Politecnico di Milano
School of Architecture Urban Planning
Construction Engineering

Curtain Wall;

Analysis of European Office Buildings with Design and Retrofitting Strategies of the Curtain Wall

Master Thesis by
Elif Altunkeyik 882965

Supervisor
Prof.Alessandra Zanelli

AY 2018/2019

Abstract

The influence of the Industrial Revolution was significant for the building construction, materials and techniques which describe the building environment. Production in mass and fabricated with mechanized systems have been the primitive methods of today's architecture. The curtain wall became one of the outcomes of industrial evolvements in the construction industry.

The race of the countries to display their power by innovative and creative building forms in the companies have reigned the last century. Particularly availability for enhanced glass types and high-rise construction carried out the curtain wall to be the most common facade type of the office buildings in Europe. Advantages of the curtain wall may be defined as lighter, thinner and more transparent than the conventional masonry facades.

In the study, types of the curtain wall systems together with their assembly techniques, components and materials will be discussed. Furthermore, performance requirements in terms of comfort, safety and energy will be examined based on the European building codes. The failures partly or integrally of the curtain wall systems which obtain in deficiency or inadequacy of the mentioned performance requirements, influence dramatically in the micro and the macro scales. In order to diminish these failures, the overall curtain wall system may be proceeded with a retrofitting project. Therefore, several methods for the retrofitting strategy will be investigated.

In conclusion the research will discuss the design and retrofitting concerns of the metal curtain wall systems. Based on the collected knowledge about the curtain wall systems, a guideline for both of the design and the retrofitting processes will be presented. The design recommendations will cover the selection criteria of the curtain wall system which results in the type, the assembly technique and the glazing method. The decision criteria of the retrofitting process depend on the different aspects will be discoursed. The recommendations for the feasibility, the design and the intervention phases of the whole process will be given to apply to the existing office building facades.

Sommario

L'influenza della Rivoluzione Industriale è stata rilevante per la costruzione di edifici, i materiali e le tecniche proprie dell'ambiente edilizio. La produzione di massa e i sistemi meccanizzati sono stati i primi metodi dell'architettura di oggi. La facciata continua o curtain wall è uno dei risultati degli sviluppi industriali nel settore delle costruzioni.

La corsa dei diversi Paesi a mostrare il loro prestigio, con forme di costruzioni innovative e creative per le aziende, ha dominato il secolo scorso. In particolare, la disponibilità di tipi di vetro migliorati e la costruzione di grattacieli hanno favorito il curtain wall come tipo di facciata più comune negli edifici per uffici in Europa. I vantaggi del curtain wall includono maggiore leggerezza, finezza e trasparenza rispetto alle facciate in muratura convenzionali.

In questo studio verranno discussi diversi tipi di sistemi di facciata continua e le tecniche di assemblaggio, le componenti ed i materiali. Inoltre, i requisiti prestazionali in termini di comfort, sicurezza ed energia saranno esaminati in base agli standard europei. Le basse o mancate prestazioni, parziali o integrali, dei sistemi di facciata continua, con carenza o inadeguatezza dei requisiti prestazionali, hanno un'influenza significativa in scala micro e macro. Per ridurre i difetti, l'intero sistema può essere oggetto di operazioni di adeguamento ("retrofitting"). Pertanto, diverse strategie di retrofitting verranno analizzate.

In conclusione, questo studio analizzerà gli aspetti della progettazione e dell'adeguamento dei sistemi di curtain wall in metallo. Sulla base delle conoscenze acquisite saranno presentate delle linee guida per la progettazione ed i processi di retrofitting. Le linee guida per la progettazione copriranno i criteri di selezione del sistema di curtain wall che ne determinano il tipo, la tecnica di assemblaggio ed il metodo di velatura. Saranno analizzati i criteri decisionali del processo di retrofitting in base a diversi aspetti. Verranno, infine, fornite raccomandazioni in merito a fattibilità, progettazione e fasi di intervento dell'intero processo, da applicare alle facciate degli edifici per uffici esistenti.

Acknowledgements

I would like to express my great appreciation to my supervisor Professor Alessandra Zanelli for her outstanding support and positive guidance throughout my whole thesis. Her persuasion to my study has made me motivated, thus I am proud, glad and grateful for her effort.

I would also like to put into words my profound gratitude to my family and friends for providing me with unfailing support and continuous encouragement throughout my years of study and during the process of researching and accomplishing this thesis. This completion would not have been possible without them. Thank you for all.

Elif

Index

Chapter 03 // The Curtain Wall

Chapter 04 // Guideline

List of Figures

List of Tables

List of Graphs

List of Drawings

1.1 | Introduction of the Current Building Stock

The influence of the Industrial Revolution was significant for the building construction, materials and techniques which describe the building environment. Production in mass and fabricated with mechanized systems have been the primitive methods of today's architecture. Advancements of the 19th century lead the technologies to the 20th century with increased forms.

The invention of the frame structure that is composed by post and beam grid, obtained a dramatic change on the building facades. Diminishing of the masonry load bearing walls brought advantages with regard to reduce wall thicknesses. As an inherent result of these aspects, facade of the buildings might be constructed with lighter components instead of typical stone or brick masonry materials. During the 20th century, particularly in the office buildings, framed structure with steel or concrete and curtain wall facades dominated the construction method. Due to its characteristic, the curtain wall is a non-load bearing facade type, it carries just the weight of itself. This unique feature of the curtain wall enabled it to participate to the building structure with high demand and ease.

Curtain wall implied possibility to design taller and lighter facades with large glazing areas. These qualifications of the curtain wall made it the most common facade type for the office buildings starting from 1950s to the current period. However, the glazed surface carry out some challenges in terms of the thermal insulation or the solar heat gain. In Europe most of the office buildings that were constructed before 1970s, designed without any energy concern or liability. Afterwards adopted regulations ensured an improved performance for the thermal comfort. Nevertheless, by time with assorted failures in the curtain wall system have caused insufficient or uncomfortable environment for the inhabitants with regard to thermal, acoustic or safety necessities.

The residential and non-residential sectors in total responsible for the 40% of the energy consumption in Europe. These crucial amount of the energy consumption must be enhanced by the building retrofitting overall the Europe. In country or region base regulations with the roadmaps and the plans of the European Commission now actively take part for the strategies of the energy reduction. In order to apply suggested strategies, analyzing of the existing building stock with their function, typology, age, construction methods and so on have extreme prevalent.

The European building sectors have been categorized as residential and non-residential. While the classification of the residential sector may be with single or multi-family houses, non-residential sector represents more heterogeneous functions. Wholesale and retail, office, education, hotels and restaurants, hospitals, sport facilities and others are composed the non-residential category. Among this classification the office buildings cover a share of 23% total floor area.

1.2 | The European Building Stock

The objective of this thesis focuses on the facade of European office buildings. Analysis and consideration about building stock in Europe has been a key point during the study. The availability and quality of data on European buildings stock, even though increased over the past years as a result of various activities at European level, is still limited. Building stock data are collected from different institutions at national and regional levels, both official and unofficial (e.g. national statistics offices, research projects or energy agencies): as a consequence, the level of data completeness and harmonization varies significantly among the different countries.

Europe has hosted various cultures in its body for many centuries and it is one of the most established continents over the world. Based on these features, built gross floor area is remarkable over the total land area. In order to understand position in the world, comparison of EU27 with US and China is given below. According to value of the building floor space over land area, Europe has the highest building density among them. Understanding the existence building typologies has significant role to sustainability in terms of energy efficiency and aesthetics. Maintenance of the existing buildings increase the value of assets and provides improved conditions for the occupants.

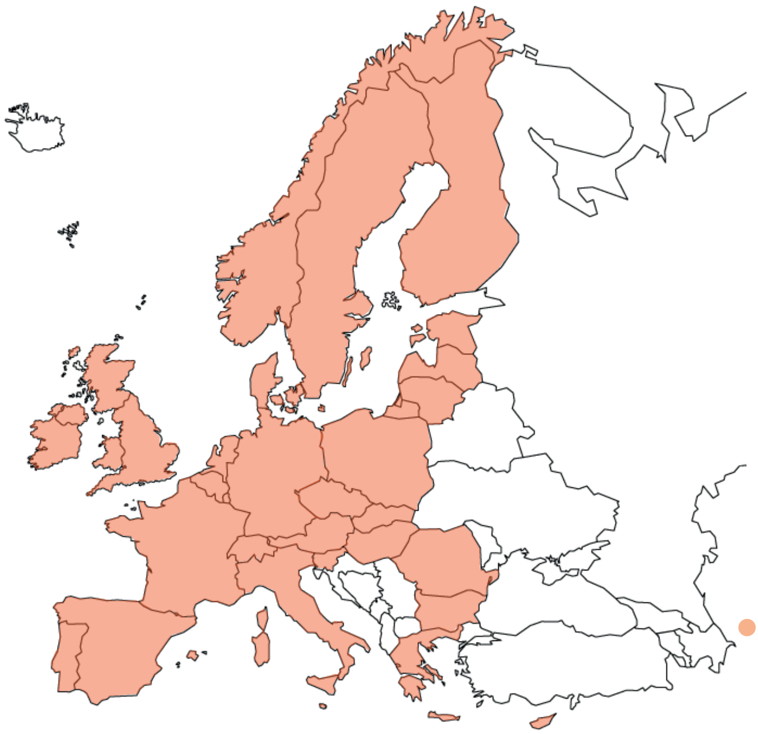
Table 1.1; Comparison of land area and building floor space in EU27, US and China.
Elaboration of the author.

Region	Population	Land Area	Building Floor Space
EU27	501 million	4.324.782 km2	24 billion m2
US	309 million	9.826.675 km2	25 billion m2
China	1338 million	9.598.080 km2	35 billion m2

In Europe, building typology from single family house to skyscraper represent wide range of differences in their functions. In general framework, building stock has been classified as residential and non-residential sectors, each category includes sub-sectors. Depend on BPIE source, European countries have been divided into three regions, based on the similarities in climate, building typology and market. These three regions and included countries are given in the figure below. The estimated floor space concentrated in the North & West region as 50% while 36% in South region, 14% in Central & East region are contained.

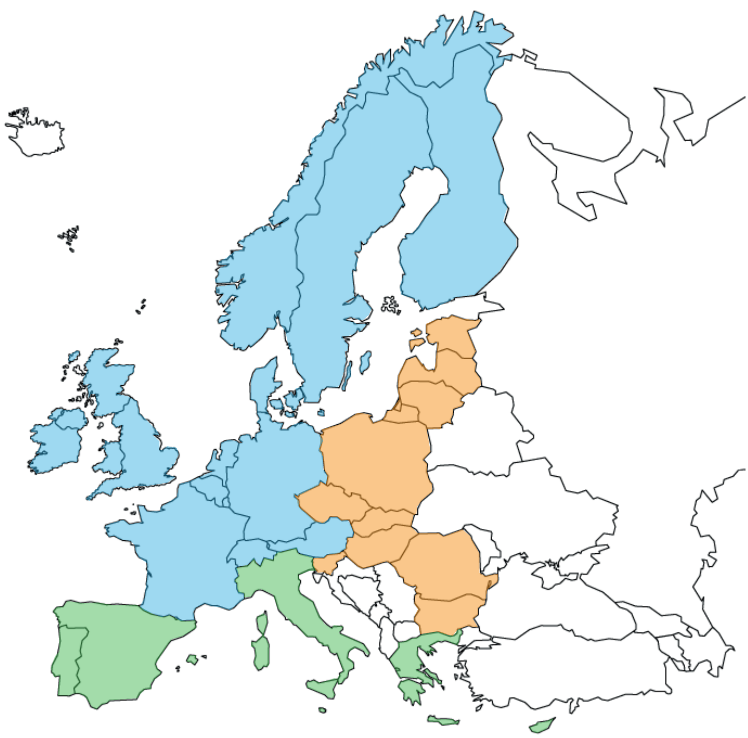
Table 1.2; Three climatic regions and included countries in Europe.
Elaboration of the author.

North & West	AT, BE, CH, DE,DK, FI, FR, IE, LU, NL, NO, SE, UK	12 billion m2
Central & East	BG, CZ, EE, HU, LT, LV, PL, RO, SI, SK	8.6 billion m2
South	CY, GR, ES, IT, MT, PT	3.4 billion m2



Drawing 1.1; Covered building floor area in the study.
Elaboration of the author.

Countries that are included to the building stock analysis



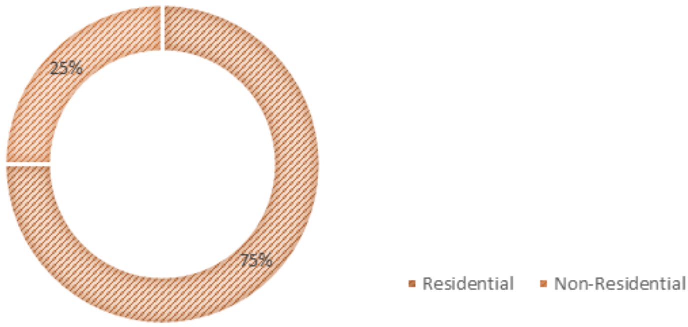
Drawing 1.2; Building floor distribution in the three climatic regions.
Elaboration of the author.

Estimated building floor space distribution

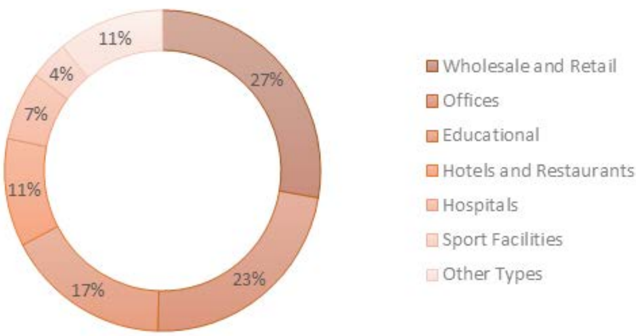
North&West 50%
Central&East 36%
South 14%

Among two main sectors, the residential stock covers the 75% floor space of total while non-residential does 25%. The residential stock consists of single family houses and apartment blocks. Instead, the non-residential stock is much more heterogeneous than the residential sector. As principal sub-sectors; wholesale and retail, office, education, hotel and restaurants, hospital, sport facilities and others are classified based on their function, size and usage pattern.

Among the non-residential sector, wholesale and retail buildings compose the majority. Office buildings and educational buildings follow it with corresponding floor spaces. These two sub-sectors have similarities to residential sector, in terms of heating and cooling conditions and usage pattern. The figure below shows the share of non-residential stock based on the floor space.



Graph 1.1; Distribution of residential and non-residential sectors in Europe.
Elaboration of the author.



Graph 1.2; Distribution of different building types in non-residential sector in Europe.
Elaboration of the author.

The data about the European building stock clarified that the office buildings have the second largest portion in non-residential stock. Actively used office buildings have been participated the total energy consumption. These buildings have existed for decades and under the actual conditions, a big amount of them require improvement in terms of energy, aesthetics, comfort and other issues. In order to understand deeper the office stock in Europe, subsequent synthesis from the different sources have been collected.

Sub-sector	Share	Definition
WHOLESALE&RETAIL	28%	Detached shops, shopping centres, department stores, large and small retail, food and non food shops, bakeries, car sales and maintenance, hair dresser, laundry, service stations (in gas stations), fair and congress buildings and other wholesale and retail.
OFFICE	23%	Offices in private companies and offices in all state, municipal and other administrative buildings, postoffices
EDUCATIONAL	17%	Primary and secondary schools, high schools and universities, research laboratories, professional training activities and others.
HOTEL&RESTAURANT	11%	Hotels, restaurants, pubs and cafés, canteens or cafeterias in businesses, catering and others.
HOSPITAL	7%	Public and private hospitals, medical care, homes for handicapped, day nursery and others.
SPORT FACILITY	4%	Sport halls, swimming pools, gyms etc.
OTHER	11%	Warehousing, transportation and garage buildings, agricultural (farms, greenhouses) buildings, garden buildings.

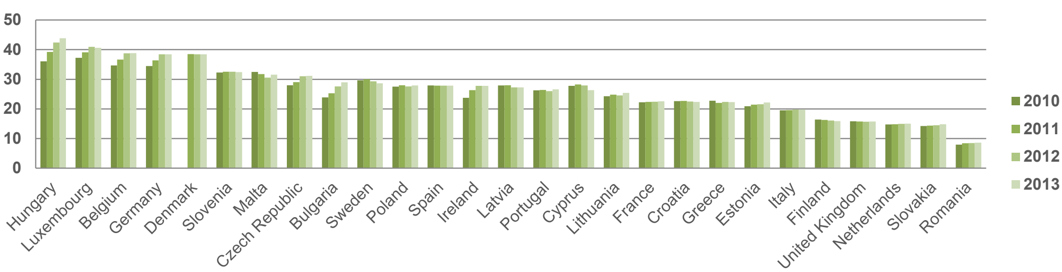


Table 1.3; Definition of sub-sectors in non-residential category. Elaboration of the author.

Graph 1.3; Share (in %) of office floor area in non-residential sector. Elaboration of the author.

1.3 | The European Office Building Stock

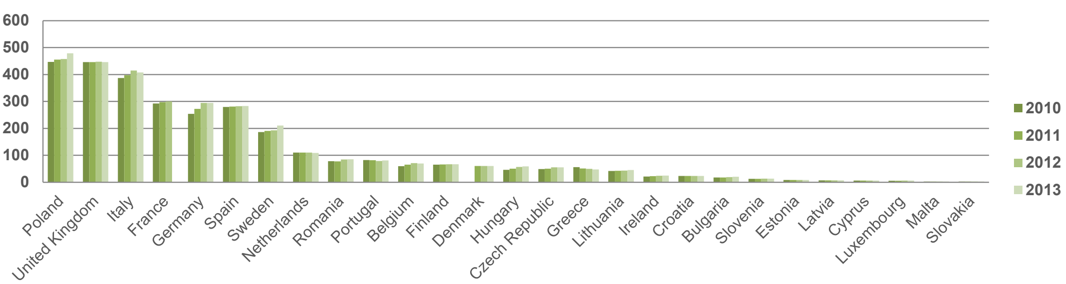
As shown in the Europe's Buildings Under the Microscope report by BPIE (2011), the office buildings account for 23% of the total non-residential floor space. Most of the population spend approximately one-third of the time in a day at the offices. Therefore, office building should serve good conditions and environment to the employees. The analysis about the existent stock has a significant importance to improve their lacks in relation with the thermal insulation, sound transmission and so on.

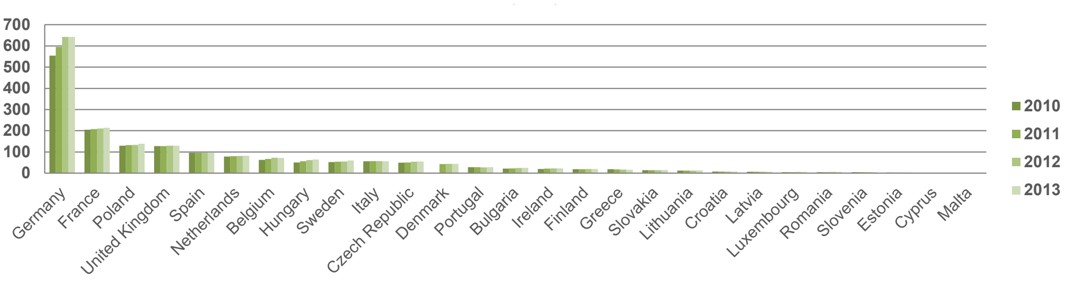
According to the research, in this chapter office buildings will be analyzed country to country in EU27 and Switzerland, Norway. Even if, it doesn't cover all the European countries, this study has been helpful to provide general framework.

The total office floor area in the EU27 is approximately 1.251 billion m2 (INSPIRE project, 2016). Almost three-quarters of the total floor area, i.e. 71%, lies in Germany, France, UK, Spain, Italy and Poland. Little is known about the age of the current office stock, particularly those built pre-1980. In general terms, the office stock is mostly younger than the residential stock, which dates mostly to before 1970s, when the post-war reconstruction of the 1950s and 1960s was driven by a pressing necessity to rebuild rapidly and cost effectively.

Graph 1.4; Number (in thousand) of EU27 offices.
Elaboration of the author.

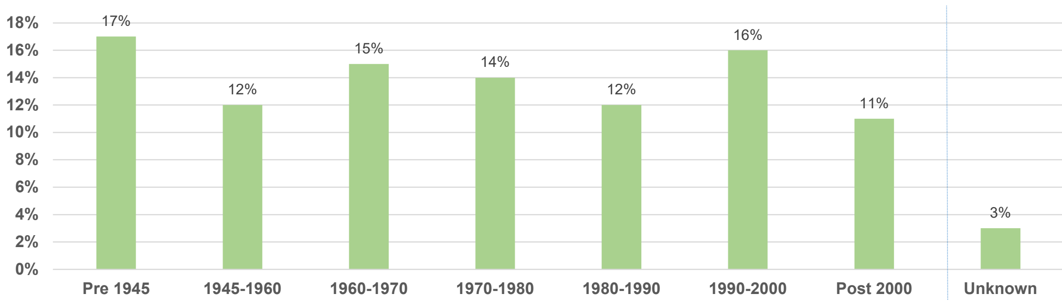
Graph 1.5; Total floor area (in Mm^2) of EU27 offices.
Elaboration of the author.





Given graphs has shown that, the floor space and number of the office buildings have changes on the rankings country by country. For example, Germany is the first country for the total office floor area, however it takes part as the fifth country for number of the office buildings. This drives from size variabilities of the buildings.

The age profile of buildings across Europe varies from country to country. Although a large proportion of the office stock within the EU27 countries was built before 1980, the construction of office buildings increased from 1960s, reaching a peak in the 1990s. The weighted average age profile across all EU27 countries is shown in the following table (figures sum up to 97%, since 3% is unknown);

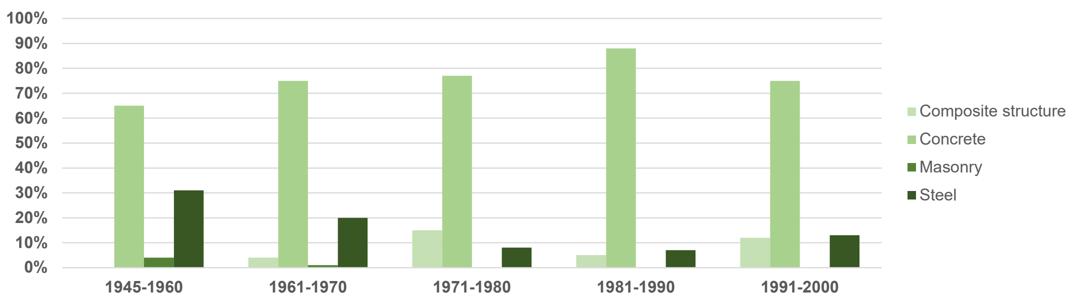


Graph 1.6; Average construction by age band for EU27 office (weightings applied).
Elaboration of the author.

As regards the building type and construction, instead, most countries show a uniform level in the general construction types, where the main material used in the structure appears to be concrete. It goes without saying that some characteristics like the number of floors, size, geometries, etc. may be different across countries, making even harder to classify the office stock.

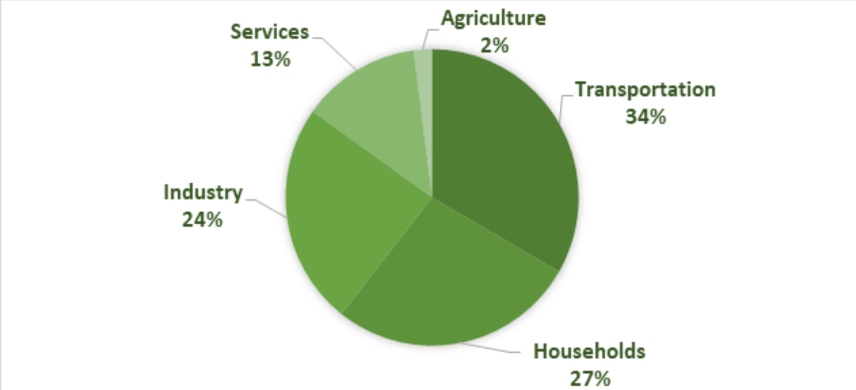
The analysis performed by the Inspire project (2016) highlights that the older buildings, built pre-1960, were often built from masonry brick, with brick structural walls and an exposed wall façade (pre-1945 stock) or concrete structures with a brick or concrete façade (1945-1964). Over the subsequent years, following the introduction of the first curtain walls, concrete structures continued to be predominant (1970-1980s) and the level of glazing increased. Prefabricated sandwich walls started to appear as well. Finally, as regards the post-1980s stock, glass curtain walls and/or aluminum panels were more common, along with pre-fabricated elements. Overall, the curtain wall façade appears to be the main type of construction.

Graph 1.7; Trend of EU27 office buildings by structural material.
Elaboration of the author.

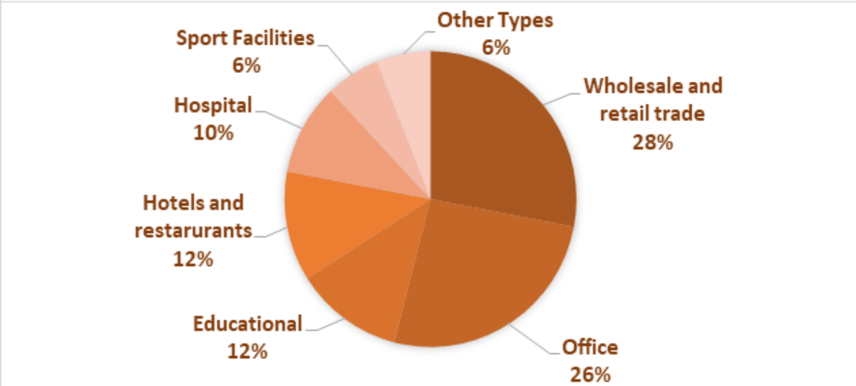


By comparison, as reported in the Final Guidebook of the Inspire project ("Guidebook for Energy Renovation Packages", 2016) over half of the residential stock within the EU-27 countries dates from before 1971, when standardized buildings methods where introduced followed by industrially prefabricated constructions and composite construction methods. Prior to this year, standards, policies and regulations associated to energy efficiency in buildings were very poor if not existent.

The residential sector, as a consequence, consumes approximately 14 times more energy than the office stock. This, by taking also into account that just nearly 40% of residential buildings in Europe are publicly owned, highlights the importance of the residential sector in energy-reduction retrofit.



Graph 1.8; Share (in %) of energy consumption in different sector in Europe. Elaboration of the author.



Graph 1.9; Share (in %) of energy consumption in non-residential sector. Elaboration of the author.

Table 1.4; Seven climatic regions and included countries in Europe. Elaboration of the author.

Region	Countries	Total floor area Mm²	Heated floor area Mm²	Cooled floor area Mm²
Southern Dry	Portugal, Spain	105	94	94
Mediterranean	Cyprus, Greece, Italy, Malta	81	73	73
Southern Continental	Bulgaria, France, Slovenia	234	211	149
Oceanic	Belgium, Ireland, UK	157	142	100
Continental	Austria, Czech Rep., Germany, Hungary, Luxemburg, Netherlands	469	422	300
Northern Continental	Denmark, Lithuania, Poland, Romania, Slovakia	155	140	99
Nordic	Estonia, Finland, Latvia, Sweden	59	44	31

		U-Values of Wall (W/m^{2}K)						U-Values of Windows (W/m^{2}K)					
Country	**Total Floor Space(Mm^2)**	**Pre 1945**	**1945-1970**	**1970-1980**	**1980-1990**	**1990-2000**	**Post 2000**	**Pre 1945**	**1945-1970**	**1970-1980**	**1980-1990**	**1990-2000**	**Post 2000**
Portugal	21	2.0	2.0	1.6	1.5	1.3	0.8	4.5	4.5	4.5	4.4	1.6	3.8
Spain	84	2.5	2.2	2.2	1.8	1.7	0.9	5.8	5.8	6.1	3.3	3.3	2.8
Weighted Average		2.4	2.2	2.1	1.7	1.6	0.8	5.5	5.6	5.8	3.6	2.9	3.0
Cyprus	2	2.1	1.9	1.5	1.5	1.5	1.5	6.2	6.2	6.2	5.9	2.5	1.6
Greece	26	2.5	2.4	2.1	0.8	0.7		5.1	5.0	5.3	3.7	3.5	
Italy	52	1.2	1.2	0.8	0.8	0.8		5.5	5.5	4.9	4.2	3.6	3.6
Malta	1	2.0	1.9	1.6	1.6	1.6	1.7	6.1	6.1	5.9	5.8	5.7	5.3
Weighted Average		1.6	1.6	1.2	0.8	0.8	1.6	5.4	5.4	5.0	4.1	3.5	3.6
Bulgaria	28	1.6	1.5	1.4	1.3	1.0	0.4	3.1	3.1	3.1	3.1	2.7	1.9
France	199	2.1	2.1	1.2	1.2	1.0	0.4	5.0	5.0	4.4	3.4	3.3	2.7
Slovenia	7	1.4	1.4	1.4	0.9	0.9	0.6	2.4	2.4	2.1	1.6	1.6	1.6
Weighted Average		2.0	2.0	1.2	1.2	1.0	0.4	4.7	4.7	4.2	3.3	3.1	2.5
Belgium	25	1.9	1.8	1.8	1.7	1.3	0.8	4.5	4.6	4.5	3.8	3.7	2.3
Ireland	10	1.9	1.8	1.8	0.8	0.7	0.3	4.8	4.8	4.8	3.3	2.9	2.3
UK	122	1.8	1.7	1.3	0.7	0.5	0.4	4.9	4.9	4.9	4.6	2.7	1.8
Weighted Average		1.8	1.7	1.4	0.8	0.6	0.4	4.8	4.9	4.8	4.4	2.9	1.9
Austria	21	0.7	0.7	0.6	0.6	0.4	0.3	3.2	3.4	2.4	2.1	1.4	1.3
Czech Rep.	36	0.8	0.8	0.7	0.7	0.5	0.4	2.8	2.8	2.8	2.8	2.0	1.5
Germany	360	1.5	1.5	1.2	0.9	0.4	0.4	2.9	2.9	2.9	1.9	1.6	1.3
Hungary	5	1.4	1.2	1.2	0.7	0.7	0.5	3.0	3.0	3.0	2.7	2.7	2.2
Luxemburg	1	1.5	1.5	1.7	0.6	0.5	0.4	4.5	3.9	3.2	2.0	1.6	1.2
Netherlands	47	1.8	1.6	1.6	0.6	0.5	0.4	3.8	3.7	3.7	3.4	2.9	1.8
Weighted Average		1.4	1.4	1.2	0.8	0.8	0.4	3.0	3.0	2.9	2.1	1.8	1.4
Denmark	45	1.2	1.0	0.6	0.4	0.4	0.3	2.6	2.5	2.5	1.4	1.4	1.7
Lithuania	8	1.0	0.9	0.6	0.6	0.4	0.3	2.4	2.4	2.3	2.3	1.9	1.9
Poland	89	1.3	1.3	1.3	0.8	0.6		4.7	3.7	2.6	2.6	2.3	2.1
Romania	8	1.9	1.6	1.6	1.4	1.4	1.0	2.6	2.7	2.7	2.4	2.4	1.3
Slovakia	7	1.5	1.0	1.0	0.7	1.1	0.5	3.2	3.2	2.9	2.9		
Weighted Average		1.3	1.2	1.0	0.7	0.6	0.4	3.8	3.2	2.6	2.2	2.0	1.9
Estonia	2	0.5	0.5	0.3	0.3	0.2	0.2	1.8	1.8	1.8	1.1	1.0	1.0
Finland	16	0.8	0.6	0.5	0.3	0.3	0.3	2.4	2.3	2.2	2.0	1.7	1.5
Latvia	4	1.0	1.0	1.0	1.0	0.8	0.5	2.7	2.7	2.5	2.5	2.5	1.8
Sweden	27	0.6	0.4	0.3	0.3	0.2	0.2	3.2	3.1	3.0	2.5	2.5	0.9
Weighted Average		0.7	0.5	0.4	0.4	0.3	0.2	2.8	2.7	2.6	2.3	2.2	1.2

Table 1.5; Wall and window U-values of European countries by years.
Elaboration of the author.

1.4 | Generic Review of Six Main Countries

Based on the Inspire project data as it is concerned before, 70% of the office building stock in Europe is constituted by six countries; Germany, France, United Kingdom, Italy, Spain and Poland. The facade is directly interrelated with the thermal performance of the building. While well-insulated facades provide enhanced performance in different seasonal periods, the buildings without or with insufficient insulation have dramatic performance challenges. In existing European office stock many of the constructions date back before the 2000s. The period between the 1945 until the 2000s accounts 86% of the existing office building stock.

Six main countries present diversified type of structures, constructions and materials in the mentioned period. The facade transmittance is changeable from region to region for these countries.In a broad speaking about these six countries, curtain wall have dominated the other facade systems for the office buildings category. As the structure type, frame structure with reinforced concrete have had the highest ratio for all the six countries.

a) Germany

Germany is the first country for the total floor area and the fifth for the number of the office buildings in Europe.

Number of the office buildings, 189.000, takes part with 31% share ratio in total non-residential floor area. These buildings cover 359.5 Mm2 floor area in total and large amount of them are located in the top seven cities i.e. Berlin, Munich, Hamburg, Frankfurt, Cologne, Stuttgart and Düsseldorf. The office building stock in these cities represent a quarter of the total stock (INSPIRE, 2016).

In the age profile new constructions after 2000s is involved 16% of the total office buildings (INSPIRE, 2016). The period between 1990s and 2000s cover the 19% and it is the decade with the highest construction ratio among all.

Definition of the construction types of the structure and the facades may sum like; most common type of the offices is reinforced concrete with the curtain wall facade. Typical concrete framework structure with 91% and curtain wall facade with various cladding materials with 92% dominated their categories (BSRIA database, 2014).

In 1977 first thermal insulation ordinance for the building was submitted. Afterwards in 1984 and 1995 it updated with specified features. A large amount of the buildings in Germany didn’t have thermal insulation before 1977 (INSPIRE, 2016). The energy consumption for the heating and the cooling is a result of the uninsulated buildings. Total energy consumption have been parallel to the thermal insulation ordinances which dates 1977, 1984 and 1995 years.

b)France

France is the second country for the total floor area and the fourth for the number of the office buildings in Europe.

In the existing stock fall into 200.000 office buildings which cover 198.7 Mm2 total area. Country review shows that 23% of the non-residential stock lay over for the office buildings (INSPIRE, 2016).

In France stock, the office buildings that were constructed between 1960 and 1973 year period, 36%, cover majority of the total. Pre-1960 category has the second largest amount with 25% ratio (BSRIA database, 2014). It shows that a big number of the age distribution in office buildings date back before 1973.

In France office building stock, concrete structure with the curtain wall facade cover the most common combination. Masonry structure have been popular in pre-1960 buildings and afterwards offices mostly with concrete, 73%, or composite structure, 17%,have been introduced (BSRIA database, 2014).

Throughout the time like many other European countries, France have enhanced the thermal performance of the new constructions after 1970s. Nevertheless, majority of the existing office stock, 61%, date from pre-1970s. These buildings require a profound retrofitting or reconditioning in terms of energy efficiency.

c)Poland

Poland is the third country for the total floor area and the first for the number of the office buildings in Europe.

Offices buildings account for approximately 23% of the total non-residential floor area with 88.5 Mm2 total floor area (ENTRANZE database). During the research the age distribution couldn't be available on the sources.

Pre-1945 offices were built with brick or chipped stone as load bearing structure. Between 1945 and 1964 period, burnt brick became the most common material for the facade cladding. Around 1960s Poland produced big pre-fabricated panels and many of the offices were accomplished with this system. In contrary to generic Europe office building perspective, in Poland most common office type was concrete structure with the concrete facade panels.

Building codes about the thermal insulation was introduced firstly in 1966, however around 1976 and afterwards an energy reduction of the offices was reached.

d)United Kingdom

United Kingdom is the fourth country for the total floor area and the second for the number of the office buildings in Europe.

Among the six main countries, share of the office category in non-residential sector is smaller than other ones. UK offices cover just 18% of the non-residential stock.

Approximately 491.280 office buildings cover 135.6 Mm2 total floor area (ENTRANZE database).

In the age profile constructions after 1980s up to 2000s are involved 35% of the total office buildings (BPIE database). Surprisingly in UK, constructions before 1920s have a dramatic amount with 21% ratio. The period between 1920s and 1960s has the lowest share of existing office stock, 17%.

The data about the structure and the facade type ensured that concrete structure with the curtain wall facade have been the most typical system for the UK office buildings. During the pre-1940s and early 1950s, offices frequently were composed by masonry load bearing walls. Solid or cavity walls with brickwork and low-glazing levels, 30%-50%, on the facade constituted the generic style. After 1950s frame worked buildings obtained glazing level up to 75%. In 1970s it was started to design more energy efficient facades with less glazing areas. This was provided by double or sometimes triple-glazing and with the contribution of some infill materials on the glazing units.

e)Spain

In Spain, the office stock covers 24% of the non-residential sector in terms of total floor area. In comparison with other European countries amount of the new constructions are relatively more than older ones.

Pre -1945 buildings take part as 33%, 1945 and 1970 period buildings as 19%, 1971 and 1990 period buildings as 21%. The share of the offices that were built after 1991 is 27% (BSRIA database).

Like other European equivalents, in Poland until 1960s solid brickwork facades were very common. Afterwards until 1970s frame structured reinforced concrete buildings and curtain walls with prefabricated infills became widespread. Thermal regulations after the Oil Crisis participated insulation layers to the facade designs. 1980s and 1990s dominated by steel or concrete frame structure with thermally improved curtain wall facade systems.

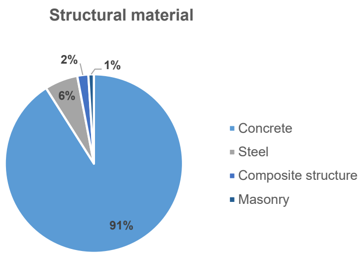
f)Italy

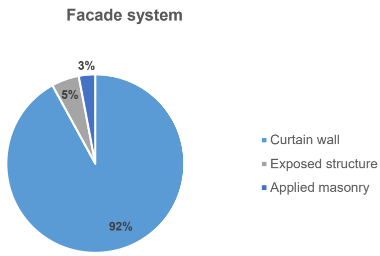
The office building stock accounts 14% of the non-residential sector in Italy. Number of the office buildings is approximately 65.000 and they lay out on a 56.7 Mm2 floor area (ENTRANZE database).

In Italian office stock, pre-1945 category takes into largest amount for the existing buildings. While pre-1945 buildings have 29% share, after-2000 buildings have just 9% share. Age profile shows that Italy stock accommodates mostly historic office buildings.

Buildings up to 1945 was typically constructed with masonry. Afterwards reinforced and frame structure were participated to the office designs. Reinforced concrete commanded many of the structures in period between 1965 and 1980. Cavity walls and prefabricated panels were main components. Curtain wall facades dominated after 1990s.

Germany

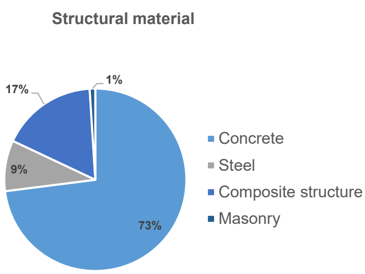


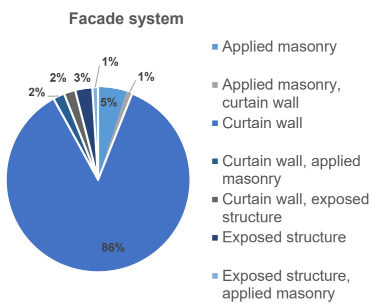


Graph 1.10; Distribution of structure type in office buildings in Germany. Elaboration of the author.

Graph 1.11; Distribution of facade system in office buildings in Germany. Elaboration of the author.

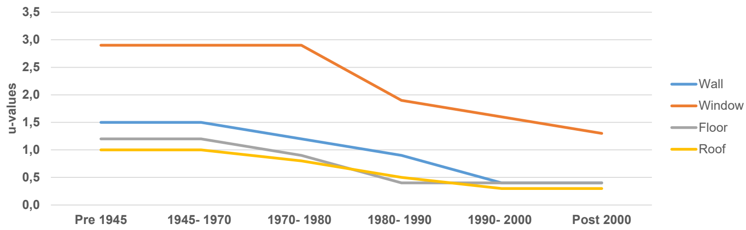
France



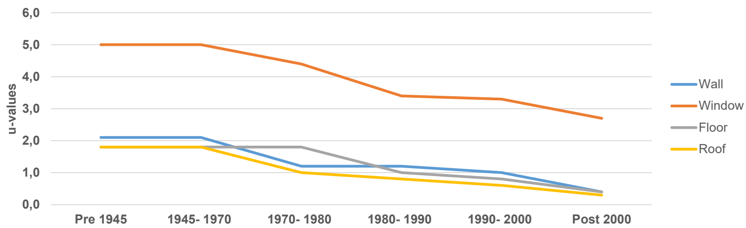


Graph 1.12; Distribution of structure type in office buildings in France. Elaboration of the author.

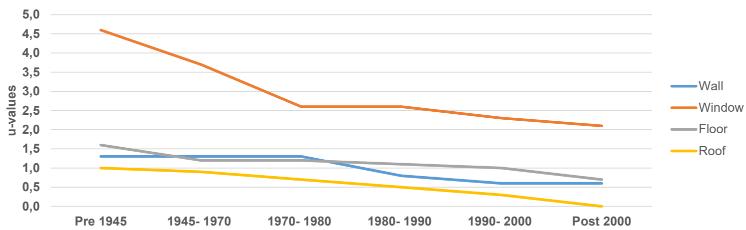
Graph 1.13; Distribution of facade system in office buildings in France. Elaboration of the author.



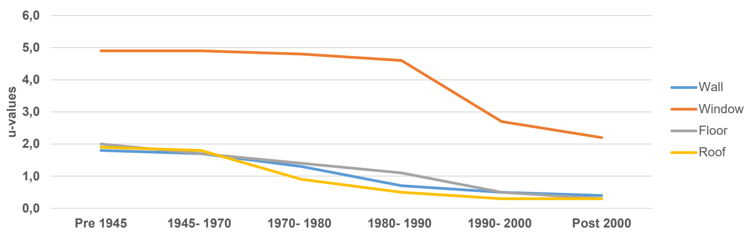
Graph 1.14; Change in U-values by age and building component of office buildings in Germany.
Elaboration of the author.



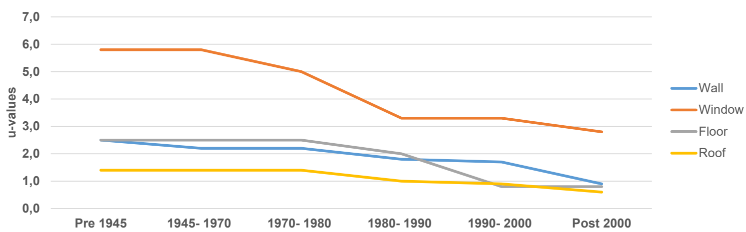
Graph 1.15; Change in U-values by age and building component of office buildings in France.
Elaboration of the author.



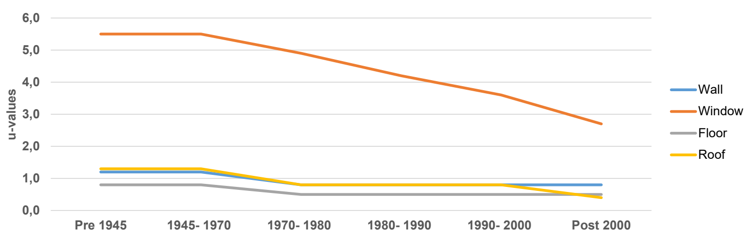
Graph 1.16; Change in U-values by age and building component of office buildings in Poland.
Elaboration of the author.



Graph 1.17; Change in U-values by age and building component of office buildings in UK.
Elaboration of the author.



Graph 1.18; Change in U-values by age and building component of office buildings in Spain.
Elaboration of the author.



Graph 1.19; Change in U-values by age and building component of office buildings in Italy.
Elaboration of the author.

Germany

Building Element	Pre 1945	1945-1970	1970-1980	1980-1990	1990-2000	Post 2000
Wall	1.5	1.5	1.2	0.9	0.4	0.4
Window	2.9	2.9	2.9	1.9	1.6	1.3
Floor	1.2	1.2	0.9	0.4	0.4	0.4
Roof	1.0	1.0	0.8	0.5	0.3	0.3

Table 1.6; Change in U-values by age and building component of office buildings in Germany.
Elaboration of the author.

France

Building Element	Pre 1945	1945-1970	1970-1980	1980-1990	1990-2000	Post 2000
Wall	2.1	2.1	1.2	1.2	1.0	0.4
Window	5.0	5.0	4.4	3.4	3.3	2.7
Floor	1.8	1.8	1.8	1.0	0.8	0.4
Roof	1.8	1.8	1.0	0.8	0.6	0.3

Table 1.7; Change in U-values by age and building component of office buildings in France.
Elaboration of the author.

Poland

Building Element	Pre 1945	1945-1970	1970-1980	1980-1990	1990-2000	Post 2000
Wall	1.3	1.3	1.3	0.8	0.6	0.6
Window	4.6	3.7	2.6	2.6	2.3	2.1
Floor	1.6	1.2	1.2	1.1	1.0	0.7
Roof	1.0	0.9	0.7	0.5	0.3	-

Table 1.8; Change in U-values by age and building component of office buildings in Poland.
Elaboration of the author.

United Kingdom

Building Element	Pre 1945	1945-1970	1970-1980	1980-1990	1990-2000	Post 2000
Wall	1.8	1.7	1.3	0.7	0.5	0.4
Window	4.9	4.9	4.8	4.6	2.7	2.2
Floor	2.0	1.7	1.4	1.1	0.5	0.3
Roof	1.9	1.8	0.9	0.5	0.3	0.3

Table 1.9; Change in U-values by age and building component of office buildings in UK.
Elaboration of the author.

Spain

Building Element	Pre 1945	1945-1970	1970-1980	1980-1990	1990-2000	Post 2000
Wall	2.5	2.2	2.2	1.8	1.7	0.9
Window	5.8	5.8	5.0	3.3	3.3	2.8
Floor	2.5	2.5	2.5	2.0	0.8	0.8
Roof	1.4	1.4	1.4	1.0	0.9	0.6

Table 1.10; Change in U-values by age and building component of office buildings in Spain.
Elaboration of the author.

Italy

Building Element	Pre 1945	1945-1970	1970-1980	1980-1990	1990-2000	Post 2000
Wall	1.2	1.2	0.8	0.8	0.8	0.8
Window	5.5	5.5	4.9	4.2	3.6	2.7
Floor	0.8	0.8	0.5	0.5	0.5	0.5
Roof	1.3	1.3	0.8	0.8	0.8	0.4

Table 1.11; Change in U-values by age and building component of office buildings in Italy.
Elaboration of the author.

1.4 | Most Common Facade; The Curtain Wall

Since the invention of skeleton-frame structure, most of the European office buildings have been completed with transparent skins. Comfort and flexibility on the facade design with frame structure competed conventional masonry structure during the time. Demolishing of load-bearing exterior enclosure created potential of transparency and thinner facades which could combine with glass.

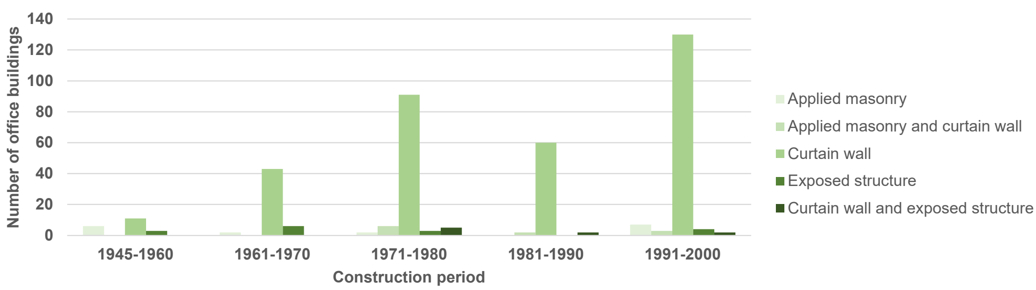
As a symbol of power and innovation in 20th century, countries that lead by USA have started to design higher and lighter facades. Office buildings have been the force signal that indicate the capability of the companies. Therefore, an unavoidable competition have arisen in international context.

Metal and glass curtain wall have been the best matched combination among the different material and component choices. This type of facade was counterpart of an office environment with visional outside relation and maximum daylight usage. As a result of historic pure transparency trend, many office buildings have been constructed with large glazed facades.

Generic status of the European building stock shows that the curtain wall became the most popular facade type for the office buildings category since 1950s. Ascent of the curtain wall facades continued rapidly until 1970s and then with the Oil Crisis in 1973 a sudden decline was analyzed over the new constructions. By 1970s, the facades in search of maximum glazed surfaces were designed without or with a few thermal insulations. This aspect have resulted in high energy costs for heating and cooling demands of the offices. After the Oil Crisis, due to thermal and acoustic concerns, improved performance and innovative designs can be seen in overall European offices, however nowadays the buildings that were constructed in poor thermal conditions require detailed retrofitting.

Throughout the study, building examples approved that the metal curtain walls constitute the widespread category in Europe. The graph below shows the facade trends of the office buildings among different decades in Europe.

Graph 1.20; Trend of facade structure in European office buildings. Elaboration of the author.



According to The American Architectural Manufacturers Association, following definition can be given for the metal curtain walls:

“Metal Curtain Wall – An exterior curtain wall which may consist entirely or principally of metal, or may be a combination of metal, glass and other surfacing materials.”

Six generic curtain wall assembly techniques have been investigated during the evaluation. Distinction among these systems are caused by component configurations and installation methods. The study defines all the six curtain wall assembly techniques. Nevertheless, the stick and the unitized systems cover the contemporary curtain wall facade practice. Other techniques such as panel system or column cover and spandrel system are composed by opaque materials with small glazed areas. These two mentioned systems are not located in the metal curtain wall classification. Pre-cast concrete, thin stone, terra cotta or custom designed cladding materials are the most common panelizing substances. Column cover and spandrel system has similarity to the stick system; however, configuration is ensured with opaque cladding materials for structural elements and spandrel or vision panels for in-between spaces. This system does not define a metal curtain wall facade.

Unit and mullion system is a hybrid system between the stick and the unitized systems. Even if this system takes part under the metal curtain wall class, its physical examples reach until 1970s. Unit and mullion system utilizes in advantages of the unitized system and for the installation it leans on the vertical metal components which are called as mullions. After 1980s, high performed unitized systems with interlocking joints have been introduced. Thus the necessity of the hybrid system diminished by time.

The categorization includes also the structural glazing system. This system sometimes even is not accepted as a curtain wall cladding. The system is constituted by the sealed glass units with the structural silicone and a supportive structure at the back side. In extensive definition, the metal curtain wall describes the metal framed facade system with vision or opaque infills. Even if primitive examples of the structural glazing system includes aluminum mullions, this kind of system doesn’t indicate a metal frame grid like the stick or the unitized systems. Most of the time trusses or cables stabilize the glazing system. While this system has advantage to create continuous glass surface, in terms of structural integrity and durability it is just reliable for the low-rise building designs.

The analysis about European office buildings demonstrated the curtain wall facade became pioneer around 1950s and afterwards. Demand of improved daylight into the building and visional connection with the outside was concluded on the transparent facade designs. Among six main curtain wall assembly techniques, the stick and the unitized systems have been the most applied systems in terms of response to architectural demands. Therefore focus of the study with design and retrofitting recommendations will be over the stick system and the unitized system.

Following table shows the classifacation of the curtain walls based on type, assembly technique and glazing method.

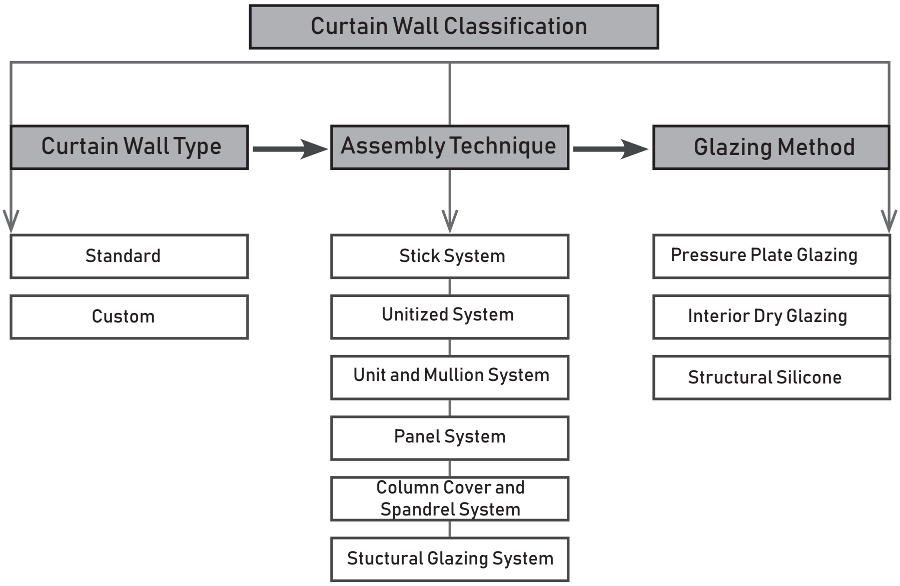


Table 1.12; Classification of the curtain wall by type, assembly technique and glazing method.
Elaboration of the author.

Table 1.13; Comparison of six generic curtain wall systems.
Elaboration of the author.

The reviewing of the six different assembly techniques of the curtain walls are examined like on the table. The comparison is accomplished into to two main aspects as design and durability. Among these systems, the stick, the unitized and the hybrid system of them, unit and mullion system contribute to metal curtain wall classification. While other three systems may be composed by metal components, they don't describe a required framework system on the metal curtain wall definition.

	Curtain Wall Features	Stick System	Unitized System	Unit and Mullion System	Panel System	C.Cover Spandrel System &Spandrel System	S.Glazing System
Design	Still Taking Part Actively on Designs	✓	✓		✓	✓	✓
	Metal Framed Structure	✓	✓	✓			
	Convenience to Large Glazing Surface	✓	✓	✓			✓
	Convenience to Large Opaque Surface	✓	✓	✓	✓	✓	
	Enhanced Daylight Intake	✓	✓	✓			✓
	Convenience to Pre-Fabricated Elements		✓	✓	✓		
Durability	Enhanced Thermal Insulation		✓	✓	✓	✓	
	Enhanced Acoustic Insulation		✓	✓	✓	✓	
	Convenience to High-Rise Designs		✓		✓		
	Joint Reliability(Sealant,Gasket)		✓		✓		

✓ Indicates the existence of the given feature for that system.

2.1 | Revolution of the Office Layouts

2.1.1 White Collar Factories of the Early 20th Century

The early 20th century had welcome enormous growth in the number of the offices in Europe. This revolutionary growth was caused thanks to concentration of enterprise and finance sectors. We can understand this by UK example about number of the office workers which was 0.8% of the working population in 1851 it became 7.2% in 1921. The techniques of mass-production had required more coordination and administration for creating large professional corporations. Increasing of the office work was a result of this professional corporations. At this century mentality of the office work started to change concretely comparing to preceding ages. Until the 20th century office workers were mostly men who were educated and had ability to read and write. Therefore office jobs had a prestige in the society. After 20th century, office work became widespread and became less prestigious. Also women had have more active role at the offices. Thus of all this reasons office work started to become more similar to factory work. Sociologists referred this as 'proletarianization' of the office work which indicates the social process whereby people move from being either an employer, unemployed or self-employed, to being employed as wage labor by an employer.' (www.definitions.net).

Figure 2.1;
Larkin Building,Buffalo

http://rubens.anu.edu.au/raid2/no_dgb/modern_architecture/modern_architecture.html

Changing of the office environment and the growth of the corporations effected to design of the office buildings. Before they have been more like residential buildings now they became 'white collar factories.' First commercial offices were built in the industrial cities of United States at the late 19th century. In the 1920s American engineer Frederick Taylor gave way to new office organization for hosting many workers who use new technologies like the typewriters, calculating machines and telephones. This kind of factory-like offices with many workers and technologies required large open floor spaces. Tayloristic office ideology was the organization with the orthogonal arrangement of the desks which were all facing towards supervisor. Clerical staff was no more separated from each other by partitioned spaces. Larkin Building in Buffalo was designed by Frank Lloyd Wright was the iconic example of Tayloristic open plan. It was the office building of Larkin Soap Company for the mail order business. The building hosted over 1000 women workers for handling paper works. The preliminary form of the air-conditioning systems and skylights were located at building for interior comfort. Thanks to the huge success of this kind of organization for 'new office buildings' it influenced European offices after America. But Taylor's ideology about office planning were too modern for European offices in that time. European business culture was more traditional and less rationalized when comparing with America. Besides this, European office market was less developed and professional. Therefore, Tayloristic open-planed office buildings spreaded some decades after America. Headquarters building of Thule, a Swedish insurance company, was a good example of this ideology in Europe. It was designed with the base of Taylor's ideas with more standardized workplaces and classroom-like layouts which were located on the both sides of central corridor.

2.1.2 Pure Glass Boxes of the 1950s

After the Second World War, the office work grew due to economic expansion of the European countries. Especially Western Europe covered post-war ruins and raised up the wealth. Pioneer of this spectacular economic emerge was Germany, Italy and Sweden. This success brought new constructional technologies and new approaches in the sense of architecture. America was again the country to emulate. Because America had already set up a tradition of high-rise buildings starting from the 1920s. Iconic buildings like Chrysler Building and Empire State Building were early examples of high-rise buildings in America. With the innovations in construction field after 1950s, brought new ideas about high-rise building culture. A rectangular high-rise office block with glazed facades which was called as 'The glass box' was accepted for the new typical form of the office buildings. This kind of facade exhibited 'modernist' and 'light' characteristic. Thanks to that features the glass boxes became the most copied style of the office buildings all around the world for next fifty years. Besides the facade also the interior organizations changed due to new technologies. Introduction of the air-conditioning and fluorescent lighting caused changing of the floor depth which was before

Figure 2.2;
Pirelli Tower, Milan

https://www.venividivici.us/design/gio-ponti-artista-eclettico/

limited by the need of daylight and natural air-ventilation. Now it was possible to create office buildings with deep corridors and open-plan organizations which had the universal space characteristic. Moreover the universal space value of the buildings, it was economic, easy to divide and it didn't let the creation of awkward corners.

In Europe, the modern glass boxes of America were adapted easily. However European glass boxes were created in the smaller scale than American ones. Main reason of this difference was urban settings in European cities were more historical and complex. Besides, European countries had limits and regulations for the building height for preserving the historical characteristic of the cities. For example in Berlin, the height of the building was related to street width but the maximum height could be 22 meters.

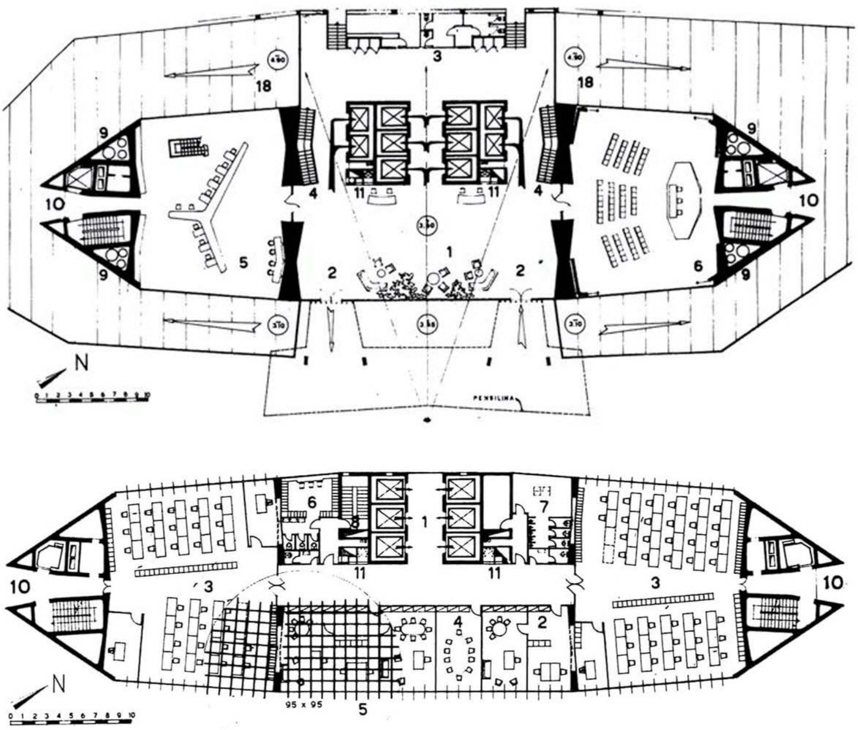


Figure 2.3;
Plan of Pirelli Tower in Milan

https://www.venividivici.us/design/gio-ponti-artista-eclettico/

Except the building height, the scale of the floor plans were also smaller than American buildings. For example the depth of the floor was 18.5 m in Pirelli Building (Milan), which was about in 3 times smaller scale than Union Carbide Building (America). Deeper plans could be applied in the sense of artificial lighting and air-conditioning systems which were already available in European market. But this difference came from the different business cultures between America and Europe. Still, American open-plans didn't match with European culture. Apart from this, European architects were not so interested at the interior layout of the buildings. They investigated American high-rise buildings mostly about the facade systems

and technical properties. They studied the thickness of the skin and dimensions of the window module. European architects strongly tried to find on office buildings which kind of window module could be most efficient and flexible one for creating different size of the rooms. Architectural Design, a British magazine, wrote in 1958: 'In planning an office the first consideration is the module to be adopted.' In Europe of 1950s, the office building concept totally focused on the building skin and its application with new kind of technologies. After the Second World War, it was time for countries to reflecting the power of large corporations. Despite being understood lately problems about heating and cooling, number of fully glazed facades increased as a phenomenon. Since this kind of facade was modernist according to architectural authorities due to its continuous and light appearance.
The Pirelli Tower in Milan was an excellent example of this concept. It represented impressive facade for showing the force of the country in that time. Interior space was divided into two with a central corridor. The based on 95 cm window module, office space was divided into cells.

2.1.3 Office Landscapes of the 1960s

In 1960s Europe achieved the chief position after the domination of America for the office design. A German consultancy group had radical ideas about the new office concept. They believed that conventional office buildings were not suitable for the modern office work needs. This group developed a new office concept based on the human relations like the American concept that was born few decades ago. The flow of the information was no longer vertical, but it was along the functional lines. It ignored the hierarchical and departmental limits. Another idea additionally to this was needing of rapid organizational changes at the office spaces. Buildings had to be able to flexibility without disconnection of the on-going work activities. Last idea about the new office concept was related to information technologies. In that time large frame computers started to take place at the office environment. This new technological devices effected to design of interior layout of the office buildings.

Figure 2.4; Bertelsmann Building reached to success in "office landscape" concept

https://culturalpolicy.princeton.edu/sites/culturalpolicy/files/wp39-hookway.pdf

Communication, flexibility and new technologies were main focus on the design of new office buildings. German consultancy group called this concept as Bürolandschaft that means 'office landscape'. According to this concept the information and communication had to go on freely without limited by the separations, walls or any other dividing elements. It supported the relations of the employees who had hierarchically different positions. This concept had an ability to uniting entire employee classes in one space. There were no rooms, no private offices. All equipment of the interior part such as desks, cabinets and others were located without a strict interior layout. The office space was large and open thanks to air-conditioning systems. It was inspired by American office organizations that promoted the deep floors. The workplace organization was the result of a deep study of communication lines between the different groups of staff.

The very first example of the office landscape was a study project for a German publishing house Bertelsmann. At the beginning a trial project was developed for 270 employees. The building had basic rectangular open floor plan. All the office equipment was chosen from lightweight furniture which was suitable to remove. For the sense of controlling the noise, there were wall to wall carpets, acoustical surfaces and ceiling insulations. When study project performed well, the company decided to build a real office building for 2000 employees.

After the project finished, the office landscape concept seemed very successful and became fashionable across Europe. Now European society was more open and tolerant to the progressive ideas about the office design. For the all parties like architects, business community and users of the offices this concept reacted eagerly. Architects were enthusiastic because this concept represented totally different solution from the others. Business community was charmed by the economic conditions of the concept. It was cost-efficient, easy to organize and reformer. Also for the part of the users it was perceived as a good working space with its facilities inside.
Out of Germany, first large-scale project was constructed in Sweden for Volvo headquarters. The group of representatives from Volvo Company had many study trips to the other office landscape buildings in Europe. Based on this studies they designed the headquarters building. Although it was outcome of long and profound studies about communication in work environment project didn't work as had been expected later.

2.1.4 Experimental Office of the 1970s

After the oil-crisis in 1973, the office landscape lost its popularity all over Europe. Main reason for this fade was the costs of heating and lighting of the buildings. The optimism about the technological developments and economic progress that had been seen at the previous two decades started to be questioning.
In a certain point, UK and Continental Europe began to split in the sense of office design ideas. Both UK and Continental European architects started to find new solutions for the new office type.

In Continental Europe, according to the surveys that was seen the employees of the office landscape were not satisfied at the end. The primary dislike was caused by unpleasant temperature changes, low humidity, high noise level, lack of natural lighting and ventilation and lack of visual contact with the outside. Additionally to this practical problems, European office culture was not still open like it was supposed. Professor Carl Christiansson, who had been one of the protagonists of the office landscape in Sweden, said: ‘I reached the conclusion that there was no functioning culture on which to build here in Sweden. We were not accustomed to so much openness and tight contact’.(The European Office BUİLDİNG)

New identical office designs were mostly driven by requirements of the employees. In 1970s, employees became more decision-maker about the organizations of the offices due to laws and regulations about their rights. Some countries had regulations about the space per each employee and sturdy connection with the outside view and daylight. This regulations triggered the employees to be stand against the office landscape.

After the studies about better working environment for users, cellular office took place on the stage. Sweden was head of this radical reaction about office design. Project of IBM Headquarters Building in Stockholm started in 1970 for creating a large office landscape. However, oil-crisis made them stop the plans. In 1974, after few years later the first planning, the committee had a radical shift in thinking about the office design. They recommended to build a new type of office building with cellular style of offices. It was designed with individual rooms for all employees that had practical common for controlling the climate, daylight and outside view. For the other Northern European countries cellular offices and standards for increasing the space were seen.

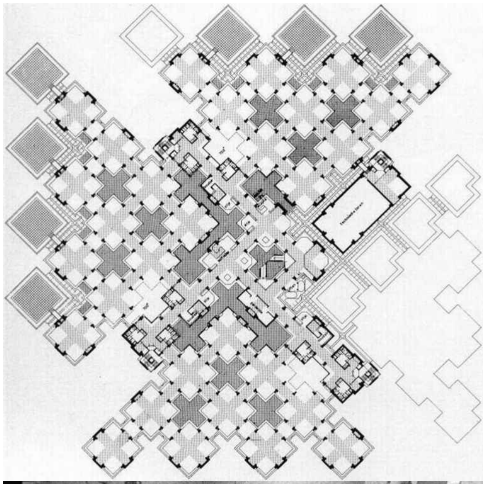


Figure 2.5;
Plan of the Centraal Beheer, Netherlands

https://wharferj.wordpress.com/tag/centraal-beheer/

Figure 2.6;
Centraal Beheer in Netherlands as a “cellular office”

https://wharferj.wordpress.com/tag/centraal-beheer/

On the other hand not all the architects and clients had wiling to turn back conventional type office buildings. One of the example of this contrary idea and design was Centraal Beheer Building in Netherlands (1972). About the design process human scale was the key factor. The employees must had feel of being part of the company and they should had not lost in the working community. In this project architect Herman Hertzberger transformed office space into a small village. Little office units for 8-10 people were arranged and all units were connected to each other by raised walkways, atrium and common spaces. Additionally he offered the idea of finishing building by employees. They could bring their furnitures from their homes and add decorative elements to the office space for feeling part of it.

Another experimental office project was designed a couple of years after in Sweden. Canon Swedish Headquarters was built in 1978. It represented hybrid solution between open and cellular offices. Therefore this concept was called as 'combi-offices'. The cellular offices were located on the edges of the building with transparent partitions. This divided small rooms obtained serenity and private working environment for the employees. In the middle of the layout open space was organized which included common facilities like photocopy machines and archives. The open space had to promote interaction of the employees.

In the UK, the office landscape never really worked at British offices. British office culture was more hierarchical and rigid than the rest of the Europe. At the end of the 1970s, after some examples of the office landscape in UK, it was clear that the office landscape is not suitable for them. The employees were complainted about same reasons like Continental Europe but also there was another point that comes from the British office culture. Senior staff was unpleasant to loss of their privacy in visually and acoustically.

Therefore British architects started to new experiments about office design. In UK, employees had no rights to make decisions about their working environment. There was not many regulations about employees' office environment like Continental Europe. Besides, British market was dominated by the developers. In UK, less

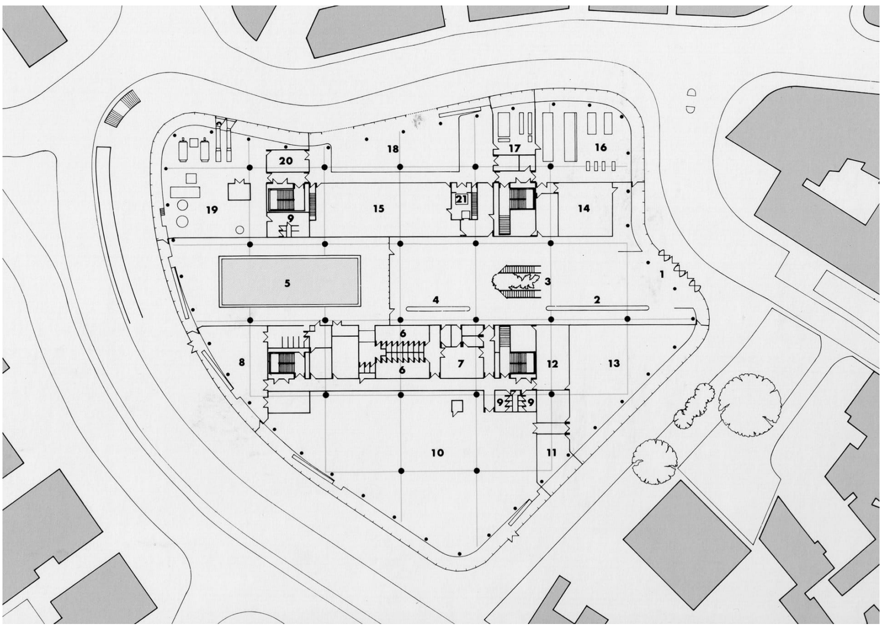


Figure 2.7;
Willis Faber&Dumas Building, Ipswich

https://www.fosterandpartners.com/projects/willis-building/

than one-fifth of the office space was occupied by owner. It meant owners had less opportunity to contribute the office design. All these reasons created main segregation between the UK and Continental Europe.

In that time British offices became like 1920s open-plan office but just being as more sophisticated. It was began to produce combi-offices like other part of Europe. A good example of this kind of plan in UK was Willis Faber & Dumas Building (1975) by Norman Foster. It had very rigid and orthogonal arrangement with controlled and clean working environment.

2.1.5 Electronic Era Offices of the 1980s

After the oil-crisis, economic growth appeared again in Europe. Now it was time of large corporations to manifest their power by fascinated buildings. In 1980s office design was influenced by addition of computers to the working spaces. Personal computers came to the employees' desks instead of paper work like before. The computers brought data cabling and extra cooling loads to the buildings. They had to be considered now at the modern offices of 1980s. In this time HVAC (Heating, Ventilation, Air Conditioning) systems was supplied for by computers. Buildings that had this systems was called as 'intelligent' or 'smart' buildings.

The new problems because of the computer was same all around the Europe. However, this new technological development didn't unify the UK and Continental Europe. They went on the different ways for searching of the office design.

In UK, London was the financial capital of the Europe.

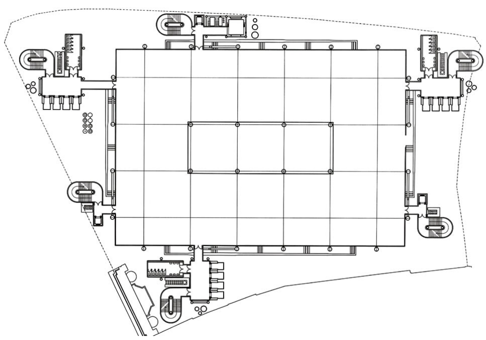


Figure 2.8;
Plan of the Llyod's of London

https://www.lloyds.com/about-lloyds/uk-building-services/the-lloyds-building

Figure 2.9;
The Llyod's of London exposes all the secondary function at the outside

https://www.lloyds.com/about-lloyds/uk-building-services/the-lloyds-building

Therefore information technology drove the business conditions. Office buildings were designed suitably according to demands of computerized trade. The floors had to be air-conditioned and large for accommodate the capacity of infrastructure.

The development boom was enormous in London. City was under a rapid transformation. Thanks to this, American developers and architects were attracted

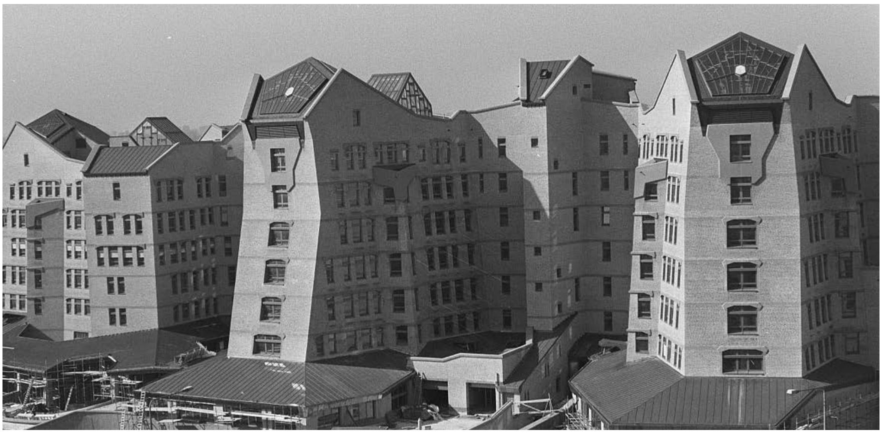


Figure 2.10;
NMB Headquarters, Amsterdam

https://nl.wikipedia.org/wiki/Hoofdkantoor_ING#/media/Bestand:NL-

by UK. That's why they started to work in there for the modern office space. As an example, One Canada Square Tower İn London (1991) was designed totally by Americans. It was full-size copy of the Manhattan Skyscraper. It achieved to being tallest building in Europe for that time. In the layout it had central core with large uncomplicated slabs.

Another example of this concept was Lloyd of London that was designed by Richard Rogers. All the secondary functions like stairs, toilets, lifts were located at the outside during the perimeter of the building. This kind of organization gave a high-tech appearance to the building. The large central atrium supported to taking daylight into deep of the building. Suspended ceilings with cabling and services caused to raising of floor heights. With all this features building represented how information technology affected to the architecture.

Contrary to UK, in Continental Europe didn't decide to design at the base of information technologies. The concept of cellular office from 1970s continued its existence about the office designs. Architects focused on the human factor in the sense of privacy, daylight, climate control, natural air-ventilation and connection with the outside view. The idea of contact with the nature became a phenomenon. Thus at the layout, workplaces were located next to the windows so cables could run all around the perimeters. Air-conditioning took place at the buildings but raised floors like in UK was not necessary for cabling. Colonia Building in Germany (1984), the NMB Building in Netherlands (1987) and the SAS Building in Sweden (1988) were examples of the office buildings which had primary focus on user comfort. These buildings were designed as small cities. In the plan they were formed from separated houses that were united by internal streets and squares. These atriums had function for socializing more than taking daylight to inside.

2.1.6 Virtual Offices of the 1990s

In the early 1990s, number of constructions of new buildings slowed down relatedly with the economic conditions. The improvements about information technology carried on its effect on the office building's design. Furthermore with the new hardwares and softwares like mobile phones, laptops, internet browsers, e-mails working people became more free of place and time. Business culture oriented to virtuality. These advancements on the technology broke the limits for working space. Now office staff could work in cafes, home or any other place out of the physical office building. One more time about the new office design variated ideas was shown between the UK and Continental Europe.

In the UK, open plan organizations kept on going for the office buildings. Alternative applications of desk sharing aspect got started to use. Stockley Park was a good example of this subject. The building was constructed by Foster and Partners for British Telecom and it represented a sample of 'business park' concept. Layout included both private and common spaces for the staff. The connections of audio, data and video were supplied by flexible infrastructure.

During 1980s the Sick Building Syndrome appeared at the office environments which was a dissatisfaction of employees' from the offices without outside view and daylight. Thus design developers took consideration to reach more humanistic and user friendly working environments. That's why in 1990s buildings started to design with not profound plans and operable windows.

In Continental Europe, the situation was same in terms of creating more interactive office spaces which encourages the teamwork instead of cellular-styles. Open work areas were increased and shallower plans were designed. In this time in different styles alternative new office space was searched. For example in Germany and Netherlands, Swedish style combi-offices became popular. In Finland, in the office of a cleaning company 75 employees shared 26 workstations.

2.2 | Representation of the Facade

Figure 2.11;
Facade of Holland Park School, London

https://www.archdaily.com/325611/holland-park-school-

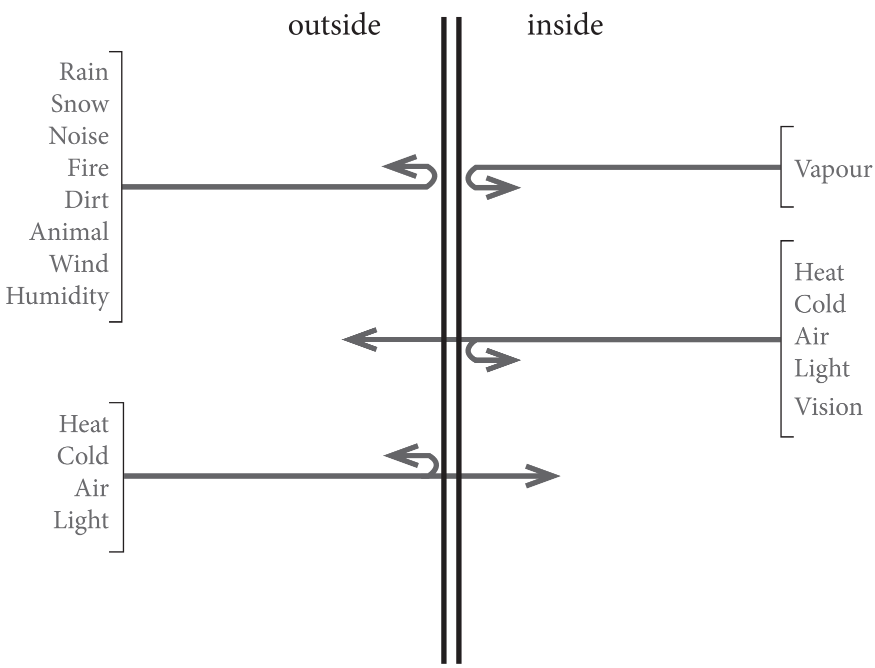
The facade is the meeting place of the interior and the exterior of architectural space and, at the same time, it is also the meeting place of architecture and the city. (1) For the mankind starting from the ancient times, building facade has a fundamental and crucial function which can be identified as a protection from weather conditions (rain, wind etc.) and providing the interior climate control. Except from that fundamental functions facades get responsible to expressing the buildings itswelf to the urban context. It can clearly understandable from the origin of the word "facade". The term "facade" is derived in Latin lades, in Italian faccia which means "face". Philosopher F.Nietzsche mentions this architectural phenomenon in his writing Aphorism 291 as "houses look at us like faces". The idea of having face of the buildings is quite realistic and natural for perceiving the architectural form which surrounds the interior void and the street fronts with their faces describes the exterior void. The facade defines both spatial spheres. The facade is the product of integration between the inner and the outer spaces. It gives a scale to the entire space all around it. The urban space is formed thanks to the space-defining power of the building surfaces. The urban space is a yield of contiguous architectural surfaces. That bounding surfaces give their volumetric transposition, form and specific atmosphere to the streets and squares which are components of the urban space. This physical bounding shows the transformation of the external void from abstract space to the concrete space. By this way it is created unique and unforgettable spaces which can be experienced by the senses and at the same time it defines the identity of the city. The facade creates first image about the building when it is seen from the outer side. It is a transmission between the interior and exterior. The building surface doesn't exist just physically, but exists also psychologically. Because in a basic determination "the walls" define the psychological boundary between the private and public, inside and outside.

As a transition between inside and outside – between the building and the urban space- the building skin plays an especially important role. First and foremost it provides protection from the elements, demarcates private property and creates privacy. But its aesthetic and cultural function is just as important. The building skin and especially the facade is the calling card of a building and its designer. Set into context, it characterizes the face of a city. No wonder that it draws more attention than any other building component.

The ideas established by modernism stipulate that the external appearance of a building should reflect its internal life. Harmony should reign between form and function, inside and outside. Recently, this demand has been questioned with growing intensity.
According to Quiroutte, in order to achieve mentioned concerns, the building enclosure must meet with following properties;

Control of air flow
Control of heat flow
Control over the entry of rain and snow
Control of sunlight and other forms of radiant energy
Control of water vapour diffusion
Accommodation of building movements

In adddition to these factors can be as control of noise and fire. The figure below shows the inside and outside concepts of the building enclousre.

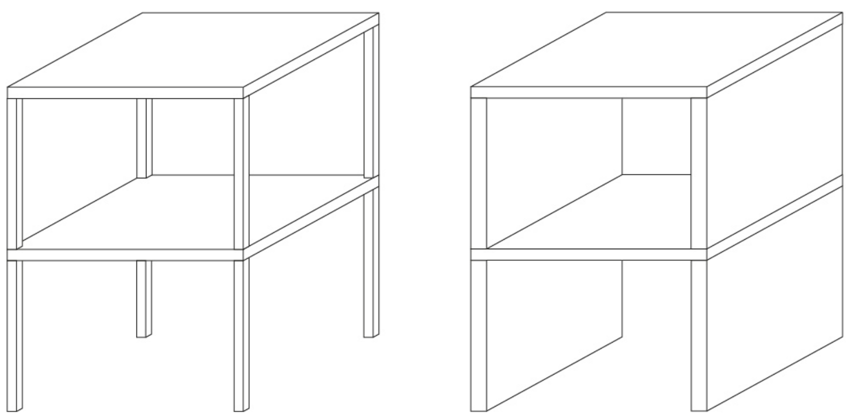


Drawing 2.1; The building facade as a selective filter. Elaboration of the author.

3.1 Evolution of the Curtain Wall

The curtain wall can be defined as a non load-bearing exterior enclosure of the building. In another way of definition, it doesn’t carry any other weight of the structure but just the weight of itself. The curtain wall hangs from a structure like original curtain and attaches the building structure. It has many different assembly techniques and also various appearances thanks to material variations. Typically, curtain walls consist of a framework system which can be fulfilled with other materials like glass, stone etc.

Initial curtain wall trials were shown in America at the late 19th century. After the invention of skeleton-frame structure which is a construction system of columns and beams with concrete, steel or iron material, it obliged architects to rethink about the facade of this kind of building style. Before, enclosure of the building was formed by masonry elements which were supportive. Now, frame-structure allowed the design more freely about the structure of the building facade that could become apart from the main structure.



Drawing 3.1;
Diagramatic drawing of frame structrue and conventional masonry structure.
Elaboration of the author.

In 19th century Chicago had a building boom and architects and constructers were trying to achieve taller building heights. In that period, starting to use of elevators at the constructions provided ease of reaching higher. On the other hand with masonry walls it was hard to go taller height. Because masonry load-bearing walls had to be ticker at the bottom when the building height gets higher. This condition forced them to build with frame-structure and its corollary curtain wall. In this term Reliance Building in Chicago was a milestone for its architectural technology according to Chicago School. Fifteen story office building represented radical reinterpretation of the building facade. Curtain wall facade characterized by large glass arrangements with narrow operable windows. Surrounding of the glass was covered by white-glazed terra-cotta cladding. It articulated delicate Gothic based ornaments. Combination of its steel columns that were masked by the exterior cladding and with delicate white cladding and glass walls, building showed a new dialogue between the structure and the skin of the building.

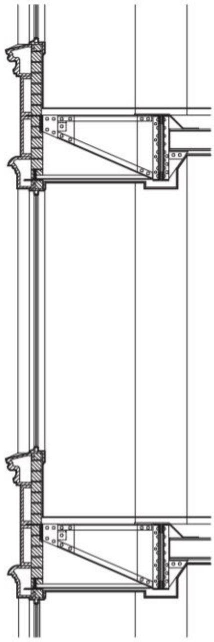


Figure 3.1;
Facade of Reliance Building, Chicago 1895

"Contemporary Curtain Wall Architecture", Murray, 20019

Figure 3.2;
Exterior wall section of Reliance Building

"Contemporary Curtain Wall Architecture", Murray, 20019

At 20th century, the integration of frame-structure and curtain wall facade became very popular also in Europe after the US. Architects started to question of standard coplanar positions of the building structure and its skin. With the erosion of load-bearing walls, it was possible to open larger windows between structural elements. It clearly provided more daylight, ventilation and outside view. In the first two decades of 20th century, architects seeked for a separation of the glass membrane from the structural frame by changing the individual windows to continuous glass wall. Fagus Shoe-Last Factory was a good example of this approach. Building was designed by Walter Gropius at 1911. Brick-faced concrete columns with plane glass curtain obtained the building facade. The curtain wall was located in-between the structural columns of the building. Three-story height assiduous facade system cover the enclosure. Regard to floor slabs, configuration of the transparent and the spandrel infills were integrated to the curtain wall frame. Diminishing of the column at the building corner, provided continuity on the glass surface of two sides.

Figure 3.3;
Fagus Shoe-Last Factory, designed by Alfed an der Leine, 1911

https://www.architecture.com/image-library/RIBApix/image-information/poster/fagus-factory-alfeld-an-der-leine-lower-saxony/posterid/RIBA24085.html

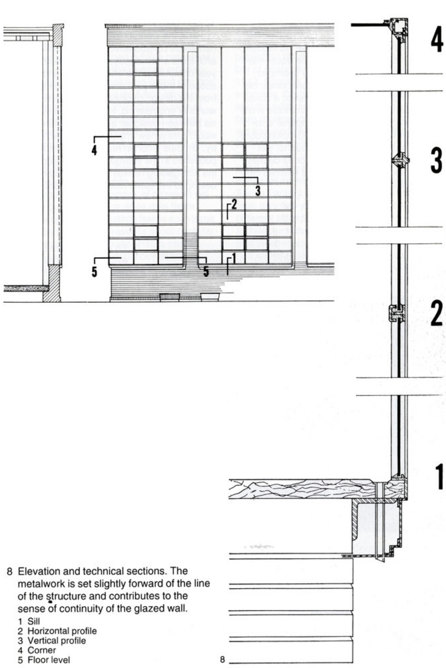


Figure 3.4;
Technical Wall Section of the Fagus Shoe-Last Factory

https://www.archdaily.com/612249/ad-classics-fagus-factory-walter-gropius-adolf-meyer

At the same period in America, also it was tried to create pure curtain wall concept on the building facade. Revolutionary Hallidie Building in San Francisco (1918), was the first large scale urban building with its all glass curtain wall facade. Seven story continuous wall consisted of its subdivided glass panels and wall was suspended 0.9 m in front of the column line. The glass wall was fixed with thin steel mullions with occasional pivoting windows for ventilation. The structural system was organized by reinforced-concrete frame. At the edge of each floor slab, a perimeter beam supports the non-wide secondary slab which was located between the curtain wall and the building structure. Thanks to this feature it acted like fire-breaker between the floors. The curtain wall was completed with iron ornaments at the cornices and fire escapes. Like its European quasi Fagus Shoe-Last Factory, in Architectural Record publishing understated its practical features about taking daylight in and increasing floor space comparing with masonry walls with this sentence; “possesses more than ordinary interests to architects”.

Bauhaus Building (1926) that was designed by Gropius and Meyer was called by Reyner Banham as “The first really big masterpiece of the modern movement” due to building’s pure and fascinating skin. Bauhaus Complex included three different wings of the buildings with the functions of dormitory, classroom and workshop. Each wings’ facade were designed according to their interior functions and needs. The dormitory had individual punched windows and balconies, the classrooms had strip windows and workshop sections had continuous glass curtain wall which hung to reinforced-concrete structure all along the building height. Bauhaus Building obviously was designed over the Gropius’ earlier building Fagus shoe-Last Company Factory with some rectifications such as using entirely vision glass on the curtain wall instead of spandrel glass. Besides, in here the building structure was set at the back completely.

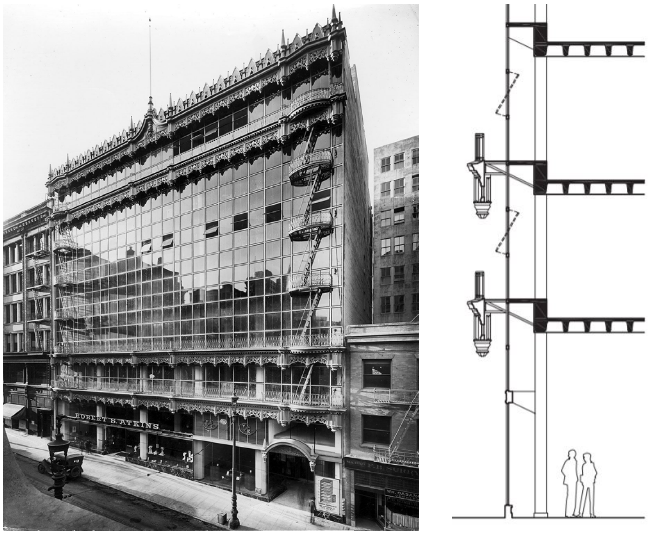


Figure 3.5;
Hallidie Building, San Francisco, 1918

https://www.architecture.com/image-library/RIBApix/image-information/poster/hallidie-building-san-fransico/posterid/RIBA3160-42.htmlimage-information/poster/hallidie-building-san-fransico/posterid/RIBA3160-42.html

Figure 3.6;
Bauhaus Building, Dessau, 1926

https://trydesignlab.com/blog/bauhaus-school-five-lessons-for-todays-designers/

Steel mullions, pulley-operated vents and repetition of units composed the curtain wall system which was a manifestation of Gropius' new architecture concept with its rationalized, machine production character.

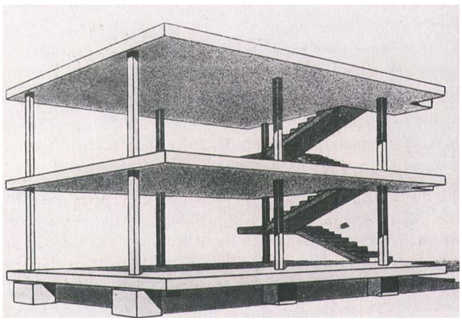
In spite of having negative technical features like insufficient acoustic insulation or single-pane glass, curtain walls became the icon of modern movement and machine age. It was the response of architecture to the frame structure's potential to originate the building skin with the dialogue of interior space. At the beginning it was revealed by experimental sprit of seeking for possibilities and evolved by various ideas about new construction techniques, materials, efficiency and expressive way of glass.
After the invention of the curtain wall, the interest centered on the transparency in the architecture world thereby glass became the primary element of the new building skin. At the early 20th century, this brought two developing trajectories as theories of glass architecture and technologies of glass production. Berlin based poet and novelist Paul Scheerbart in his book Glasarchitektur describes an imagined future that glass dominates the architecture and this glass architecture would impact society as this;

We live for the most part in the closed rooms. These form the environment from which our culture grows. Our culture is to a certain extent the product of our architecture. If we want our culture to rise to a higher level, we are obliged, for better or for worse, to change our architecture…We can only do that by introducing glass architecture, which lets in the light of the sun, the moon and the stars, not merely through a few windows., but through every possible wall, which will be made entirely of glass-of colored glass. The new environment, which we thus create, must bring us a new culture.

In this period, modern architecture meant the concept of transparency which would have liberating effect and it could lead to improved modes of cultural expressions. In Europe especially Mies van der Rohe, Walter Gropius, Bruno Taut led a design movement based on this concept with designing and thinking over it.

Figure 3.7;
Maison Domino,
Theoretical Drawing by
Le Corbusier, 1914

"Contemporary Curtain Wall Architecture", Murray, 20019



In 1914 Le Corbusier developed a proposal, Maison Domino, in France for economical mass-production housing unit which could be arranged in rows like dominos. He envisioned a solution for the reconstruction process after World War I. The two-story building was designed with reinforced concrete columns with cantilevered floor slabs but without any enclosure. This provocative drawing represented both free plan and free facade ideas. Thus architects were pushed to think about transparency concept and questioning about the exterior wall which could become everything now.

Although they are unbuilt, Mies van der Rohe designed two skyscrapers project both in Berlin after a few years Maison Domino effect. His projects were remarkable for their frame structure and its corollary all-curtain wall facades. Both the projects were astonishing in terms of using floor to floor transparent enclosure for such a tall buildings. He explained relationship of skin to structure by his words;

Instead of trying to solve new problems with old forms, we should develop the new forms from the very nature of the new problems. We can see the new structural principles most clearly when we use glass in place of the outer walls, which is feasible today since in a skeleton building these outer walls do not actually carry weight. The use of glass imposes new solutions.

Apart from the theories about glass architecture, Scheerbart also concerned about the glass a material. He recognized glass architecture would suitable only in certain climates but not in tropical or polar regions. Besides the climate there were other factors such as energy and industrial production for succession of the new glass architecture. At that time unfortunately glass industry was not capable to find solutions to problems that was concerned. Thanks to inventions and new manufacturing techniques in glass industry it was started to produce glasses behalf of architecture such as drawn glass, tempered glass or double-pane insulating glass unit.

In the early 20th century, most of the time transparency concept was perceived as a necessity of modern architecture. The advantages in enhance daylight intake and inside-outside relation between the two sides of the glass, carried out it as a rapid spreading on the construction industry. It was symbolized as milestone of the new open society.

The magical disappearance of the outside wall that Korn described in 1929 certainly captures the spirit of the era but would prove, in reality, to be a myth. Further development and dissemination of the glass curtain wall in the mid-20th century would require more not less attention to the tectonics of materials and their assembly. (Murray, 2009)

When it was arrived to mid-20th century the term of "glass box" became popular from 1940s to 1960s in diverse of buildings around the world. This term describes an architecture characterized by basic volumetric form which consists of frame structure and covered by glass curtain walls. In 1950s most significant examples of glass box architecture was seen in three different office buildings that were United Nations Secretariat, Lever House, Seagram Building in New York City.

Figure 3.8;
United Nations Secretariat, 1950

http://www.skyscrapercenter.com/building/united-nations-secretariat-building/3737

Figure 3.9;
Lever House, 1952

https://www.shorpy.com/node/21392

Figure 3.10;
Seagram Building, 1958

https://www.archdaily.com/59412/ad-classics-seagram-building-mies-van-der-rohe

Design team of UN Secretariat (1950) included international architects like Le Corbusier and Oscar Niemeyer. The building was located in east-west orientation parallel to the East River with its long axis. Structure of the building completed by steel-framed and the skin of long elevations were composed by glass curtain walls. Contrarily, north-south elevations were enclosure by marble without any windows. The structure of the curtain wall included aluminum mullions in 1.2 meters horizontal spanning and vertical floor to floor spanning. It was filled with double hung aluminum windows and blue-green-tinted, heat-absorbing glass spandrels. Also wired glass was used for covering the low masonry wall which was painted in outer surface. During the design process Le Corbusier defended the idea of brise-soleil for the sun protection of the building. He wrote this letter to UN Headquarters Committee; My strong belief is that it is senseless to build in New York, where the climate is terrible in summer, large areas of glass which are not equipped with a

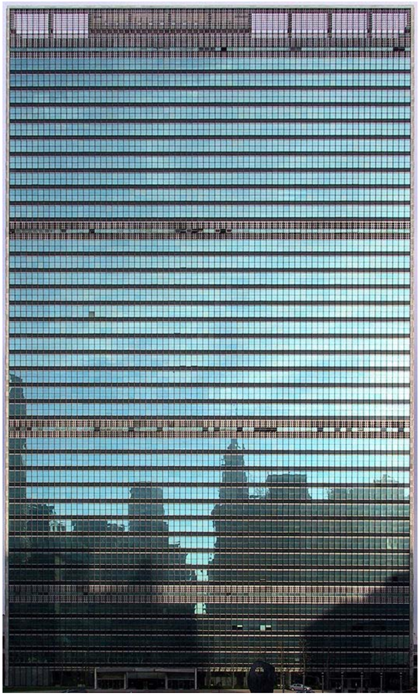


Figure 3.11;
United Nations Secretariat was one of the first examples in "Glass Box" concept

http://www.skyscrapercenter.com/building/united-nations-secretariat-building/3737

'brise-soleil'. I say this is dangerous, very seriously dangerous.(p.31) Committee didn't make attention to his warning due to additional cost of exterior sunshades and future maintenance problems. After the finalizing of the building according to authorities it achieved great success in terms of aesthetic. Thanks to its dark colored glass facades it acted like a gorgeous mirror in the urban context. On the other hand Le Corbusier was right in his concerns about sun shading. Building received excessive solar heat gain during the summer and it forced users to kept interior blinds totally drawn in the day time. Eventhough its problem about shading UN Secretariat represented a major development in the curtain wall for its period.

Another building of that era was Lever House (1952) that was designed by SOM as 21-story, steel-framed. It had similar curtain wall style to UN Secretariat which was completed by blue-green-tinted, heat-absorbing continuous glass and wire glass for masking the masonry part for fire safety. The primary glass was single pane with its heat absorbing feature for blocking the 45 percent of the sun's heat and transparent vision glass constituted 50 percent of the wall. The building was designed with any operable windows for using entirely air-conditioning system and glasses were fixed in place. Fixed glass obtained 30 percent less cost for the final cost of the building. Lever House was the first building that had corner to corner uninterrupted glass membrane. This ensured no employee was far to windows. Lever House also had innovative window washing system. The motor-driven system was located on the top of the building and it carried workmen who were suspended from a crane. This was first attempt for maintaining the glass curtain wall until that time.

Seagram Building joined to Park Avenue in 1958. 39-story, steel-framed building designed by Mies van der Rohe. It brought new breathe to the site with its public square and warmer colored skin. It was characterized by bronze-tinted glass and bronze spandrels with exterior mullions in contrary to Lever House and UN Secretariat. The glass panels were organized floor to ceiling and they were supported by I- shaped mullions which extended floor to floor. According to some authorities this kind of use of mullions gave machine-like appearance and depth to the facade but no technological advantages.

Certainly the commercial buildings were the curtain wall's most seen form at the mid-20th century. But also institutional, educational and residential buildings participated to exposing for evolution of the curtain wall history.

1950s curtain wall designs were influential for architecture and construction industry. SOM, Mies and some other designers pioneered the industry with their prototypical curtain wall systems which could be manufactured with ease and repeated in variations.

Main architectural critics were towards about the architects and constructers who apply the curtain wall without any sense of imagine which is contrary to main idea of curtain wall itself as a construction method. In the following years, also architects engaged with the prevalent critics and they enforced to discover more beyond the high modernism with new solutions. Unfortunately, new vocabularies that were added for the mid-20th century curtain wall soon would become very problematic due to environmental incompetence.

Figure 3.12;
Facade detail of Seagram Building in New York

http://ced.berkeley.edu/downloads/academic/arch_thesis_2014/2014%20Thesis_Gwen%20Fuertes_2058%20Seagram.pdf

Figure 3.13;
Facade detail of Lever House in New York

https://www.som.com/projects/lever_house

Starting from the 1960s until the present day, the design strategies and ideas about the curtain wall have been characterized in relation to economic and environmental impacts. Each decade brought new concepts such as postmodernism, high-tech, deconstructivism and sustainability. Energy crisis in 1970s and widespread environmental sensibility on 21th century, caused to think about building skin performance. The curtain wall's endurance have provided to adapt variable strategies and concepts during the different periods and approaches.

In 1964 Eero Saarinen and Associates designed Deere & Company Headquarters in Illinois with external steel skeleton and gold-tinted reflective glass. The final configuration was completed with steel brise-soleil. The gold-tinted reflective-coated glass was kind of new product in that period and it rejected 70 percent of the solar heat gain. The multilayered metal and glass curtain wall of Deere Headquarters had influence on widespread. Many other examples with reflective coated glass were constructed in the sense of solar control.

Figure 3.14;
Facade of the Willis Faber and Dumas Headquarters was designed with structural glazing system

https://www.architecture.com/image-library/RIBApix/image-information/poster/head-office-for-insurance-firm-willis-faber-and-dumas-limited-ipswich-suffolk-detail-of-glass-wall/posterid/RIBA77342.html

Figure 3.15;
Willis Faber and Dumas Headquarters with its super transparent facade

https://www.arch2o.com/willis-faber-dumas-headquarters-fosters-partners/

Another example of innovative curtain walls was Willis Faber and Dumas Headquarters which was designed by Norman Foster. Three-story building had glass skin without any metal mullions. The curtain wall was hung from a rail along the roof and each glass was bolted to the other one vertically with steel plates. For lateral stability there were glass fins which were hung from the underside of the floor slabs.

Even if this glass to glass joint system provided smooth appearance for the building and minimized the width of silicone seal it was not practical for tall buildings. After the first usage of Foster's glass fins, it has been used for small-scale buildings and it has been adapted for use with insulating glass and structural backup systems such as cable trusses and nets.

Structural silicone glazing was another important development for maximizing the glass surface while minimizing the framing. This system describes the fixing glass to its supporting mullion by glue without other mechanical attachment. After extensive testing and small-scale applications, silicone glazing became primer for the curtain wall construction in US around 1980s. I.M Pei designed Allied Bank Tower (1986) in Dallas with structural silicone glazed curtain wall skin. Thus fifty-nine story steel-framed building with its reflective green-tinted facade it achieved the tallest structural silicone glazed curtain wall in the world.

These processes in order to explore innovative facades, resulted in the improved forms of today's curtain wall practices. The expectations about custom design, besides the standard curtain wall systems have been encouraged by long qualifications.

In 1980s some architects started to experiment alternative challenges that breaks the dominancy of modernism. It has been described as postmodernism movement. Especially with leadership of Philip Johnson in America some remarkable postmodernist buildings were erected. One of them was Hooker Building (1980) along the Niagara Falls. This project's most important feature was having double skin as a result of the environmental concerns. Building could have maximum view with transparency of the glass while achieving the energy efficiency. Besides maximizing the glass area could provide minimizing the artificial light need. It was arranged with insulating air cavity between two layers of glass walls for the protection of heat loss in winter. Additionally, there were sunshade louvers and natural ventilation in the cavity for overheating in the summer time. Inner and outer skins were located in 1.2 meters space between them and in span of 1.5 meters extruded-aluminum mullions. Outer skin comprised green-tinted insulating glass for blocking the sun effect and inner wall be formed by floor to ceiling clear glass. Since the building was created with energy efficiency goal it had solar cells and automatic sunshade louvers for optimum solar control.

Similar example in the concept of skin performance was Arab World Institute (1987) of Jean Nouvel. The building was known with its unique and complex curtain wall design. The curtain wall be formed by conventional double-pane insulating glass which fulfilled between prefabricated story-high units of extruded aluminum framing. Behind the insulating glass there was unique mechanism of shutter that was equipped with photocells. This system of sunshade was operating automatically according to amount of sunlight. At the inner side of the wall there was layer of monolithic clear glass for protection of the system and in need to access for maintenance. Except from technical features, shutters within the glass was referred to Arabic decoration. Thus project was evaluated as poetic and symbolic by the critics. Although this innovative curtain wall system was inevitable and hard to maintenance during the years after it was constructed, it was an important experiment for promoting of intelligent curtain wall systems. Both Hooker Building and Arab World Institute showed that how curtain wall could respond to changing environmental conditions.

Figure 3.16;
Arab World Institute was designed by Jean Nouvel with a kinetic facade system

https://www.archdaily.com/162101/ad-classics-institut-du-monde-arabe-jean-

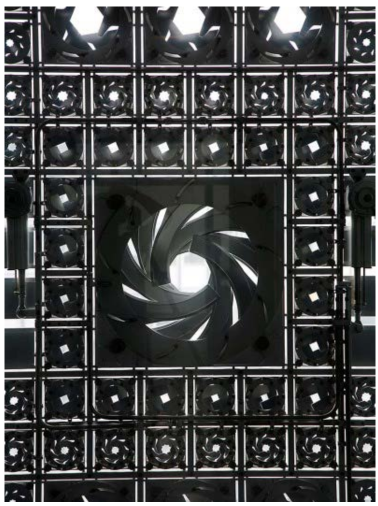
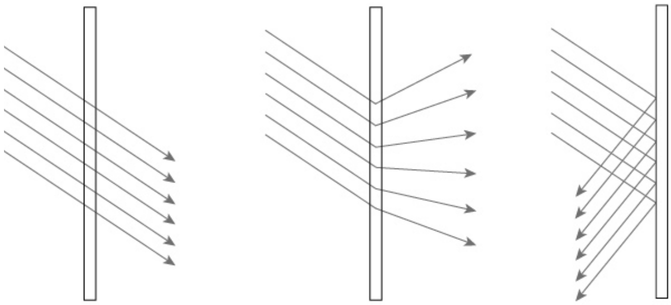


Figure 3.17;
Photo celled facade detail of Arab World Institute, 1987

https://www.cool-cities.com/institut-du-monde-arabe-1164/

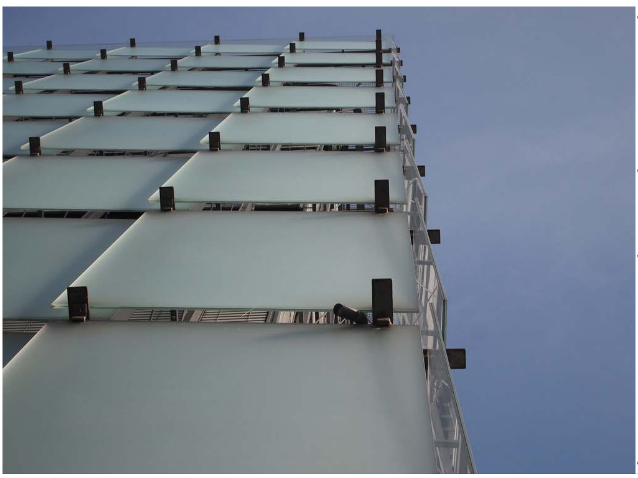
20th century was dominated by the conditions of transparency and reflectivity in architectural context on building skin that was motivated by aesthetic and experimental impulses. Starting from the end of the century the interest of translucency of the building envelope increased between the architects. In this period many of the projects aimed to use glass that is not just transmit or reflect light but collects and scatters which was product of different glass fabrication techniques. The Kunsthaus (1997) and the Kursaal Auditorium (1999) were successful interpretations of translucency idea in architecture.



Drawing 2.2;
Transparency, translucency and opaqueness concepts. Elaboration of the author.

“I was never really interested in just transparency. In fact, I was always suspicious of it. The zone very comfortable in is the distance between the translucent and the opaque.”
Steven Holl

The Kunsthaus was designed by Peter Zumthor in Austria. The building skin consisted of outer translucent skin and inner wall with concrete and glass. Outer layer stood 90 centimeters in front of inner layer and it was constructed by hundreds of laminated glass panels around all four sides of the building. The panels were supported by steel angles from bottom and top corners of each of them. Through the acid-etched glass building envelope had matte finish without any direct views into the building. Therefore at the night it created faint indications and excitement about what was beyond the skin.



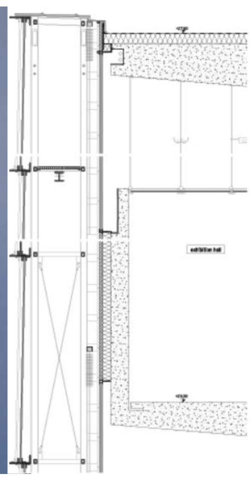


Figure 3.18;
The Kunsthaus was designed with translucent panels on the facade

https://hiveminer.com/Tags/europe%2Czumthor

Figure 3.19;
Facade section of the Kunsthaus

http://www.detailsinsection.org/?p=725#prettyPhoto/0/

Other example of this concept was the Kursaal Auditorium in Spain. The building had dramatic location owing to Urumea River and Bay of Biscay on its surrounding. Architect of the building, Rafael Moneo, created it as an element of landscape rather than the city. The building envelope was formed by double-skin which was supported by cage-like structural steel-framework. This framework went 2.4 meters from inside to outside and beared both exterior concave glass planks and interior flat sandblasted low-iron glass. The exterior glass was composite glass of bent and laminated glasses. The laminated glass was produced by heating and passing the glass over patterned ceramic rollers. The combination of complex glass types were necessary to reach different glass treatments for giving impression. Thanks to this complex curtain wall system it was provided creation of changing atmosphere according to sun. When sun came directly it became opaque and solid, when sunlight was behind it revealed its depth in shadow. Besides it glowed and reflected the water of the river and the sea at the night.

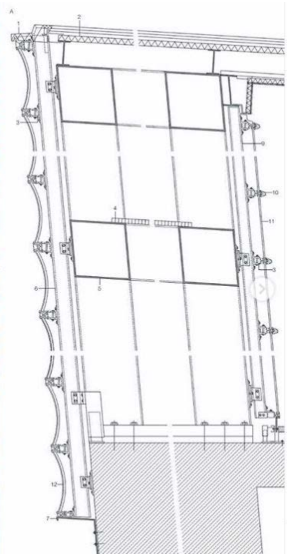


Figure 3.20;
Double skin facade of the Kursaal Auditorium

https://www.archilovers.com/projects/101748/gallery?767443nouvel/50381c2728ba0d599b000f1d-ad-classics-institut-du-monde-arabe-jean-nouvel-image

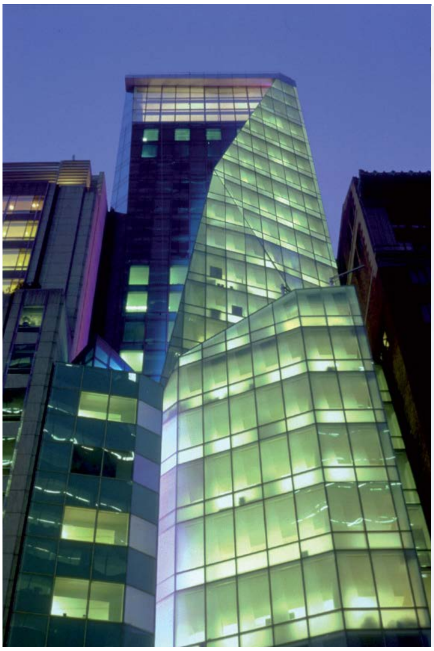
Figure 3.21;
Facade detail of the Kursaal Auditorium

https://tr.pinterest.com/pin/512706738827974501/

In 1990s, except from translucency also with the developed glass manufacturing techniques it began to try new alternatives of glass building skin. The LVMH Tower (1999, Atelier Christian de Portzamparc) in New York started a tradition among the luxury brands for showing their aesthetic and innovative standing through their showrooms. Some notable buildings were; Prada Flagship Store (2003, Herzog de Meuron) in Tokyo, Dior Building (2004, SANAA) in Tokyo, LVMH (2004, Kengo Kuma) in Osaka. All on this projects it was focused to unique glass treatments and custom surface treatments for reaching sculptural quality.

In the early 21st century, the issue of sustainability, energy efficiency, responsibility of resources, responsiveness to local climate and creation of healthy environments have pervaded all world in different sectors also in architecture. Now building envelope has more significant role to response this senses. The glass and metal curtain wall has dominated most of the office buildings' facade in various types both in US and Europe starting from the mid-20th century. In 21st century architects has been exploring optimum ways to adaption of environmental conditions. This shows glass is conceived not anymore as a single element but it is one component of the entire enclosure system of the buildings. In such a system main aim is providing internal comfort while minimizing energy consumption. The main components usually include double-skin glass envelope with in a way of sun shading or diffusing elements also with power-generating components like photovoltaic cells, wind turbines. This new type of facades often integrated directly with mechanical systems of the building which forces architects to be in collaboration with engineers and building scientists to defining and realizing intelligent facade systems.

William McDonough points out:" Being less bad (or more efficient) is not necessarily being good." It is likely that we will soon see a major shift in emphasis, from deigning buildings that are simply more energy efficient to conceiving and implementing new technologies that allow buildings to actually sustainably generate energy (making a positive difference and not simply a less negative one), and it can be expected that the building envelope, as the interface between exterior and interior environments, will continue to play an essential role in this pursuit. (Murray, 2009)



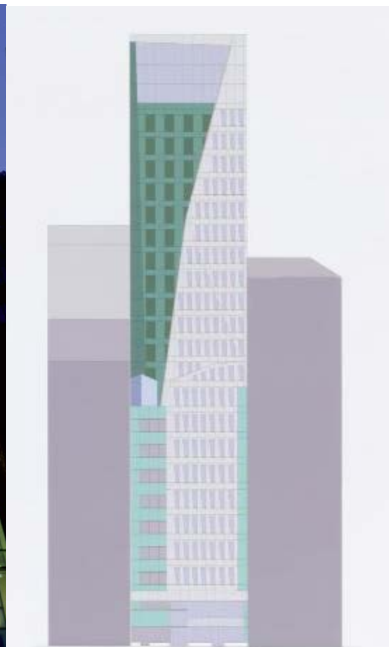


Figure 3.22;
The LVMH Tower by Atelier Christian de Portzamparc, 1999

https://www.world-architects.com/ca/atelier-christian-de-portzamparc-paris/project/lvmh-tower-new-york

Figure 3.23;
Front elevation of the LVMH Tower, New York

https://www.moma.org/collection/works/168060

Figure 3.24;
Dior Building designed by SANAA, 2004

https://architecturetokyo.wordpress.com/2017/06/18/2003-dior-omotesando-sanaa/

Figure 3.25;
Prada Flagship Store, designed by Herzog de Meuron, 2003

http://www.galinsky.com/buildings/pradatokyo/index.htm

General trends and concepts of the curtain wall facades in the 20th century is given below on the table. Industry based or international aspects have had role to give form of contemporary curtain wall practices.

Curtain Wall Trends

Early 20th Century	1940s-1960s	1960s-1980s	1980s	1990s
• Initial trails of the curtain walls • Continous and pure glass trends were very common • Insufficient thermal and acoustic features as a result of single-pane glass	• Glass Box concept • Modernism was associated with transparency • Different glass types were introduced in the industry (heat-absorbing single-pane, tinted glass)	• After Oil Crisis on 1973, concerns about thermal performance increased • Sun-shading elements were located on the facade • Reflective glass took place in order to provide solar control • Structural silicone glazing were invented for maximum glass surface without frame	• Double-skin facade started to be seen • Kinetic facade systems were applied for better environmental adaptation	• Translucency concept dominated the super clear glass facades • Double-skin facades spreaded in various forms and combinations • Unique and combined glass types were supplied on the market

Table 3.1; Curtain wall trends in different time periods.
Elaboration of the author.

3.2 | Definition of the Curtain Wall

The curtain wall may be defined in the most literature as any building wall of any material that is resistant to its own weight and the lateral loads which are caused by wind or earthquakes. In current practice, the curtain wall is a designed system of the different components. While any dead load is not carried by the curtain wall, own weight of the system transposes from its body through the principal structure of the building.

The focus of the study is about glass and metal curtain walls. This kind of system is accomplished by metal mullion and transoms with transparent vision panels and opaque spandrel panels. As regard of the project, the combination of the infill panels and their opacity may change, however defined metal frame is constant.

The metal curtain wall system can be divide into three parts as head, body and cover. Head is constituted by vertical metal elements probably that is made with aluminum profiles. Head is the warm side of the curtain wall system. The infill panels are installed into the body part. Last one is the cover part and it represent the cold side of the curtain wall. Pressure plates or snap caps of the mullions take part in this side. The head and the cover parts are more exposed sides of the curtain wall. Due to aesthetic or technical demands, components of these two parts have many types in the industry. Interconnections with each other of the three parts are ensured by weathering elements such as sealants and gaskets.

The figure below indicates the three typical parts of the metal curtain wall system.

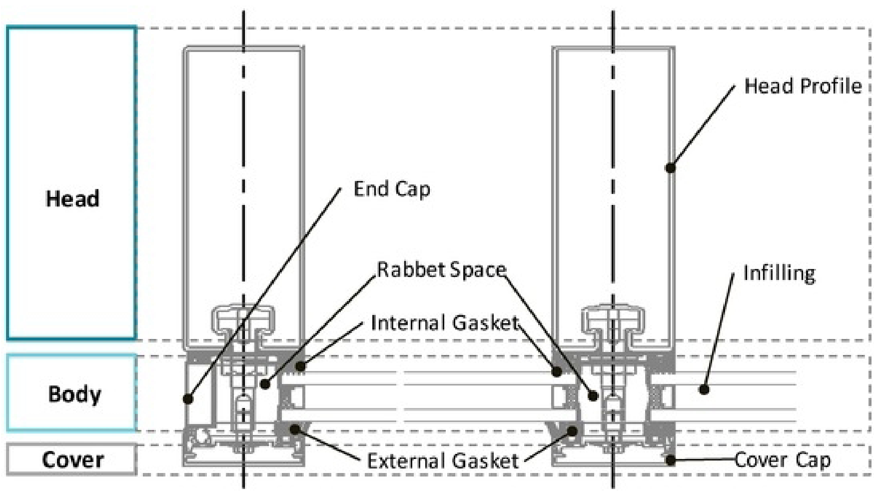


Figure 3.26;
Head, body and cover parts of the typical metal curtain wall system

https://www.mdpi.com/1996-1073/9/12/1055/htm

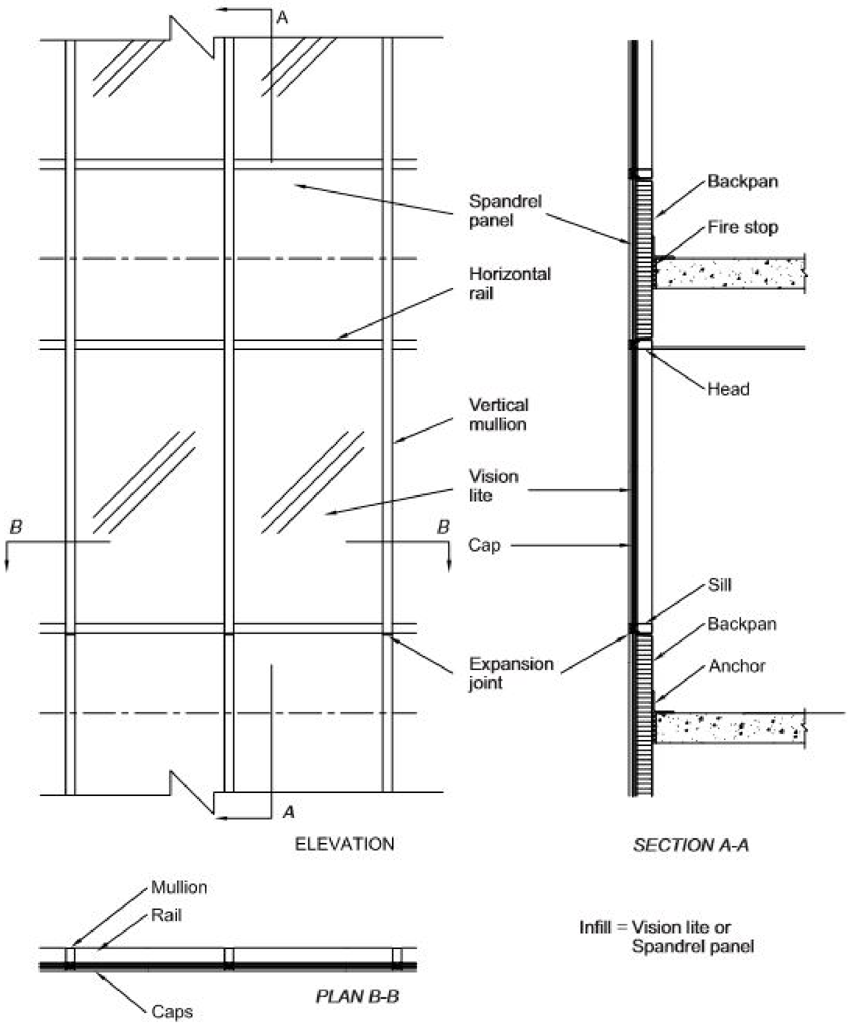


Figure 3.27;
Components of the metal curtain wall system

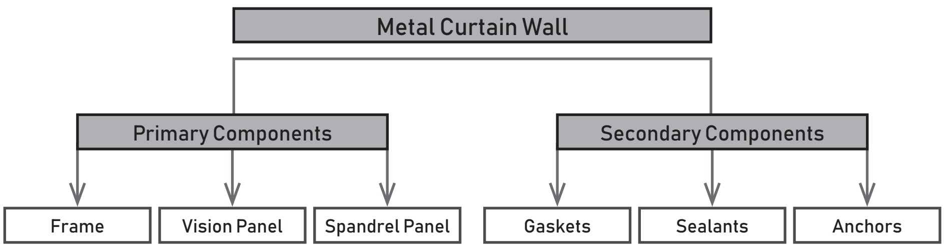
"Glass and Metal Curtain" Walls, CMHC, 2014

3.3 | System Components

In compare with other external closures, metal and glass curtain walls combine of few structural components. The system consists of fundamental materials, typically aluminum or steel framing elements and glass, and it is accomplished by sealants, gaskets and insulation products.

Even if several kind of metal extrusions or glass types exist, the principal integration of the components is similar. Assembly to the overall system of each component is a result of high engineering.

The table below shows the classificaiton of the metal curtain wall system components



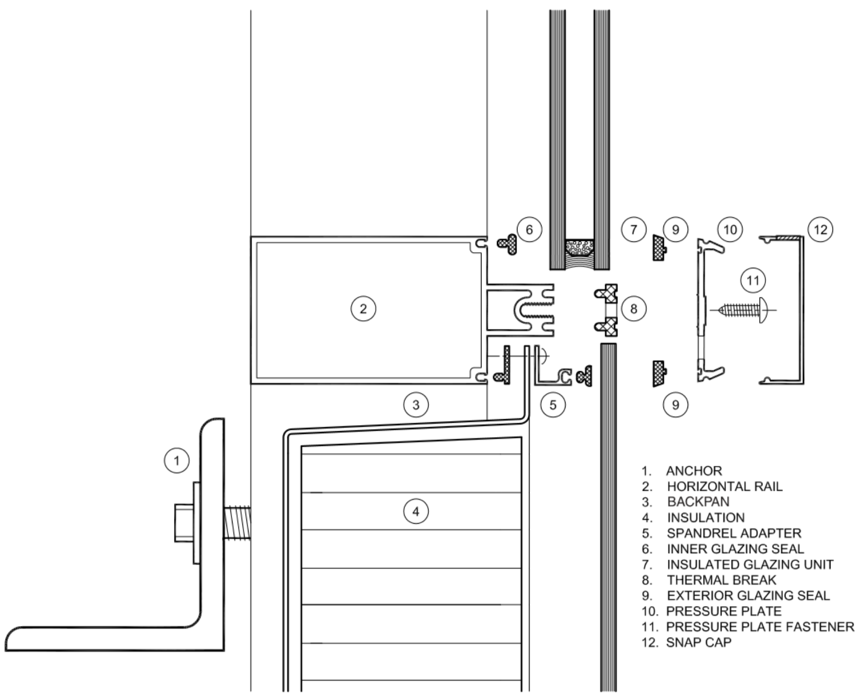


Figure 3.28;
Technical drawing of a stick system metal curtain wall components

"Glass and Metal Curtain" Walls, CMHC, 2014

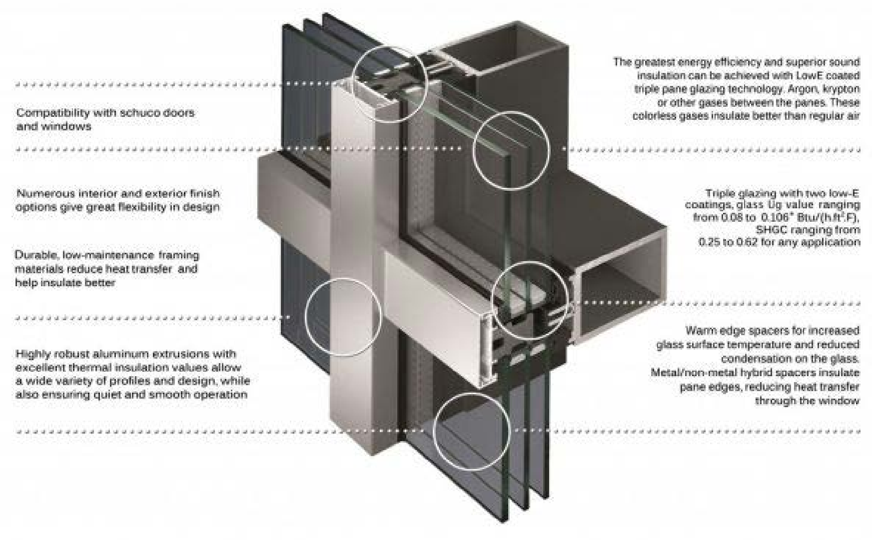


Figure 3.29;
Explanation of the metal curtain wall system components

https://www.modlar.com/brands/intus-windows/fw-50-.si-curtain-wall-system/

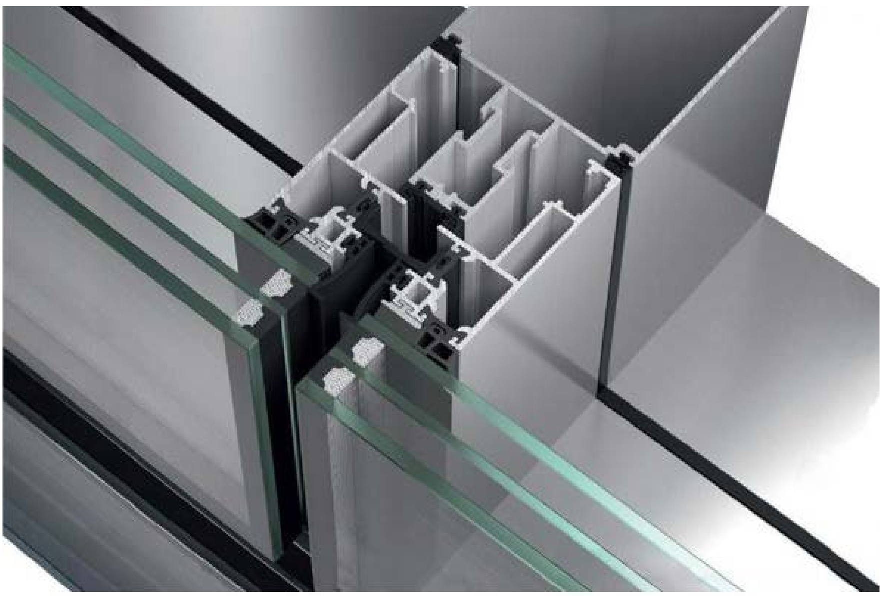


Figure 3.30;
Frame, glazing and gasket section of the system

https://www.modlar.com/brands/intus-windows/fw-50-.si-curtain-wall-system/

3.3.1 Frame

Structure of the metal framing is constituted by mullions and transoms which are load-bearing elements of the body. Presure plates and snap caps take place on the framing depend on the curtain wall type and design.

Material
Even if steel profiles are used in some cases, aluminum extrusions are the most common type for metal curtain wall frames. Metal profiles of the mullions and transoms with also pressure plates and snap caps are made by aluminum alloys. Additionally T5, T54 and T6 are the usual temper classes for the curtain wall applications. The strength of the profiles and mechanical properties are variable in different classes. Alloy 6063 and alloy 6061 are the most common materials. 6061 serves more strength and it is often selected for anchor installations.

Frequently, standard aluminum extrusions have adequate strength for usual spans. In need for longer spans, steel reinforcing can install to the aluminum sections.

Profiles
Vertical and horizontal structural components of the framing are constituted by metal profiles. In the market, variability of the profiles and their detailing may change from one manufactures to another. Furthermore, the sections of the stick and the unitized systems have differences.

Pressure Plates
All the metal curtain wall systems are not arrange with pressure plates; however it is a very common element on the unitized systems. It is located at the exterior side of the curtain wall and the vision or spandrel panel is attached to the framing by pressure plates. Typically it is composed by same aluminum alloy with the main framing elements. Vertical and horizontal frame members are may interlocked by the pressure plates. Important concern is ability to drain of the system.

Snap Caps
Snap caps are located at the exposed side of the curtain wall and they cover the pressure plates and fasteners. Apart from the aesthetic function they are baffle to the drainage openings in the horizontal pressure plates. Typically same alloy with main framing members or steel, copper forms are used.

Standard and custom section are available on the market. The deep or non-rectangular forms have higher risk to disconnection from the main structure.

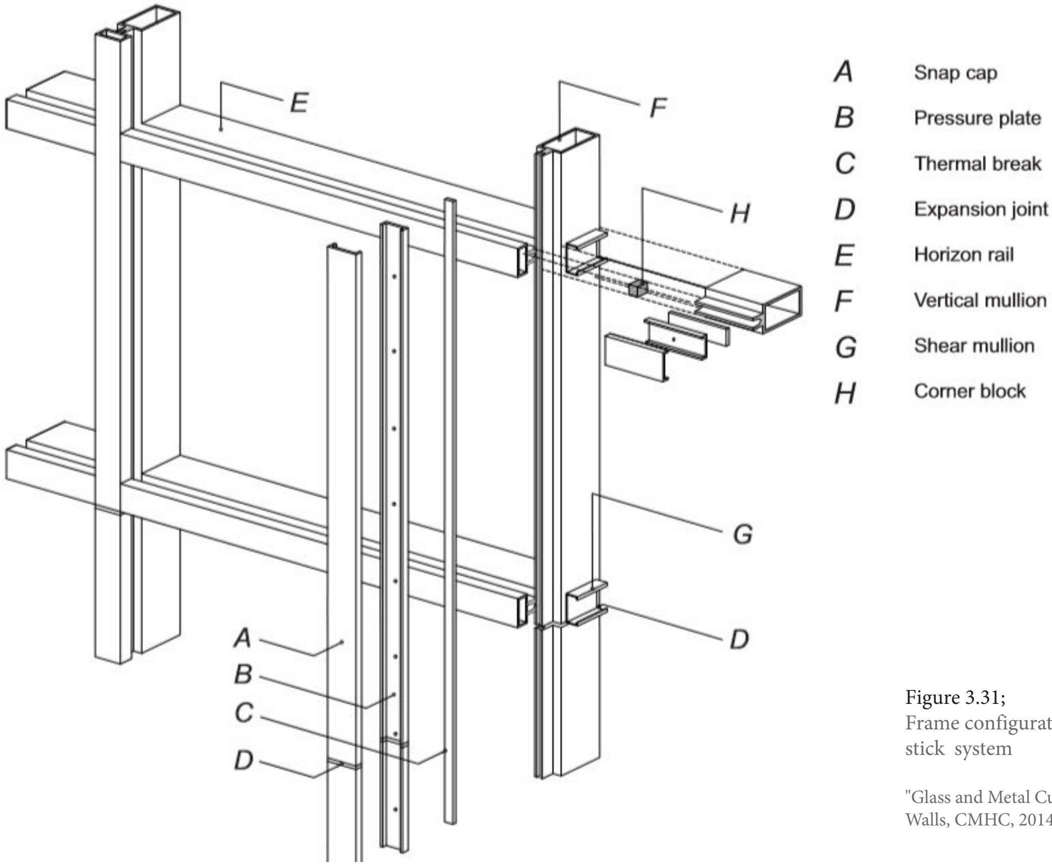


Figure 3.31;
Frame configuration of the stick system

"Glass and Metal Curtain" Walls, CMHC, 2014

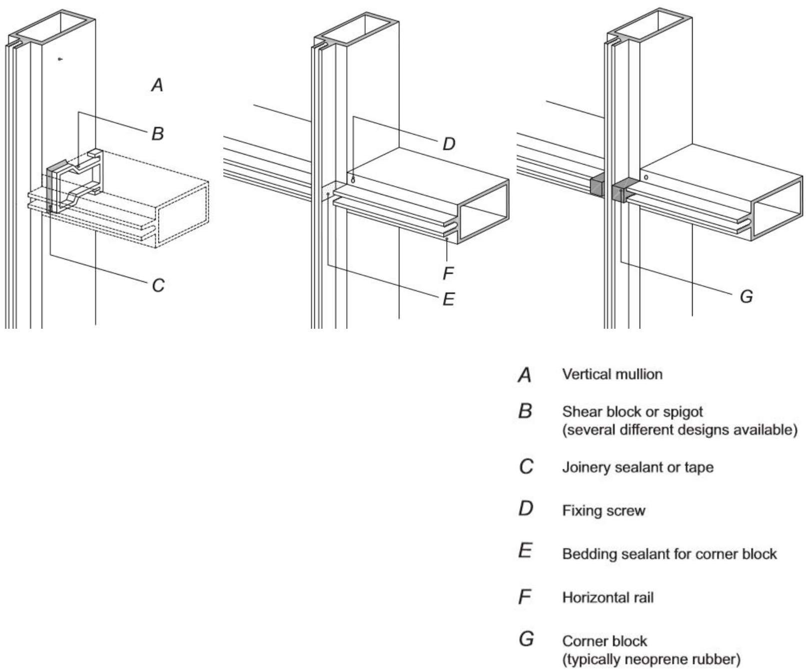


Figure 3.32;
Joinery details of the stick system

"Glass and Metal Curtain" Walls, CMHC, 2014

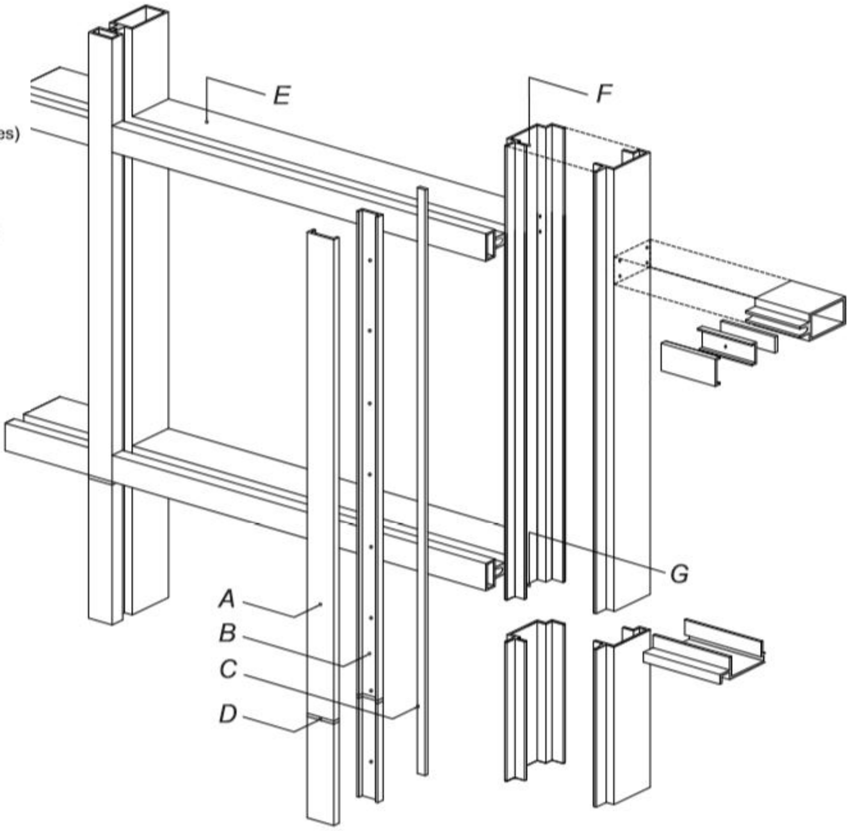


Figure 3.33;
Frame configuration of the unit system

"Glass and Metal Curtain" Walls, CMHC, 2014

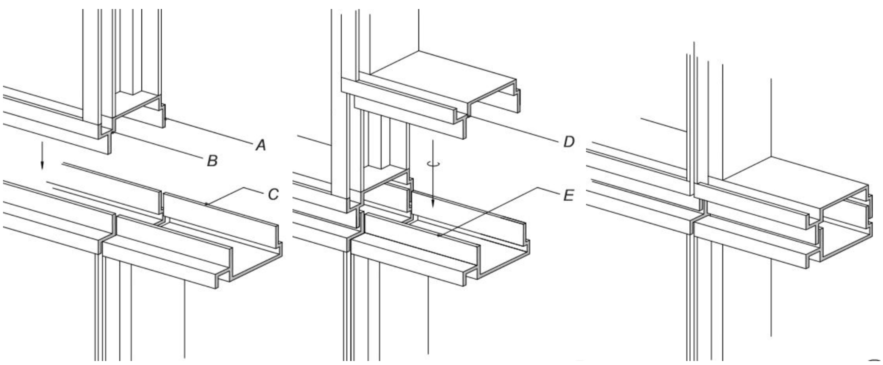


Figure 3.34;
Joinery details of the unit system

"Glass and Metal Curtain" Walls, CMHC, 2014

Safety Glass

Safety glass is defined as glazing material combined or treated with other materials that is resulted to minimize injuries when it is broken. It means when the safety glass breaks into it is eliminated unreasonable risks to harm people. In Europe tempered and laminated glasses are under the safety glass category by regulations. In America also wired glass, organic coated glass and plastic safety glazing material are belong to safety glass.

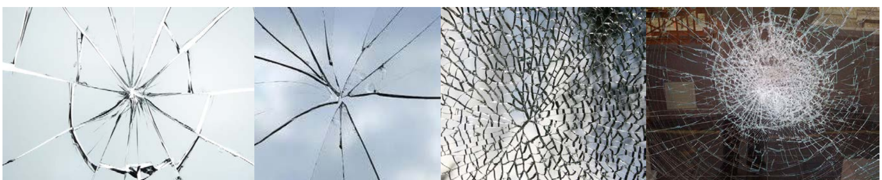
Glass Type	Reference
Toughened	EN 14179-1, EN 14179-2
Laminated	EN ISO 12453-1, EN ISO 12453-2, EN ISO 12453-3, EN ISO 12453-4, EN ISO 12453-5, EN ISO 12453-6

According to the European regulations, a specific requirement affecting the glass type concerns the portion of the glass pane located in the height of 1 m from the ground of each floor. This portion must be toughened, laminated or both.

Laminated Glass

Laminated glass consists of two or more glass layers which are bonded with an interlayer. Common interlayer materials are PVB and cured liquid resin but for aesthetic demands it can be printed with patterns, colors etc. Laminated glass qualifies as safety glass because when the glass is broken, fragments tend to adhere to the interlayer. Another advantages of interlayer is having UV protection against to sun and giving good acoustic characteristic. Due to its benefits laminated glass has wide range of installations on curtain walls.

Breakage patterns of different glass types;



a)Annealed glass b)Heat-strength glass c)Tempered glass d)Laminated glass

Figure 3.33;
Breakage patterns of different glass types;
a)Annealed glass b)Heat-strength glass c)Tempered glass d)Laminated glass

http://karioglass.com/news/spontaneous-breakage/

Insulating Glass Unit (IGU)

Insulating glass units are produced for higher thermal performance as an alternative to monolithic glass. Vision glass of the curtain wall with the insulating glass units may be double or triple glazed depending on the wind loads, solar radiation, cooling and heating requirements. A typical IGU consists of two layers of glass with a spacer which separating the glass panes to uniform cavity thickness. The spacers may be aluminum or fiberglass. For reducing the heat-loss at the edge of the IGU or increasing the inside edge glass temperature, fiberglass spacers perform better. When improved thermal performance is required stainless steel and thermoplastic spacers may be use for insulating properties. IGUs are often fulfilled with a powder to absorbing humidity and it provides condensation control. The airspace between the glass panes can be filled with either dry air or a low-conductivity gas, such as sulfur hexafluoride or argon.

Reflective or low-emissivity (low-E) coatings also have significant effect for higher thermal insulating and solar heat-gain when they are added to double-glazed or triple-glazed glasses. Depending on the design, it can be produced with custom patterns and colors. Also based on the requirement, laminated insulating glass can be involved the curtain wall system.

Apart from the thermal performance of IGU, also it contributes to acoustic performance of the building envelope. The air space between the glass panes reduces the sound transmission. When it is compared insulating glass units assures ahead of thermal and acoustic performance than single pane.

Wired Glass

Wired glass is obtained by laying wire mesh between the two sheets of glass. When it breaks, wire provides adhering surface to glass fragments and also it enhances the fire resistance of the glass. Although it is used in safety glass applications in America, it is not accepted as safety glass in Europe.

Table 3.2; Glass types with referred European codes. Elaboration of the author.

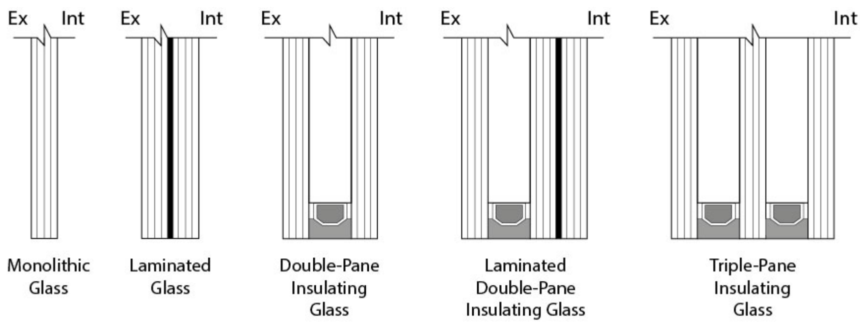
to absorbing humidity and it provides condensation control. The airspace between the glass panes can be filled with either dry air or a low-conductivity gas, such as sulfur hexafluoride or argon.

Reflective or low-emissivity (low-E) coatings also have significant effect for higher thermal insulating and solar heat-gain when they are added to double-glazed or triple-glazed glasses. Depending on the design, it can be produced with custom patterns and colors. Also based on the requirement, laminated insulating glass can be involved the curtain wall system.

Apart from the thermal performance of IGU, also it contributes to acoustic performance of the building envelope. The air space between the glass panes reduces the sound transmission. When it is compared insulating glass units assures ahead of thermal and acoustic performance than single pane.

Wired Glass

Wired glass is obtained by laying wire mesh between the two sheets of glass. When it breaks, wire provides adhering surface to glass fragments and also it enhances the fire resistance of the glass. Although it is used in safety glass applications in America, it is not accepted as safety glass in Europe.



Drawing 3.2; Different glass types with various insulation levels. Elaboration of the author.

3.3.3 Gaskets

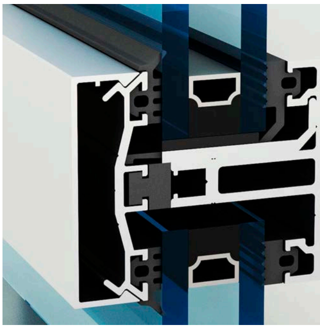


Figure 3.35;
Gaskets ensures the air and water tightness of the system.

https://www.letuautomotive.com/extruded-rubber/curtain-wall-gaskets-seals/

The gaskets or tapes have function as cushion to the glass which avoid contact with the metal components. Besides, these elements provide water and air barrier at the perimeter of the glass. The glazing gaskets and glazing tapes are different from each other in terms of stiffness.

Glazing Gaskets
These products have been used for a long time in the curtain wall designs. That's why it is available standard products in various sizes. They are highly stiff and elastic products which supply a seal. Gaskets take place into joints and they count on the interface pressure in order to create the seal. Neoprene, ethylene-propylene-dienemonomer (EPDM), silicone, silicone-compatible and thermoplastic rubbers are usual materials for the gaskets.

Glazing Tapes
Butyl rubber-based and stiff, non-shimmed tape are common types of glazing tapes. Glazing tapes are often take place in the glazing industry and they are UV, ozone and heat resistant products. Although glazing tape has tendency to collect dust on its surface, it has ease to adhere many building materials. 6 mm to 25 mm width and 1.5 mm to 9 mm thickness are standard sizes for glazing tapes.

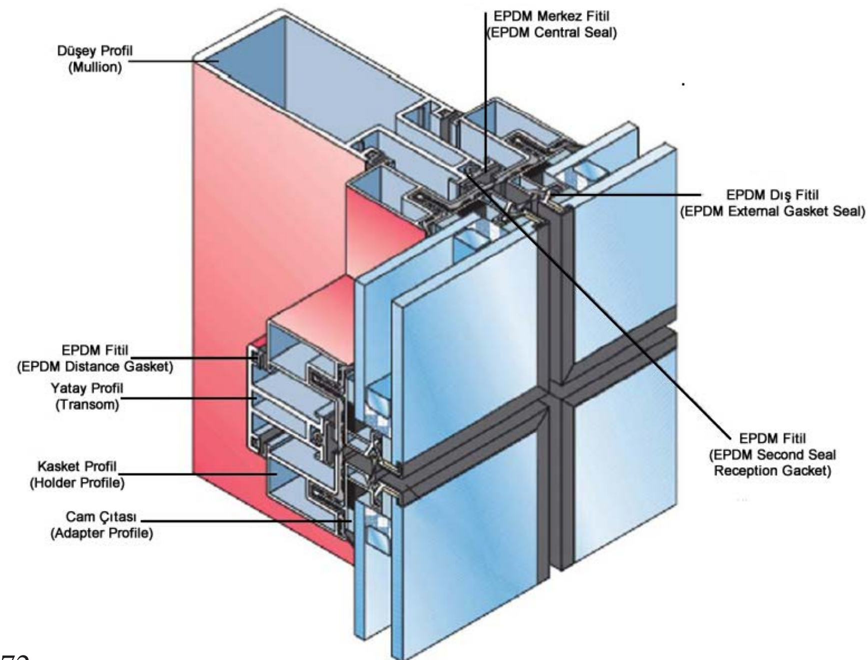


Figure 3.36;
A curtain wall system with integrated gaskets

https://www.safircephe.com/strukturel-silikonlu-cam-cephe/

3.3.4 Sealants

In contemporary practice, it is in trend of decreasing design of sealant relied systems. Due to their characteristic, sealants require cleaning and maintenance and furthermore they are elements of workmanship. These challenges of the sealants make them less desirable on the curtain wall systems; however, metal to metal joints always need to seal.

Sealants can be categorized in three main classes which are low-range sealants, medium-range sealants and high-range sealants. Low and medium range sealants are composed by resin based caulks, polybutene-based or butyl. These applications almost diminished from the current practices. Instead of these two classes, high-range sealants have installs in wide range of the curtain wall industry. Silicone based products accommodate movement thanks to their elasticity. Highly resistance to UV and ozone and well-adhesivity even on the crucial surfaces make them distinguished.

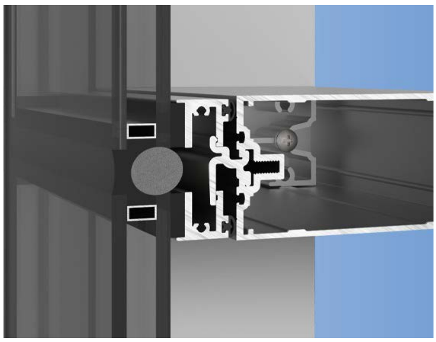


Figure 3.37;
A curtain wall system with integrated sealants

https://www.ykkap.com/commercial/product/curtain-walls/ycw-750-ssg/

3.4 | Curtain Wall Assembly Technique

In contemporary practice, curtain wall describes a system of wall with its components which are designed for specific performances. The curtain wall is a framework that can be formed in various ways depending on the form, function, material and the assembly technique. Eventhough it was developed many expression varieties owing to building's design concept, the fundamental design principle of the curtain wall consists of frames and panels. According to Allen, Quirouette and Ochshorn there are six different assembly types of curtain walls;

- Stick System
- Unit System
- Unit and Mullion System
- Panel System
- Column Cover and Spandrel System
- Structural Glazing System

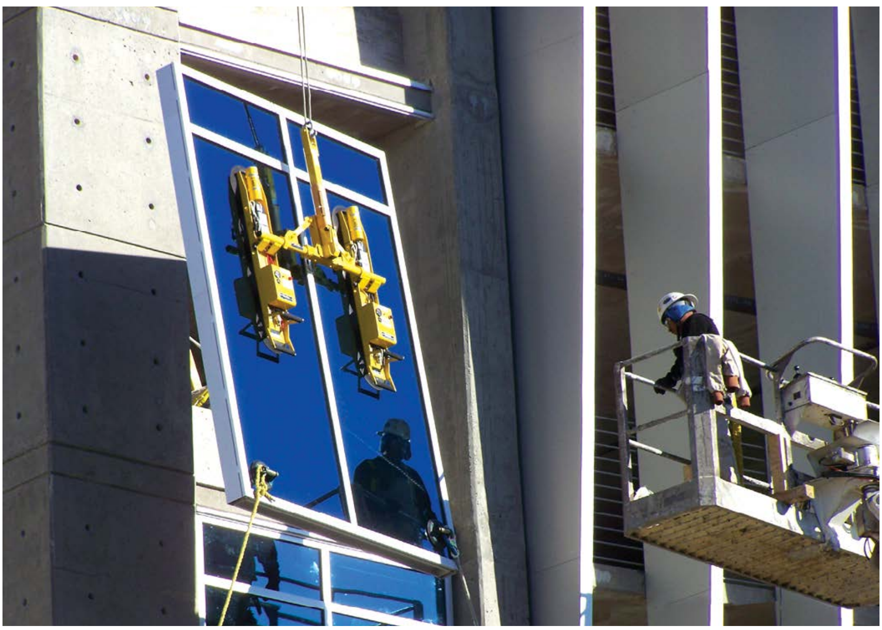


Figure 3.38;
Installation of a unit system to the building facade

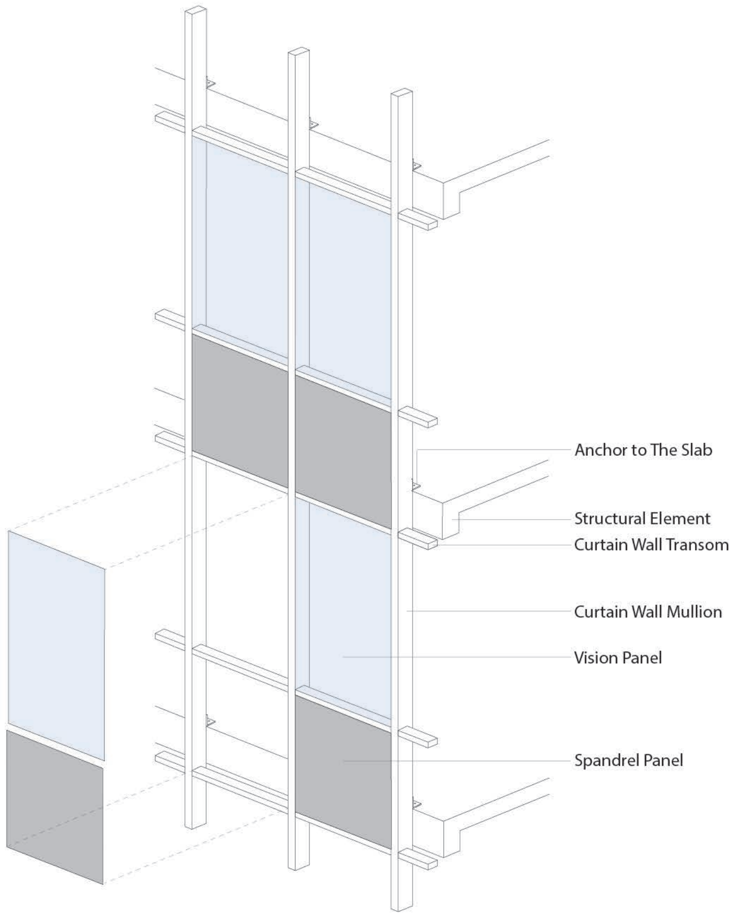
https://glassmagazine.com/article/commercial/trouble-finding-labor-go-unitized-1918834

3.4.1 Stick System

Stick system constitutes the oldest curtain wall application method. In a stick system all individual components are assembled piece by piece to the system on-site. This system is hung on the building structure from floor to floor and generally it describes a frame system with steel or aluminum mullions, rails and sub-connection elements that are fulfilled by panels.

Usually, first primary mullions are connected to the building structure by anchors and then if there are secondary mullions for spanning they are installed between the primary mullions. The attachment of the rails (horizontal mullions) to the mullions follows on the process for creating the frame. Finally, in-fill panels fulfill the framing. In the traditional curtain wall systems generally there are two types of panels which are called like vision panel and spandrel panel. While the vision panel is created by insulating glass units for the transparency, the spandrel panel is formed by opaque material for covering the floor slabs or mechanical areas of the building. In contemporary curtain wall systems thanks to the diversity of the structural materials it can be built in various types such as entirely with reflective or translucent glasses.

Most of the stick systems are standard and off-the-shelf, by this way they are relatively low priced products. Owing to the efficiency of packaging separated components it has low transporting expenses. On the other hand installation in the field causes higher labor costs and slower pace of the process. Additionally, it occurs potential problems about quality and precision comparing with the prefabricated elements. Because of difficulties for accommodate in-plane movements by sway or seismic events, stick systems are generally use for low or mid-rise building envelopes.



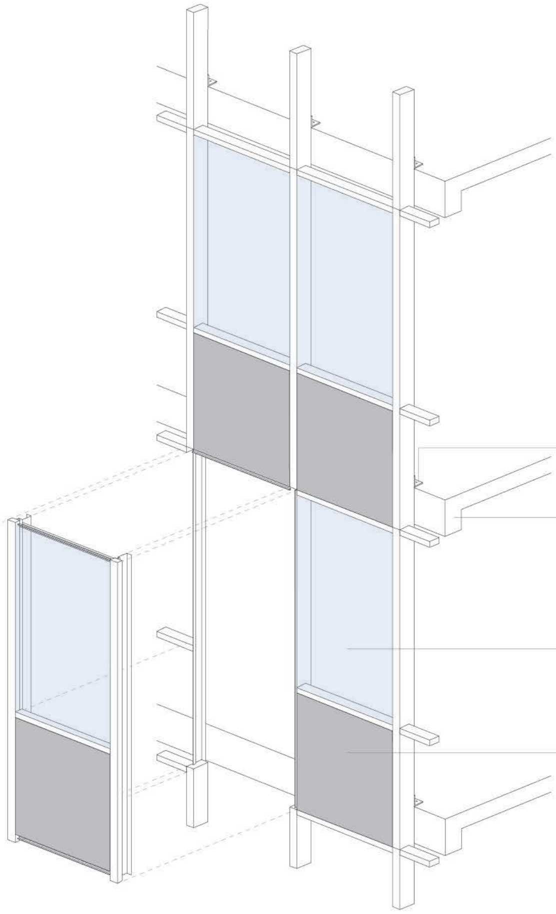
Drawing 3.3;
Stick curtain wall system
Elaboration of the author.

3.4.2 Unit System

Unit system curtain wall consists of prefabricated modules which have same components with the stick system but as a unit. Most of the time it comprises aluminum mullions with vision and spandrel panels mounted in a prefabricated aluminum frame.

When it is compared with the stick system curtain wall, it has many advantages for installation speed on the site and for the less labor costs due to prefabricated units. Another advantage of this system is having greater quality control during the fabrication process. Besides, for durability it accommodates building movement that is caused by deflection or wind loads. Therefore unit system curtain wall has a great amount for the high-rise building construction in present time. Nearby this advantages it has high shipping costs and it needs sequential installation. Because unit system panels have half sectioned mullions and rails instead of tubular sections and each panel interlocks to next one. The panels are started to apply from bottom and it goes around the each floor until to up for the entire closure. Although there are many possibilities for the dimensions of the units, generally typical curtain wall unit has 1.2 meters to 3 meters width and one to two story height. These units are anchored to each floor slab or to beam.

The differences in assembly methods between two main systems can be seen in details. Even if they are used same material types in both systems, they have different mullion plans and detailing joints. Floor to floor extruded-aluminum mullions with 1.5 meters spaced with an infill of double-pane insulating glass create the common curtain wall system for both of them. In detailing, the stick system mullion is extruded in a rectangular box shape with recessed channels that accept continuous gaskets along the front edge. After these mullions and horizontal mullions are attached to the floor slab glass panels are set in place. The glass panels are held to the mullions by an extruded-aluminum plate which is screwed to the mullion for fixing glass to the frame. Generally, pressure plate is divided by a rubber or plastic from the mullion for the purpose of limiting heat loss. On the exterior face, this pressure plate is covered by another aluminum element for completing the aesthetic finishes of the surface. While the mechanical connection of stick system is like this, unit system mullion is composed by two adjacent unit frames. This mullion is called as split or dynamic mullion due to allowing relative moment between adjacent units for the thermal expansion and contraction. For interlocking unit system mullions to each other four-way stack joint is very common method. Glass is glued onto its frame by high-strength silicone instead of an exterior pressure plate and cap. This method provides continuous glass surface on the facade and limits the potential heat-loss by decreasing the amount of metal exposed to the exterior. Clearly, unit system mullion connection requires high quality control and precision on the application.

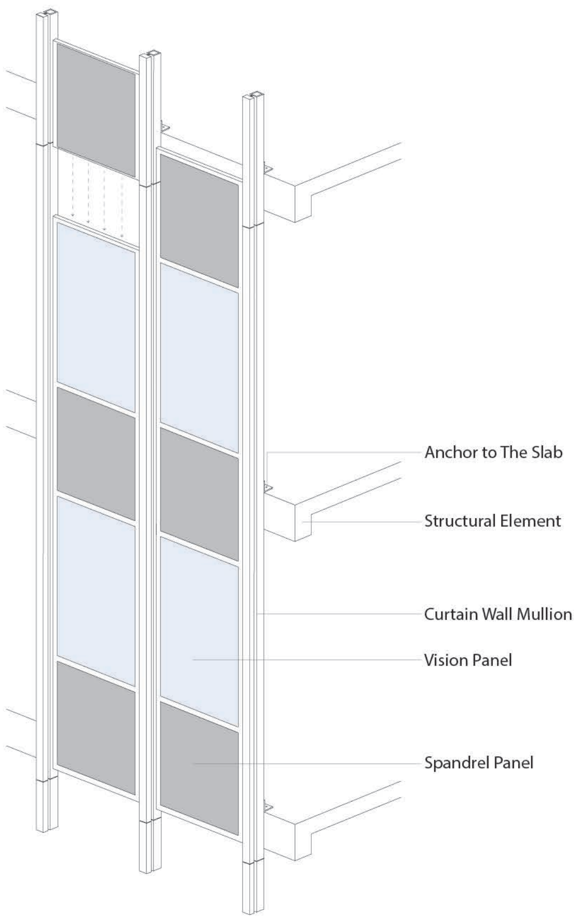


Drawing 3.4;
Unit curtain wall system
Elaboration of the author.

3.4.3 Unit and Mullion System

The unit and mullion system describes a kind of combination of both systems. However, it was a popular curtain wall assembly system in 1970s, now it is chosen very rarely in contemporary architecture. This system is used where mullions with a particularly large cross-sectional area causes using full unit impractical.

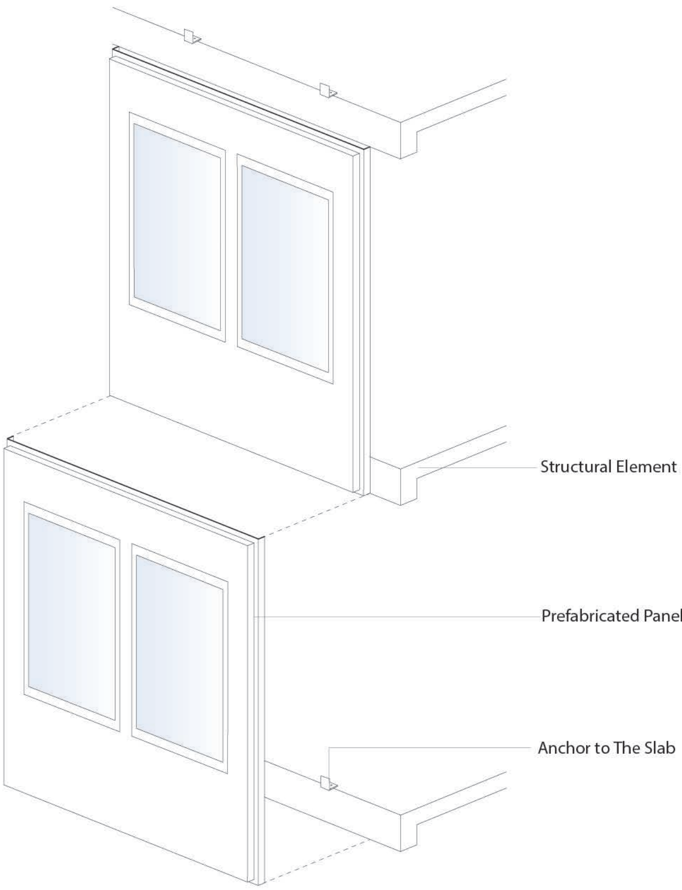
The mullions are installed to the building structure on the field like stick system application then frames are fulfilled by pre-assembled units. In variations vision panels and spandrel panels with changeable heights compose these units. Unit and mullion system represents similar advantages and disadvantages to the unit system.



Drawing 3.5;
Unit and mullion curtain wall system
Elaboration of the author.

3.4.4 Panel System

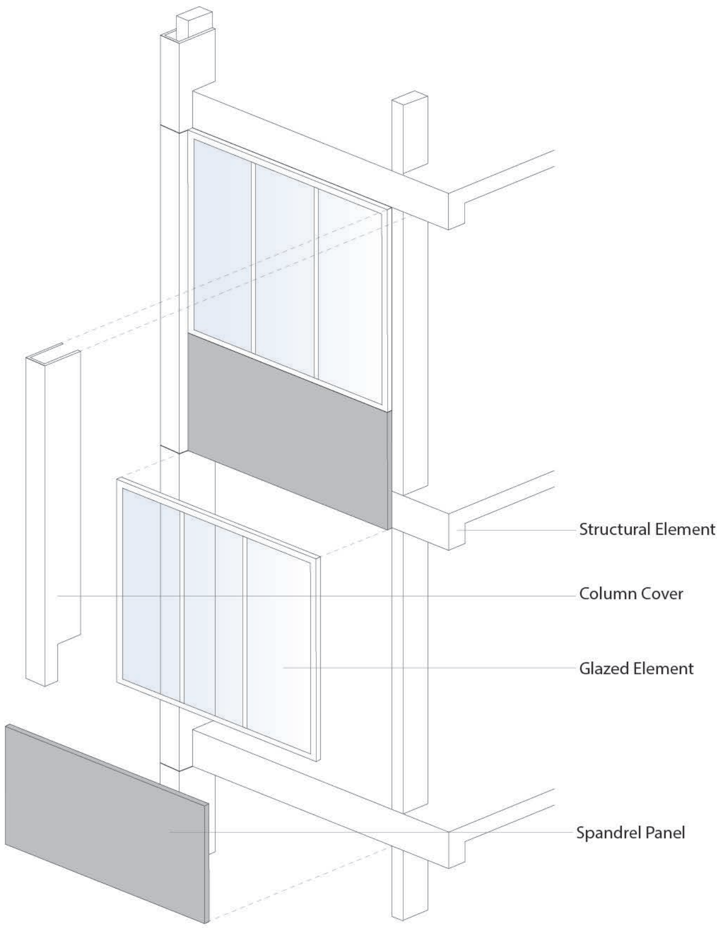
The panel system is formed by homogenous units that include composite materials. Panel system resembles the unit system in terms of installation to the building structure. Lightweight honeycombed materials with metal elements, foamed plastic insulation sandwiched panels that are consisted of two thin sheet metal layers, precast concrete panels or stone veneer panels are common panel system elements for curtain wall construction. Depending on the design even brick and stucco have become the part of prefabricated panel units. Apart from the similarities to unit system curtain wall, panel system is separated from design in custom most of the time. The dimensions of the panels have changes based on the building facade. Therefore it requires higher tooling cost of custom-made mold.



Drawing 3.6;
Panel curtain wall system
Elaboration of the author.

3.4.5 Column Cover and Spandrel System

Column cover and spandrel system instead of creating its own framing on the building facade it emphasizes the structural elements of the building through covering perimeter columns and floor slabs. This system especially has necessity to custom design because of changing column spans and floor heights for each project. Alike the stick system, first column covers are installed as mullions. These covers can be in various materials and generally one or two story heights. After the column covers spandrel panels and at the end glazing infills are fixed between the column covers. In this systems spandrel panels support the window strips so spandrel panels require attention for ensure that they receive when the loads are applied. In contrary, under the loads, window strips can be subjected to loadings which can deform the mullions.



Drawing 3.7;
Column cover and spandrel curtain wall system
Elaboration of the author.

3.4.6 Structural Glazing System

Structural glazing curtain wall system is often used when a smoothness, pure glass facade is required. Most of the time it is perceived as contemporary design and it obtains straight connection with it surrounding without any exposed curtain wall framing. Owing to its characteristic, it is also called bolt-fixed glass by another name. The continuous glass surface facilitates the flow of water and contrary to other curtain wall systems dirt and pollution can't gather on the external metal profiles. These features make easier to maintenance of the curtain wall.

In this system mullion necks are eliminated for creating a capless vertical joint system. The structurally-glazed glass is held by an adhesive silicone on one or more sides instead of captured edges by framing. Set of glass panels are assembled by brackets or bolts in order to supporting the glass against direct bearing loads. The structural frame can be created by series of aluminum mullions, cable-mesh point-fix joints or metal trusses. The cable tension structures is relatively younger than conventional mullion system. For some projects cable structure provides more aesthetical view in terms of reduced metal frame elements. This systems can be found in two or four sided capless glazing assembles.

The silicone sealant between the glass units is vapor permeable. When high indoor humidity is demanded where the structural silicone may be subjected to high humidity during the winter, a cap head of moisture resistant sealant can be applied for minimizing the diffusion of humidity.

3.5 | Performance Requirements of the Curtain Wall

As well as the other exterior wall systems, for any kind of curtain wall system it is needed several performance requirements. Air leakage control (the air barrier function), vapour diffusion control (the vapour barrier function), heat loss-gain control (insulation and thermal breaks) and rain water penetration control compose to performance requirements of the curtain wall. The building envelope often represents a significant portion of the overall cost of the building construction. The evaluation of the envelope performance during the pre-construction and construction process has remarkable role in order to prevent undesirable conditions and costly problems among the life span of the building.

Majority of the envelope based performance problems are occurred by air leakage and water penetration issues. Thus controlling the air leakage and creating waterthighted curtain wall systems have an essential importance for the envelope performance.

Performance requirements of the curtain wall systems should be established according to different design parameters like building height, geographic location etc. on case by case.

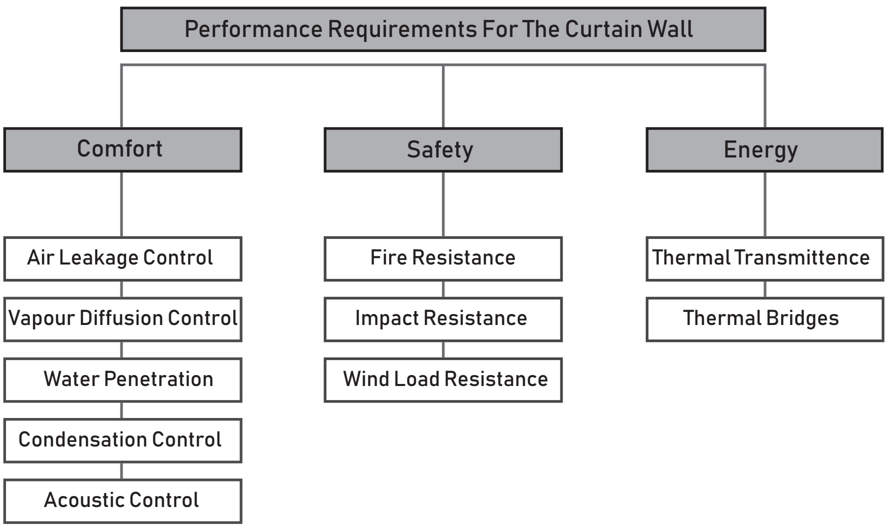


Table 3.3; Classification of the curtain wall performance requirements Elaboration of the author.

3.5.1 Comfort Performance Requirements

Air Leakage Control

Air leakage generally occurs due to poor product design, poor quality control during the manufacturing and poor detailing during the installation. Any kind of air leakage to the interior of the building causes undesirable interior comfort for the users, excessive condensation on the interior side of the building. Additionally in winter, it can form icicles on the aluminum caps, at parapets and soffits that can be sometimes even harmfully dangerous for the people and property. Condensation is became on the glazing cavities damage the IGUs and it can decay the backpans and fasteners. Excessive condensation can bring into an IGU to prolonged edge dipping in water. This can destroy an IGU in a few years even if the dipping in water runs for a few months.

When it occurs pressure difference between the interior and exterior by wind or temperature differences, air will flow through cracks between window components. Air leakage leads to higher heating or cooling loads. Also it takes part on the summer cooling loads by raising interior humidity. Generally operable windows generate the air leakage by sash and frame elements between the window and wall joints. That's why sealing and weather stripping have importance for air controlling. While this is the situation for operable windows, fixed glazing elements of the curtain wall are more efficient for sealing and tightening.

The amount of infiltration depends on the climate and especially wind conditions. Also rain can penetrate the curtain wall if it is not well sealed or air tight. Through the wind pressure, rain water enters into glazing cavities of curtain wall. The rain water can accumulate in a cavity until it overflows into the building. Under the water effect it occurs decays as it was mentioned above.

Generally, an aluminum curtain wall is air tight. In a typical stick built curtain wall section, the air barrier plane is continuous and structurally supported. Specifically, the air barrier plane may be traced through a section to include the glass of the IGU, the seal between the glass and the aluminum mullion, the aluminum of the mullion, the seal between the aluminum mullion shoulder and the backpan, the metal liner of the backpan, the seal between the bottom of the metal pan and the shoulder of the mullion below which connects with the glass of the sealed unit below. In plan, the same tracing of the air barrier plane would apply. The leakage of air at the glass aluminum joint is minimized with either a wet or dry seal. In a unitized system, the mullions are split and therefore include an additional air barrier joint between the half mullions. This joint is usually hidden and inaccessible once assembled.

Air leakage resistance performance are established by local building and energy codes of the each region. They have changes for the fixed and operable sections. In Europe reference standards are EN 12152 and EN 12153 for airtightness performance of the curtain wall under positive and negative static air pressure. The classes are determined according to the length of the fixed joint or to the total area of the testing envelope. Based on the EENSULATE module, these classes are listed below together with the associated pressure tests that must be made in order to ensure that the class is reached.

Table 3.4; Air tightness classes according to EN 12152 standard. Elaboration of the author.

Max Pressure Pmax (Pa)	Allowed Permeability (m3 /m.h)		Class
	Length of Fixed Joint	Total Area	
150	0.5	1.5	A1
300	0.5	1.5	A2
450	0.5	1.5	A3
600	0.5	1.5	A4
>600	0.5	1.5	AE

For air permeability > 0.5 (1.5) m3/m h at pressure < 150 Pa there is no classification possible. For air permeability < 0.5 (1.5) m3/m h at pressure > 600 Pa modules are classified as E (Exceptional).

Vapour Diffusion Control

Sometimes wall cavity wall wetness or condensation can occur vapour diffusion through an exterior. But in a contemporary curtain wall regardless from its type; stick, unitized or structural glazing components such as aluminum extrusions, glass, sheet metal panels, gaskets are produced vapour diffusion resistant. Cavity moisture is not problematic except from the silicone sealant on the inside surface of the IGUs. Also that can be protected with a butyl cap sealant.

Water Penetration Control

Like all the other exterior wall systems rain water penetration of curtain wall is one of the crucial point for pretending the building skin and interior. Generally curtain wall components are aluminum, steel, glass etc. While these materials are corrosion resistant and interaction with water does not give damages to the system materials, they don’t have ability for water absorbing and releasing.

The rainscreen principle is applied for exalting the water penetration control on a glass and aluminum curtain wall system. According to the Quirouette, the rainscreen principle incorporates many features to control such as:

- Direct entry of rain or melt water
- Capillary action
- Surface and cavity drainage
- Pressure equalization of the glazing cavities

In a stick built system, exterior seals and gaskets at the glass to cap joints provide resistance against direct rain and melt waters. However, a minor amount of water will pass through the head, jamb and sill gaskets or seal of the vision glass. It is channeled via the jamb cavity laterally and downwards to the sill glazing cavity.

Then it is conducted to the drain holes by the corner blocks and into the curtain wall snap caps to drainage outside.

In a unitized system, a sealed glazing unit is often placed on two setting blocks which are located at the quarter spans. At these support blocks, manufacturers of the units punch a third drain hole in the centre of pressure plate for drain off the moisture that can enter the glazing cavity along the sill between the setting blocks. Punching the drain holes in the pressure plates should be no higher than the bottom of the drainage cavity.

Water penetration performance requirements have changes depending on the building's height, location and exposure classification. In Europe, reference standards for watertightness are EN 12154 and EN 12155. These standards define the requirements and classification of watertightness both for fixed and operable parts of curtain wall. This EN 12154 standard is constituted by five classes which cover all locational and regional conditions can be experienced. Based on the EENSULATE module, these classes are listed below together with the associated pressure tests that must be made in order to ensure that the class is reached.

Class	Pressure steps in Pa and test duration in minutes Pa/T	Water Spray Rate I/min m2
R4	0/15; 50/5; 100/5; 150/5	2
R5	0/15; 50/5; 100/5; 150/5; 200/5; 300/5	2
R6	0/15; 50/5; 100/5; 150/5; 200/5; 300/5; 450/5	2
R7	0/15; 50/5; 100/5; 150/5; 200/5; 300/5; 450/5; 600/5	2
RE XXX	0/15; 50/5; 100/5; 150/5; 200/5; 300/5; 450/5; 600/5; above 600/5 in steps of 150 Pa and 5 minutes duration.	2

Table 3.5; EN 12154 standard pressure steps and corresponding water tightness classes. Elaboration of the author.

Specimens with water leakage at less than 150 Pa cannot be classified.
Specimens without water leakage more than 600 Pa are classified E (Exceptional).

Condensation Control

Condensation resistance performance requirements additionally the building's location and climate conditions it is also directly related with the interior hygrothermal design conditions as well as the interior function.

Condensation occurs on the glass and aluminum surfaces of the curtain wall whenever the humidity of air contacts with a cold surface and it changes form from vapour to liquid. At the dew point (condensation) temperature of surrounding air, this change happens. For determining the dew point temperature the dry bulb temperature and relative humidity should be known. By psychrometric chart, at a given temperature and relative humidity which are decided based on the building function may be determined the dew point temperature. After finding the dew point temperature for the designing building it must be provided that temperatures of the glass and aluminum surfaces not falling below that temperature for preventing

the condensation on the glass or aluminum surfaces of the curtain wall. Then it is determined minimum curtain wall indoor surface temperature according to outdoor and indoor design temperatures with temperature index (Tindex) or with another name f-factor of curtain wall components. The result of the calculation gives the temperature at the indoor surface of the glass (Tglass) and it must be higher than dew point temperature. If it is not condensation will occur on the glass surface. For reaching this temperature, it can be chosen components with higher temperature indices or it can be prescribed lower indoor humidity. The temperature factors generally are calculated at the weakest positions of the envelope. The temperature index concept provides specifying the minimum thermal performance value for an IGU or other curtain wall components.
The psychrometric chart is given on the figure and the formulas are below for calculating the temperature index;

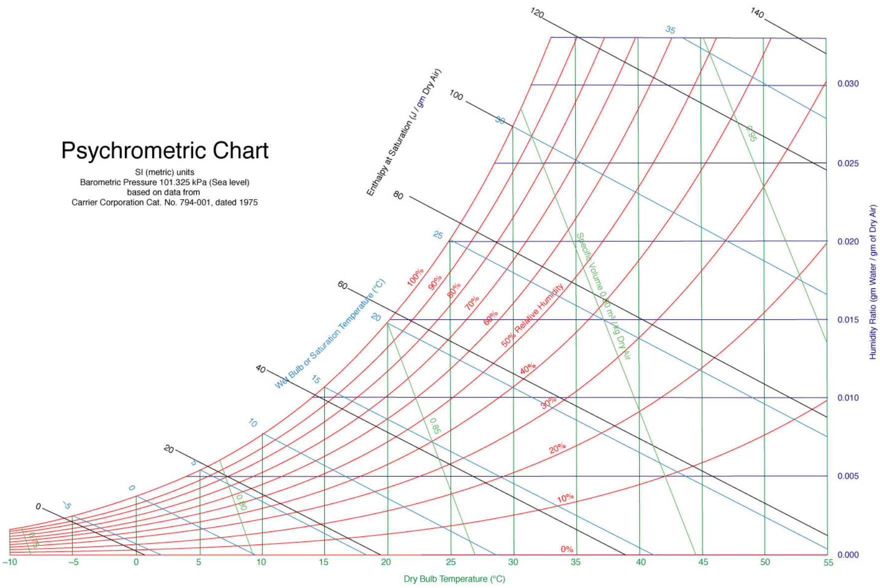


Figure 3.39;
Psychometric Chart.

https://sciencing.com/read-sling-psychrometer-5333022.html

$$T_{glass} = T_{index} \times (T_{ind} - T_{out}) + T_{out}$$
$$T_{index} = (d_{tind} - T_{out}) / (T_{ind} - T_{out})$$
(*d_{tind} describes the dew point temperature)

In Europe, several regulations reference the EN ISO 13788 methods for minimum permissible temperature factors. These values are created based on the specific outdoor conditions and critical surface relative humidity values. Thus these factors show alterations according to countries. There are some European country examples are given below on a table. For most of the countries of central and northern Europe, the critical humidity of the inner surface is taken 80%. Based on the surrounding climate conditions take into considerations about condensation issues of the curtain walls are important for both comfort performance requirements and the life span of the curtain wall. Because condensation can cause mould formation on the internal surface of the building elements.

Country	Minimum f-factor $f_{Rsi,cr}$	Comments
Czech Rep.	0.75	Requirements for the temperature factor are set differently for opaque structures and fill openings. For opaque structure the criterion is the formation of mould exclusion, for windows the exclusion criterion is the surface vapour condensation. Critical relative humidity of the inner surface 80% (mould formation).
Germany	0.7	Critical relative humidity of the inner surface 80%
England	0.30	Storage buildings
	0.50	Offices, retail premises
	0.75	Dwellings, public buildings
	0.80	Sport halls, kitchens, canteens (builidngs with un-flued gas heaters)
	0.90	Buildings with high humidity e.g. swimming pools, laundries, breweries
Ireland	0.75	Temperature factor at the thermal bridges positions.
Italy	0.766	Critical relative humidity of the inner surface 80%
Poland	0.72	
Spain	0.42/0.90	Critical relative humidity of the inner surface 80%. The values of fRsi,cr as given in the relative regulatory document differ with regard to the hygrometric class and to climatic zone.

Table 3.6; According to EENSULATE module limit f-factors as indicated in several national regulations of EU countries. Elaboration of the author.

3.5.2 Safety Performance Requirements

Fire Resistance and Fire Reaction

There are two main concerns about national regulations regarding the fire safety of the buildings. Fire resistance and fire reaction describe different notions.
According to EENSULATE module the fire resistance indicates the length of time during the fire a construction can;

- Conserve its mechanical properties (Criterion R-Load bearing capacity)
- Avoid the spread of flames, combustion gases, inflammable gases and smoke on the non-affected side (Criterion E – integrity)
- Prevent the temperature rise in the not exposed to the fire surface (by 140°C on average and by 180°C at maximum) (Criterion I – insulation)

The fire resistance of the building and constructions have different or combined classes of both. The fire resistance classification is monitored in minutes (ie 30, 60, 90, 120 and others), which determines the time during which a performance criteria is met during a standard fire test.

The fire reaction defines another concept different from the fire resistance of the building. It is characterized by the materials as their combustible behavior. Combustibility corresponds to the quantity of heat emitted by absolute combustion of the material. Inflammability corresponds to the quantity of more or less inflammable gases emitted by the material under the action of a heat source (EENSULATE module). In Europe A1, A2, B, C, D, E and F classes exist for the building material based on the fire reaction tests. Additionally, smoke development (s1, s2, s3) and potential projected burning droplets (d0, d1, d2, d3) are regarded on the rating schemes. The Euroclasses has been replaced with most of the national classifications of countries. The inspected fire reaction features are ease of ignition, spread of flame, evolution of smoke and toxic gases, and heat release rate of the burning material which are prominent to define if a fire is likely to start and how it will be improved.

	Performance Aspect	
Building Components and Materials	Reaction to Fire (EN 13051-1)	Resistance to Fire (EN 13051-2)
Building Materials	Belgium, Denmark, Finland, Iceland, Italy, Norway, Poland, Spain,	Germany
Insulation Materials	Belgium, Denmark, Finland, France, Germany, Iceland, Italy, Norway, Poland, Spain, Sweden, UK	Germany
Flame Retarded Insulation Materials	France, Germany, Iceland, Italy, Norway, Poland, Spain, Sweden, UK	Germany
Walls	Czech Republic, Denmark, Finland, Germany, Iceland, Italy, Sweden, Spain, UK	Cyprus, Czech Republic, Finland, Germany, Greece, Italy, Poland, Spain
Sandwich Panels	France, Germany, Iceland, Italy, Norway, Poland, Spain	Czech Republic, Germany, Italy
Facades	Czech Republic, Denmark, Finland, France, Germany, Sweden, Spain, Poland	Czech Republic, Germany, Italy, Spain
Cladding Systems or Complete Products	Germany, Italy, Spain, Poland	Italy

Table 3.7; Reaction and Resistance to fire. Elaboration of the author.

Impact Resistance

Impact resistance is a building envelope necessity for defending against impacts that are occurred by heavy winds, strong raining, storm, hurricane and also burglary so on. For impact resistance, EN 12600 (flat glass), EN 14019 (curtain wall) standards are reference in Europe. The EN 14019 standard specifies the requirements and classifications of a curtain wall under an impact load. The classes are characterized according to maximum impact load depending on the drop height. Under this conditions expectation is taking any breakage, hole or any permanent deformation of the curtain wall. The table below shows the impact resistance classes with the associated load tests.

Drop Height (mm)	Class
Not Applicable	I0/E0
200	I1/E1
300	I2/E2
450	I3/E3
700	I4/E4
950	I5/E5

Table 3.8; Impact resistance classes according to EN 14019. Elaboration of the author.

Wind Load Resistance

The wind loads are predicted during the design process of the building based on the building's type, height and configuration. The wind load resistance is a measure of structural strength of the profiles and it is tested by applying air pressure for simulating the wind loads. There can be seen differentiations country to country in the sense of special applications. For example high rise buildings or irregular formed buildings are usually experimented by wind tunnel tests. The curtain wall components must be resistant to deflections and failures with respect to these tests. In Europe related performance standard about curtain wall wind load resistance is EN 13116. This standard mainly sets the allowable deflections and recovery of deformation over the curtain wall components. According the EN 13116 standard, where L is the length of the longer frame element;

- Deflections under the design wind load must be < min (1/200 of L, 15 mm)
- Also 95% of the accounted deformation under the design wind load must be recovered in 1 hour.

3.4.3 Energy Performance Requirements

Thermal Transmittance

Thermal transmittance describes the heat flow due to conduction, radiation and convection through building components into to building. The value of the thermal transmittance coefficient is known as U-value of a building component. The thermal transmittance is strongly in relation with building's energy efficiency and performance. The value of the thermal transmittance of a building component is calculated based on the national regulations with international standards. In Europe EN 13947 is a standard for calculating U-value of curtain wall components as glazed or opaque and fitted in or connected to frames.

International standard ISO 12631:2017 specifies a method for calculating U-value of the building components in equal differentiation with EN 13947 standard as glazing and opaque and fitted or connected to frame. The calculation includes;

- Different types of glazing, single or multiple layers of glazing, with or without low-e coating, cavities with or without filled air or other gases.
- Any kind of material that composes the frame without thermal breaks.
- Different types of opaque panels cladded with any materials.
- Thermal bridge effects at the connection between the glazing, the frame and the panel areas.

The calculation does not include;

- Solar radiation effects.
- Heat transfer through air leakage.
- Condensation.
- Shutter's effect.
- Extra heat transfer at the curtain wall's edges and corners.
- Connections to building's main structure nor through fixing lugs.
- Curtain walls that include integrated heating.

As it seen, calculation of the U-value is based on the elements which are constituted by different material layers, thicknesses, boundary conditions and other various properties. In this sense, type of glazing units with low U-value and usage of spandrel panels with any kind of insulation have significant importance for envelope performance of the building. The thermal transmittance of an opaque element is affected by three different aspects which are existence of an insulation layer, the thickness of the element and thermal conductivity value of it. The regulations of the maximum allowable U-values of building components have changings depending on the European countries. Primary cause of this differentiation is countries have

various climatic conditions according to their geographical locations. Additionally, some countries have different U-value limits for each zone that are subjected to different climates in the same country.
There have been many assorted standard tests for evaluating the thermal transmittance of curtain wall components. In modern age, computer simulations with combination of standard test results determine the U-values of glass products. This procedures include an overall U-value depending on the glass edge and the centre of glass unit.

Thermal Bridges

Thermal bridges define the thermally weak parts of the building envelope that behave highly conductive for heat flow. These thermal bridges mostly occur on the connection points of envelope with main structure. Existence of thermal bridges on the envelope elements increase considerable amount of energy consumption of the building.

Thermal bridges can be categorized as liner thermal bridges and point thermal bridges. The categorization between these two types includes differentiation on dimensions, characteristic of the heat flow based on the position.

Based on the EENSULATE module, in the almost all European country regulations there are reference values for linear thermal bridges and recommendations for avoiding the extreme thermal losses. But limiting values for thermal bridges are very rare. Limitations for point thermal bridges are even less common, as well as some countries disregard it (for example Greece). In Spain, Denmark and Ireland building codes there can be seen various linear thermal loss at various positions specifically for at jambs, windows and roofs.

The mullions of the curtain wall must be considered as thermal bridges. Generally, mullions are made of aluminum profiles and they act four times more conductive than steel profiles. Even if spandrel panels and floor areas in connection with them are insulated, mullions may create thermal bridges among the all curtain wall system. Thus typically thermal break elements with less conductive materials like polyester reinforced nylon are located between the face plate and the rail of the mullion in line with the glazing pocket. These thermal break elements obtain cold side for the exterior part of the frame and warm side for the back. Insulation of the spandrel panel is often settled inner surfaces of the rails along the backside of it and is supported by a metal backpan. Usage of this kind of insulation detail depending on the conditions, decreases 70% of the thermal performance.

Additionally to this system, according to AIA Upjohn Research Initiative other techniques are experimented for improving the thermal bridge insulations on the industry. One of them is inserting spray foam into the rails for creating continuity between the insulation and the thermal break. Comparing with the air filled rail, this system achieved a little success. Because aluminum is conductive for the heat and insulation inside the frame is insufficient for thermal break. It is observed 60% decrease on the thermal performance as the result of spray foam experiment. Another examination is adding a insulation band along the backside of the rails. This created continuous thermal barrier as it is aimed, however, rigid insulation band requires a metal backpan due to being flammable character and suitable for damages. Metal backpan is wrapped around it and attached to the mullions. It is provided an efficient continuous path for heat loss through very thin metal backpan. As same as the spray foam assembly this method created 60% decrease. The last alternative for thermal performance reduce is application of structurally glazing steel frame with triple glazed unit. In this system, glass surface covers the mullions on the front side due to its configuration. Therefore inherent restriction is provided for metal elements of the curtain wall. As a result 30% reduction on the R-value of spandrels is seen.

Region	Countries (Main six ones in colour)	Total floor area Mm^2	Heated floor area Mm^2	Cooled floor area Mm^2
Southern Dry	Portugal, Spain	105	94	94
Mediterranean	Cyprus, Greece, Italy, Malta	81	73	73
Southern Continental	Bulgaria, France, Slovenia	234	211	149
Oceanic	Belgium, Ireland, UK	157	142	100
Continental	Austria, Czech Rep., Germany, Hungary, Luxemburg, Netherlands	469	422	300
Northern Continental	Denmark, Lithuania, Poland, Romania, Slovakia	155	140	99
Nordic	Estonia, Finland, Latvia, Sweden	59	44	31

Table 3.9; Climatic regions, countries and associated office heated and cooled floor area m^2 Elaboration of the author.

3.6 | Failures of the Curtain Wall Systems

Alike the other building enclosures many factors affect to the curtain wall performance. During the curtain wall's life span inherently these factors often can cause hazards and be problematic for the occupants and the building itself. In the fundamental forms the curtain wall composes of frame and glazing. Natural reasons and inadequacies of the materials and the connections that subject at the starting point or late after during the building's existence are shown on the frame or glazing units of the curtain wall. If these deficiencies will not be fixed it affects very badly to the curtain wall performance as a building envelope. When the curtain wall is subjected with four main factors inadequacies or damages occur. These are;

- Environmental Factors (Wind, moisture, water, temperature, sunlight)
- Design Factors (Unmatched designs with the environmental conditions or building height, loads etc.)
- Product Factors (Choice of unsuitable glass or frame types, products with manufacturing problems)
- Application Factors (Undesirable joint connections, improper construction staff and field control)

Based on these factors, main problems that are shown on the curtain walls are water leakage, corrosion, heat gain and heat flow issues, lack of acoustic insulation, structural attachment problems, uncontrolled sunlight and aesthetic imperfections.

3.6.1 Glazing Failure

Nickel Sulfide Inclusions

Initially Nickel sulfide (NiS) doesn't take part in the glass components. It is the result of chemical reaction between nickel and sulfur which are put to glass batch during the manufacture. NiS stones are not harmful itself for the float glass and it doesn't take concern. When the glass is tempered or toughened they become very dangerous for the glass. Depending on the building location and the size of stone, the trapped NiS transforms to other phase. It causes spontaneous breakage with cat-eye shape on the tempered glass. Currently, the float glass process technology can't totally eliminate of NiS stone inclusions. For minimizing it requires more attention during the process and application of suitable tests after the manufacturing.

Hairline Cracks

They occur on the glass surface by excessive thermal loading. Particularly if the glass has a coating like tint or low-e film it is observed more. When the sunlight subjects to exposed portion of the glass, it tends to expand but unexposed portion remains cool. This obtains tensile stress that can lead to cracking, especially if the glass is not tempered or heat-strength.

Condensation
The condensation of the glass can indicate the interior relative humidity is too high or hermetic seal may have failed. If the problem causes by the interior relative humidity it can fix with an adjustment of heating and cooling equipment. While curtain wall components obtain, it permits air intrusion into the cavity and it compromises thermal performance and aesthetic values of the building.

Broken Glass
Except from the user's extreme approach to the glazing, it may break due to inappropriate engineering. Throughout the design process unforeseen differential movements can affect to the building during its performance. This movements can harm both the frame elements and glass depending on the type.

Inadequate Acoustic Insulation
Most of the time excessive access of noise to the interior space of the building happens with usage of single-pane glass. This maybe does not give any damage to building structure but it occurs unpleasant interior space. Replacement with the laminated or insulating glass can provide some noise reduction. Also for the spandrel panels, sound diminishing infills can be chosen.

Glare
Poorly designed glazing units in terms of glaring may occur issues to looking at the computer monitors or televisions. Besides more significantly, glare can affect badly to building's energy performance. Generally, Visible Light Transmittance (VLT) ratings is 40 out of 100 which reducing glare without compromising access of exterior view. When tinted glass is applied, VLT reaches about 70. Under this condition visual connection is obstructed. Both cases furnish uncomfortable interior space. Thus proper glazing should supply ample and sufficient view with natural light and comfortable indoor temperature.

Figure 3.40;
Various glazing failures of the curtain wall

https://pressroom.pella.com/why-did-my-new-window-crack/
https://glassmagazine.com/article/commercial/curta-in-wall-cautions

3.6.2 Framing Failure

Deflection

For a long time aluminum elements have been dominated the curtain wall framing systems. Aluminum framing provides many advantages comparing with the steel such as being lightweight material and having less costs. However, it is three times more deflects when same amount of load applies.
Even if the aluminum frame is not affected by the forces it can damage the glazing. Glass breakages may be caused by differential movements of the building. For preventing excessive deflection, mullions may be extruded into maximizing forms of the area moment of inertia or resistance of a particular cross-sectional shape. I beams is used often in the building construction for its wide-flange element particularly for the high area moments of inertia.
Another option may be steel-reinforcement to the aluminum curtain wall frame. It provides reducing the deflection while without adding excess depth to the frame. In this case apart from the aluminum components also steel profiles require water resistance for preventing corrosions and expansions which bring along the bowing outward of aluminum.

Free Fall of Frame Components

When it is adhered just with structural glazing tape solely without any mechanical attachments, trim covers constitute danger for people and properties below. Additionally, construction sequencing has consideration because swing staging and scaffolding can give damages to mullion covers. In this sense, maintenance of trim elements should be controlled regularly.

Aesthetical Issues

In contemporary practice, most of the time main body of the curtain wall constitutes by extruded aluminum mullions and transoms with metal joinery elements. Based on the different reasons such as abrasions by extreme weather conditions, corrosions as result of the contact with water, dirtiness etc., aesthetic imperfections can be seen.
These components require routinely maintenance and cleaning. Application of chemicals and refreshing the coating will protect the exposed sides of the metal elements while ensuring the appearance.

Figure 3.41;
Various framing failures of the curtain wall

https://www.researchgate.net/publication/271291199_Experimental_program_and_simplified_nonlinear_design_expression_for_glass_curtain_walls_with_low-level_blast_resistance/figures?lo=1&utm_source=google&utm_medium=organic

3.6.3 Sealant or Gasket Failure

Water and Air Ingress

Issues about water penetration is major problem since the curtain wall has been constructed. Rain water infiltration is preventing by interface elements; gaskets and seals. During the time water penetration systems of the curtain wall have been developed to achieve better water-tightness. There have been three main design concepts for controlling water penetration: exterior face seal, internal drainage and pressure equalized rainscreen (PER). Among these concepts the PER is the most contemporary and common water penetration resistance system in nowadays. Also the quality of the interface elements have been improved. Even so gasket and seal materials and water penetration systems serve a successful accomplishment, still water ingress may come true to the interior. This can happen due to workmanship on the field or abrasion on the components by time. In this sense, controlling during the construction process and maintenance regularly in the future have remarkable import.

Water penetration and air leakage of the curtain walls are closely interlinked. Limiting air leakage through the building envelope is significant for controlling energy efficiency, moisture problems, noise transfer, smoke propagation, indoor air quality, and durability (Becker, 2010). The face sealed and the rainscreen concepts have capability to provide an air barrier due to an impermeable plane. Apart from this, most components of the curtain wall such as glazing, frame, gaskets and sealants composed of airtight materials with contact or sliding joints. Thus the air flow is limited to the contact areas. The largest variables in the airtightness are the quality of workmanship, design flaws or deformations caused by loads (thermal, gravitational and wind) (Becker, 2010). In the aim of protecting water and air ingress through curtain wall there are off-site and on-site tests.

Gasket and Seal Degradation

A common cause of curtain wall issues are failure of gaskets and seals which are sub-elements between the frame and glazing and their aim is securing the glazing. Gaskets are located in between the glazing and the frame while they are generally plastic or rubber strips. It acts as a watertight seal and welcomes the glass against wind, thermal and seismic loads. During the years, under the effect of UV radiation and freeze-thaw cycle gasket material gets dry, shrinks and cracks. Because of the air spaces that are created by shrinking, system starts to take air inside and condensation, drafts and leaks occur. When gaskets get age they become disintegrated and pull away from the frame. This situation causes losing of glass stability and may crack.

Instead of compression gaskets, also structural sealant is used on the curtain wall systems. It defines the high-strength silicone product and it stabilize the glass to the frame. The signs of replacing the perimeter sealants are shrinking, pulling away from the surface, gaps, discoloration, brittleness.

Durability of the gaskets and sealants have significant role in terms of preventing from corrosion of metal components, condensation of the glass units and inadequate thermal performance. Due to these reasons, doing maintenance routinely and replacement when it is needed is important for both the gaskets and sealants on behalf of the curtain wall system.

3.7 | Retrofitting Conditions of the Curtain Wall Systems

Curtain wall failures are caused by various reasons such as degradation of framing, inadequate thermal performance or material issues. These problems need to be refurbished in sake of increase the envelope performance and the interior comfort of the building. The problems that every facade faces can be quite different from each other. Some of them solely responsible for energy saving problems, while some others can have serious abrasion problems. Like it was concerned before, curtain wall failures are related with environmental, design, product and application factors. In this sense every single case needs to be treatment individually. Also the life expectations are mutable based on the each facade. Due to variable characteristics of the building envelopes the refurbishment on the unified way is inconvenient and constrained.

General potential benefits that are provided by retrofitting the existing curtain wall are given on the below;

- Provision on higher thermal performance
- Improvement on the energy efficiency
- Reduction on the costs by energy consumption
- Provision on higher air and water control
- Improvement on the interior comfort
- Increment on the material sustainability
- Improvement on the appearance of the facade

The refurbishment methodology of the curtain wall can be complied according to the levels of the failures. While some cases require relatively superficial treatments, some needs deeper and complicated interventions. These are the main classification of the curtain wall refurbishment methodology, based on the variable intervention levels;

1. Maintenance (addition of the films or interior panels)
2. Over-cladding (addition of new exterior or interior layer)
3. Renovation (reposition of the glass and/or the frame components)
4. Re-cladding (creation of a new facade)

Nowadays many buildings in Europe have been abandoned or demolished in relation of the high energy consumption of the classical postwar curtain wall designs. As a result of modernism perception in that years, very transparent and clear-glazed buildings have been constructed.

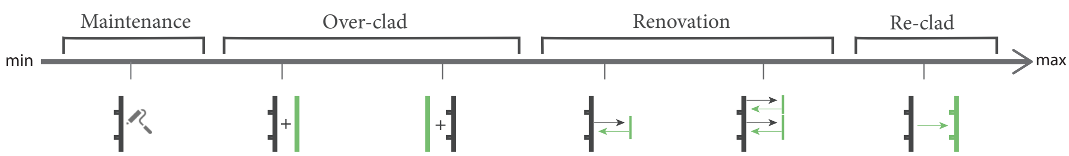
These buildings were built with very low insulation or even without insulation. Due to this, over the years buildings faced with challenges and crucial energy problems. When it is concerned to retrofit of the existing facade, sometimes totally demolition and rebuilt could be very first approach. But most of the time this solution brings the high costs and inappropriate designs with the original facade. Additionally if we mention to the middle-high rise office buildings, for the management of the waste materials which could last for a longer time period is problematic in terms of sustainability. Apart from this, another concern about the retrofitting is importance of keeping the same characteristic of the existing building facade. Not all but in some cases this situation can have essential importance. If we talk about a landmark building for the city or a historical building with its own aesthetic, giving back its original facade identity after the facade intervention must be substantial.

Retrofitting challenges usually are about financial, labor and time relevance. Furthermore occupation of the existing building, aesthetical matters and the site logistics are other adversities to deal with. In order to achieve optimum solution, every project should be recognized and understood for the existing conditions, the skin problems and the requirements for the future life. Among the life span of the building envelope, application of suitable strategy for maintenance, refurbishment and conservation are key elements for sustainability of the building.

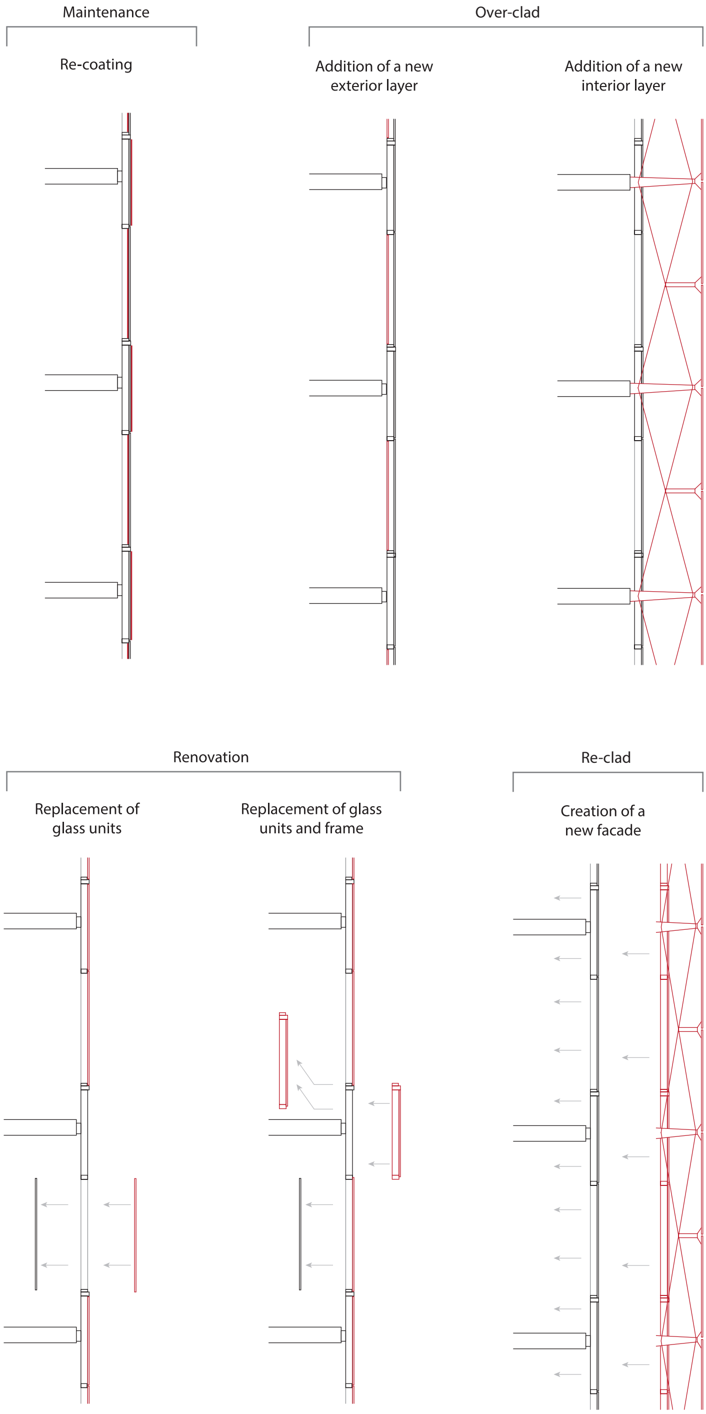
When all different factors are taken account for the curtain wall refurbishment there are six main subdivisions under the various intervention levels which were explained above;

1. Re-coating
2. Addition of a new exterior layer
3. Addition of a new interior layer
4. Replacement of glass units
5. Replacement of glass units and frame
6. Creation of a new facade

Drawing 3.8;
Six generic retrofitting strategies
Elaboration of the author.



Addition of a new coating layer over the existing frame components againist to the environmental factors. Also applicaiton of a new film layer to the glass units for thermal performance is act of maintenance.	Creation a double skin facade with addition of a new exterior curtain wall. This system does not give any changes to the exisitng facade but provides an insulation layer between the two skins.	It defines an addition glass unit with high insulation performance to the existing facade. Most of the time new units are film coated. The space between the existing and the additional glasses is filled with insulation gas. This system creates a sort of double facade.	Generally this system is used for reposition of the existing single-pane or low insulated glass units with the higher performance glass units. In some cases also for replacement of the broken glasses can be applied.	Depends on the project, degragated glass units, frame elements and sealants are replaced with the high performanced new ones.	In this system, totally new and high performanced facade is desigend. Demolition of the existing facade and construction of the new one require more effort than the other options. This way is chosen for very indispensable situations for continuity of the building.



Drawing 3.9;
Section of the six generic retrofitting strategies
Elaboration of the author.

3.8 | Case Studies

An overall study about the glass and metal curtain wall examples with their assembly techniques, failures and suitable retrofitting methods have been accomplished during the research process. Approximately 100 hundred case studies in international contexts have been scanned. The building examples have served in different periods of the history with the various assembly techniques and the materials. Interrelated with these aspects, some lacking or insufficiency of the glazing, the frame or the sealant components resulted in failures of the curtain wall systems.

Explained six curtain wall retrofitting methods have been found in assorted case studies. While the office building examples in Europe have had limited technical documents, drawings or information in terms of retrofitting processes, USA equivalents have supplied more open sources to public. Furthermore, it might be a result of the historical value or landmark status of the USA examples. Although they are located in different geographical locations, there is not any disparity in terms of building typology, function, environmental conditions and material in studied European and USA office buildings. Thus six case study have been chosen in USA for explaining and understanding the common metal curtain wall failures and the strategies for facing with them.

Figure 3.42;
860-880 Lake Shore Drive

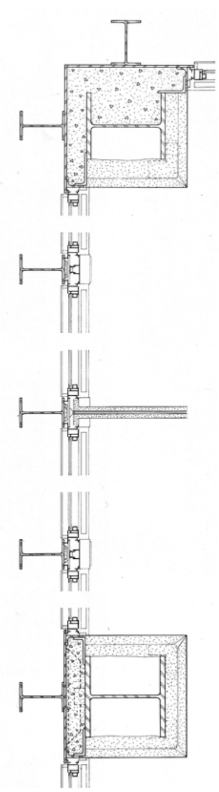
https://www.archdaily.com/54260/mies-van-der-rohe-lake-shore-drive-restoration-

3.8.1 860-880 Lake Shore Drive

Location: Chicago, USA
Completion: 1951
Material of original curtain wall: Glass and stainless steel-aluminum
Retrofitting date (for curtain wall): 2009
Main problems: Corrosion of the exterior cladding
Method of retrofitting: Re-coating
Architect of retrofitting: Krueck & Sexton Architects

The residence complex with two towers which is located along Lake Michigan, was designed by Mies van der Rohe. It was imitated many times internationally due to its glass and metal facade. The curtain wall was composed by painted steel plates and I-sections which were fulfilled with aluminum windows. In contrary to aesthetic and elegant view of the steel framing, it faced with repairing problems of the steel mullions. In terms of the thermal performance, steel does not serve the best material performance. Additionally, maintenance of the steel frame is difficult and require higher costs. The two towers of the Lake Shore Drive had challenges about these concerns.

In 1992, the building had already a restoration due to water leakage. This time the facade needed a deep maintenance to solve corrosion issues on the exterior cladding. According to the site investigations, the over-coated steel frame lost its original color and at least 10% of the exterior surface had corrosion.



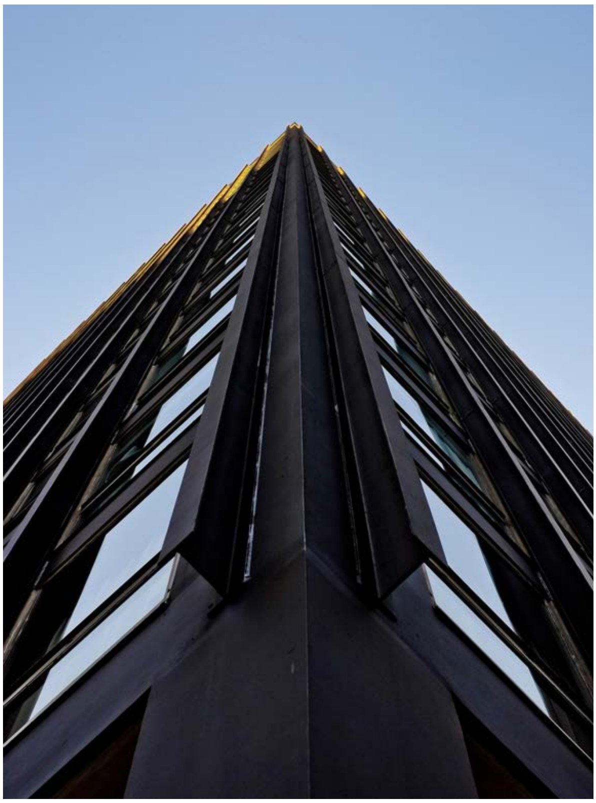


Figure 3.43;
Section and facade detail of 860-880 Lake Shore Drive

https://www.archdaily.com/54260/mies-van-der-rohe-lake-shore-drive-restoration-

Two alternative solutions were developed by the retrofitting team. These are; "strip to bare metal using a chemical peel, sandblast and repaint with a high-performance three-coat paint system with a semi-gloss urethane finish coat; or overcoat with the existing paint layers with a lower performance, although more forgiving, and flatter acrylic system."

After the considerations about optimum cost and longevity, the flatter acrylic system was applied on the steel frame. Before recoating process, rust and corrosion were removed from the surface.Apart from recoating on the steel framing, aluminum window surfaces were cleaned, the steel beams of the plaza were strengthened, the glass of the ground floor replaced with the low-iron sandblasted lites.

Figure 3.44;
Peter W. Rodino Federal Building

http://davidcoleaia.com/projects-by-type/civic/peter-rodino-federal-building/

3.8.2 Peter W. Rodino Federal Office Building

http://davidcoleaia.com/projects-by-type/civic/peter-rodino-federal-building/
Location: New Jersey, USA
Completion: 1968
Material of original curtain wall: Concrete clad
Retrofitting date (for curtain wall): 2013
Main problems: Deteriorating glass facades
Method of retrofitting: Addition of a new exterior facade
Architect of retrofitting: Dattner Architects

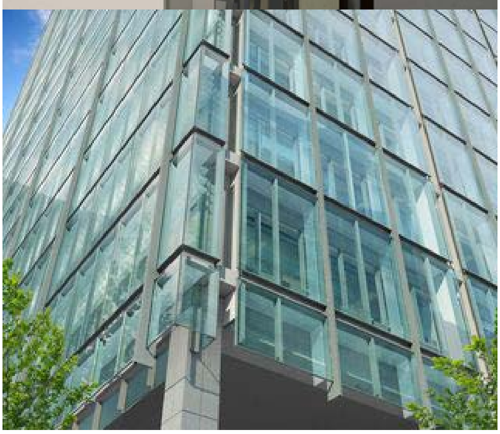


Figure 3.45;
Section of Peter W. Rodino Federal Building

http://davidcoleaia.com/projects-by-type/civic/peter-rodino-federal-building/

Figure 3.46;
Facade detail of Peter W. Rodino Federal Building

http://davidcoleaia.com/projects-by-type/civic/peter-rodino-federal-building/

The Peter W. Rodino Federal Building hosts many federal agencies such as Immigration and Customs Enforcement, General Administration office in the city of Newark.

After the decades of its construction, 16 – story Peter W. Rodino Building did not match with the current facility standards for buildings. The facade of the building was deteriorated and fossil fuel wasting was so high. In order to upgrade low energy performance of the building, it was decided to go on a refurbishment of the concrete clad facade. The exterior retrofitting process includes an over-cladding system in order to ensure blast protection for occupants, increment of energy efficiency and protection of existing precast concrete facade from further disruption.

Addition of a new suspended curtain wall in front of the existing facade dramatically changed the energy performance of the building. Multilayered facade prevents the uncontrolled, direct sun-light into the building. By this concept double-skin projection provided 32% reduction in energy consumption. After the modernization, the project achieved LEED V2.0 Silver certification.
Apart from the energy performance, addition of the new curtain wall facade at the outer side of the existing one transformed significantly identity of the building. It changed from solid concrete enclosure to the light and transparent skin. New facade enhances the cityscape with aesthetic value.

Besides the facade refurbishment, project includes full renovation of nine floors, repair of HVAC system, infrastructure work, domestic water distribution system and fire protection system.

Figure 3.47;
Retrofitting strategy of Peter W. Rodino Federal Building

http://davidcoleaia.com/projects-by-type/civic/peter-rodino-federal-building/

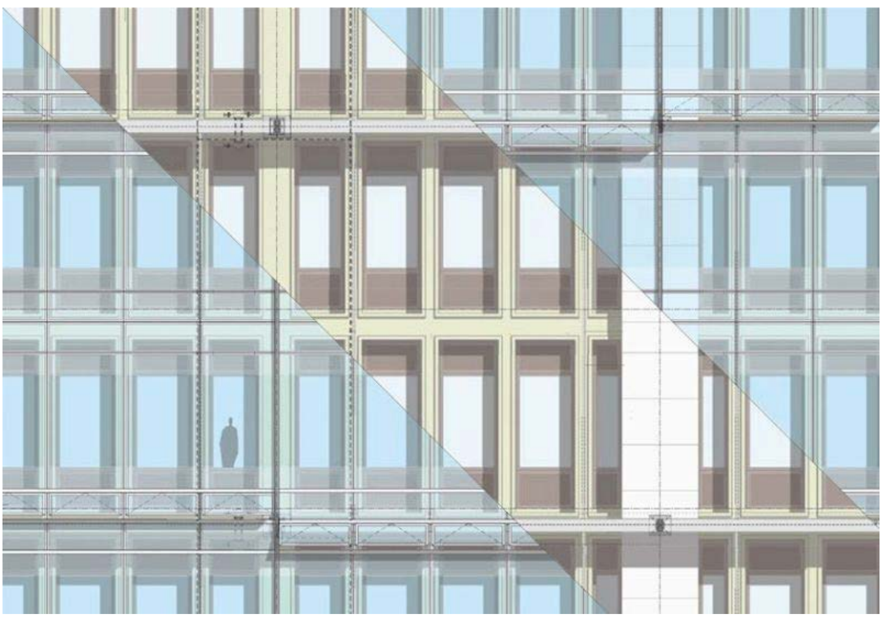


Figure 3.48;
Retrofitted facade of Peter W. Rodino Federal Building

http://davidcoleaia.com/projects-by-type/civic/peter-rodino-federal-building/

Figure 3.49;
10 Lafayette Square

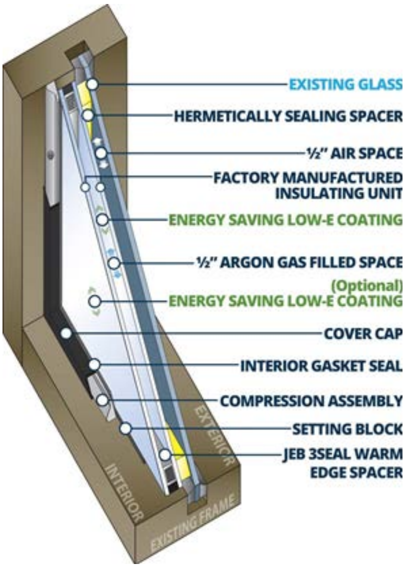
https://prismpub.com/renovate-by-berkowitz-transforming-an-historic-landmark/

3.8.3 10 Lafayette Square

Location: New York, USA
Completion: 1959
Material of original curtain wall: Glass and aluminum
Retrofitting date (for curtain wall): 2014
Main problems: High energy consumption
Method of retrofitting: Addition of a new internal layer
Architect of retrofitting: Carmina Wood Morris

Figure 3.50;
Insulated glass section

http://www.rbbwindow.com/renovate-system/



Designed by Emery Roth & Sons, 21-storey 10 Lafayette Square building was constructed in the International Style, modern look. When it was built, had disassociated from the surrounding buildings with its metal and glass curtain wall façade. 10 Lafayette Square served as an office building for a long time until 2003, then in relation with the ownership it was transformed to mixed-use building which has involved some restaurants, hotel, market-rate apartments and corporate offices.

At the time, it was built with single-pane glass units that does not match with the winter and summer conditions of the building. The increased complications about the solar heat gain in summer and insufficient heating in the winter times, dragged to go on a retrofitting on the curtain wall facade. Initially, design team have decided to replace existing glass units with the new ones, however according to the historic preservation criteria original glass and frame system must have to remain in place. Thus, optimum option became as an addition to the interior surface of the facade. By this way the historical appearance of the building have preserved.

The additional glass system is composed by two-lites of high performance glass which are low-e glasses to reduce heating and cooling requirements and provide solar control. The glass configuration have applied to meet with the northern climate zone conditions. 760 new insulating glass units have been installed on the interior surface.

Except from the addition of new insulating glass units, also replacement of broken glass, removing existing window film and cleaning the original glass and framing were included the retrofitting process. The project completed from top floor to bottom in three months. When it was accomplished, new facade system was fulfilled with thermal and acoustic improvements and cost-efficiency which could not be provided with other internal additions such as glass films and similar alternatives.

Figure 3.51;
The Empire State Building

https://www.structuremag.org/wp-content/uploads/2014/09/Empire-State-Building.pdf

3.8.4 The Empire State Building

Location: New York, USA
Completion: 1931
Material of original curtain wall: Limestone panels, steel framed windows, cast aluminum spandrel panels
Retrofitting date (for curtain wall): 2009
Main problems: Energy demand and thermal issues
Method of retrofitting: Replacement of the glass units
Architect of retrofitting: Empire State Realty Trust

Since it was built around 1930s, The Empire State Building has been one of the most iconic building in America. 103-storey Art-Deco styled building is located in the Manhattan. The original facade was composed by limestone facade with steel-framed windows and cast-aluminum spandrel panels, as back-up brick masonry. The huge energy consumption pushed building to a renovation on the existing facade. Thus an innovative and unusual retrofitting process has started in 2009. The program concentrated on the improvement of 6514 double hung windows in terms of thermal efficiency.

The original glass units have already retrofitted with the double-pane hung windows in 1991. This replacement changed the insulating R-value from R-1 to R-2. After 2000s again improved R-value was required and it could be provided by addition of new pane of glass. This scenario would be bring very high costs to replacement of both glass and frames. Thus suspended coated films, SCF as they known, served a better option. Without addition of extra weight or geometry, these film layers can be placed between two glass panes while they ensure equal or even better R-value than the third pane.

In this new process all the window units removed from the facade and they were transferred to the production area. By this way 4% of the existing windows became residual and 96% was reused on the facade again. The upgrading process of the

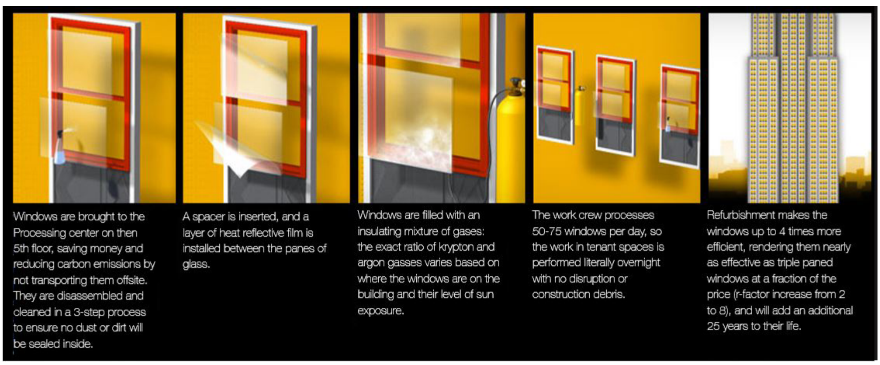


Figure 3.52;
Retrofitting strategy of the glass units

http://www.rbbwindow.com/renovate-system/

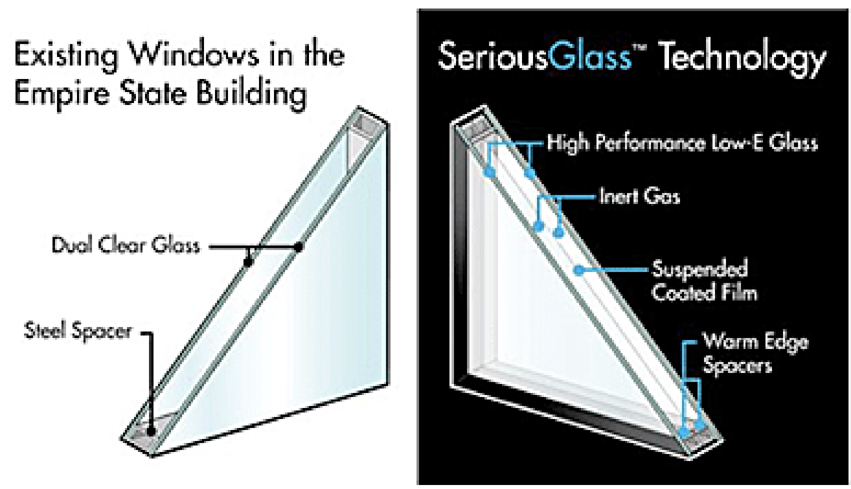


Figure 3.53;
High performed glass section

http://www.rbbwindow.com/renovate-system/

deconstructed windows was fitting of the new steel spacers, treatment with a film layer, baking in the oven and sealing with the gas of Kyrpton-Argon. Subsequently to all this process, upgraded window units were put back to the original aluminum frames. The manufacturing program of the insulated glass units took place in the one floor of the Empire State Building. Thus logistic costs were avoided and as well as time saving was provided.

As a result of facade retrofitting, reduction on the solar heat gain reached more than half of the former facade. In 2011, it was rewarded with LEED certificate for the energy efficiency.

Figure 3.54;
Retrofitting process on the site

https://www.structuremag.org/wp-content/uploads/2014/09/Empire-State-Building.pdf

Figure 3.55;
Lever House

https://www.som.com/projects/lever_house__curtain_wall_replacementkruek/5037dc3f28ba0d599b000010-mies-van-der-rohe-lake-shore-drive-restoration-kruek-photo

3.8.5 Lever House

Location: New York, USA
Completion: 1952
Material of original curtain wall: Glass and stainless steel
Retrofitting date (for curtain wall): 2001
Main problems: Water damage, breakage of vision and spandrel panels
Method of retrofitting: Replacement of the glass and frame
Architect of retrofitting: SOM

Figure 3.56;
Facade with vision and opaque panels

https://www.som.com/projects/lever_house__curtain_wall_replacementkruek/5037dc3f28ba0d599b000010-mies-van-der-rohe-lake-shore-drive-restoration-kruek-photo

Lever House has been an iconic office building which was constructed in Manhattan in 1952. It had innovative features in terms of facade construction detailing when it was designed. The tower was one of the first sealed-glass building and it became a pioneer to industry fabrication methods of the curtain wall. 24-storey building has represented a successful example of the glass box concept of 1950s. Lever House affected significantly high-rise building design to change from masonry to glass facades.

The facade of the building was composed by heat-strength glass and stainless steel framing. Blue-green heat-resistant vision glass able to reduce heating and cooling costs. All the facade was designed without any operable windows in terms of avoiding the dirt that can come into from the city. Even if building had an innovative maintenance system on the rooftop, over the years deterioration became on the curtain wall due to material and climate conditions. Therefore bowing of the horizontal mullions with breakages on the vision and spandrel panels come arise in relation to water damages. Additionally thermal stresses over the facade created cracks on the wired spandrel glass. In order to give back rewarded character to this historical landmark a retrofitting project was set about.

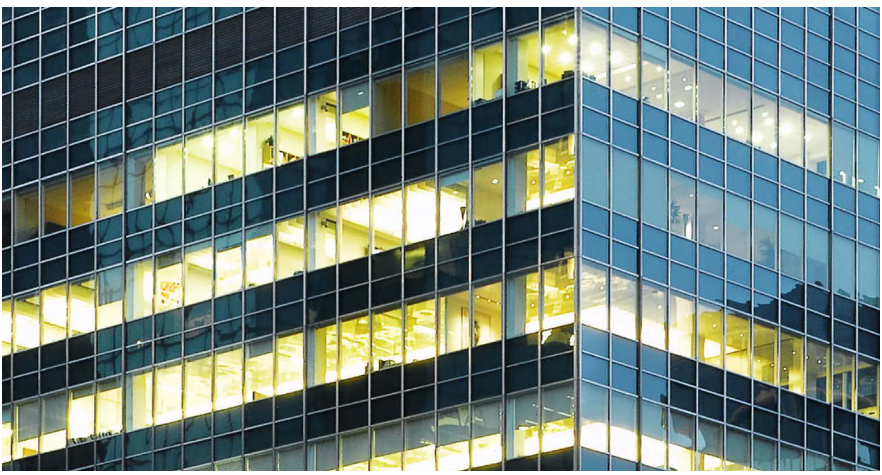


Figure 3.57;
View after retrofitting process

https://www.som.com/projects/lever_house__curtain_wall_replacementkruek/5037dc3f28ba0d599b000010-mies-van-der-rohe-lake-shore-drive-restoration-kruek-photo

The project led by Skidmore, Owings & Merill as same architecture office with 1952 original design. The retrofitting process was explained by SOM like this;

“To preserve the modern landmark without changing its appearance, old materials and systems were successfully replaced with state-of-the-art solutions in modern wall technology, including concealed aluminum glazing channels, stainless steel mullions and caps, and new panes of heat-strengthened PPG solex glass. Once again, this 20th-century icon is a glittering jewel in the Manhattan cityscape, expressing how enlightened design can make a work of art out of office space. The project also set a precedent for restoring a modern landmark.”

Additionally, underlying carbon steel structure of the curtain wall preserved as original, however just rust and recoated parts were removed. The new aluminum receiver system was supplied the old one.

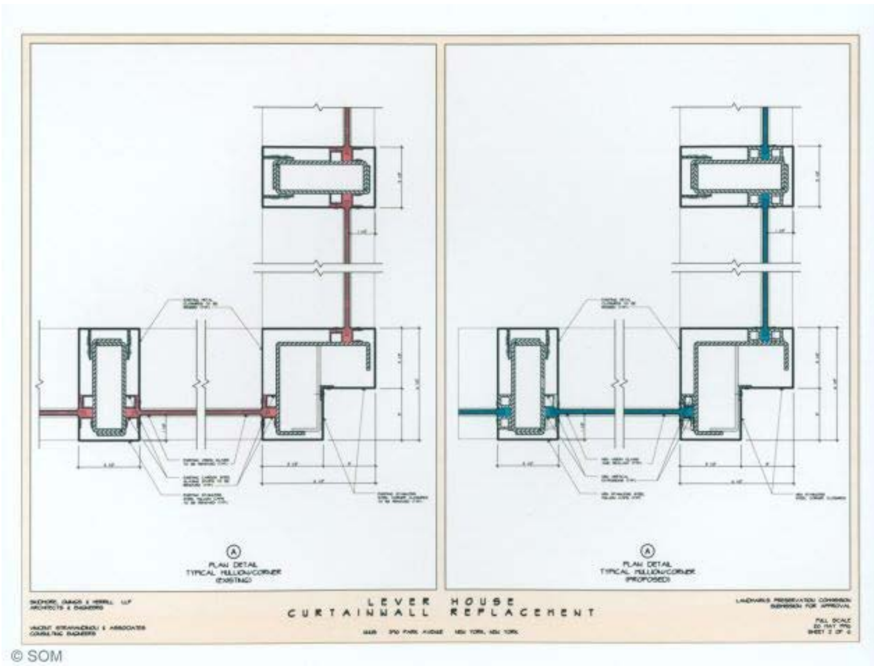


Figure 3.58;
Technical drawings of retrofitting project

https://www.som.com/projects/lever_house__curtain_wall_replacementkruek/5037dc3f28ba0d599b000010-mies-van-der-rohe-lake-shore-drive-restoration-kruek-photo

Figure 3.59;
475 Park Avenue South

https://commercialobserver.com/2014/06/talent-partners-takes-two-floors-at-cohens-475-pas/

3.8.6 475 Park Avenue South

Location: New York, USA
Completion: 1969
Material of original curtain wall: Brick
Retrofitting date (for curtain wall): 2015
Main problems: Lots of leaking from facade to into it
Method of retrofitting: Creation of New Facade
Architect of retrofitting: Rafael Pelli

35-storied 475 Park Avenue South is located as an office and commercial center in New York. Original facade was constructed with international style which had brick and inset windows underwent it.

Due to the extreme brick failures on the facade, brought the concern about the pieces that might fall on the ground below. Additionally to this, the original facade needed to aesthetic upgrade for marketing in the New York, center of the commerce. These reasons was pushed the building for totally new facade application.

While all the intervention phases building was occupied. In order to minimizing discomfort of occupants, removal of the windows was proceed at the nights and weekends. By this way, it was provided to keep going on construction without interrupting interior actions.

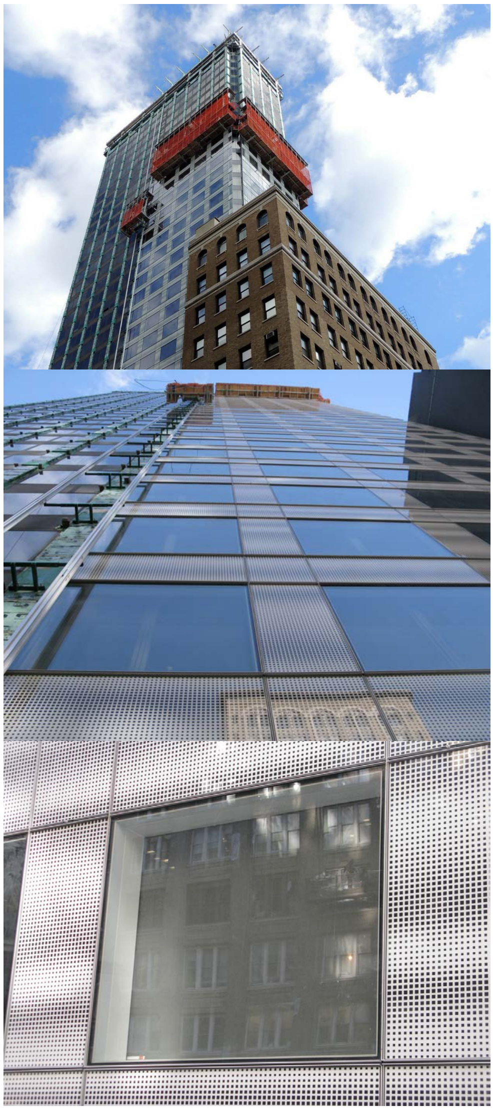


Figure 3.60;
Glazing details on the facade

https://commercialobserver.com/2014/06/talent-partners-takes-two-floors-at-cohens-475-pas/

As a first step, brick cladding was removed from the facade and for temporary period, it was covered by waterproof material. Meanwhile, Pelli and his team were experiencing varieties of different glass solutions. After studying many variations, final design of the facade included clear and patterned glasses. Patterned glasses were result of special combination of the clear glass and ceramic frit coatings. Six different frit patterned glasses completed the facade with contemporary aspect.

Secondly, new curtain wall units were installed by a suspended scaffolding system at the exterior side of the building. Application of the new units continued from top to bottom of the facade. The design team had deep studies for the chamfered edges of the building for reaching better image. They decided to extend curtain wall over the chamfered edges. Therefore more defined surface acquired on the facade. Stabilization of the curtain wall units to the building supplied by both new and existing anchorage elements.

When the facade was completed, it presented contemporary and unique stance. The appearances from far and close were different. Observation from the far provided a perception about patterned parts as metals. While at the close looking, it was clear that they were coated glasses. Thus the design team achieved success in order to create an illusion on the facade. This unrivaled study on the glass treatment showed how the glass might transform to other materials on its appearance.

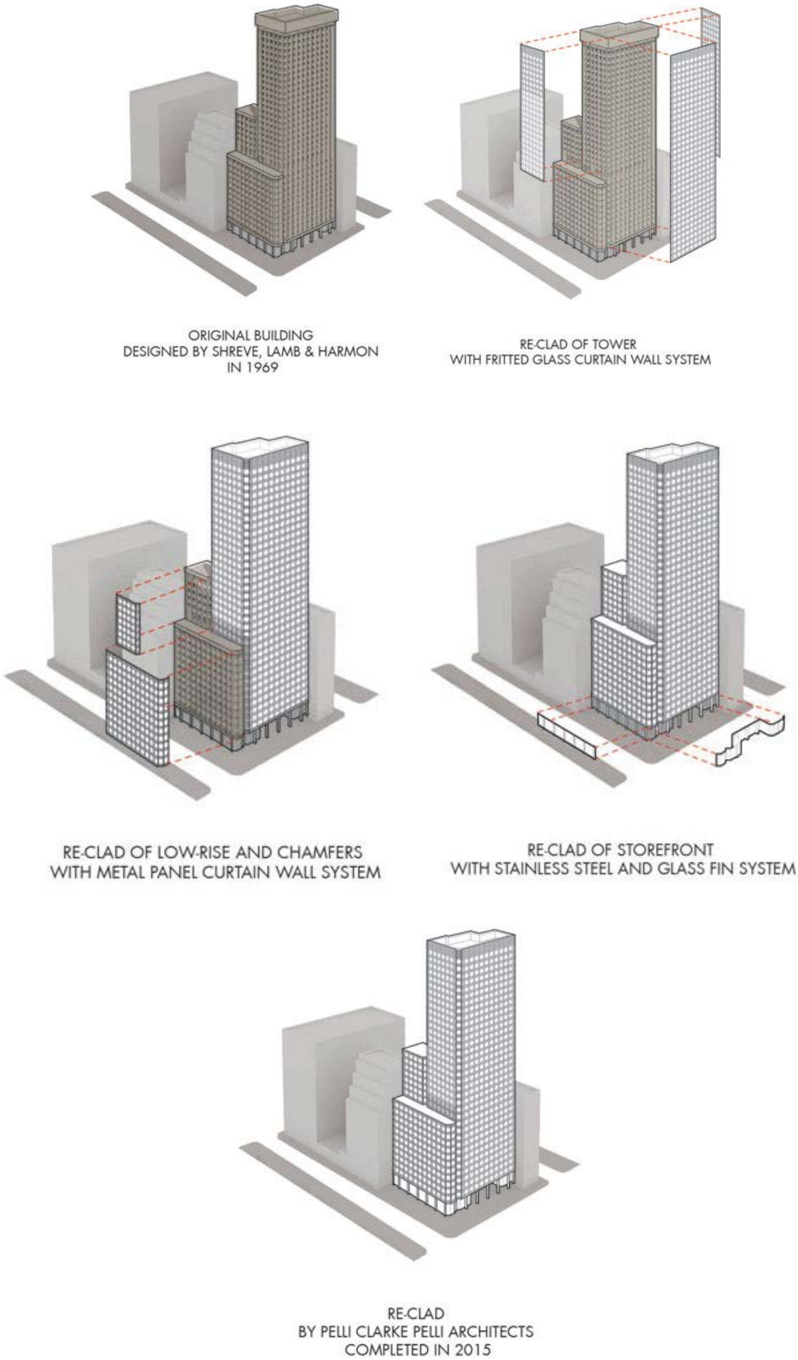


Figure 3.61;
Retrofitting strategy and process

https://commercialobserver.com/2014/06/talent-partners-takes-two-floors-at-cohens-475-pas/

4.1 | Summary of the Study

During the thesis, facade of the office buildings from 1950s to 2000s in Europe have been investigated. In general terms, the facade of the building is a transmission between the interior and exterior space, private and public. This significant role of the facade has triggered the idea of research and analysis office facades and their relations with the urban context and the interior space.

Based on the analysis from different sources, the office buildings take part as second biggest amount, %25, among the non-residential category of the building stock in Europe. When specifically the facade of the office buildings have been analyzed, it has seen, starting from the 1950s to nowadays curtain wall has contributed as the highest amount for facade type. Depend on the changing construction techniques and developments, different materials and application systems have been used. As a result of the researches, during the thesis six main curtain wall systems have been determined which are stick system, unit system, unit and mullion system, panel system, column cover and spandrel system, structural glazing system. Positive and negative sides of all the systems have been discussed at the other chapters before. Over these systems, stick and unit systems are most common for today's construction practices.

The structure of the usual curtain wall is composed by framing, glazing and sealant components. This kind of body requires attention for all the design, application and maintenance phases for whole components. Performance of the curtain wall is in direct relation with these elements. Three main performance requirements - comfort, safety, energy - for the curtain wall facade have been predicted on. In the conditions of lack or insufficient, curtain wall facade may failure in various ways. Throughout the research, four essential factors have been identified as the causes for the failures. These factors include environmental, design, product and application factors.

After studied different cases studies, it is understood that the curtain wall failures have been occurred intrinsically for each case. Most of the office buildings that have been built between 1940s and 1960s face with extreme energy concerns. Due to popular "glass box" trend of these years many of the office buildings have been designed without or incapable insulations for the building enclosure. Deficiencies on the country regulations also eased to design building facades just with philosophical and aesthetical matters. After 1960s and especially lately then oil-crisis in 1973, architecture world and European governments started to concern about thermal performance and solar control for avoiding exceed energy demands. At the following periods until 21st century, new advanced technologies and materials about glass facades have been explored and experienced. The comprise between the aesthetic and the performance have been fundamental issue in the design.

4.2 | Design Concerns

4.2.1 Curtain Wall Selection Criteria

It is understood that metal curtain walls can be composed by the metal framing and vision or spandrel panels with the glass. The classification of the metal curtain walls may be in various ways. After the all study, in here they are classified by type, assembly technique and glazing method. The following table shows the categorization of the metal curtain walls in mentioned concepts;

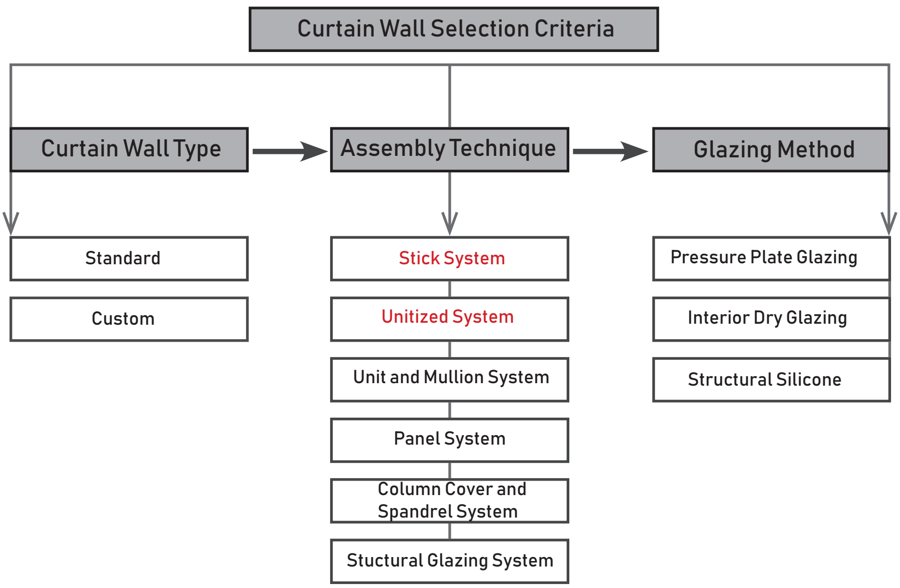
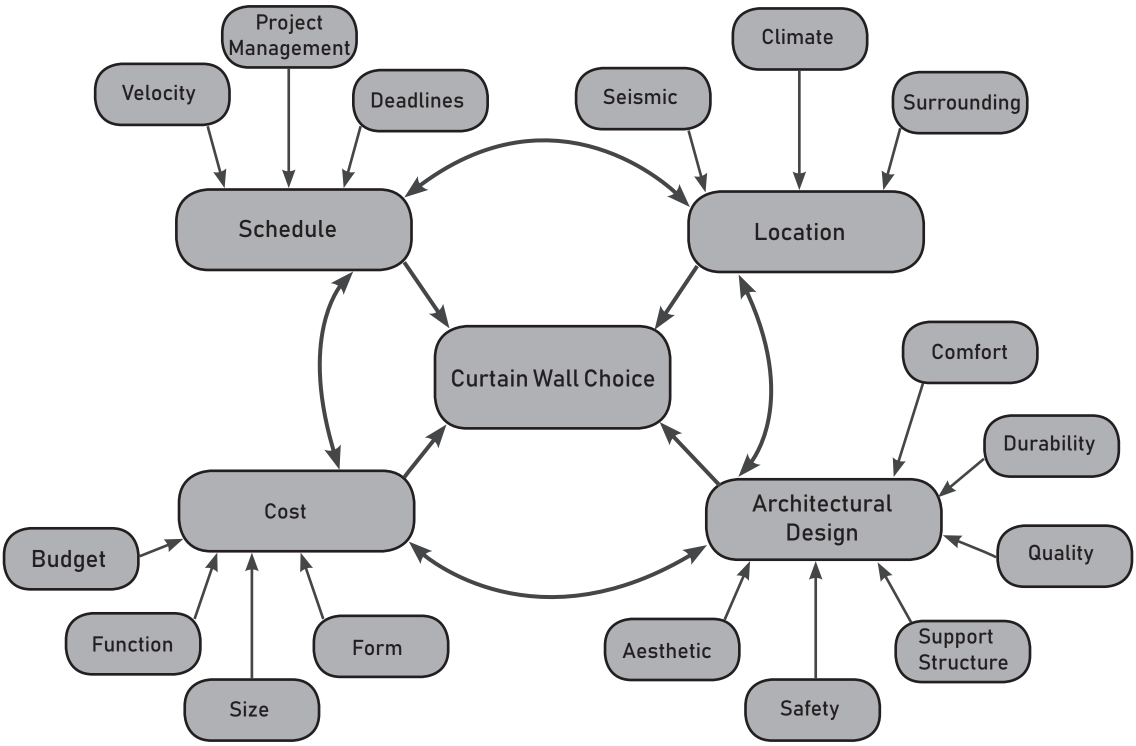


Table 4.1; Classification of the selection criteria Elaboration of the author.



Drawing 4.1;
The factors that influence
to curtain wall selection
Elaboration of the author.

4.2.2 Choosing the Curtain Wall Type

Two generic curtain wall types can be given as standard and customize. These two terms only refer to features of the curtain wall components, not to the curtain wall configuration on the facade. In order to build the curtain wall facade, most of the time standard curtain wall components may be chosen. On the other hand, for some specific facade designs, standardized component dimensions may not be convenient. In these kind of cases customized components that are created based on the project, can provide ease and satisfaction for the visual matter.

Standard Type: Components designed and fabricated by the manufacturers. Typically 6.5 m to 8.2 m are standard lengths for metal components. Frame width 50 mm - 63.5 mm, frame depth 75 mm - 150 mm are common standard dimensions.

Custom Type: Components and details designed specifically for a single project. In order to achieve architectural design requirements, it serves optimum material usage and flexibility.

Quality, aesthetic and durability can be supplied by both of the curtain wall systems. Since standard products have been used on the other projects, they have advantage to being reliable. Custom systems can require to improvement and testing against to the curtain wall failures.

Factor	Description of the Aspect	Standard	Custom
Architectural Design	Matching with required aesthetic level	●●●	●●●
	Matching with unique aesthetic level	●	●●●
	Meet with non-usual sections	●	●●●
	Reliability of durability and quality control	●●●	●●
	Historical references	●●●	●
Cost	More economical when facade size increases	●	●●●
	Suitabiliy to small-budget projects	●●●	●
Schedule	Fast site-delivery	●●●	●
	Assembly velocity on the site	●●●	●●
	Workmanship dependency	●●●	●●
Location	Access to the products in smaller locations	●●●	●
	Matching with extreme weather conditions	●●	●●●
	Compatibility to the country codes	●●●	●●

Table 4.2; Comparison of standard and custom systems.
Elaboration of the author.

4.2.3 Choosing the Assembly Technique

At the earliest chapters it was explained the generic six curtain wall assembly techniques. Over these systems while stick and unitized systems are still used the most prevalent, usually other techniques are not preferred due to not responding contemporary practices. In relation to this aspect, just these two systems will take place in the assembly category.

General features and configuration of the components were clarified for both of the systems. The table below shows the main comparison points between stick and unitized systems;

Adv./Dis.	Stick System	Unitized System
Advantages	• Less costs for shipping • Arriving to site on shorter lead time	• Significant quality control • Less dependent labour on the site • Rapid erection on the site • Arriving to site on longer lead time • Accommodates building movements • Provision of full pressure equalization control at the each floor • Allowance to the incremental expansion on the joints
Disadvantages	• Hard to control quality • Dependent to workmanship on site • Longer time of installation • Difficult to accommodate building movements • Challenges on the water drainage control • Poor acoustic and thermal performance • Possible deterioration on the expansion joints and sealant joints • It requires storage space for the components before the installation	• Arriving to site on longer lead time • Higher shipping costs

Table 4.3; Advantages and disadvantages of stick and unit systems.
Elaboration of the author.

The selection criteria of the curtain wall assembly technique is related to various factors. According to the some facade consultant firms and found researches, most crucial aspects can be like below for choosing the most suitable system for the project;

- The total size of the facade
- The form and dimension of the facade
- Behavior under seismic movements
- The degree of repetition parts
- The degree of planarity

Evaluation Based on the Crucial Aspects

The total size of the facade: When it goes larger facade size, it is more convenient to design with unitized system. Due to rapid erection and less labour costs, for a typical all-glazed curtain wall facade, unitized system has more advantages. Independently from other factors, for the total area less than 3.000 m2 stick system and more than 5.000 m2 unitized system could be more effective. Development of a unitized system for a facade less than 3.000 m2 area, would not be convenient when it is consider the production and shipping costs. Contrarily for the facade area more than 5.000 m2, stick system is not reliable for the quality control. Besides, it brings slow erection and herewith higher costs. The facades between 3.000 m2 and 5.000 m2 area, other factors should be evaluated.

The form and dimension of the facade: The buildings higher than 4-5 floors could be very risky to erect with stick system. Because of the joints of curtain wall components, unitized system provides incomparisonable quality. Manufactured units arrive to the site already with protection against climate conditions such as rain and wind. Also for the buildings with large vision area on the facade, unitized system has ease for installing.

Behavior under seismic movements: About structural movements, certainly unitized system perform better than the stick system. If the building is not located in the seismic zone and not taller than 4-5 floors, there is not too much risk to choose stick system. On the other hand, in relation with the joinery, unitized system absorbs differential movements better.

The degree of repetition parts: When the floor heights are constant and space between the mullions is equal, unitized system could be more comfortable, fast and less costly. In this way, the facade closure might be finished quickly. Otherwise, installing piece by piece all components to the building facade requires more time and more labour costs as a result.

The degree of planarity: Depending on the other factors, for the plain, vertical facades both of the systems can be convenient. When the facade is designed with sloped or amorphous forms, unitized system provides better solutions. In terms of composed of prefabricated units with factory controlled sealants and interlocking joineries, unitized system ensures higher performance.

Generic Evaluation

The type, the assembly technique and the glazing method of the curtain wall have been decided based on the mentioned selection criteria. These four main titles have been helpful during the study in order to create a generic overview in two systems. Advantages and disadvantages have combined in sub-categorizes under four main factors. A comparative table have come up as a decisive summary.

When it is considered four main selection criteria as;

- architectural design
- cost
- schedule
- location

of the curtain walls, an overall evaluation can be predicted. The following table is a sum of the substantial aspects and their responses on the both two systems.

In summary, based on the mentioned main factors, unitized system has much more advantages in general approach. Unitized systems can be applied on the large or high facades. In contrary, stick system has glazing challenges on the high buildings. It contains risks for the labors at the installation process. Also when building has repetitive facade design with same patterns or unusual slopes on the facade, unit system provides the best solution. Interlocking system of the unitized curtain walls provide ease for sequential installation.

When it is compared with the other systems, only concern about unitized system could be higher costs. Although it has higher manufacturing and shipping costs, on-site costs are less than the stick system. But most of the time, excellent performance features make the compromise.

Performance based study has shown, unitized system have more convenient in thermal and acoustic ways. Manufactured products under high testing and evaluation processes in the factory as a unit with its frame, glazing and sealants are more reliable than workmanship installations.

Factory assembled units are already weather treated for the environmental conditions. They have less potential to allow water, air or noise penetration into the building. Nevertheless, stick systems require weather conditioning on the field. Thus this kind of system are more dependent to the on-site applications. Quality of the sealing cannot be ensured in all the cases. Furthermore, unitized systems have more structural integrity. While they allow to in-plane movements, stick systems are not able to accommodate them.

Factor	Description of the Aspect	Stick System	Unit System
Architectural Design	Convenience on large facade designs	●●	●●●
	Convenience on high facade designs	●	●●●
	Convenience on repetitive facade designs	●●	●●●
	Convenience on amorphous designs	●	●●●
	Allowance to incremental expansions	●●	●●●
	Potential deterioration on the sealant joinery	●●●	●
	Reliability of the joints	●●	●●●
	Reliability of the quality control	●●	●●●
	Avoid water penetration	●●	●●●
	Ensure thermal comfort	●●	●●●
	Ensure acoustic comfort	●●	●●●
Cost	Economical on the shipping costs	●●●	●
	Economical on the labor costs	●	●●●
	Storage requirement for the components	●●●	●
Schedule	Fast site-delivery	●●●	●
	Assembly velocity on the site	●	●●●
	Workmanship dependency	●●●	●
Location	Accommodation of the building movements	●●	●●●
	Convenience on the seismic zones	●	●●●
	Protection against the climate conditions	●●	●●●

Table 4.4; Comparison of stick and unit systems. Elaboration of the author.

4.2.4 Choosing the Glazing Method

The classification based on the glazing method have defined the attachment styles of the infill panels to the curtain wall framing. After the researches, in this part, three most common glazing methods have been determined that are exterior batten, stop and structural silicone. Other methods such as structural gaskets and channel glazing have been discussed at the other chapters before. These methods are not promoted for common practices anymore. Therefore, they are not mentioned in this chapter.

Pressure Plate Glazing: This glazing method composes of framing elements and infill panels and exterior metal battens in order to hold infill panels. This system is most common and easiest one for the glazing. Outer gaskets are applied on the exterior and they are compressed against to the glass panels in order to ensure a continuous pressure plate. These elements apply pressure to the gaskets or tapes at the edge of the infill panels. Typically, pressure plates are covered with snap-on mullion cover. Exterior gasket is generally not waterproof. It serves a reasonable performance but it is sensitive to the corner or joint leaks on the dry gaskets. Additional four-sided gaskets or wet sealants could improve the performance. Air barrier continuity between the frame and backpan is supplied by interior gaskets.

Interior Dry Glazing: In this method infill panels are installed from the interior of the building. By this way it does not require an exterior scaffolding system for installation. When curtain wall framing and exterior dry gaskets took place, glass units are put into framing. In interior dry glazing method, removable stops are located at the interior. Tapes or gaskets are compressed by the stop and it creates the seal. Due to metal to metal joints, performance is lower than the pressure plate glazing. In this case, some systems with wet sealant and extra gaskets could provide an air barrier.

Structural Silicone: There are two different ways of structural silicone method. One is 2-sided structural silicone which describes the connection of the glazing units to the framing on the two sides with adhesive silicone. Then these sides compressed with pressure plates. Other method is 4-sided structural silicone and four edges of the glazing are adhered to the framing. 2SSG method can be installed on the site, but 4SSG must be shop installed for better quality. Unitized systems are manufactured usually structural silicone glazed.

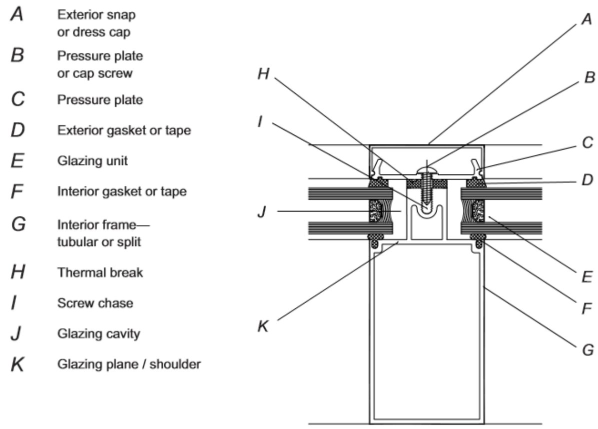


Figure 4.1;
Pressure plate glazing system

"Glass and Metal Curtain" Walls, CMHC, 2014

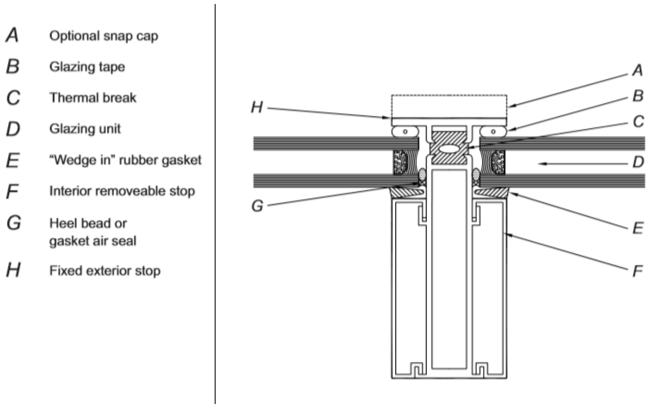


Figure 4.2;
Interior dry glazing system

"Glass and Metal Curtain" Walls, CMHC, 2014

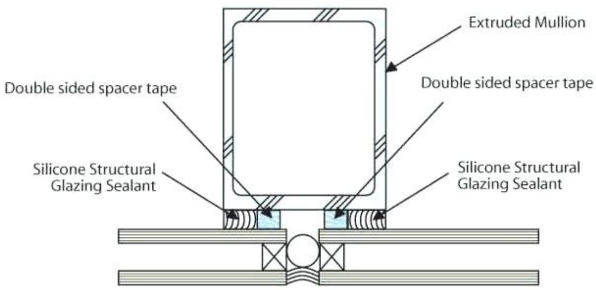


Figure 4.3;
2SSG glazing system

https://ronniebrownlifesystems.com/

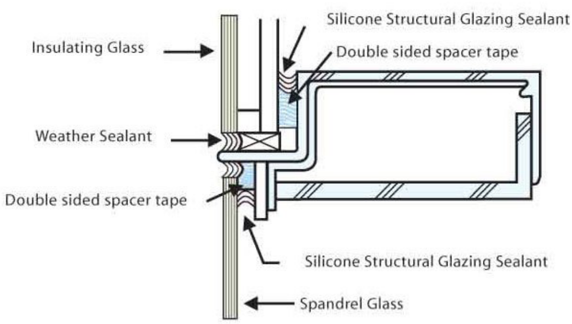


Figure 4.4;
4SSG glazing system

https://ronniebrownlifesystems.com/

Factor	Description of the Aspect	Pressure Plate Glazing	Interior Dry Glazing	Structural Glazing
Architectural Design	Convenience on the exterior installation	●●●	●	●●●
	Convenience on the interior installation	●	●●●	●●●
	Convenience on the stick system	●●●	●●●	●
	Convenience on the unitized system	●●●	●●●	●●●
	Convenience on the high facade designs	●	●●●	●●●
	Requirement for elaborate extrusions	●	●●●	●●●
	Reliability of the sealant or gasket	●●●	●●●	●●●
	Reliability of the quality control	●●●	●●●	●●●
	Ensure air barrier	●●●	●●●	●●●
	Ensure thermal comfort	●●●	●●●	●●●
	Ensure acoustic comfort	●●●	●●●	●●●
Cost	Exterior scaffolding requirement	●●●	●●●	●●●
	Requirement for exterior snap cap	●●●	●●●	●●●
	Requirement for extra sealant element	●●●	●●●	●●●
Schedule		●●●	●●●	●●●
	Assembly velocity on the site	●●●	●●●	●●●
	Workmanship dependency	●●●	●●●	●●●
Location	Application on dense surrounding	●●●	●●●	●●●
	Convenience on the seismic zones			
	Protection against the climate conditions			

Table 4.5; Comparison of glazing methods.
Elaboration of the author.

4.3 | Design Fundamentals

As a building enclosure, a curtain wall concentrate on the fundamental points of the facade design. Performance requirements of the curtain walls are categorized in three aspects as comfort, safety and energy. These explanations and necessities of all the requirements have given before at the other chapters. Most of the failures about curtain walls occur in the lack of performance requirements. In this matter, at the design stage it is important to achieve performance criterias.

Certainly, curtain wall design should involve all the performance requirements, however in this chapter some crucial and fundamental design concerns and recommendations will be referred. These design fundamentals that will introduce are;

- Waterproofed Performance
- Airtight Performance
- Acoustic Performance
- Fire Control
- Thermal Control

4.3.1 Design for Waterproof Performance

While a curtain wall is designed, it should be considered external glazing seals, perimeter sealants, drainage details, frame gaskets and curtain wall sills have potential to leak inside. Water can enter from exterior to interior by different factors such as gravity, kinetic energy, air pressure difference, surface tension or capillary action. In order to provide water resistance, these factors must be accounted in the facade design process. Watertight frame corner and well-designed glazing pocket drainage are the key points for reliable waterproofed performance.

The following summary is the general recommendations that are collected from several sources for any kind of water management system:

- Frames should be selected with wept glazing and pocket sills sloped to collect and drain the penetrated water at the exterior.
- Vertical mullions should not be used as drain conductors.
- Drainage system should be designed also for condensation issues.
- Air and water barrier flashings should be located at the perimeters of the curtain wall.
- Perimeter sealants should not be only air and water barrier. They should be support by other systems.

Since the curtain walls have erected, through the time three main water penetration systems have been developed and used. These systems called as exterior face seal, internal drainage and pressure equalized rainscreen.

Exterior Face Seal: This system was initially popular over 1960s and then with other improved technologies, it decreased. Nowadays, it takes place very rarely at the curtain wall designs. Exterior face seal was common in 4 sided SSG systems and for facade retrofits. It consists of continuous seals between the glass units and the frame and between the all frame components. Exterior plane provides also air barrier. Due to depending on the exterior sealants and gaskets, this system distrustful for long-term.

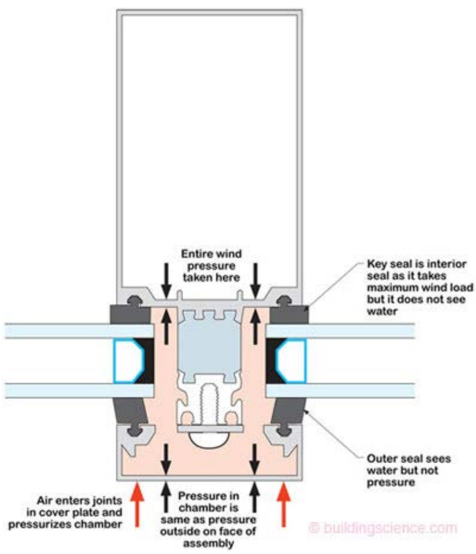
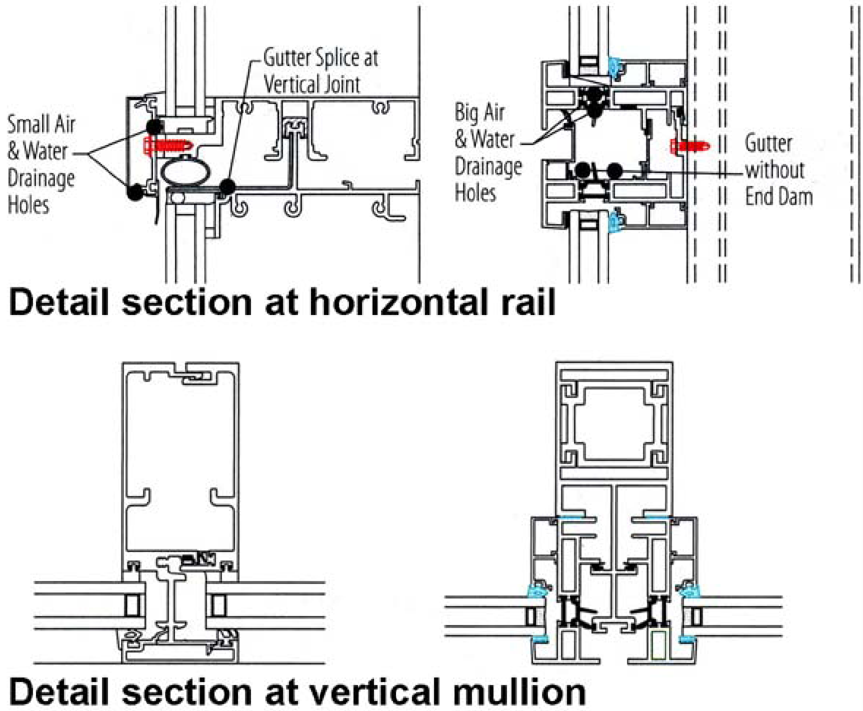


Figure 4.6;
Pressure equalized rain system

https://courses.cit.cornell.edu/arch262/notes/11b.

Figure 4.7;
Internal drainage system



Internal Drainage: Since it is compelling to maintain excellent exterior seal, this system composes of backup drainage. There is not any effort to create an air barrier. Thus substantial amount of water enforce into to system and it must be wept away. In this system, drainage of the water inside the glazing pockets is provided by weep holes. These openings in the air barrier could lead to condensation on the glazing units.

Pressure Equalized Rainscreen: It is the most common method in contemporary practice. Both water and air barrier is ensured by this system. Primary aim of the PER is elimination of pressure difference and by this way water tightness is supplied as a result of it. Exterior face of the glass, exposed framing and glazing materials work as a rainscreen and take away the water from the facade system. While the interior glass face, interior side of the glazing pocket and connected gaskets perform as an air barrier. In the cavity of these two interior and exterior sides, a pressure equalization chamber is created for eliminating the pressure difference. Weep holes allow the air movement between the two sides. Most significant feature of this system is all the glazing pockets are isolated from the adjacent units by seals.

The comparison between these tree systems could be according to their sustainability and performance. Exterior face seal served at the very poor and initial curtain wall designs. Only exterior gaskets and seals with butyl or polysulphide based materials are not reliable. Because over the time these materials get degrade under the environmental conditions. That kind of curtain wall facades have been retrofitted at least one time in their lives.

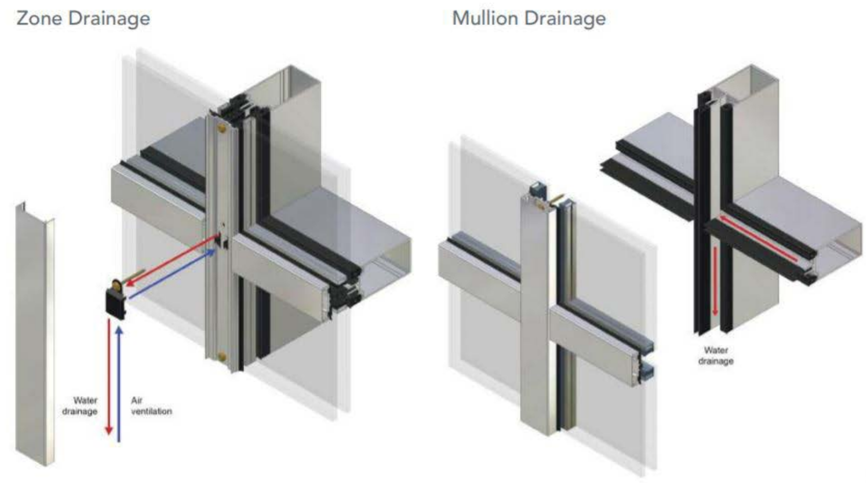


Figure 4.8;
Two types internal drainage system

https://www.buildingscience.com/documents/insights/bsi-004-drainage-holes-and-

Thus certainly this system has weak points in order to provide water tightness. Although they have challenges to incorporate into 4SSG systems, internal drainage and PER systems are much more convenient than the exterior face seal. Normally small portions of the 4SSG systems have often designed with face sealed sections. While large buildings with 4SSG should be integrated with PER system.

4.3.2 Design for Airthight Performance

The airtight design concepts are interrelated with the water penetration management systems of the curtain wall. The chosen watertight concepts that were mentioned before directly or with supportive designs, provide airtight of the system. Apart from the controlled air flow, these systems indirectly impact also to smoke control, sound transmission and possible ice accumulation on the wall.

In the pressure equalized rainscreen and the exterior face seal systems, an impermeable air barrier is theoretically exist. While in the face seal system the air barrier is on the outer side of the curtain wall, in the PER system it is located in the inner side. Third method is internal drainage system and for the air barrier it is less reliable one among them. Typically the outer surface provides the airtight. Only, there are weep holes for water penetration and in some designs these holes are filled with open cell foam in order to reduce air flow.

When it is considered that the primary curtain wall components are impermeable, air leakage issues focus on the joineries, gaskets and seals.

4.3.3 Design for Acoustic Performance

As mentioned before the acoustic performance primarily lead by the glazing units and the internal seals. Additionally, for improved performance sound diminishing infills could be install to the curtain wall system. Based on the CMHC curtain wall guide, the process to achieve level of acceptable noise is given below;

- Evaluation of environmental noise
- Determination of the minimum acceptable Transmission Loss or Sound Transmisson Class
- Choice of infill panels
- Design of frame
- Installation

Generally, this process is applied from a sound consultant for assessing TL and STC ratings. After this in a curtain wall system for the vision and spandrel panels, acoustic performance are considered differently from each other.

Vision Panel
Glazing air space thickness, glass thickness and interlayer damping are the three factors that impact on the glazing design in terms of acoustic performance.

- Glazing air space thickness varies between 6 mm to 150 mm. The spaces until 20 mm are typically sealed with hard surfaces spacers. Over the 20 mm spaces, seals are not involved and they may have vented or sıft spacers.
- In the wide arrange of designs, glass thickness are chosen between 3 mm to 6 mm. Most of the time, these dimensions are convenient, however; for specific projects with highly sound emission is required, glass units can reach up to 12.5 mm.
- Common interlayer damping refers to 0.76 mm to 1.52 mm with polyvinyl butral laminated.

STC ratings are accessible in the various standard glazing configurations. When it is necessary to develop better performance, usually intervention starts from the interlayer and goes towards the glass thickness.

Spandrel Panel
The opaque spandrel panels of the curtain wall may be considered as a standard wall portion, however the specific characteristic of the curtain wall crates challenge to apply handbook values for STC ratings. When an increased performance is necessary, backpan materials such as laminating gypsum board measure can be increased at the interior part. Another solution can be addition of weighted sheet products to the mullions.

4.3.4 Design for Fire Control

It is expected that a curtain wall must resist to fire and smoke migration between different floors. In a typical curtain wall, all the primary materials of the components are non-combustible. Thus, combustible secondary components such as gaskets and seals are allowed in the overall system. Under the significant fire, vision glasses of the system tend to break in few minutes. Due to this fact, curtain wall should be designed flame spread resistant to the exterior. In a typical curtain wall, slab edge is the essential point for fire stopping. Most of the time smoke migration is more dangerous than the flame and in a good designed system, it must be eliminated smoke access from floor to floor.

In a building with usual curtain wall facade, fire stop and smoke seal are located between the floor slab and the backpan of the curtain wall system. Fire stops compose by inorganic insulation material. In order to provide reliable fire control system, fire stop rating should be equal or higher than the floor slab rating. The width of this element refers to the dimension of the slab and the depth is verified by the required resistance rating. As a material of the smoke seal is urethane sealant is very common. Role of the backpan is significant in terms of integrity of these elements. Rigid backpans perform better against wind loads. Therefore, for a fire resistant design backpan deflection 6 mm at the slab level is optimum.

4.3.5 Design for Thermal Control

Since the curtain wall have taken places very primitive forms in the building facade, thermal comfort have been considered one of the main concerns. In our era, environmental responses and high energy costs push to design more convenient buildings in terms of thermal comfort. When it's investigated, overall curtain wall system - glazing, frame, back structure for opaque areas and perimeter details - is accountable for the thermal performance. In design process, choice of well-matched components with weathering conditions is worthwhile. Furthermore, European codes and regulations have impact to design better thermal performance.
In order to deep knowledge, each part of the system will explain in their requests and solutions.

Frame
In the metal curtain wall designs, often aluminum extrusions are used as framing. Due to its very thermal conductivity character, in common practices low conductivity thermal breaks are integrated to the framing system. PVC, neoprene rubber, polyester-reinforced nylon can be accounted for common thermal break materials. Minimum ¼" thickness up to 1" polyester-reinforced nylon breaks frequently supply improved performance. In case of colder environments, deeper thermal breaks help to avoid conduction from one side to other side.

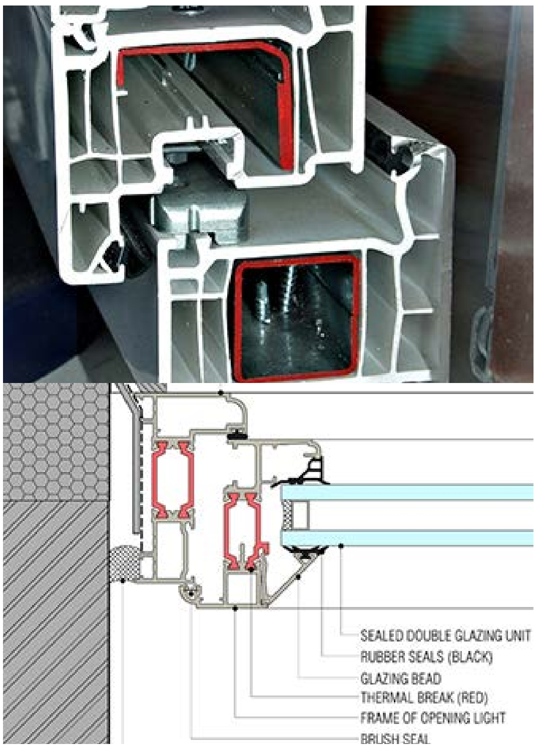


Figure 4.9;
Thermal breaks of the frame components

https://www.hitechextrusions.com/thermal-breaks-for-curtain-walls/

Glazing
In 21st century, incorporation of the insulating glass is a fundamental strategy for enhanced thermal performance. Since the very first examples of curtain wall until to 1970s, many office buildings have been designed with poor insulating glasses. These buildings have faced with the high energy costs

and undesirable comfort for the inhabitants. After 1970s, majority of the European countries introduced legitimations about the insulating glass. Due to determinative criteria, nowadays designing with the single pane glass or low-performed glazing types are forbidden. When layer of glass pane increases, the thermal performance ascends as well. Also addition of low emissivity coatings can highly affect to glass performance. These kind of coatings reflect the radiation of sun and reduce the solar heat gain.

Back Structure
Back pans are often composed by aluminum or galvanized steel and they are located at the behind of opaque panels. They are attached to the curtain wall framing. The insulation should be install between the exterior face and back pan. This method provides a double barrier for the air and vapour and contributes to the thermal performance.

Perimeters
Proper design of the perimeter details helps to reducing energy loss of the system. Provision of the air barrier at the curtain wall perimeters decrease the air flows. Also integrated perimeter flashings participate to water tightness.

4.4 | Retrofitting Concerns

When it has been investigated, in European building stock significant amount of the residential and non-residential buildings have required a retrofitting in variable levels. Most of these buildings do not meet anymore with the actual conditions or they serve worse comfort for the occupants. The huge existing building stock consume the enormous energy. Therefore, in order to supply improved performance and reducing to energy concerns, refurbishment of the existing buildings takes the attention.

The retrofitting is a chance to mend of the curtain wall failures. By the proper intervention to the existing facade, building can transform from current state to the better one. The potential benefits of the curtain wall retrofitting are given below;

- Reduction of the energy consumption
- Improved air and water control
- Improved aesthetic appearance
- Upgraded energy efficiency
- Incorporation to the material sustainability

The study about the European office buildings has focused on the curtain wall facades. According to this, four main retrofitting strategies have been analyzed. These are categorized as maintenance, over-clad, renovation and re-clad, they represent from minimum intervention to maximum. Like it was explained deeply before, re-coating, addition of a new exterior layer, addition of a new interior layer, replacement of glass units, replacement of glass units and frame and creation of a new facade are 6 categories for the curtain wall retrofitting.

Based on the researched case studies, some different impacts have role to decide the level of the intervention. Retrofitting costs, time, occupancy of the building, aesthetic view, historical value of the building could compose the general structure of the retrofitting strategy. Since retrofitting of every building depend on these factors, it is hard to make a exact classification for the intervention level. That's why each project should be evaluated in their retrofitting conditions. Furthermore, sometimes initial idea can transform to another which is a result of building codes or requirements.

In example of 10 Lafayette Square, about facade retrofitting, replacement of the glass units have predicted, however it was not a valid option for the historical building preservation criteria. In order to keep the historical appearance of the building, an internal intervention was applied. Understood another concern is from the Lake Shore Drive example, in terms of balance between the cost and longevity. In this case just a superficial maintenance was required. The material choice for the re-coating of the framing was selected among two alternatives. Even if it had lower performance relatively to the other one, acrylic coating was the final selection due to its less costs.

Like the design process of the curtain wall, also retrofitting needs to organization for selecting the optimum methodology. Mentioned concerns and others obtain the fundamentals for the selection criteria. Furthermore, advantages and disadvantages of the 6 main retrofitting techniques take part in the planning process. Sometimes compromise between the different factors lead the process. For example addition of a new interior layer of facade can be the best choice in terms of cost and easily access, however if the building is actively occupied challenges about work flow and timing can be main problems. In this kind of situations it should be decided which factor is more important to not compromise and dominant to the other.

Since they all have pros and cons, it can't be told one is more superior than the other methodology. In relation with this, in the retrofitting process each project must be evaluated with its own existing conditions and life expectancy for further.

The determination of the best retrofitting strategy for an existing building composed by the feasibility study for examination of the alternatives with their weakness and strengths. This integrated design process before in the planning phase has significant role for the future of the building. Whether maintenance, over-clad, renovation and re-clad are chosen, the final result after the retrofitting gives higher value to the building. Besides, it serves a comfortable enclosure to the occupants with modern and practical solutions than the current situation.

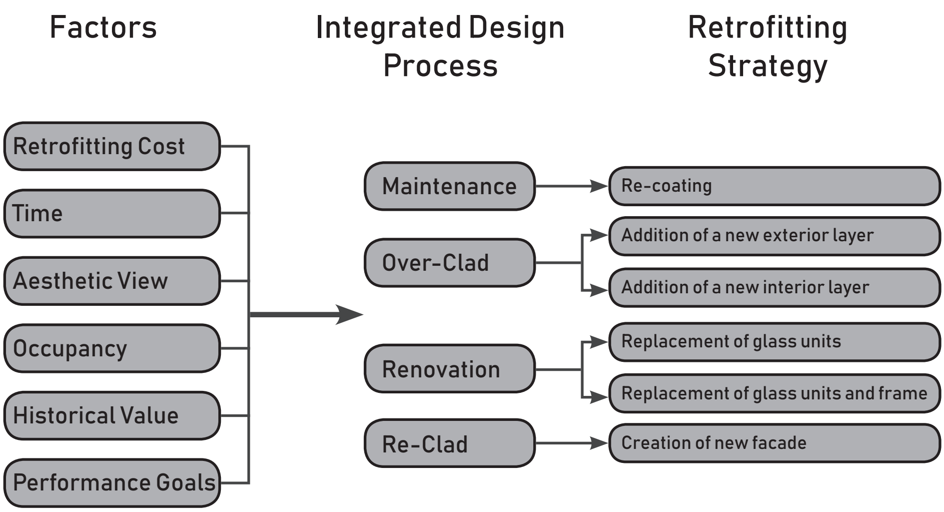


Table 4.6; Factors and selection of retrofitting method.
Elaboration of the author.

4.5 | Retrofitting Fundamentals

Any kind of the retrofitting strategy is most of the time complex and costly. It includes high potential of waste materials and sometimes inefficiency as well as. Therefore, retrofitting process should be considered as an entire body from decision making to physical intervention phases.

In usual, the buildings that need retrofitting, face with the fundamental design insufficiencies. The request for the improved facade performance is frequently related with the comfort of the inhabitants or reduction of the energy consumption. At this moment, understanding the building problems and evolve convenient solution for the future life of the building should be key point.

After investigated case studies and researches, a developt program has executed for the retrofitting process of the curtain wall. The program is composed by three main phases which are feasibility study, design process and intervention. The following table shows the details of the program.

Feasibility	• Building Survey • Program Definition • Financial Analysis
Design	• System Development • Costing
Intervention	• Material supply • Fabrication • Assembly • Commissioning • Post-occupancy monitoring

Table 4.7; Phases of retrofitting process. Elaboration of the author.

Feasibility study is constituted by preliminary processes of the program. In this phase the current situation of the existing building should be understood and the building program should be determined. Building survey includes an examination about actual facade performance, function of the building, anchor situation and so on. These step has substantial act to definition of the current conditions. All the following perpetuation take form based on the building survey. Another crucial step is definition of the building program. It is composed by large list of elements such as budget for retrofitting, prediction of disruption and aesthetic intent. Taken decisions in this part give shape for the choice retrofitting strategy. After first two steps, in consideration with the financial analysis optimum retrofitting strategy might be decided as a result of feasibility study. Four main possible strategies are investigated depend on the compatibility to existing conditions and financial borders.

In the following phase, according to chosen strategy a design process is started. A system development for the existing facade is an outcome of the engineering and architecture. Apart from the environmental conditions and the budget, aesthetical demand or if there is a historical value of the building are decisive factors for the design. Since it is a retrofitting project, an upgraded facade performance is expected from the new solution. All the decisions about facade components and their materials and also their combinations or integrations to the existing body compose the new facade system. The costing is calculated for the proposed system and balance between these two factors can be provided in usual cases.

Last step is physical intervention to the facade. It doesn't present many differences from a new building construction. In this phase, firstly procurement of the components and then fabrication of the designed curtain wall system are accomplished. Subsequently, this system is installed on the site. By this way retrofitting process is completed, however afterwards ordinary maintenance and cleaning have an importance for the sustainability of the new system.

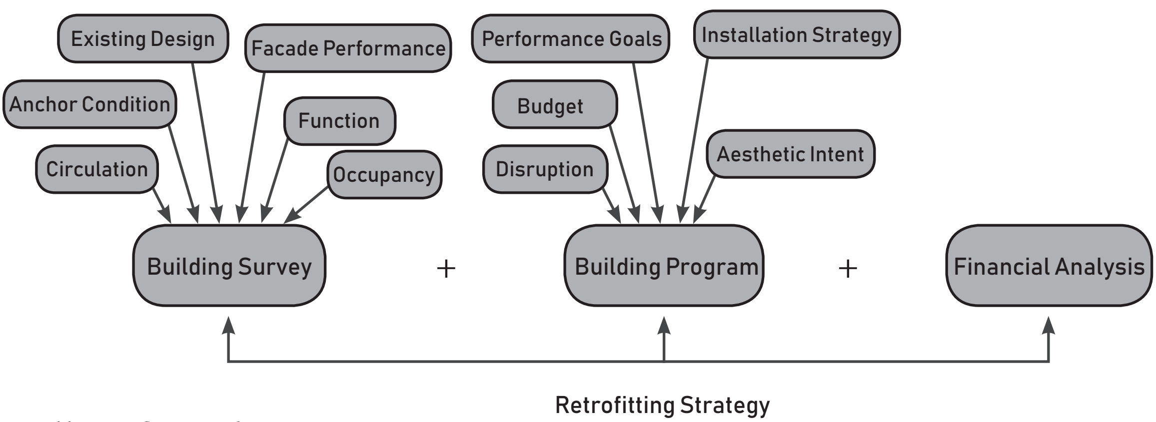


Table 4.8; Influencers of retrofitting process. Elaboration of the author.

References

1. Appolonia D., 2016. Development of innovative lightweight and highly insulating energy efficient components and associated enabling materials for cost- effective retrofitting and new construction of curtain wall facades, Requirements and drivers of EENSULATE module, EENSULATE.

2. Birchall S., Wallis I., Churcher D., Pezzutto S., Fedrizzi R. and Causse E., 2014. Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems, iNSPiRe Project, BSRIA.

3. Canada Mortgage and Housing Corporation, 2004. Glass and Metal Curtain Walls, Public Works and Government Services Canada.

4. Dumez K.M., 2017. Analysis of Energy Efficient Curtain Wall Design Considerations in Highrise Buildings, University of Colorado, Master of Science, Department of Civil, Environmental, and Architectural Engineering.

5. Europe's Buildings Under The Microscope 2011. A country-by-country review of the energy performance of buildings, Buildings Performance Institute Europe (BPIE).

6. Gembinski C., 2016. Curtain Wall Construction, Columbia University, In The City Newyork.

7. Klee C. and Love A., 2014. Thermal Performance of Facades, 2012 AIA UpJohn Grant Research Initiative.

8. Kliment S. A., 2002. Building Type Basics for Office Builings, John Wiley and Sons, United States of America.

9. Martinez A., Patterson M., Carlson A. and Noble D., 2015. Fundamentals in Façade Retrofit Practice, Procedia Engineering, 118, 934 – 941.

10. Meel J., 2000. The European Office, Department of Real Estate and Project Management, Rotterdam.

11. Murray S., 1993.The Curtain Wall in Architectural Education: Technology, History and Design, University of Illinois, Urbana-Champaign.

12. Quirouette, R. L. and Arch B.,2001. Glass and Aluminum Curtain Wall Systems, Canada Mortgage and Housing Corporation, QBS Project.

13. Quirouette, R. L., 1982. Building Envelope Design Using Metal and Glass Curtain Wall Systems, Division of Building Research, National Research Council Canada, Ottowa.

14. Patrick M., Farid M., Hiba A, Brenda M., Arash S., Berardis P. and Richard L., 2017. Window Wall and Curtain Wall: An Objective Review, Leadership in Sustainable Infrastructure, Vancouver, Canada.

15. Remoy H. and Jonge H., 2007. Transformation and typology; Vacancy, characteristics and conversion-capacity, Delft University of Technology.

16. Sanders R.M. and. Hargrove C.A., 2012. Preventing and Treating Failure in Glazed Curtain Wall Systems, Hoffman Architects,2, Vol. 29, 2.

17. Sanders R.M., 2006. Curtain Walls: Not Just Another Pretty Façade, Hoffman Architects,1, Vol. 23, 1.

18. Staib S. and Sobek B.S., 1999. Glass Construction Manual, Basel, Switzerland.

19. Tywoniak J., Volf M., Bures M. and Lupisek A., 2014. Curtain walls for building retrofit purposes, Proceedings of 8th International Conference Improving Energy Efficiency in Commercial Buildings (IEECB'14), 1-3 April, Frankfurt, Germany.

20. Veitch J., 2012. Work Environments, The Oxford Handbook of Environmental and Conservation Psychology.

21. Yeomans D., 1998. The Pre-history of the Curtain Wall, Construction History, 14.