Limited, 2012)

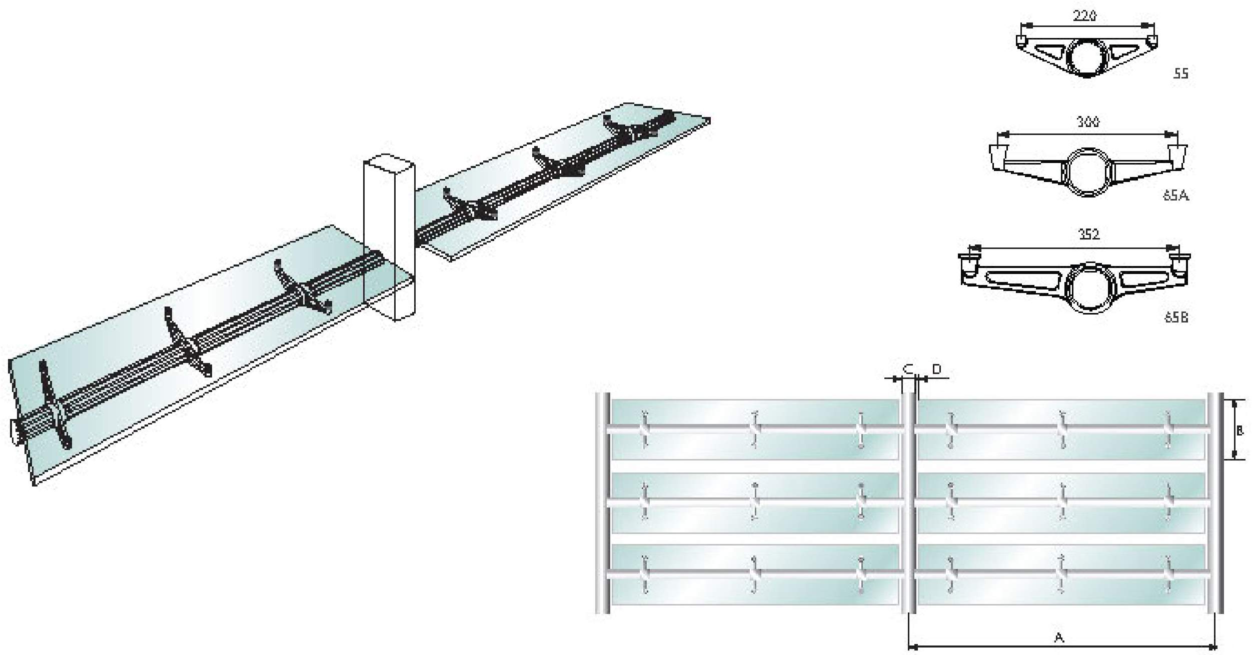


Figure 2.6.8: Diagram showing a type of Colt Shading system (Source – Colt International Licensing Limited, 2012)

In this regard studies conducted by Kim, Jung, Choi, & Kim, 2010 was of good use to identify weather the idea would be feasible or not. In summary the study took into consideration three main factors;

- Energy produced by PV Cells
- Daylight levels indoors for comfortable illumination.
- Glare and optimum angle of louver slats.

The cross section of the control volume with all components is shown in the Figure below:

The study did not provide any amount of energy output data or value, but it was a useful experiment to prove that the concept could work. The study summarises that the electricity produced by PV panels is proportional to the solar irradiation. The angle of each slat kept normal to suns altitude will not give comfortable indoor illumination (lesser that 500lux) based on the test location. If not the value this experiment is quite useful to determine the parameters which need to be considered for the shading system. The optimum angle and depth will vary based on the climatic conditions, the indoor illumination levels and the amount of solar irradiation. The proposed recommendation in the experiment is that during a dark day (cloudy conditions) the slats are preferred to be horizontal to the floor plant to allow maximum light in.

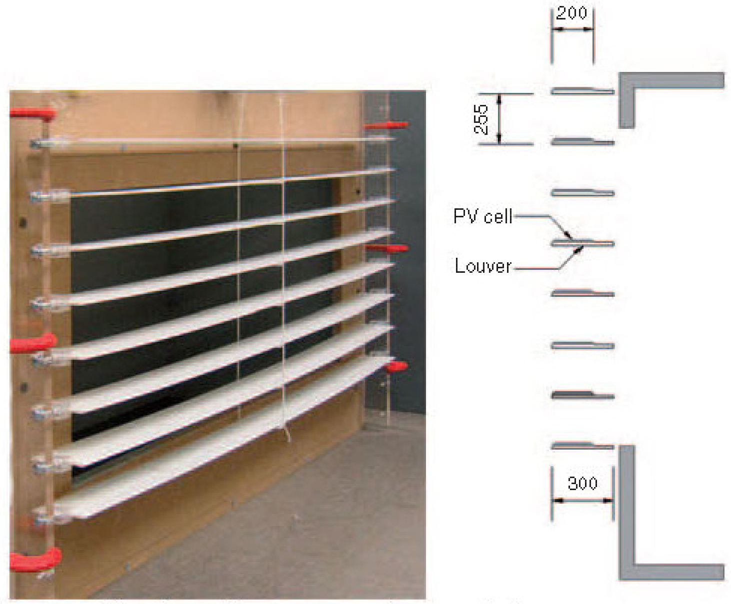


Figure 2.6.9: Eight slats of louver-type shading (Source – Kim, Jung, Choi, & Kim, 2010)

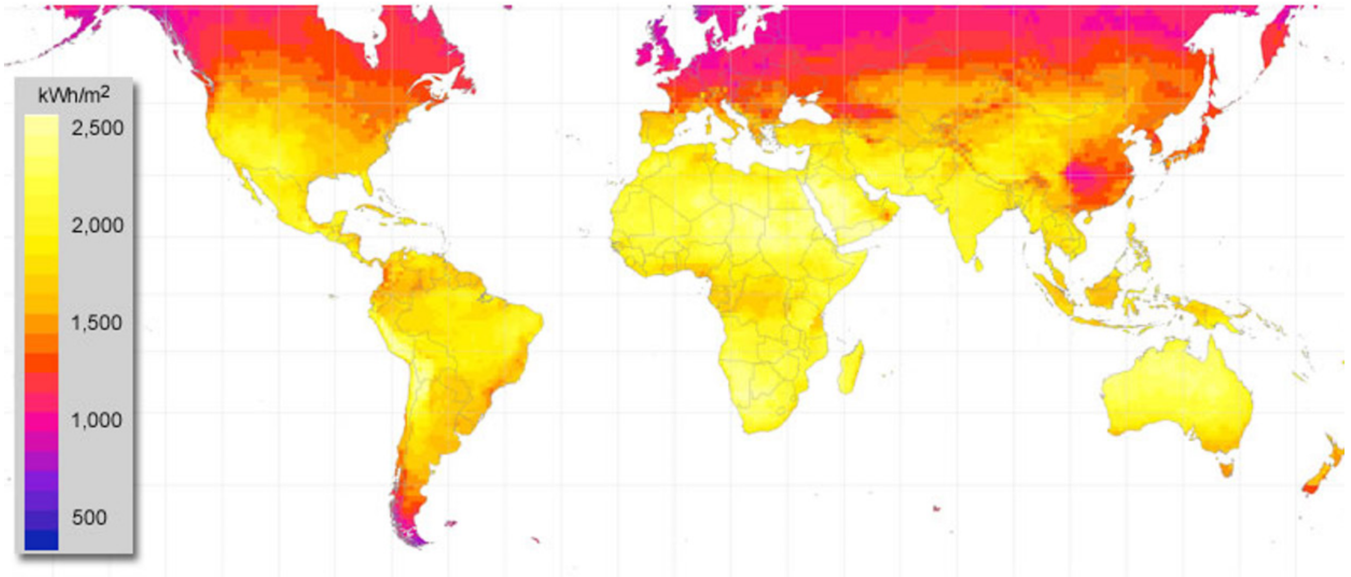


Figure 2.Figure 2.6.10. World Map showing annual average irridiation levels (Source - https://photovoltaic-software.com/principle-ressources/solar-radiation-databases)

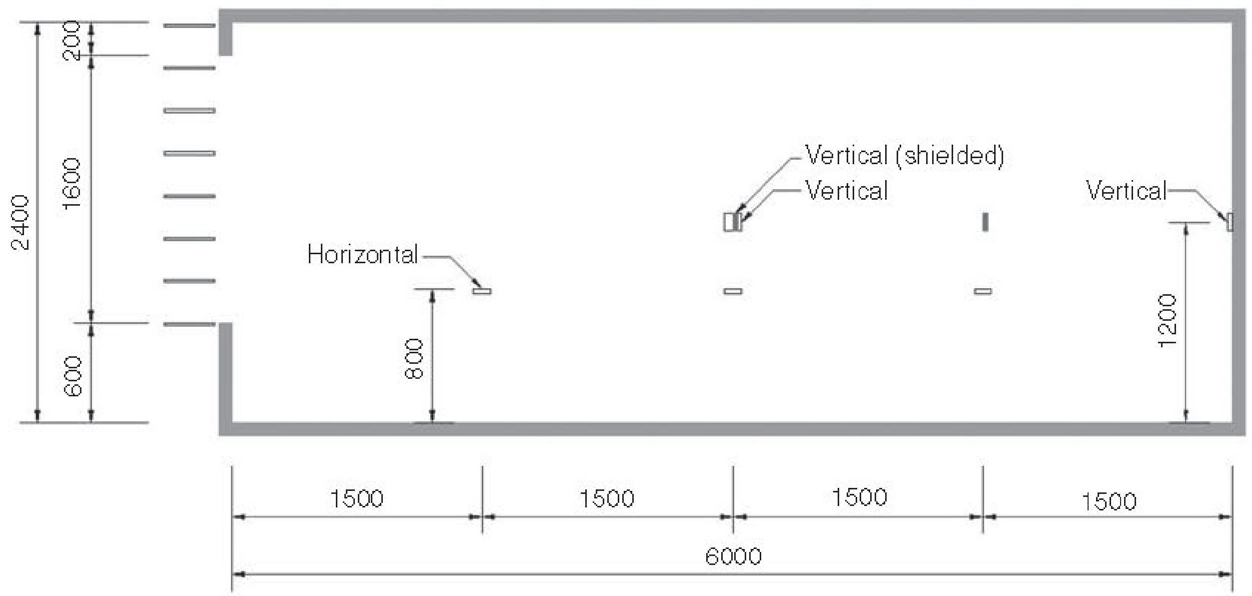


Figure 2.6.11: Cross section of the test model (Source – Kim, Jung, Choi, & Kim, 2010)

2.6.5. Location and Climate Study

The United Arab Emirates has an Arid maritime climate which is determined by the North Sea and the Atlantic Ocean. The summers are cool, and the winters are moderate.

The temperature ranges from 17°C to 26°C in winters and 31°C to 41°C in the summers ("Wikipedia" 2019). The average yearly wind speed varies per each region in the country. However, for the sake of this design, we have considered a national average of 7.9 MPH (12.7 KPH) and the windiest it has been in last three years is at an hourly average of 9.2 MPH (14.8 KPH). (Airport International Dubai, 2019).

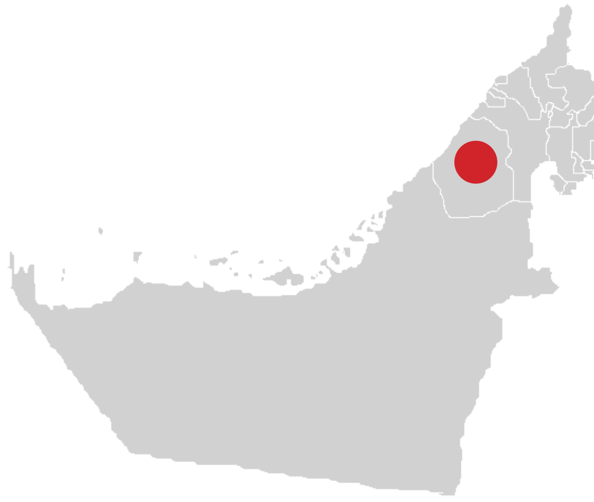


Figure 2.6.12: Location of Dubai, United Arab Emirates (Source – https://www.shutterstock.com/ko/image-vector/united-arab-emirates-map-high-detailed-781302664?src=cnGqG7Atjn_sKd0742_zDg-1-29)

The average precipitation just like winds varies per region in the country. However, again the national average for precipitation is 0.5 to 0.7 Inches (1.2 to 1.7 centimetres) (Airport International Dubai, 2019).

It can be noted that Dubai is not quite windy in general, but as the buildings go taller, the wind load will play an essential role in the design of any structure. Moreover, the direction of the wind is a variable due to turbulent wind flows, although statistical data extracted from "WindFinder," 2018, informs us that the region is mostly windy from north-west direction throughout the year.

We can hence also determine that any new modification must be able to withstand the wind from the side where the wind flow is the greatest and the movements (or deflections) caused by an estimated amount of wind pressure from that direction.

An initial climate study as shown in 2.6.14. was conducted for Abu Dhabi, the United Arab Emirates as no weather data was available directly for Dubai. However, based on an intensive search online, It was conferred that Dubai and Abu Dhabi share same climate patterns as they are quite close to each other with a difference of about 140 kilometres between them (Mohammad, 2002).

The weather data for Abu Dhabi in *.EPW format was downloaded from the energyplus website (https://energyplus.net/weather), and the evaluation had been done in software called Climate Consult 6.0 developed by Robin Liggett and Murray Milne of the UCLA Energy Design Tools Group. The analysis of the weather data was based on 'ASHRAE Standard 55 and Current Handbook of Fundamentals Model' Comfort Model. The psychometric chart was generated to fit the data on the screen setting.

As seen in Figure 2.6.14. , the Dry Bulb Temperature (x-axis) varies from 8 degree Celsius (°C) to 48 °C and the Humidity Ratio (y-axis) ranges from 0.002 to .028, also the Relative Humidity (curved lines in x-y

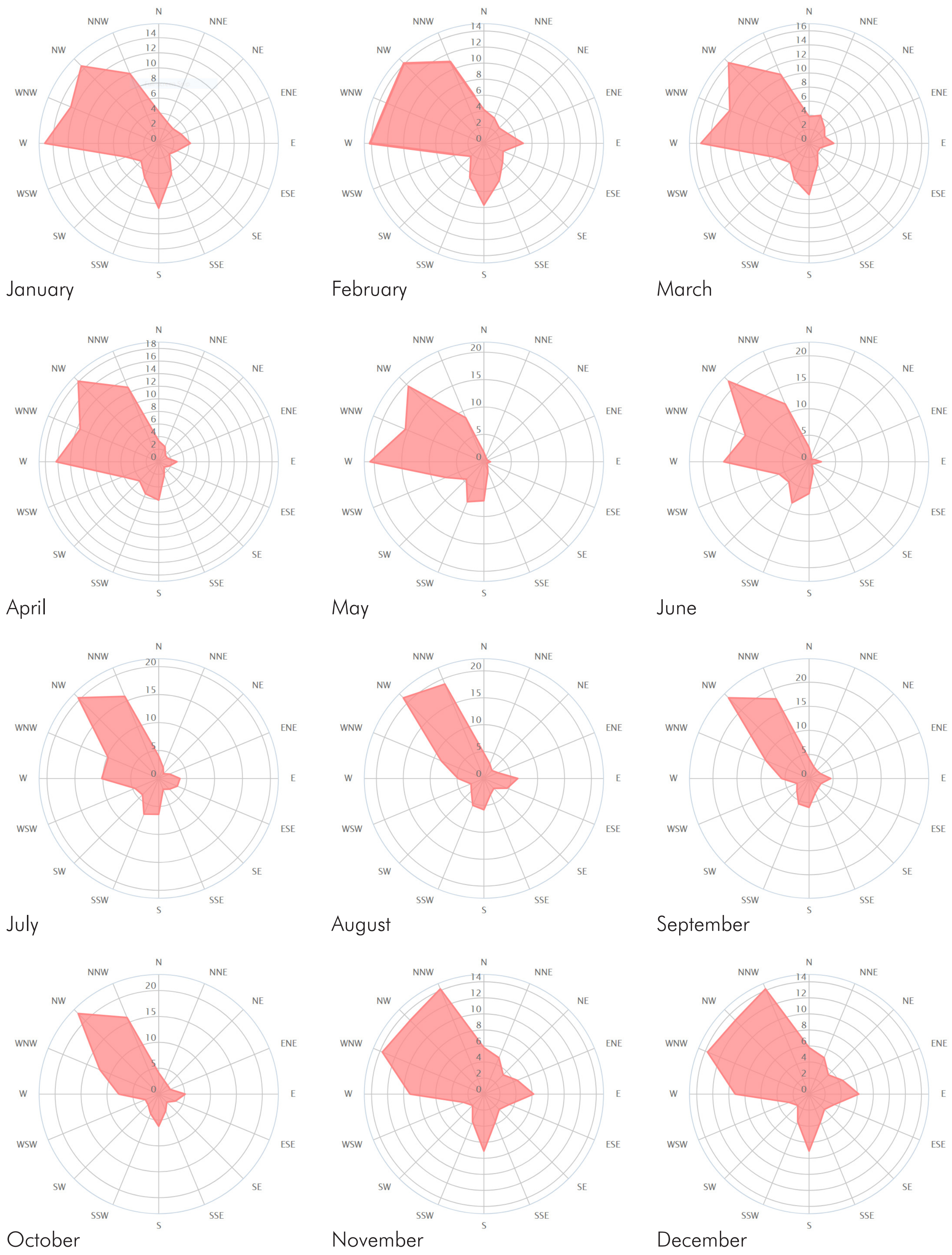


Figure 2.6.13: Contextual wind analysis for 2018 for Dubai Airport (Source – https://www.windfinder.com/windstatistics/dubai)

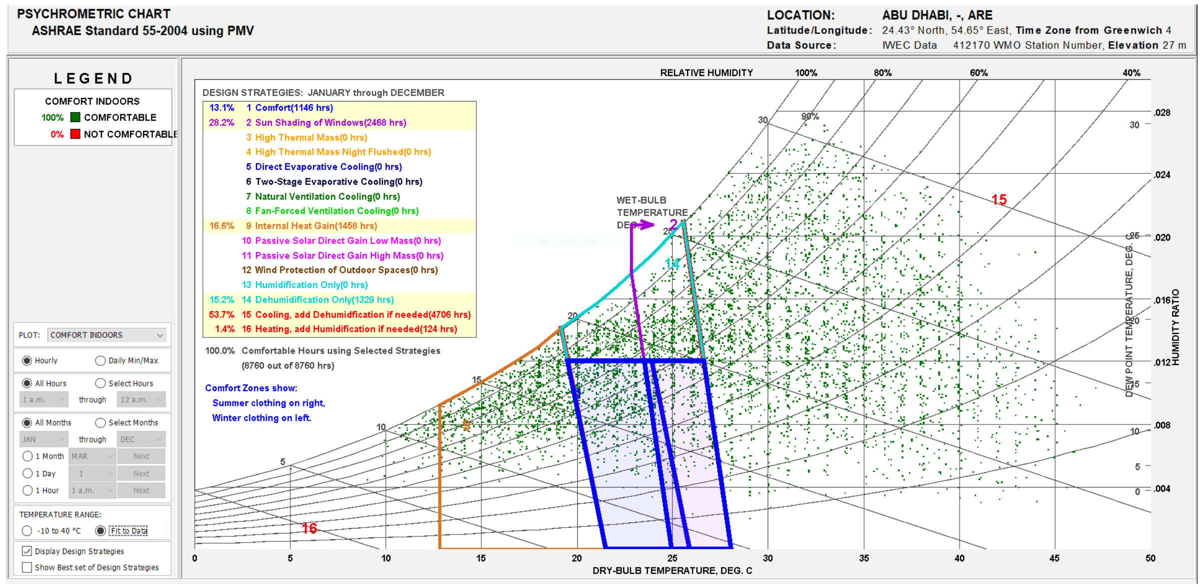


Figure 2.6.14: Psychometric Chart of Abu Dhabi, United Arab Emirates (Source – Self: Generated with Climate Consult 6.0)

axis direction) starts from 5% all the way to 100% throughout the year. This data means that the weather is quite complex and will require large amounts of cooling and dehumidifying the air during summer and a sizeable amount of heating and humidifying the air. The comfort zone in winters and summers is shown in the area shaded blue in Figure 2.6.14. is what should be achieved, and each dot represents an hourly set record of the weather reading throughout the year (Hence, there would be 8,760 dots or hours). Although, since the weather data file from the energyplus website is the only tool which can be used for measuring the comfort levels in Climate Consult Software, and the source has been verified by large governmental agencies such as U.S. Department of Energy's (DOE) Building Technologies Office (BTO), and managed by the National Renewable Energy Laboratory (NREL). All further assumptions will be made based on the weather data collected from energyplus website.

It can also be observed from Figure 7.2.2. in the Appendix. that the annual average radiation ranges from 250 to 850 Wh/Sq.m per hour (watt-hours per square meter per hour).

Figure 2.6.15. is an extract from Figure 2.6.14., and it suggests an optimised climate design strategy for the climate of Abu Dhabi. The yellow highlighted region shows the percentage and the number of hours for achieving a 100% efficient comfort level design. As shown in the data 13.1% of the hours are already in the comfort zone and requires no amount of active or passive cooling strategy. However, the remaining 86.9% need to be a combination of Cooling and Dehumidification for summers and Heating and Humidification for Winters. Shading the building well will also result

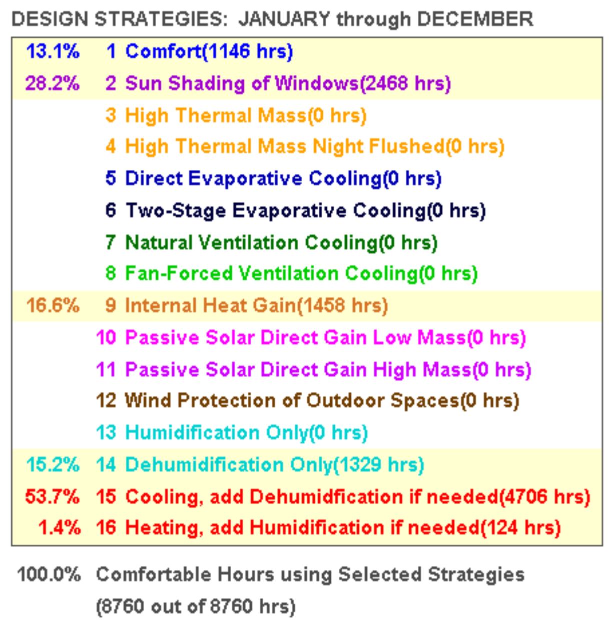


Figure 2.6.15: Recommended Climate Design strategies Abu Dhabi, United Arab Emirates (Source – Self: Generated with Climate Consult 6.0)

WEATHER DATA SUMMARY LOCATION: ABU DHABI, -, ARE
Latitude/Longitude: 24.43° North, 54.65° East, Time Zone from Greenwich 4
Data Source: IWEC Data 412170 WMO Station Number, Elevation 27 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	395	477	466	517	578	576	555	562	545	500	421	374	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	512	597	438	459	552	553	490	526	553	575	547	493	Wh/sq.m
Diffuse Radiation (Avg Hourly)	119	119	169	172	145	135	159	146	131	117	109	117	Wh/sq.m
Global Horiz Radiation (Max Hourly)	793	907	990	1045	1051	1038	1036	1017	983	916	793	716	Wh/sq.m
Direct Normal Radiation (Max Hourly)	935	975	965	954	922	895	881	888	906	927	922	924	Wh/sq.m
Diffuse Radiation (Max Hourly)	366	427	492	538	455	258	468	353	250	350	399	350	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	4220	5322	5545	6507	7634	7771	7404	7215	6623	5707	4557	3939	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	5459	6647	5201	5781	7293	7458	6545	6743	6712	6555	5918	5191	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	1275	1333	2019	2169	1915	1827	2127	1884	1596	1345	1185	1239	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	42786	51554	50983	56239	63215	63408	61596	62294	60355	54911	46273	40652	lux
Direct Normal Illumination (Avg Hourly)	48484	57714	42090	44937	54370	54658	47217	50889	53873	56139	52374	46754	lux
Dry Bulb Temperature (Avg Monthly)	18	19	22	26	30	32	34	34	32	28	24	20	degrees C
Dew Point Temperature (Avg Monthly)	11	11	15	15	17	20	22	22	22	18	18	13	degrees C
Relative Humidity (Avg Monthly)	70	64	69	55	49	52	54	53	61	59	70	65	percent
Wind Direction (Monthly Mode)	320	290	320	330	320	300	320	320	160	80	310	310	degrees
Wind Speed (Avg Monthly)	3	3	3	3	4	4	3	3	3	3	2	3	m/s
Ground Temperature (Avg Monthly of 3 Depths)	24	22	21	21	23	26	28	31	32	31	30	27	degrees C

Figure 2.6.16: Weather Data Summary Abu Dhabi, United Arab Emirates (Source – Self: Generated with Climate Consult 6.0)

in providing 28.2% of additional comfort hours, which seems like a sizeable helpful amount of energy saving to gain passively.

This comfort hours data will provide the basis for the retrofit redesign. As an initial hypothesis the shading provides large possibility of energy saving and enough surface for solar panels to harvest solar energy and the design strategies data provides sufficient information of the amount of heating and cooling required. Heating as such is not of a large issue since a well-sealed building can use the internal heat gains from the people, appliances and the fixtures during the time of their operation. Although Cooling and Dehumidification which attributes to 53.7% of total energy use will remain a large challenge.

One should also note that the proposal here is of refurbishment and retrofit. That means that the buildings ideally will have an existing chiller system. Depending on the type of building and its functions the chiller system may vary and it can be deemed that all buildings in Dubai by code must have any HVAC system to provide necessary thermal comfort (Gb & Building, 2013). Hence, the purpose of the retrofit is to improve the energy efficiency of the existing buildings. This would be the starting point for the entire research ahead.

Since the main research question still focuses on retrofit strategies in "Arid Climates", an evaluation study of the weather data of various cities shown in Figure Figure 2.6.13. in such climates conferred that the similar parameters need to be considered for the climate responsive design.

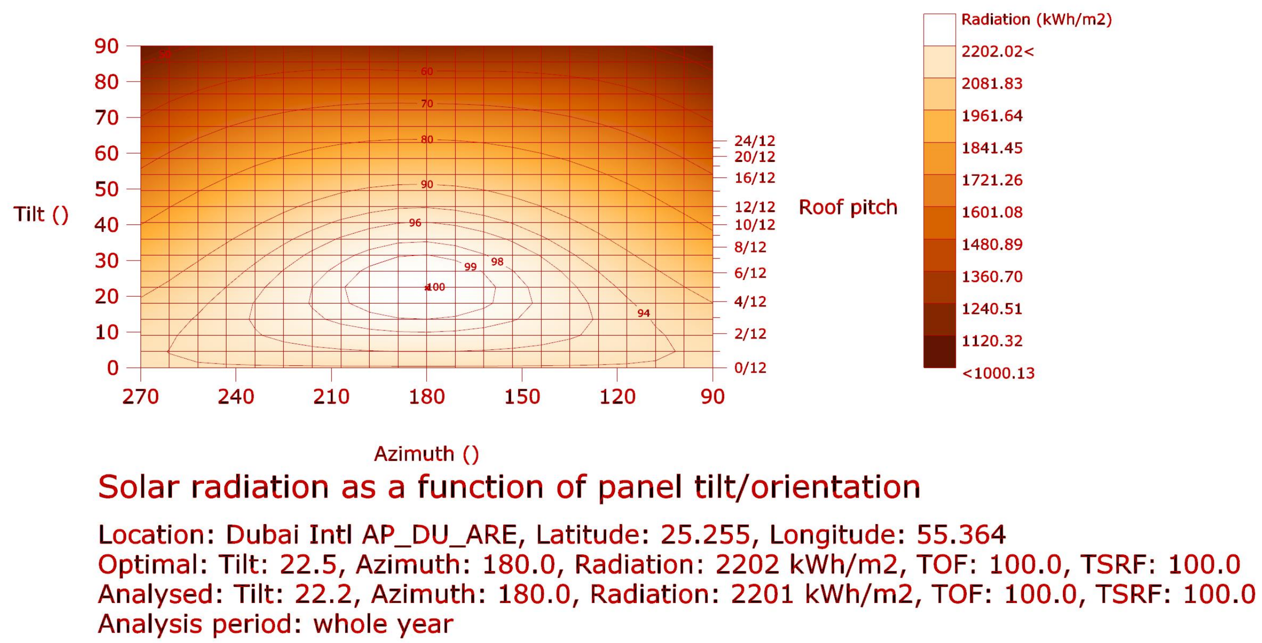


Figure 2.6.17: Azimuth based Irradiation map to optimize the angle of the PV panels for Dubai (Source – Self: Generated with Grasshopper)

03
DESIGN DEVELOPMENT

3.1. Life Cycle Assessment

3.1.1. Introduction

The flow of materials in the construction of building and post its lifetime at the moment is quite linear in the industry (Crowther, 1999). Figure 3.1.1. describes how the materials from extraction to demolition is managed and post demolition all the materials go to waste disposal stream, leaving no or very less capacity for transformation. This process is known a one end-of-life scenario. This practice becomes unsustainable leaving large amounts of waste which could have been re-used or recycled to form some other product in building industry to even in another industry.

The preferred use of materials and components would be where there is a circular loop, of the flow of materials within the construction, use and after the end-of-life of the buildings. (See Figure 3.1.2) a good analogy would be to compare the flow of building materials with nature where there is a circular food chain, and all by-products of nature is consumed or used by another living organism.

In order to achieve such a paradigm, necessity comes in prudent design, which already includes end-of -life (EOL) scenarios for building materials and identify a potential use for those materials past its use in the building or to use the material till its service life is met and then recycle them to

supply for the use in the building stream again.

Based on the premise of a life cycle approach, buildings and building components should be designed considering the future and its future uses. Life cycle design (Figure 3.1.3) means that components or systems should not be just made for a specific use, but instead for the time of the for the function considering sustainable measures, ecological and economic impact that the design has to provide. (Durmisevic, 2006)

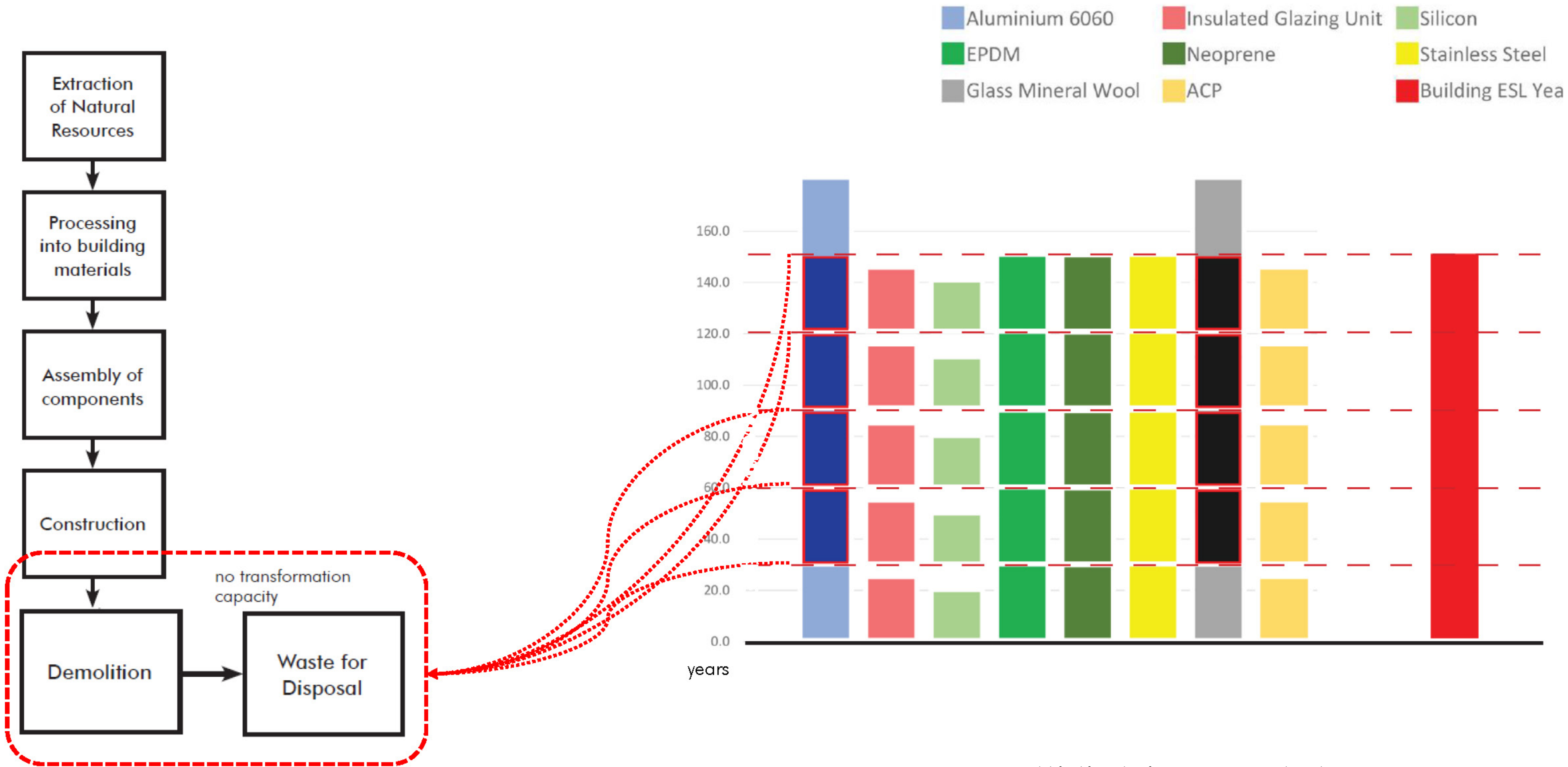


Figure 3.1.1: Linear model for life cycle of construction materials and components in comparison to existing case (Source - Durmisevic, 2006)

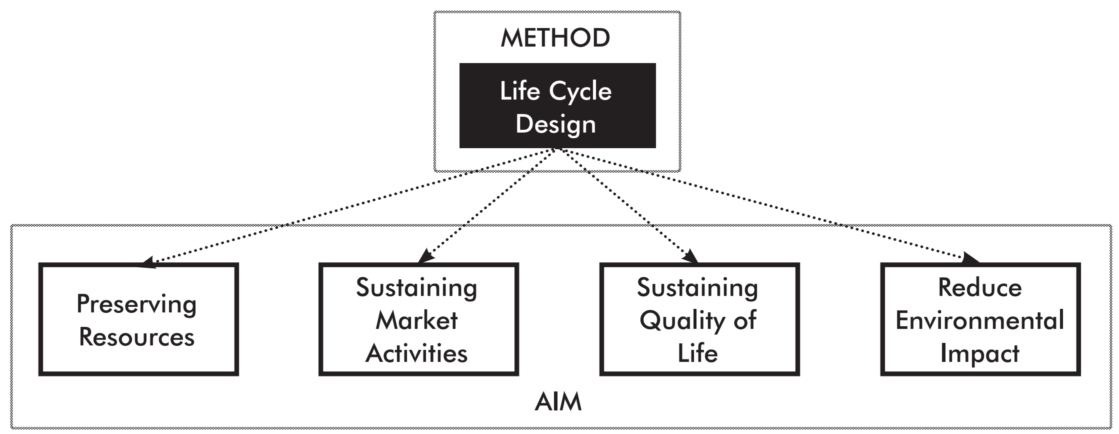


Figure 3.1.2: Sustainable refurbishment model for life cycle of construction materials and components (Source - Durmisevic, 2006)

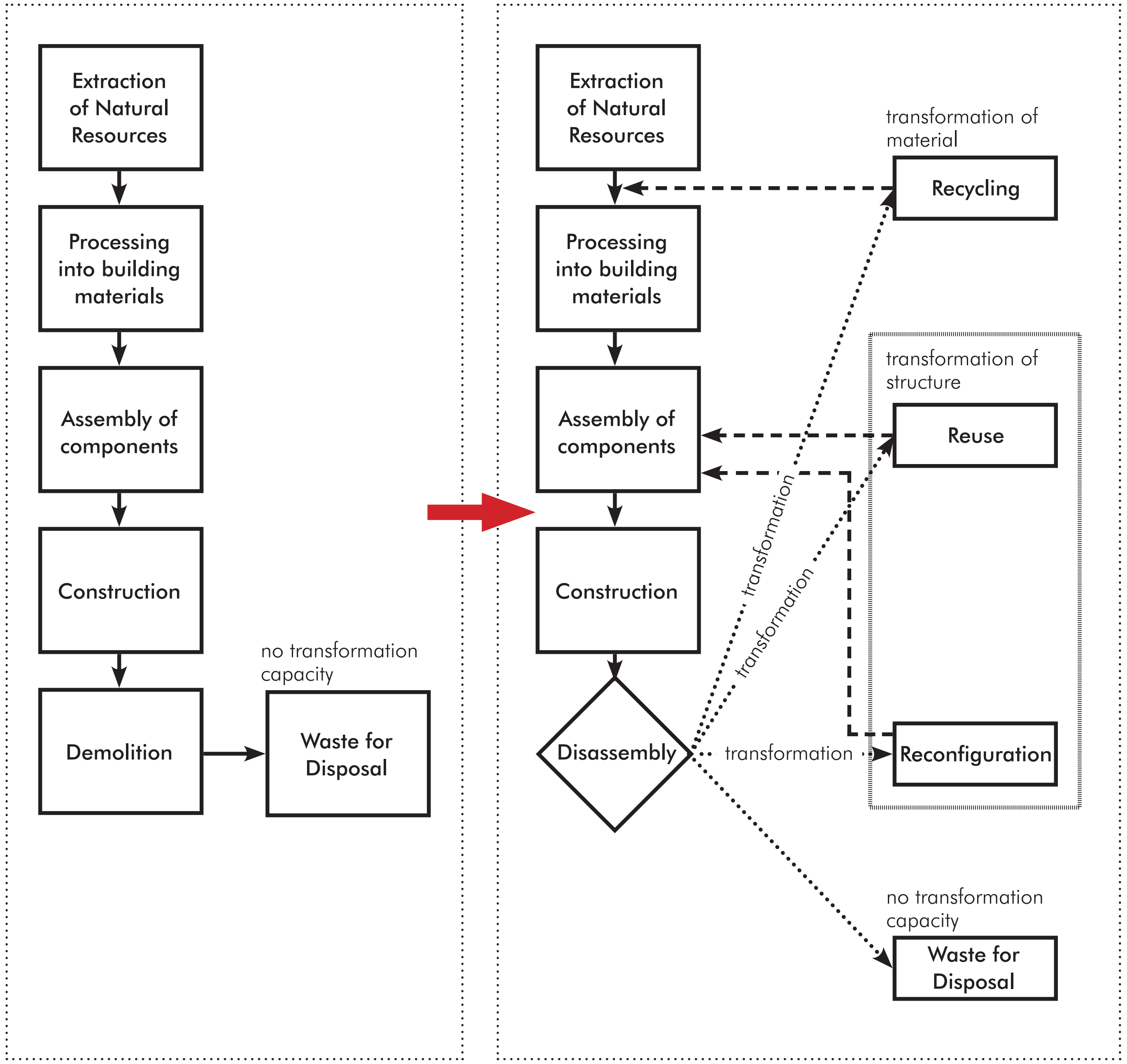


Figure 3.1.3: Transformation from linear model to circular sustainable refurbishment model for life cycle of construction materials and components (Source - Durmisevic, 2006)

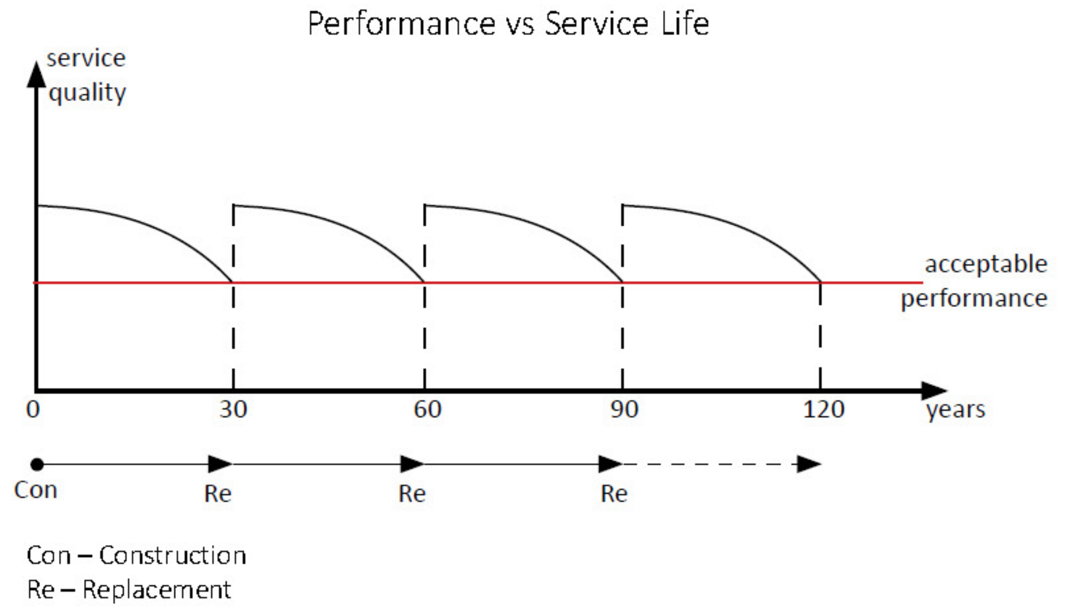


Figure 3.1.4. Performance Vs Service life for facades with 30 Year cycles (Source - Kakolyri, 2015)

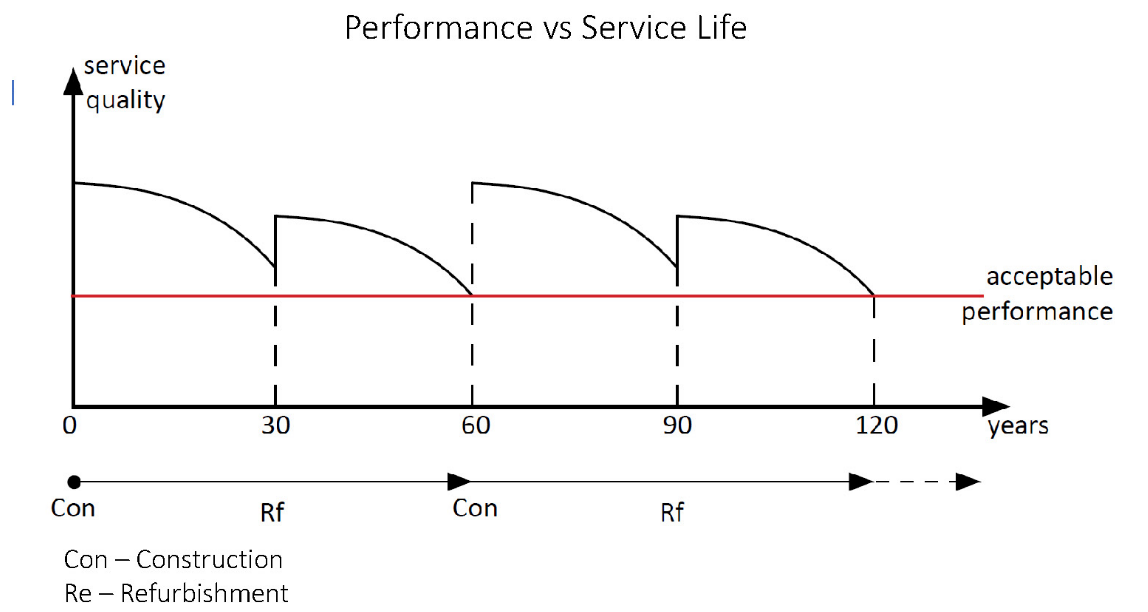


Figure 3.1.5. Performance Vs Service life for facades with 60 Year cycles (Source - Kakolyri, 2015)

3.1.2. Analysis

Figure 3.1.1 describes how the facade at the moment performs in terms of service life. Different components which are comprised of a collection of different materials have varying end-of-service life. Each material which has its own physical property and can work for certain operation cycles.

Physical limit of a material is reached after a certain number of years (depending on the material) because of factors such as seasonal weathering, temperature changes, corrosion, physical expansion and contraction, exposure to sunlight, due to growth of microorganisms or molds or algae etc... its can also happen than if the components are operational then wear and tear due to friction and regular activity, the components reach its operational limit and hence result in failure. This types of failures are a large problem in facade of a building and more so in curtain wall facades.

Failures in facade cause water penetration, vapor penetration, poor thermal performance which will lead for poorer energy performance of the building, acoustic permeability and many more which effects the user comfort inside the building. "What use is a skin if it can't protect you from anything?"

Facade refurbishment as discussed in Chapter 2.2 elaborates on the reason why it is important to keep the facade in good condition. As per studies of (Kakolyri, 2015)is that the general milestones for facade refurbishments are when they are 25-30 years old or in newer buildings when they are older than 60 years, especially for office buildings. The graphs below in Figure 3.1.4 & Figure 3.1.5 show the Performance vs Service life for the facade systems designed for 30 years and 60 year cycles. Main characteristics, advantages, and disadvantages of facade ESL's are described in the table in Figure 3.1.7.

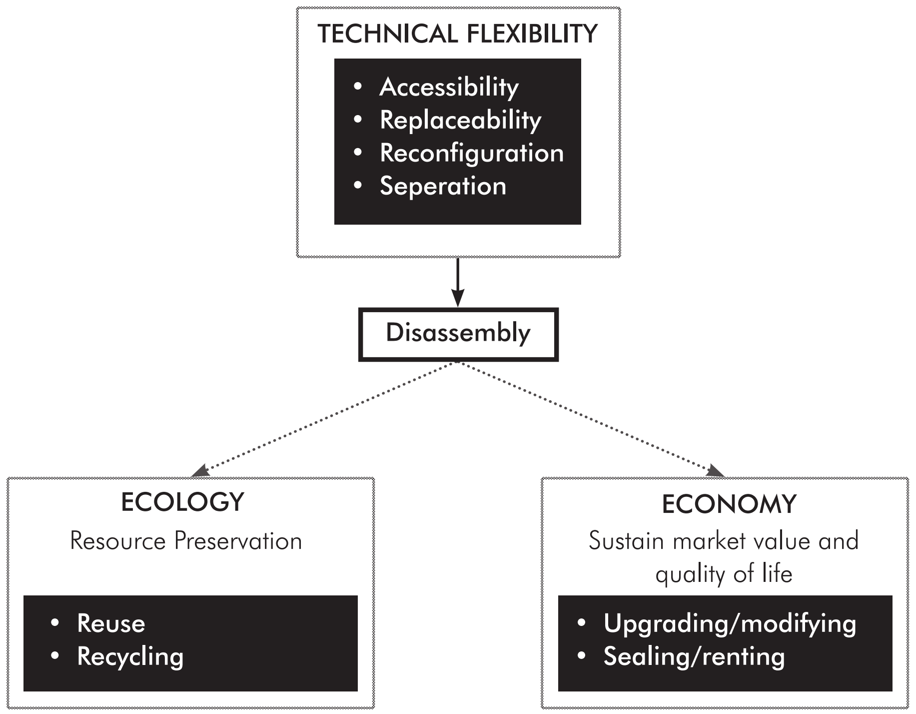


Figure 3.1.6: Proposed option for extending the ESL of facade and hence the building (Source - Author)

	FACADES WITH 30 YEAR ESL CYCLES	FACADES WITH 60 YEAR ESL CYCLES
CHARACTERISTICS	• Design for near present • No Refurbishment • Complete replacement after 30 Years • Elements Recycled and Remanufactured	• Design for near future • Refurbishment is required once, • Recycling elements near End of Life • Temporarily removed and components replaced or taken back to factory and reinstalled
ADVANTAGES	• Use of Technological Developments	• Less expensive, less environmental burden • Saves time in comparison to replacement • Possibilities of reuse
DISADVANTAGES	• Expenses of complete replacement (Transport, Construction & Assembly) • Ecological impact because of new materials • Ecological impact due to recycling materials at lesser life span	• Current designs are not made for reuse • Demolition is preferable because the process of sorting and rearranging is a large burden • High chances of error during re-fixing

Figure 3.1.7: Characteristics of facades with 30 vs 60 Year cycles (Source - Kakolyri, 2015)

3.1.3. Design

Curtain wall facades have a complex composition of materials in a specific geometry arranged in functional progression. In other words parts are configured in specific location after careful consideration and design, where each part represents a different functionality. For example, the aluminium profiles are for structural purposes, the glass is for transparency, thermal breaks such as neoprene or PVC are for reducing the heat transfer within the aluminium frame, the gaskets are for locking the components together and providing air and water tightness etc... All elements have a function for its on and the current design and construction of curtain wall systems are rigid, which does not allow for disassembly easily.

The principles of design which will be considered in this chapter is as follows:

1. **Design for Full end-of-life scenario:** Commonly, the building envelopes are designed for a short term of 30 years whereas the building itself can live up to 5 times more than the envelope, it is designed this way because of various aspects such as project budget or just careless design. It can

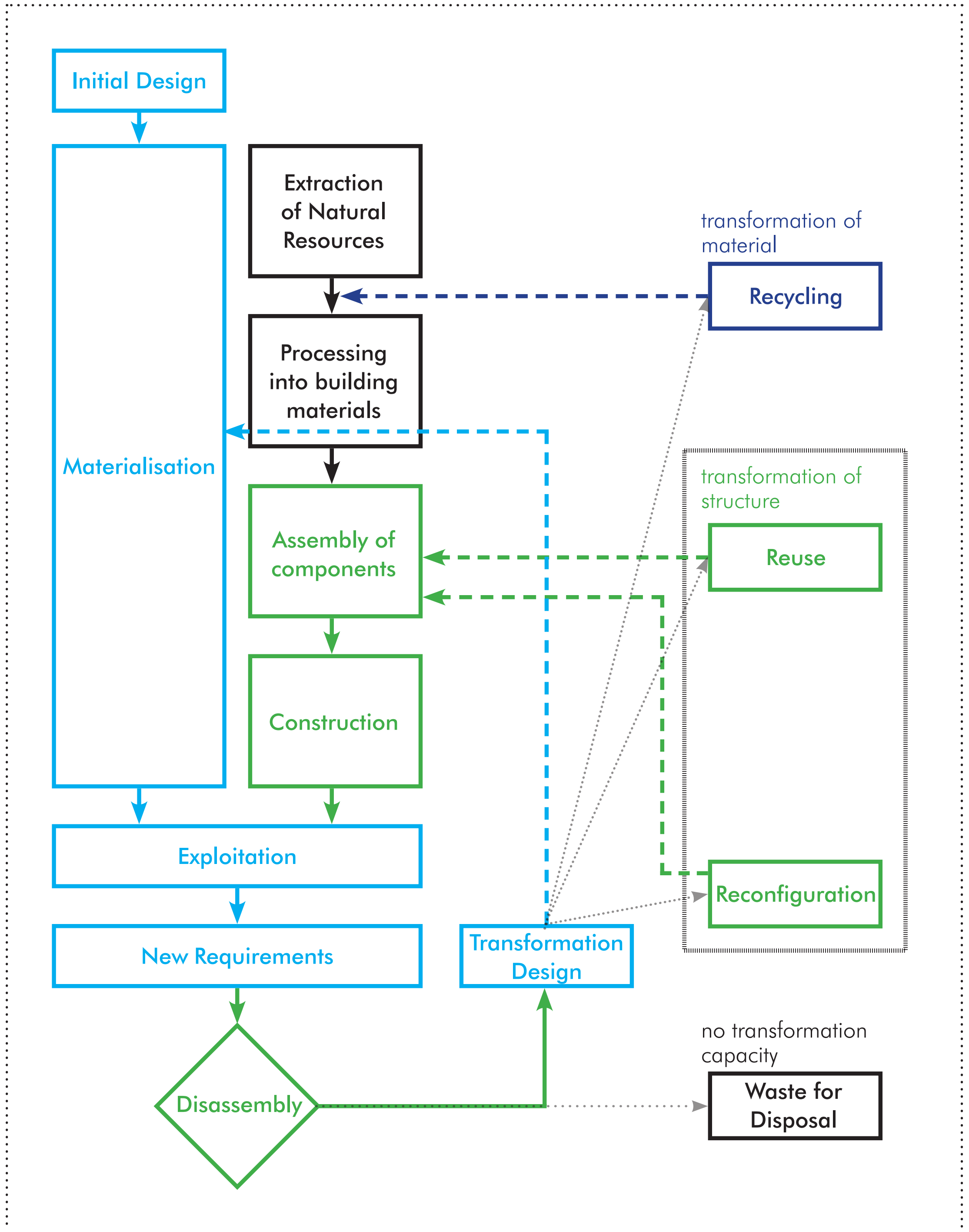


Figure 3.1.8: Sustainable refurbishment model for life cycle of construction materials and components intergrated with trasnformation design (Sources- Durmisevic, 2006. Intergration Scheme - Author)

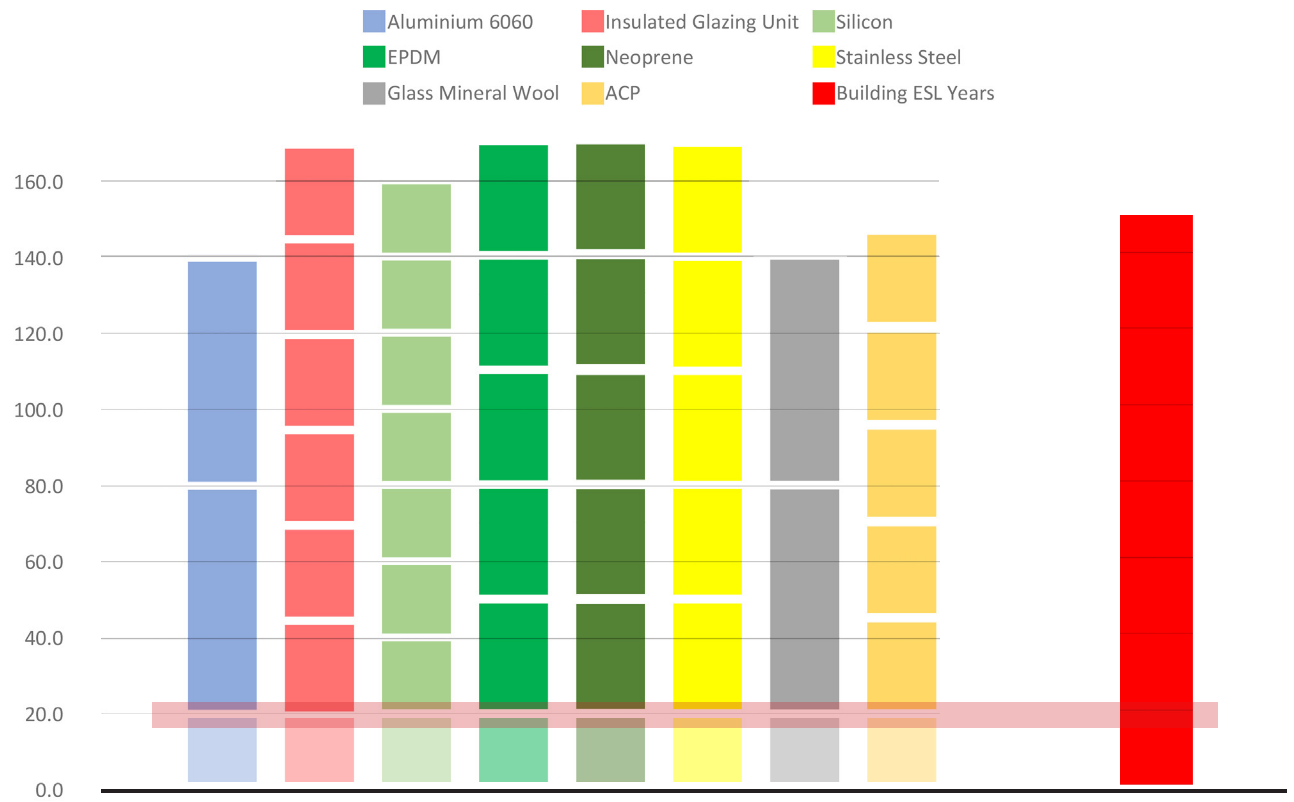


Figure 3.1.9: Proposed option for extending the ESL of curtain wall facade and hence the building (Source - Author)

be understood that materials with lesser service life, which is part of a complex composite system will perform poorly and hence reduce the performance of the whole system as well. The functional service life of the facade hence has been kept at a lower value as the performance of the entire curtain wall facade is determined by its weakest material or component.

Also, there would be interest from the market and businesses to keep the service life lesser to allow for further business opportunities. A direct effect of this is that the operations of the building will be expedited to get the investments of the back quickly. In a way, the facade does determine the life of a building, which is also the reason why some buildings are torn down prematurely because the cost of maintaining and operating the buildings increases exponentially after the facade has deteriorated over time post its end-of-service-life.

To abate 30-year mandatory facade replacement or to allow the building to underperform after the weakest component fails the objective of the design is to allow for disassembly on site and make replacing the component as simple as changing a damaged lightbulb. This allows for accessibility to any part of facade with ease (of course the complexity to go by this rule increases as the height of the building increases, but it can be achieved through design as well). The solution here is to think of the facade as a large transparent window or a door, which has the capacity to withstand the elements as a regular facade of course but has an added function to allow for individual panel accessibility. The design will allow easy replaceability of components or elements which have failed or are underperforming at any given point of time. Figure 3.1.9. shows the proposal to the problem identified in Chapter 1.3 and showcased in Figure 3.1.1. The design for existing matured buildings will allow for an intervention when deemed necessary and then the proposed Plug&Play facade with disassembly will be installed at a 20 - 30 year period (which is the ideal time for facade replacement or refurbishment). after that, the design of the proposed system will allow for accessibility to any component in the facade, which will ensure that all components can perform to its full extent, and not be wasted prematurely or that the building underperforms energy wise till the end-of-life of the building. Figures 3.1.10 and 3.1.11 shows a typical facade or the existing facade along with the ESL of the curtain wall facade material. It can be seen that the facade when replacing every 30 years has materials such as silicon, IGU's, cladding etc... which fail and reduce the energy performance of the building and certain materials such as aluminium and insulation which has been highlighted with a darker colour and red border shows overlap which means that those materials could last for more have to be replaced and hence wasted. This composite nature of facade components needs to be addressed through design for disassembly. Figures 3.1.12. moreover, 3.1.13. show the solution to this issue by breaking down the period of intervention to allow access to failed or failing components when required.

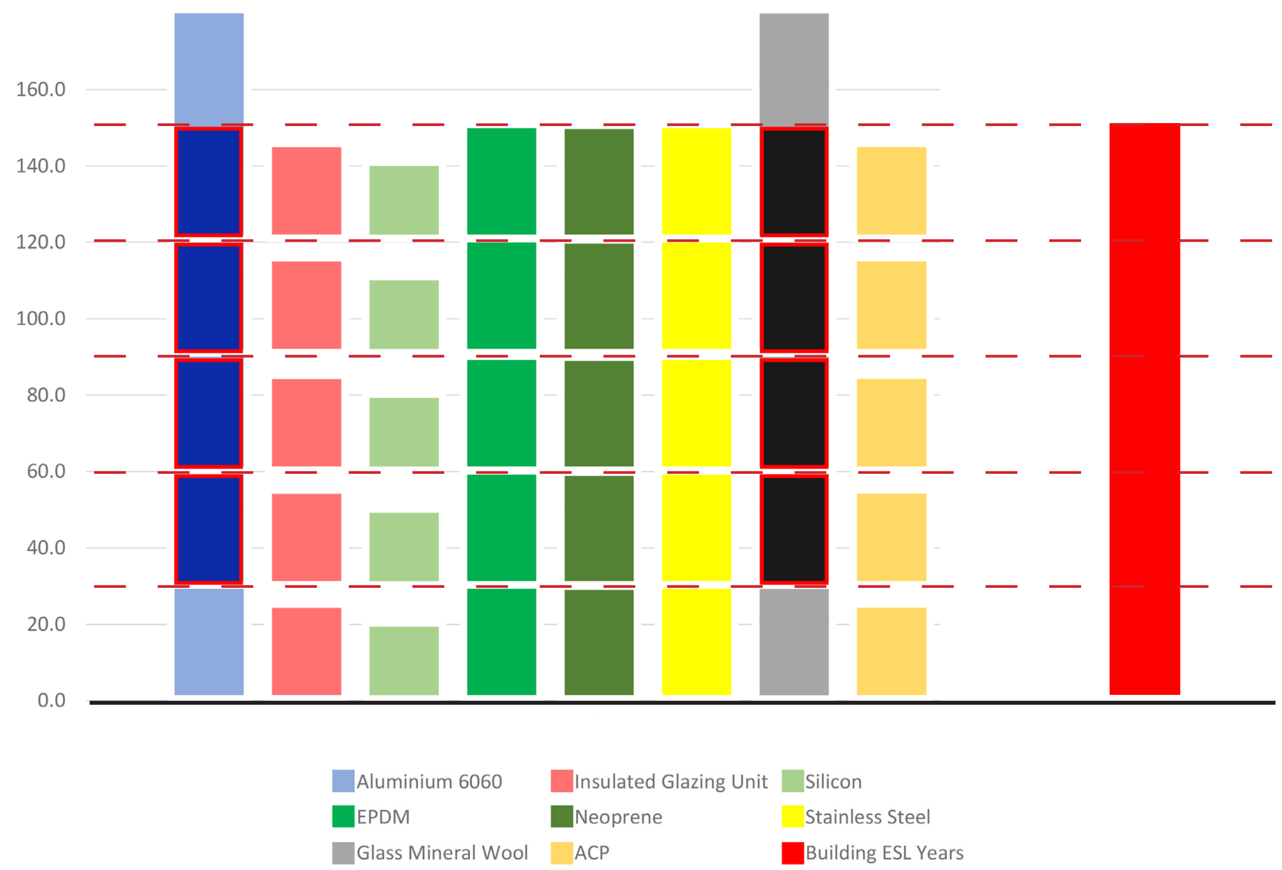


Figure 3.1.10. Overview of ESL of existing facades in comparison to probable ESL of the building (Source - Author)

2. **Design for maintenance:** Accessibility holds the key to allow for maintenance, As explained in Chapter 3.2. Maintenance holds the most significant monetary value for the performance of the facade. Apart from failing components and poorer performance of the facade which leads to energy overuse. Curtain walling because it is subjected to external weather conditions needs to be cleaned, and inspected for structural integrity for safety at least bi-annually for cleaning of debris and sand operation of components and annually for inspection of damage, shrinkage, and lubricating the hinges and connections which allow for thermal and structural movements (Moody & Needles, 2008).

   For and bi-annual and annual maintenance the current system for curtain walling allows for external building maintenance units BMU's (which is particular to the case study under investigation for this project). Otherwise, it is typical to have external access cat-way around the periphery of the building per floor and another facade over it. Providing access to the facade panels from the point where it needs maintenance will save up the need for large expensive maintenance systems and hence have a significant impact in reducing the cost of maintenance of the facade over time. Although this would also mean that the number of labourers may increase if the maintenance is to be scheduled within a specific time or that the

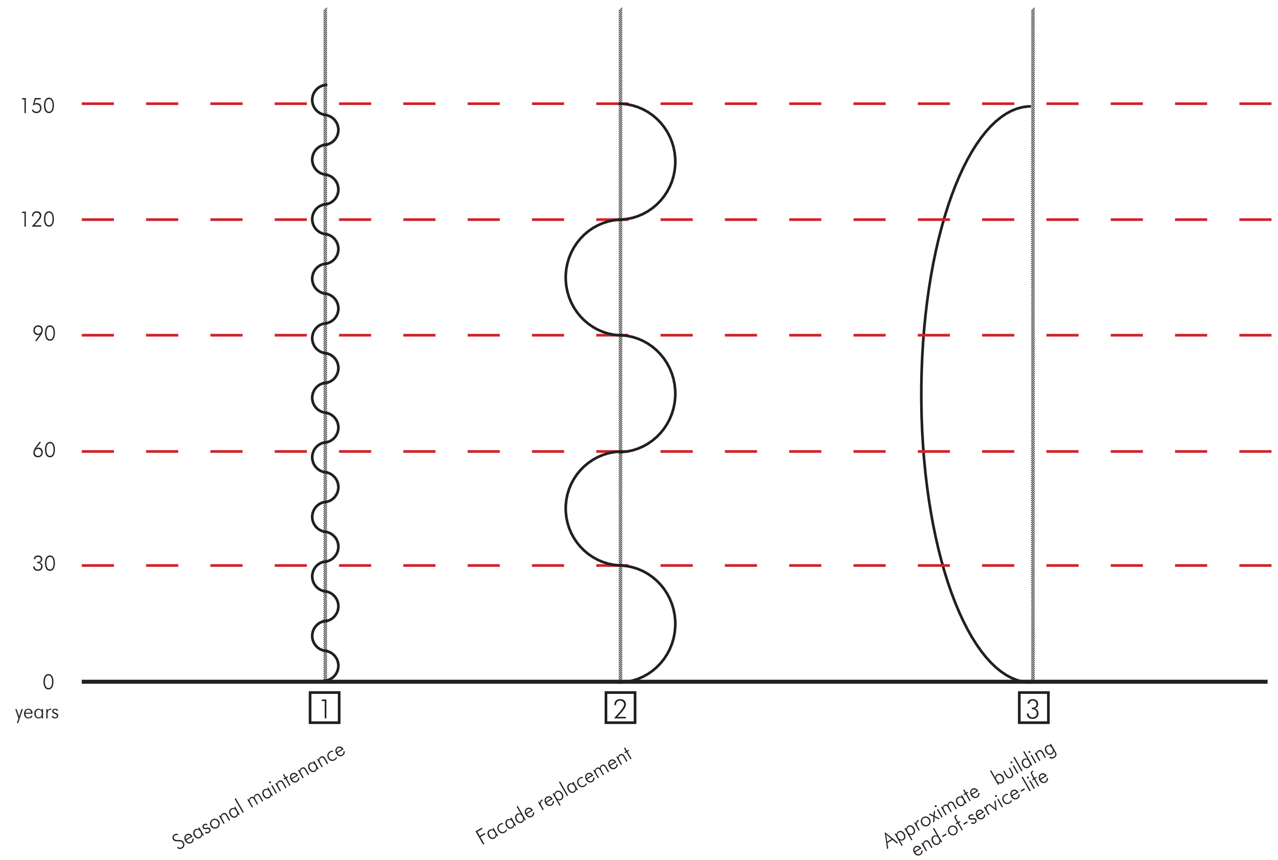


Figure 3.1.11. Technical life cycle overview of ESL of existing facades in comparison to probable ESL of the building in maintenence perspective(Source - Author)

maintenance process will be slow because almost all accessible panels of the facade will need to be opened once or twice every year.

Problems with such system are that it increases the onus for the facilities management team to coordinate if the seasonal maintenance is carried out properly and that the envelope is sealed back sufficiently after the maintenance, otherwise the whole concept could fail. The solution to this could be that there could be low power fail-safe mechanisms installed thanks to the concept of plug and play or an engineered detail which does not allow the pressure plates to be fixed back until the operable panel is tightly shut. On the other hand, a strict checklist could be developed to ensure people operating the system have sealed the envelope enough.

In terms of opening each and every panel, it could be also that for seasonal maintenance which involves cleaning the glass and checking for damage does not really require for all panels to be opened. Instead, it could be that one panel per room could be opened and then the person could use a harness to access other 7 panels per room to step outside and clean the facade if necessary. As for this particular case, the since the building is a Hotel, the operation of the hotel itself will allow for the panels to be accessed as not all rooms are occupied at the same time. Hence, the rooms which are unoccupied at a certain time can maintain that part of the facade when required and the facilities management and the hotel operations team can work together to coordinate the maintenance of the facade as well as the empty rooms at the same time. It is clear that more thoughts need to be put in this particular aspect, But the premise of the system is not just to allow for bi-annual access but also for complete replacement of parts of the facade which needs to be changed. Here the proposed system gains some points as such service happens every 15 years or more and the design allows for disassembly at the point of maintenance and replacement or maintenance at the same location. So the operations of the building would not have to be stopped for many months or sometimes even a year till the facade is removed and the new facade comes in.

3. **Design for disassembly:** Design for disassembly can be considered as an opportunity to explore sustainable design. The premise being that transformation design allows for disassembly potential. Higher transformation capacity means lower environmental impact resulting in improved sustainability. In other words the more the building or building elements are disassemblable the more environmentally friendly and energy efficient the building could be (Durmisevic, 2006).

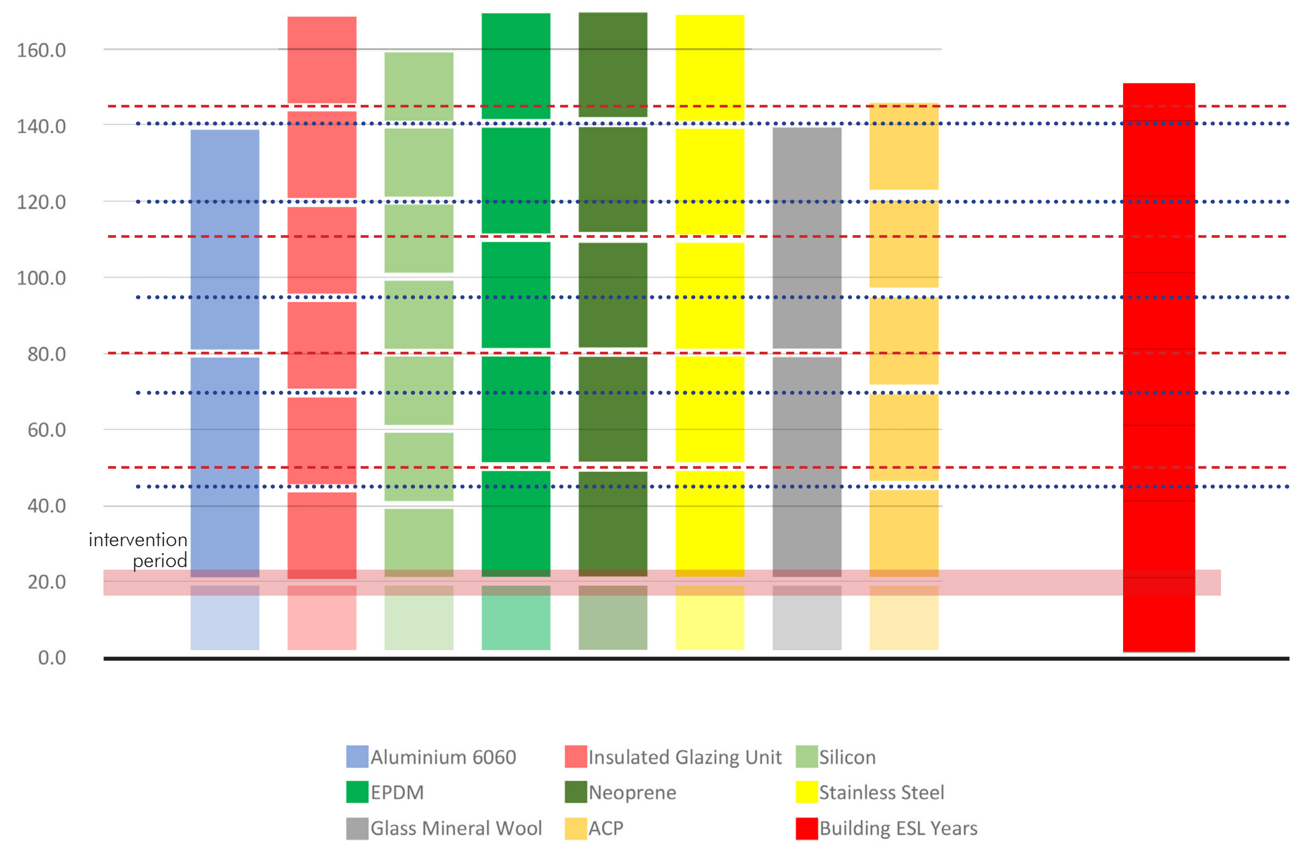


Figure 3.1.12. Proposed option for extending the ESL of curtain wall facade and hence the building (Source - Author)

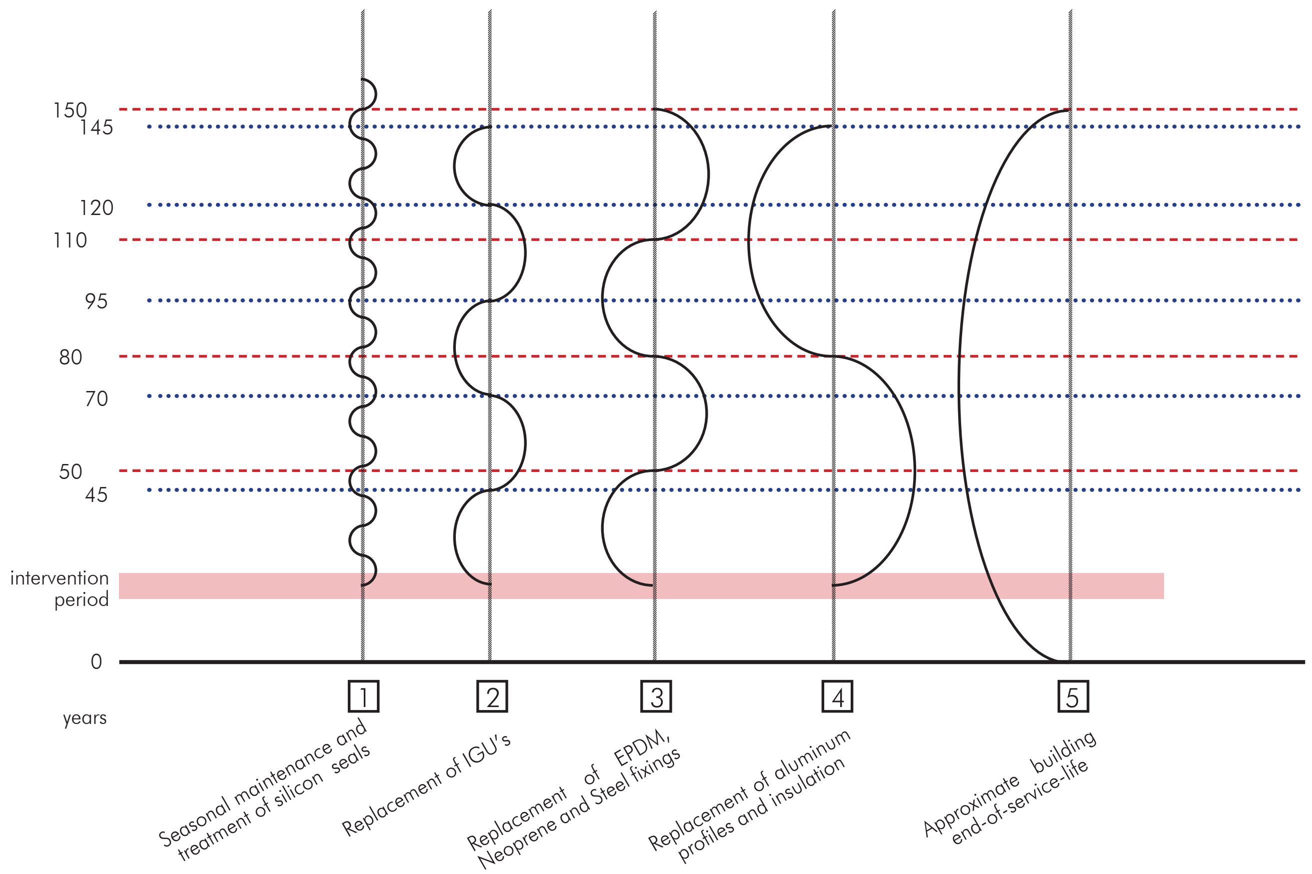


Figure 3.1.13. Technical life cycle overview of ESL of proposed facade in comparison to expected ESL of the building in maintenence perspective (Source - Author)

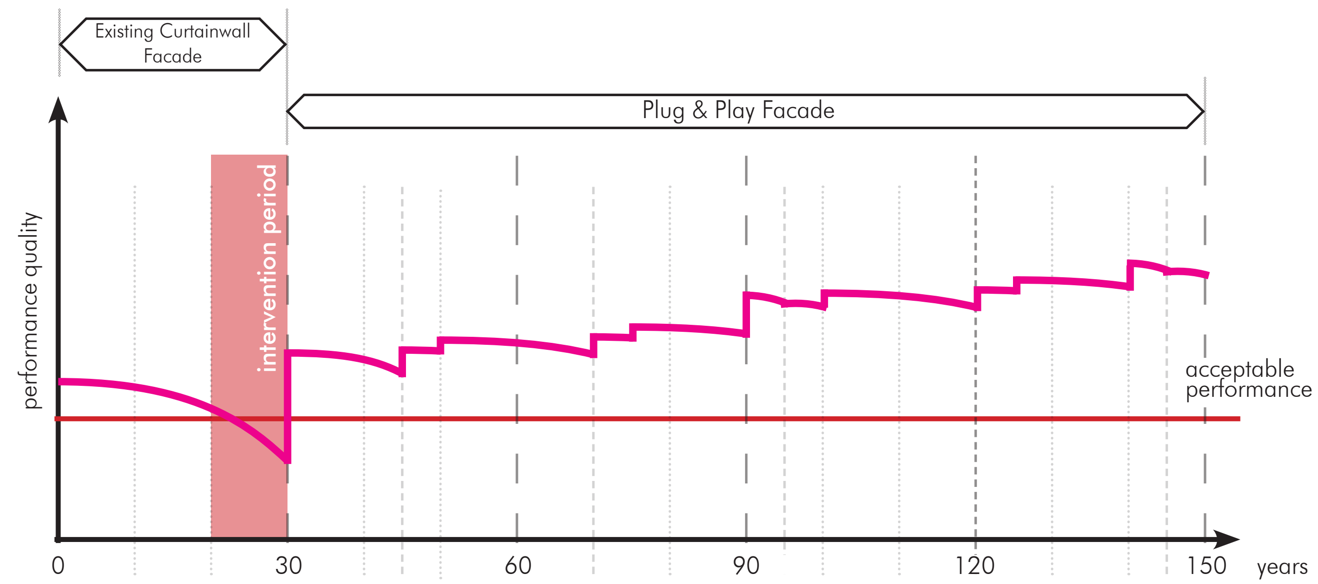


Figure 3.1.14. Perdicted Performance VS Service Life Graph (Source - Author)

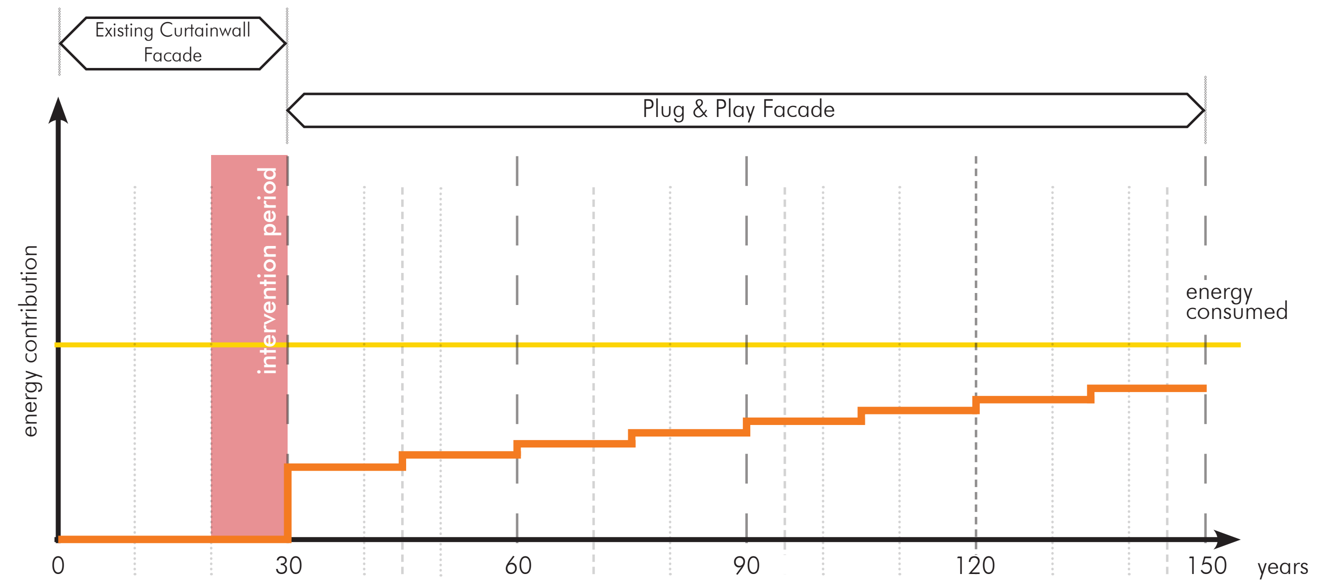


Figure 3.1.15. Predicted Energy VS Service Life Graph (Source - Author)

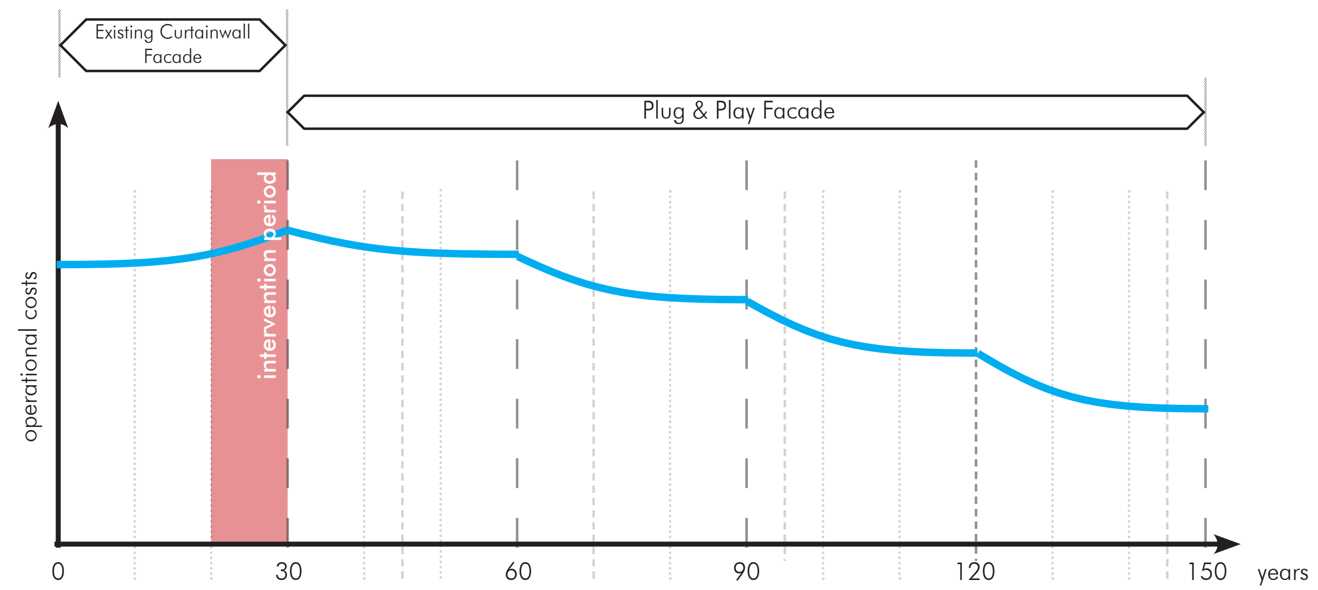


Figure 3.1.16. Predicted Costs VS Service Life Graph (Source - Author)

ESL of building:	**150 years**
Façade ESL:	**30 years**
Façade Maintenance:	**0.5 years**

Figure 3.1.17: Summary of Boundary Conditions (Source – Author)

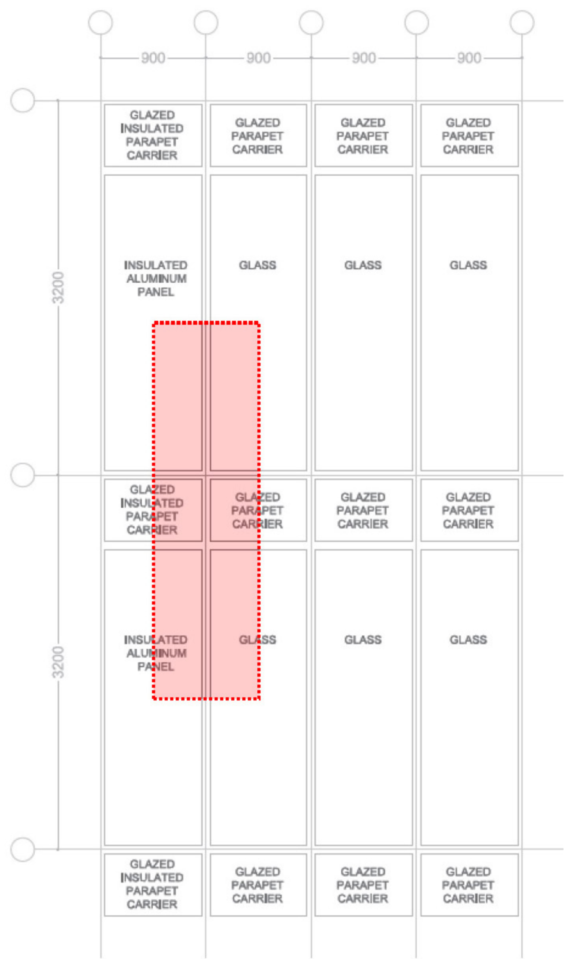


Figure 3.1.18: Area of facade under investigation for LCA analysis (elevation of an existing facade from the case study)

Design for disassembly can be considered as an opportunity to explore sustainable design. The premise being that transformation design allows for disassembly potential. Higher transformation capacity means lower environmental impact resulting in improved sustainability (Durmisevic, 2006) The most important aspect to design for disassembly is to understand how each material behaves through all phases of its life and its precise function within the whole ecosystem. Typical curtain wall facade systems have fixed integration of components and are closed systems. Any change in the physical or mechanical property of the panel or its components could lead performance issues which is harder to fix, and when more panels reflect similar failures the whole facade needs to be demolished and rebuilt. This is because the system is rigid and ignores the aspect of elements having a different operation and technical life capacity. It is excruciatingly hard at the moment to isolate (target) and fix issues particular to any location in the facade. The solution in this account is to have a systems approach in facade design.

Figure 3.1.8. elaborates how such a system can help. Design for disassembly can also include in its umbrella transformation design which will create a feedback loop. Where newer components can be incorporated into the existing system which is only governed by design or geometrical rules. Hence, the system allows for not just replacement of components when required but also includes the future-proofing aspect, where better and improved technologies can be incorporated into an existing system if the building development needs to do so.

Design for disassembly becomes more interesting to evaluate when compared with different disposal options, against a number of steps required for disassembly. (Graedel & Crutzen, 1997). In summary, the research suggests that the end-of-life costs and in this case operational costs can be minimised if the product is designed to be disassembled in few steps.

Material Category	Material Specification	Material Cost	Travel Distance of the Raw Material from Source	Travel Distance of Raw Material to Factory	Mass	Volume	Weight	Percentage of Material per Pannel	Weight per Truck	New Product Cost	Cost Including Removal, Disposal and New Installation	Travel Distance to Factory	Travel Distance of Pannels to Site	Overall Travel Distances	Mass of Material Per Category	Overall Mass till ESL for Existing Façade	Required number of Changes till ESL	Overall Mass till ESL for PnP
		EUR/kg	km	km	kg	m^3	N	%	kg	EUR/m2	EUR/m^2	km	km	km	Kg	Kg		Kg
Aluminium Curtainwall	Aluminium 6060	1.81 €	2600.00	63.60	9.755	0.0036	95.60	7.6%	0.01353	360.00 €	2,400.00 €	106.0	139.0	384.0	28.18	140.91	3	84.54
	Aluminium 6060	1.81 €			18.426	0.0068	180.58	14.3%										
	Aluminium 6060	1.81 €			0.000	0.0000	0.00	0.0%										
	Aluminium 6060	1.81 €			0.000	0.0000	0.00	0.0%										
Insulated Glazing Unit	Tempered Clear Glass	6.43 €	0.00	45.00	61.506	0.1070	602.76	47.8%	0.02953			139.0		139.0	61.51	307.53	5	307.53
	PVB		2600.00															
	Tempered Clear Glass	6.43 €	0.00															
	Argon Gas		0.00															
	Polyisobutylene		0.00															
	Silicone/Polysulfide	9.46 €	0.00															
	Silica Gel		0.00															
	Stainless Steel	3.00 €	2600.00															
	Tempered Glass Low-E	1.35 €	0.00															
Mixed Plastics for Seals and Weather Protection	Silicon		11345.88	63.60	2.833	0.0025	27.76	2.2%	0.00384			163.0		441.0	6.14	30.70	7	42.99
	Silicon				3.308	0.0030	32.42	2.6%										
	EPDM	2.54 €	11345.88	63.60	0.663	0.0006	6.50	0.5%							1.86	9.28	4	7.42
	EPDM	2.54 €			1.192	0.0011	11.69	0.9%										
	Neoprene	3.62 €	11345.88	63.60	0.000	0.0000	0.00	0.0%							0.00	0.00	4	0.00
Other Metals for Connections	Stainless Steel	3.00 €	2600.00	63.60	0.520	0.0038	5.10	0.4%	0.00025			163.0		441.0	0.52	2.60	4	2.08
	Aluminium 6060	1.81 €			0.000		0.00	0.0%										
	Stainless Steel	3.00 €			0.000		0.00	0.0%										
	Stainless Steel	3.00 €			0.000		0.00	0.0%										
	Stainless Steel	3.00 €			0.000		0.00	0.0%										
Insulation	Glass Mineral Wool	4.67 €	0.00	63.60	16.524	0.1530	161.94	12.8%	0.00793			163.0		441.0	16.52	82.62	3	49.57
ACP	Coil-coated Aluminium	1.81 €	12273.20	63.60	14.054	0.0122	137.73	10.9%	0.00675			163.0		441.0	14.05	70.27	6	84.33
	Polyethylene/Polyurethane																	
	Coil-coated Aluminium	1.81 €																
			40164.96	490.20	**128.782**	**0.294**	**1262.06**	**100.0%**	0.06183							643.91		578.46

Table 3.1.19: Material list for typical curtain wall system and necessary parameters for Life Cycle Assesment (Source – Author)

3.1.4. Predictions

Combining performance with life cycle analysis calls for a system which answer to time along with the the function it is supposed to do. As discussed in the chapters above design for disassembly has a solution for it.

Figures 3.1.14, 3.1.15. & 3.1.16 are are preducted results of the proposed system.

1. **Predicted Performance vs Service Life:** Figure 3.1.14. suggests that everytime the facade is serviced over large periods of time considering aspects of transformation design, a prediction can be made that the technology is likely to have improved. Better insulation, better composition, improved material quality etc... can contribute to improve the performance of the building, if not improvement it can be so that constant maintanence can atleast not reduce the performance of the building, so that it had to be torn down.

2. **Predicted Energy vs Service Life:** Figure 3.1.15. suggests that intergration of technologies or systems such as shading, solar thermal, photovoltaic, thermoelectrical systems and many more can contribute to energy production and hence reduce the capacity of the building to rely on non-renewable sources. This intergration will allow sustainability and lesser carbon emmissions to the environment.

3. **Predicted Costs vs Service Life:** Figure 3.1.16. suggests that due to combination of improved performance and energy production the operational costs of the building is prone to go down overtime in the future. But, it must be noted that this prediction is not to scale and does not clearly reflect the inflation rate of commodities, fuel, and operational costs due to increased labour wages yet.

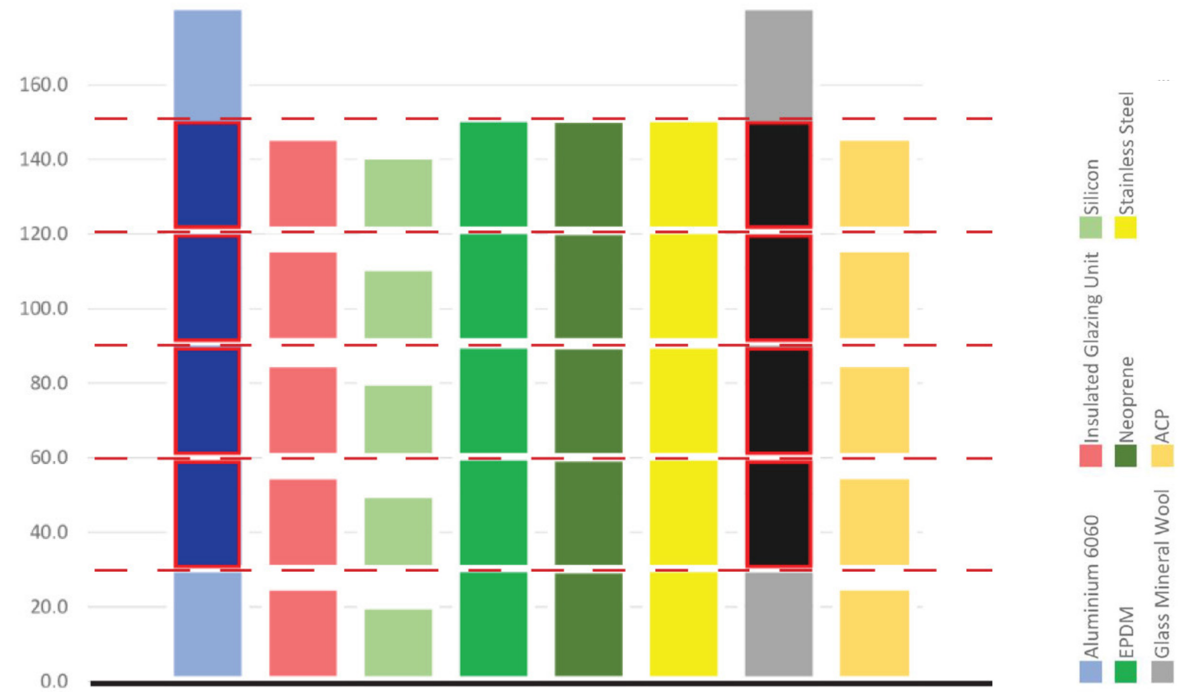


Figure 3.1.10. Overview of ESL of existing facades in comparison to probable ESL of the building (Source - Author)

3.1.5. Conclusion

Table 3.1.19 shows the calculations, and the red highlighted box indicates a comparison of the mass of the selected portion of a facade till its ESL, as shown in Figure 3.1.18. as per the boundary conditions extrapolated for a standard curtain wall facade.

The overall section mass of existing facade is based in simple addition of materials for 5 full facade changes over the life (See Figure 3.1.10) of the building and the overall section mass of facade for PnP would provide the mass of the selected portion of the facade for variable component changes as elaborated in Figure 3.1.12. (Please note that the number of changes per material is mentioned in the table section Required number of changes till ESL).

When both these values are multiplied by the overall surface area of the building we get the mass of the entire facade. It should be noted that the mass of the overall facade at a time for the selected case is about 3,900 tons.

Mass of existing facade = 19,500 tons (approx)
Mass of proposed PnP facade = 16,200 tons (approx)

Hence, it can be observed that the amount of material saved is about 3,300 tons (approx). This means that with design for disassembly and accessibility (proposed concept) the mass of material equivalent to a whole new facade can be saved.

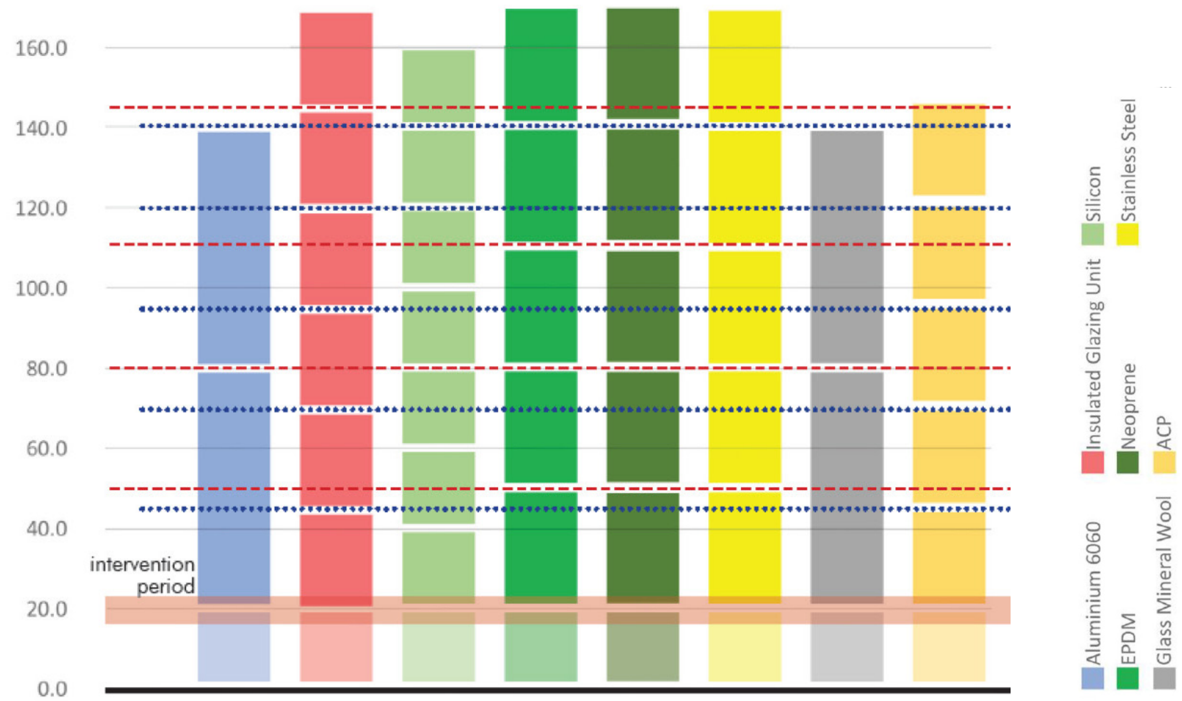


Figure 3.1.12. Proposed option for extending the ESL of curtain wall facade and hence the building (Source - Author)

3.2. Economic Assessment

3.2.1. Introduction

The economic assessment aims at comparing the impacts of typical or existing curtain wall systems to the proposed system, considering the aspects of assembly, demolition and disassembly along with with with replacement post the period of required intervention. The assessment will include all the aspects and materials which have a direct impact on the cost throughout the lifetime of the building.

The universal equation to perform the economic assessment is used. The equation was developed by M. Kim, 2013 following methods by Symonds along with ARGUS, COWI and PRC Bouwcentrum, 1999. The equation has been adopted from the research to evaluate the conditions in this thesis. The universal equation is described as Figure 3.2.1. as follows.

<Net costs from each scenario>

$$C_{net} = HL + E + W_1{*}S + T{*}\Sigma(W_n{*}K_i) + \Sigma W_n{*}P/D_j - \Sigma W_n{*}R_k$$

Labor (HL), *Machinery* (E), *Sorting* (W_1*S), *Transportation* ($T*\Sigma(W_n*K_i)$), *Recycling or Disposal* ($\Sigma W_n*P/D_j$), *Recovery* (ΣW_n*R_k) [Cost in different phases]

Where,

H: Execution hour (h),

L: Labor cost(€/h),

E: Equipment cost(€),

S: Cost of sorting process (€/kg),

T: Cost of transportation (€/kgkm),

K_i: Travel distances (km)

W: Weight of materials (kg)

P/D_j: Cost of recycling or disposal process(€/kg)

(1)P_{alu}: Aluminum recycling, (2)P_{gl}: Glass recycling, (3) P_{pla}: Plastic incineration and (4)D_{re}: Residue landfill

R_k: Revenue from material or energy recovery

(1)R_{sc}: Aluminium Scrap(€/kg), (2)R_{pro}: Secondary Aluminum profile(€/ kg), (3)R_{gl}: Secondary glazing unit(€/ kg), (4)Re: Electricity (€/ kg) = (€/kWh)*(kWh/kg)

Figure 3.2.1: Universal equation for economic analysis (Source – M. Kim, 2013)

3.2.2. Boundary Conditions

The overview of the boundary conditions has been summarized in Figure 3.2.2.

1. **Building Data:** The building data was extracted from the existing case study building of Address Hotel, Dubai as described in Chapter 1.6.
   Surface area of the building was extracted from the rhino model, using which the amount of panels was determined based on the approximate width of the panel.

2. **Facade Data:** Various studies from (Du, Wood, Stephens, & Song, 2015), (Barrington, 2018),

Data Type	Description	Values	Units	Source
Building Data	Typical Floor Area	2745	m^2	*~ Approximate Measurements from 3D model developed by the author*
	Overall Floor Area	137250	m^2	
	Surface Area of the Building	28,540.56	m^2	
	Number of Panels (if Width is 0.9m)	9,910	nos	
	Number of Panels (if Width is 1.2m)	7,432	nos	
Façade Data	Façade ESL Years	30	years	*(Kakolyri, 2015)*
	Building ESL Years	150	years	*(Du, Wood, Stephens, & Song, 2015) (Barrington, 2018) (Durmisevic, 2006)*
Construction Workers Data	Number of Construction Workers	4	nos	*~Industry Expert Interview on March 2019 Company: TECHNAL, UAE*
	Labor Salary	2,500	AED/month	*(DubaiFAQs, 2019)*
		30,000	AED/year	
	Number of Working Hours	48	per week	*(MoHRE)*
	Overhead Costs or Markup	25%	-	*~Industry Expert Interview on March 2019 Company: TECHNAL, UAE*
PnP Predictions	Number of Construction Workers	2	nos	*~assumption based on design expectations*
Maintenance Standards	Average Age of BMU's	60	years	*(BVM, 2016)*
Transportation Standards	Capacity of the Truck	20,411.66	kg	*(cerasis, 2015)*
		22.50	tons	
	Price of Diesel	2.49	AED/liter	*~price per liter is based in oil prices in Dubai as of 10th March 2019*
	Average Milage of Truck	3.00	kms/liter	*(cerasis, 2015)*
Recycling	Amount of Material Sorted Per Hour	666	kg	*~Industry Expert Interview on March 2019 Company: TECHNAL, UAE*
	Number of Hours Spent Sorting per 1 Ton	1.5	hours	
Universal Standards	Conversion Rate AED to EUR	0.24	-	*~standard conversion rate as of 10th March 2019*
	Number of Weeks in an Year	52.14	weeks	*~universal standards*
	Number of Hours in an Year	8,760	hours	

Figure 3.2.2. Summary of Boundary Conditions (Source – Author)

(Durmisevic, 2006) predict that average service life of a building varies based on materials, local by-laws, type of construction and the expectations of the local government for the future of the neighbourhood where the building resides, although most studies conform to an average of 100 years-150 years of life of the building. Durmisevic, 2006 also went ahead to elaborate that the cladding of the building tends to last to up to 20 years and the interior fit-out tends to be changed every 3 years at an average. However, for the scope of this study Kakolyri, 2015 has defined the average service period of the façade as 30 years.

3. **Construction Workers Data:** The data provided in this section is largely an assumption based on verbal and literature surveys from the practising architects, engineers, internet and few experts in the industry. A middle eastern representative from a popular aluminium extrusion company TECHNAL also suggested some inputs in the matter. The number of people working to install a façade varies from the scale of project to the type of façade, but at an average it becomes difficult to assume people per panel as the façade is installed by a team of experts who will range in working positions from a constructions worker, metal welder, glass installer, crane operator, communications handy-man, supervisors, site inspectors, cad draftsman, company manager etc.. And as for the size of the team is determined by the project handover time and the pace of construction. At an average for the scale of the project, in this case, it has been assumed that the size of the team could be around 40 people with about 4 people required to fix a panel at a time. Salaries were determined from DubaiFAQs, 2019 and the average working hours was as per Dubai Labor Law of 48 hours per week as per Ministry of Human Resources and Emiratisation (MoHRE)

4. **Maintenence Standards:** Several Building maintenance unit manufacturers were identified, such as MaltTechnics, XS Platforms, TRANSWILL, Manntech, Oriental Equipment Factory, BVM, Mitsulift (Mitsubishi Electric) etc.. Most maintenance units manufactured according to European Regulations (EN 1808) have a life span of 30 years and the long availability of spare parts can be determined for another 30 years. (BVM, 2016)

5. **Transportation Standards:** Although transportation of various materials varies based on location, requirement and type and quantity of consignment. For the ease of calculation, it was assumed that all the materials will be transported from the Shipping port to the factory, to the area of assembly and then to the construction site.

   The travel distances were measured by the location of popular factories for each material in the region to the fixed location of the construction site, which in this case is Downtown, Dubai, UAE.

   The size of the truck and the mileage was based on a standard Freight Trailer (cerasis, 2015) with a 45,000 lbs. capacity (equivalent to 20,411.66 kilograms). The price per litre is based on oil prices in Dubai as of 10th March 2019.

6. **Recycling:** Amount of materials sorted at the construction site or the project site varies again based on the circumstances of the project. Although with large Hydraulic cranes an about 2-3 skilled construction workers can process up to 1 ton of material in one and half hours as recommended by industrial experts.

7. **Universal Standards:** Values represented in this section is provided for ease of perusal and reference.

3.2.2. Analysis

Values entered into the universal economic assesment equation consists of following parameters:

1. Breakdown of Materials in Curtain Wall per sq.m:

   The red highlighted are as shown in Figure 3.2.3 is a portion of the existing facade which contains all necessary typical materials to conduct a fair evaluation of the facade. It must be noted that the opaque element called Insulated aluminium panel is not as ubiquitous as the glass in the whole facade but, has been deemed necessary for exploring effects of more materials than the most common one. The breakdown of the materials is similar to the one discussed in Chapter 1.3 of the thesis and has been further elaborated in Table 3.2.4.

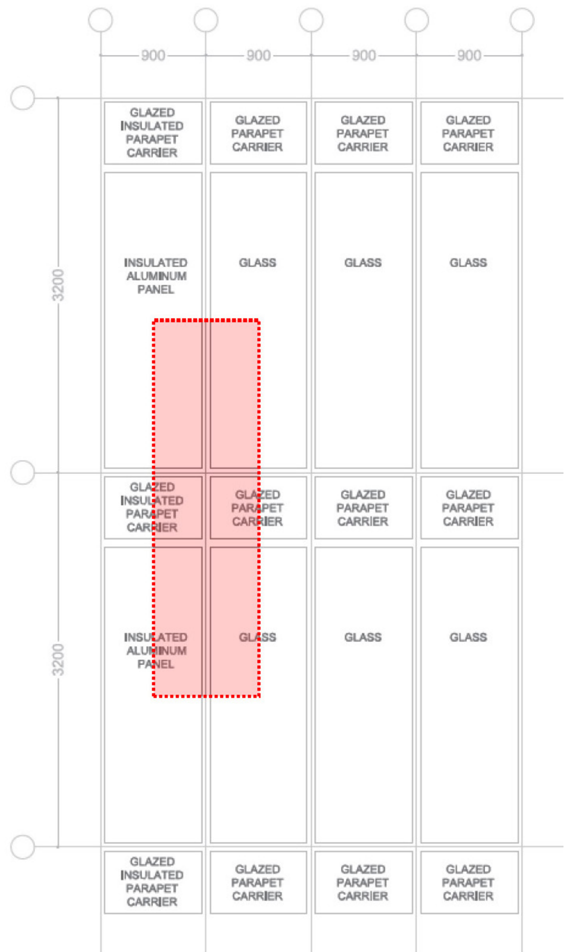


Figure 3.2.3: Area of facade under investigation for economic analysis (elevation of an existing facade from the case study) (Source – Author)

2. Cost of Materials & Facade

   It was first necessary to identify the cost of an average new curtain wall for the region and the study conducted by Turner & Townsend, 2016 called International construction market survey 2016 provided valuable information where the cost of new façade per meter square for jobs more around or more than 1000 sq.m m and the cost of removal, disposal, and new installation of curtain wall on existing façade has been rounded off to 2,400 AED per sq.m based on a market survey. It must be noted that the values provided here are a lump sum of the figure as the façade contractors do not provide the breakdown per material for a student thesis and the companies contacted with this purpose were unwilling to share monetary data.

   But, Table 3.2.4. has the price per raw material costs which was extracted from CES EduPack 2018 Software.

Material Category	Material Specification	Material Cost	Travel Distance of the Raw Material from Source	Travel Distance of Raw Material to Factory	Mass	Volume	Weight	Percentage of Material per Pannel	Weight per Truck	New Product Cost	Cost Including Removal, Disposal and New Installation	Travel Distance to Factory	Travel Distance of Pannels to Site	Overall Travel Distances	Mass of Material Per Category	Overall Mass till ESL for Existing Façade	Required number of Changes till ESL	Overall Mass till ESL for PnP
		EUR/kg	km	km	kg	m^3	N	%	kg	EUR/m2	EUR/m^2	km	km	km	Kg	Kg		Kg
Aluminium Curtainwall	Aluminium 6060	1.81 €	2600.00	63.60	9.755	0.0036	95.60	7.6%	0.01353	360.00 €	2,400.00 €	106.0	139.0	384.0	28.18	140.91	3	84.54
	Aluminium 6060	1.81 €			18.426	0.0068	180.58	14.3%										
	Aluminium 6060	1.81 €			0.000	0.0000	0.00	0.0%										
	Aluminium 6060	1.81 €			0.000	0.0000	0.00	0.0%										
Insulated Glazing Unit	Tempered Clear Glass	6.43 €	0.00	45.00	61.506	0.1070	602.76	47.8%	0.02953			139.0		139.0	61.51	307.53	5	307.53
	PVB		2600.00															
	Tempered Clear Glass	6.43 €	0.00															
	Argon Gas		0.00															
	Polyisobutylene		0.00															
	Silicone/Polysulfide	9.46 €	0.00															
	Silica Gel		0.00															
	Stainless Steel	3.00 €	2600.00															
	Tempered Glass Low-E	1.35 €	0.00															
Mixed Plastics for Seals and Weather Protection	Silicon		11345.88	63.60	2.833	0.0025	27.76	2.2%	0.00384			163.0		441.0	6.14	30.70	7	42.99
	Silicon				3.308	0.0030	32.42	2.6%										
	EPDM	2.54 €	11345.88	63.60	0.663	0.0006	6.50	0.5%							1.86	9.28	4	7.42
	EPDM	2.54 €			1.192	0.0011	11.69	0.9%										
	Neoprene	3.62 €	11345.88	63.60	0.000	0.0000	0.00	0.0%							0.00	0.00	4	0.00
Other Metals for Connections	Stainless Steel	3.00 €	2600.00	63.60	0.520	0.0038	5.10	0.4%	0.00025			163.0		441.0	0.52	2.60	4	2.08
	Aluminium 6060	1.81 €			0.000		0.00	0.0%										
	Stainless Steel	3.00 €			0.000		0.00	0.0%										
	Stainless Steel	3.00 €			0.000		0.00	0.0%										
	Stainless Steel	3.00 €			0.000		0.00	0.0%										
Insulation	Glass Mineral Wool	4.67 €	0.00	63.60	16.524	0.1530	161.94	12.8%	0.00793			163.0		441.0	16.52	82.62	3	49.57
ACP	Coil-coated Aluminium	1.81 €	12273.20	63.60	14.054	0.0122	137.73	10.9%	0.00675			163.0		441.0	14.05	70.27	6	84.33
	Polyethylene/Polyurethane																	
	Coil-coated Aluminium	1.81 €																
			40164.96	490.20	**128.782**	**0.294**	**1262.06**	**100.0%**	0.06183							643.91		578.46

Table 3.2.4: Material list for typical curtain wall system and necessary parameters for economic assesment (Source – Author)

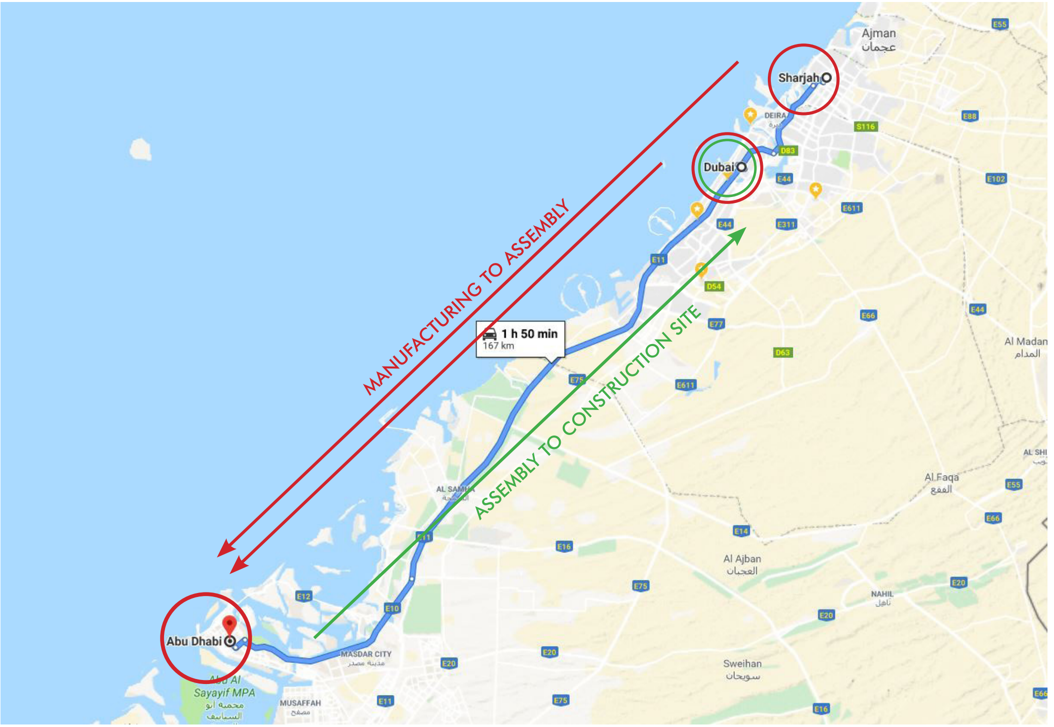


Figure 3.2.5: Travel distances between locations of manufacturing, assembly and construction site (Source – https://www.google.com/maps/)

3. Transportation Distances

The transportation Figure 3.2.5 was broken down to:

- Area of Manufacturing: Sharjah, UAE – As most of the fabrication companies based on a local market survey reveal that raw materials are brought to Sharjah, gaskets, metal connectors, insulation and cladding materials are fabricated here and distributed.
- Area of Assembly: Abu Dhabi, UAE has glass manufacturers, and there is abundance of sand graded for glass manufacturing in the region. The glass manufacturers along with sub-contractors occupy the onus to assemble the unitized system in the factories here to distribute the final panel to the construction site.
- Construction Site: Dubai, UAE has aluminum fabrication companies in the free-zone industrial area and it is also the location where the taken case is situated.

The “travel distance to the factory” section describes the distance from the area of manufacturing of individual components (Dubai / Sharjah) to the area of assembly (Abu Dhabi) and the “travel distance from factory to site” as the name describes is the distance from there the unitized panels are assembled and then distributed to the construction site.

Over all travel distance to move all the materials from various manufacturing locations to the construction site has been estimated to be 2,287 kms. Although it must be stressed that this is a large assumption and does not include aspects such as manufacturer reputations, trust, and profile of the companies. The assumed location is based on the area heat or density of local manufacturers available in the area in concentration. After an telephone interview with a representative of the company TECHNAL, client preferences, designer specifications etc.. can play a large role in how the companies are selected and certain products such as Silicon have a leading manufacturer such as DOW CORNING which is only locally distributed but is manufactured in USA and Canada, similarly it is also common that European companies such as Schüco, Permasteelisa and many more who produce and test the façade panels and components such as gaskets in Europe and then distribute the manufactured products via shipping to the construction location.

4. Mass of Material till ESL

Mass of material till ESL was calculated twice based on a concept which will be discussed in the next chapter see Figure. The first calculation of mass of material was done for the façade who need replacement every 30 years post end of service life of many components as discussed elaborately by Kakolyri, 2015 and in the next chapter.

But post refurbishment with the introduction of Plug&Play façade system which also as an aspect of demountability and disassembly at site to replace only those elements which are faulty or have reduced in performance enables us to save material per sq.m of panel which reduces from 643.91 kgs to 578.91kgs per sq.m for the overall ESL of the building.

Estimates when compared to the overall surface are of the building can save up to 1,855,136.4 kgs or about 2044 tons of materials for existing building.

Five simlutaneous caluclations were made using the universal economic equation (Figure 3.2.1) to determine a comparison between assembly, dis-assembly, demolition, and replacement of both a typical facade system and the proposed Plug&Play facade system. The portion of the facade discussed in the Chapter 1.3 was taken into consideration and for the ease of calculation and comparison the mass of both systems was taken as the same value. Although, later detail design estimates the plug&play facade panel to have more mass than a typical one.

3.2.3. Calculations

1. Labor

The number of construction workers required, as explained in Chapter 3.2.2. Boundary Conditions for each type of construction process was multiplied with the amount of time required to perform each task. The amount of time required was determined mostly by research performed by M. Kim, 2013 and was confirmed from verbal discussions from the experts in the industry. As for the proposed design, it was assumed that a disassemblable panel could be serviced in half an hour. The time per task multiplied by average labour cost per hour DubaiFAQs, 2019, with a 25% additional markup value determined the labour costs per function per system. The relevant equation for the labour cost per sq.m of the facade is given below:

HL = Execution per hour per sq.m * (Hourly Salary * Amount of Working Hours)

HL (Overall) = HL + HL*(25/100)

		H	L	
		Execution Hour	Overall Labor Costs	Oveall Including Markup
		(h)	(EUR/Hour)	(EUR/Hour)+%
Assembly	Curtain Walls	1.00	11.51 €	14.38 €
	PnP Walls	0.30	5.75 €	7.19 €
Demolition	Curtain Walls	0.56	11.51 €	14.38 €
Disassembly		5.00	11.51 €	14.38 €
Replacement	PnP Walls	0.30	5.75 €	7.19 €

Table 3.2.6. Calculation of Labour Costs (Source – Author)

2. Machinery

Cost of machinery was mostly determined by the cost of Building Maintenance Units (BMU). For the selected case, only one BMU was considered and but ideally based on the profile, surface area and the type of façade the building could have two or more BMU's. A USA based façade maintenance company (Big Apple, 2019) quotes the cost of an average BMU to be around $1-2 million and cost of maintenance and re-certification per year is estimated to be around $10,000 to $ 20,000. Overhead costs like mandatory cable replacement per every two years will cost to about $10,000 - $20,000 extra.

For calculation in this project, the cost of BMU based on the previous reference has been considered as 1.76 million euros which will be replaced every 60 years (See Figure 3.2.2.) and maintained every year with 17,631 euros. (The cost of cable management has been assumed within this approximation)

The above cost of equipment along with maintenance was then multiplied with average labour cost to determine the cost of façade maintenance for the whole façade till the end of the service life of the building. Since Plug&Play proposal has a value but it could not be assumed within the scope of this research as on May 2019, it has been left as zero. But, it must be noted that the premise of Plug&Play is to eliminate the use of external access altogether and encourage complete maintenance of façade from inside of the building the large cost of BMU can be eliminated and the other costs of labour, and machinery will be negligible to this scale. The relevant equation for maintenance cost per sq.m of the facade is given below:

E = (Expected age of the building * Average age of BMU * Cost of BMU) + (BMU Maintenence Cost * Expected age of the building)

E (Overall) = E / Expected age of the building / Overall Hours in a Year

		E			
		Equipment Cost	Equipment Maintenance Cost	Equipment Cost Per Façade ESL	Equipment Cost Per Hour
		(EUR)	(EUR/Year)	((EUR*Number of Equipments)+(Maintenance*ESL Years))	(EUR)
Assembly	Curtain Walls	1,764,000.00 €	17,631.36 €	7,054,704.00 €	5.37 €
	PnP Walls	0.00 €	-	-	-
Demolition	Curtain Walls	1,764,000.00 €	-	-	5.37 €
Disassembly		1,764,000.00 €	-	-	5.37 €
Replacement	PnP Walls	0.00 €	-	-	-

Table 3.2.7: Calculation of Machinery Costs (Source – Author)

Figure 3.2.8: Image of Building Maintencene Unit
(Source – http://atlas-anchor.com/products/building-maintenance-unit-roof-car/)

3. Sorting

Since the façade panels in either case if assembled would be for new construction, there would be no sorting process required intrinsically for the assembly process. Although, during disassembly, demolition or replacement process the materials from the existing façade would have to be removed – then sorted to get the mass of material. The value here is per sq.m of façade and then the second column shows the mass of material removed per sq.m for the whole life of the building. As explained in Chapter 5.3.1.2 in a mass of materials till ESL section the mass of materials for typical façade will vary to a proposed new Plug&Play façade. The relevant equation for sorting cost per sq.m of the facade is given below:

Mass of Mateials till ESL of Building = Mass of old facade*(Expected age of the building/ESL of typical facade)

$W_S S$ = Mass of Mateials till ESL of Building / Amount of Material Sorted per hour / Hours in an Year

		W_S		S	WS
		Mass of Material	Mass of Material Sorted for the Service Life of the Building	Cost of Sorting process	Cost of Sorting per Hour
		(Kg)	(Kg)	(EUR per Kg)	(KG*EUR)/
Assembly	Curtain Walls	0.0	0.0	480.00 €	0.00 €
	PnP Walls	0.0	0.0	480.00 €	0.00 €
Demolition	Curtain Walls	128.8	643.9	480.00 €	0.05 €
Disassembly		128.8	643.9	480.00 €	0.05 €
Replacement	PnP Walls	128.8	578.5	480.00 €	0.05 €

Figure 3.2.9: Calculation of Sorting Costs (Source – Author)

4. Transportation

Cost or transportation can be determined by Figure 3.2.2. where the price of fuel is divided by the mileage of the truck multiplied by the mass per sq.m to the overall volume of the truck this whole value was then multiplied to the overall transportation distance assumed in the Chapter 3.2.2. transportation section. Here it is to be noted that the value is AED 0.01, which is rounded off in the chart. However, the calculation has yet been done with the nominal value, which closes to zero but not precisely. The final number provided is 0.17 euros per sq.m of material. The relevant equation for transportation cost per sq.m of the facade is given below:

Cost of Transportation = Price of Diesel/Milage of the truck * (Mass of Material per sq.m/Capacity of truck)

TK = Cost of Transportation * Travel Distance (approximated)

		T	K	W*K
		Cost of Transportation	Travel Distances	-
		(EUR/(Kg*Km))	(Km)	(Kg*Km)
Assembly	Curtain Walls	0.00 €	139.00	0.17 €
	PnP Walls	0.00 €	139.00	0.17 €
Demolition	Curtain Walls	0.00 €	139.00	0.17 €
Disassembly		0.00 €	139.00	0.17 €
Replacement	PnP Walls	0.00 €	139.00	0.17 €

Figure 3.2.10: Calculation of Transportation Costs (Source – Author)

5. Recycling, Disposal & Recover

Proper estimates were not found for conducting this portion of the calculation, and the equation follows summation of these aspects we could either consider them to be equal or leave it out for simplifying the calculation. So, it was safely left out of the equation. Although, since the premise of this calculation is to identify and compare different approaches and between old and new façade, it can be safely determined by the more significant aspects considered in the equation before. The modified equation for economic assessment is as shown in the highlighted region in Figure 3.2.11 below.

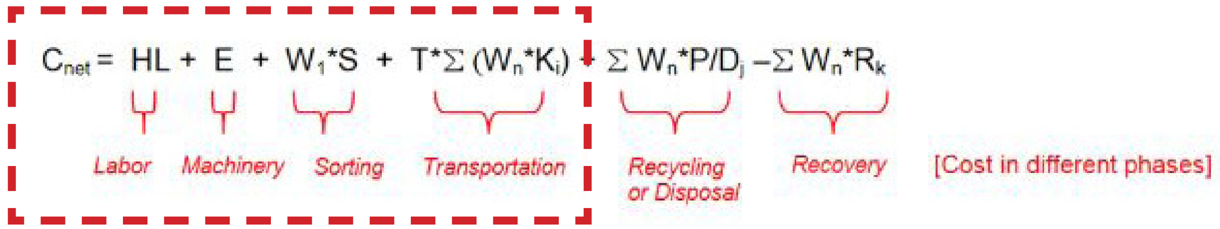


Figure 3.2.11: Modified equation used in the scope of this thesis (Source – M. Kim, 2013)

3.2.4. Conclusion

The economic assessment helps to identify the costs per process for different façade typology. Figure 3.2.12 has an overview of the calculation performed, and the end results per sqm. of the façade has been provided in Figure 3.2.13. Which has been further summarized with the help of graphs in Figure 3.2.16. which represent the cost per façade in case of a typical façade and the cost per façade per Plug&Play system.

The two governing cost factor which was determined from this assessment was the cost of maintenance equipment and the number of construction workers required and the time they have to do the work. Disassembly in this particular case is heavily labour intensive, which explains why it is common in the current market for contractors or clients to prefer demolition. Plug&Play number is surely not realistic as it requires a more complex estimation of the amount of time and people required to maintain and access the building post development. But this research does provide sufficient background to help future researchers to construct upon the idea.

		HL	E	W*S	T*Σ(W*K)
		Labor	Machinery	Sorting	Transportation
		cost of (X) workers in AED/hour (inl. Overhead)	(AED)	(Kg)	(Kg*Km)
Assembly	Curtain Walls	14 €	7,200,000.00 €	0.00	0.17 €
	PnP Walls	7 €	0.00 €	0.00	0.17 €
Demolition	Curtain Walls	14 €	24,000.00 €	0.05	0.17 €
Disassembly		14 €	48,000.00 €	0.05	0.17 €
Replacement	PnP Walls	7 €	0.00 €	0.05	0.17 €

Figure 3.2.12:Summary of Economic Analysis (Source – Author)

		Net Cost
		(EUR/m²/year)
Assembly	Curtain Walls	20.00 €
	PnP Walls	3.00 €
Demolition	Curtain Walls	14.00 €
Disassembly		78.00 €
Replacement	PnP Walls	3.00 €

Figure 3.2.13: Results of Economic Analysis (Source – Author)

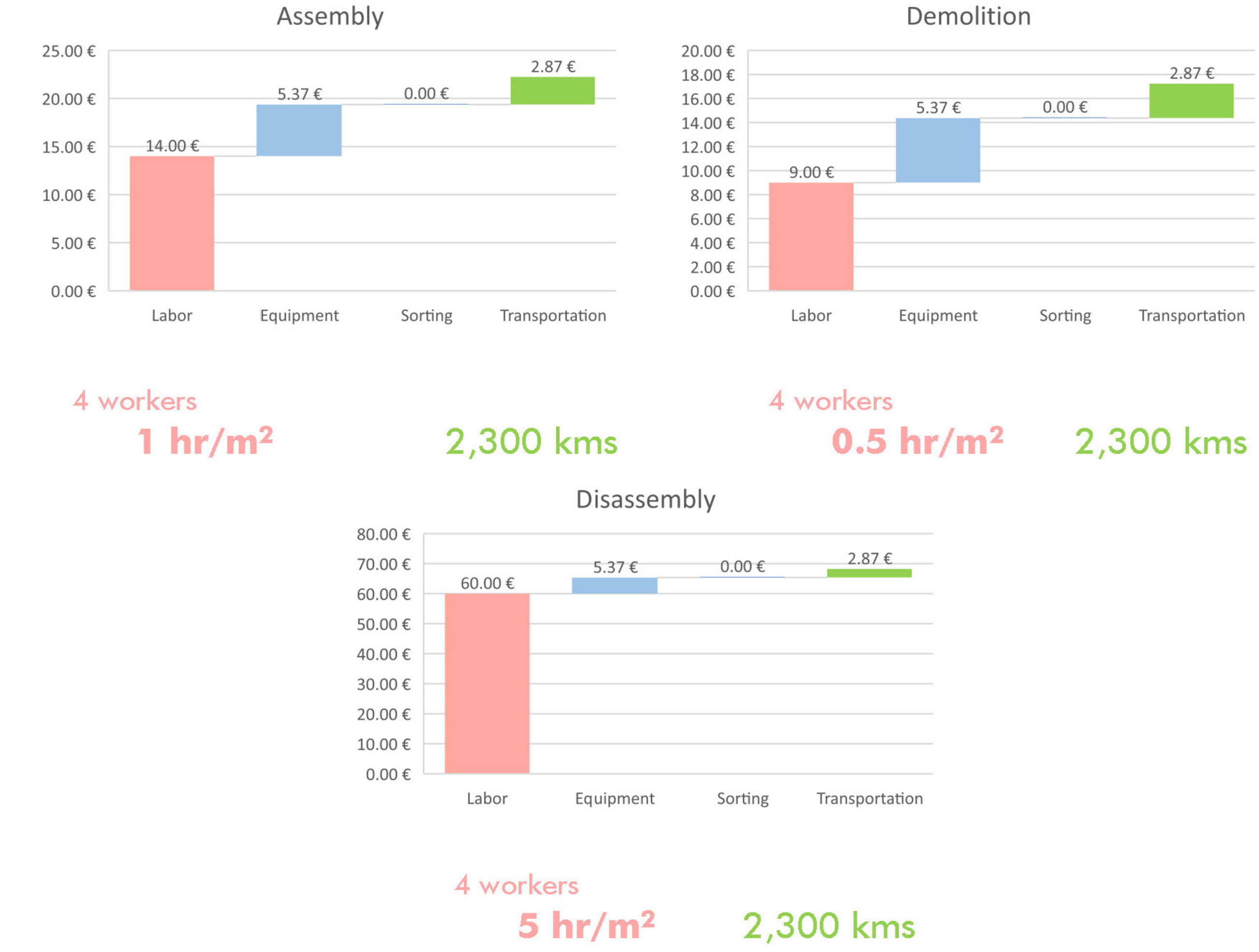


Figure 3.2.14: Summary of Economic Analysis for Conventional Curtain Wall System (Source – Author)

Figure 3.2.15: Summary of Economic Analysis for porposed Plug&play System (Source – Author)

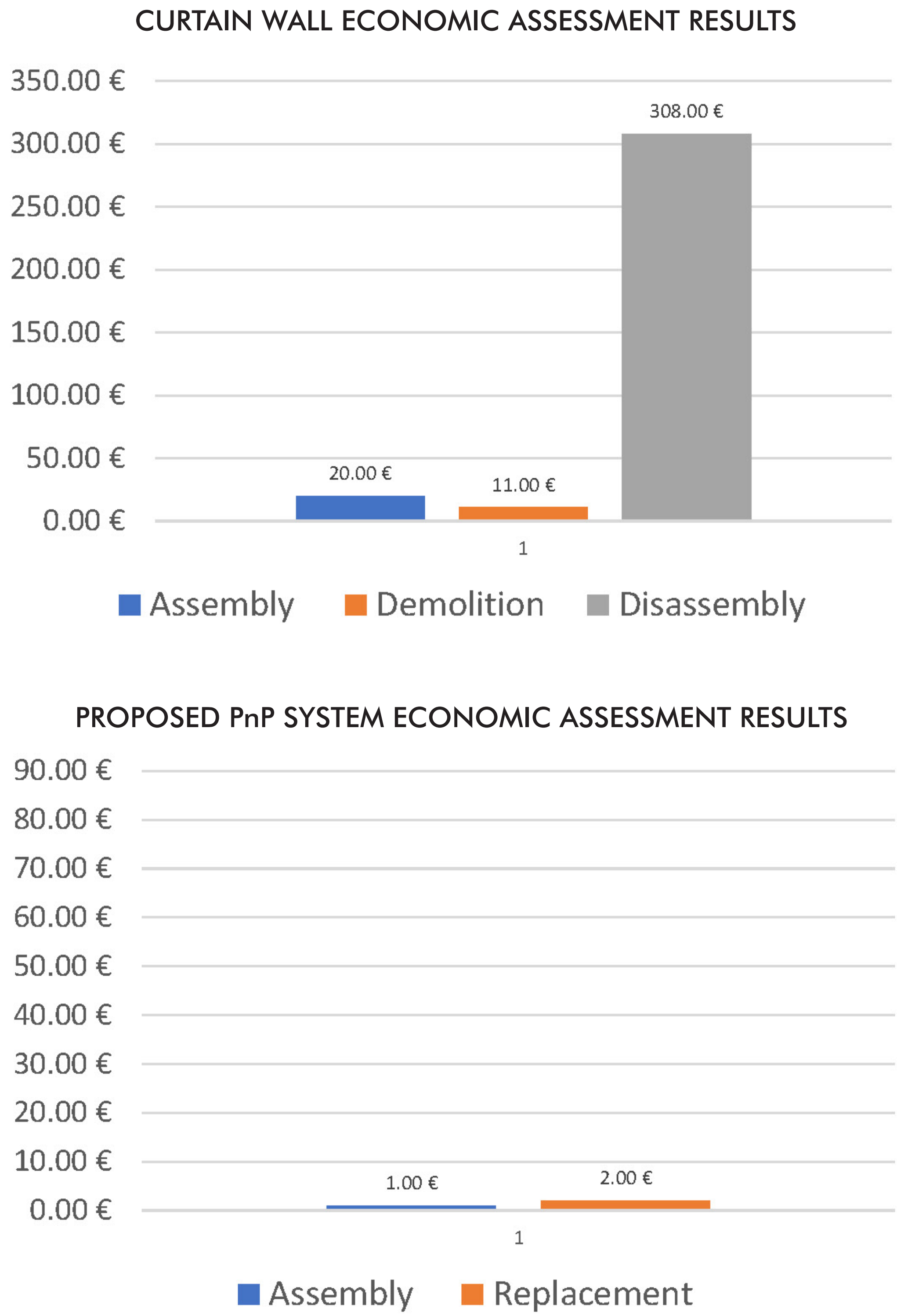


Figure 3.2.14: Overview of economic analysis (Source – Author)

The calculations described in this chapter is to identify the feasibility of the newly proposed concept in comparison to merely replacing the old one with the same facade. The assessments helped identify that design for disassembly is economically feasible and maybe even easier in the broader perspective of the life of the building. The universal equation helped compare costs in five scenarios, and the breakdown of the calculations helped identify where the focus should be for the modification.

Here it can be concluded that the labour cost and the maintenance cost are the once which have the most economic capacity and if fixed, could reduce the costs considerably. The design for disassembly using plug and play systems does that, as seen in the summary of results shown in Figure 3.2.14. If the design is able to reduce the number of people who will be involved in construction, reduce the amount of working hours they will spend and allow for easy accessibility so that the building operations do not rely on heavy and expensive maintenance units and the fact that the whole facade does not need to be torn down which will waste the materials and the monetary value attached with those materials a lot can be saved from this approach.

3.3. Energy Performance

3.3.1 Thermal Evaluation

3.3.1.1. Introduction

Thermally protecting the facades is quite essential for achieving an energy efficient building design. Optimizing the performance of individual facade components to reduce heat transfer through thermal conductivity and thermal resistance will result in energy savings and reduced cooling loads for any building.

For evaluating the thermal performance and maintaining the credibility of the calculation the International Standard ISO 12631: 2017-06 edition (thermal performance of curtain walling - calculation of thermal transmittance) was used. The standard specifies the following calculation methods:

1. Component Assessment Method
2. Single Assessment Method

Single assessment method is mostly a detailed computer calculation of the overall facade construction and is typically complex. Single assessment method will provide graphical results and help designers identify the weaker nodes of heat transfer in the facade construction. This calculation is well suited for non-standard facade areas which is very relevant with curtain wall facades systems. On the other hand the Component assessment method is handy during early design stages, where large geometries can be quickly approximated with minimum effort.

In this section we shall use both methods to evaluate the thermal performance of the Facades.

Component Assessment Method

U - Value of Curtain Walls (U_{CW}) can be calculated using the following formula:

$$U_{cw} = \sum \frac{A_g{*}U_g + A_p{*}U_p + A_f{*}U_f + A_m{*}U_m + A_p{*}U_p + A_t{*}U_t + l_{f,g}{*}\Psi_{f,g} + l_{m,g}{*}\Psi_{m,g} + l_{t,g}{*}\Psi_{t,g} + l_p{*}\Psi_p + l_{m,f}{*}\Psi_{m,f} + l_{t,f}{*}\Psi_{t,f}}{A_{CW}}$$

According to the formula the thermal transmittance (U-values) of all components are multiplied by the their respective surfaces and the linear heat transfer co-efficient (Ψ-values) is multiplied by respective lengths and the whole value is divided by the total facade surface area. This is summarized to the standard formula for U-Value Calculation provided below.

$$U_{cw} = \sum \frac{A{*}U + \Psi{*}l}{A_{CW}}$$

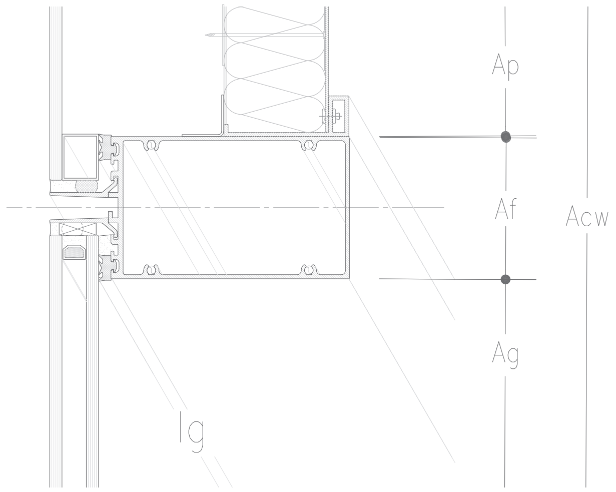


Figure 3.3.1.1: U-Value calculation indicative curtain wall section diagram (Source – Author)

Following signs are used for U-Value Calculations:

Symbol	Description	Units
A	Area	m^2
b	Height of thermal barrier zone inside a profile	mm
B	elevation width of a profile	mm
l	linear thermal bridge	m
U	heat transfer coefficient U – Value	W/m^2K
ε	emissivity	-
λ	thermal conductivity	W/mK
Ψ	linear heat transfer coefficient	W/mK

Following Indices are used for U-Value Calculations:

Symbol	Description
cw	Curtain Wall
d	Door
f	Frame
m	mullion
p	Panel
t	Transom
v	Glazing
w	Window

Figure 3.3.1.2: Indicative elevation view of typical curtain wall facade (Source – Author)

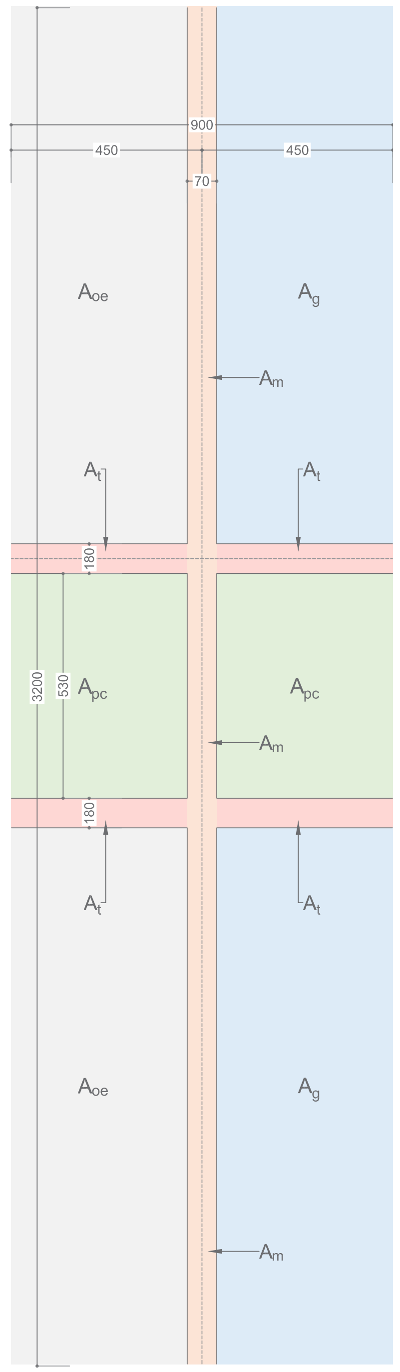


Figure 3.3.1.3: Enlarged elevation view showing surface areas of typical curtain walls (Source – Author)

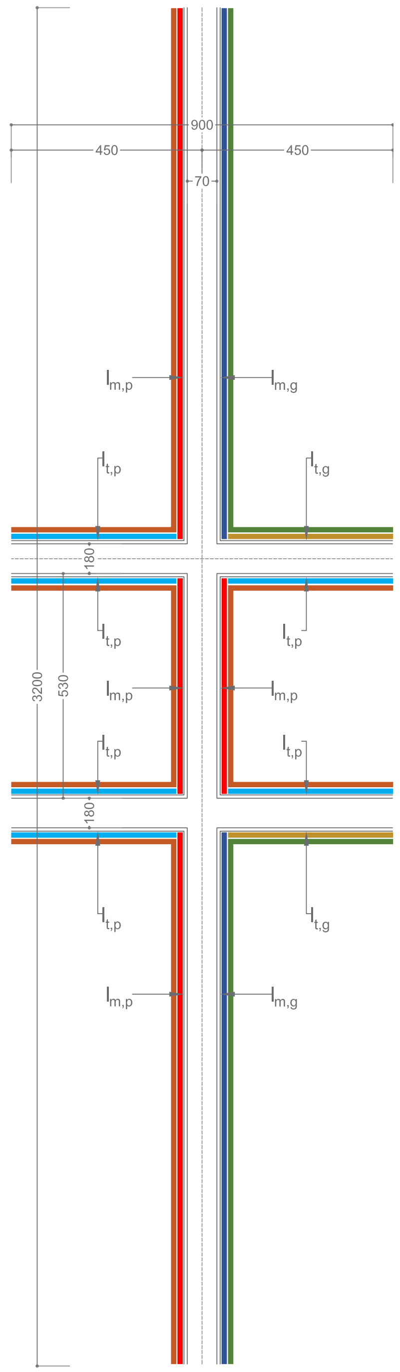


Figure 3.3.1.4: Enlarged elevation showing lengths of facade components of typical curtain walls (Source – Author)

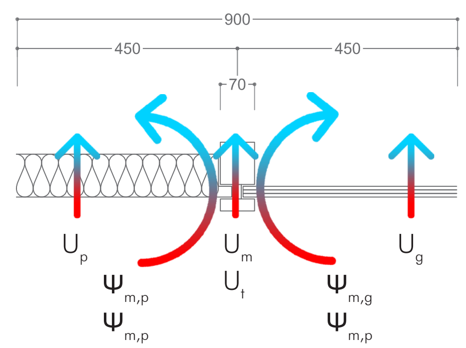


Figure 3.3.1.5: Enlarged plan view showing U & Ψ - values exchange through typical curtain walls (Source – Author)

3.3.1.2. Pre-requsites for analysis

An extract part of the facade has been considered for the assessment, the extracted area will contain an elevation of an area where there are opaque panel and glass panel area and the detail will be studied from the slab level which will include a parapet carrier. Transom and mullion sections will be measured according to their presence in the detail. The types of facades studied would be as follows;

1. Typical Curtain Wall Systems - with standard and regularly used details,
2. Existing Curtain Wall Systems - with the details used in existing case study of Address Hotel, Dubai.
3. Proposed Plug & Play Facade System - with the the proposed design in this thesis.

The thermal analysis comparison will provide sufficient feedback on the performance of the building in terms of heat transfer and insulation capacity of the types of facade system studied here. The thermal analysis will be done with both; Component and Single Assesment methods. Although the Single assessment will only be done for the proposed Plug & Play facade system. Figure 3.3.1.14 & Figure 3.3.1.15 indicate the surface areas and the linear measurements of each component in the selected extract of the facade type.

3.2.1.3. Component Assesment

1. **Thermal Analysis of Typical Curtain Walling**

Figure 3.3.1.2 to Figure 3.3.1.5 here shows the elevations and the plan of the area taken into consideration. This elevation is a typical detail which is common in most of the curtain wall systems presently in the market. Although the sizes and the elements may vary according to buildings function, requirements, location etc... However, most of the geometry will remain the same.

Figure 3.3.1.6: Indicative elevation view of existing curtain wall facade for selected case (Source – Author)

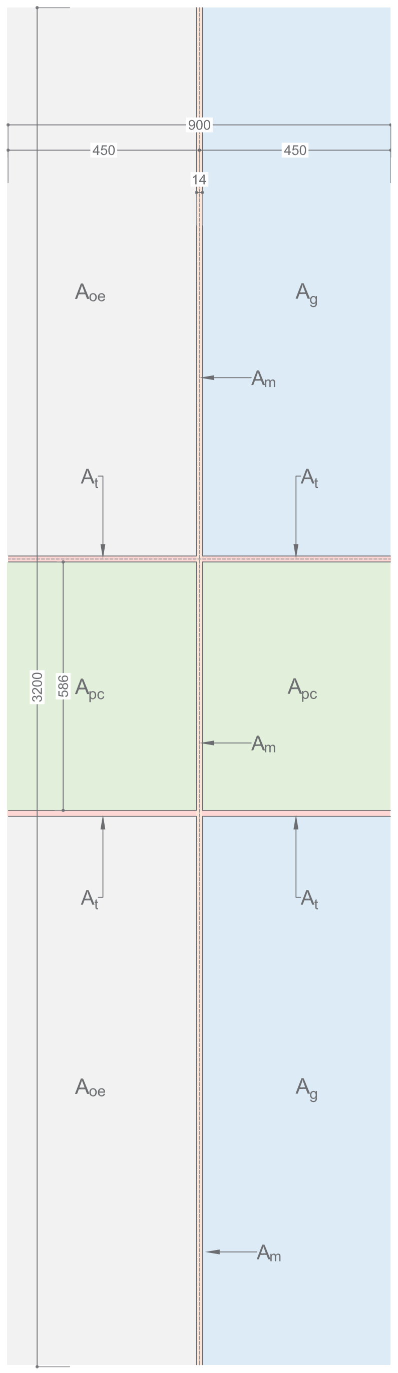


Figure 3.3.1.7: Enlarged elevation view showing surface areas of existing curtain wall for selected case (Source – Author)

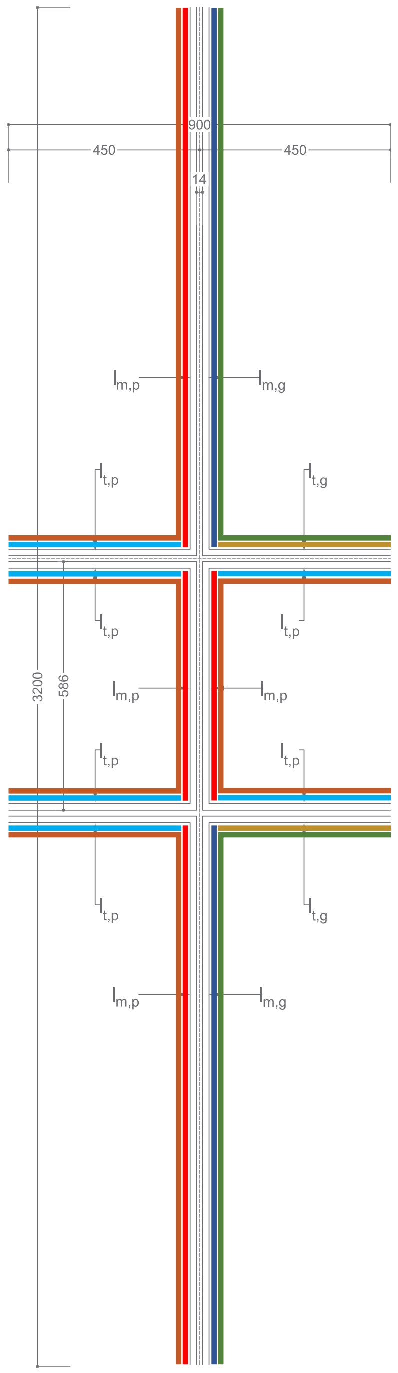


Figure 3.3.1.8: Enlarged elevation showing lengths of facade components of typical wall for selected case (Source – Author)

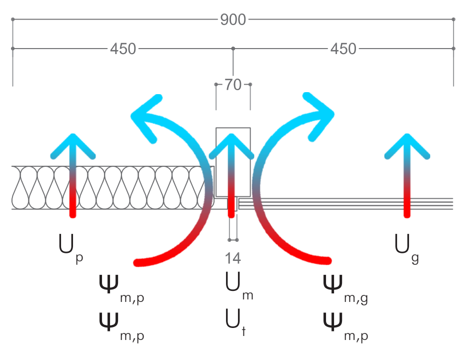


Figure 3.3.1.9: Enlarged plan view showing U & Ψ - values exchange through typical curtain wall for selected case(Source – Author)

2. Thermal Analysis of Existing Curtain Walling

Figure 3.3.1.6 to Figure 3.3.1.9 here shows the elevations and the plan of the area taken into consideration. This elevation is an extract of the existing facade system from the selected case study of the Address Downtown Hotel, Dubai detail which is also one of the common types of structural glazing curtain wall systems presently in the market. The sizes and the elements here are particular to the studied case, although the design data is mostly assumed as not all details were available for investigation. However, based on the available data, we can safely assume the design of structural glazing system and identify using literature research, the type of glass used in the facade system. It was identified that most of the facades have a double glazing system, and the structure was indeed extruded aluminium profiles.

Figure 3.3.1.10: Indicative elevation view of existing curtain wall facade for proposed case (Source – Author)

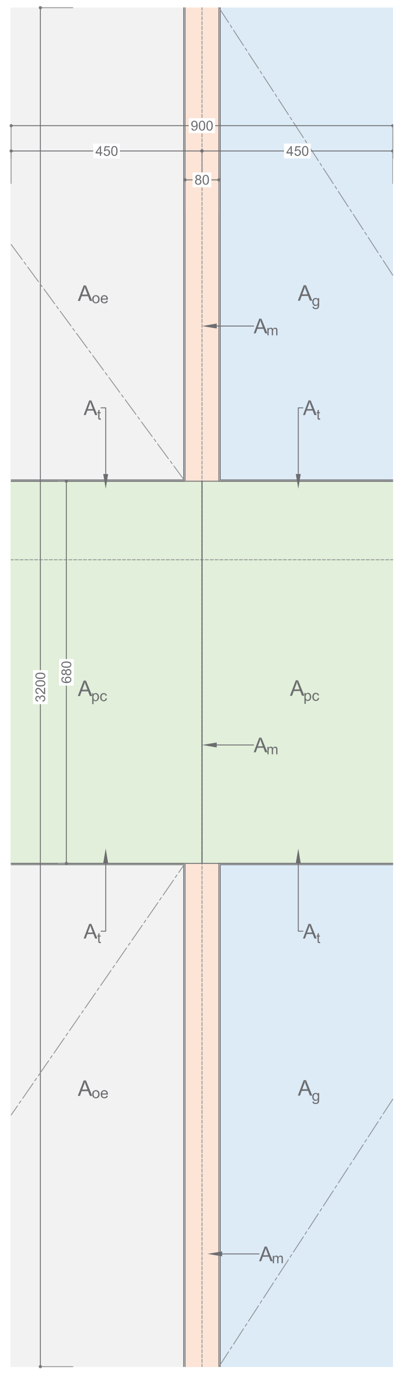


Figure 3.3.1.11: Enlarged elevation view showing surface areas of existing curtain wall for proposed case (Source – Author)

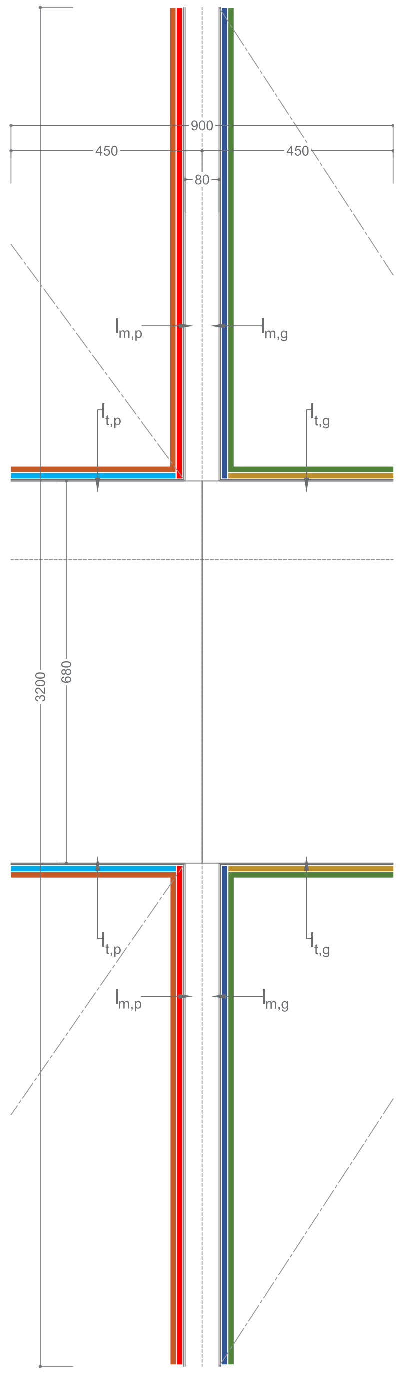


Figure 3.3.1.12: Enlarged elevation showing lengths of facade components of typical wall for proposed case (Source – Author)

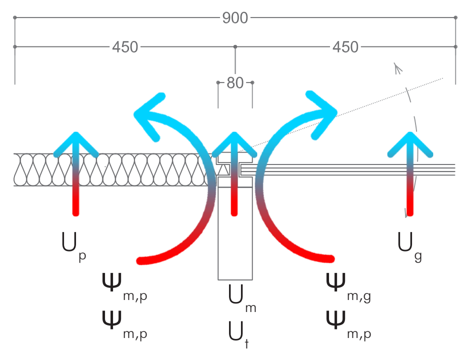


Figure 3.3.1.13: Enlarged plan view showing U & Ψ - values exchange through typical curtain wall for proposed case (Source – Author)

3. Thermal Analysis of Proposed Plug&Play System

Figure 3.3.1.10 to Figure 3.3.1.13 here shows the elevations and the plan of the area taken into consideration. This elevation is an extract of the proposed Plug & Play facade system for the selected case study of the Address Downtown Hotel, Dubai. The design of the system is elaborated in Chapter 4. The premise of this proposed system is to develop a design which is entirely disassemblable and hopefully performs better than the existing systems. The benefit of this design here is that the system irrespective of its current thermal performance will provide scope in the future to have improved functionality and performance upgrades whenever it is available or economically feasible. The sizes and the elements here are particular to the designed case, although the design data were reasonably accurate to the degree of optimised material selection. For a fair study, the type of glass and material of the construction used for the design is the same as the one on the existing facade system. Hence, the comparison data will provide useful aid in terms of choosing the future facade renovation or a facade for completely new construction.

Components		Cladding Area & Area Percentage					
Symbol	Description	Typical	A_x ratio	Existing Case	A_x ratio	Proposed	A_x ratio
A_g	Glazing	1.04 m^2	36.75 %	1.14 m^2	40.08 %	0.94 m^2	32.75 %
A_{pc}	Parapet Carrier	0.43 m^2	15.19 %	0.51 m^2	17.93 %	0.81 m^2	28.22 %
A_{oe}	Panel	1.04 m^2	36.75 %	1.14 m^2	40.08 %	0.94 m^2	32.75 %
A_f	Frame	0.00 m^2	0.00 %	0.00 m^2	0.00 %	0 m^2	0.00 %
A_m	Mullion	0.21 m^2	7.42 %	0.04 m^2	1.57 %	0.18 m^2	6.27 %
A_t	Transom	0.11 m^2	3.89 %	0.01 m^2	0.35 %	0 m^2	0.00 %
ΣA		2.83 m^2	100.00 %	2.84 m^2	100.00 %	2.87 m^2	100.00 %

Figure 3.3.1.14: Calculated surface area of the facade component per evaluation typology for the selected region of the facade (Source – Author)

Components		Gasket Lengths & Length Percentage					
Symbol	Description	Typical	l_x ratio	Existing Case	l_x ratio	Proposed	l_x ratio
l_g	Glazing	3.38 m	26.37 %	3.46 m	26.00 %	6.10 m	41.16 %
$l_{m,g}$	Mullion, Glazing	2.52 m	19.66 %	2.58 m	19.38 %	4.46 m	30.09 %
$l_{t,g}$	Transom, Glazing	0.86 m	6.71 %	0.88 m	6.61 %	1.64 m	11.07 %
l_p	Panel	0.00 m	0.00 %	0.00 m	0.00 %	0.00 m	0.00 %
$l_{m,p}$	Mullion, Panel	3.58 m	27.93 %	3.74 m	28.10 %	0.82 m	5.53 %
$l_{t,p}$	Transom, Panel	2.48 m	19.34 %	2.65 m	19.91 %	1.8 m	12.15 %
Σl		12.82 m	100.00 %	13.31 m	100.00 %	14.82 m	100.00 %

Figure 3.3.1.15: Calculated linear length of the components of facade per evaluation typology for the selected region of the facade (Source – Author)

3.2.1.4. U-Value calculation and comparison study

Thermal transmittance of components are measured as per the percentage of area and the Ψ-Value of the components interacting between the components. The calculation here has been largely based on physical and geometrical factors.

The hand calculation is kept quite simple and the measurements of each component based on the selected case has been elaborated in the Figures 3.3.1.14 & 3.3.1.15. The U-Value of the curtain wall is determined by the surface area A and the length l of the contacting components. It can be observed that the glazing and the opaque panel occipies about 85% of the facade area and the facade profiles (A_t & A_m) consume about 10% of the overall area per panel.

As for the lengths of the interacting components it can be observed that the lenghts vary from 8 meters to 14 meters based on the studied facade type. The components to which these lengths are mostly attributed to are mostly gaskets of EPDM and their main function is to hold the glass in place and to avoid the contact between the frame and the glass ($l_{t,g}$ & $l_{m,g}$)or the frame and panel ($l_{t,p}$ & $l_{m,p}$) the degree of optimised material selection. For a fair study, the type of glass and material of the construction used for the design is same as the one on the existing facade system. Hence, the comparison data will provide useful aid in terms of choosing the future facade renovation or a facade for a completely new construction. The tables have color coded and symbolic indication which matches with the diagrams in the 3.2.1.2 to 3.3.1.13 from each facade type for ease of perusing between the table and the diagrams.

It is necessary to obtain the necessary U & Ψ values of the individual facade components for calculating the overall U_{cw} - Value. Literature research states that corresponding tables of the standard are available in the Table A.1 and Table B.6 in ISO 12631:2012. Although, for the scope of this research the book was not purchased and hence certain values were assumed based on a comparative internet study of products from various facade manufacturers.

Frames, Transoms and Mullions

Since the studied cases do not have an additional window element the value of all frame related measurements are considered as zero. But, as for the mullion or transom the thickness of the profiles, the internal depth, filling element and the thermal breaking will determine the precise values.
As per *Springer, 2015* standard systems for U_t and U_m can have values of upto 2.1 W/m²K.

Linear thermal transmittance can be calculated according to ISO 10077-2:2012. But Table B.6 in ISO 12631:2012 provides Ψ values for gaskets ranging from 0.05 to 0.11 W/mK and hence the average of value of 0.07 W/mK (*Springer, 2015)* can be assumed where the details are not known. As for the gaskets *Rosu, 2017* recommends the Ψ value to be around 0.16 W/mK.

Glazing

ISO 10077-1:2006 has standard u-values provided for U_g, or one can calculate the measurements using european standards for thermal transmittance of glazing such as EN 673:2011, EN 674:2011 and EN 675:201. indicates the U_g value of a regular double glazing as 1.3 W/m²K.

Linear thermal transmittance for typical glazing spacers $Ψ_{i*,g}$ can be extracted from B.1, B.2, B.3 and B.4 in ISO 10077-2:2012 or calculated using the same. The values indicated in Figure 3.3.1.17 showcase different materials within the spacers providing contrasting values (with the improved Plug & Play facade having lower Ψ value of 0.11 W/mK with desicant infill) and the typical and existing DGU glazing having Ψ value of 0.24 W/mK for spacers as per *Svendsen, 2000*. It is to be noted that the Plug and Play facade has triple glazing hence, the linear meters of the glazing spacers is doubled in value.

Panels

Typical U_p value is made available in ISO 6946:2007. But for the case of this calculation, two materials have been considered. Mineral Wool (RW) and Extruded Polystyrene (XPS). Calculations were done using both materials as alternatives for thermal insulation between aluminium sheets cladding and the results are mentioned in the 3.3.1.16. the thermal resistance for each material in this case has been extracted from CES EduPack 2018 software. With comparable thermal resistance value of 0.04 W/mK for both the materials. Although the U-value here is a mixtural option of various combination of materials as indicated in the "Component Arrangement" section in the table. The combination is mostly based on the presence of various materials in the panel arrangement and ranges from aluminium composite panels (ACP) to mild steel frames (MSF).

Linear thermal transmittance for the gaskets for panels can be assumed to be similar to the one for glass. Hence, Ψ value of 0.16 W/mK as per *Rosu, 2017* will be used.

Components				Measurements & Properties			
Description				Thickness		Thermal Conductivity (λ)	Thermal Resistance (R-Value)
U_g	Glazing	GL	Glass	4 mm	0.004 m	0.95 W/mK	0.00 m^{2}K/W
		AG	Argon Gas (90%)	12 mm	0.012 m	0.02 W/mK	0.75 m^{2}K/W
		GL	Glass	4 mm	0.004 m	0.95 W/mK	0.00 m^{2}K/W
		AG	Argon Gas (90%)	12 mm	0.012 m	0.02 W/mK	0.75 m^{2}K/W
		GL	Glass	4 mm	0.004 m	0.95 W/mK	0.00 m^{2}K/W
U_{pc}	Parapet Carrier	ACP	ACP Cladding	4 mm	0.004 m	0.43 W/mK	0.01 m^{2}K/W
		SV	Stone Vineer	5 mm	0.005 m	2.07 W/mK	0.00 m^{2}K/W
		MSF	Mild Steel Frame	3 mm	0.003 m	48.60 W/mK	0.00 m^{2}K/W
		XPS	Extruded Polystyrene	50 mm	0.05 m	0.04 W/mK	1.25 m^{2}K/W
		RW	Rockwool	50 mm	0.05 m	0.04 W/mK	1.25 m^{2}K/W
U_{oe}	Panel	ACP	ACP Cladding	4 mm	0.004 m	0.43 W/mK	0.01 m^{2}K/W
		SV	Stone Vineer	5 mm	0.005 m	2.07 W/mK	0.00 m^{2}K/W
		XPS	Extruded Polystyrene	150 mm	0.15 m	0.04 W/mK	3.75 m^{2}K/W
		RW	Rockwool	150 mm	0.15 m	0.04 W/mK	3.75 m^{2}K/W
U_f	Frame	AL	Aluminum	0 mm	0 m	147.00 W/mK	- m^{2}K/W
		PVC	PVC Thermal Breaks	0 mm	0 m	0.39 W/mK	- m^{2}K/W
U_m	Mullion	AL	Aluminum	25 mm	0.025 m	147.00 W/mK	0.00 m^{2}K/W
		PVC	PVC Thermal Breaks	25 mm	0.025 m	0.39 W/mK	0.06 m^{2}K/W
U_t	Transom	AL	Aluminum	25 mm	0.025 m	147.00 W/mK	0.00 m^{2}K/W
		PVC	PVC Thermal Breaks	25 mm	0.025 m	0.39 W/mK	0.06 m^{2}K/W

Figure 3.3.1.16: U-Value calcualtion per material in Panel (Source – Author)

Components				Measurements & Properties			
Description				Length		Linear Thermal Conductivity (ψ)	$l_{i,i} * \psi_{i,i}$
Typical	l_g	Glazing	Glass Spacer	3380 mm	3.38 m	0.24 W/mK	0.81 W/mK
	$l_{m,g}$	Mullion, Glazing	EPDM	2520 mm	2.52 m	0.16 W/mK	0.40 W/mK
	$l_{t,g}$	Transom, Glazing	EPDM	860 mm	0.86 m	0.16 W/mK	0.14 W/mK
	l_p	Panel	-	0 mm	0.00 m	-	-
	$l_{m,p}$	Mullion, Panel	EPDM	3580 mm	3.58 m	0.16 W/mK	0.57 W/mK
	$l_{t,p}$	Transom, Panel	EPDM	2480 mm	2.48 m	0.16 W/mK	0.40 W/mK
Existing Case	l_g	Glazing	Glass Spacer	3460 mm	3.46 m	0.24 W/mK	0.83 W/mK
	$l_{m,g}$	Mullion, Glazing	EPDM	2580 mm	2.58 m	0.16 W/mK	0.41 W/mK
	$l_{t,g}$	Transom, Glazing	EPDM	880 mm	0.88 m	0.16 W/mK	0.14 W/mK
	l_p	Panel	-	0 mm	0.00 m	- W/mK	-
	$l_{m,p}$	Mullion, Panel	EPDM	3740 mm	3.74 m	0.16 W/mK	0.60 W/mK
	$l_{t,p}$	Transom, Panel	EPDM	2650 mm	2.65 m	0.16 W/mK	0.42 W/mK
Proposed	l_g	Glazing	Glass Spacer	6100 mm	6.10 m	0.11 W/mK	0.67 W/mK
	$l_{m,g}$	Mullion, Glazing	EPDM	4460 mm	4.46 m	0.07 W/mK	0.31 W/mK
	$l_{t,g}$	Transom, Glazing	EPDM	1640 mm	1.64 m	0.07 W/mK	0.11 W/mK
	l_p	Panel	-	0 mm	0.00 m	- W/mK	-
	$l_{m,p}$	Mullion, Panel	EPDM	820 mm	0.82 m	0.07 W/mK	0.06 W/mK
	$l_{t,p}$	Transom, Panel	EPDM	1800 mm	1.80 m	0.07 W/mK	0.13 W/mK

Figure 3.3.1.17: Linear transmission coefficient calcualtion per material in Panel (Source – Author)

Individual U Value Results		U Value per Case		
Component Arrangement	Thermal Transmittance (U-Value)	Typical $A_{typ}*U_{typ,i}$	Existing Case $A_{ext}*U_{ext,i}$	Proposed $A_{pro}*U_{pro,i}$
GL + AG + GL	1.32 W/m^{2}K	1.37	1.50	0.62
GL + AG + GL + AG + GL	0.66 W/m2K			
ACP + MSF + XPS	0.79 W/m^{2}K	0.34	0.40	0.64
ACP + MSF + RW	0.79 W/m^{2}K	0.34	0.40	0.64
SV + MSF + XPS	0.80 W/m^{2}K	0.34	0.41	0.65
SV + MSF + RW	0.80 W/m^{2}K	0.34	0.41	0.65
ACP + XPS	0.79 W/m^{2}K	0.34	0.40	0.64
ACP + XPS	0.27 W/m^{2}K	0.28	0.30	0.25
ACP + RW	0.27 W/m^{2}K	0.28	0.30	0.25
SV + XPS	0.27 W/m^{2}K	0.28	0.30	0.25
SV + RW	0.27 W/m^{2}K	0.28	0.30	0.25
-	-	-	-	-
AL + PVC	2.10 W/m^{2}K	0.44	0.09	0.38
AL + PVC	2.10 W/m^{2}K	0.23	0.02	0.00

Figure 3.3.1.18: Summary of results
(Source – Author)

3.2.1.5. Determining the Curtain Wall U-Value (U_{cw})

The formula mentioned in the component assessment method 3.3.1.1 is used and the results can be seen in the 3.3.1.19. It is to be noted that the various combinations of the component have been used in for study and the differences in the combinations can be discerned using the gradation of the same colours within the table.

For example:

- two types of glazing have been used such as Double glazing for existing facades and Triple glazing for the new proposed facade.
- five combinations of parapet carrier can be identified in the 3.3.1.18.
- four combinations of opaque panels which includes mineral wool (RW) and polystyrene (XPS) insulation materials and cladding materials such as aluminium composite panels (ACP) and stone veneer (SV).

3.2.1.6. Conclusion:

Thermal Optimisation of U_{cw} for Plug and Play Facade Proposal

The premise of the Plug and Play approach is that the design allows for disassembly, which means that any part or component of the facade can be modified or upgraded when required and when it is economically feasible to do so. As a result, if we can assume that the performance of the facade elements will improve over time as the technology progresses and the industry matures. It is almost certain that the performance of the facade will increase over time after every time any component is serviced. As for the purposes of thermal calculation of this chapter, a logically feasible U-value and □ value numbers were taken into consideration as per the availability of these improved materials in the current market.

Based on the results shown in the 3.3.1.19 we can already see approximately 40% improvement in thermal performance by the proposed facade. Hence, the proposed composition of materials can be used for the final design.

Final U_{cw} Value per Case

Typical U_{cw_typ}	Existing Case U_{cw_ext}	Proposed U_{cw_pro}
1.76	1.66	1.11

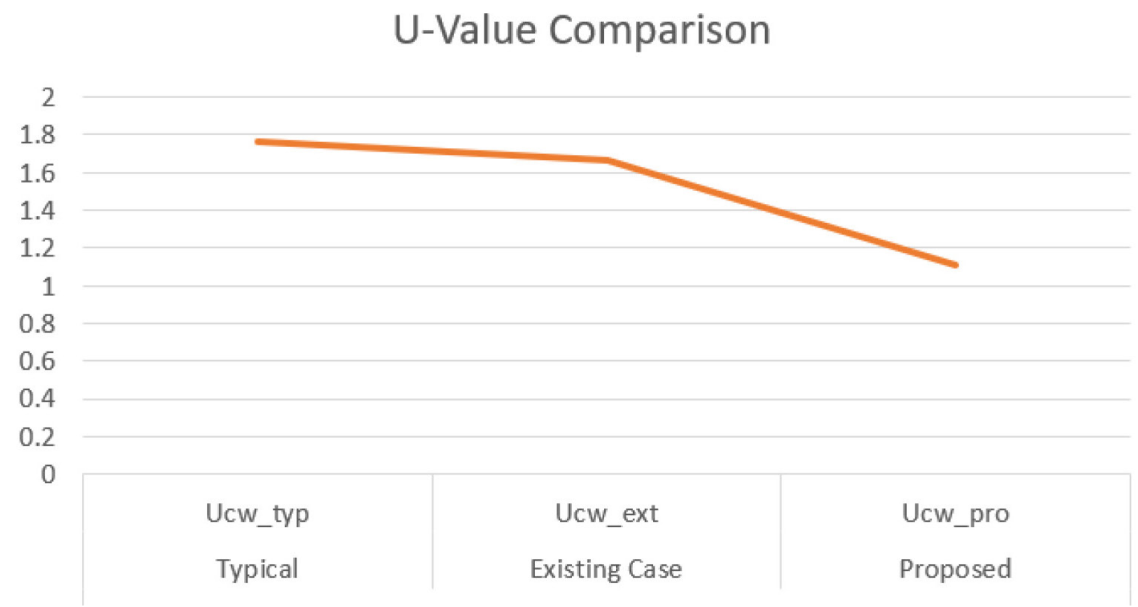


Figure 3.3.1.19. Final U-Values per typology (Source – Author)

3.3.2. Shading Evaluation

3.3.2.1. Introduction

As discussed earlier in chapters before and specifically addressed in chapter 2.5.1.4. Shading Potential Evaluation, it is remarkably necessary to incorporate passive design strategies in the building design. And the study from Yassine, 2013 determined the two types of shading system to be used in the facade. Hence was the case with this particular case for refurbishment.

In this research, the focus was to identify the shading potential and also use the new shading as a tool to harvest solar energy for electricity production. The part of Solar Photovoltaic will be elaborated later in chapter 5.3.8. But for the moment in this chapter, we shall focus on identifying a building envelope which effectively responds to solar radiation in Dubai. Since this is an intervention project, there will be a limitation of the amount of energy reduction we may be able to achieve.

3.3.2.2. Goals

Goals for this part of research was as follows:

1. Identify the ideal angle per orientation for the required size of panel to recieve maximum radiation
2. Design a shading system and improve the building envelope which reduces the cooling load to achieve the lowest Energy Performance Index value.
3. Identify the impact of shading per each cardinal orientation.

The results of these goals will hence determine the design characteristics.

3.3.2.3. Analytical Method

1. Shading devices angle

During the first stage of analytical analysis, simulation software such as Grasshopper with Ladybug plugin and Galapagos simulation was used to simulate the ideal angle of the panel per orientation of the facade and the weather data for Abu Dhabi in *.EPW format was downloaded from the energyplus website (https://energyplus.net/weather) and used as the basis of climate data for the simulation.

Each simulation was set to run for about half hour where the parameters were set as the size of the panel, the required orientation and variable was to maximize the amount of solar radiation falling on the panel for the overall year by adjusting the angle. Figure 3.3.2.1. provides the summary of results of the simulation for both the typologies of shading of Horizontal overhang and External louvres. The premise of this simulation was two-fold, one was to provide adequate shading to the building and hence reduce the cooling load and the second was to use the shading devices as a basis for BIPV system to generate electrical power, where each shading device will also receive a photovoltaic panel and hence completing the idea of Plug&Play facade. And the primary reason the shading system had to be inclined was to improve the solar collector's yield.

Shading Element	Width	Depth	Simulation Time	Orientation	Total Radiation	Sunlight Hours	Preferred Angle
Overhang	0.9 m	0.5 m	30 mins	South	1052.82 kWh/m^2	331.19 hr	22 deg
	1.2 m				1403.76 kWh/m^2	441.60 hr	22 deg
	1.5 m				1756.70 kWh/m^2	552.00 hr	22 deg
	0.9 m	0.5 m	30 mins	West	984.93 kWh/m^2	331.19 hr	0 deg
	1.2 m				1313.24 kWh/m^2	441.60 hr	0 deg
	1.5 m				1641.55 kWh/m^2	552.00 hr	0 deg
	0.9 m	0.5 m	30 mins	East	985.01 kWh/m^2	331.19 hr	1 deg
	1.2 m				1313.35 kWh/m^2	441.60 hr	1 deg
	1.5 m				1641.69 kWh/m^2	522.00 hr	1 deg
External Louvers	0.9 m	0.3 m	30 mins	South	526.41 kWh/m^2	165.59 hr	22 deg
	1.2 m				701.88 kWh/m2	220.80 hr	22 deg
	1.5 m				877.35 kWh/m2	276.00 hr	22 deg
	0.9 m	0.3 m	30 mins	West	492.46 kWh/m2	165.59 hr	0 deg
	1.2 m				656.62 kWh/m2	220.80 hr	0 deg
	1.5 m				820.77 kWh/m2	276.00 hr	0 deg
	0.9 m	0.3 m	30 mins	East	492.50 kWh/m2	165.59 hr	1 deg
	1.2 m				656.67 kWh/m2	220.80 hr	1 deg
	1.5 m				820.84 kWh/m3	276.00 hr	1 deg

Figure 3.3.2.1: Radiation analysis per shading device based on orientation (Source - Author)

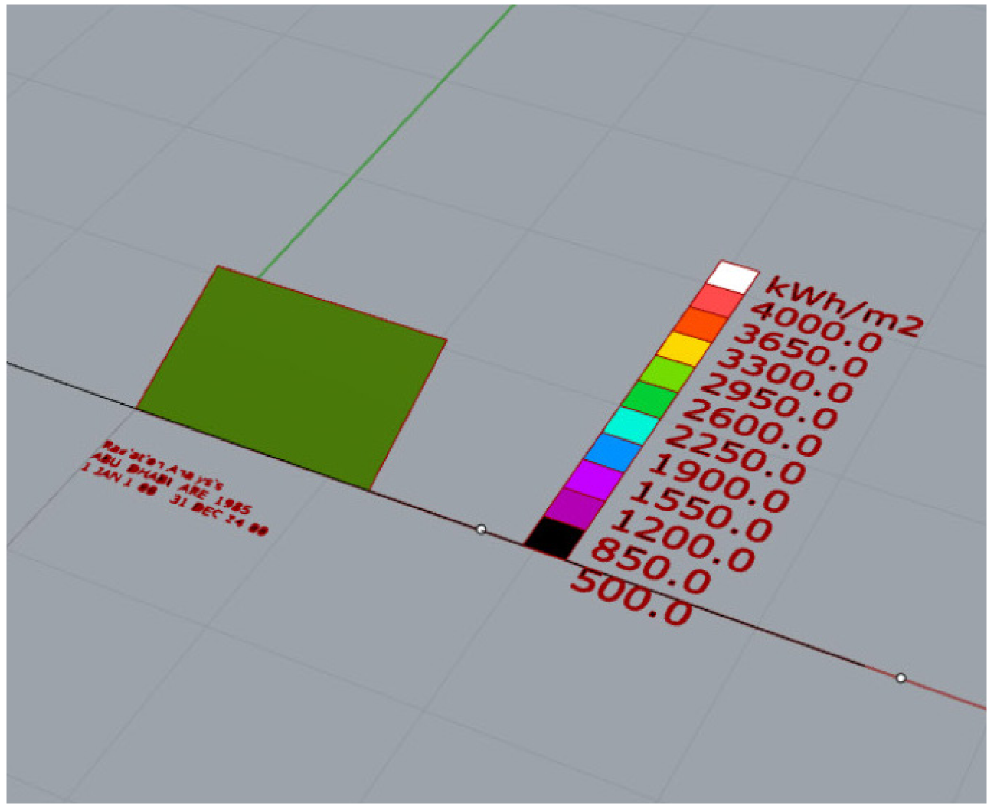


Figure 3.3.2.2: Simulation model of the louver panel (Source - Author)

Analysis

Studies conducted by Jafarkazemi & Saadabadi, 2013 for identifying the optimum tilt angle and orientation of solar surfaces in Abu Dhabi, UAE suggests that tilt and orientation are the most important factors which will determine the efficiency of the solar surfaces. Studies confirm that the optimum orientation for PV panels is the south direction. However, the required angle of tilt of the PV panels has to be determined based on calculations. The study mentioned above suggests that most calculations used an isotropic model where they assumed the radiation on an inclined plane by combining beams, diffuse and ground-reflected radiation.

It is to be noted that the solar radiation would be symmetrical in the morning and evening, the only difference will be the change in orientation due to the movement of the sun. Hence, it can be assumed that the tilt angle determined for the east-facade PV panel will also be the required tilt for the west-faced PV panel or vice versa.

Azimuth angle γ	β_{opt}	Global radiation	Ratio to radiation on horizontal
0	22	7746.9	1.057
10	22	7737.6	1.056
20	21	7709.8	1.052
30	21	7665.3	1.046
40	19	7606.1	1.038
50	17	7536.3	1.028
60	14	7462.3	1.018
70	10	7394.3	1.009
80	6	7345.4	1.002
90	0	7327.7	1.000

Table 3.3.2.3: Yearly optimum tilt angles, annual solar radiation (MJ/m2) for different orientations and their ratio to the horizontal (Source - Jafarkazemi & Saadabadi, 2013)

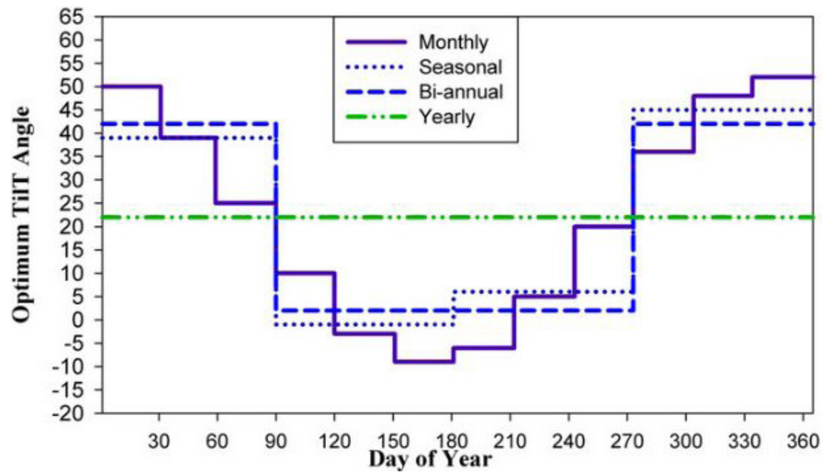


Figure 3.3.2.4: Monthly, seasonal, bi-annual and yearly optimum tilt angle for south orientation in Abu-Dhabi (Source - Jafarkazemi & Saadabadi, 2013)

Tilt angles specific to the yearly optimum based on all orientations were provided by the study conducted by Jafarkazemi & Saadabadi, 2013 and can be seen in Table 3.3.2.3. The results show that the annual global solar radiation decreased when the orientation moves away from south facing direction. The table also provides the ratio of annual solar radiation to the horizontal. The results from the study conclude that the amount of solar radiation from the south-facing side at the tilt angle of 22 degrees is about 6% higher than the horizontal surface. Moreover, since the design will only focus on a possible prototype for south facade the study also has provided the monthly optimum tilt angles graph (see Figure 3.3.2.4). It can be noted from the graph that ideal design should be allowed to accommodate manual or automized system to change the angle of the tilt for shading system and the louvres. The ideal case being manual adjustments bi-annually to compromise between the amount of manhour required and the amount of solar energy collected. This is an essential aspect to consider, but at the moment the design will not include this parameter as the focus of the design is to incorporate the functionality and evaluate the potential of integration and necessary life cycle assessment. Studies to optimize the perfect BIPV system can follow in different research.

Conclusion

It is to be noted that the efficiency of the BIPV on a shading will considerably vary depending on the month, season and the general forecast of weather during the day (e.g cloudy, shadows by adjacent buildings, shadows cast by other PV panels, and the tilt). The selected intervention case has some location-based benefits so that there are no overshadows by any adjacent buildings and the design phase should accommodate a safe distance between shading panels so that they don't shade each other.

The grasshopper simulation and the literature from Jafarkazemi & Saadabadi, 2013 provide sufficient data for the tilt angle of the shading system and the approximate size per panel to be used for design case. The tilt angle used for design development will be based on the annual average of angles required for each orientation to simplify the design process.

The study also concludes that the optimum tilt angle for shading system to have a BIPV panel is:

South: 22° to the horizontal
East: 0° to the horizontal
West: 0° to the horizontal

moreover, the optimum orientation angle is the south direction and that the optimum tilt angle reduces by when we move away from the south direction to east or west direction.

2. Reducing the Solar Gains using shading devices.

The study here aims to evaluate the amount of reducing the amount of solar heat gains by incorporating permanent shading devices on the facade panel after an extensive literature review whose summary can be found in Chapter 2.6.3. A concept shading system was modelled and tested on the base-case hotel building as introduced in Chapter 1.6. During the second stage of the shading devices analysis, In order to understand the amount of energy savings, a comparison study would be required between the base-case building and the proposed design concept.

Design-builder simulation was used to analyze and to understand the performance of the building and the effects of shading on cooling loads. However, the analysis of the whole building would be impossible using the software in a personal laptop computer with medium to low processing power. Hence a portion of the building was assumed, and a typical floor plan was made based on data found in developers and property finder websites. (See Chapter 1.6 Intervention Case)

Hence, the volume of the building occupying the 49th floor and to the 58th floor was considered for evaluation the Figures 3.3.2.6. and 3.3.2.7. indicates the same and the red highlighted area indicates the 53rd floor which will be detailed enough for the evaluation. Figure 3.3.2.8 shows the typical floor plan and the red highlighted area indicate Bedroom 01 for the West orientation, Bedroom 08 for the East orientation and Bedroom 11 for the South orientation, respectively.

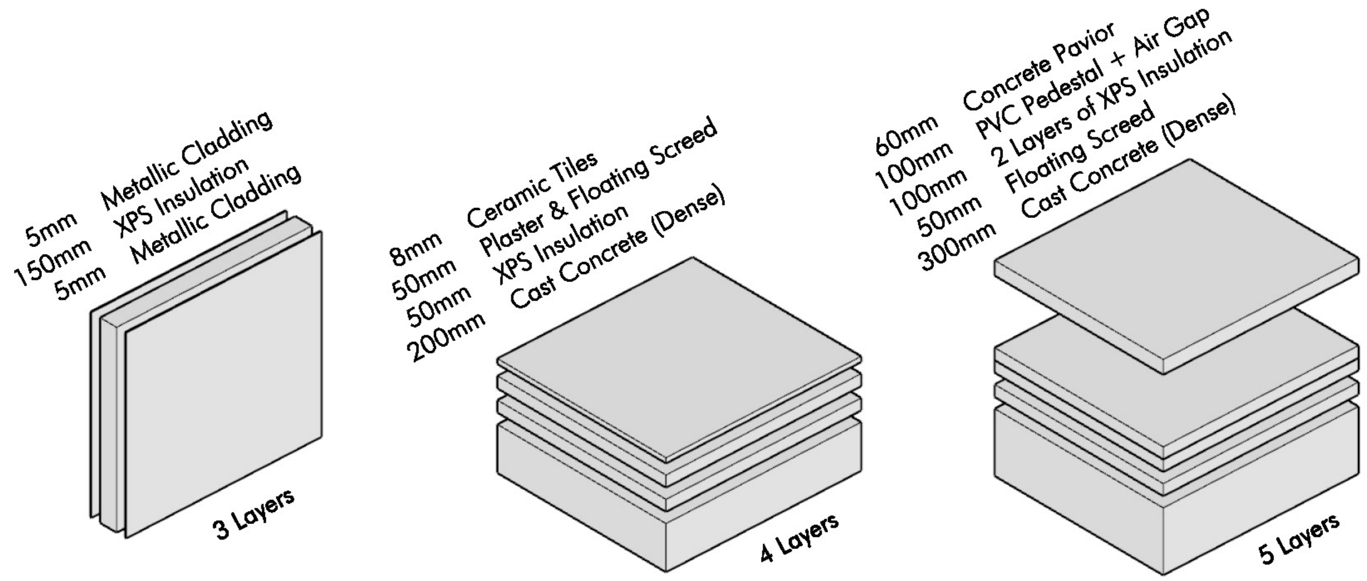


Figure 3.3.2.5: Boundary conditions set for the construction for simulation (Source - Author)

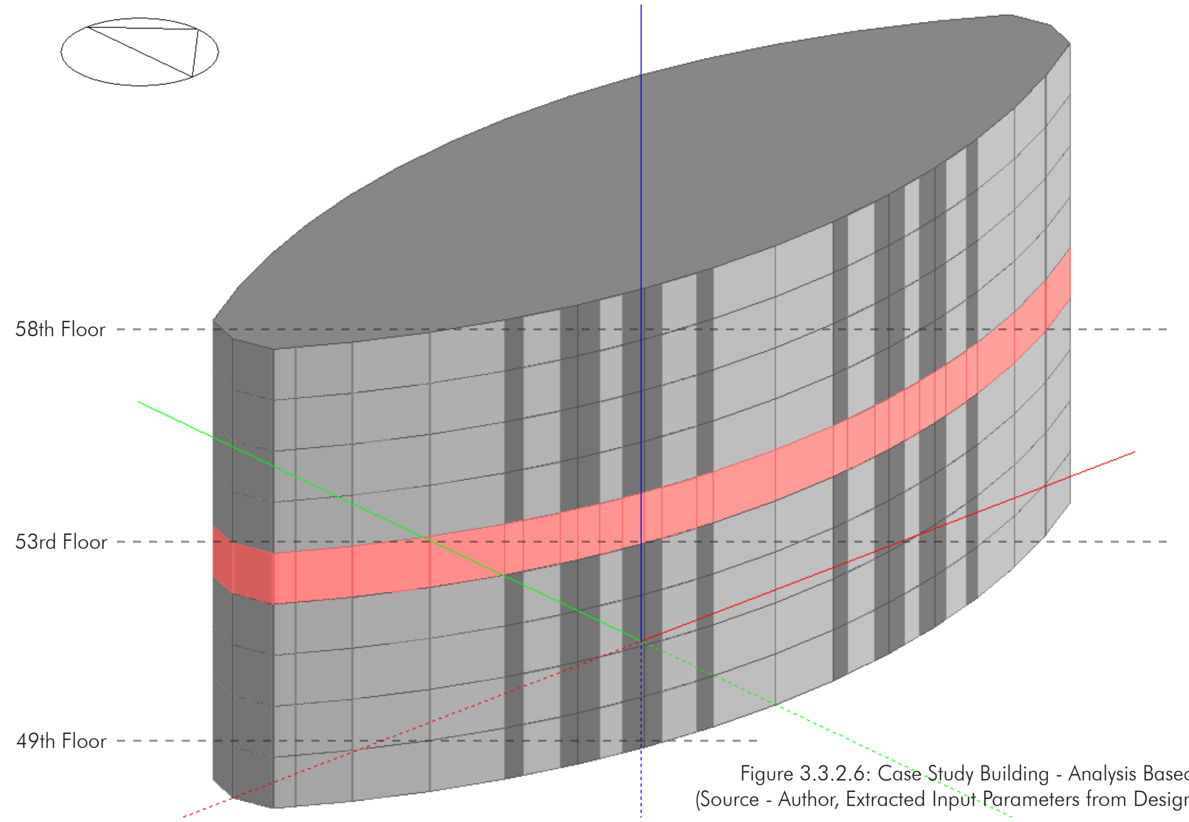


Figure 3.3.2.6: Case Study Building - Analysis Basecase
(Source - Author, Extracted Input Parameters from Design Builder)

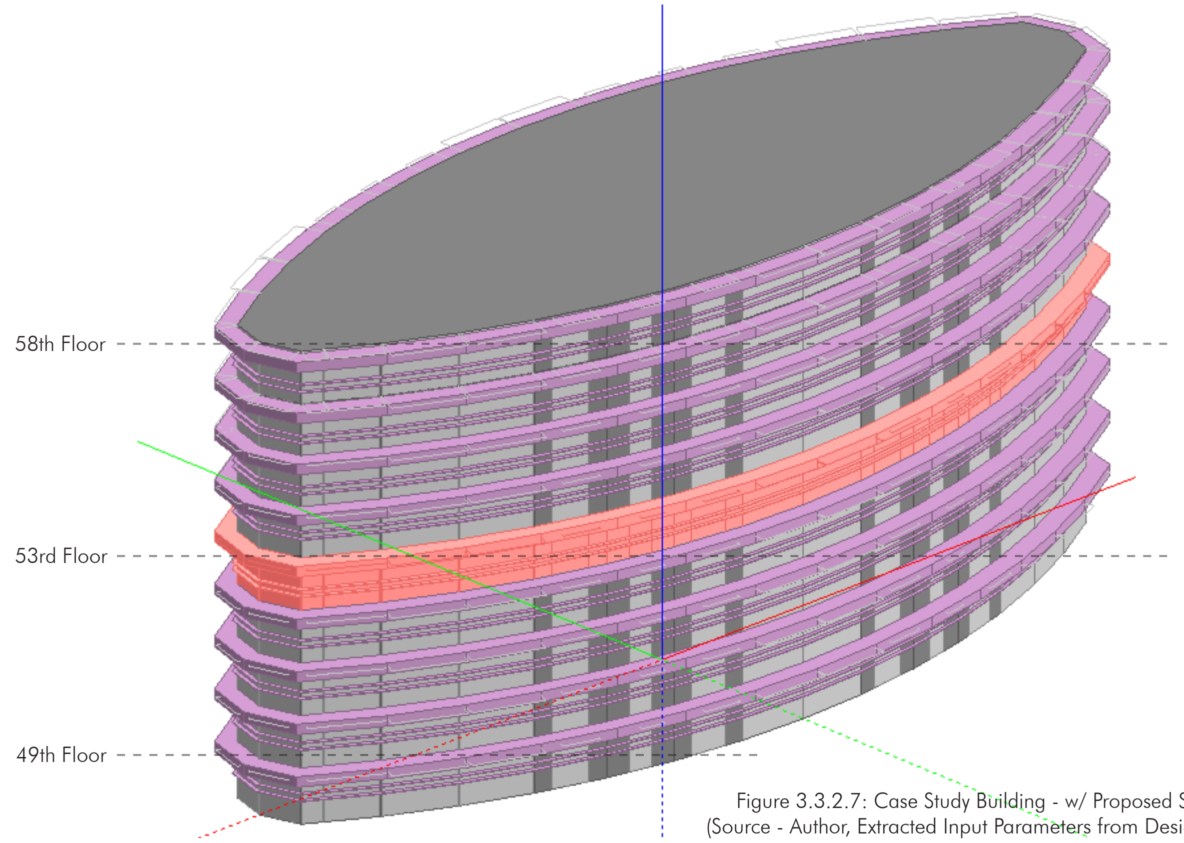


Figure 3.3.2.7: Case Study Building - w/ Proposed Shading
(Source - Author, Extracted Input Parameters from Design Builder)

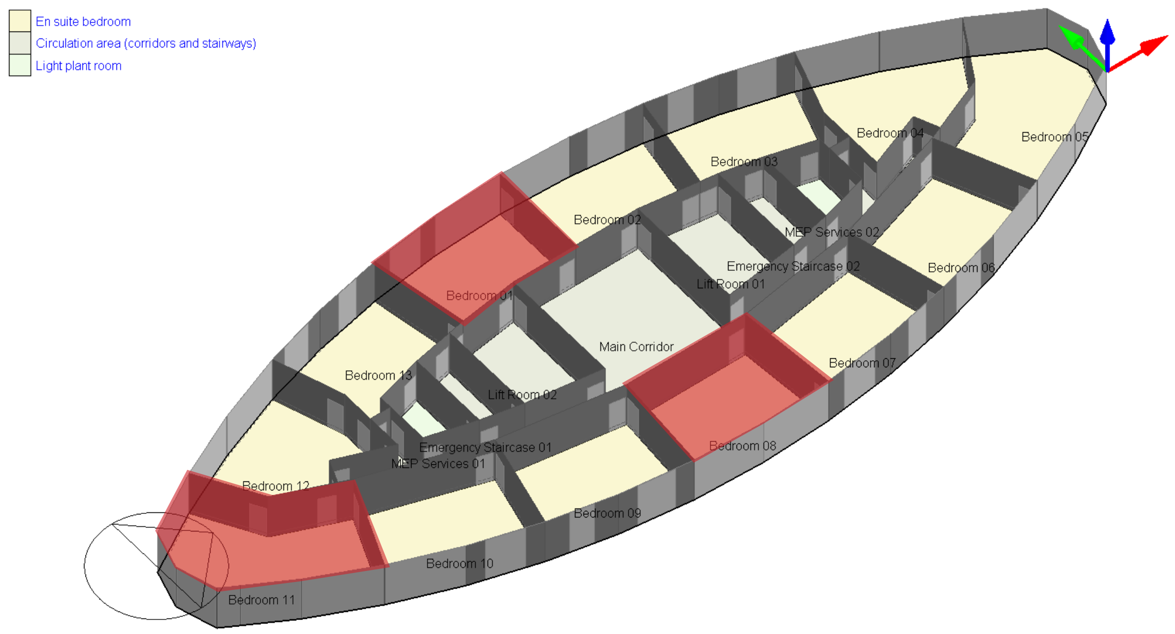


Figure 3.3.2.8: Typical floor plan of the hotel at 53rd Floor as highlighted in Figures 3.3.2.6 & Figure 3.3.2.7:
(Source - Author, Extracted Input Parameters from Design Builder) - *[Red highlighted rooms are the once used for shading investigation]*

Boundary Conditions

For the comparison study, it is imperative that both cases have standard and fixed construction data. Since all aspects of the design were not available for accurate modelling, certain aspects such as activity, construction, HVAC, lighting and glazing was set based on an educated assumption. The study at the moment does not require accurate results, but instead requires the comparison of energy usage data for fixed circumstances at the given location. Appendix 7.3 elaborates on all the fixed boundary conditions assumed for both proposed and base-case building conditions.

It is to be noted that the activity, construction, HVAC and lighting data are kept same for both the simulated cases and the only change between both the cases in the incorporation of shading devices and improved facade parameters which was extracted from the calculations in the previous study shown in Chapter 3.3.1. above.

A brief overview of boundary conditions for the construction of the building is shown in Figure 3.3.2.5 above. Moreover, as for the functional and operational aspects, the following aspects were incorporated:

- Appendix 7.3 | Figure 7.3.4 | Basic function per room was set for each zone in the activity tab and an overview of the assigned activity can be seen in Figure 3.3.2.8 and this data would be same for both base-case and proposed building simulation cases.

- Appendix 7.3 | Figure 7.3.5 & 7.3.6 | Boundary condition for construction elements explained in 3.3.2.5 and Figures 7.3.1 to 7.3.3 was incorporated into the construction template and this data would be same for both base-case and proposed building simulation cases. The only difference is for the airtightness levels which is supposedly assumed to be improved in the proposed case. The design hence has to accommodate this aspect.

- Appendix 7.3 | Figure 7.3.7 | In boundary conditions for HVAC a regular Fan Coil Unit (4-Pipe) with water-cooled chiller is incorporated and the cooling system CoP was set to 3.5. A survey with industry experts suggested that it was most likely that the actual HVAC system at the site could be a district cooling system. But, to simplify the calculations the above-mentioned case as considered and this data would be the same for both base-case and proposed building simulation cases.

- Appendix 7.3 | Figure 7.3.8 | Basic lighting data as per function was considered for all zones of the building and only the corridor would have general lighting on for 24x7 because of no natural lighting on the corridor and because the selected building belongs to a Hotel typology and this data would be same for both base-case and proposed building simulation cases.

- Appendix 7.3 | Figure 7.3.9 & 7.3.10 | The difference in construction is only prominent in the facade part of the construction where the existing double glazing would be replaced to triple glazing, window to wall ratio would increase and the shading would be always on in the proposed case while the existing case would have none. The depth of the proposed shading system has been set as 1.0 meters overhang and mid-pane louvres have been introduced.

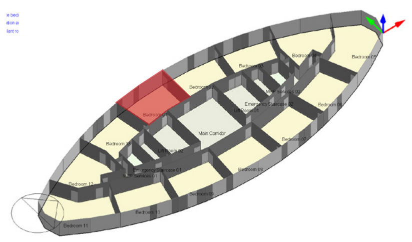
Analysis

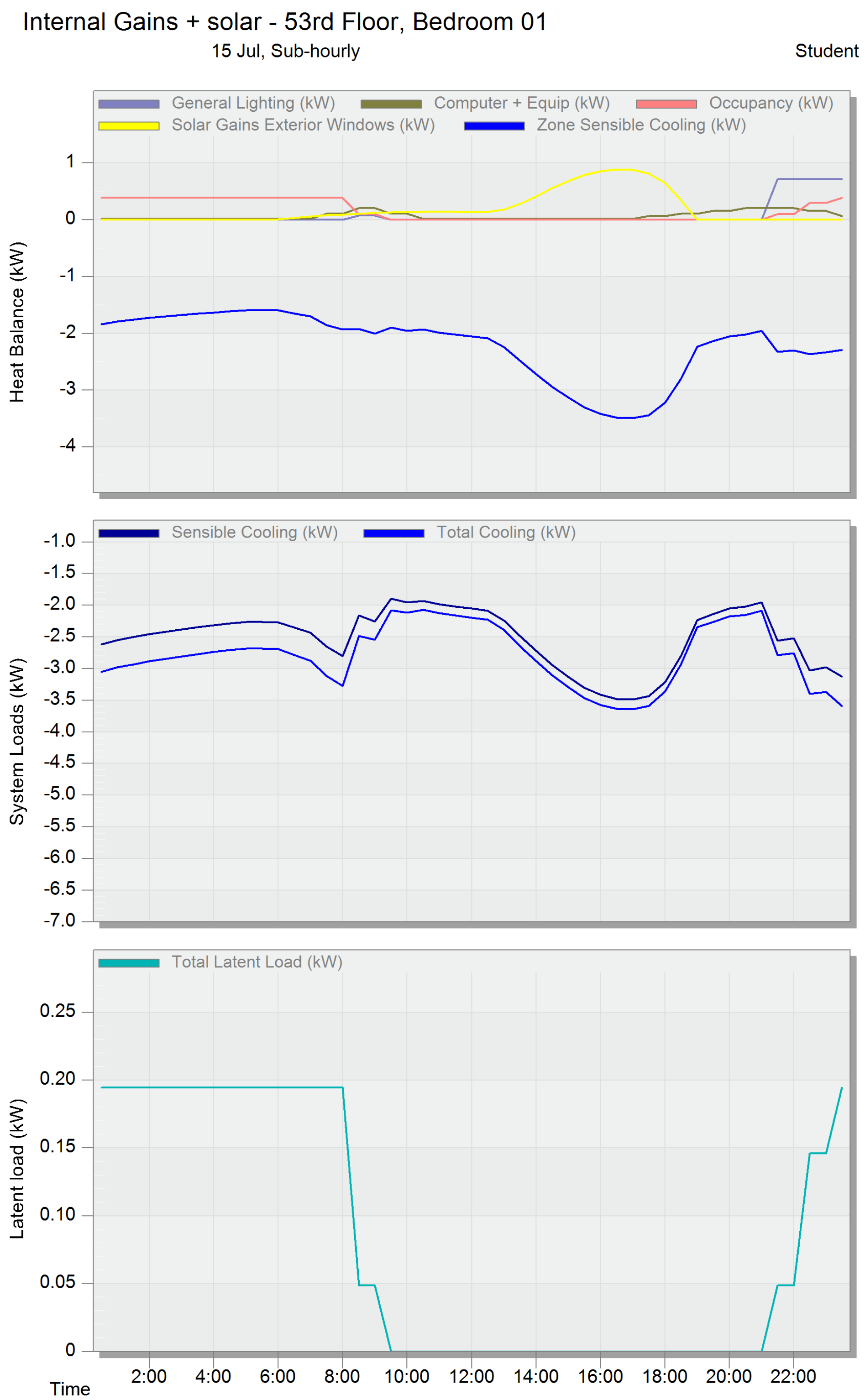
After entering the parameters mentioned above into the design-builder model, simulations were conducted for specific rooms on the identified 53rd floor in each prominent orientation, for a peak summer day (15th July in this case for Dubai) and the results of the data is published in sub-hourly data in Figures 3.3.2.9 to 3.3.2.14. where the Figures 3.3.2.9, 3.3.2.11, & 3.3.2.13 show the simulation results for the existing building case and the Figures 3.3.2.10, 3.3.2.12 & 3.3.2.14 show the results of simulations for the new proposed case.

Conclusion

The results of the simulation are published in Figures 3.3.2.9 to 3.3.2.14. wherein the graphs and the red highlighted area, it can be observed that the internal gains have reduced by more than half by the incorporated facade type improvement and the proposed shading system. This means that the amount of air conditioning required to cool these spaces would also reduce significantly which will, in turn, contribute to energy savings.

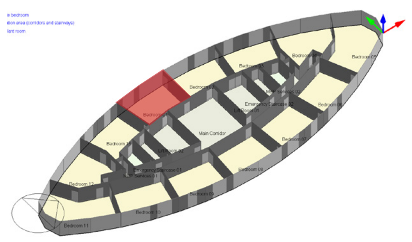
This concludes that the proposed concept to incorporate a louvre and a shading system would provide large amounts of energy savings. The results of the amount of energy savings will be discussed in the next chapter.

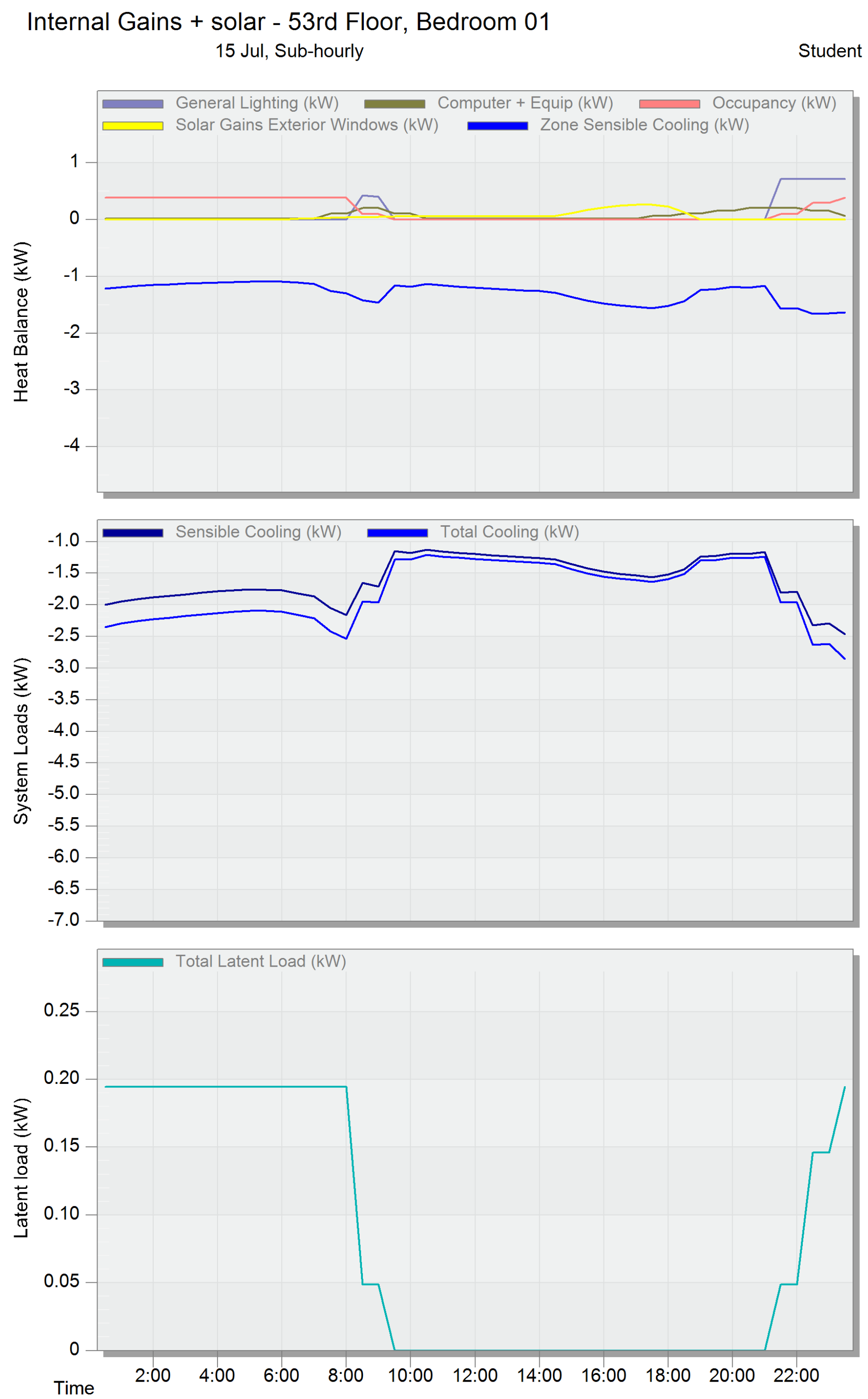




Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.72
Computer + Equip (kW)	0.01	0.01	0.01	0.11	0.11	0.01	0.01	0.01	0.06	0.16	0.21
Occupancy (kW)	0.39	0.39	0.39	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.10
Solar Gains Exterior Windows (kW)	0.00	0.00	0.01	0.10	0.14	0.14	0.41	0.86	0.65	0.00	0.00
Zone Sensible Cooling (kW)	-1.73	-1.63	-1.59	-1.93	-1.96	-2.05	-2.72	-3.41	-3.22	-2.05	-2.29
Sensible Cooling (kW)	-2.45	-2.31	-2.27	-2.80	-1.96	-2.05	-2.72	-3.41	-3.22	-2.05	-2.52
Total Cooling (kW)	-2.89	-2.74	-2.69	-3.27	-2.12	-2.19	-2.89	-3.58	-3.36	-2.18	-2.76
Total Latent Load (kW)	0.19	0.19	0.19	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.05

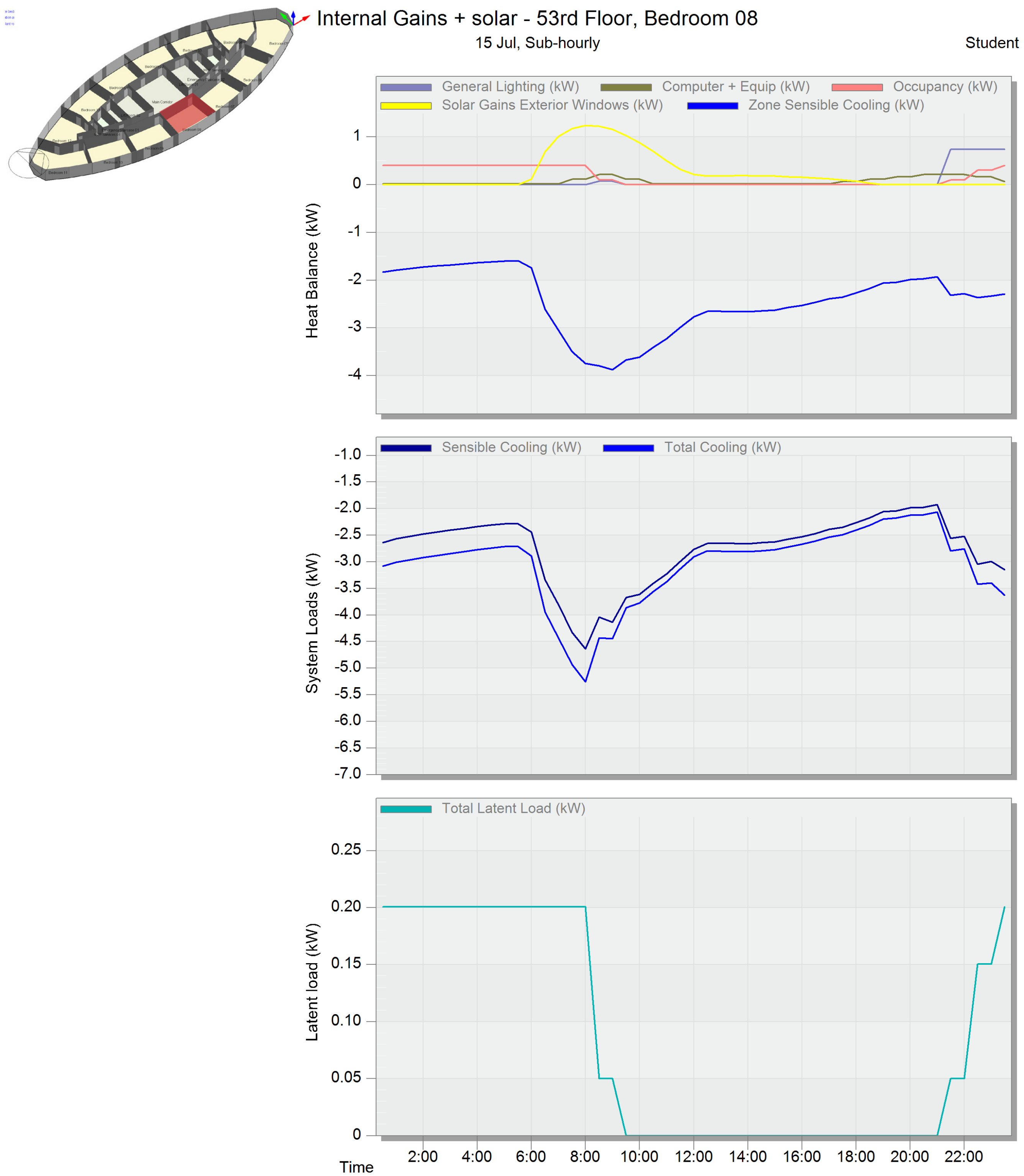
Figure 3.3.2.9: Simulation results for internal gains on predicted existing envelope - West Facade
(Source - Author, Extracted Input Parameters from Design Builder)





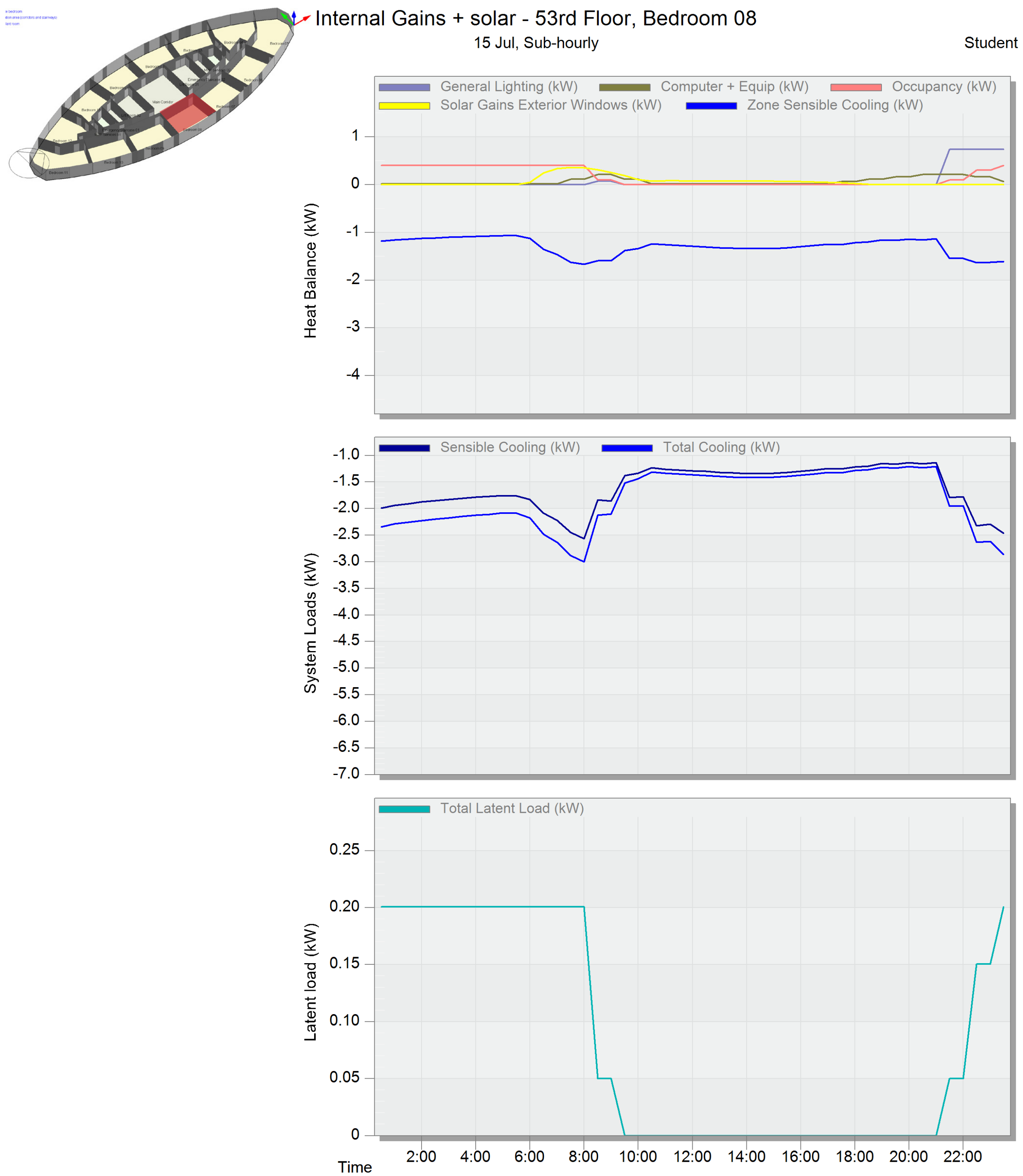
Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.72
Computer + Equip (kW)	0.01	0.01	0.01	0.11	0.11	0.01	0.01	0.01	0.06	0.16	0.21
Occupancy (kW)	0.39	0.39	0.39	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.10
Solar Gains Exterior Windows (kW)	0.00	0.00	0.00	0.04	0.06	0.06	0.06	0.22	0.23	0.00	0.00
Zone Sensible Cooling (kW)	-1.15	-1.11	-1.09	-1.29	-1.18	-1.20	-1.26	-1.48	-1.52	-1.19	-1.56
Sensible Cooling (kW)	-1.88	-1.79	-1.77	-2.16	-1.18	-1.20	-1.26	-1.48	-1.52	-1.19	-1.79
Total Cooling (kW)	-2.23	-2.13	-2.11	-2.54	-1.28	-1.27	-1.33	-1.56	-1.60	-1.25	-1.96
Total Latent Load (kW)	0.19	0.19	0.19	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.05

Figure 3.3.2.10: Simulation results for internal gains on proposed envelope - West Facade
(Source - Author, Extracted Input Parameters from Design Builder)



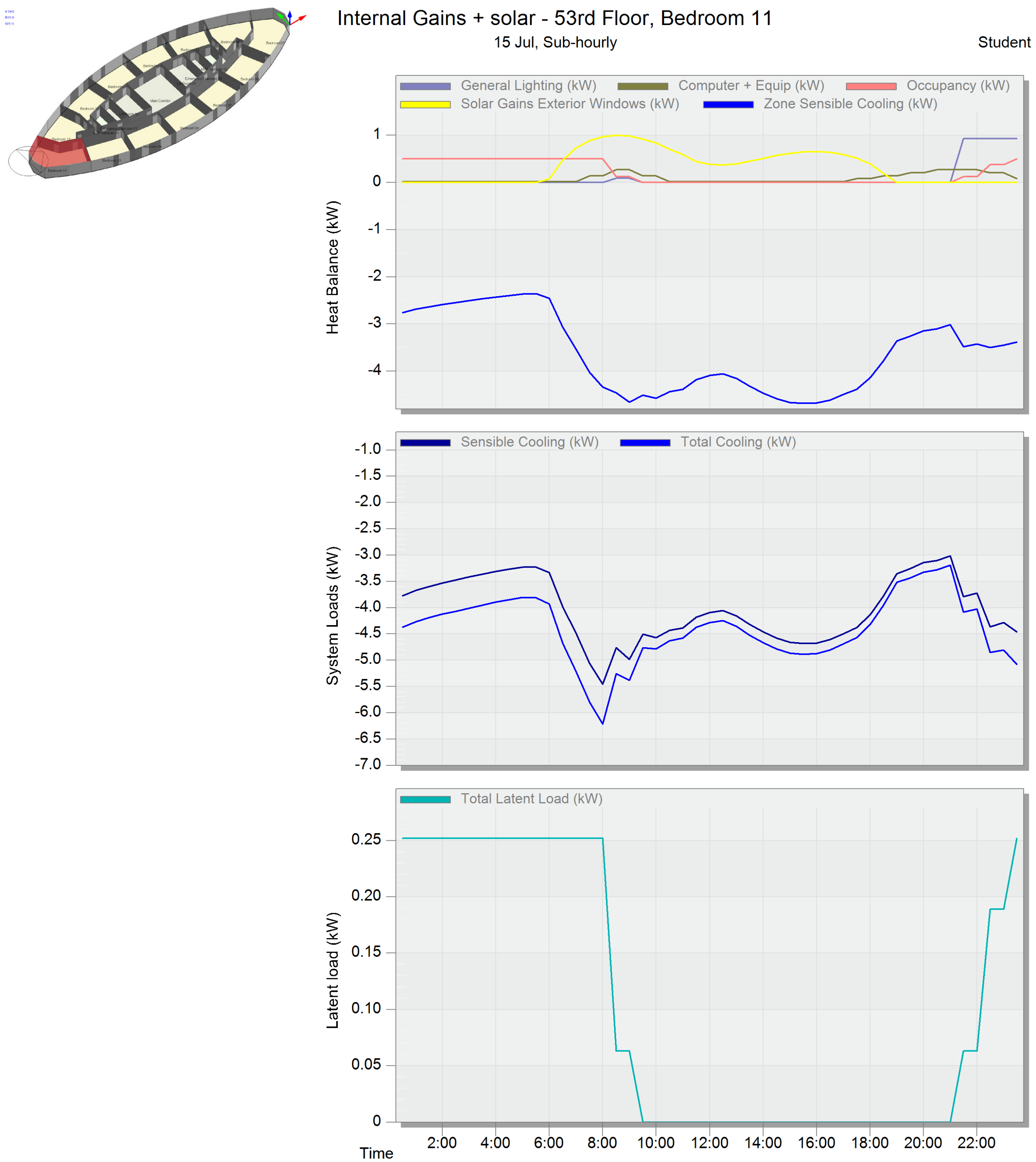
Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.74
Computer + Equip (kW)	0.02	0.02	0.02	0.12	0.12	0.02	0.02	0.02	0.07	0.17	0.21
Occupancy (kW)	0.40	0.40	0.40	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.10
Solar Gains Exterior Windows (kW)	0.00	0.00	0.12	1.24	0.88	0.21	0.19	0.16	0.07	0.00	0.00
Zone Sensible Cooling (kW)	-1.73	-1.63	-1.74	-3.75	-3.61	-2.77	-2.66	-2.53	-2.26	-1.98	-2.29
Sensible Cooling (kW)	-2.48	-2.34	-2.44	-4.64	-3.61	-2.77	-2.66	-2.53	-2.26	-1.98	-2.52
Total Cooling (kW)	-2.92	-2.77	-2.89	-5.26	-3.78	-2.90	-2.81	-2.67	-2.40	-2.12	-2.76
Total Latent Load (kW)	0.20	0.20	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.05

Figure 3.3.2.11: Simulation results for internal gains on predicted existing envelope - East Facade
(Source - Author, Extracted Input Parameters from Design Builder)



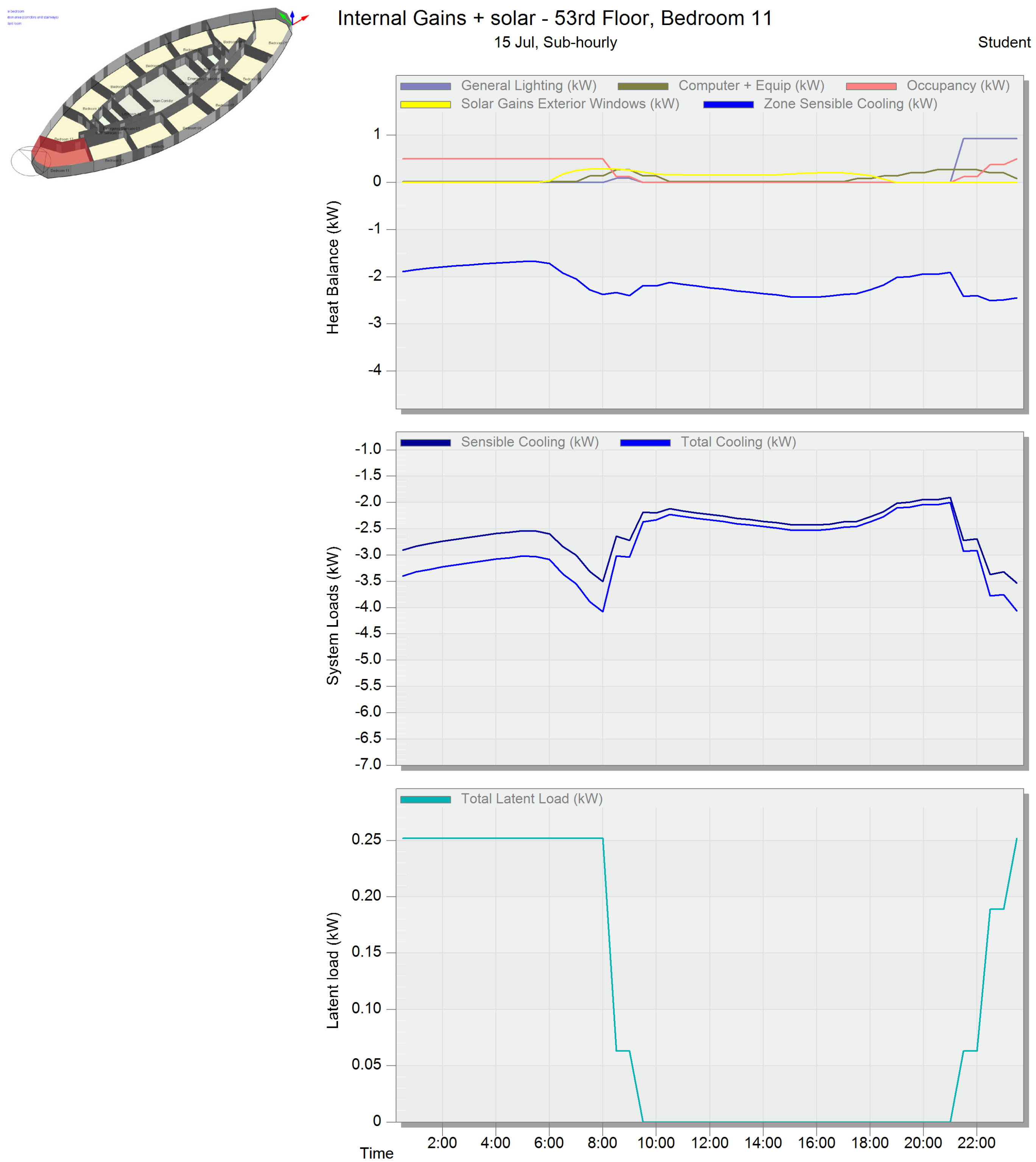
Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.74
Computer + Equip (kW)	0.02	0.02	0.02	0.12	0.12	0.02	0.02	0.02	0.07	0.17	0.21
Occupancy (kW)	0.40	0.40	0.40	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.10
Solar Gains Exterior Windows (kW)	0.00	0.00	0.05	0.35	0.11	0.08	0.08	0.06	0.03	0.00	0.00
Zone Sensible Cooling (kW)	-1.13	-1.08	-1.12	-1.67	-1.34	-1.29	-1.34	-1.30	-1.21	-1.14	-1.54
Sensible Cooling (kW)	-1.88	-1.78	-1.83	-2.56	-1.34	-1.29	-1.34	-1.30	-1.21	-1.14	-1.78
Total Cooling (kW)	-2.22	-2.12	-2.17	-3.00	-1.44	-1.37	-1.42	-1.37	-1.29	-1.21	-1.95
Total Latent Load (kW)	0.20	0.20	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.05

Figure 3.3.2.12: Simulation results for internal gains on proposed envelope - East Facade
(Source - Author, Extracted Input Parameters from Design Builder)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93
Computer + Equip (kW)	0.02	0.02	0.02	0.14	0.14	0.02	0.02	0.02	0.08	0.21	0.27
Occupancy (kW)	0.51	0.51	0.51	0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.13
Solar Gains Exterior Windows (kW)	0.00	0.00	0.08	0.97	0.84	0.39	0.51	0.66	0.39	0.00	0.00
Zone Sensible Cooling (kW)	-2.59	-2.43	-2.45	-4.34	-4.57	-4.09	-4.46	-4.67	-4.14	-3.14	-3.42
Sensible Cooling (kW)	-3.53	-3.31	-3.34	-5.46	-4.57	-4.09	-4.46	-4.67	-4.14	-3.14	-3.72
Total Cooling (kW)	-4.12	-3.90	-3.93	-6.21	-4.79	-4.28	-4.67	-4.87	-4.32	-3.32	-4.03
Total Latent Load (kW)	0.25	0.25	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.06

Figure 3.3.2.13: Simulation results for internal gains on predicted existing envelope - East Facade
(Source - Author, Extracted Input Parameters from Design Builder)



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93
Computer + Equip (kW)	0.02	0.02	0.02	0.14	0.14	0.02	0.02	0.02	0.08	0.21	0.27
Occupancy (kW)	0.51	0.51	0.51	0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.13
Solar Gains Exterior Windows (kW)	0.00	0.00	0.03	0.30	0.18	0.16	0.16	0.21	0.15	0.00	0.00
Zone Sensible Cooling (kW)	-1.79	-1.71	-1.71	-2.38	-2.19	-2.23	-2.36	-2.43	-2.27	-1.94	-2.39
Sensible Cooling (kW)	-2.73	-2.59	-2.59	-3.50	-2.19	-2.23	-2.36	-2.43	-2.27	-1.94	-2.69
Total Cooling (kW)	-3.22	-3.08	-3.08	-4.08	-2.33	-2.33	-2.46	-2.53	-2.37	-2.03	-2.91
Total Latent Load (kW)	0.25	0.25	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.06

Figure 3.3.2.14: Simulation results for internal gains on proposed envelope - East Facade
(Source - Author, Extracted Input Parameters from Design Builder)

3.3.3. Energy Performance Assessment Results

Existing Façade Base Case

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	2527902.13	240.02	240.02
Net Site Energy	2527902.13	240.02	240.02
Total Source Energy	3420004.07	324.73	324.73
Net Source Energy	3420004.07	324.73	324.73

energy performance index: **240 kWh/m²/year**

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00
Cooling	0.00	0.00	0.00	2172021.78	0.00	0.00
Interior Lighting	278004.43	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	437.25	0.00	0.00	0.00	0.00	0.00
Interior Equipment	77438.68	0.00	0.00	0.00	0.00	0.00

energy required for cooling: 217 kWh/m²/year

~210 kWh/m²/year

Figure 3.3.3.1: extract of simulation results for EPI for the case study existing building
(Source - Author, Extracted Input Parameters from Design Builder)

Conclusion

Incorporating the design measures discussed in Chapters 3.3.1 and 3.3.2 provide us with insights that improving the quality of facade using passive strategies will reduce the heat transfer into the building and the internal heat gains. These design aspects will be essential in hot arid places like Dubai. However, the most important reason why there aspects are considered useful is that they help reduce the energy consumption of the building and reduce utility costs. The simulation results suggest that if the strategies from the above-mentioned chapters are incorporated, then the energy performance of the selected building will reduce from 240 kWh/m2/year to 190 kWh/m2/year. This difference mentioned above is considerable. But, the motive for this calculation is to predict the amount of energy saved in cooling and the data from Figures 3.3.3.1 and 3.3.3.2 which is an extract of the simulation results from design builder (See Appendix 7.3 for complete results overview) suggests that the amount of energy required for cooling has reduced from 210 kWh/m²/year to 160 kWh/m²/year with around 50 kWh/m²/year of energy savings per sqm. per year.

These results were used to evaluate the amount of expenses the building management have to pay by using the Dubai municipality utilities consumption calculation, which is available in https://www.dewa.gov.ae/en. The results of the calculation are shown in Table 3.3.3.3. The summary of the results can be seen in Figure 3.3.3.4 where it can be estimated that the amount of energy saved by passive design strategies introduced in the design accounts for 28% of overall energy consumption in comparison to the base case and the utility bill calculation Figure 3.3.3.5. suggests the proposed design will save up to 455,000 (rounded off) euros worth of savings per year.

Proposed Façade with Shading

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	1970711.27	187.12	187.12
Net Site Energy	1970711.27	187.12	187.12
Total Source Energy	2845271.21	270.16	270.16
Net Source Energy	2845271.21	270.16	270.16

energy performance index: **190 kWh/m²/year**

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00
Cooling	0.00	0.00	0.00	1608448.72	0.00	0.00
Interior Lighting	284386.63	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	437.25	0.00	0.00	0.00	0.00	0.00
Interior Equipment	77438.68	0.00	0.00	0.00	0.00	0.00

energy required for cooling: 160 kWh/m²/year

~160 kWh/m²/year

Figure 3.3.3.2: extract of simulation results for EPI for the case study after proposed modifications
(Source - Author, Extracted Input Parameters from Design Builder)

EPI of the Building		kWh/m²/year	**150**	**190**	**210**	**240**
Overall Energy Consumption		kWh/year	14,535,000	18,411,000	20,349,000	23,256,000
		kWh/month	1,211,250	1,534,250	1,695,750	1,938,000
Energy Bills	Green Slab	AED/kWh	460	460	460	460
	Yellow Slab		560	560	560	560
	Orange Slab		640	640	640	640
	Red Slab		457,995	580,735	642,105	734,160
	Total		459,655	582,395	643,765	735,820
Fuel Surcharge	Electricity Total	AED/kWh	78,731	99,726	110,224	125,970
Combined Utility	Bill		538,386	682,121	753,989	861,790
VAT @ 5%			26,919	34,106	37,699	43,090
Total Bill Incl. VAT		AED/kWh	565,306	716,227	791,688	904,880
Total Bill Incl. VAT		EUR/kWh	141,326	179,057	197,922	226,220
Total Bill Incl. VAT/ per Year		EUR/kWh/yr	**1,695,916.69 €**	**2,148,681.94 €**	**2,375,064.56 €**	**2,714,638.50 €**

Table 3.3.3.3: Utility consumption calculation results
(Source - Author, Utility calculation bar data from DEWA,Dubai)

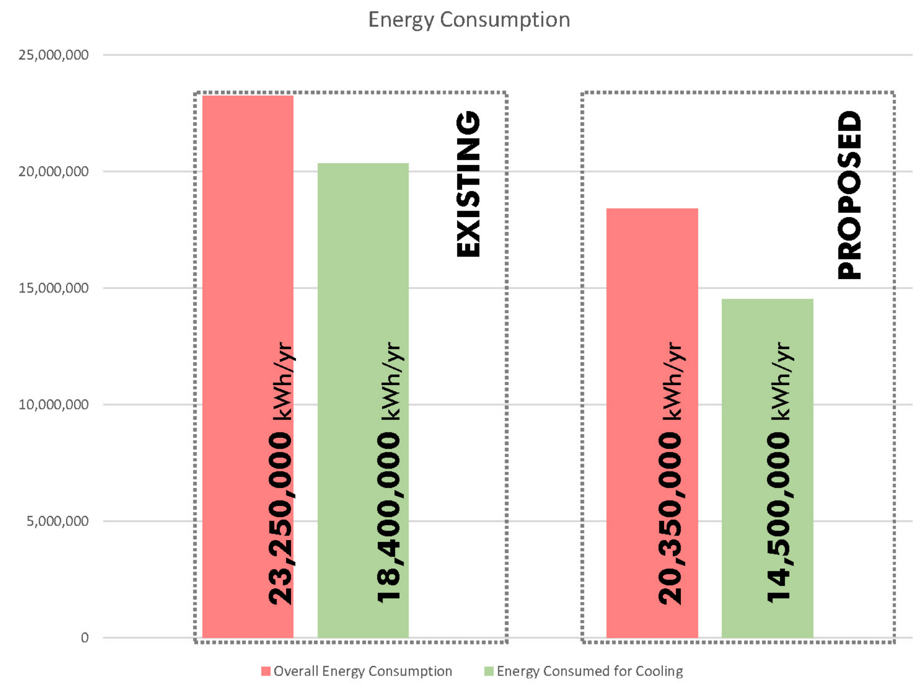


Figure 3.3.3.4: Comparison of consumed energy for the whole building for existing and proposed cases (Source - Author)

Figure 3.3.3.5: Comparison of energy expenses for the whole building for existing and proposed cases (Source - Author)

3.4. Daylighting Evaluation

3.4.1. Introduction

The facade of the building apart for the first degree of separation from elements is also responsible for the indoor environmental quality. Sufficient daylighting inside the rooms mean lesser dependence on the artificial lighting system which consumes energy. Designers should attempt to integrate sufficient daylighting inside the building for comfort and efficiency strategies. There would be a certain amount of tradeoffs due to the balance between thermal performance and comfortable lighting requirements inside the room. This requires a parametric approach where the software helps make rational judgements for the maximum amount of louvres to receive a sufficient amount of daylighting required inside the building. Goals for this part of the research is to identify the right balance between the amount of shading horizontal louvres and indoor illumination, and the results of this study will hence determine the louvre design characteristics.

3.4.2. Analysis

For the analysis, simulation software such Grasshopper with Ladybug plug-in was used to simulate the ideal angle of the panel per orientation of the facade and the weather data for Abu Dhabi in *.EPW format was downloaded from the energy plus website (https://energyplus.net/weather) and used as the basis of climate data for the simulation. The size of the room was modelled parametrically with grasshopper with the depth of the room as 8.0 meters, and the width as 4.5 meters the height of the room for this simulation was considered as 3.6 meters. The daylighting simulation was done with the ladybug plug-in. Appendix - 7.4 contains the full information of the simulation script used to conduct the study.

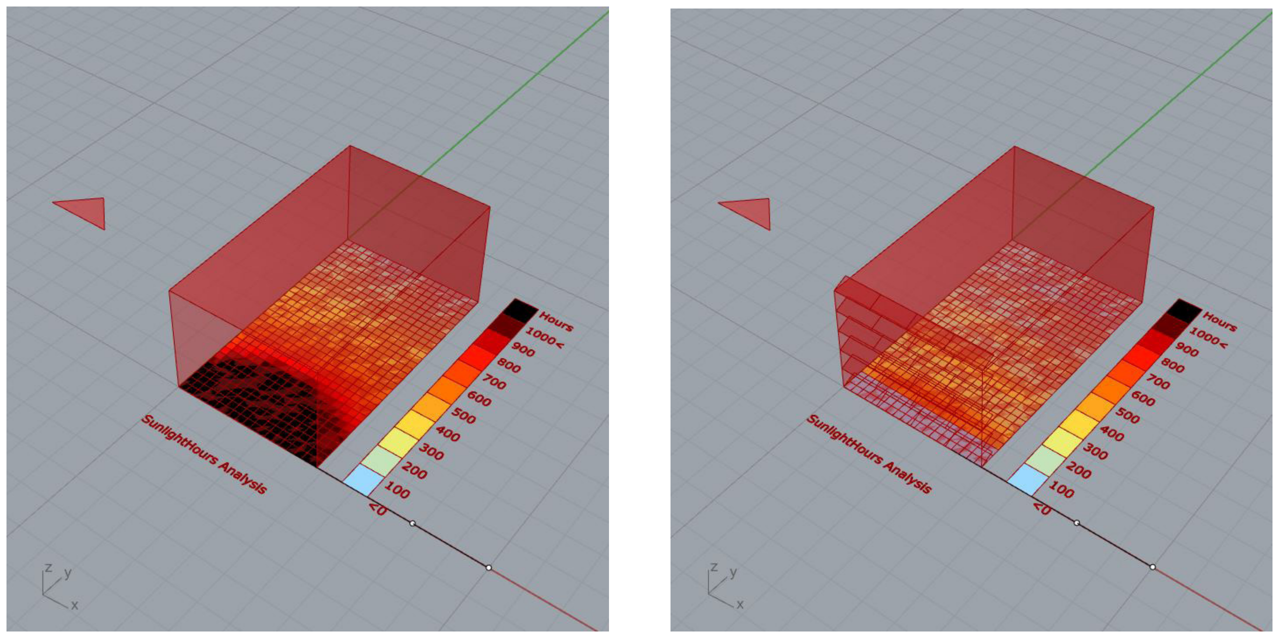


Figure 3.4.1: Daylighting simulation comparison without louvers and with 5 louvers in vertical direction (Source - Author)

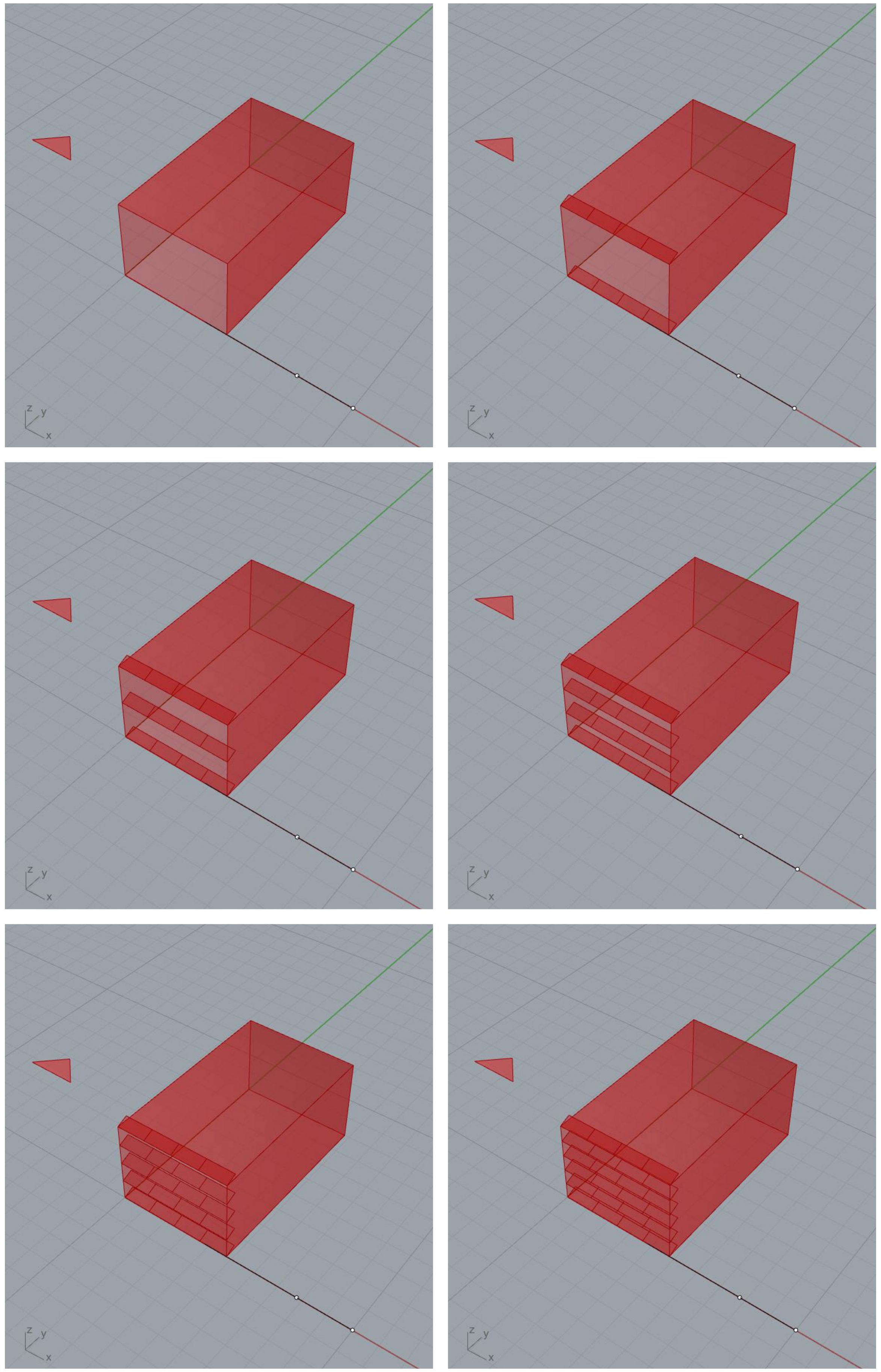


Figure 3.4.2: Daylighting evaluation options for number of louvres
(Source: Author)

Figure 3.4.1 shows the simulation results for the amount of daylighting hours received for south orientation opening for conditions with no panels and a maximum of five panels. This study was conducted for 6 iterations starting with no horizontal louvres and a maximum of 5 horizontal louvres shown in Figure 3.4.2. with a tilt angle of louvres adjusted to 22 degrees, as discussed in Chapter 3.3.2.

3.4.3. Conclusion

Results suggested that for all facades, a maximum of two panels would provide a sufficient amount of sunlight hours and the required levels of illumination of 500 to 1000 lux. Figure 3.4.4 indicates the design intent of having both the louvres at a bottom level to maximize visibility towards outside.

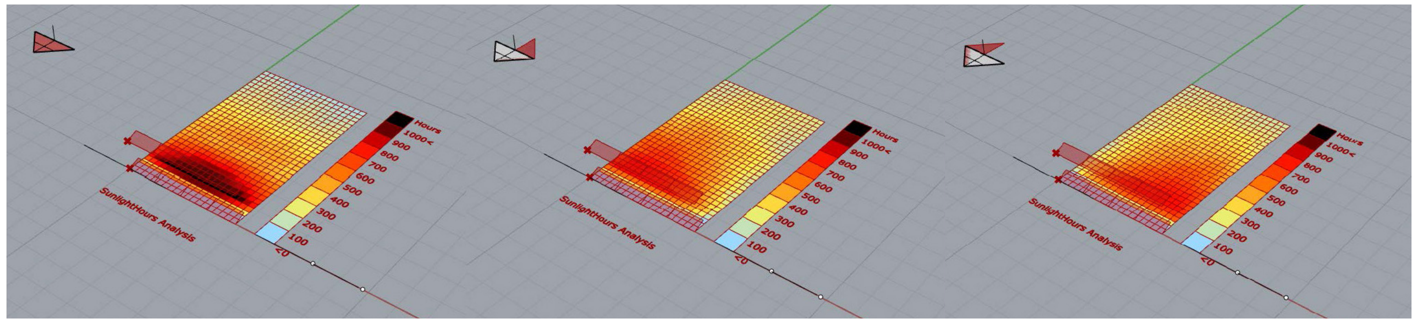


Figure 3.4.3: Daylighting evalaution results
(Source: Author)

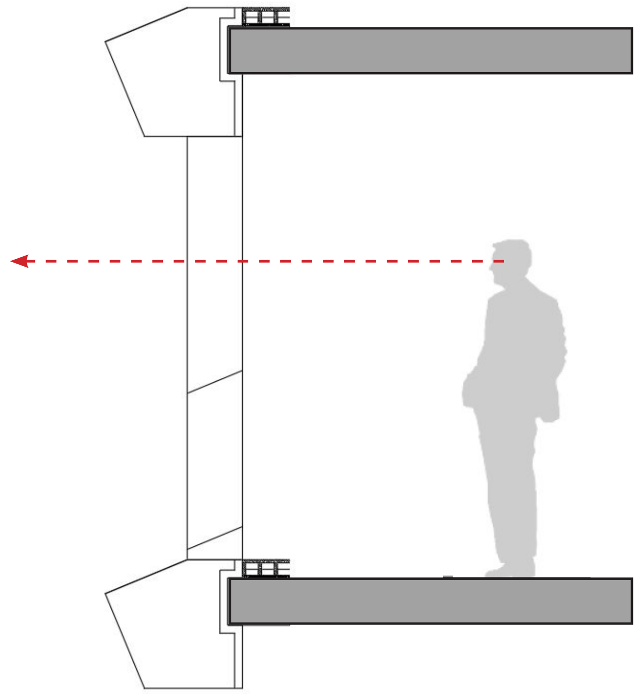


Figure 3.4.4: Louvers are placed at a lower level to maximize view outwards
(Source: Author)

3.5. Concept Design

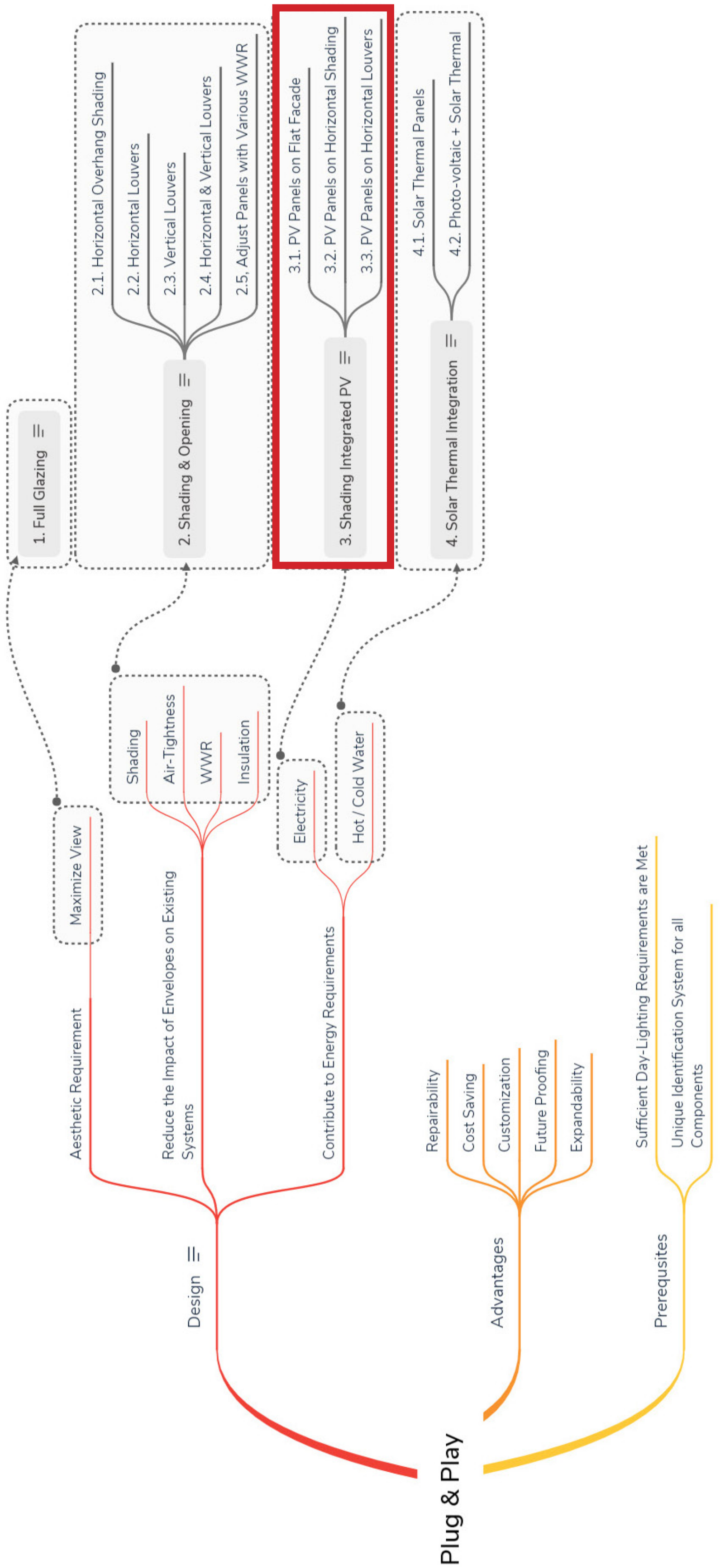


Figure 3.5.1: Plug&Play design requirements mindmap (Source – Author)

	Shading System	Blind Panel				Glazing Panel				Reduced WWR Panel			
		North	East	South	West	North	East	South	West	North	East	South	West
No Function	No Projections	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙
	Overhang	-	-	-	-	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙
	External Louvers	-	-	-	-	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙
PV Panels	No Projections	-	⊙	⊙	⊙	-	⊙	⊙	⊙	-	⊙	⊙	⊙
	Overhang	-	-	-	-	-	⊙	⊙	⊙	-	⊙	⊙	⊙
	External Louvers	-	-	-	-	-	⊙	⊙	⊙	-	-	-	-
ST Panels	No Projections	-	⊙	⊙	⊙	-	-	-	-	-	⊙	⊙	⊙
	Overhang	-	-	-	-	-	-	-	-	-	⊙	⊙	⊙
	External Louvers	-	-	-	-	-	-	-	-	-	-	-	-
TEC Panels	No Projections	⊙	⊙	⊙	⊙	-	-	-	-	⊙	⊙	⊙	⊙
	Overhang	-	-	-	-	-	-	-	-	⊙	⊙	⊙	⊙
	External Louvers	-	-	-	-	-	-	-	-	-	-	-	-

Table 3.5.2: Plug&Play Technology potentials (Source – Self)

3.5.1. Introduction

The design challenges to combine all the aspects discussed till now into one functional conceptual component. Mindmap in Figure 3.5.1 explores all the essential potentials for a plug&play facade design. The design will include within its umbrella of functionality the following key aspects:

1. **Improve the facade quality:** Improving the quality of facade by ensuring materials with higher u-values, material properties and improved performance of the facade will ensure that the new facade will reduce the energy consumption of the building.

2. **Provide sufficient shading:** This is an energy reduction strategy, as discussed in the shading potential evaluation in literature study in Chapter 2.6.3. The results of the study have confirmed that having shading on the facade in middle-east will provide from 10 to 30% of energy savings based on the orientation of the facade. Hence, the design will incorporate this parameter.

3. **Provide sufficient day light inside:** The literature in chapter 2.6.4 by Kim, Jung, Choi, & Kim, 2010 confirms that the indoor illumination of a room should be around 500 lux for comfortable lighting, this value will determine the number and position of horizontal louvres on the glass panel.

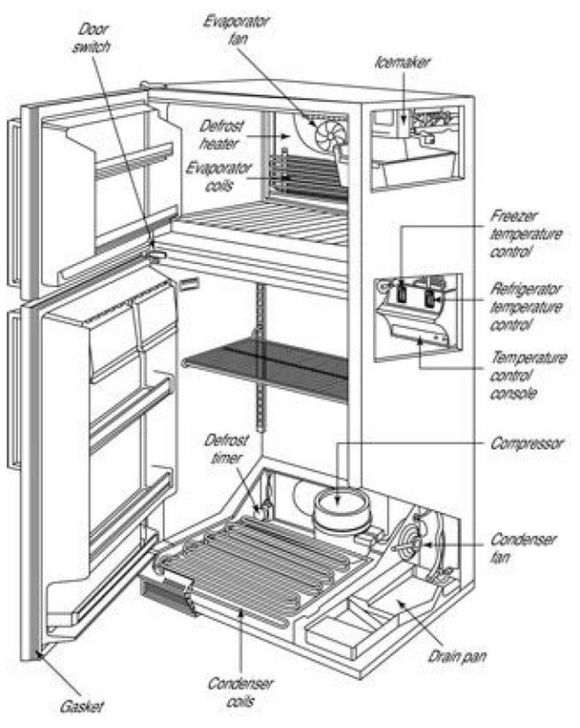


Image 1: Fridge diagram

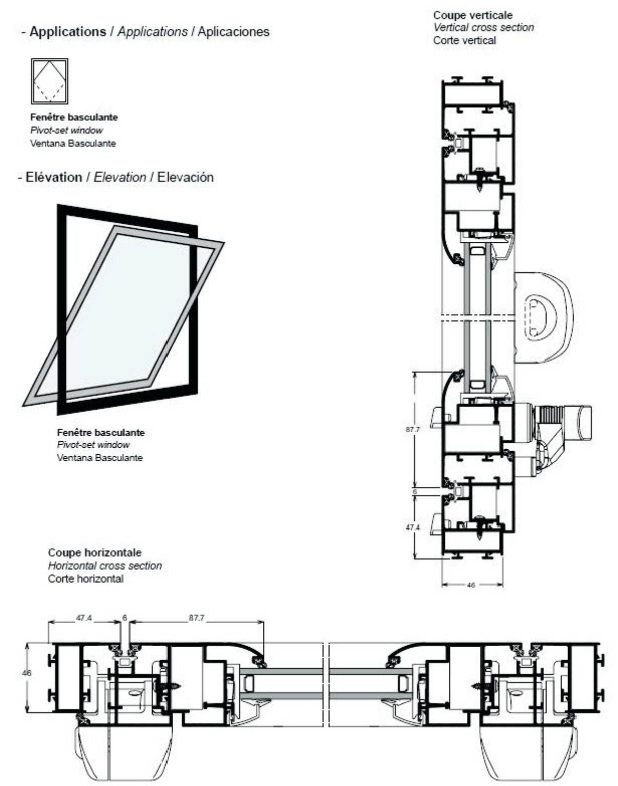


Image 2: Pivot windows

Figure 3.5.3: Inspiration for concept
(Source – Pivot Window – http://www.hotel-le-provence.fr/fenetre-basculante-5-8044/
Fridge Diagram – https://fppi.ca/maintain-your-fridgefreezer/

4. **Intergrate BIPV on the shading:** Building integrated photovoltaics is one of the strategies to explore for energy production, the strategy will help the current systems to rely less on the power grid which is mostly from non-renewable sources, and BIPV approach will also reduce the energy consumption bills.

5. **Focus on design for disassembly:** Design for disassembly is mostly the guideline for this thesis, as stated in chapter 3.1 for Life Cycle assessment, design for disassembly is the call for the hour. Potential materials are discarded prematurely, which causes a lot of material wastage. Secondly, the concept of Plug&play fits perfectly with the design for disassembly. Because, when we combine additional functionality which will help the facade reduce the buildings reliability on expensive non-renewables and help save material at the same time.

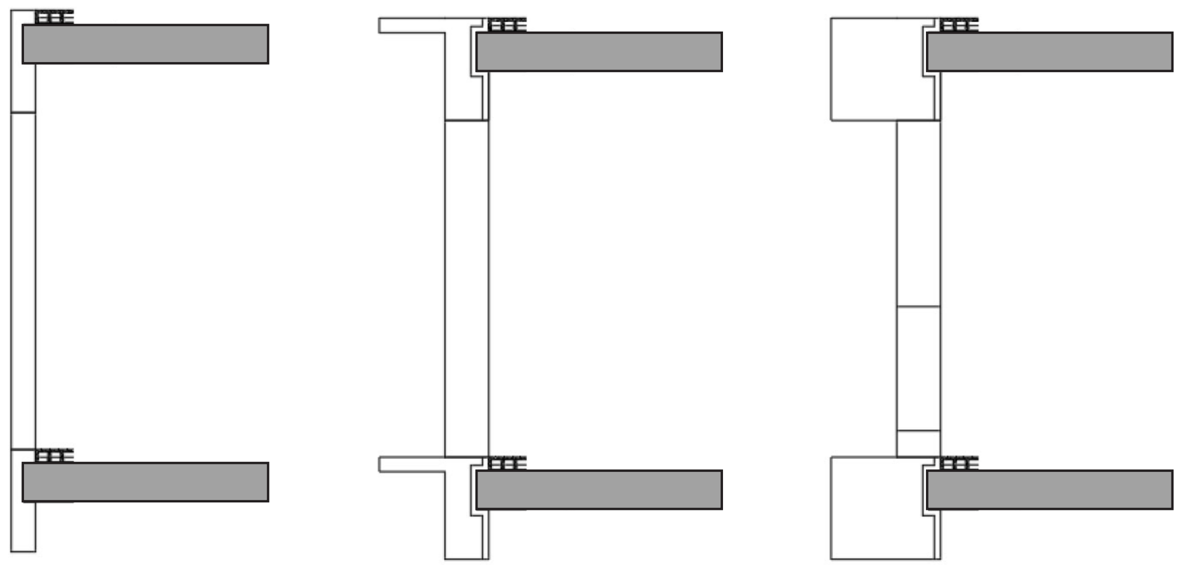
6. **Focus on accessibility:** Life cycle assessment (Chapter 3.1) and Economic Assessment (Chapter 3.2) have discussed mostly upon the number of materials wasted due to the refurbishment requirements of an existing curtain wall facade and that how expensive it becomes to maintain or refurbish the facade itself. Accessibility is a solution to the above two problems, and the concept remains to allow for easy accessibility of the facade elements to replace, clean or maintain them in any required way. This solves the issue of depending on heavy expensive BMU's on top of the building and the high-risk conditions people the glass or facade maintenance crew will be working in from outside.

The mindmap in Figure 3.5.1 and the table in Figure 3.5.2 are self-explanatory, although the general idea is that the design aspect will consider aesthetic requirements, energy consumption reduction and energy production strategies and they can give either of full glazing, shading or shading with PV system in it. Which have the benefit of repairability, cost-saving, customization, future proofing and expandability, etc.. The use of technology is also deeply dependent on the orientation of the building where it is placed. Table 3.5.2. identifies different technologies and informs where it can be placed based on its location.

The concept plug and play as described in Chapter 2.5 and the primal considerations for the design comes together calling for integrated functionality. The red highlighted region is the area where the design for this thesis will focus upon. The number of technologies to be used itself is endless as shown in Figure 2.4.2. However, based on the research question, the focus of the design will be to incorporate PV panels on a shading system for south orientation.

Moreover, hence, the concept was inspired by a refrigerator door and a pivot window (Figure 3.5.3). Based on the principles of an operable air-tight element and an accessible panel which can be removed with all functionality in it had a design integration potential.

3.5.2. Preliminary Design



Step 1

Existing curtain wall design. Hung to the edge of the slab.

Step 2

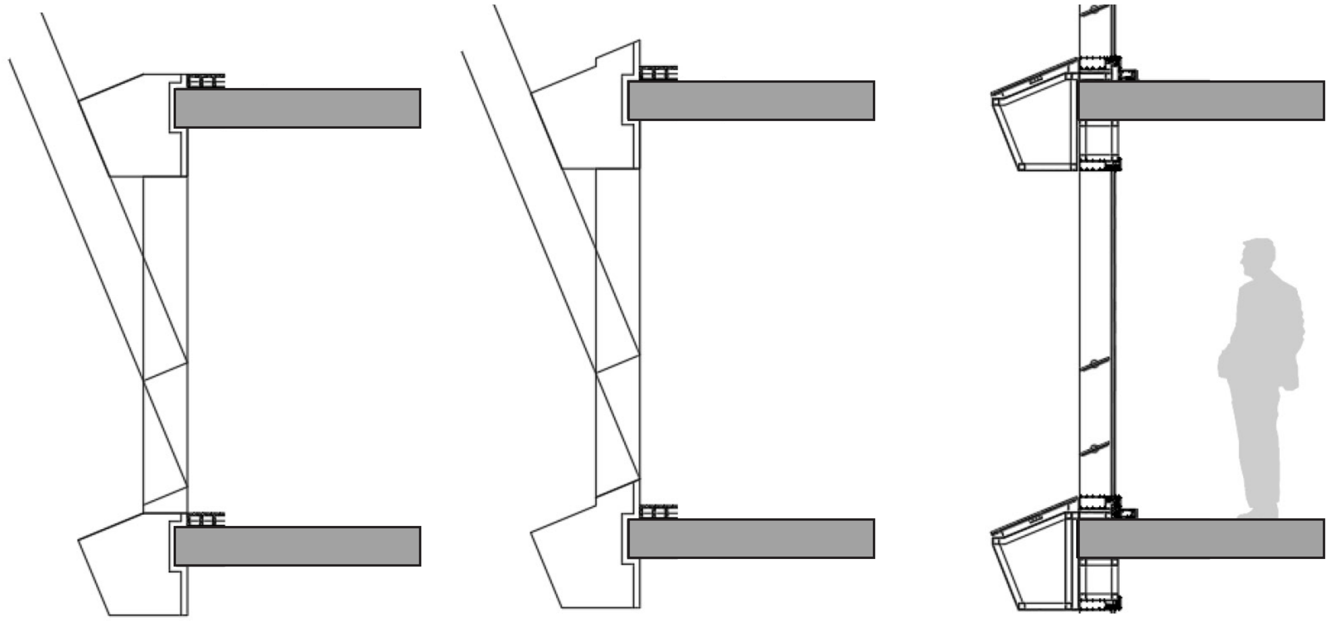
Incorporation of a shading element with sufficient projection to reduce solar heat gains.

Step 3

Modifying the bulkhead design to identify a functionality potential.
e.g. PV panels or ST panels

Also incorporating horizontal louvres to maximize shading potential.

Figure 3.5.4: Form Development (Source – Self)



Step 4

Adjusting and optimizing the angle of the horizontal shading and the louvres to receive maximum solar radiation for the selected orientation (South) and the selected functionality (PV)

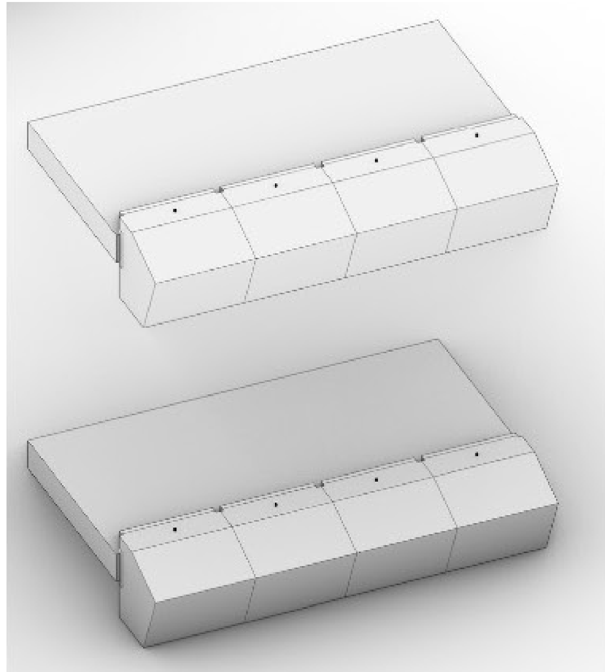
Step 5

Experimenting with maximizing the solar collector surface area and ensuring that
the shading element above does not overshadow the BIPV shading panel on the bottom.

Step 6

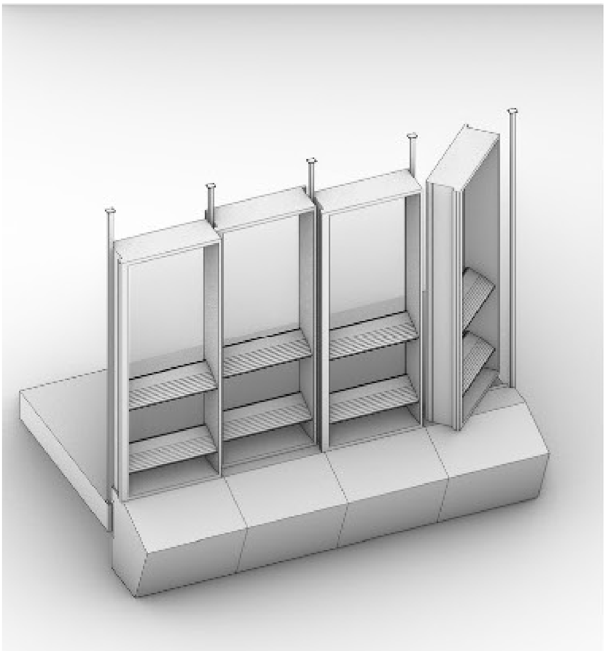
Final design with integrated functionalities.

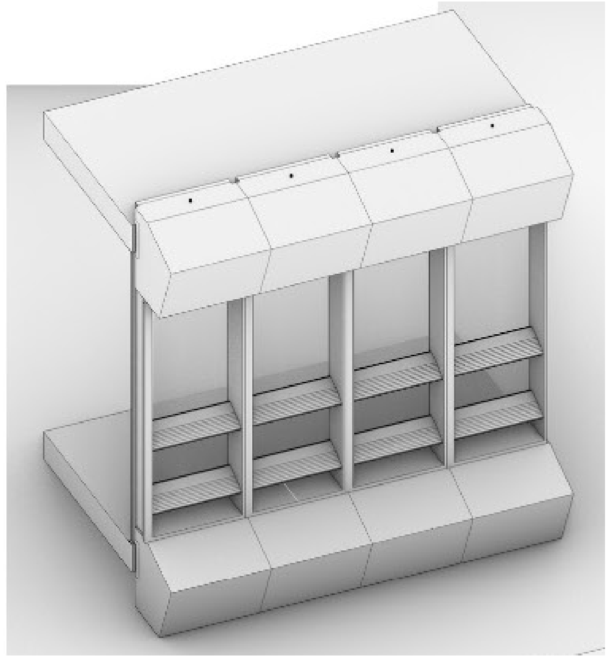
Figure 3.5.4: Form Development (Source – Self)



Bulkheads
Bulkheads are placed / mounted on the edge of the slab and will remain as the bed on which the twist and turn panels will be rested.

Structural Framework
Slender columns would provide sufficient structural support against the wind load and also provide the mount to fix the pivotable facade panel.





Central Pivot System
Central pivot for accessing the doors mean that the facade panels will require less space to operate during maintenance.

Overview
Each panel is accessible and serviceable from inside the building and once closed all the panels act as one to extend the functionality.

Figure 3.5.5: Preliminary Design Assembly (Source – Self)

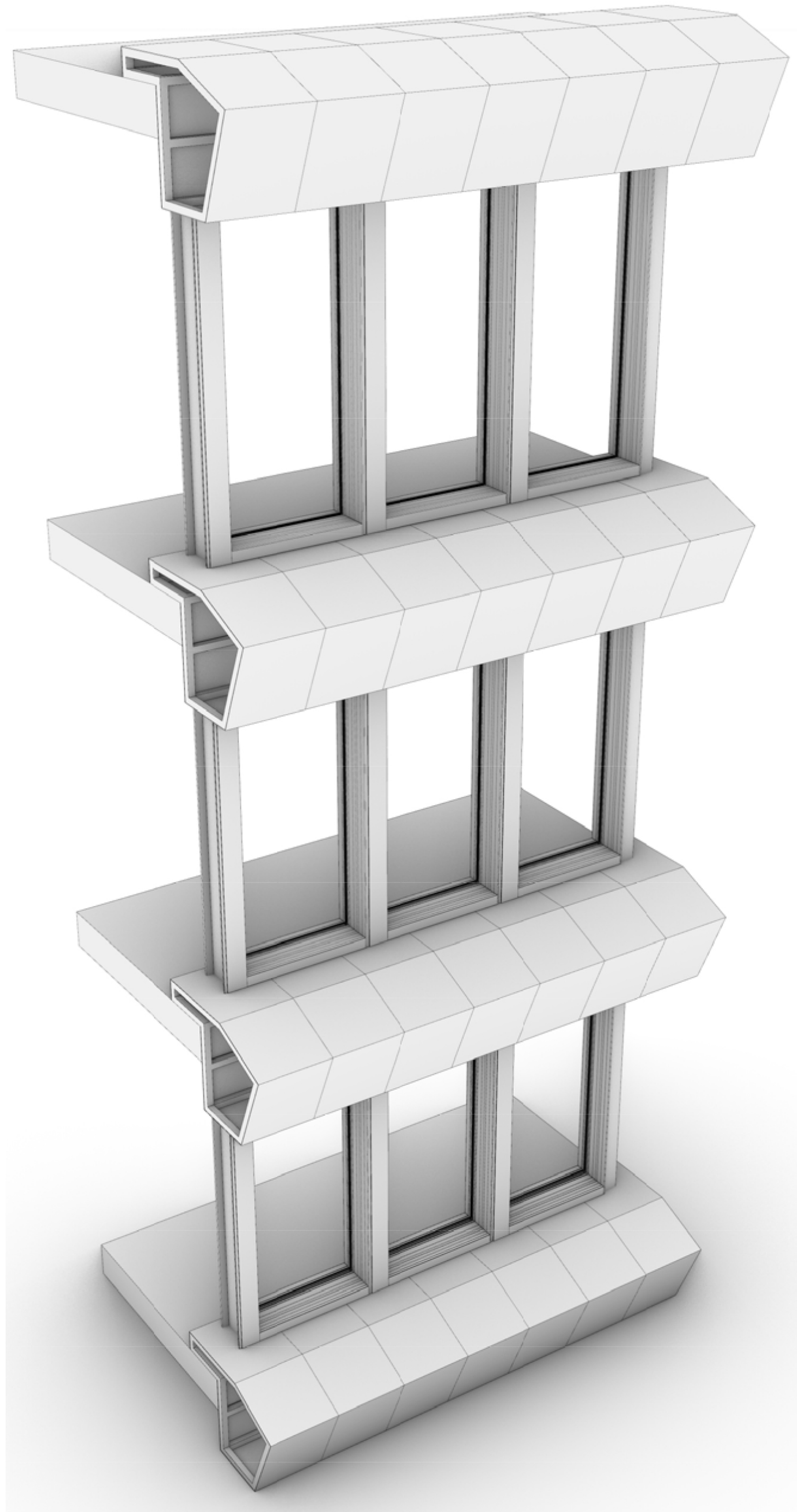
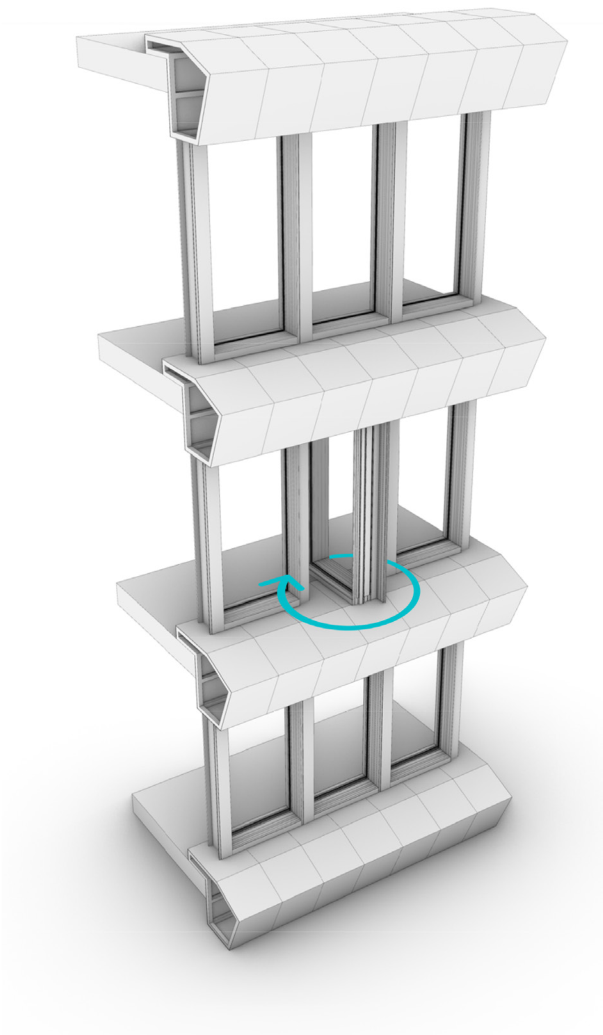


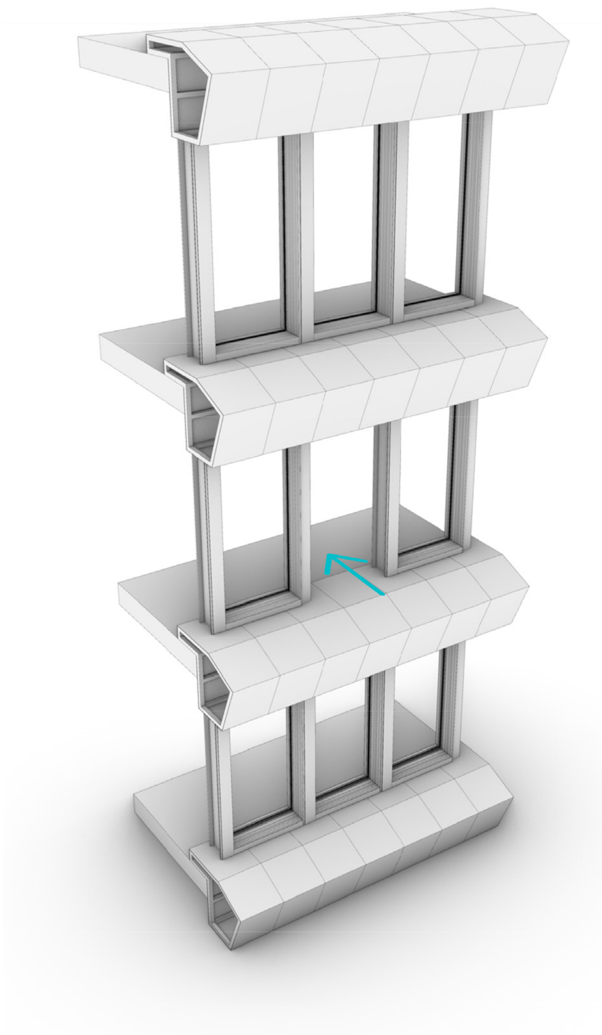
Figure 3.5.6: Preliminary design construction overview (Source – Self)

3.5.3. Preliminary design elaboration



Step 1

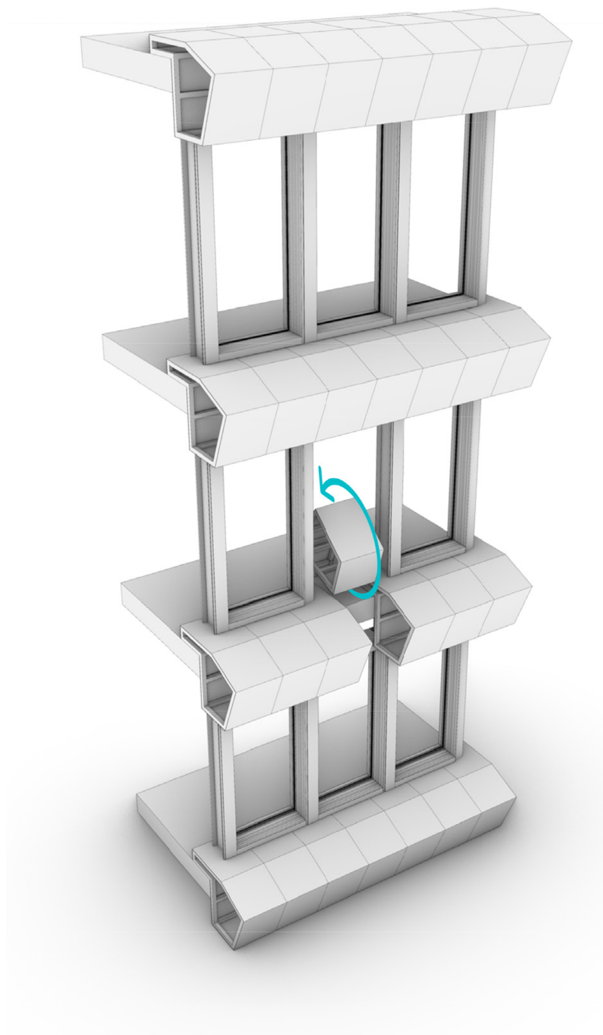
The original idea to allow easy accessibility was to ensure that the facade panel during operations for maintenance would not occupy space inside the room. Secondly, the design also allows for cleaning the panels when necessary. The pivoted door type panel will allow for a twist and turn to operate the panel and even remove it.



Step 2

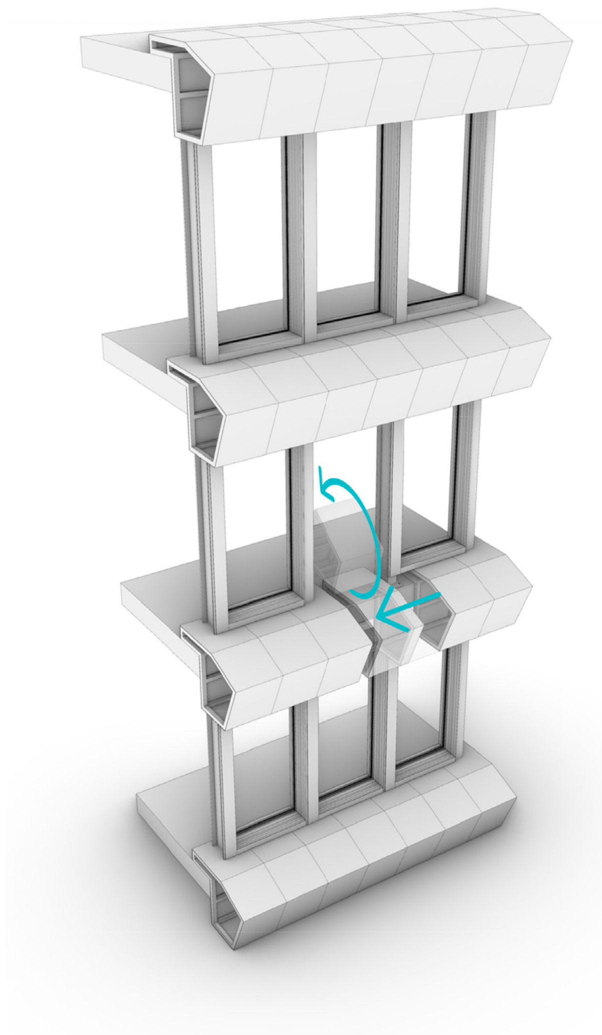
Once the panel is removed as shown in Step 1 by twisting and turning, the maintenance workers can service the panels from inside the building. They can also now change specific components or service the facade panel as necessary.

Figure 3.5.7: Preliminary design access and maintenance elaboration (Source – Self)



Step 3

In order to remove the bulkhead which is designed to be shorted than the width of the panel itself, the whole facade panel had to be removed and then the bulkhead would be disconnected by removing the bolts and then flipped over as indicated in the image.



Step 4

The bulkheads which are not accessible, or in cases where it becomes unnecessary to remove all the panels, the bulkheads could be slid over to required position (Where the facade panel is removed), and the action described in Step 3 would be repeated.

Figure 3.5.7: Preliminary design access and maintenance elaboration (Source – Self)

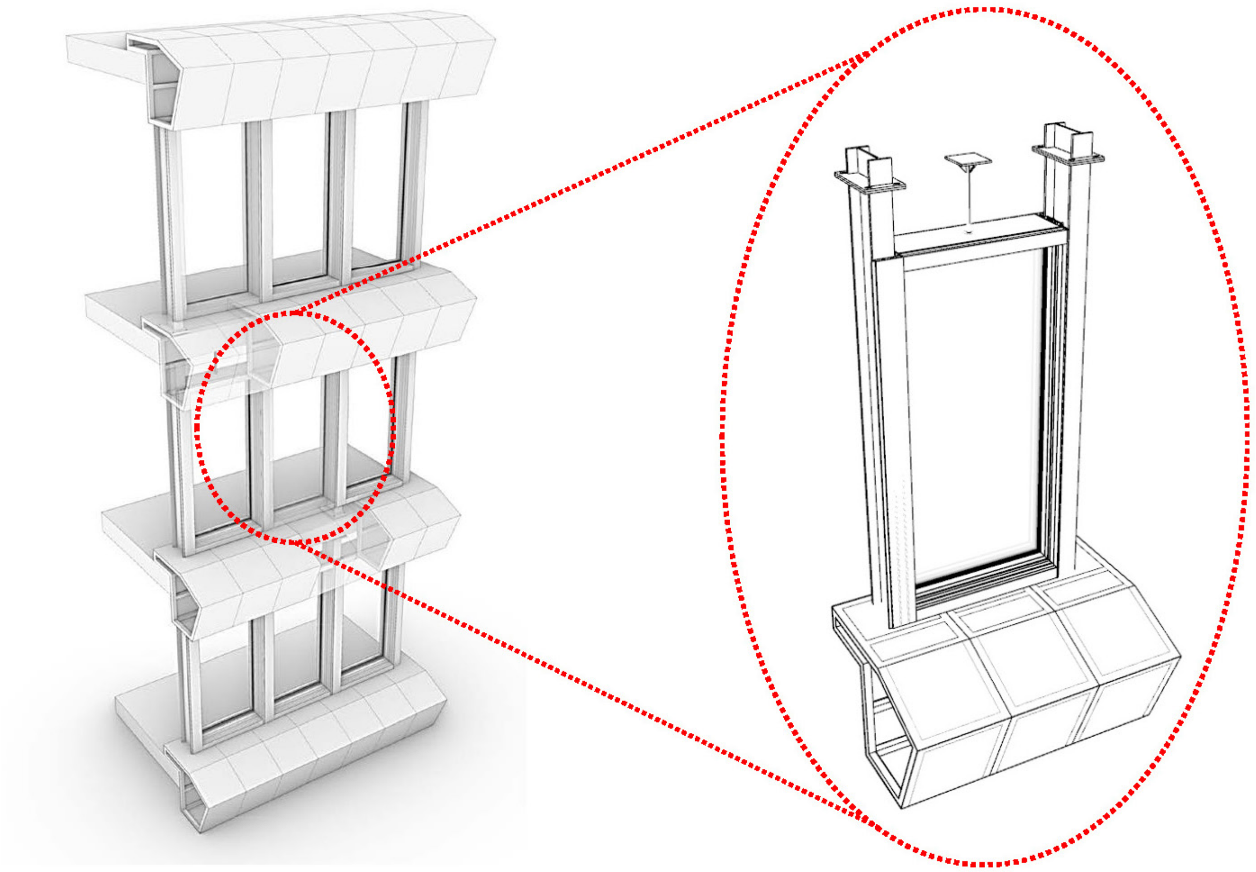


Figure 3.5.8: Expanded view of the preliminary design facade panel (Source – Self)

3.5.4. Preliminary design conclusion

The preliminary design provided the necessary foundation to construct the design over, ideas such as operability, accessibility, disassembly was taken forward. Apart from its benefits, the most prominent shortcoming of the preliminary concept was that the design would have serious airtightness issues, which would, in turn, affect the energy performance of the building. e.g. the conditioned air would seep out, there would be moisture penetration, the small gap would allow for dirt and debris to accumulate, and hence the facade would require more maintenance than required from the pivoted part of the hinge because the pivoted hinge as per design itself is a geometric problem. The pivot requires space to move in multiple directions, and the door seal would be on either side until halfway.

Apart from the pivot complexity, it would also be challenging to remove all panels and service them bi-annually and would require more time and coordination to execute and when you really need to access or change the panels which would be every 15 to 20 years it may not be necessary to provide a pivoted hinge operation because of the reduced frequency of use.

On the other hand, the design is mature enough to proliferate necessary options, as seen in Figure 3.5.9, which is an elaboration of the Table 3.5.2 with multiple possibilities of functionalities of Plug&play panels.

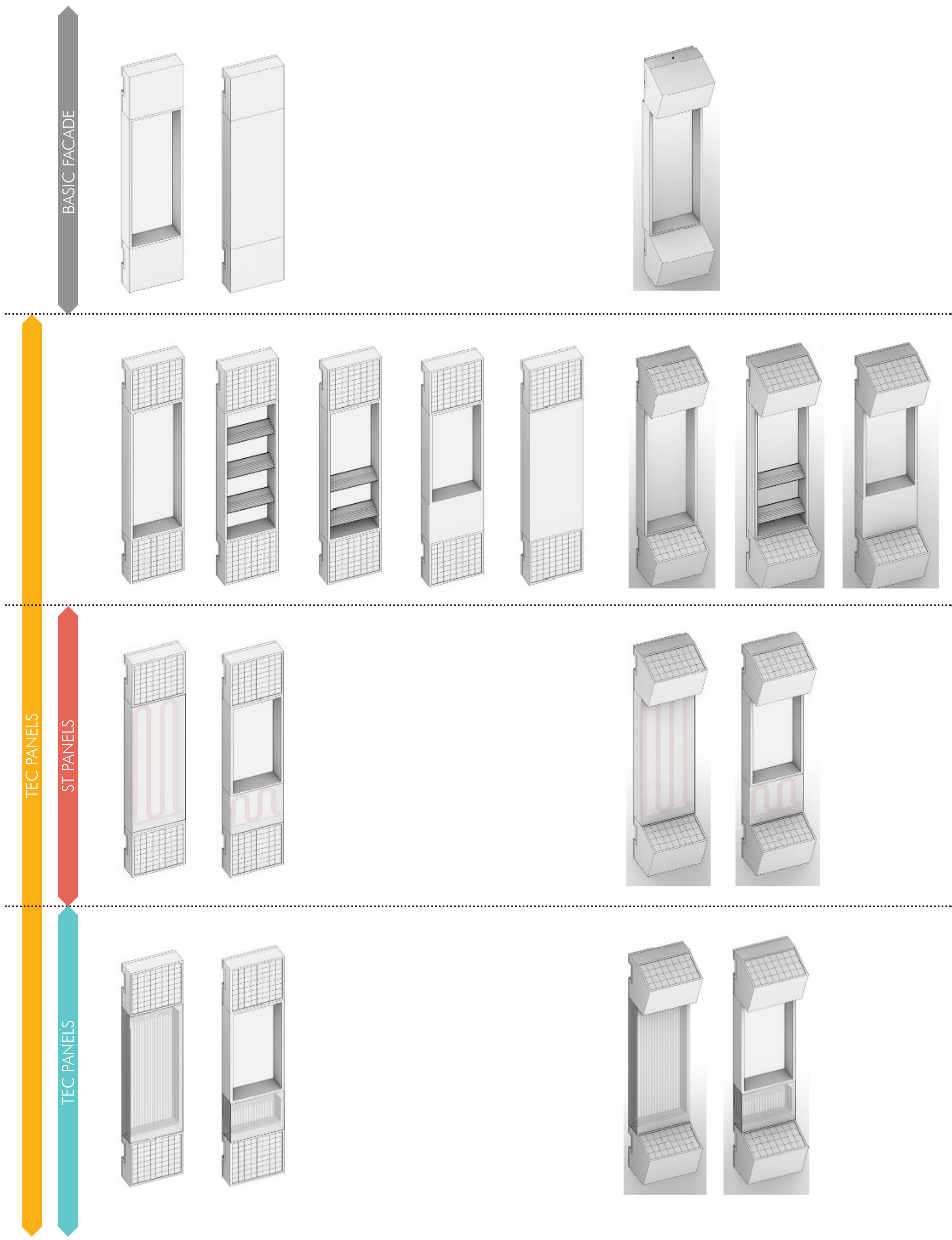


Figure 3.5.9: Typologies of potential plug&play facade types (Source – Self)

04
DESIGN PROPOSAL

4.1. Design Documentation

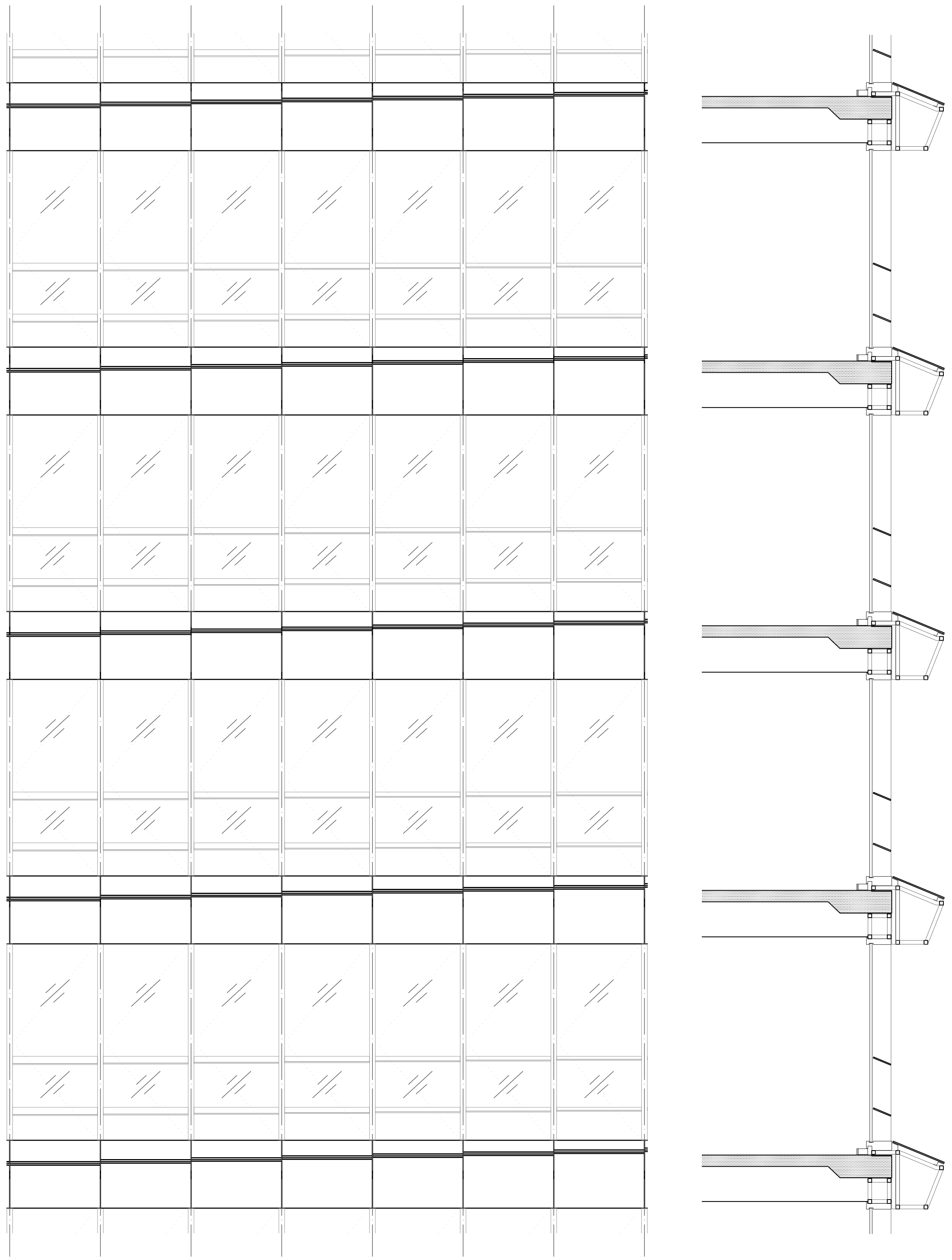


Figure 4.1.1: Elevation and corresponding section of the proposed facade (Source – Self)

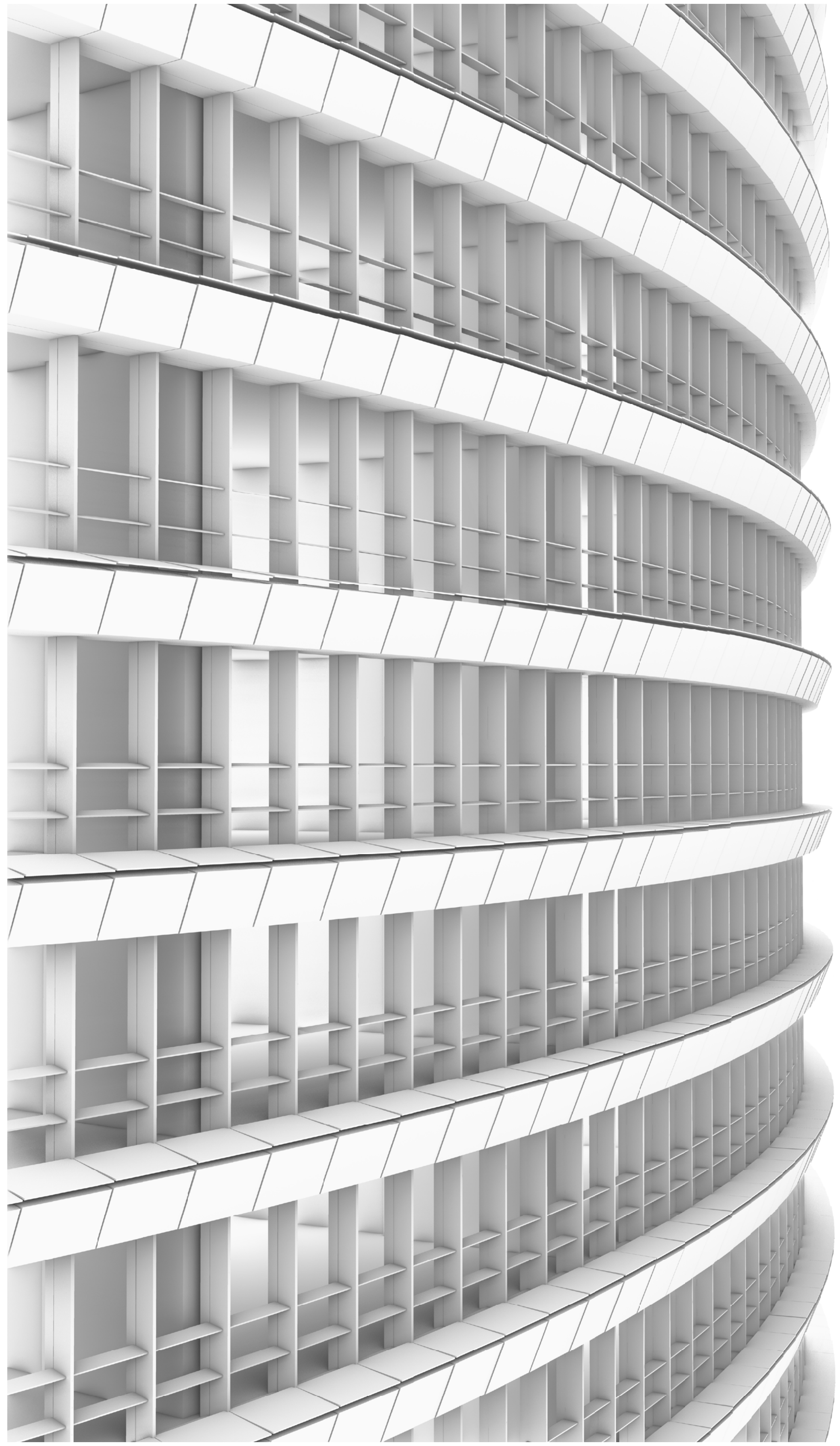


Figure 4.1.2: Concept view of proposed facade (Source – Self)

4.1.1. Introduction

Learning from the shortcomings in the concept design. The new proposed design will still attempt to follow the premise set in Figure 3.5.1. The new design will explore the possibility to design an integrated shading and BIPV panel, which is removable or disassemblable and provides easy access for maintenance. The key aspects discussed in Chapter 3.5.1 will still be considered.

The design will now focus on ensuring accessibility, from inside the building, however, unlike the concept design where all panels are completely removable with a twist and turn hinges. The new panels will have an accessible door, which will be sealed shut by mechanical systems such as pressure plates and cover caps. Only a skilled maintenance worker will be able to access/open the panel and service any component which is damaged and requires replacement or just the regular seasonal maintenance. This reduces the complexity of functional systems such as pivoted hinges, a fully twistable and turnable panel which will be quite heavy and hard to remove, airtightness issues, and complexity in power connection for PV cells between each panel because of the modularity (waterproofing & insulating etc.). Making one element with all functionality in real time may not have been a good starting point.

Hence, in the new design, the key concepts discussed before was retained, and the shortcoming in the previous concepts was eliminated. Now, instead of a functional panel, the design caters for functional components which at a whole provide access, disassembly, functionality and is much easier to operate. Figure 4.1.1. shows the elevation and a general cross-section of the new design. It can also be observed in Figure 4.1.1. elevation the nature of change in the angle of the horizontal overhang shading with PV to adjust to the orientation. At the south, the angle of incidence of the sunlight will be at 22 degrees and at the East & West orientations the angle will be at 0 degrees incidence to the horizontal. Figure 4.1.2. shows the view from outside the building to provide an idea about the appearance of the building from an aesthetic perspective.

The final design will contain a set of parts which can be accessed at any point in time. However, as shown in Figure 3.1.13, each component will be accessed and removed at a certain point of time where the requirement aligns with the need for regular maintenance. This allows for more than one component to be removed and does not cause disturbances during maintenance. The design also now eliminates the use of bulky and expensive BMU's which after economic analysis, we understand that it shoots up the cost of facade related expenses. Saving the maintenance equipment expenses for the life of the building will save the cost and material worth of one whole facade in the future. The next few chapters will explain in detail how the construction would look like and how it would be easy to access and showcase the overall breakdown of all the materials in the system.

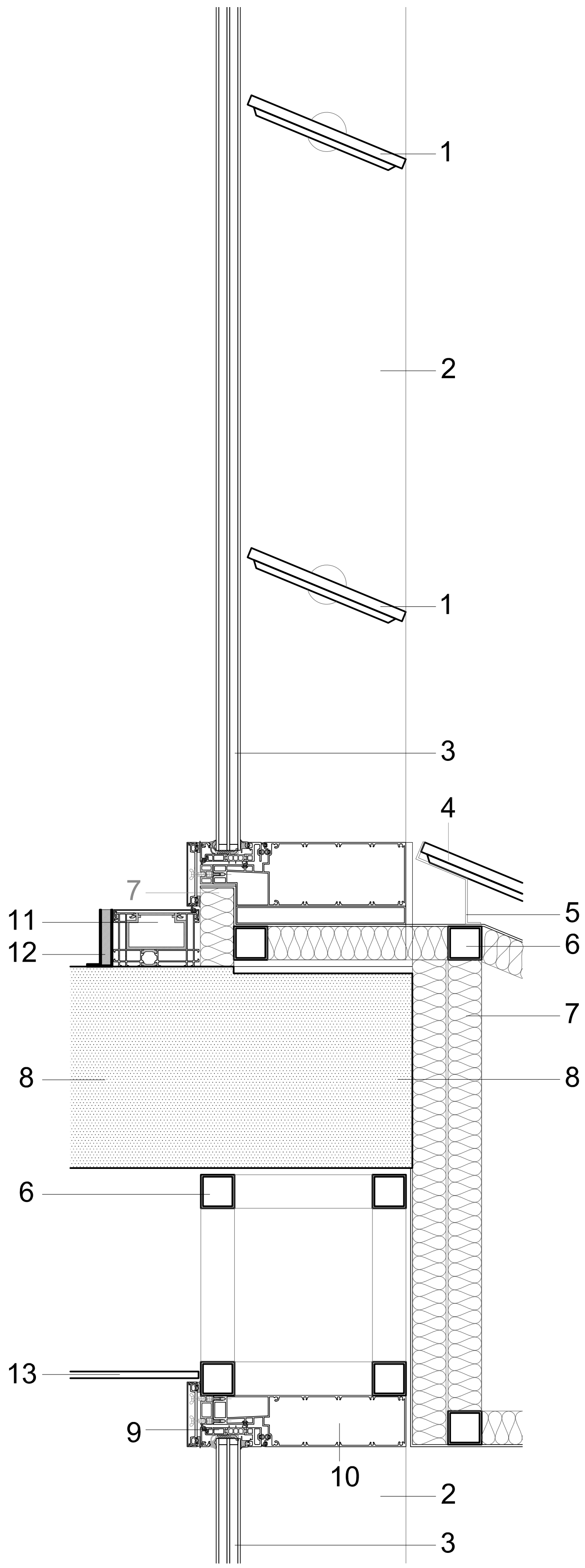
4.1.2. Final design conclusion

The final design required the foundation to construct the design over, ideas such as operability, accessibility, disassembly. Air tightness of the new design was not calculated for the scope of this thesis. However, the new design itself provides clues of air-tightness because of the increased number of gaskets and the side hinge instead of a pivoted hinge. So, the new design eliminates the geometrical issue of having gaskets inside and outside on either side of the facade panels rotation direction. Instead, the new panel acts as a refrigerator door. Besides the new facade also caters for improved quality and products with better energy labels and the calculated results suggest that there would be approximately 28% of energy savings at the moment.

Another area where the design works well now is with future proofing, now since each component is accessible and removable, Newer materials and technology could be integrated with the system at any point of time with the only restriction being that the connections or the geometry of the connections would have to be retained.

Now, it is also easier to open any panel and service them bi-annually, because they act as a door and all the maintenance can happen from inside the building. A particular advantage for the present intervention case is that because of this being a hotel building, which means that the facade panels can be accessed and operated when the adjacent rooms are empty or not occupied at any point of time during the maintenance requirement.

4.2. Technical Drawings



1. horizontal houvers with PV panels
2. aluminium vertical profile
3. triple glazing unit confg. 4/12/4/12/4
4. PV panel on the horizontal overhang tilted to 22 degrees (for south facade) with 6cm gap between the cladding and the panel.
5. connection mount for PV panels
6. 50 x 50 mm box section profiles welded together to from the horizontal overhang shading frame
7. 50 mm thick XPS insulation
8. existing concrete slab
9. customised aluminium profile door type frame for accessibility and disassembly
10. aluminium horizontal profile
11. provision for electrical conduits for PV panel inside the room
12. thermally broken horizontal frame for electrical conduits
13. false ceiling

Figure 4.2.1: Enlarged view at the slab showing top and bottom details (Source – Self)

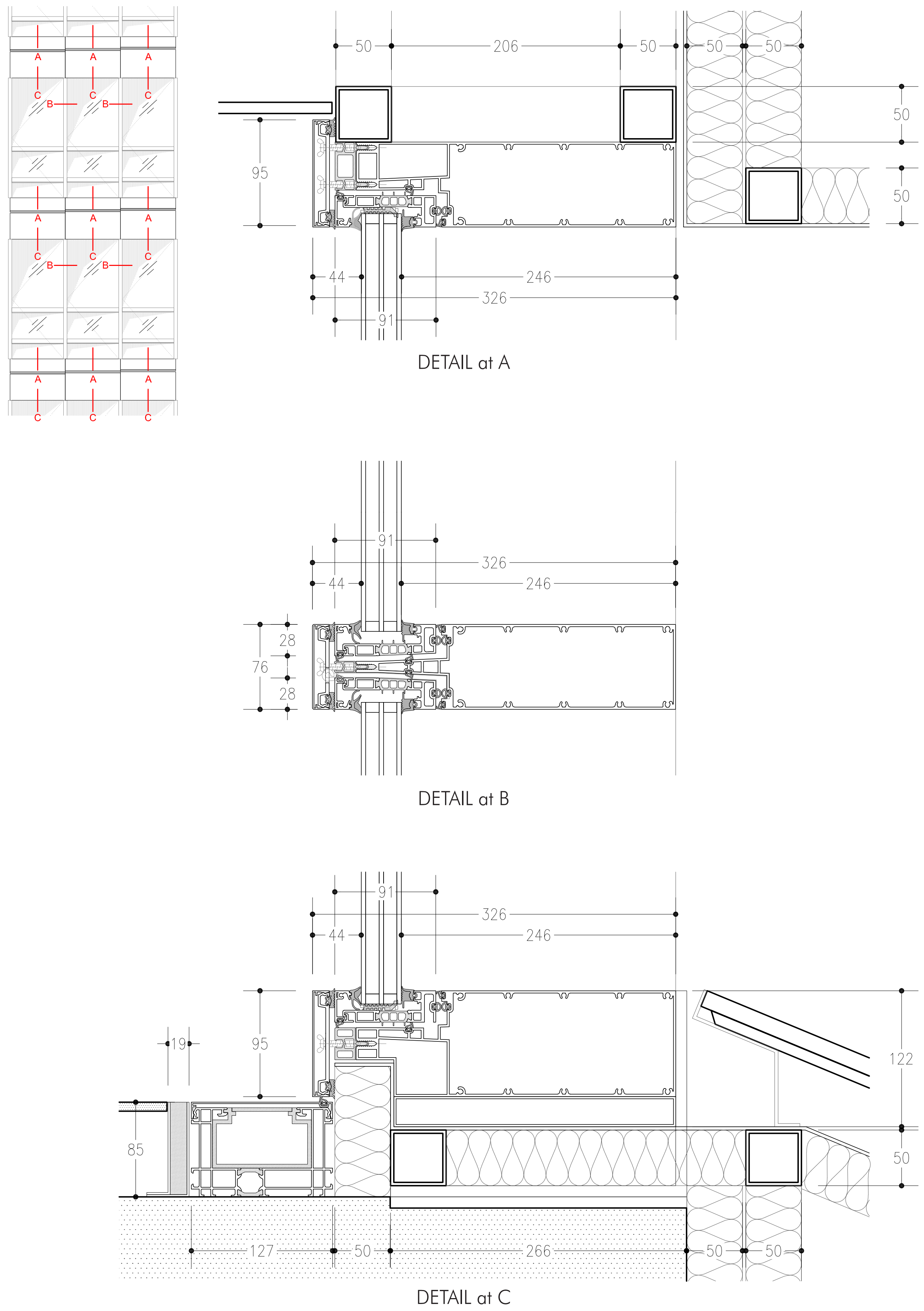
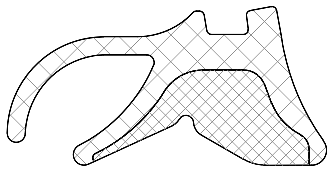


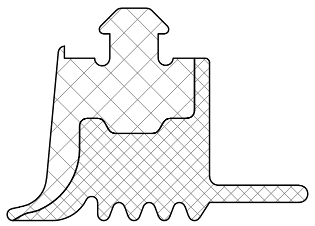
Figure 4.2.2: Enlarged Details (Source – Self)



GAL01
Glazing Gasket

Material: EPDM
Surface: Gliding Polymer
Color: Black
Provision: >12mm gap

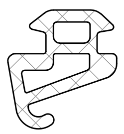
Reference Manufacturer: schüco
Availability: Available in UAE



GAL02
Glazing Gasket

Material: EPDM
Surface: Gliding Polymer
Color: Black
Provision: >14mm gap

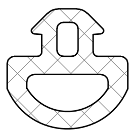
Reference Manufacturer: schüco
Availability: Available in UAE



GAT01
Operable Pane Gasket

Material: EPDM
Surface: Slliconized
Color: Black
Provision: >5mm gap

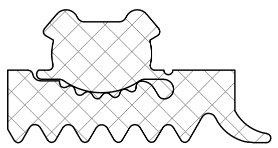
Reference Manufacturer: schüco
Availability: Available in UAE



GAT02
Operable Pane Sealing Gasket

Material: Cellular Rubber
Surface: Slliconized
Color: Black
Provision: >5mm gap used in combination with another

Reference Manufacturer: Customised
Availability: -



GAP01
Pressure Plate Gasket

Material: EPDM
Surface: Slliconized
Color: Black
Provision: >5mm gap

Reference Manufacturer: schüco
Availability: Available in UAE

Figure 4.2.3: Detail of all gaskets (Source – Self)

4.3. Assembly Instructions

4.3.1. Exploded View

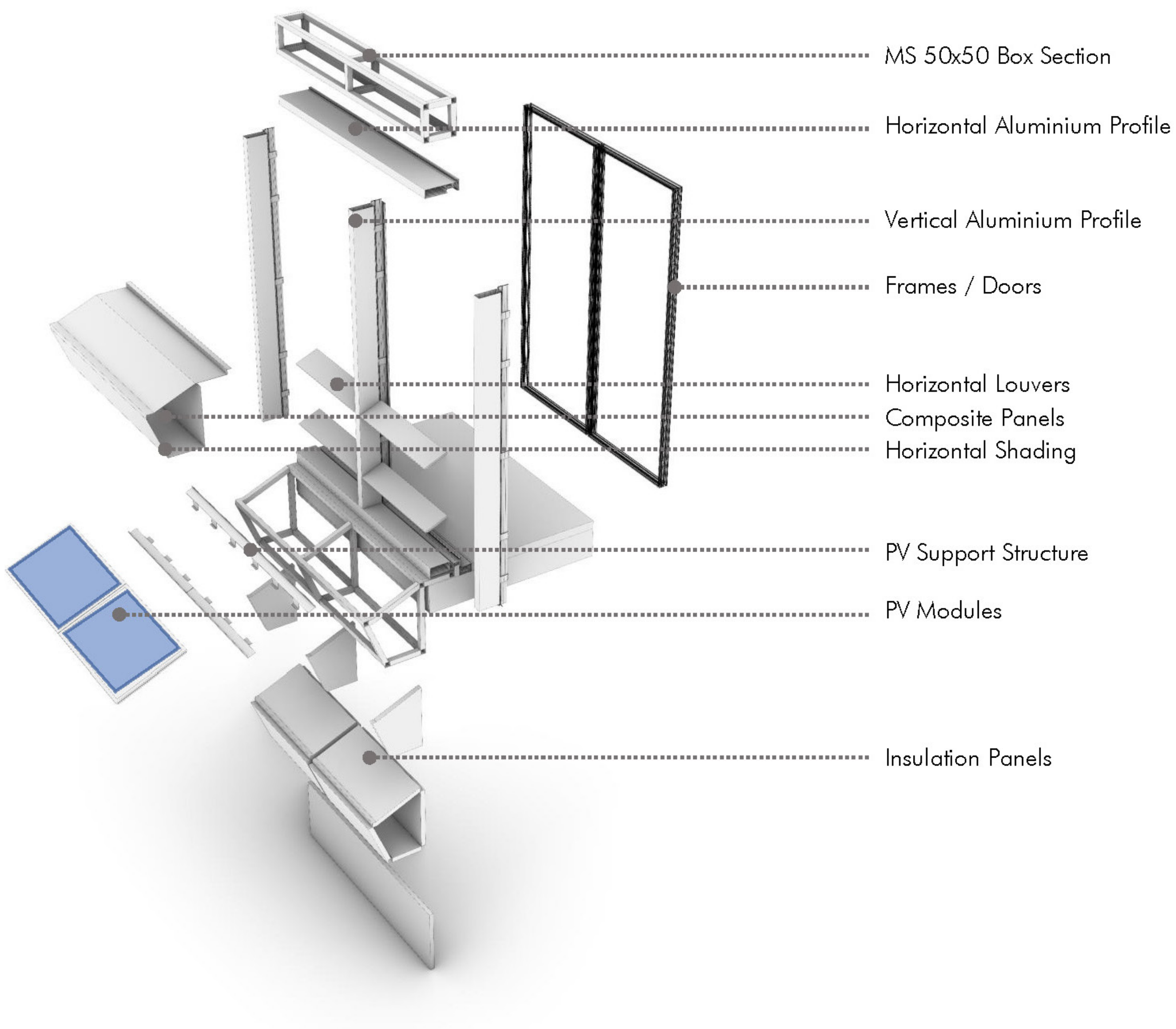
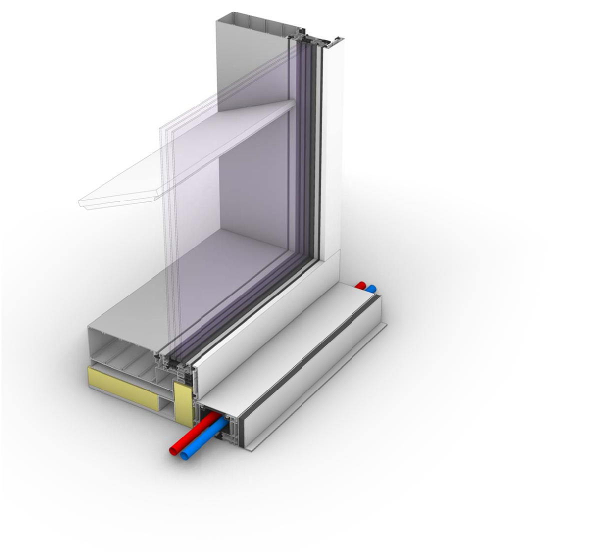
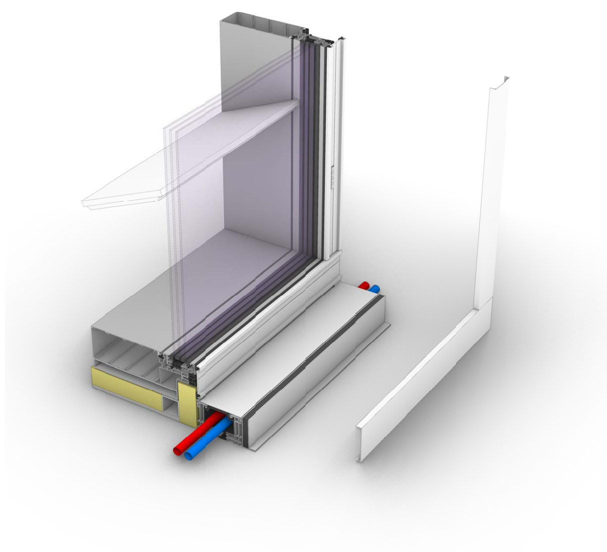


Figure 4.3.1: Exploded view of the whole system (Source – Self)

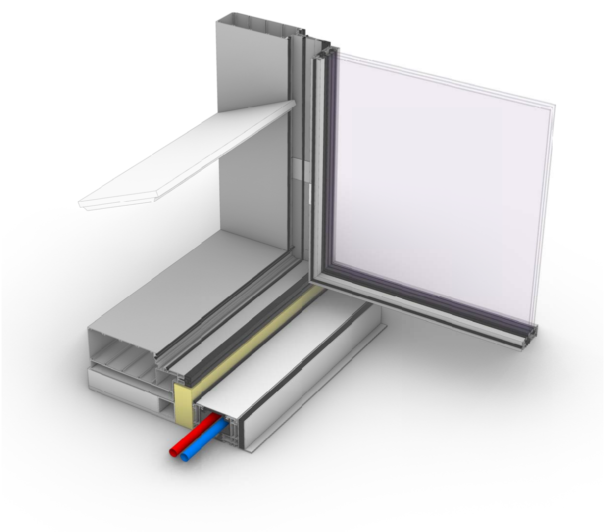
4.3.2. Disassembly Scheme



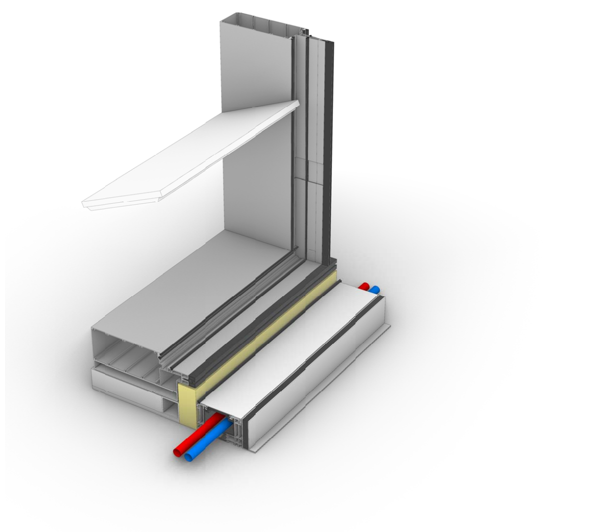
Step 1: Closed complete facade panel



Step 2: Pressure plate cap is removed

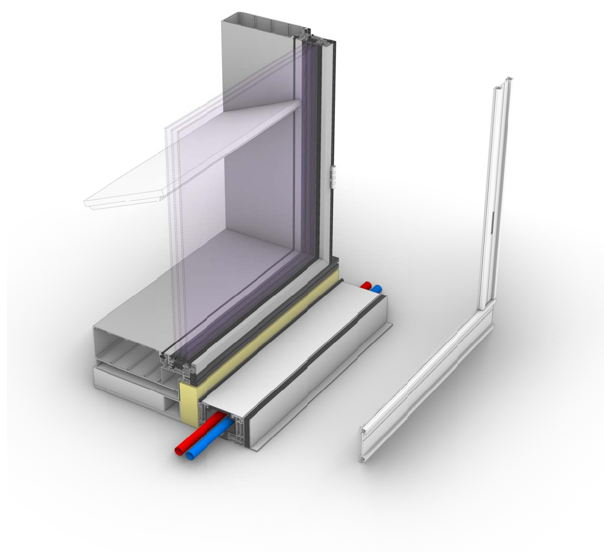


Step 5: Accessible facade door panel is opened and ready for removal

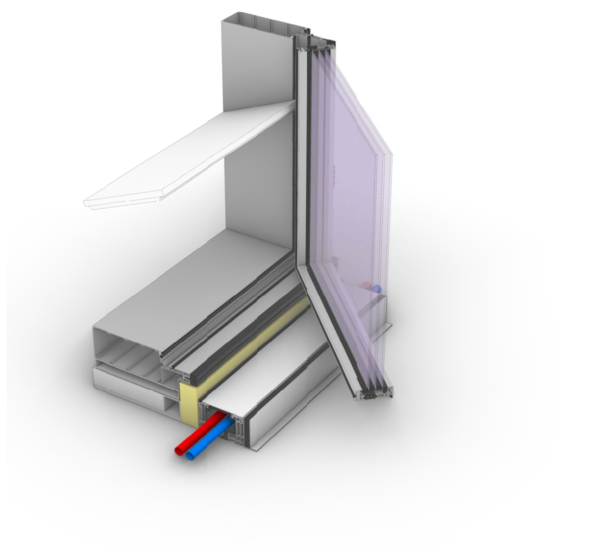


Step 6: Accessible facade door panel is removed

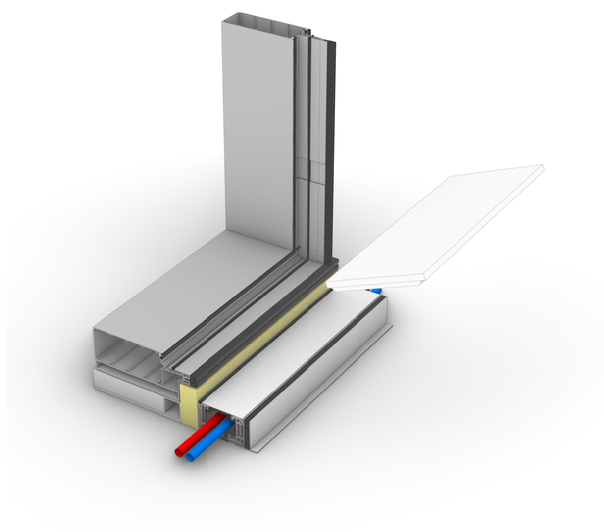
Figure 4.3.2: Instruction for disassembly (Source – Self)



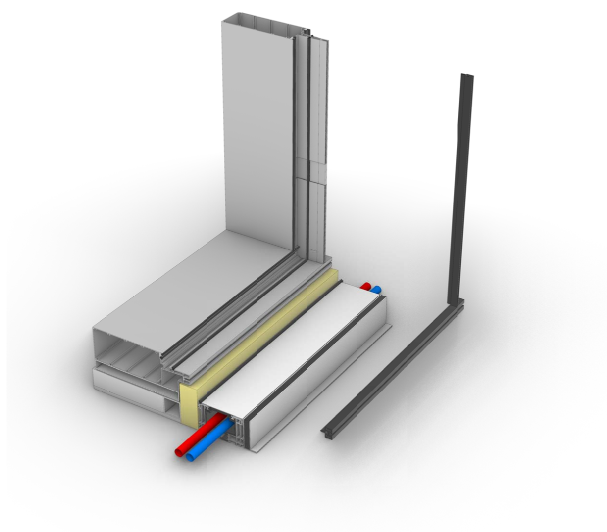
Step 3: Pressure plate is removed



Step 4: Accessible facade door panel is openable

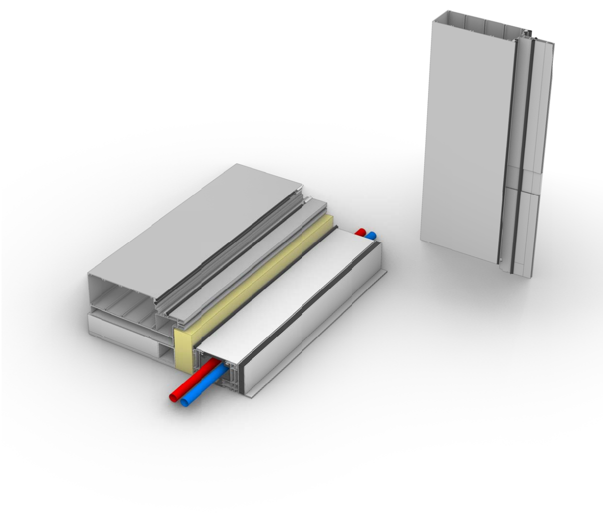


Step 7: Horizontal shading panel is removed

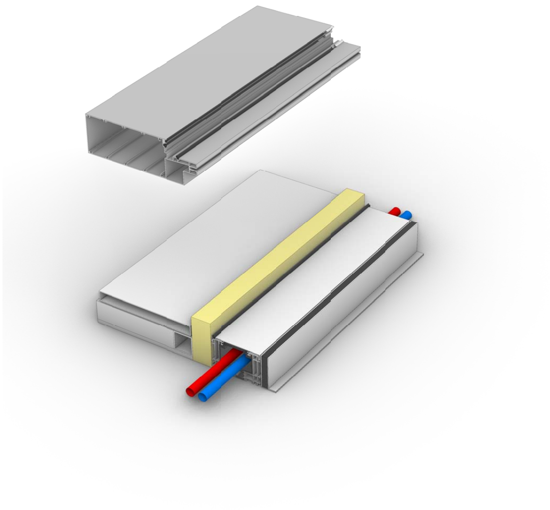


Step 8: Thermal breaks are accessible and openable

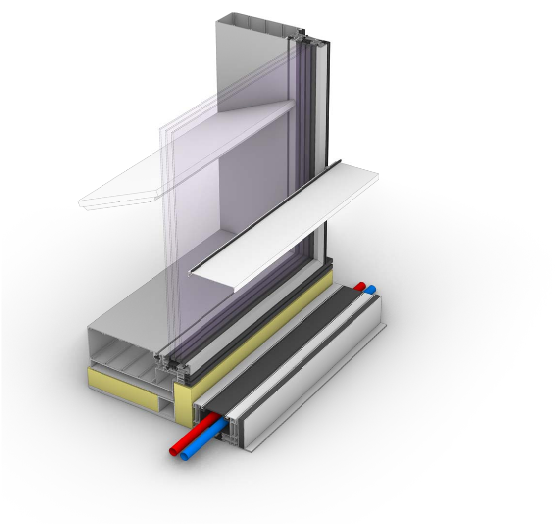
Figure 4.3.2: Instruction for disassembly (Source – Self)



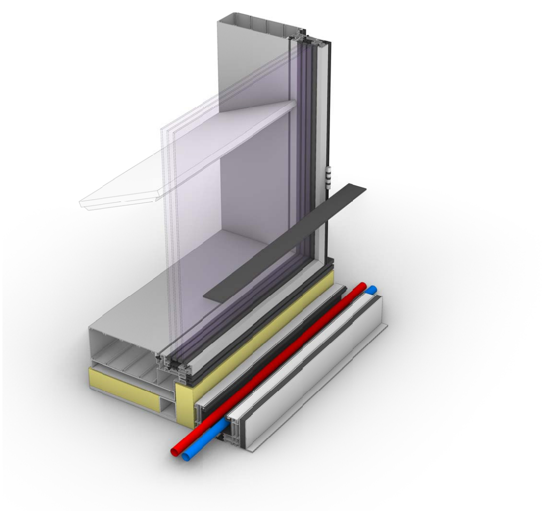
Step 9: Vertical facade frame is removable



Step 10: Horizontal facade frame is removable

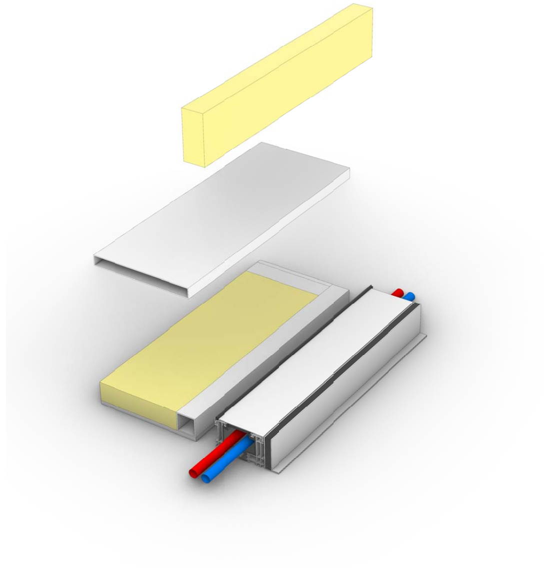


Step 3.1: The cover plate for the floor channel can be removed to access the cables

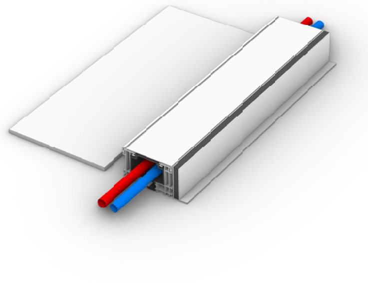


Step 3.2: The thermally broken cable conduit cap can be removed for cable management

Figure 4.3.2: Instruction for disassembly (Source – Self)



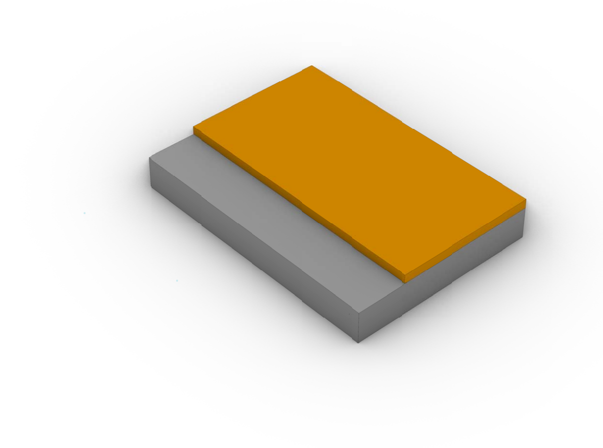
Step 11: Insulation and facade cladding is removable



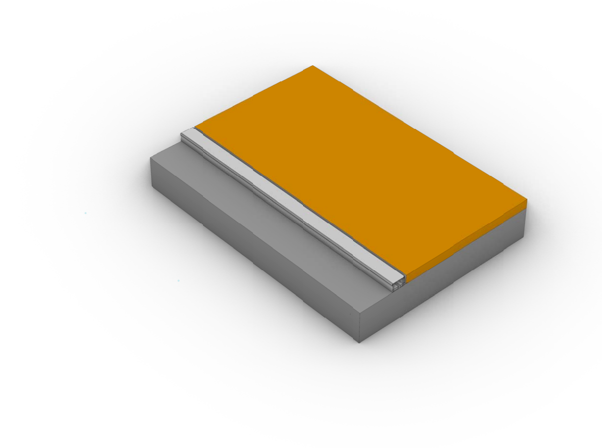
Step 12: Floor connector plate is kept for access

Figure 4.3.2: Instruction for disassembly (Source – Self)

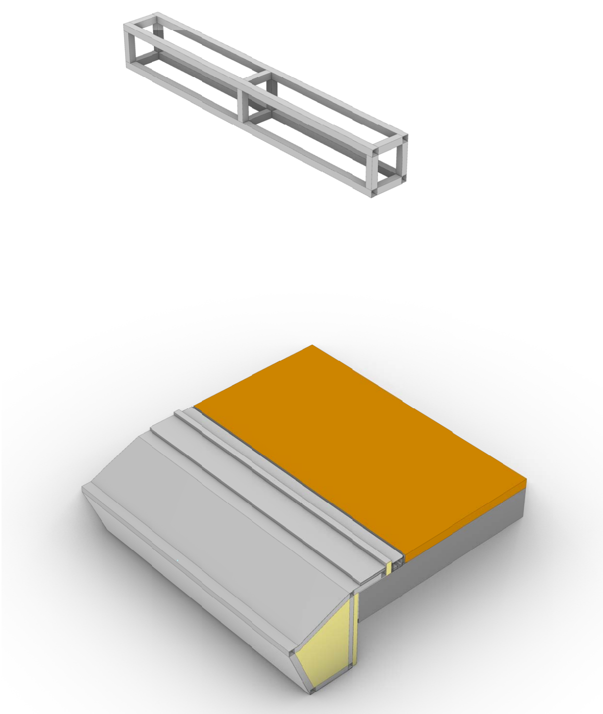
4.3.3. Facade Assembly



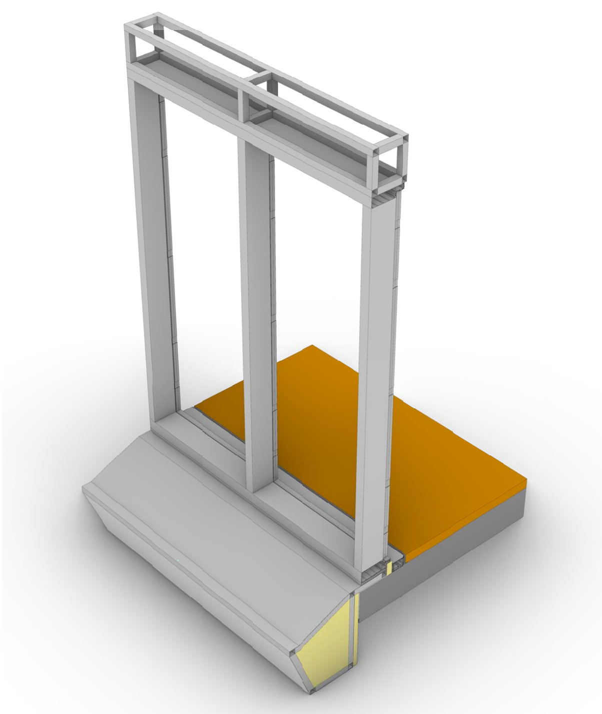
Step 1:
Existing floor slab edge with flooring.



Step 2:
Floor conduits location is considered with spacers to adjust the width of the upcoming facade assembly

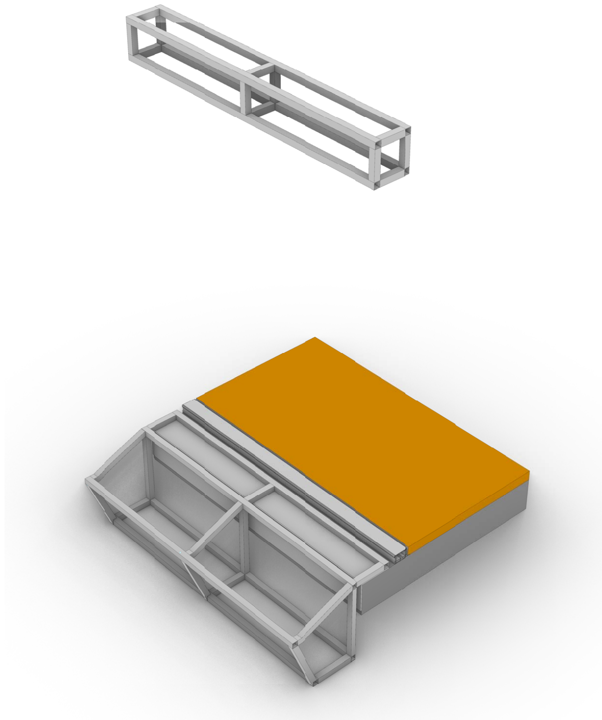


Step 5:
Aluminium cladding to cover the framework and the insulation

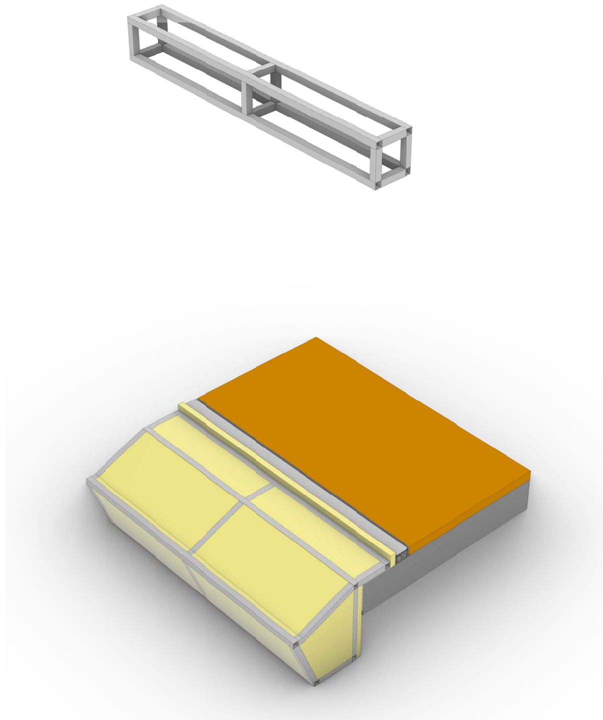


Step 6:
The horizontal and the vertical aluminium frame is introduced and fixed to the framework

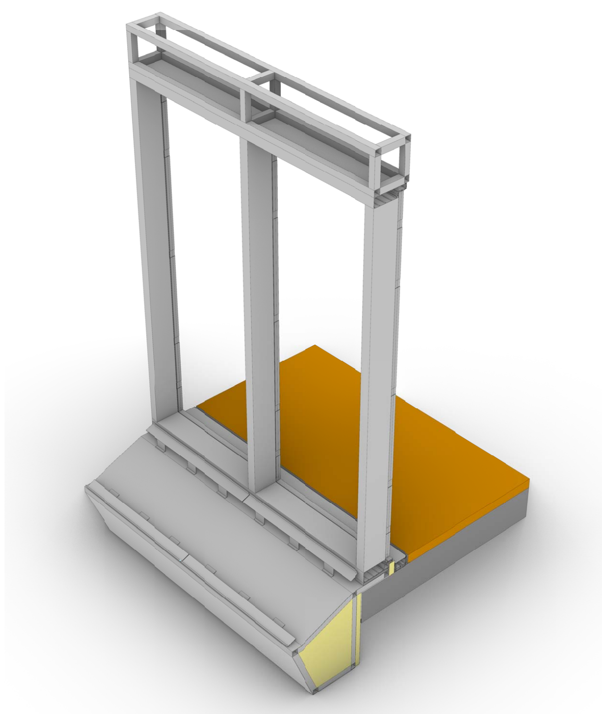
Figure 4.3.3: Instruction for construction (Source – Self)



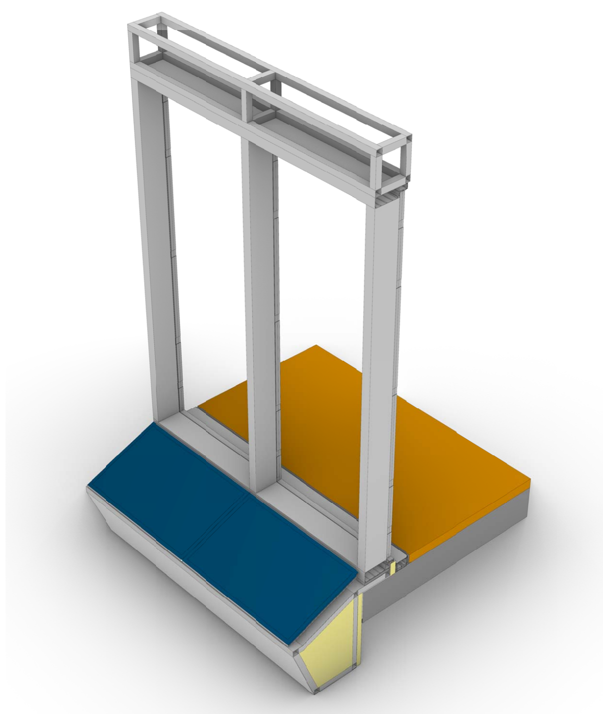
Step 3:
Galvanized mild steel, coated with intumescent paint is fixed to the edge of the slab and the soffit of the floor slab above



Step 4:
XPS insulation is inserted within the space of the mild steel as part of thermal insulation

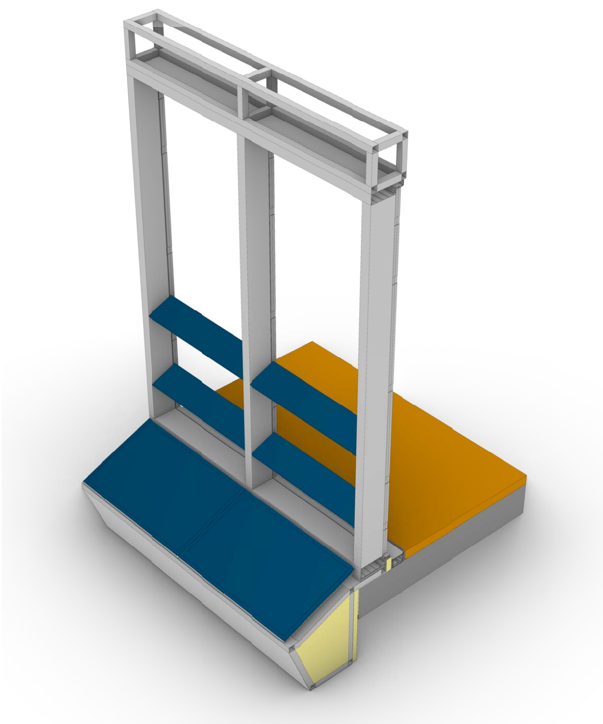


Step 7:
Supports for the PV panels are fixed on the horizontal overhand shading system

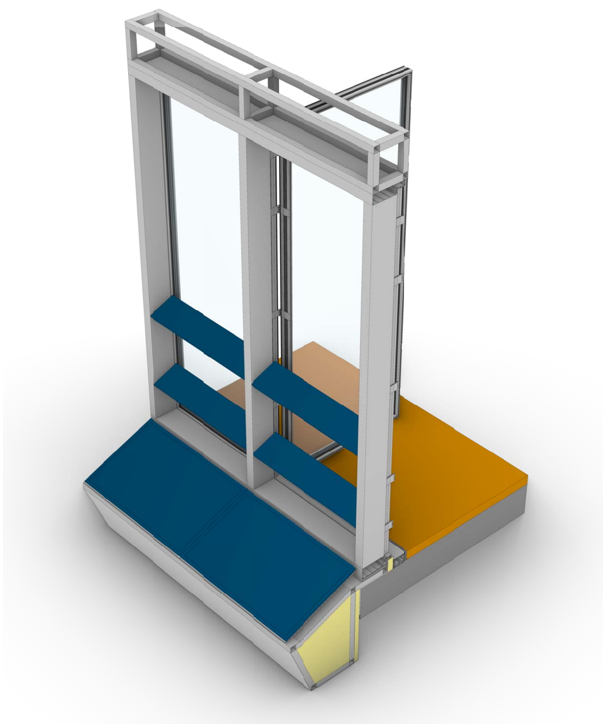


Step 8:
PV panels are installed on top of the horizontal shading system using the supports fixed in step 7

Figure 4.3.3: Instruction for construction (Source – Self)

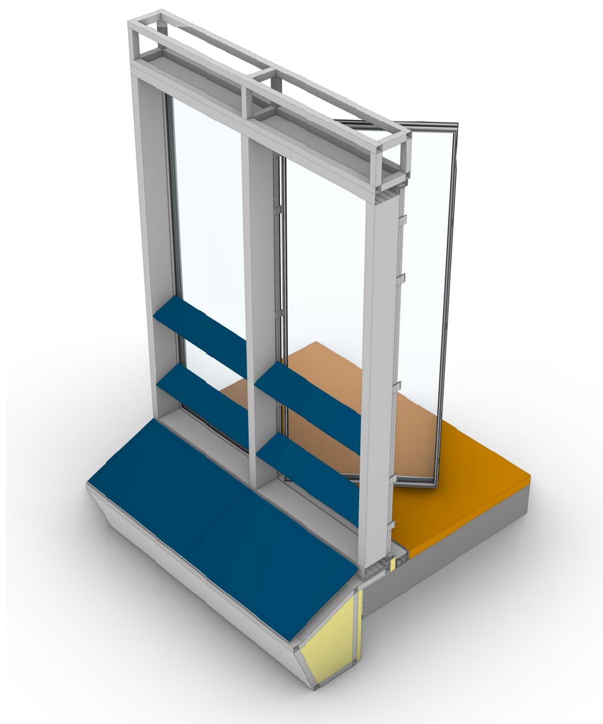


Step 9:
Horizontal louvers with PV panels are installed on the vertical frame from both ends

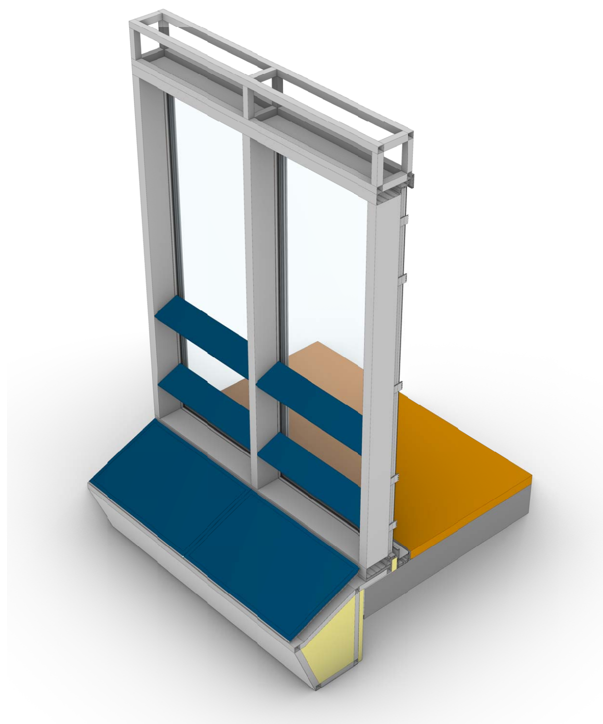


Step 10:
The operable door with the facade glazing panel is brought in and fixed using the thermally broken hinges to one side of the vertical frame.

Figure 4.3.3: Instruction for construction (Source – Self)



Step 11:
The door is then closed and locked shut using an engineered locking mechanism



Step 12:
The pressure plates and the cap is installed over the door at the vertical and the horizontal frame to complete the facade

Figure 4.3.3: Instruction for construction (Source – Self)

4.4. Intergrated Photovoltaics

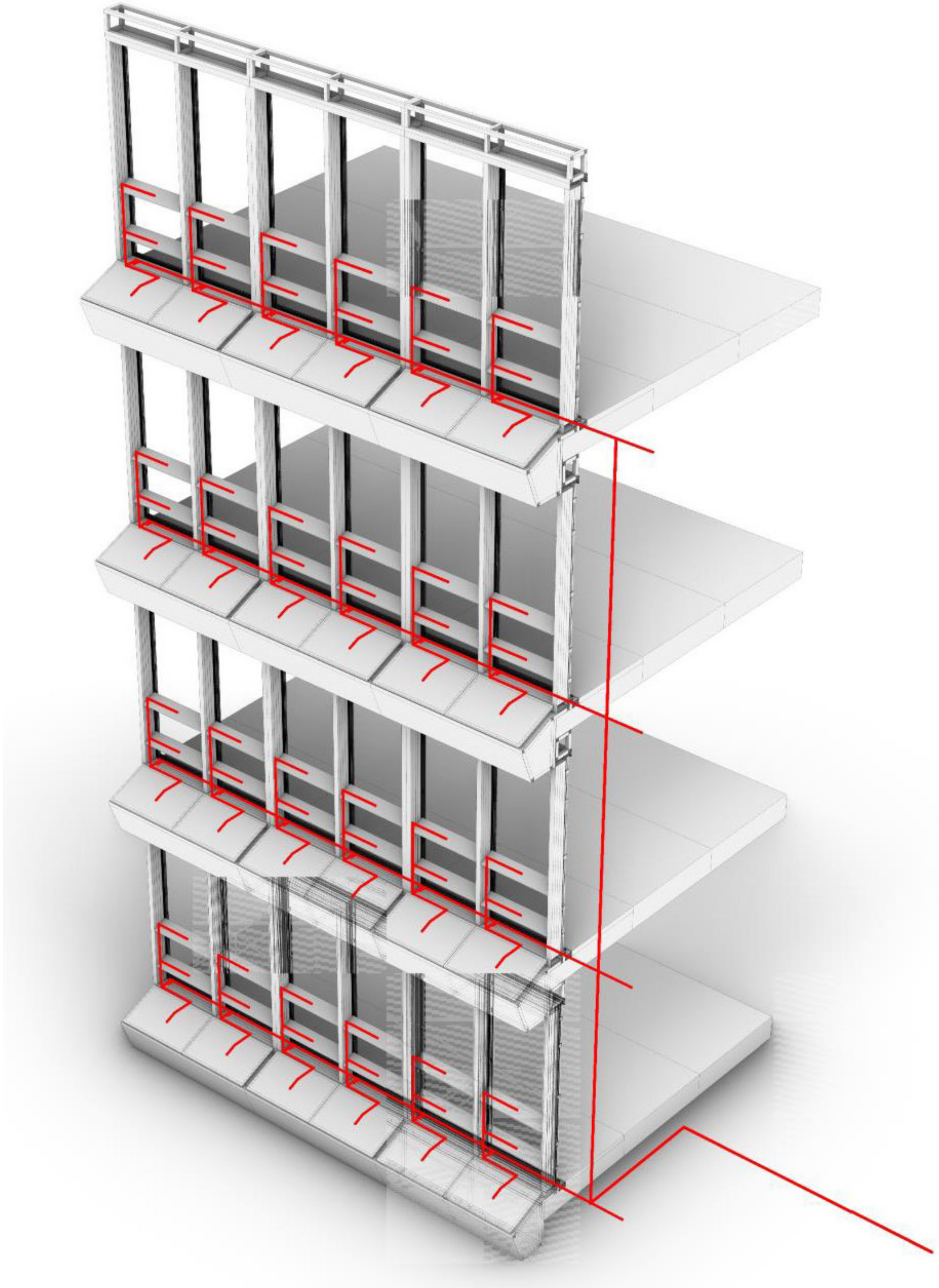


Figure 4.4.1: Network grid for BIPV systems on panels (Source – Self)

4.4.1. Introduction

There is a rising trend in moving the existing livestock of buildings to nZEB or near zero-energy buildings. One of the most ubiquitous methods is the extraction and use of solar energy to power the buildings and make the building rely less on non-renewable energy sources.

The final design as part of the Plug&play approach attempts to integrate PV panels on the shading system. The Figure 4.4.1 shows the concept integration of PV panels on top of the shading system and the red lines indicate the network of the PV array to combine all PV panels to a maximum power point tracker system. Figure 4.4.2. shows a concept sketch of how the panels would be arranged on the selected intervention case. The diagram also shows a possible combination of equipment where the inverters would be placed in the service floors and the distribution of PV panels would be between every 20 floors of the building.

4.4.2. Analysis

Firstly, it must be considered that external temperatures of Dubai go to extremely high values such as 41 degrees celcius and with solar radiation constantly falling on the PV panels, and the system can heat up and reach high surface temperatures inorder to reduce the PV efficiency. To abate the overheating issues the design for the moment accommodates a 6cm air gap based suggested research by Folkerts et al., 2016 for air to pass through and cool down the panels via convection (see Figure 4.4.3 and 4.4.4). Although there are many other types of research suggesting PCM material and fans to cool down the PV array. However, this falls in a separate category of research and does not fall in the scope of this thesis.

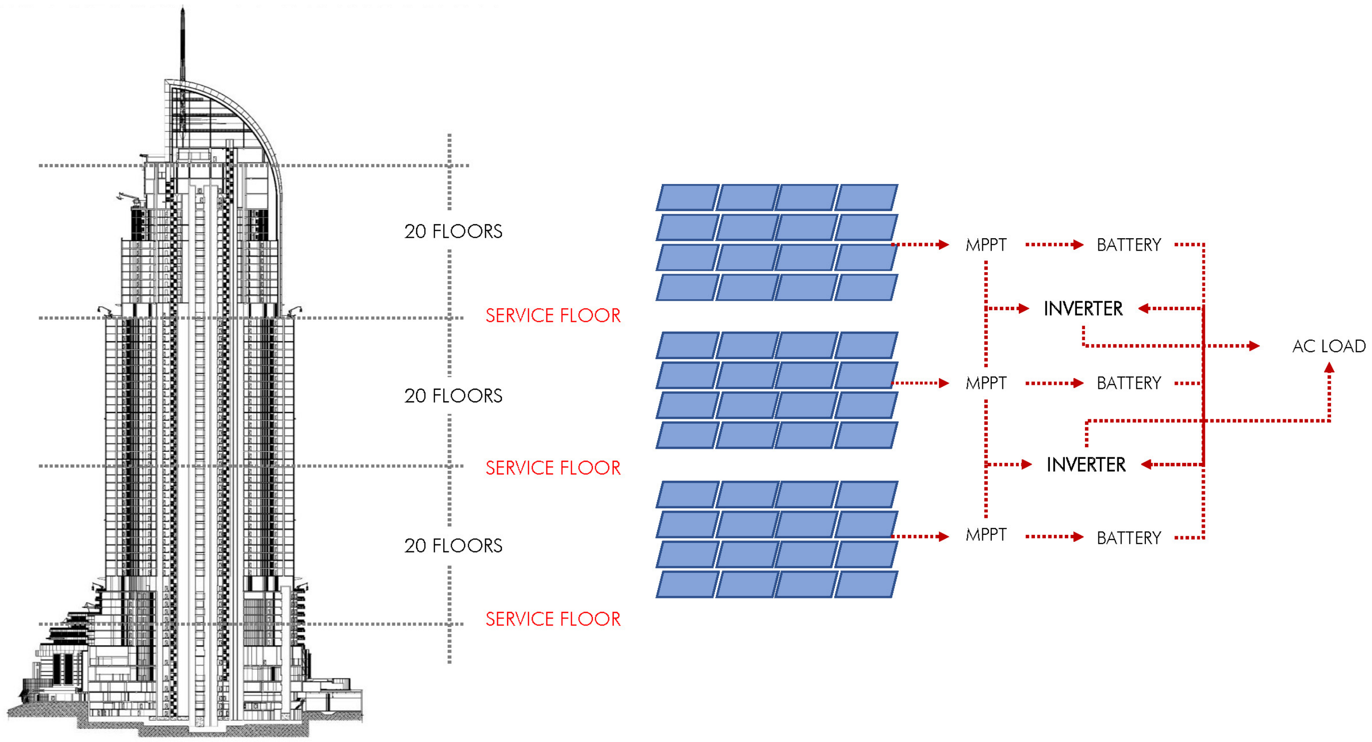


Figure 4.4.2: Consideration of solar panel array on the intervnetion building (Source – Self)

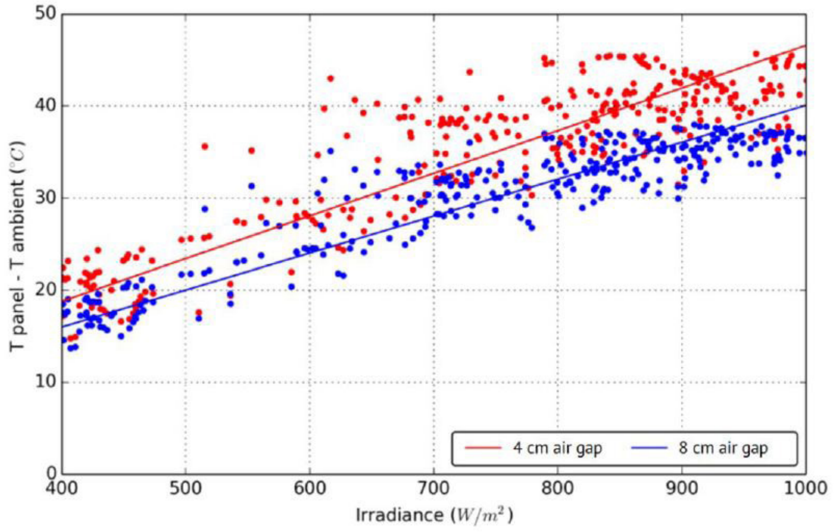


Figure 4.4.3: Effect of ventilation airgap behind PV panels (Source – Folkerts et al., 2016)

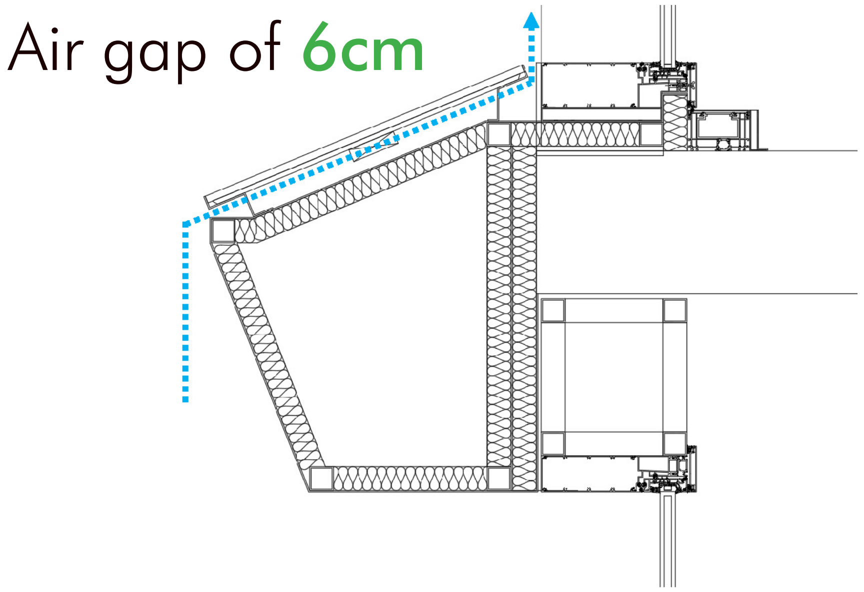


Figure 4.4.4: Indication of space between PV panel and the shading system (Source – Self)

Meanwhile, a basic calculation was done based on the amount of surface area of the facade, which will receive direct solar radiation and will be covered by PV panels (Figure 4.4.5). The calculation suggests that the facade has the potential of providing energy equivalent to 3 million kWh/year. (Figure 4.4.6)

Similar to the utility calculation in chapter 3.3.3. The overall energy required for cooling of the building is subtracted by the amount of energy the proposed PV panel system can contribute to identifying that the proposed PV panel system can help save another 350,000 euros/ year.

Calculation of the solar PV energy ouput of a photovoltaic system

(yellow)	Yellow cell = enter your own data
(green)	Green cell = result (do not change the value)
(white)	White cell = calculated value (do not change the value)

Global formula : E = A * r * H * PR

E = Energy (kWh)	3,075,031	kWh/year
A = Total solar panel Area (m²)	11,416.22	m²
r = solar panel yield (%)	16%	
H = Annual average irradiation on tilted panels (shadings not included)*	2246	kWh/m².an
PR = Performance ratio, coefficient for losses (range between 0.9 and 0.5, default value = 0.75)	0.75	
Total power of the system	1826.6	kWp

Losses details (depend of site, technology, and sizing of the system)

- Inverter losses (6% to 15 %)	8%
- Température losses (5% to 15%)	8%
- DC cables losses (1 to 3 %)	2%
- AC cables losses (1 to 3 %)	2%
- Shadings 0 % to 40% (depends of site)	3%
- Losses weak irradiation 3% yo 7%	3%
- Losses due to dust, snow... (2%)	2%
- Other Losses	0%

Table 4.4.5: Solar PV energy output calculation
(Source - Author)

					PV Contribution
EPI of the Building		kWh/m²/year	**150**	**190**	
Overall Energy Consumption		kWh/year	14,535,000	18,411,000	11,459,969
		kWh/month	1,211,250	1,534,250	954,997
Energy Bills	Green Slab	AED/kWh	460	460	460
	Yellow Slab		560	560	560
	Orange Slab		640	640	640
	Red Slab		457,995	580,735	360,619
	Total		459,655	582,395	362,279
Fuel Surcharge	Electricity Total	AED/kWh	78,731	99,726	62,075
Combined Utility	Bill		538,386	682,121	424,354
VAT @ 5%			26,919	34,106	21,218
Total Bill Incl. VAT		AED/kWh	565,306	716,227	445,572
Total Bill Incl. VAT		EUR/kWh	141,326	179,057	111,393
Total Bill Incl. VAT/ per Year		EUR/kWh/yr	**1,695,916.69 €**	**2,148,681.94 €**	1,336,714.63 €

Table 4.4.6: Utility consumption and production calculation results
(Source - Author, Utility calculation bar data from DEWA,Dubai)

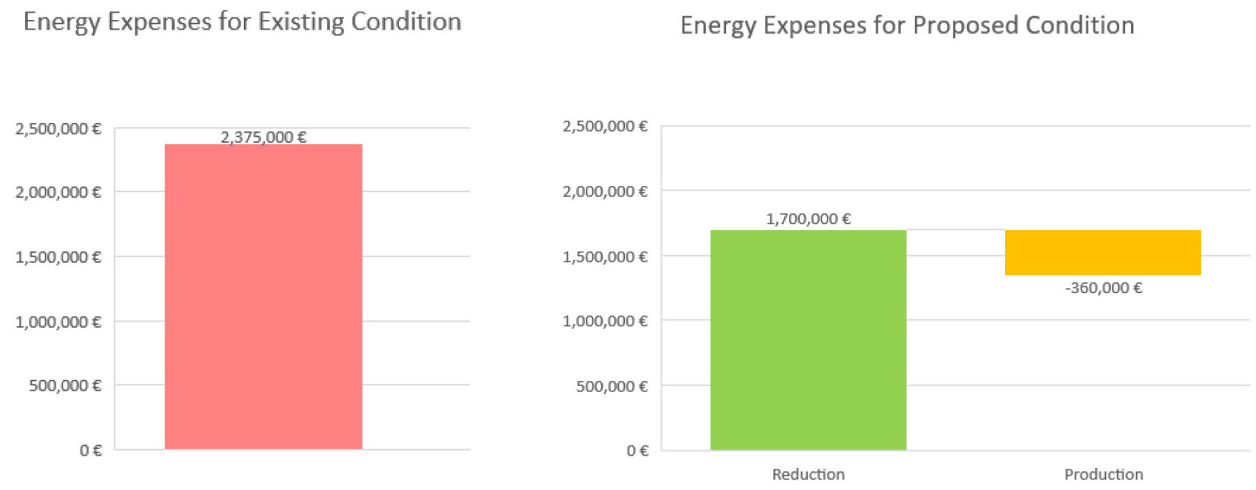


Figure 4.4.7: Summary of Utility consumption and production calculation comparison
(Source - Author, Utility calculation bar data from DEWA,Dubai)

4.4.3. Conclusion

Figure 4.4.7 shows the summary of utility expenses in terms of electricity consumed by the selected case-study building. As shown in the data the existing building with the set parameters (boundary conditions consumes electricity of about 2.3 million euros/year for cooling and the proposed design can help save about 0.63 million euros by passive design and another 0.36 euros/year by active PV elements.

Hence, the new design can save upto a million euros per year in terms of utilities alone.

This can be further calculated to identify the amount of time required to break-even with the expenses of the new proposed facade. It must be clarified that the cost of the proposed plug&play facade has not been estimated and the calculation below is to provide a lump sum figure of the possible cost of the new facade.

If the cost of a new facade is 360 euros per sq.m (see Figure 4.4.8) that means that the cost of a new facade for the existing building would be around 10.2 million euros. (The surface area of the facade is considered as per Figure 3.3.2). and with the amount of energy expenses saved per year with the new facade being around one million euros per year. We can safely assume that the average recovery time for the facade expenses would be by approximately 10 years. This calculation is sufficient to provide the idea of payback period which significantly is less than the 30 years refurbishment period. Of course it can be stated that the payback could be earlier or later depending on the operations and the business within the building itself.

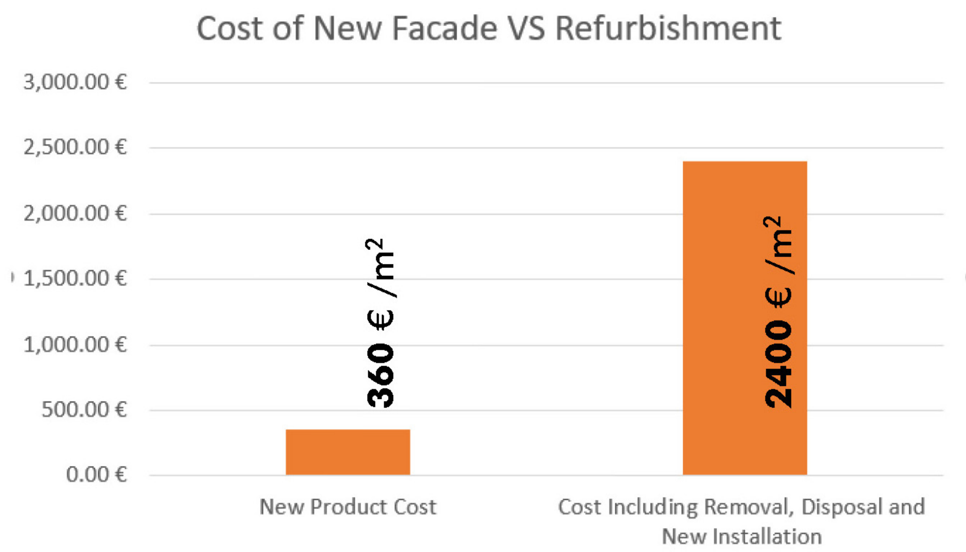


Table 4.4.8: Summary of new facade expenses and cost of refurbishment of facades as elaborated in Chapter 3.1 and Table 3.1.19
(Source - Author)

05
SUSTAINABILITY EVALUATION (TiSD)

5.1. Sustainability Evaluation

The building industry plays a pivotal role in most environmental related aspects of the world. Hence, it as crucial for the building industry to abate the cause of the ecological effect by the industry. The research here only focuses on building envelopes, as they hold a significant portion of responsibilities on how a building would perform in terms of energy performance. The facade determines the behaviour of building in terms of energy consumption in the aspects of illumination, temperature regulation, and ventilation. This thesis primarily considers the essential function of a curtain wall facade and identifies opportunities to improve its current standing from a strict environmental impact perspective. The three principles, which were the core of the research, was refurbishment, reduction & production. The factor of refurbishment considers that all already built buildings are already materials which are assembled to provide sufficient function, demolition or disregarding them results in excessive wastage, which is to be eliminated as much as possible. The reduction focuses on passive strategies in terms of reducing energy consumption and life cycle consideration in terms of reducing material wastage.

On the other hand, production strategies were focusing on the incorporation of multiple passive functionalities into the facade to help buildings sustain by themselves instead of relying on primitive fossil fuels source of energy which is one of the critical causes of increased carbon emissions around the planet. Curtain walls tend to have high-grade materials such as aluminium which have high embodied energy, and massive industrialization has left the areas with aluminium ore extraction mines with irreversible environmental effects. The premise of this chapter is to use the available resources more sustainably by using the plug & play approach.

5.1.1. Sustainable refurbishment of facades using Plug & Play Concept

With the global motivation to follow sustainable design and construction practices and current technological advancements in the area of facade engineering, the future vision for the industry should be to have high performing facades with sustainable life cycles on already built buildings. The design as discussed in the Chapter 3.1.1. should not only be intrinsic in terms of following only the primary function of a protective layer or separation between inside or outside but, also should have an extrinsic functionality of sustainable practice in terms of embodied energy, life cycle and recyclability.

Modularity advocates design for disassembly, which allows for easy accessibility for maintenance, replacing parts or components, reducing the reliability on heavy transportation, eliminates the process of demolition and possibly prolong the use of any material till its physical service limit. Apart from a maintenance perspective, modularity also allows for disassembly and reassembly of the system elsewhere. Further, ensuring that the components will not go to landfill or any other waste disposal system after the original purpose served. The same method could potentially be used in a different building with similar boundary conditions. Hence, plug & play design based on modularity principles would make a positive impact on the life-cycle of the facade construction in terms of material savings. Another, benefit of the proposed system is the reduction of the embodied energy because the previously discussed Chapter 3.1.2. 30 year period of refurbishment intervention will be eliminated. Due to zero demolition, zero wastage of materials, using materials till the end of their ESL. A good example to this concept without plug&play approach is already existing. Works from companies such as Cepezed, Delft, Netherlands with their office building (See Figure 5.1.1) shows good examples of sustainable refurbishment of old builings. This concept can be upscaled to highrise buildings to get to the expectations from this research.

Figure 5.1.1: Cepezed office building, delft as an example of sustainable refurbishment
(Source - https://archello.com/project/cepezed-office)

As mentioned in the introduction chapter, sustainable development is gaining importance over time; the trend is aiming to abate the growing concerns of the environment and the global temperature changes, concepts such as circularity, cradle-to-cradle, life-cycle assessment, embodied energy and many others are all focusing on measures to reduce impact on the environment and co-exist with the nature sustainably. Concepts such as LCA and LCCA, which is more relevant to this research, aims at identifying and standardising the movement of materials across already built or proposed buildings to ensure optimal social and functional performance.

Facades design, as a result, should also undergo this degree of standardisation, and to make it future proof apart from disassembly the facade will have to assume more responsibilities by absorbing the ideas such as Active Building Envelope (ABE). This concept of ABE is explored here in this thesis by examining possibilities to incorporate additional functionality such as photovoltaic panels, solar thermal panels, shading systems, and maybe in future more concepts like thermoelectric systems, lighting systems and many more as explained in chapter 2.4. The most prevailing principles adopted for this design is shown in the the Figure 5.1.2 below.

5.1.2. Global Objectives

The objective of the research in terms of sustainability were as follows:

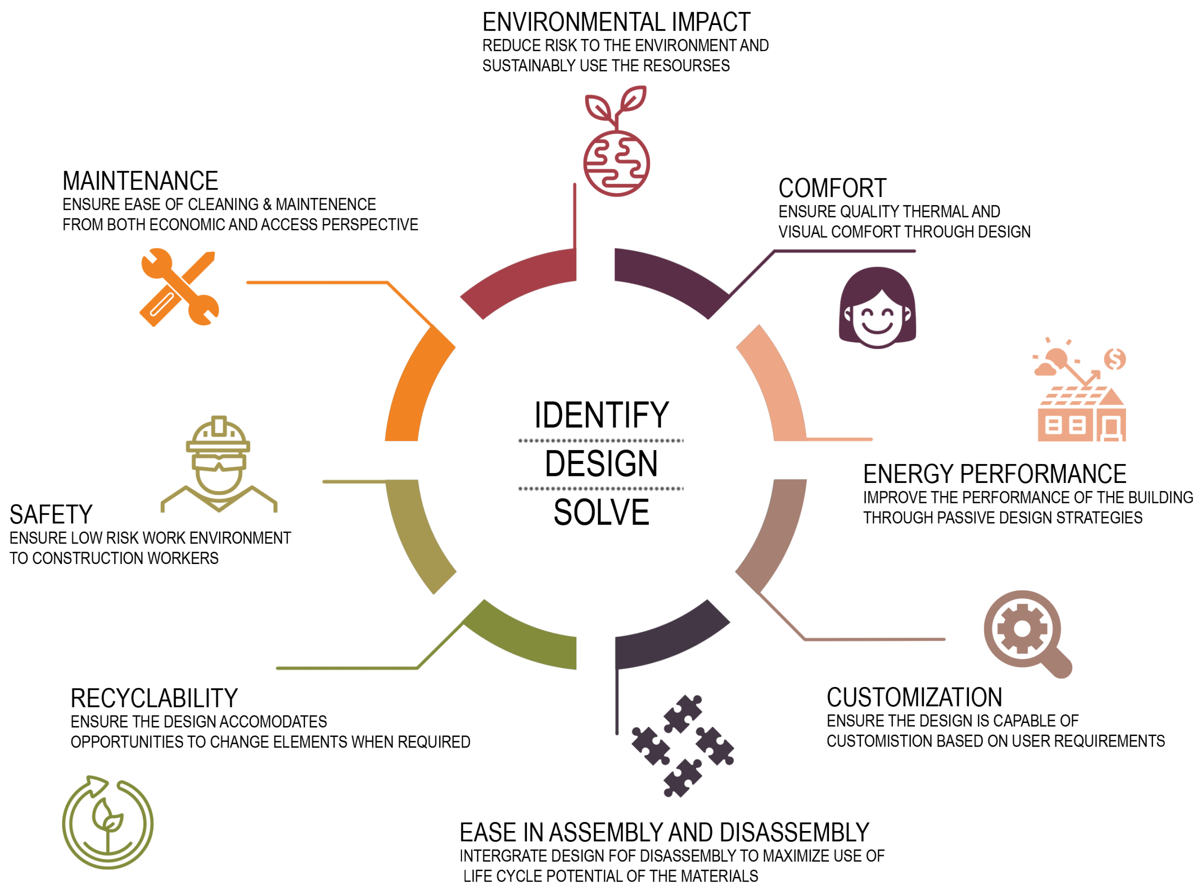


Figure 5.1.2: Sustainability Objectives (Source - Self)

5.1.3. Primary Objectives

The primary premise of this thesis apart from the golbal perspective of things is that all elements of the envelope should be able to contribute to improving the performance of the building and reduce environmental impact as much as possible.

In the design proposal, the following targets have been specified to aim for more sustainable design:

1. Almost all mass weight percentage of used facade materials and products should be disassemblable.
2. Almost all parts of the facade should be accessible from inside the building to completely eliminate the use of BMU's.
3. All materials should be able to used to the end of its physical service life.
4. Intergrated functionalities should contribute to reduce energy consumption of the building and help contribute energy to the building.

5.1.4. Conclusion

Regarding the first objective about the disassemblable panel, all components are designed to be joined through a mechanical fixation, silicon is only used in areas where there is an air or water leak potential. The silicon joints and the EPDM membranes can be peeled off easily by any mechanical method (preferably by using a knife or a screwdriver), where there should not be any difficulty while removing and refixing the silicon or the EPDM membrane. So, a typical panel is designed to be nearly 100 % demountable, and re-mountable.

Accessibility issue if incorporated was one of the aspects which will bolster the argument of a feasible demountable facade. Now each facade panel can be considered as a full height window or a door. Which is protected of course to prevent access by tenants or the unit owners and only skilled maintenance crew will be able to access the panel using specialised equipment. The design allows for access to any component at any given time. Throughout the facade to change, clean, replace any part during the event of failure.

The added benefit of the disassemblable-accessible panel is that all materials in the facade can last till its physical limit and hence reduce redundancy of replacing a functional component or its constituent material with a newer part with the same material.

It was imminent to use additional functionality along with the accessible-demountable panel concept. Based on the premise that the facade has to pay for itself and also help reduce the energy usage of the building by providing energy to the building. The design in this thesis only explores the concept of BIPV on a shading system. But, the potential of this study can be extended to many other functionalities as explained in the introduction above.

The conclution of data of energy savings and effects of desgin for disassembly through Plug&Play is explained in next chapter. The design as such is at a nacent stage and needs to be developed further but, as for the intent of a sustainable practice this thesis elaborates on sufficient characteristics to be considered to have a comperhensive sustainable design approach.

06
CONCLUSION

6.1. Conclusion

Aim of the thesis was to find out a sustainable refurbishment solution for buildings with curtain walls in UAE by the following measures:

1. Ensuring that all materials in the curtain wall reach their end of life potential.
2. Ensure that the façade lasts until the ESL of the building itself.
3. Reduce the material wastage due to premature demolition of the façade.
4. Ensure that the new façade can pay itself off as much as it can by saving energy.

The system proposed should be suitable for replacing either stick or unitized curtain walls.

Further studies in the economics of the curtain wall façade systems illuminate the aspects that most of the expenses for curtain wall systems are allocated to labour costs and machinery cost. Both these costs are noticeable because apart from their involvement in construction, the fact that the façade requires constant maintenance in terms of cleaning and inspection, which as of now, often happens from outside the building. Any design which can alleviate these extra costs of machinery, labour charges and ensure that all materials function till their ESL and the façade itself lasts till the ESL of the building is the ideal solution.

To solve the first three points, it is only logical to explore a design which allows for disassembly and reassembly, so that each and every component in the façade is accessible and easily serviceable.It has been demonstrated through this research that, design for disassembly can be one of many essential approaches to ensure that all materials used in curtain wall systems reach their full-service potential and that easy accessibility allows for minimizing wastage of usable materials.

As for the fourth point, about façade being able to pay itself off, is for the proposed system to help reduce the energy consumption and possibly help in contributing to the energy requirements of the building. Energy reduction strategies explored in this thesis was using shading systems, improving the façade WWR and Glazing types. Energy contribution strategy explored here as the opportunity allows for it was to use Building Integrated Photovoltaics (BIPV) on the shading system.

When all the above-discussed aspects are combined to form a universal solution, Plug&Play façade system was the ideal candidate, as the design allows for disassembly and reassembly and as the name suggests each panel with integrated functionality can be attached to an array of several groups with similar functionalities, to form a technical grid.

To evaluate the potential of the new façade, economic analysis, life cycle analysis and energy performance markers were used here, and the results are as follows:

	Existing Facade	Proposed Facade	Savings
End of Service Life Analysis	• Façade is replaced every 30 years • Components which failed before the replacement period contribute the reduced energy performance • Components which have longer service life above 30 years will be discarded	• Replacement, repair and regular maintenance of the façade happens during regular intervals of maintenance. • All components or materials last till their own end of service life hence no material is wasted or causes the energy performance of the building to reduce	-
Cost Analysis	• High labor and maintenance costs • Use of heavy and expensive machinery for maintenance	• Low labor and maintenance costs • Façade can be accessed and maintained from inside	-
Energy for Cooling	18,400,000 kWh/yr	14,500,000 kWh/yr	3,900,000 kWh/yr energy is saved
Reduction	0 kWh/yr	28% Energy saving in comparison to existing	455,000 eur/yr worth of energy is saved
Production	0 kWh/yr	3,075,000 kWh/yr	360,000 eur/yr worth energy is produced
Mass of Material	19,500 tons	16,200 tons	3,300 tons of material is saved

The aspects of disassembly and plug&play covered in this thesis will make the refurbishment more cost-effective and reasonably sustainable.

It is to be noted that the true value of the environmental benefits cannot be precisely estimated due to unavailability of data of costs. However, the overall concept is still quite young for practical implementation. This thesis attempts to promise that further investigations in the field and tighter building regulations could motivate, current building owners, developers and builders of UAE to consider the plug&play approach of sustainable refurbishment as a plausible and economical option.

6.2. Reflection

6.2.1. Introduction

During the entire endeavour, I found that it is one thing to come up with an idea, but to validate it with critical reasoning and to make it practical, along with convincing others that the concept may be worth pursuing was a considerable challenge. Moreover, most of the time, I found myself to be open-ended with taking inspiration with many things I come across during my study and find opportunities to use them, which resulted in ambiguity in research focus. Thankfully I had the support of my mentors dr.ing. Alejandro Prieto Hoce and ing. Eric van den Ham who have been thoroughly evaluating my progress for almost about half year since the start of this programme and guide me to an area where the research was not only exciting but also feasible during the studio. Hence, over time my decision to pursue research in "Sustainable refurbishment of facades in existing high rise building using Plug and Play approach" allowed me to understand a lot in specialisations of Façade and Climate Design.

Before the start of the exercise, I knew that there would be umpteen amount of challenges I have to deal with. Some might be entirely new that I may have to engineer it, and I was also quite aware that this entire proposal may be a bit jejune, with a high possibility of undesired results and failure. However, after discussions with the professors, sufficient backing from literature research and with some motivation, we just said that Let us do it". The premise was quite clear from then on, "To design a façade panel which is detachable from the entire grid of façade system, each panel which can have a certain functionality (Photovoltaic system for the scope of this research). And the possibility to access individual elements to the component level, to keep extending and improving the life and performance of the façade system and then to the end of the service life of the building itself". The whole attempt itself would provide a high learning curve of what is possible and what is not. The most substantial part of the thesis was to comprehend the ideas which you knew existed before and understood some aspects of it. However, when you learn about them individually, it is immensely vast that the new information tends to become overwhelming. Same was the case with me and most of the thesis.

Learning about the concepts such as active and passive design, shading systems, thermoelectric system, sustainable refurbishment, thermal calculations, nature of curtain walls, end-of-service life, life cycle analysis, vast amounts of HVAC design, types of facades, types of glass, how a solar thermal system works, how a photovoltaic system works, precise nature of façade engineering, the complexity of creating a detachable or disassemble façade, software's such as design-builder, grasshopper, simulations such as thermal modelling, and even up to using calculation operations in excel and many more was all new information for me. I cannot for sure confirm that I have absorbed all the values from these concepts and literature yet. However, I can, for sure, agree that I am happy to have spent my time to overlook these concepts and try and apply them in whatever way I could in the thesis.

Well, for starters, I knew that curtain wall façade systems have a smaller end of service life (ESL) in comparison to the life of the whole building. It was basically because some of the individual components had a shorter life in contrast to the entire system. The idea then was to figure out a way to way to access these failed components and either replace them or fix them without stripping out the whole façade itself. The general practice for the moment was to wait for the façade to fail entirely and then change it or sometimes even demolish the building itself both of which are unsustainable in various aspects such as reduced energy performance or wasting good materials leading to increased carbon emissions as a consequence. Hence I tried to tackle just that, which was to make all components easily accessible, reduce the cost of maintenance and use specific elements as long as they can be used. Apart from extending life, the aspect of the integration of certain functionality was to target two points. One - cost saving by making the refurbishment of façade to pay for itself by making it contributes to certain functionality of the building (such as energy production, thermal protection, etc..), and second to make it future proof by having demonstrability, repairability and expandability. These points would ensure the performance of the façade will improve over time based on the possible technological advancement in the future.

6.2.2. Overview

The thesis was an opportunity for me to exercise my understanding of the sciences I learnt during my masters in a controlled environment. As for me and my argument, I would say it was a success because what I did was identify an existing system with a shortcoming in it. In this case, were curtain walls and its poor performance over time and the reasons for it due to failing components with shorter lifespans. The solution was to apply a previously existing tried and tested concept. However, tailoring it in a way to suit the requirements of the posed problem. In this case, the Plug&Play approach allowed for disassembly, future proofing and improved performance. It was necessary to study the how and why systems fail and learn from the experiences of others about what needs to be considered, applied, avoided and maybe the reason the results. This was an iterative process. Discussions with mentors, industry experts, other faculty members and even friends from the industry were all enlightening. At certain occasions, prototyping what was thought about also helped visualise the problem at hand to determine what could work and what could not. For example, one of the versions of the design was to twist and turn the façade panel, and detail design continued for a while. Later, one of the external advisors suggested that twist and turn in a pivot contains a geometric problem which cannot be solved with the conventional approach and there is a reason why facades do not have pivot hinges in their design. This was an eye-opener. The design then was accommodated to a swing system due to the feedback received. Similarly, there were larger ambitions which did not address to the core of the design, and it was necessary for tailored guidance from my mentors to help me choose elements and aspects which reasoned for the design and the research instead of another task just done.

6.2.3. Thesis Summary

1. Sustainable refurbishment ensured that materials are not wasted before they reach their assigned end-of-life and as a result, the building itself reaches its potential end-of-life without premature demolition and hence wastage of all the materials and carbon emission contribution

2. Propose a solution to the part of the world which needs sustainable measures the most.

3. Economic analysis optimised the precise activity which would inflate the costs of the building, and the design approach was to abate it.

4. Plug&Play concept allowed for the integration of newer technologies in the façade and authorised for

access to keep them functioning.

5. Simulations, calculations and various tests validated the hypothesis that proposed systems with required functions would work if implemented.

6.2.4. Relevance

Sustainable design is the call for the hour, and the reasons behind it are well known. It should be our earnest attempt as future designers and engineers to understand the effects of our contribution to the planet. The prudent design should not just be limited to the immediate function but also the consequences of the design in the future. My earnest attempt was to do just that with my thesis.

6.2.5. Ethical Issues

One of the aspects which kept me pondering was that research could only do so much, the design is of no value beyond the report post the graduation. However, it should be. The hardest part of any design is to convince the people that the proposal could indeed be helpful and solve problems. Yet, it has to be based on scientific reasoning and not a gut intuition or personal preference, of course. The Plug&Play approach elaborated in this particular setting would fare well as the design addresses many relevant vital concepts, holds answers to certain aspects which needs to be solved pretty soon if not immediately. This thesis is not about identifying the precise tools to solve problems but to ask the right questions and seek answers; however, it may be. I cannot claim that the thesis has perfect results that can be adopted immediately. However, it will trigger thoughts which can provoke future researchers to think in a line which could probably solve the questions asked here.

The following are some points that I think can be improved in my design and approach.

1. Working with a company or an association I feel would be better with this regards as it will create a routine instead of one making their own goals at once own conveniences.

2. It could have been that lesser courses could have been taken during the time of graduation thesis as it is necessary to keep oneself in a continuous workflow.

3. Discussions are critical as it allows one to think externally, and when one shares their thoughts is when one comprehends about how much one does know about the concepts they are discussing.

4. Case studies are hard to come by with approval. Hence it would be ideal to start with a concrete case before making assumptions.

In conclusion, I am content with the way the thesis analysis shaped up. I do agree that it was a bit overwhelming to design and analyse even the small portion of the façade in a given time, and I had to speculate many uncertainties. However, this is part of any learning process I assume, and all I can say by this study is that I feel more confident than before to work with façades in the future.

07 APPENDICES

7.1. Materials Breakdown

Material Category	Material Specification	Material Function	Coating	Average Service Life	Cross Sectional Area	Linear Length	Density	Mass	Volume	Weight per Material Category	Percentage of Material Category per Pannel
				years	mm^2	m	kg/m3	kg	m^3	N	%
Aluminium Curtainwall	Aluminium 6060	Transom	Powder Coated Polyester	50.0	1,003.60	3.6	2700.00	9.755	0.0036	276.17	21.9%
	Aluminium 6060	Mullion	Powder Coated Polyester		1,003.60	6.8	2700.00	18.426	0.0068		
	Aluminium 6060	Pressure Plate	Powder Coated Polyester		0.00	0.0	2700.00	0.000	0.0000		
	Aluminium 6060	Cover Cap	Powder Coated Polyester		0.00	0.0	2700.00	0.000	0.0000		
Insulated Glazing Unit	Tempered Clear Glass	6mm Inner Glass Pane	-	25.0	33,426.00	3.2	20.10	61.506	0.1070	602.76	47.8%
	PVB	1.14mm Interlayer	-								
	Tempered Clear Glass	6mm Inner Glass Pane	-								
	Argon Gas	16mm Air Gap	-								
	Polyisobutylene	Primary Seal	-								
	Silicone/Polysulfide	Secondary Seal	-								
	Silica Gel	Dessicant	-								
	Stainless Steel	Spacer	-								
	Tempered Glass Low-E	8mm Outer Glass Pane 2	-								
Mixed Plastics for Seals and Weather Protection	Silicon	Structural Sealant	-	20.0	121.60	20.8	1120.00	2.833	0.0025	78.36	6.2%
	Silicon	Weather Sealant	-		284.00	10.4	1120.00	3.308	0.0030		
	EPDM	Gaskets between Profiles	-	86.8	60.70	10.4	1050.00	0.663	0.0006		
	EPDM	Gaskets for Glazing	-		109.20	10.4	1050.00	1.192	0.0011		
	Neoprene	Thermal Breaks	-	29.7	0.00	10.4	155.00	0.000	0.0000		
Other Metals for Connections	Stainless Steel	Bolt	-	50.0	-	0.10	8000.00	0.520	0.0038	5.10	0.4%
	Aluminium 6060	Shear Lock	-	50.0	-	-	2700.00	0.000			
	Stainless Steel	Anchor Channels	-	30.0	-	-	8000.00	0.000			
	Stainless Steel	Wall Brackets	-	30.0	-	-	8000.00	0.000			
	Stainless Steel	Floor & Top Brackets	-	30.0	-	-	8000.00	0.000			
Insulation	Glass Mineral Wool	Insulation Panel	-	60.0	45,000.00	-	120.00	16.524	0.1530	161.94	12.8%
ACP	Coil-coated Aluminium	Cladding	PVDF	25.0	3,600.00	3.2	1220.00	14.054	0.0122	137.73	10.9%
	Polyethylene/Polyurethane	Core	-								
	Coil-coated Aluminium	Cladding	PVDF								

Table 7.1.1: Table of materials in a typical curtain wall system
(Source - Author)

Table 7.1.1: Table of materials in a typical curtain wall system
(Source - Author)

7.2. Climate Data

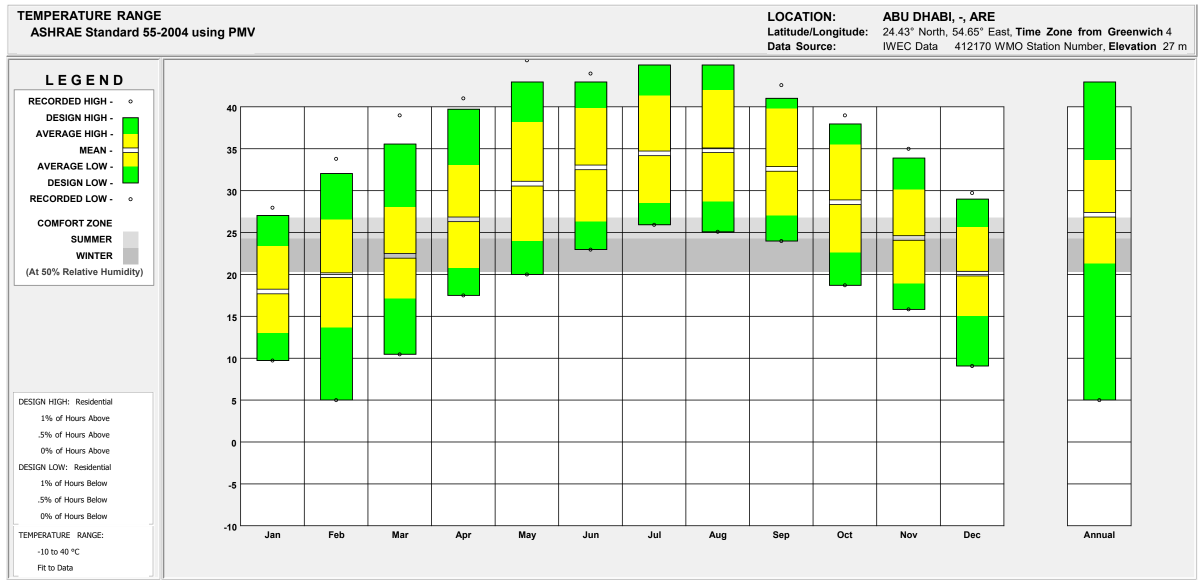


Figure 7.2.1: Temperature Range of Abu Dhabi, United Arab Emirates (Source – Self: Generated with Climate Consult 6.0)

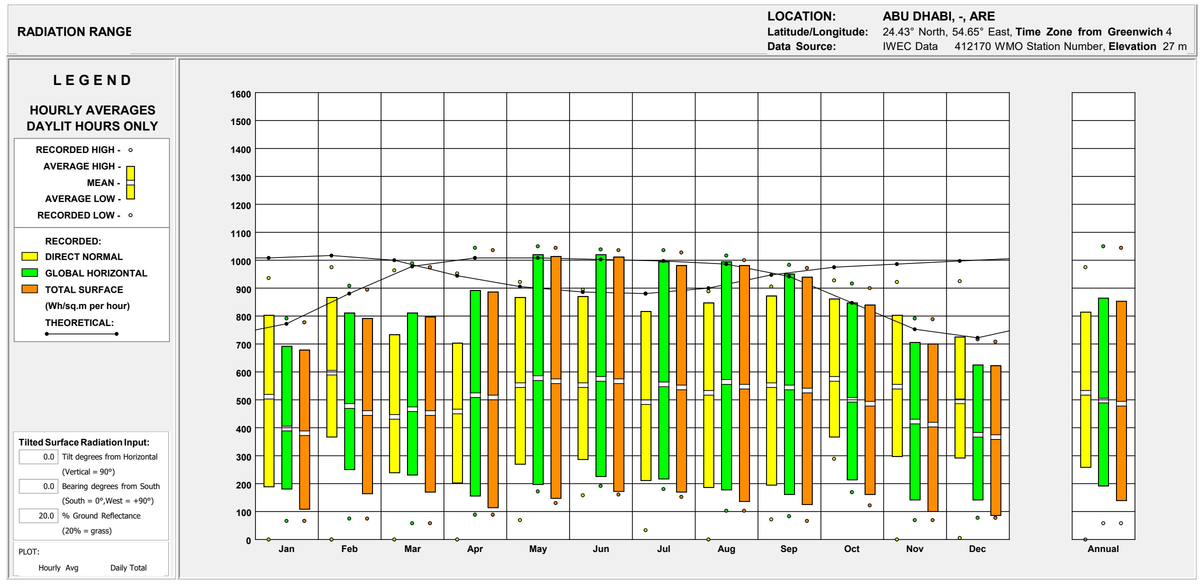


Figure 7.2.2: Radiation Range of Abu Dhabi, United Arab Emirates (Source – Self: Generated with Climate Consult 6.0)

Abu Dhabi, United Arab Emirates

13.1%	1 Comfort(1146 hrs)
28.2%	2 Sun Shading of Windows(2468 hrs)
	3 High Thermal Mass(0 hrs)
	4 High Thermal Mass Night Flushed(0 hrs)
	5 Direct Evaporative Cooling(0 hrs)
8.3%	6 Two-Stage Evaporative Cooling(726 hrs)
3.0%	7 Natural Ventilation Cooling(263 hrs)
	8 Fan-Forced Ventilation Cooling(0 hrs)
16.6%	9 Internal Heat Gain(1458 hrs)
	10 Passive Solar Direct Gain Low Mass(0 hrs)
10.5%	11 Passive Solar Direct Gain High Mass(921 hrs)
	12 Wind Protection of Outdoor Spaces(0 hrs)
	13 Humidification Only(0 hrs)
15.2%	14 Dehumidification Only(1329 hrs)
45.3%	15 Cooling, add Dehumidfication if needed(3966 hrs)
0.9%	16 Heating, add Humidification if needed(79 hrs)

100.0% Comfortable Hours using Selected Strategies (8760 out of 8760 hrs)

Cairo, Egypt

12.5%	1 Comfort(1097 hrs)
24.2%	2 Sun Shading of Windows(2116 hrs)
	3 High Thermal Mass(0 hrs)
	4 High Thermal Mass Night Flushed(0 hrs)
	5 Direct Evaporative Cooling(0 hrs)
15.4%	6 Two-Stage Evaporative Cooling(1353 hrs)
21.7%	7 Natural Ventilation Cooling(1899 hrs)
	8 Fan-Forced Ventilation Cooling(0 hrs)
32.2%	9 Internal Heat Gain(2817 hrs)
	10 Passive Solar Direct Gain Low Mass(0 hrs)
7.9%	11 Passive Solar Direct Gain High Mass(690 hrs)
	12 Wind Protection of Outdoor Spaces(0 hrs)
	13 Humidification Only(0 hrs)
6.9%	14 Dehumidification Only(607 hrs)
15.4%	15 Cooling, add Dehumidfication if needed(1350 hrs)
8.8%	16 Heating, add Humidification if needed(768 hrs)

100.0% Comfortable Hours using Selected Strategies (8760 out of 8760 hrs)

Riyadh, Saudi Arabia

8.1%	1 Comfort(708 hrs)
28.6%	2 Sun Shading of Windows(2504 hrs)
	3 High Thermal Mass(0 hrs)
	4 High Thermal Mass Night Flushed(0 hrs)
	5 Direct Evaporative Cooling(0 hrs)
60.7%	6 Two-Stage Evaporative Cooling(5316 hrs)
5.8%	7 Natural Ventilation Cooling(512 hrs)
	8 Fan-Forced Ventilation Cooling(0 hrs)
20.7%	9 Internal Heat Gain(1813 hrs)
	10 Passive Solar Direct Gain Low Mass(0 hrs)
11.1%	11 Passive Solar Direct Gain High Mass(976 hrs)
	12 Wind Protection of Outdoor Spaces(0 hrs)
2.8%	13 Humidification Only(243 hrs)
	14 Dehumidification Only(0 hrs)
0.7%	15 Cooling, add Dehumidfication if needed(58 hrs)
4.9%	16 Heating, add Humidification if needed(427 hrs)

100.0% Comfortable Hours using Selected Strategies (8759 out of 8760 hrs)

Kuwait City, Kuwait

9.5%	1 Comfort(833 hrs)
26.8%	2 Sun Shading of Windows(2347 hrs)
	3 High Thermal Mass(0 hrs)
	4 High Thermal Mass Night Flushed(0 hrs)
	5 Direct Evaporative Cooling(0 hrs)
48.3%	6 Two-Stage Evaporative Cooling(4234 hrs)
	7 Natural Ventilation Cooling(0 hrs)
8.9%	8 Fan-Forced Ventilation Cooling(783 hrs)
21.8%	9 Internal Heat Gain(1911 hrs)
	10 Passive Solar Direct Gain Low Mass(0 hrs)
10.5%	11 Passive Solar Direct Gain High Mass(918 hrs)
	12 Wind Protection of Outdoor Spaces(0 hrs)
0.6%	13 Humidification Only(53 hrs)
1.2%	14 Dehumidification Only(104 hrs)
7.5%	15 Cooling, add Dehumidfication if needed(657 hrs)
7.0%	16 Heating, add Humidification if needed(612 hrs)

100.0% Comfortable Hours using Selected Strategies (8760 out of 8760 hrs)

Giles, Australia

11.5%	1 Comfort(1004 hrs)
25.1%	2 Sun Shading of Windows(2201 hrs)
	3 High Thermal Mass(0 hrs)
	4 High Thermal Mass Night Flushed(0 hrs)
	5 Direct Evaporative Cooling(0 hrs)
41.3%	6 Two-Stage Evaporative Cooling(3621 hrs)
13.0%	7 Natural Ventilation Cooling(1139 hrs)
	8 Fan-Forced Ventilation Cooling(0 hrs)
24.5%	9 Internal Heat Gain(2145 hrs)
	10 Passive Solar Direct Gain Low Mass(0 hrs)
15.8%	11 Passive Solar Direct Gain High Mass(1381 hrs)
	12 Wind Protection of Outdoor Spaces(0 hrs)
2.8%	13 Humidification Only(242 hrs)
2.0%	14 Dehumidification Only(173 hrs)
4.2%	15 Cooling, add Dehumidfication if needed(372 hrs)
7.6%	16 Heating, add Humidification if needed(662 hrs)

100.0% Comfortable Hours using Selected Strategies (8760 out of 8760 hrs)

Jaipur, India

10.8%	1 Comfort(947 hrs)
30.4%	2 Sun Shading of Windows(2659 hrs)
	3 High Thermal Mass(0 hrs)
	4 High Thermal Mass Night Flushed(0 hrs)
	5 Direct Evaporative Cooling(0 hrs)
20.1%	6 Two-Stage Evaporative Cooling(1759 hrs)
	7 Natural Ventilation Cooling(0 hrs)
11.0%	8 Fan-Forced Ventilation Cooling(967 hrs)
18.1%	9 Internal Heat Gain(1583 hrs)
	10 Passive Solar Direct Gain Low Mass(0 hrs)
11.1%	11 Passive Solar Direct Gain High Mass(973 hrs)
	12 Wind Protection of Outdoor Spaces(0 hrs)
	13 Humidification Only(0 hrs)
1.4%	14 Dehumidification Only(122 hrs)
40.1%	15 Cooling, add Dehumidfication if needed(3511 hrs)
3.6%	16 Heating, add Humidification if needed(313 hrs)

100.0% Comfortable Hours using Selected Strategies (8756 out of 8760 hrs)

Figure 7.2.3: Recommended Climate Design strategies Arid Climates (Source – Self: Generated with Climate Consult 6.0)

7.3. Design Builder - Intervention Case Boundary Conditions

General	
OpaquePanel - Custom	
Source	DesignBuilder
Category	Panels
Region	General
Definition	
Definition method	1-Layers
Calculation Settings	
Simulation solution algorithm	1-Default
Involves metal cladding	No
Layers	
Number of layers	3
Outermost layer	
Lightweight Metallic Cladding	
Thickness (m)	0.0050
Bridged?	No
Layer 2	
EPS Expanded Polystyrene (Standard)	
Thickness (m)	0.1500
Bridged?	No
Innermost layer	
Lightweight Metallic Cladding	
Thickness (m)	0.0050
Bridged?	No
Outside Surface	
Fix convective heat transfer coefficient	No
Inside Surface	
Fix convective heat transfer coefficient	No

General	
Custom Internal Slab - Dubai	
Source	DesignBuilder
Category	Slabs
Region	General
Definition	
Definition method	1-Layers
Calculation Settings	
Simulation solution algorithm	1-Default
Involves metal cladding	No
Layers	
Number of layers	4
Outermost layer	
Ceramic/clay tiles - clay tile, hollow, 10.2mm, 1 cell	
Thickness (m)	0.0080
Bridged?	No
Layer 2	
Cement/plaster/mortar - cement plaster	
Thickness (m)	0.0500
Bridged?	No
Layer 3	
XPS Extruded Polystyrene - CO2 Blowing	
Thickness (m)	0.0500
Bridged?	No
Innermost layer	
Cast Concrete (Dense)	
Thickness (m)	0.2000
Bridged?	No
Outside Surface	
Fix convective heat transfer coefficient	No
Inside Surface	
Fix convective heat transfer coefficient	No

General	
Custom Roof Slab - Dubai	
Source	DesignBuilder
Category	Slabs
Region	General
Definition	
Definition method	1-Layers
Calculation Settings	
Simulation solution algorithm	1-Default
Involves metal cladding	No
Layers	
Number of layers	5
Outermost layer	
Concrete Paviour	
Thickness (m)	0.0600
Bridged?	No
Layer 2	
Polyvinylchloride (PVC)	
Thickness (m)	0.1000
Bridged?	No
Layer 3	
XPS Extruded Polystyrene - CO2 Blowing	
Thickness (m)	0.1000
Bridged?	No
Layer 4	
Cement/plaster/mortar - plaster	
Thickness (m)	0.0500
Bridged?	No
Innermost layer	
Cast Concrete (Dense)	
Thickness (m)	0.3000
Bridged?	No
Outside Surface	
Fix convective heat transfer coefficient	No
Inside Surface	
Fix convective heat transfer coefficient	No

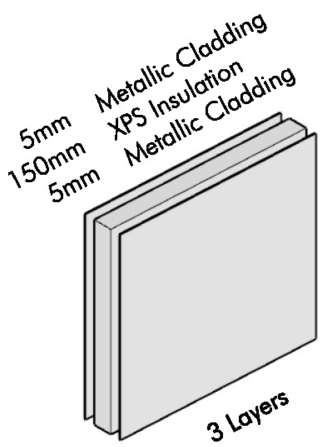


Figure 7.3.1: Boundary Condition for Opaque Panel
(Source - Author, Extracted Input Parameters from Design Builder)

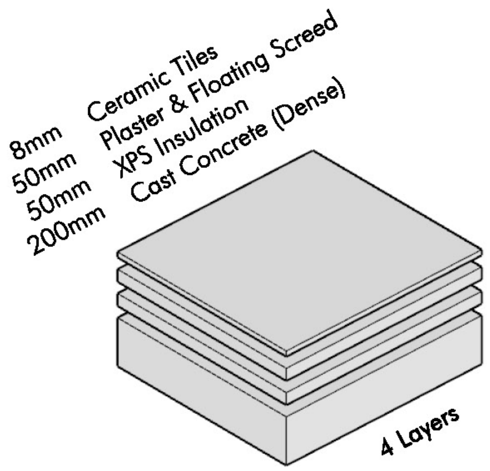


Figure 7.3.2: Boundary Condition for Internal Slab
(Source - Author, Extracted Input Parameters from Design Builder)

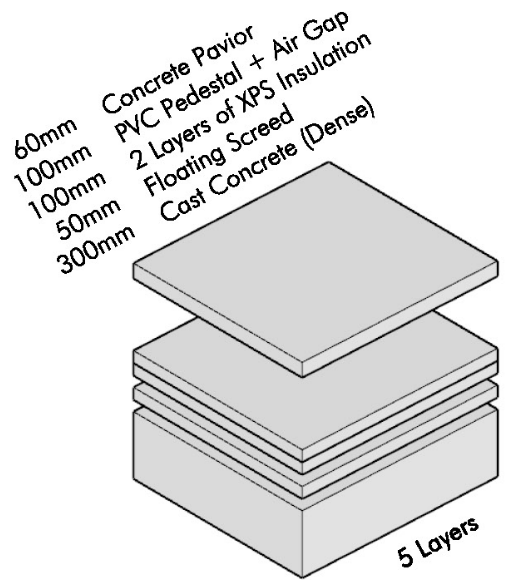


Figure 7.3.3: Boundary Condition for Roof Slab
(Source - Author, Extracted Input Parameters from Design Builder)

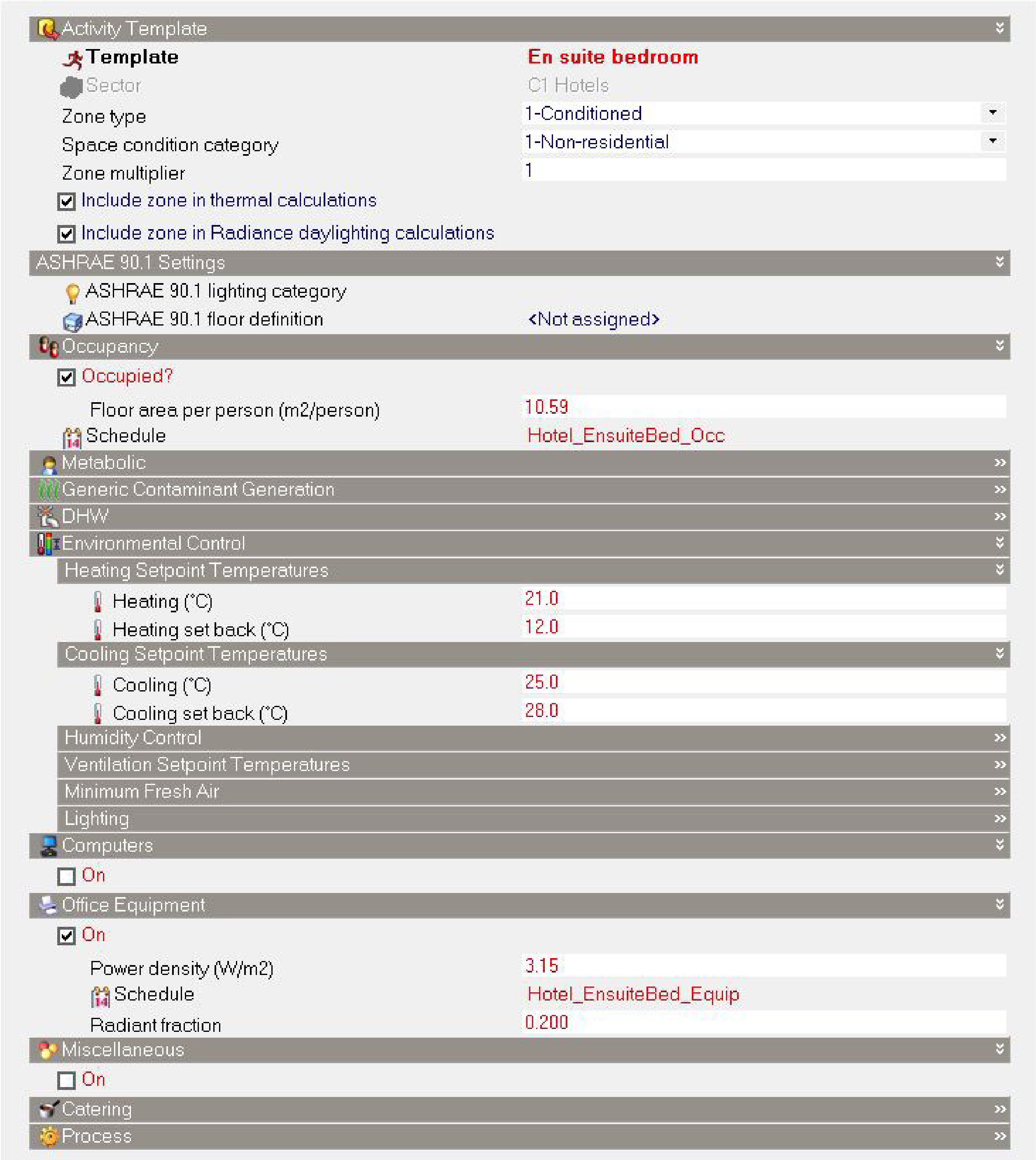


Figure 7.3.4: Boundary Condition for Activity and Occupancy
(Source - Author, Extracted Input Parameters from Design Builder)

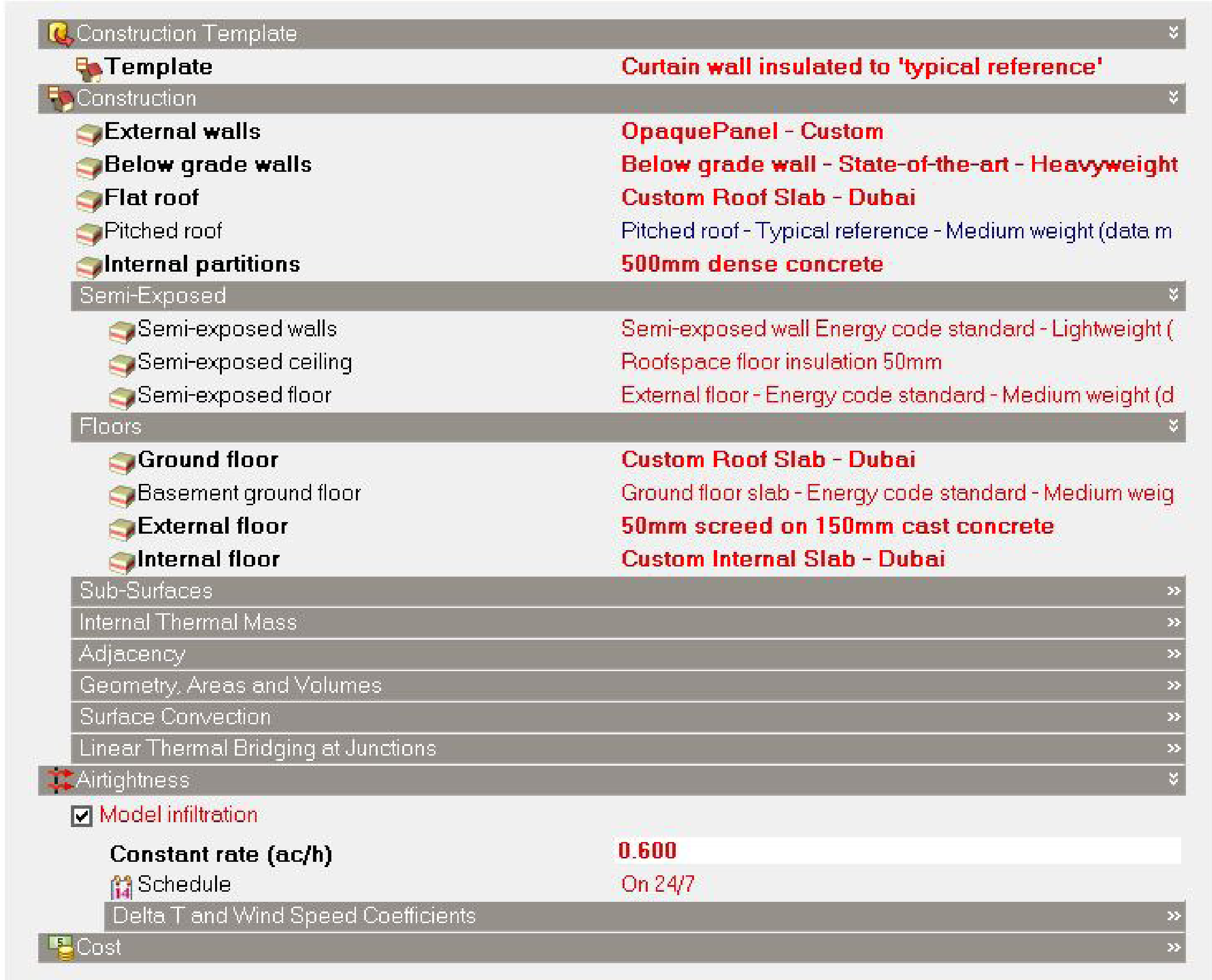


Figure 7.3.5: Boundary Condition for Construction Elements
(Source - Author, Extracted Input Parameters from Design Builder)

Figure 7.3.6: Proposed modification in Airtightness levels
(Source - Author, Extracted Input Parameters from Design Builder)

AR3B025

Figure 7.3.7: Boundary Condition for HVAC
(Source - Author, Extracted Input Parameters from Design Builder)

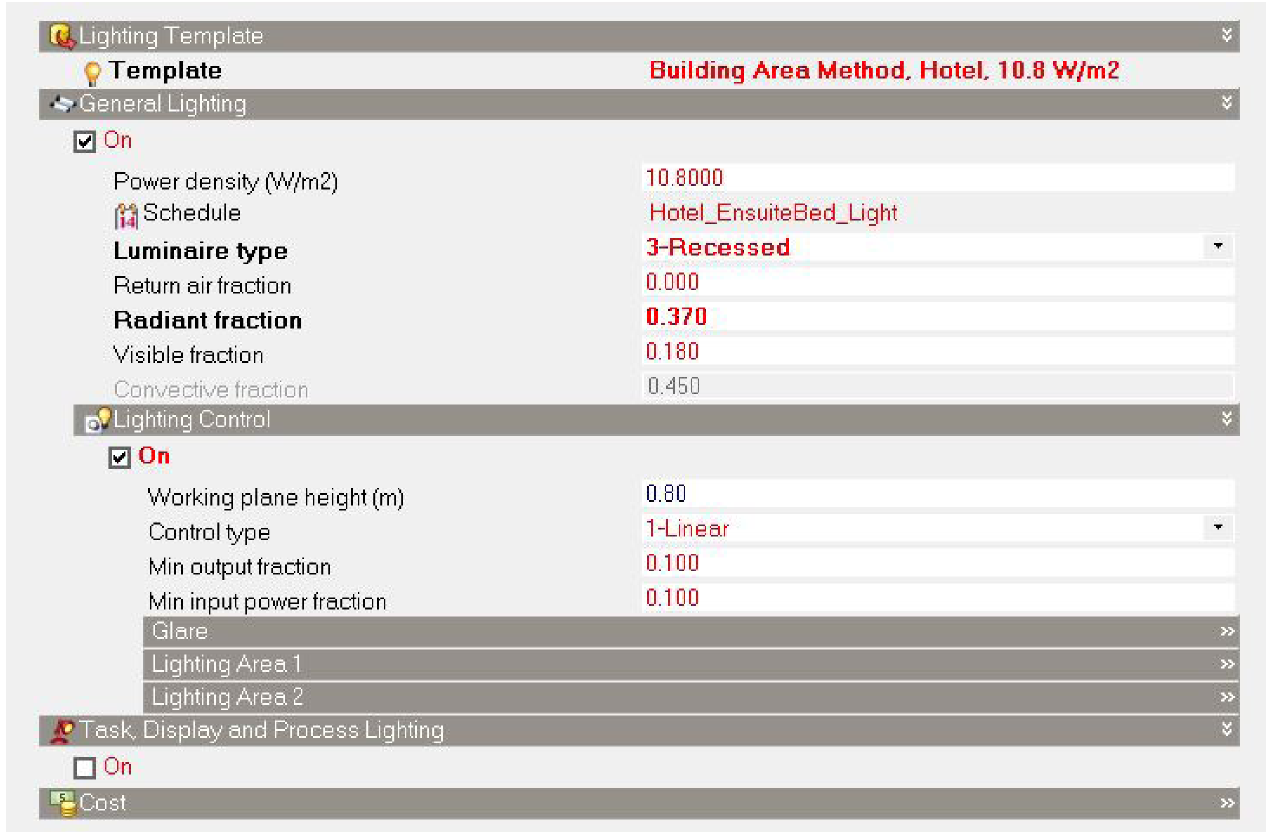


Figure 7.3.8: Boundary Condition for Lighting
(Source - Author, Extracted Input Parameters from Design Builder)

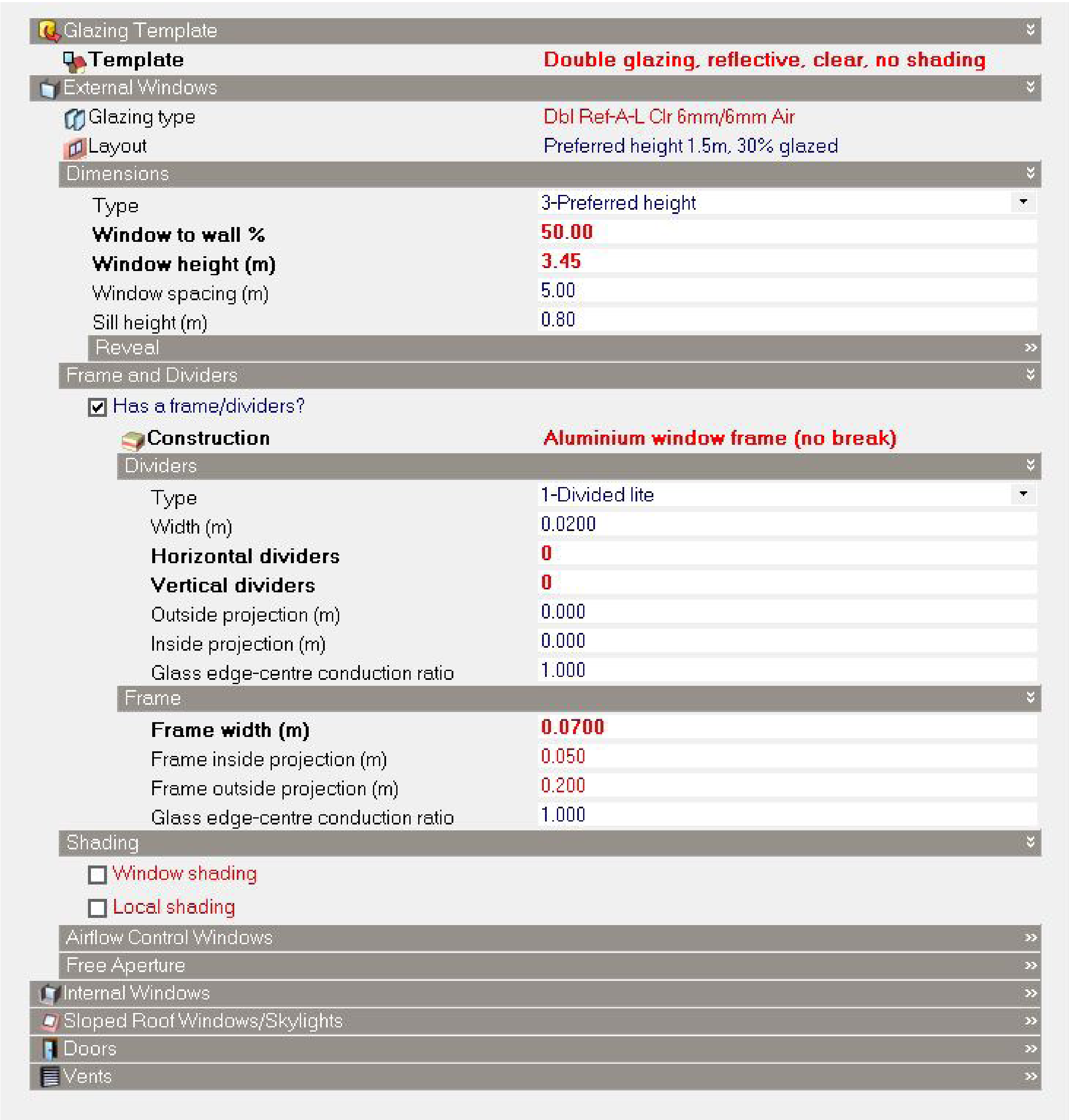


Figure 7.3.9: Boundary Condition assumed for existing envelope
(Source - Author, Extracted Input Parameters from Design Builder)

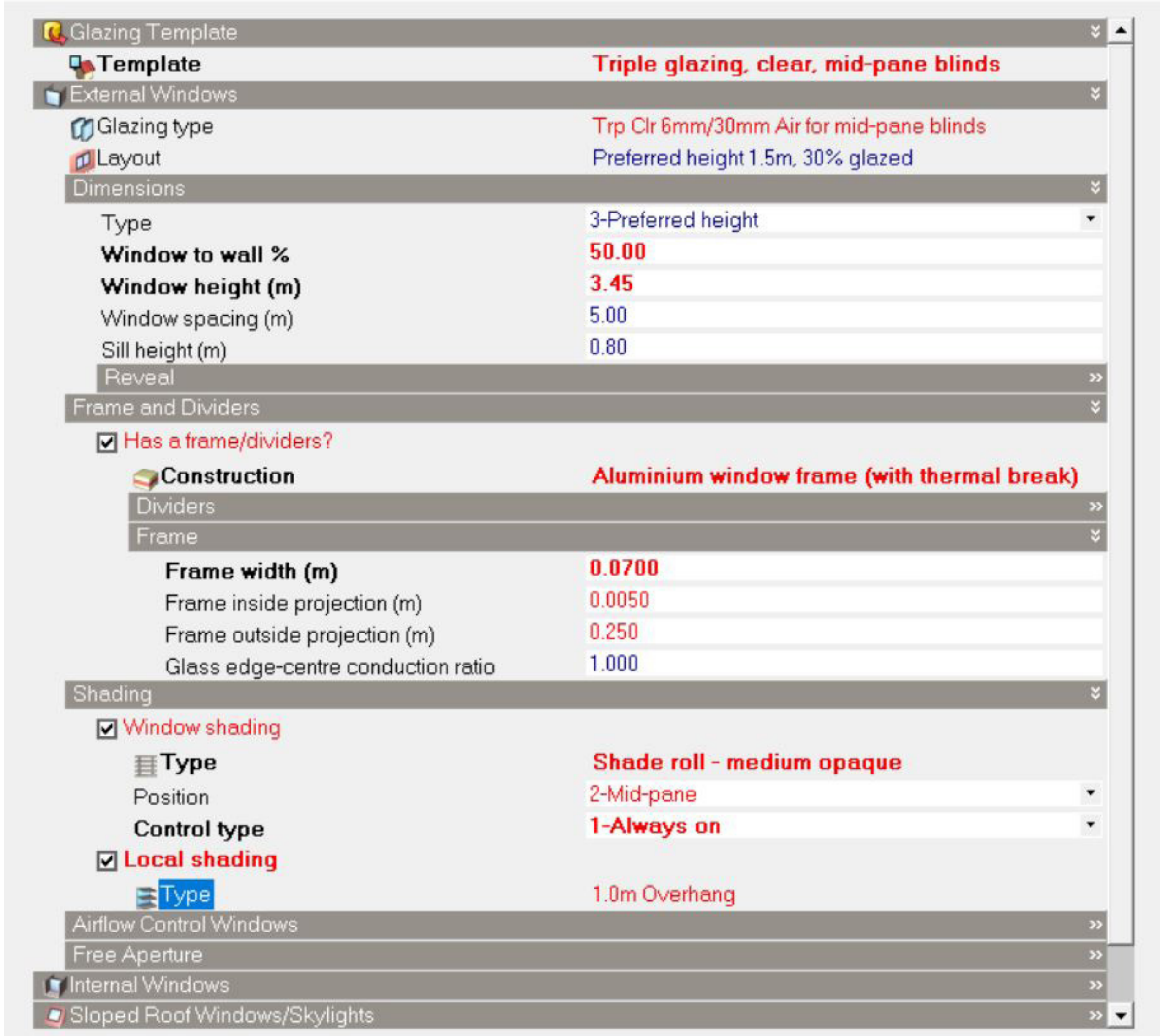


Figure 7.3.10: Boundary Condition assumed for proposed envelope
(Source - Author, Extracted Input Parameters from Design Builder)

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2019-05-10 12:24:18**

Values gathered over 8760.00 hours

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	2527902.13	240.02	240.02
Net Site Energy	2527902.13	240.02	240.02
Total Source Energy	3420004.07	324.73	324.73
Net Source Energy	3420004.07	324.73	324.73

Site to Source Energy Conversion Factors

	Site=>Source Conversion Factor
Electricity	3.167
Natural Gas	1.084
District Cooling	1.056
District Heating	3.613
Steam	0.250
Gasoline	1.050
Diesel	1.050
Coal	1.050
Fuel Oil #1	1.050
Fuel Oil #2	1.050
Propane	1.050
Other Fuel 1	1.000
Other Fuel 2	1.000

Building Area

	Area [m2]
Total Building Area	10531.88
Net Conditioned Building Area	10531.88
Unconditioned Building Area	0.00

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00
Cooling	0.00	0.00	0.00	2172021.78	0.00	0.00
Interior Lighting	278004.43	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	437.25	0.00	0.00	0.00	0.00	0.00
Interior Equipment	77438.68	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	355880.35	0.00	0.00	2172021.78	0.00	0.00

Figure 7.3.11: EPI for the case study existing building
(Source - Author, Extracted Input Parameters from Design Builder)

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2019-05-11 13:15:53**

Values gathered over 8760.00 hours

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	1970711.27	187.12	187.12
Net Site Energy	1970711.27	187.12	187.12
Total Source Energy	2845271.21	270.16	270.16
Net Source Energy	2845271.21	270.16	270.16

Site to Source Energy Conversion Factors

	Site=>Source Conversion Factor
Electricity	3.167
Natural Gas	1.084
District Cooling	1.056
District Heating	3.613
Steam	0.250
Gasoline	1.050
Diesel	1.050
Coal	1.050
Fuel Oil #1	1.050
Fuel Oil #2	1.050
Propane	1.050
Other Fuel 1	1.000
Other Fuel 2	1.000

Building Area

	Area [m2]
Total Building Area	10531.88
Net Conditioned Building Area	10531.88
Unconditioned Building Area	0.00

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00
Cooling	0.00	0.00	0.00	1608448.72	0.00	0.00
Interior Lighting	284386.63	0.00	0.00	0.00	0.00	0.00
Exterior Lighting	437.25	0.00	0.00	0.00	0.00	0.00
Interior Equipment	77438.68	0.00	0.00	0.00	0.00	0.00
Exterior Equipment	0.00	0.00	0.00	0.00	0.00	0.00
Fans	0.00	0.00	0.00	0.00	0.00	0.00
Pumps	0.00	0.00	0.00	0.00	0.00	0.00
Heat Rejection	0.00	0.00	0.00	0.00	0.00	0.00
Humidification	0.00	0.00	0.00	0.00	0.00	0.00
Heat Recovery	0.00	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	0.00	0.00
Refrigeration	0.00	0.00	0.00	0.00	0.00	0.00
Generators	0.00	0.00	0.00	0.00	0.00	0.00
Total End Uses	362262.56	0.00	0.00	1608448.72	0.00	0.00

Figure 7.3.12: EPI for the case study after proposed modifications
(Source - Author, Extracted Input Parameters from Design Builder)

7.4. Daylighting Simulation

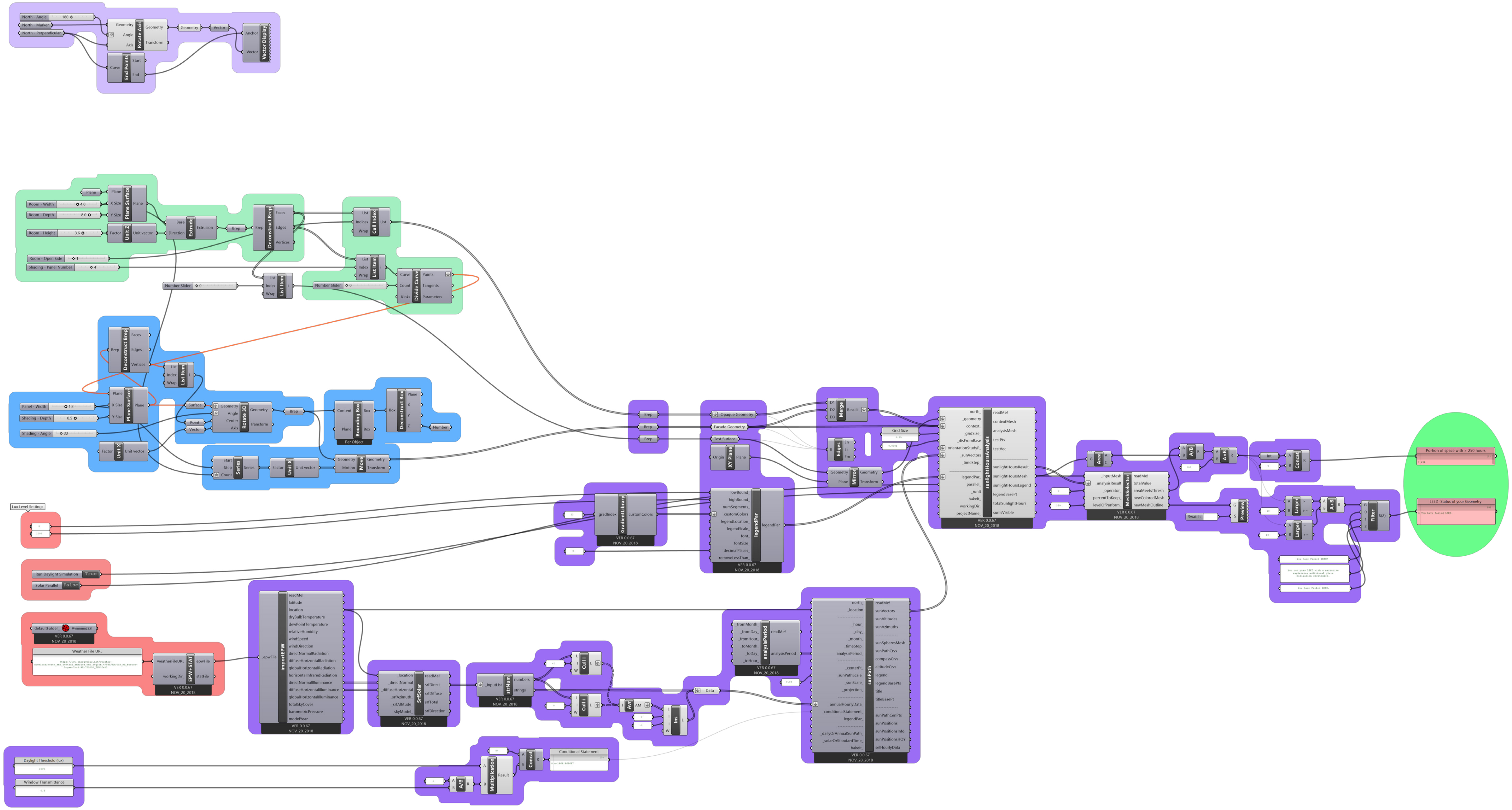


Figure 7.4.1: Grasshopper Script for Daylighting simulation
(Source - Author, Extracted script from https://hydrashare.github.io/hydra/)

7.5. Therm Simulation

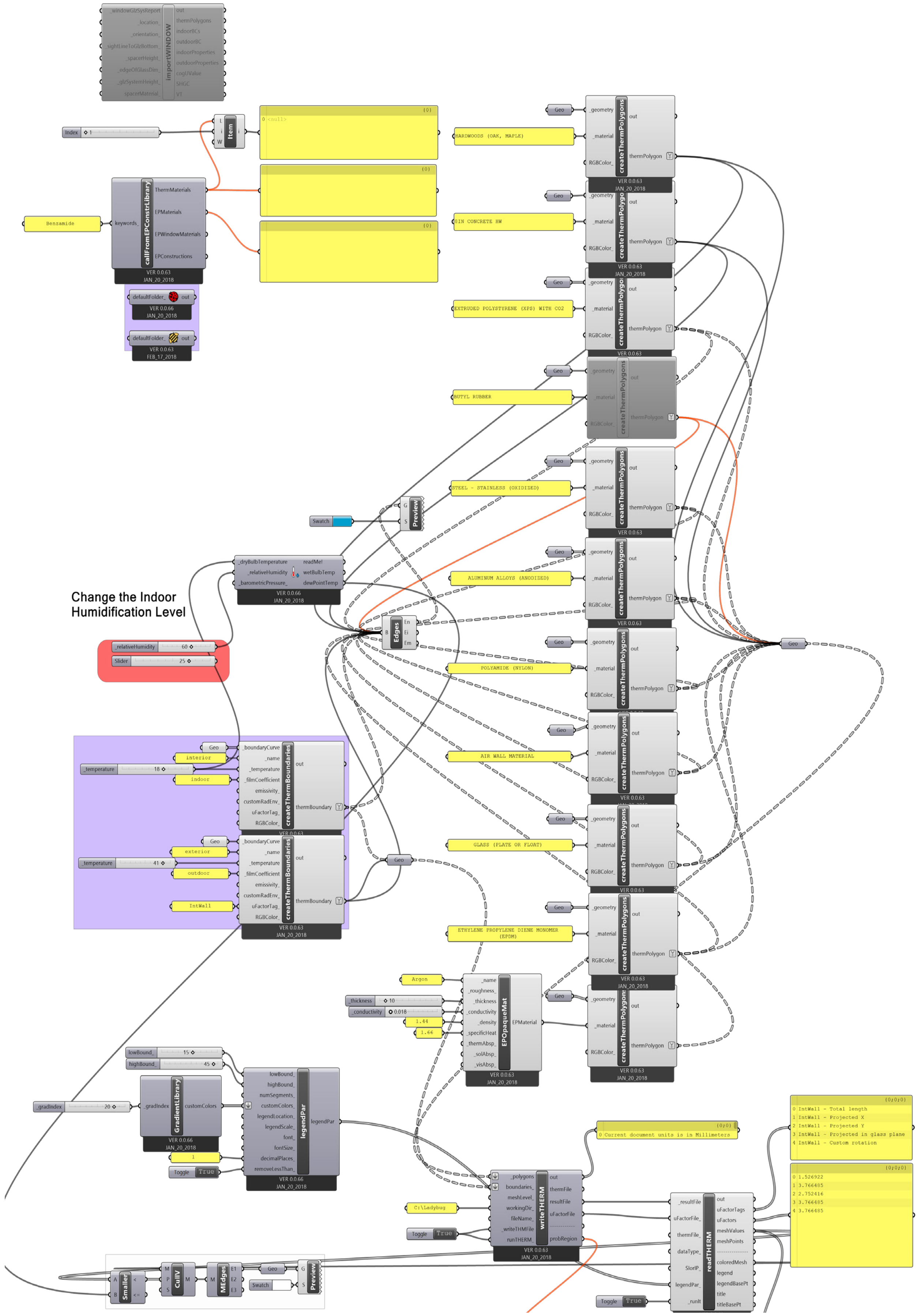


Figure 7.5.1: THERM Grasshopper Script for Thermal Analyis (Source – Author)

08
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