BCA ACADEMY

Efficient Building Envelope Design, ETTV and RETV

(16th Intake)

School of Graduate Development and Management



The Education and Research arm of the Building and Construction Authority

GMP Course

The Importance Of Building Envelope



School of Graduate Development and Management

BCA ACADEMY

The contents of this document are protected by copyright and other forms of proprietary rights. All rights, title and interest in the contents are owned by, licensed to or controlled ***by BCA*** *and shall not be reproduced, republished, uploaded, posted, transmitted or otherwise distributed in any way, without the prior written permission of BCA. Modification of any of the contents or use of the contents for any other purpose will be a violation of BCA's copyright and other intellectual property rights. No part of the course may be recorded, reproduced or transmitted in any form or by any means, without the express written permission of the course organiser.*

The reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply BCA's endorsement, recommendation, or favouring by BCA.

Lecturer Information

Mathieu Meur
Director
DP Façade Pte Ltd
E | MathieuMeur@dpa.com.sg
M | 9871 9160

DPF
DP FACADE

BCA ACADEMY

Course Overview

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

The Importance Of Building Envelope

- Impact on Heat Load
- Impact on Occupant Comfort
- Impact on Environment
- Duration: 1.5 hours

Function And Design Of Building Envelope

- Building Skin as a Responsive Skin
- Sustainable Design Consideration
- Façade Systems and Materials
- Duration: 2 hours

Daylighting

- Benefits and Issues
- Solar Sun Path
- Maximising Daylight in Interior
- Minimise Glare and Heat from Daylight
- Duration: 3.5 hours

Efficient Building Envelope Design Part 1

- Types of Walls, Fenestrations, Glass and Shading Devices
- Impact from Geometry and Location, and Façade Characteristics
- Heat Transfer Fundamentals
  - Understanding Heat Transfer
  - How to Minimise Heat Transfer

Efficient Building Envelope Design Part 2

- ETTV and RETV Equations
- Strategies to Lower ETTV and RETV
- Innovative Façade
- Energy Saving, Water Saving, Indoor Environment Quality and Other Environmental Considerations
- Total Duration of Parts 1 & 2: 6.5 hours

Final Exam

- Multiple-Choice Questionnaire
- 16 Questions
- Duration: 30 minutes

Importance of the Building Envelope

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

BCA ACADEMY

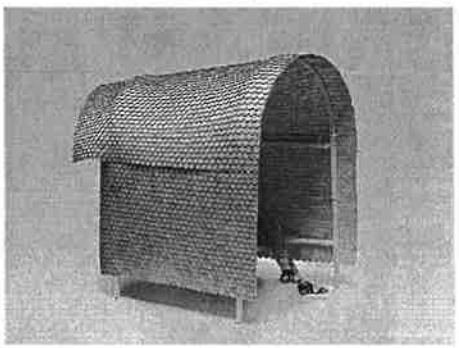
Function of the Envelope

- Building envelope
- Shelter
- Skin
- Sheath
- Clothing









Function of the Envelope

IDENTITY: façades that define city skylines

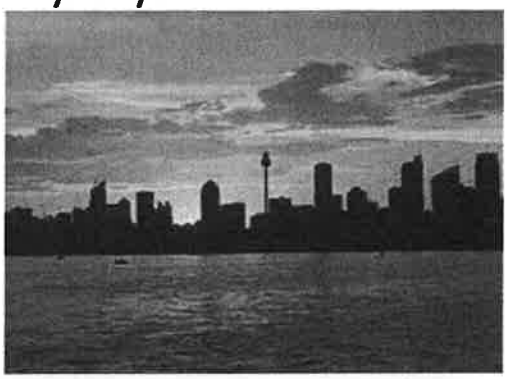





BCA ACADEMY

Function of the Envelope

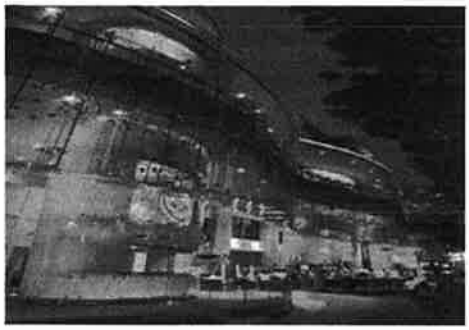
IDENTITY: façades that define city skylines

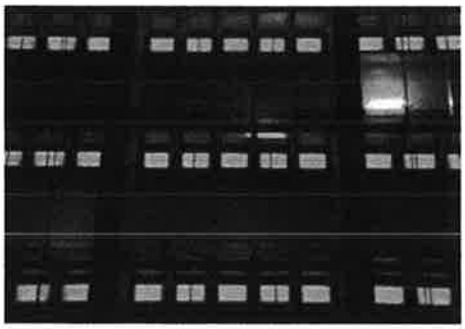


Function of the Envelope

IDENTITY: buildings that make a statement day + night




The Heeren Shopping Mall, Singapore

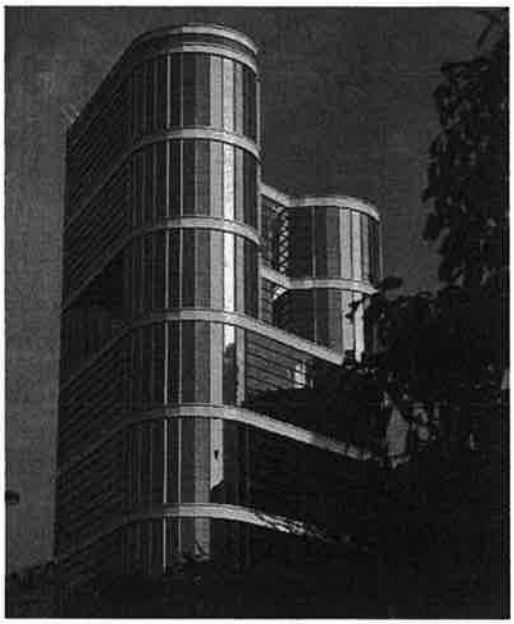



NTUC Trade Union House, Singapore

BCA ACADEMY

Function of the Envelope

IDENTITY: buildings that make a statement day + night




Citic Tower, Hong Kong

Function of the Envelope

- Sets the aesthetics of the building
- Must withstand applied forces (dead, wind, live, etc.)
- Must ensure occupant and passer-by safety
- Must appear visually safe (limited deflection)
- Must accommodate building movements

Impact of the Building Envelope on Heat Load

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

Why Care?

- Pollution from energy generation, materials production, transportation
- Up to 40% of pollution from residential and commercial buildings

BCA ACADEMY

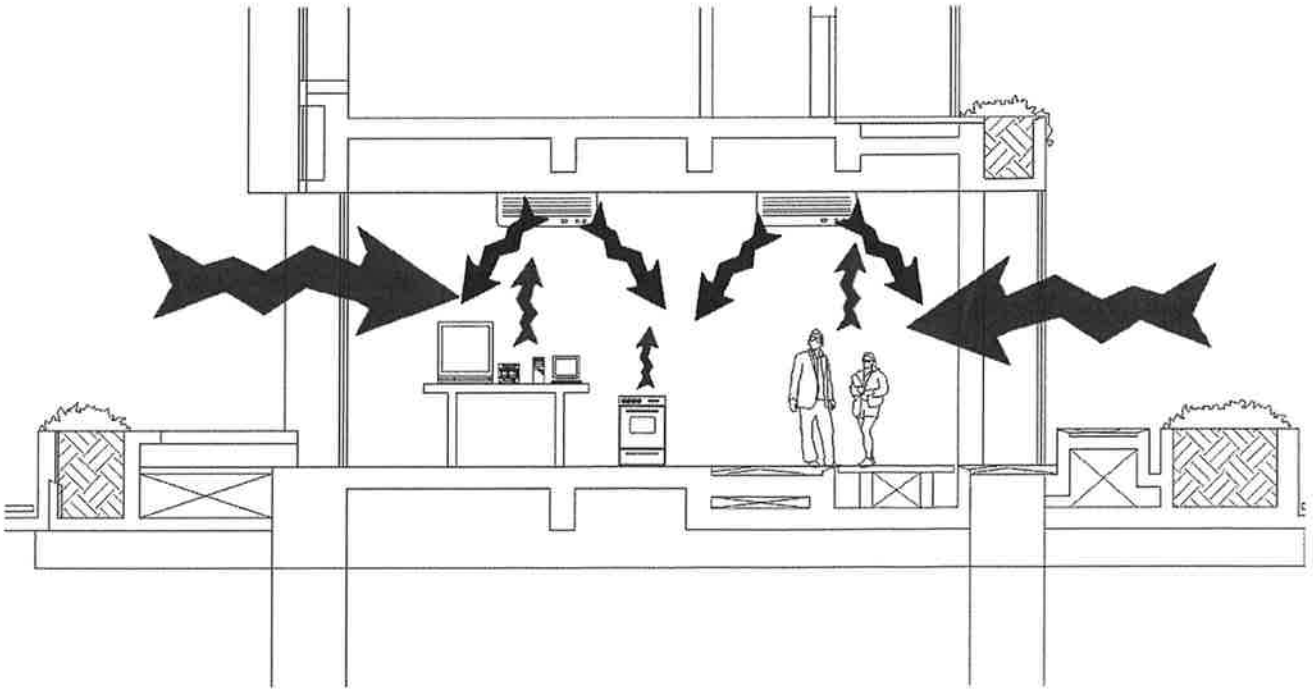
Why Care?

- Pollution from buildings due to construction materials production, energy consumption
- Energy consumption from mechanical ventilation, lighting and electrical appliances

Why Care?

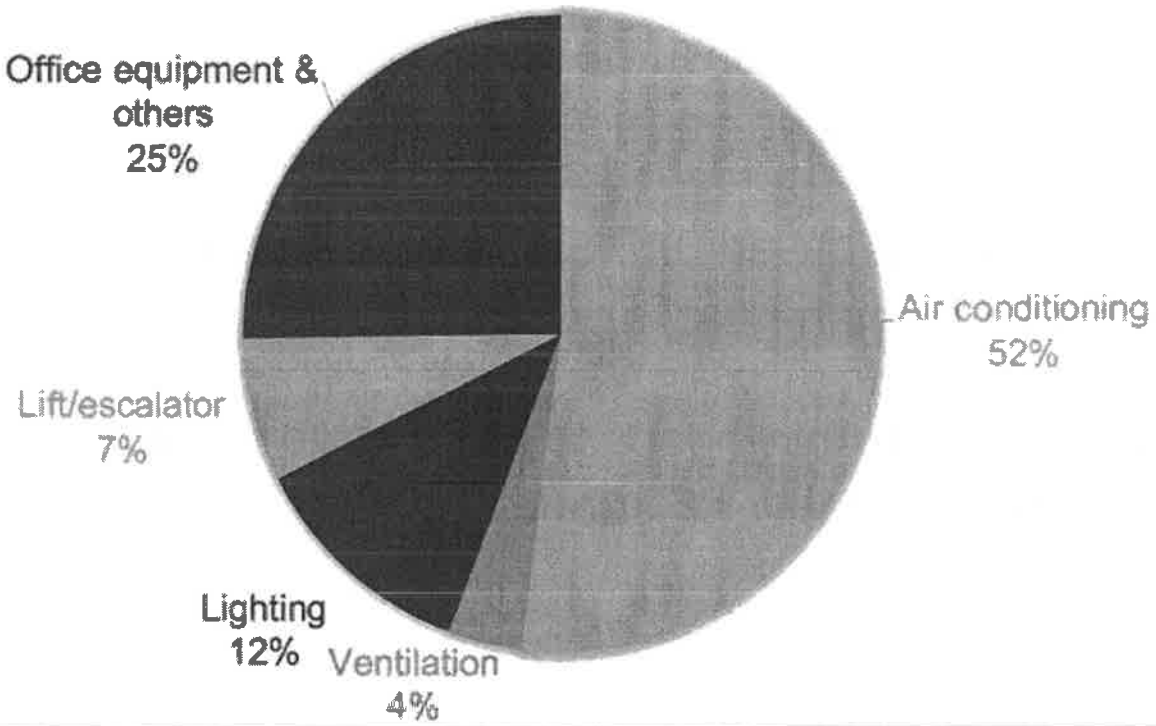
- Largest energy consumption is from mechanical ventilation
- HVAC sizing based on heat flow through facade, human heat, appliance heat
- Heat flow through façade has a large impact on mechanical ventilation

Why Care?



Why Care?

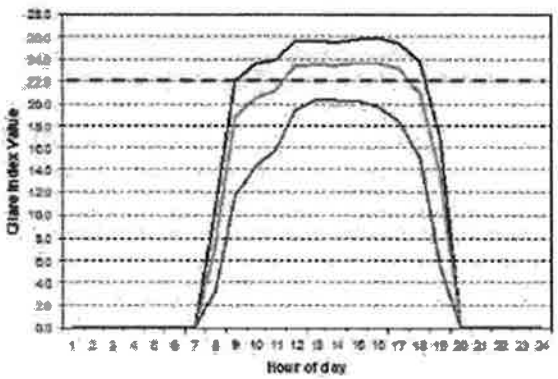
- Heat load through building envelope in tropics



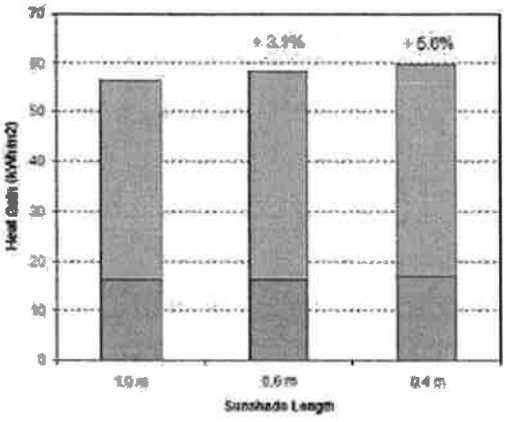
Why Care?

- Heat load through building envelope in tropics

Ensuring glare levels remain below discomfort thresholds



Facade design effects on cooling loads and energy demands



Why Care?

- HVAC require energy to operate
- HVAC systems may contain harmful chemicals
- Cooling systems release heat in atmosphere
- Heating systems burn coal or petrol products (atmospheric pollution)
- HVAC systems noisy, require insulation (more materials)

Why Care?

- Limited resources available, costly to extract and produce materials
- Recycled materials cheaper than materials manufactured from scratch
- Doubly limits pollution

Why Care?

- Building designers have a duty to limit pollution from construction sector
- Green approach difficult in past due to high cost
- Rising energy costs and collective consciousness make green approach attractive
- Need to balance aesthetics, commercial, functional and green requirements

Why Care?

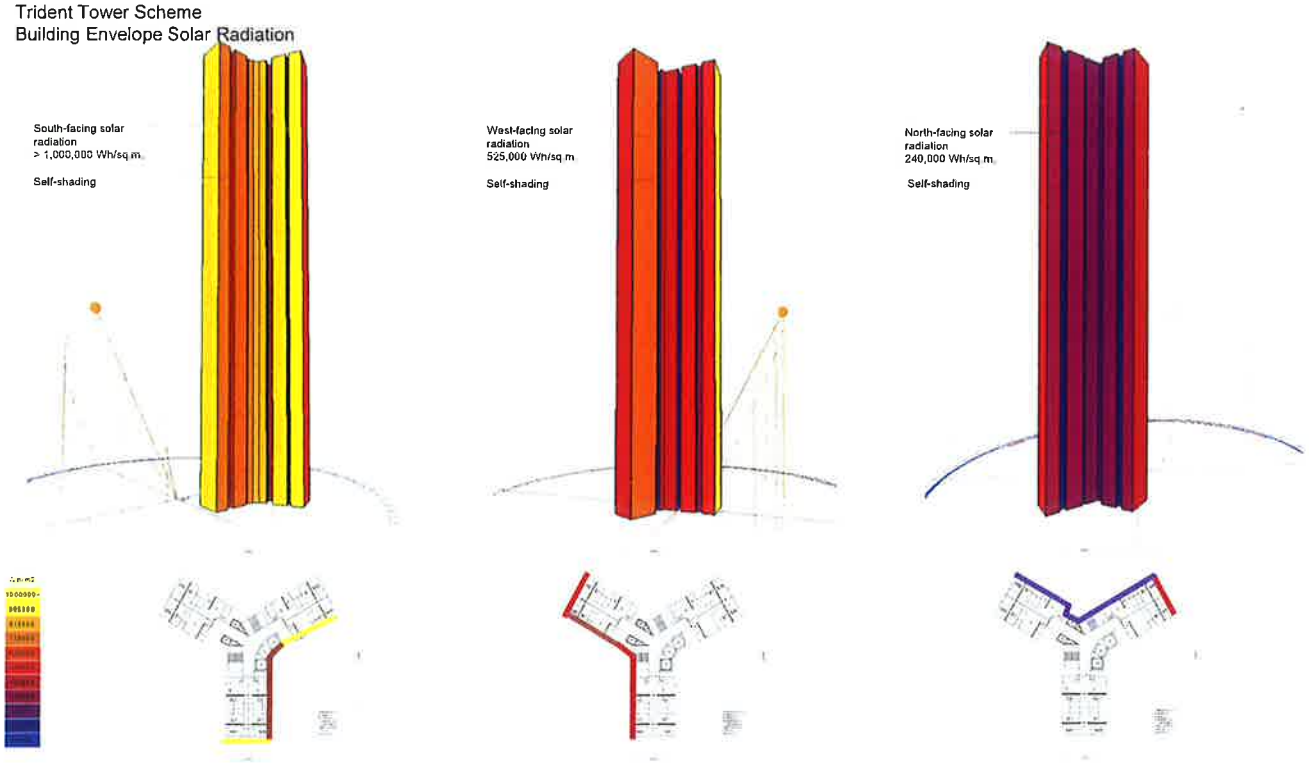
- Must be environmentally- and user-friendly
- Must incorporate light, thermal, material usage, acoustic, and other requirements
- Can measure efficiency of design by following principles dictated by "green standards" such as Green Mark

Why Care?

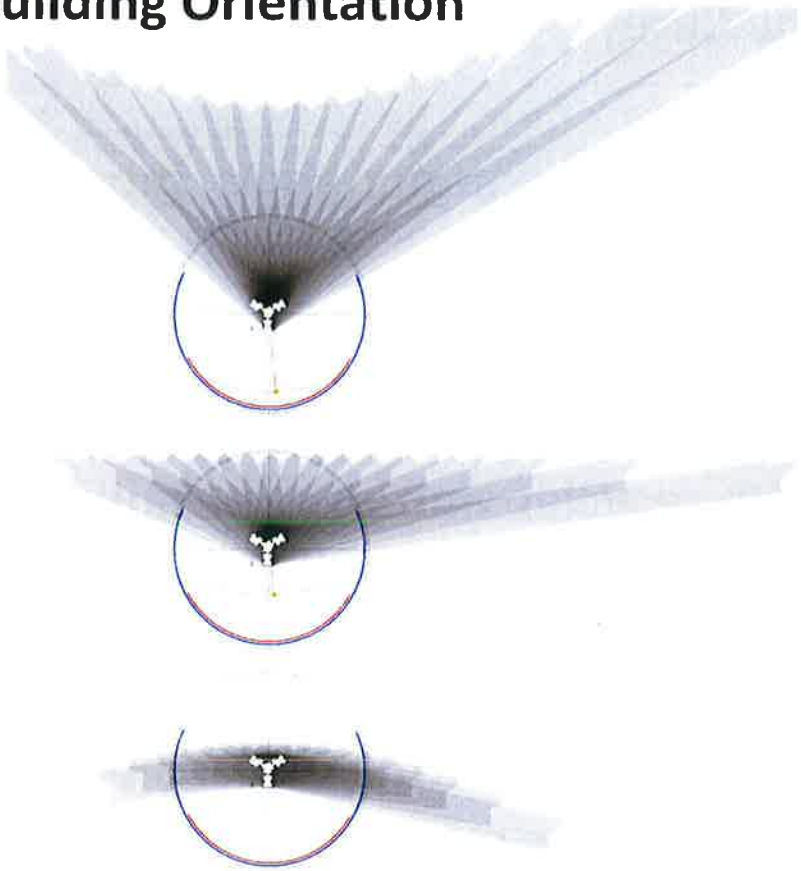
- Optimal use of materials, most efficient modulations
- Use bespoke system where possible
- Use recycled and/or recyclable materials where possible (glass, aluminium, steel, some polymers)
- Optimise performance according to building orientation and layout

Optimising Building Orientation

Trident Tower Scheme
Building Envelope Solar Radiation



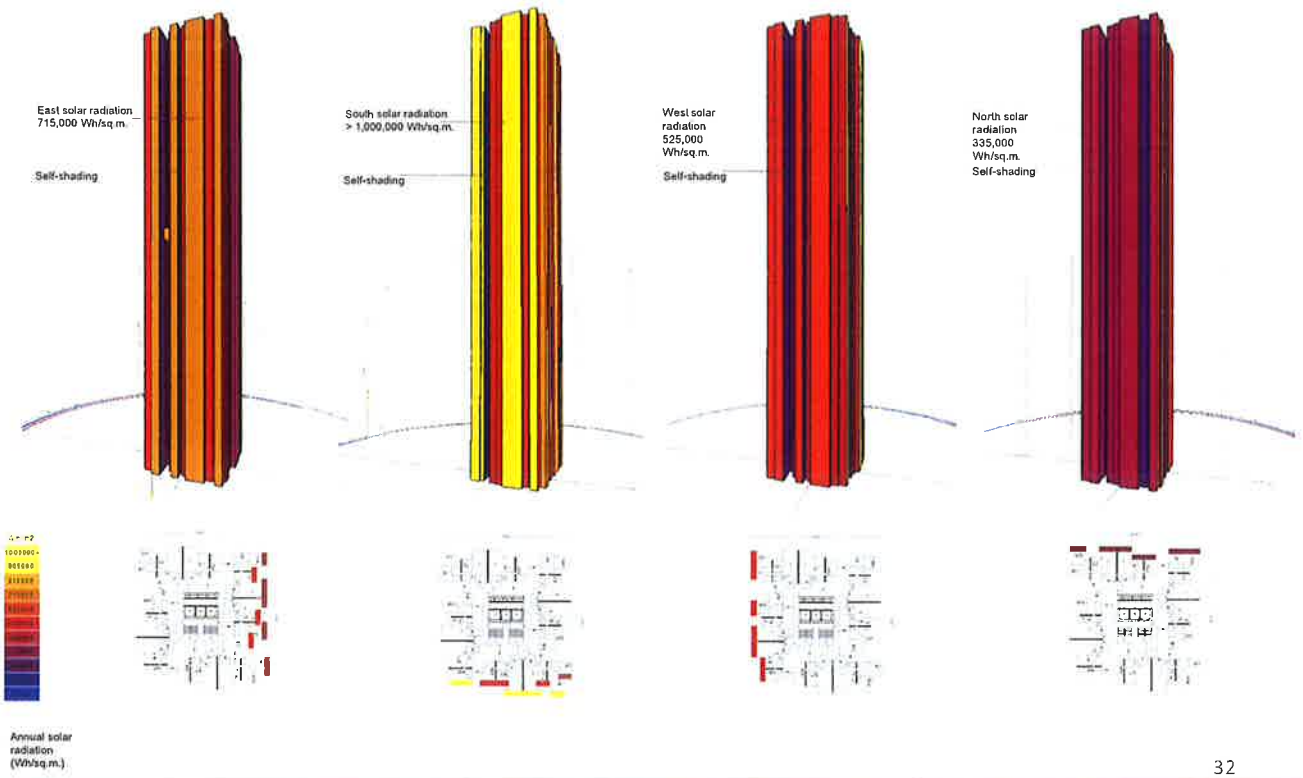
Optimising Building Orientation



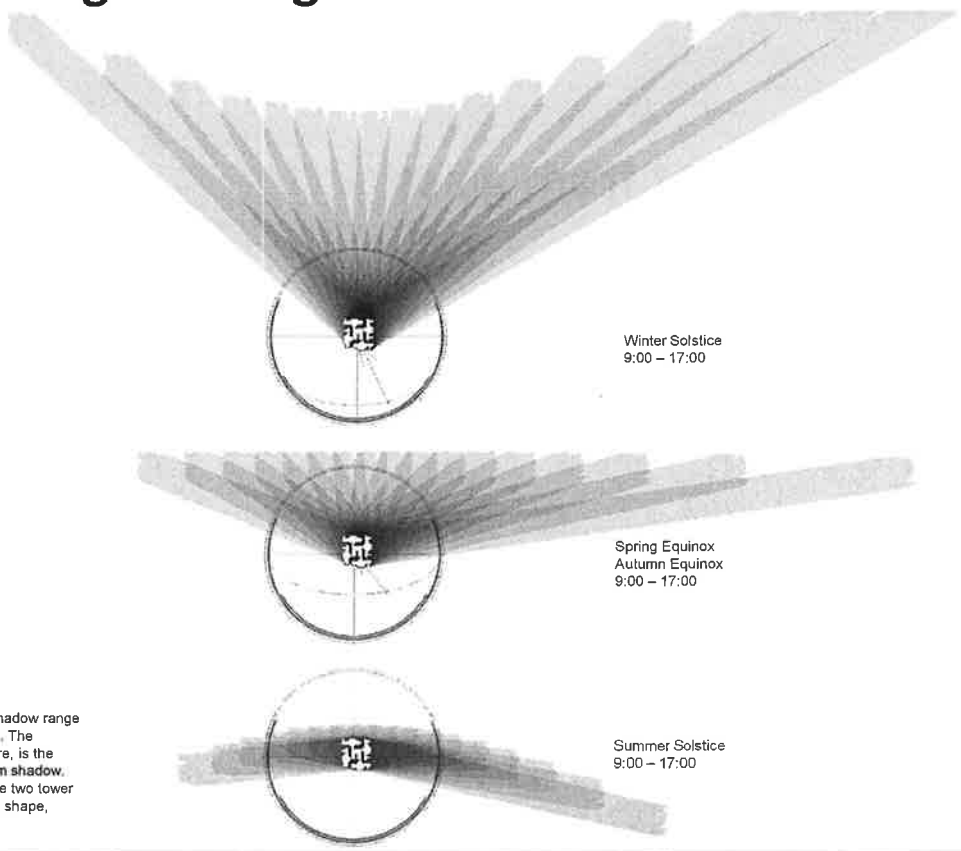
Case building in the shadow range simulation is 200m-tall. The shadow range therefore, is the outline of the maximum shadow. Shadows casted by the two tower schemes are similar in shape, length, and range.

Optimising Building Orientation

Pinwheel Tower Scheme
Building Envelope Solar Radiation



Optimising Building Orientation



Winter Solstice
9:00 – 17:00

Spring Equinox
Autumn Equinox
9:00 – 17:00

Summer Solstice
9:00 – 17:00

Case building in the shadow range simulation is 200m-tall. The shadow range therefore, is the outline of the maximum shadow. Shadows casted by the two tower schemes are similar in shape, length, and range.

BCA ACADEMY

Impact of the Building Envelope on Occupant Comfort

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

Occupant Thermal Comfort

- Radiant heat from glass

$$ETTV = 12x(1\text{-}WWR).U_w + 3.4x(WWR)U_f + \boxed{211x(WWR)(CF)(SC)}$$

Occupant Thermal Comfort

- Conductive heat from glass

$$ETTV = 12x(1\text{-}WWR).U_w + \boxed{3.4x(WWR)U_f} + 211x(WWR)(CF)(SC)$$

Occupant Thermal Comfort

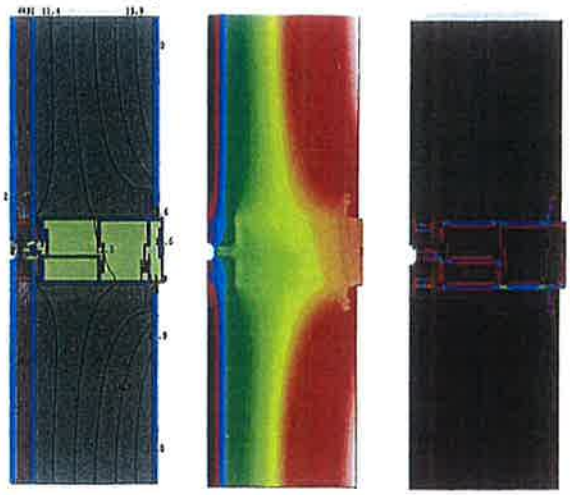
- Conductive heat from solid walls

$$ETTV = 12x(1-WWR).U_w + 3.4x(WWR)U_f + 211x(WWR)(CF)(SC)$$

Occupant Thermal Comfort

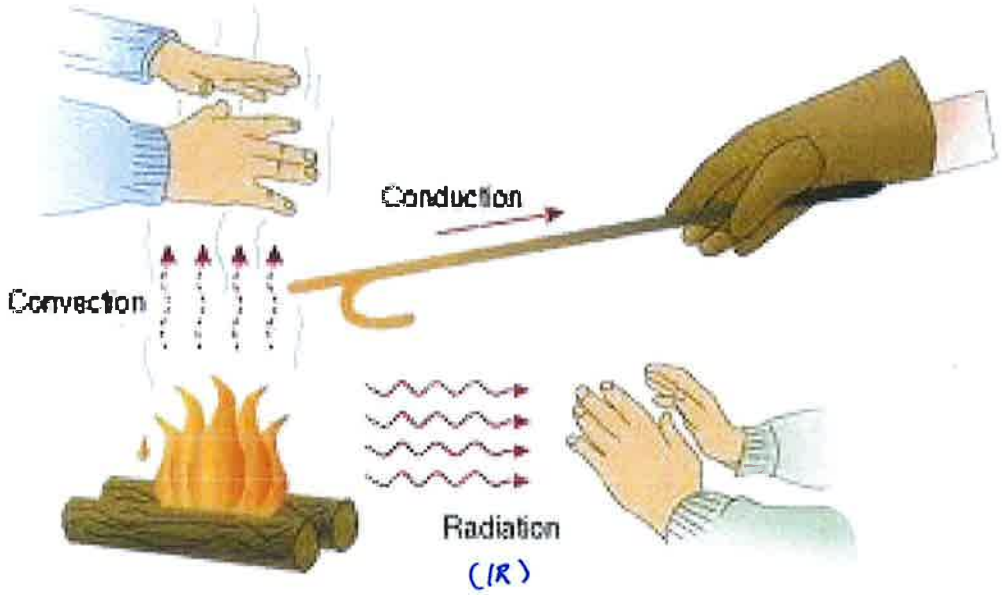
- Radiant and conductive heat from frames

~~$ETTV = 12x(1-WWR).U_w + 3.4x(WWR)U_f + 211x(WWR)(CF)(SC)$~~



Occupant Thermal Comfort

- Forms of heat



Occupant Visual Comfort

- Glare
- Disability
- Discomfort

Occupant Visual Comfort

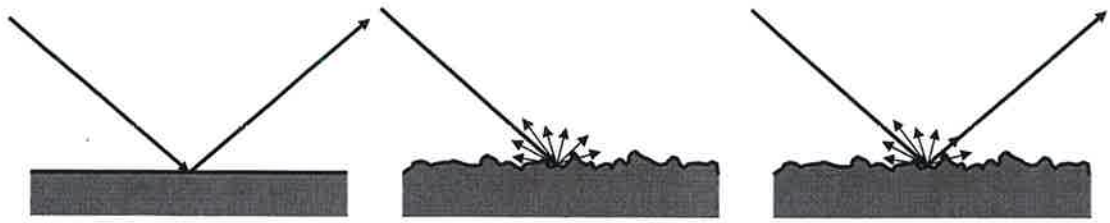
- Comfort of occupants of adjacent buildings
- Comfort of drivers
- Mandatory study in some locations

Occupant Visual Comfort

- In Singapore, external reflectance of glass is limited to 20%
- In Singapore, external reflectance of metal cladding is limited to 10%
- It may be necessary to limit these values further

Occupant Visual Comfort

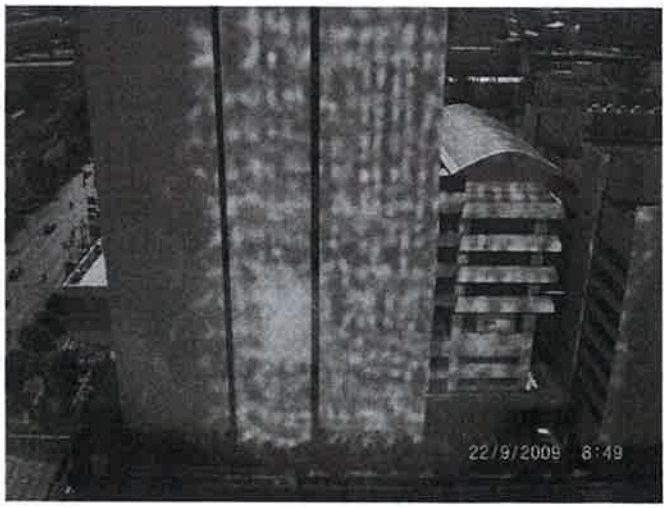
- Need to distinguish between total, specular and diffuse reflectance

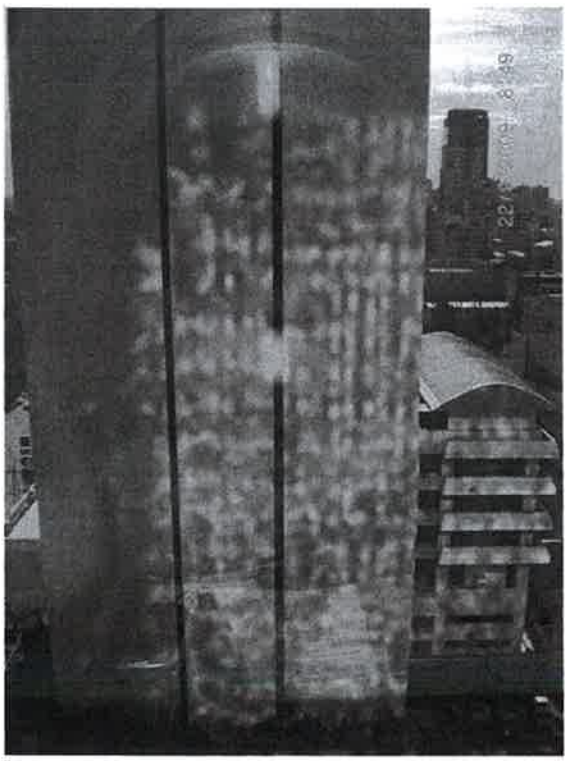


PURELY SPECULAR | PURELY DIFFUSE | MIXED / TOTAL

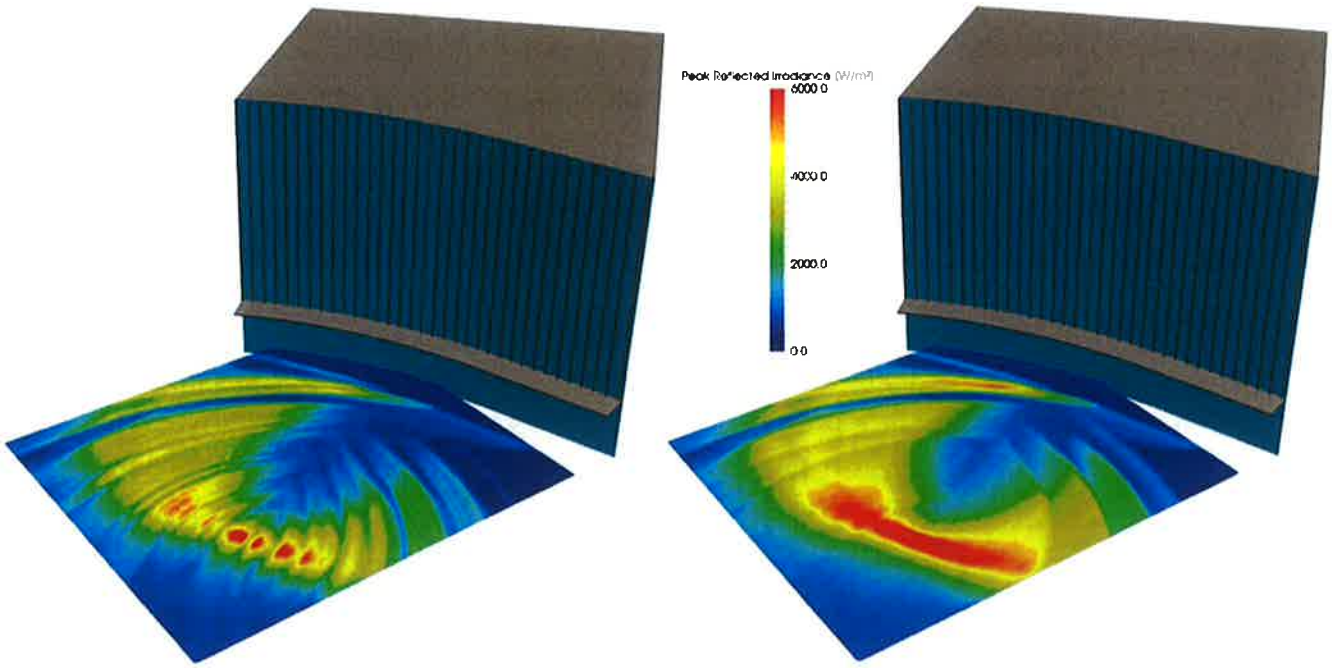
Smooth curtain eg mirror 98%

Neighbour Visual Comfort





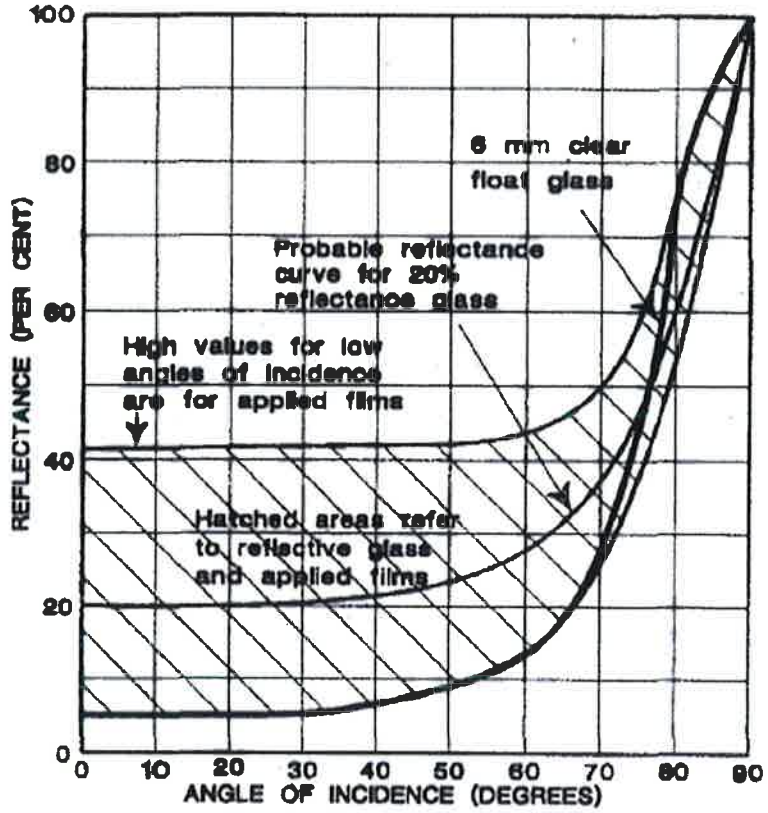
Neighbour Visual Comfort



Occupant Visual Comfort

- Values given by suppliers are based on 90° direction
- Reflectance changes with angle of façade

Neighbour Visual Comfort



BCA ACADEMY

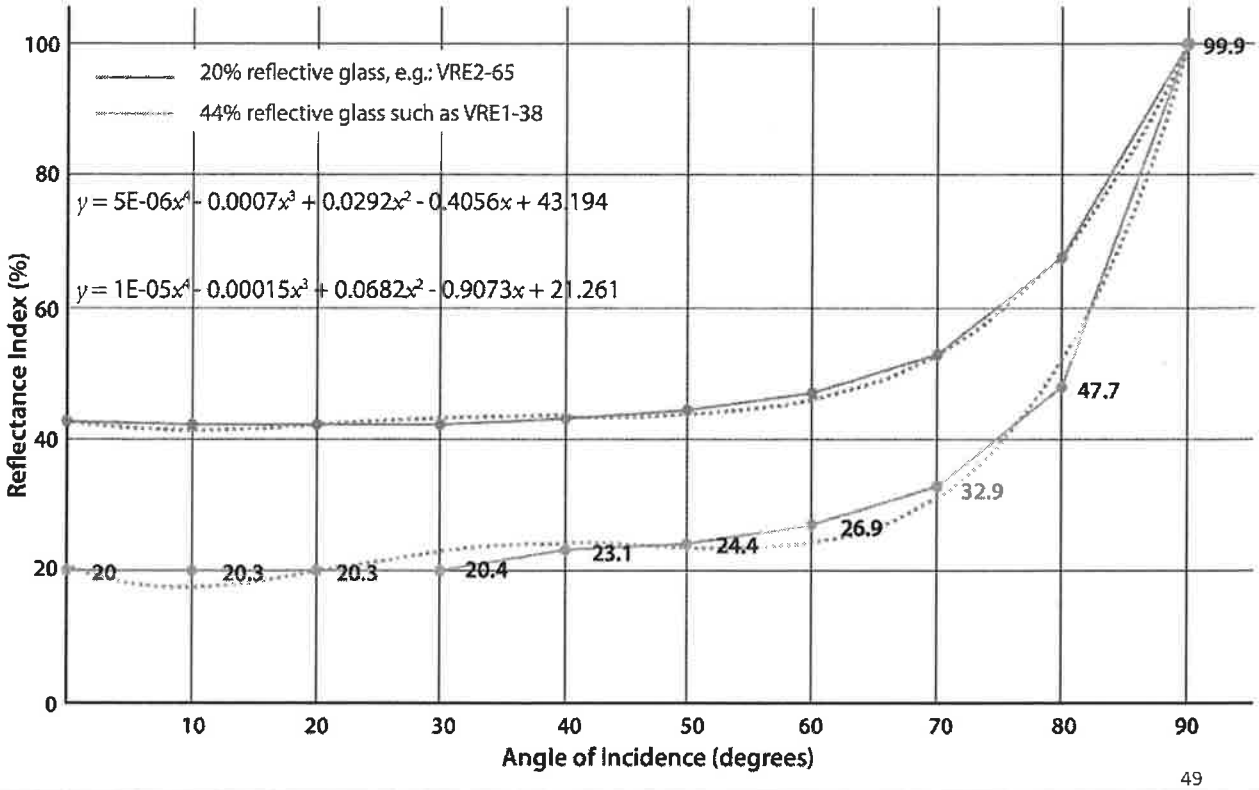
Neighbour Visual Comfort





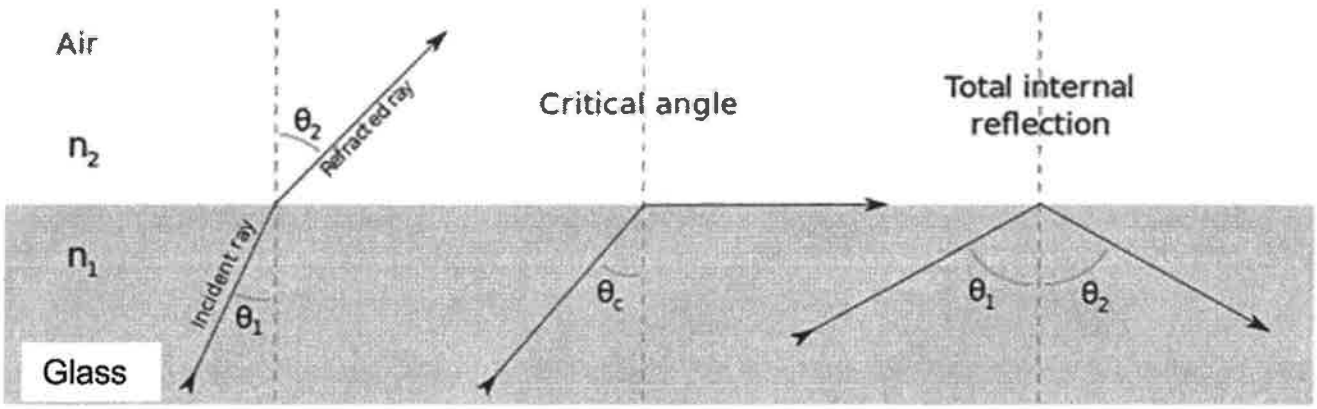
The Education and Research arm of the Building and Construction Authority

Neighbour Visual Comfort



BCA ACADEMY

Neighbour Visual Comfort

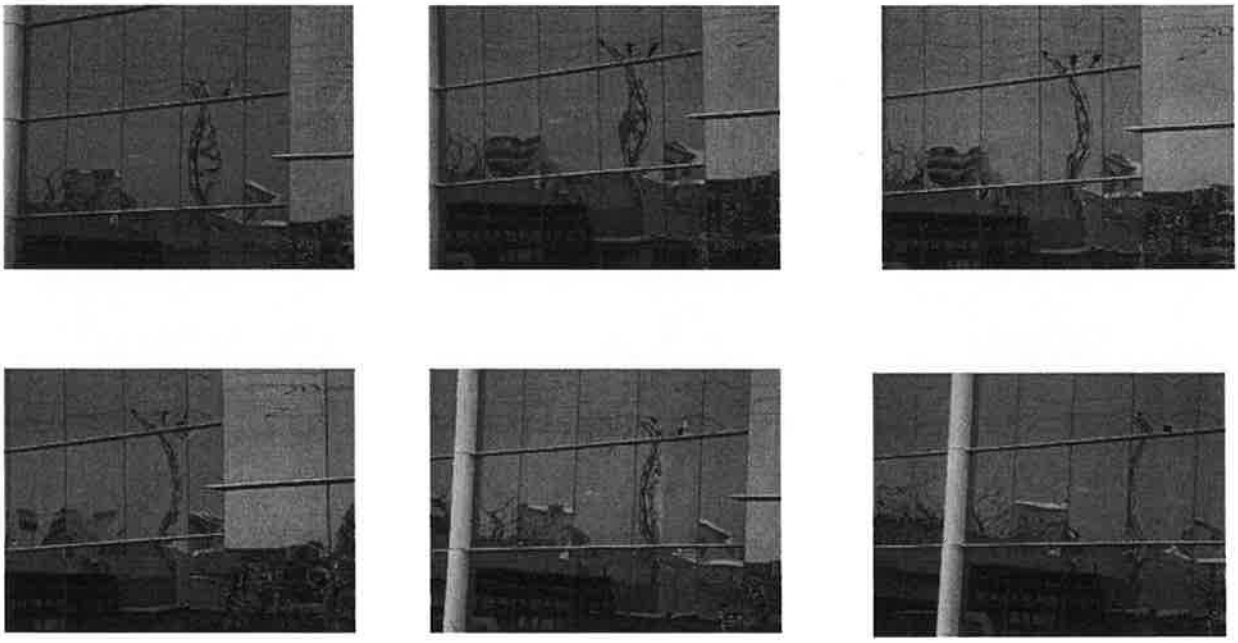


Neighbour Visual Comfort

- In Singapore, visible light reflectance is limited to 20% for glass and 10% for metals
- Not necessarily an adequate measure; performance-based approach used in other places
- Must distinguish between total, specular and diffuse reflectance

Occupant Visual Comfort

- Internal reflections



Energy Modelling Invalidation

- Depending on the project's context, intensity and duration of reflected light, adjacent properties could gain substantial thermal load that was not considered in the energy modelling of the building

Occupant Acoustic Comfort

- Sound Transmission Class / STC rating
- Most common rating used in North America for determining airborne sound transmission loss between 125 and 4,000 Hz
- Definition evolves with time. Must use recently established values.

Human 20 Hz to 20 kHz weighted average

Occupant Acoustic Comfort

- Outside Inside Transmission Class / OITC rating
- Used to determine performance of products in relation to exterior noise, which is often heavy in low frequencies
- Represents transmission loss results from 80 to 4,000 Hz using a different mathematical equation than the STC rating

Occupant Acoustic Comfort

- Both STC and OITC represent average values
- Need to account for losses through frames (e.g. 5dB)
- In specific cases, may need to look at attenuation for specific frequencies (1/3 octave bands)

Occupant Acoustic Comfort

Band Number	Quoted Frequency	Calculated Frequency
1	16 Hz	15.625 Hz
2	20 Hz	19.686 Hz
3	25 Hz	24.803 Hz
4	31.5 Hz	31.250 Hz
5	40 Hz	39.373 Hz
6	50 Hz	49.606 Hz
7	63 Hz	62.500 Hz
8	80 Hz	78.745 Hz
9	100 Hz	99.213 Hz
10	125 Hz	125.000 Hz
11	160 Hz	157.490 Hz
12	200 Hz	198.425 Hz
13	250 Hz	250.000 Hz
14	315 Hz	314.980 Hz
15	400 Hz	396.850 Hz
16	500 Hz	500.000 Hz
17	630 Hz	629.961 Hz
18	800 Hz	793.701 Hz
19	1 kHz	1000.000 Hz
20	1.25 kHz	1259.921 Hz
21	1.6 kHz	1587.401 Hz
22	2 kHz	2000.000 Hz
23	2.5 kHz	2519.842 Hz
24	3.150 kHz	3174.802 Hz
25	4 kHz	4000.000 Hz
26	5 kHz	5039.684 Hz
27	6.3 kHz	6349.604 Hz
28	8 kHz	8000.000 Hz
29	10 kHz	10079.368 Hz
30	12.5 kHz	12699.208 Hz
31	16 kHz	16000.000 Hz
32	20 kHz	20158.737 Hz

BCA ACADEMY

Occupant Acoustic Comfort

Monolithic Glass Construction	STC	OITC*	Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
			Sound Transmission Loss (dB)																	
1/8" overall - 1/8" glass	30	25	19	17	18	21	23	22	24	27	28	30	30	32	34	35	36	33	26	30
1/4" overall - 1/4" glass	31	29	23	25	25	24	28	26	29	31	33	34	34	35	34	30	27	32	37	31
3/8" overall - 3/8" glass	34	32	26	27	27	30	32	31	34	35	36	35	33	30	30	35	38	41	46	48
1/2" overall - 1/2" glass	36	33	26	30	26	30	33	33	34	36	37	35	32	32	36	40	43	46	50	51

Insulating Glass Construction	STC	OITC*	Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
			Sound Transmission Loss (dB)																	
1/2" overall - 1/8" glass, 1/4" airspace, 1/8" glass	28	26	26	21	23	23	26	21	19	24	27	30	33	36	40	44	46	39	34	45
5/8" overall - 1/8" glass, 3/8" airspace, 1/8" glass	31	26	26	23	23	20	23	19	23	27	29	32	35	39	44	47	48	41	36	43
1" overall - 1/4" glass, 1/2" airspace, 1/4" glass	35	30	27	24	29	22	22	25	30	33	35	38	40	42	42	37	37	43	46	49
1" overall - 1/4" glass, 1/2" argon space, 1/4" glass	35	29	32	29	28	22	20	25	30	33	37	40	43	45	44	39	40	45	49	52
1" overall - 1/4" glass, 9/16" airspace, 3/16" glass	37	30	32	26	25	20	24	29	33	36	38	41	43	46	46	42	36	43	48	53
1-1/8" overall - 5/16" glass, 1/2" airspace, 5/16" glass	37	32	26	24	25	31	24	32	32	35	37	39	39	38	36	38	42	44	46	49
1-1/4" overall - 3/8" glass, 1/2" airspace, 3/8" glass	37	32	29	23	23	29	31	34	34	35	36	36	35	35	36	40	43	47	49	48
1-1/2" overall - 1/4" glass, 1" airspace, 1/4" glass	37	30	22	19	27	23	31	30	35	35	36	39	41	42	41	36	37	46	51	56
1-1/16" overall - 1/4" glass, 1/2" airspace, 5/16" glass	38	33	30	24	29	26	29	33	34	36	39	41	41	40	38	37	39	43	46	48
1-1/4" overall - 1/4" glass, 3/4" airspace, 1/4" glass	38	31	27	23	28	21	27	29	34	35	37	41	43	45	44	39	39	46	49	52
1-1/8" overall - 1/4" glass, 1/2" airspace, 3/8" glass	39	34	28	26	32	29	29	31	35	37	38	39	41	43	41	40	41	44	47	49
1-3/16" overall - 5/16" glass, 1/2" airspace, 3/8" glass	39	34	29	26	26	31	30	37	36	37	39	39	40	37	35	39	43	46	48	49
1-3/8" overall - 1/4" glass, 3/4" airspace, 3/8" glass	40	33	30	23	31	28	33	37	39	40	41	39	38	38	39	39	40	47	51	53

Occupant Acoustic Comfort

Laminated Glass Construction	STC	OITC*	Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
			Sound Transmission Loss (dB)																	
1/4" overall - 1/8" glass, .015" PVB, 1/8" glass	33	30	27	23	27	24	27	28	29	31	33	35	35	35	33	31	32	37	41	45
3/16" overall - S/S glass, .030" PVB, S/S glass	35	31	29	29	29	25	27	29	29	31	32	34	34	34	34	35	33	36	39	41
1/4" overall - 1/8" glass, .030" PVB, 1/8" glass	35	31	25	26	28	27	29	29	30	32	34	35	35	36	36	35	35	38	43	46
1/4" overall - 1/8" glass, .045" PVB, 1/8" glass	35	31	24	27	27	28	28	29	30	32	34	35	36	36	37	36	35	38	43	46
5/16" overall - 1/8" glass, .060" PVB, 1/8" glass	35	31	25	25	26	29	28	30	30	32	34	35	35	36	36	36	36	39	43	46
3/8" overall - 3/16" glass, 0.15" PVB, 3/16" glass	36	32	27	25	26	30	31	31	33	35	35	35	35	33	33	37	41	44	48	51
3/8" overall - 3/16" glass, .030" PVB, 3/16" glass	36	33	27	27	27	30	31	31	33	34	35	36	36	35	34	37	41	45	49	52
3/8" overall - 1/4" glass, .030" PVB, 1/8" glass	36	33	27	28	26	30	31	31	32	34	35	36	36	35	35	36	40	44	48	51
1/2" overall - 1/4" glass, .015" PVB, 1/4" glass	36	32	25	25	27	30	32	32	34	35	35	35	33	32	35	40	43	46	49	51
9/16" overall - 1/4" glass, .075" Storm, 1/4" glass	36	35	27	30	30	31	31	33	32	33	34	35	35	34	36	40	43	45	47	47
9/16" overall - 1/4" glass, .090" SGP, 1/4"glass	36	34	31	30	29	31	32	33	33	34	35	35	34	32	34	37	40	42	44	47
7/16" overall - 1/4" glass, .060" PVB, 1/8" glass	37	33	27	28	27	30	31	31	33	35	36	37	37	37	36	37	41	44	48	51
9/16" overall - 1/4" glass, .100" StormGuard, 1/4" glass	37	35	32	31	30	31	33	34	34	34	35	36	35	35	37	41	44	47	49	51
1/2" overall - 1/4" glass, 030" PVB, 1/4" glass	38	34	25	29	28	30	33	33	34	36	37	37	37	36	37	41	45	48	51	53
1/2" overall - 1/4" glass, .045" PVB, 1/4" glass	38	34	26	30	27	30	33	33	34	36	37	38	37	36	37	41	45	48	51	54
9/16" overall - 1/4" glass, .060" PVB, 1/4" glass	39	34	26	29	28	30	33	33	35	36	37	38	38	37	38	41	44	47	51	54
3/4" overall - 1/2" glass, .030" PVB, 1/4" glass	39	36	31	35	33	33	34	36	36	37	36	35	34	39	41	46	48	50	52	56
5/8" overall - 3/8" glass, .030" PVB, 1/4" glass	40	36	29	30	28	32	34	35	36	38	38	38	36	38	42	46	49	52	55	57
13/16" overall - 1/2" glass, .060" PVB, 1/4" glass	41	36	29	30	29	32	35	35	37	38	38	38	37	41	44	48	50	53	56	56

BCA ACADEMY

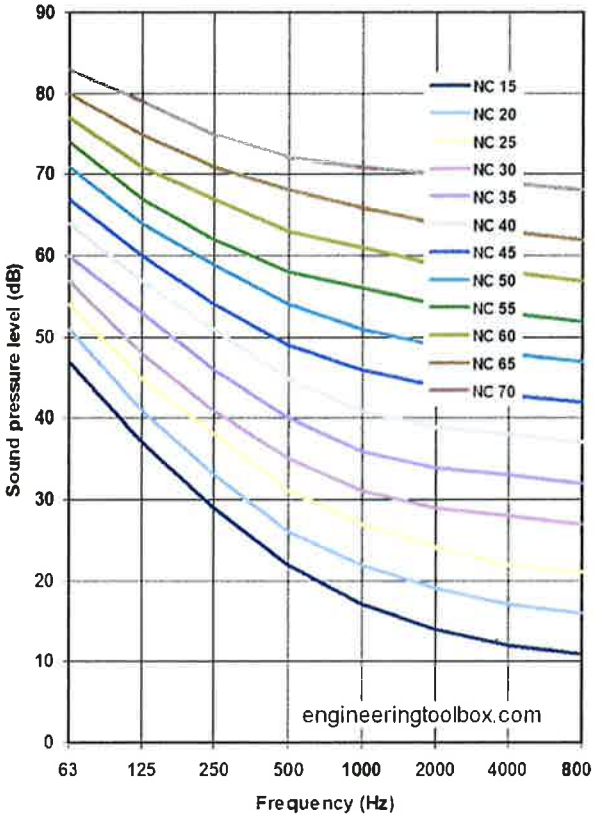
Occupant Acoustic Comfort

Double Laminated Insulating Glass Construction	STC	OITC*	Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
			Sound Transmission Loss (dB)																	
1-7/16" overall - 1/4" glass, .030" PVB, 1/4" glass, 1/2" airspace, 3/16" glass, .060" PVB, 3/16" glass	41	35	32	25	29	31	33	35	37	38	39	39	40	41	42	43	43	44	45	46
1" overall - 1/8" glass, .030" PVB, 1/8" glass, 1/2" airspace, 1/8" glass, .030" PVB, 1/8" glass	42	33	26	21	29	28	30	34	36	40	42	44	44	44	45	46	47	52	57	58
1-3/8" overall - 5/32" glass, .030" PVB, 5/16" glass, 1/2" airspace, 5/32" glass, .030" PVB, 1/4" glass	42	35	29	24	30	35	35	37	39	39	40	40	40	39	44	48	52	56	59	61
1-5/16" overall - 1/4" glass, .030" PVB, 1/4" glass, 1/2" airspace, 5/32" glass, .060" PVB, 5/32" glass	43	36	30	25	29	33	34	38	42	42	43	44	42	41	42	44	49	52	55	57

Double Glazed Insulating Glass Construction	STC	OITC*	Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
			Sound Transmission Loss (dB)																	
1-7/16" overall - 1/8" glass, .030" PVB, 1/8" glass, 1" airspace, 3/16" glass	42	33	22	27	27	28	31	35	38	41	42	43	44	45	47	47	45	50	58	61
2-7/16" overall - 1/8" glass, .030" PVB, 1/8" glass, 2" airspace, 3/16" glass	45	35	24	25	34	33	34	40	41	44	44	46	47	47	48	48	46	50	55	56
1-13/16" overall - 1/4" glass, .030" PVB, 1/4" glass, 1" airspace, 1/8" glass, .060" PVB, 1/8" glass	46	35	21	28	33	37	38	42	43	45	44	44	44	45	49	53	57	59	62	63
2-11/16" overall - 1/4" glass, .030" PVB, 1/4" glass, 2" airspace, 3/16" glass	46	39	27	36	33	33	35	39	41	45	45	46	46	46	49	51	52	56	60	62
2-7/8" overall - 1/4" glass, .030" PVB, 1/4" glass, 2" airspace, 3/8" glass	46	42	34	37	33	38	40	42	44	48	47	46	45	52	56	51	55	59	61	62
4-7/16" overall - 1/8" glass, .030" PVB, 1/8" glass, 4" airspace, 3/16" glass	48	39	26	36	34	37	37	43	44	48	49	51	51	50	51	50	47	51	58	60
4-11/16" overall - 1/4" glass, .030" PVB, 1/4" glass, 4" airspace, 3/16" glass	49	41	30	37	33	38	37	42	45	49	50	51	50	48	50	53	58	57	61	64
4-7/8" overall - 1/4" glass, .030" PVB, 1/4" glass, 4" airspace, 3/8" glass	49	44	38	38	33	40	40	43	46	51	52	52	50	45	48	53	56	59	62	64
4-15/16" overall - 1/2" glass, .060" PVB, 1/4" glass, 4" airspace, 1/8" glass	49	40	29	33	31	36	36	43	44	46	47	49	50	52	52	55	59	59	58	60

Occupant Acoustic Comfort

- Noise Criterion / NC rating



BCA ACADEMY

Occupant Acoustic Comfort

- Noise Criterion / NC rating

Noise Criterion	Octave Band Center Frequency *(Hz)*							
	63	125	250	500	1000	2000	4000	8000
	Sound Pressure Levels *(dB)*							
NC-15	47	36	29	22	17	14	12	11
NC-20	51	40	33	26	22	19	17	16
NC-25	54	44	37	31	27	24	22	21
NC-30	57	48	41	35	31	29	28	27
NC-35	60	52	45	40	36	34	33	32
NC-40	64	56	50	45	41	39	38	37
NC-45	67	60	54	49	46	44	43	42
NC-50	71	64	58	54	51	49	48	47
NC-55	74	67	62	58	56	54	53	52
NC-60	77	71	67	63	61	59	58	57
NC-65	80	75	71	68	66	64	63	62
NC-70	83	79	75	72	71	70	69	68

The Education and Research arm of the Building and Construction Authority

Occupant Acoustic Comfort

- Different NC for different spaces

Type of Room - Space Type	Recommended NC Level NC Curve	Equivalent Sound Level (dB_A)
Residences		
Apartment Houses	25-35	35-45
Assembly Halls	25-30	35-40
Churches, Synagogues, Mosques	30-35	40-45
Courtrooms	30-40	40-50
Factories	40-65	50-75
Private Homes, rural and suburban	20-30	30-38
Private Homes, urban	25-30	34-42
Hotels/Motels		
- Individual rooms or suites	25-35	35-45
- Meeting or banquet rooms	25-35	35-45
- Service and Support Areas	40-45	45-50
- Halls, corridors, lobbies	35-40	50-55
Offices		
- Conference rooms	25-30	35-40
- Private	30-35	40-45
- Open-plan areas	35-40	45-50
- Business machines/computers	40-45	50-55

BCA ACADEMY

Occupant Acoustic Comfort

- Different NC for different spaces

Type of Room - Space Type	Recommended NC Level NC Curve	Equivalent Sound Level (dB_A)
Hospitals and Clinics		
- Private rooms	25-30	35-40
- Operating rooms	25-30	35-40
- Wards	30-35	40-45
- Laboratories	35-40	45-50
- Corridors	30-35	40-45
- Public areas	35-40	45-50
Schools		
- Lecture and classrooms	25-30	35-40
- Open-plan classrooms	35-40	45-50
Movie motion picture theaters	30-35	40-45
Libraries	35-40	40-50
Legitimate theaters	20-25	30-65
Private Residences	25-35	35-45
Restaurants	40-45	50-55
TV Broadcast studies	15-25	25-35
Recording Studios	15-20	25-30
Concert and recital halls	15-20	25-30
Sport Coliseums	45-55	55-65
Sound broadcasting	15-20	25-30

Occupant Acoustic Comfort

- Design procedure:
  - Determine NC
  - Determine external noise levels
  - From the difference, pick a glazing product that achieves the required performance
  - Take frames into account!

Occupant Acoustic Comfort

- Strategies for lowering sound transmission
- Use mixed glass thicknesses
- Use IGUs
- Use laminated glass
- Use acoustic interlayer
- Insulate frames

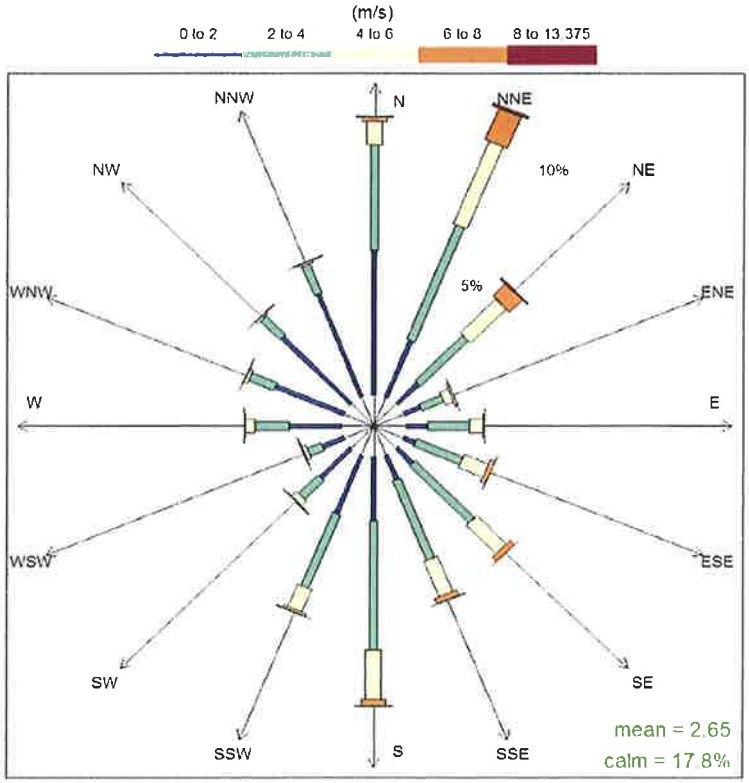
Occupant Acoustic Comfort

- Actual performance can be tested in a lab
- Actual performance can be tested on site

Vegetation Decay

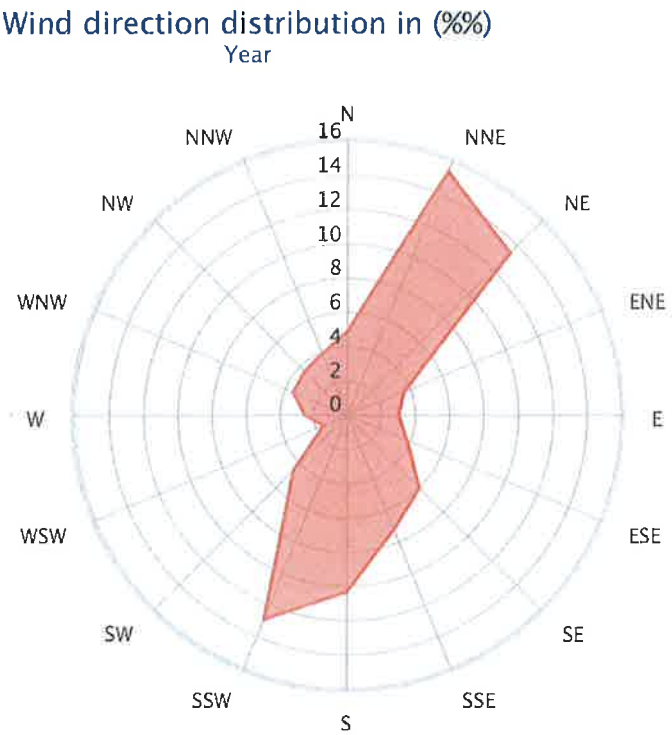
- Some plants cannot break down nutrients at certain temperatures and will eventually start to decay when exposed to excessive solar radiation

Optimised Orientation and Openings

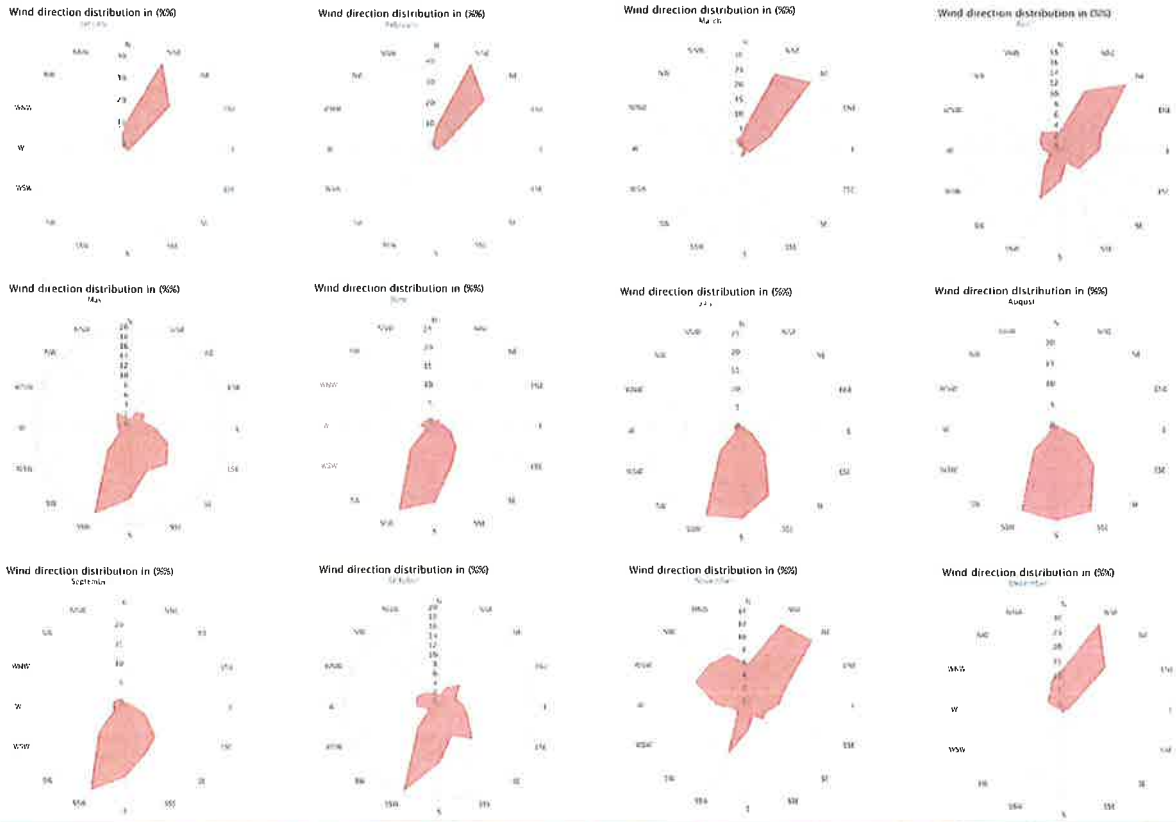


Percentage of counts by wind direction (%)

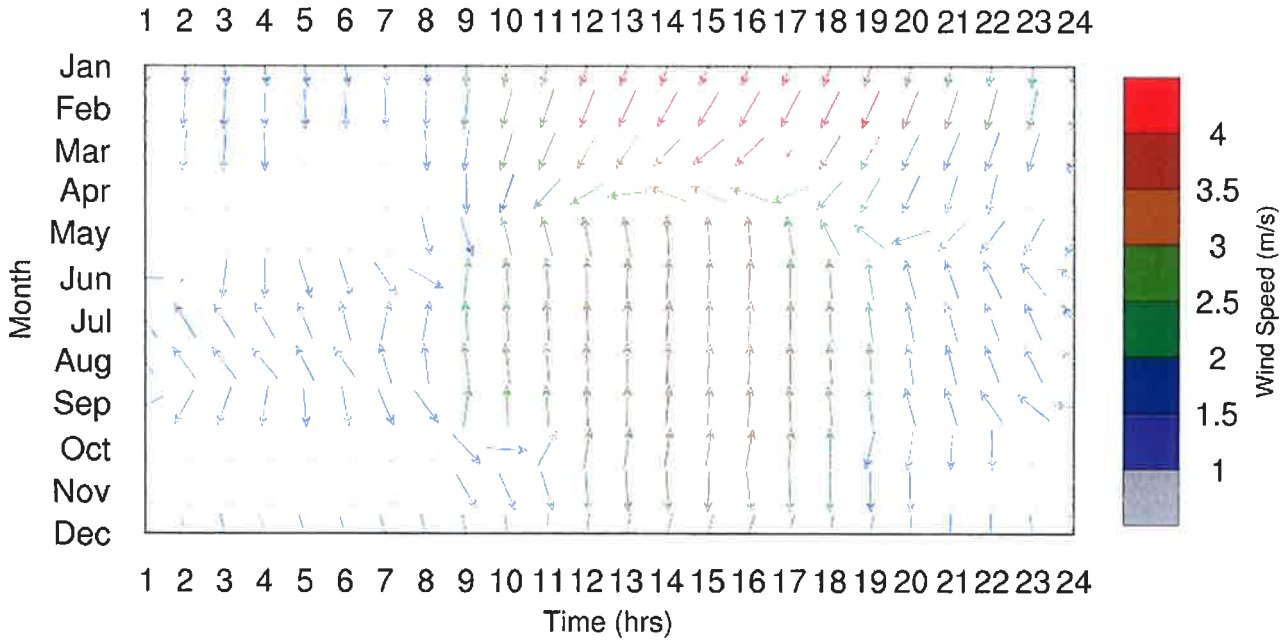
Optimised Orientation and Openings



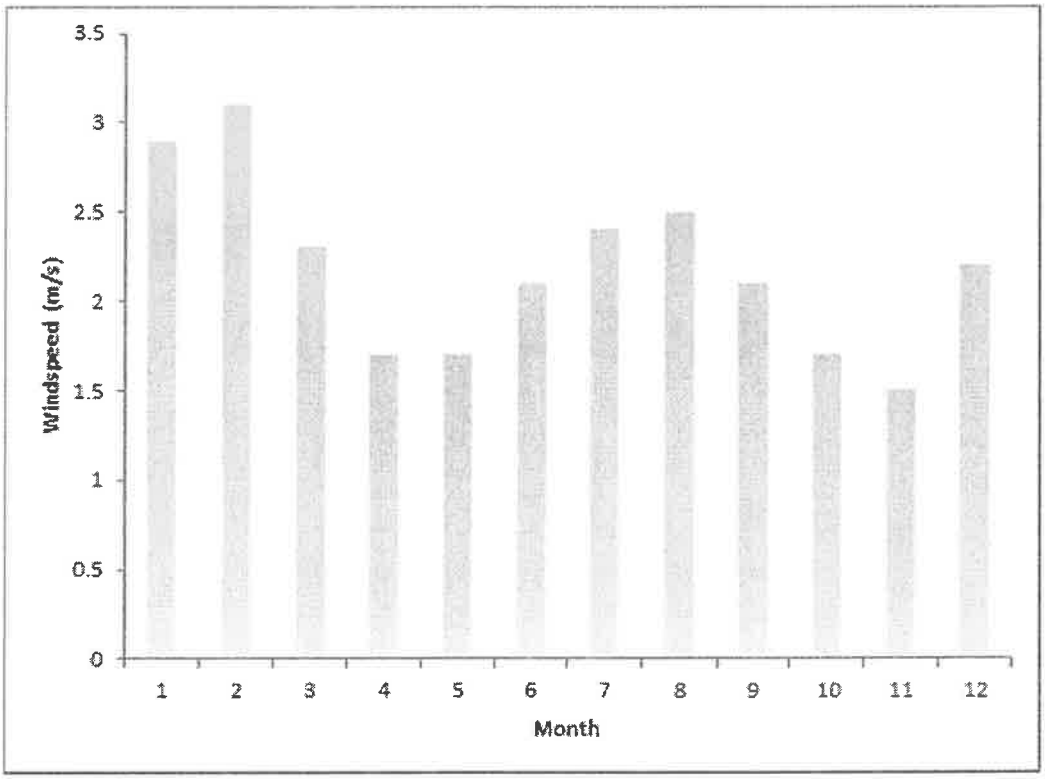
Optimised Orientation and Openings



Optimised Orientation and Openings



Optimised Orientation and Openings



Optimised Orientation and Openings

- Best to have openings along N, NE, S and SE elevations
- Verify indoors wind speed and thermal comfort using CFD
- Tweak opening sizes and orientation based on CFD results

Impact of the Building Envelope on the Environment

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

BCA ACADEMY

Impact on the Environment

Embodied Energy MJ/kg	CATI	RAMI	SCI	Structe	REAI	ICE	Hamp
Earth blocks	0.8	0.7	–	–	–	–	–
Concrete blocks	–	1.5	1.3	–	–	–	1.4
In situ concrete	1.5	1.9	1	2	1.25	1	1.7
Plaster	2.5	2.9	–	–	–	2	2.9
Clay bricks	3.3	2.5	5.8	–	–	3	2.5
Cement	5.3	5.6	–	–	–	4.8	5.6
Plywood		10.4	17	–	–	15	10.4
Glass	22.1	12.7	–	–	7.2	13.5	12.7
Structural steel	41.6	36	26.8	35	25	24	34
Plastics	75.3	90	–	–	–	61	90
Aluminium	121.3	170	–	145	101	154	170
Timber	–	–	–	5	3.6	9	11
Copper	–	–	–	–	65	–	100

Table 1 Embodied energy figures from various data sources

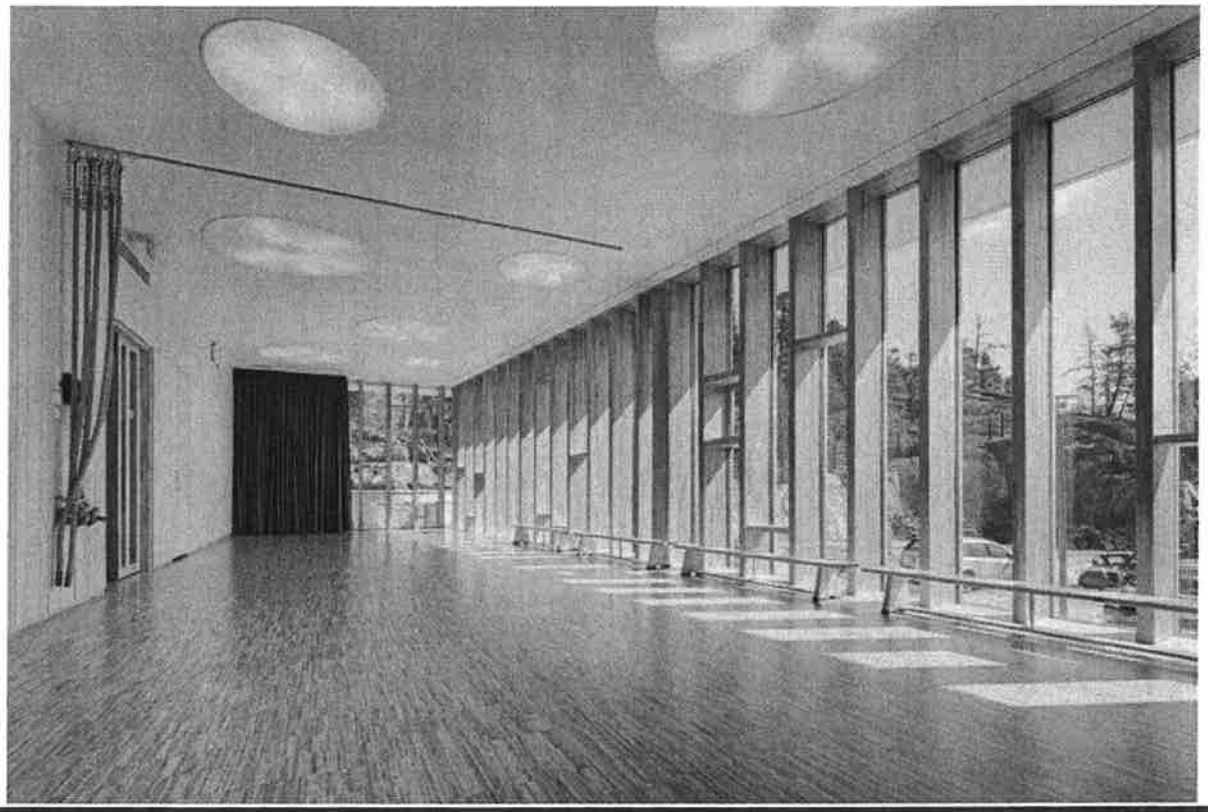


kg of CO_2	Glass	Aluminium	Insulation	Concrete
Per m^3	4,834	24,855	540	452
Per m^2	39	75	27	90

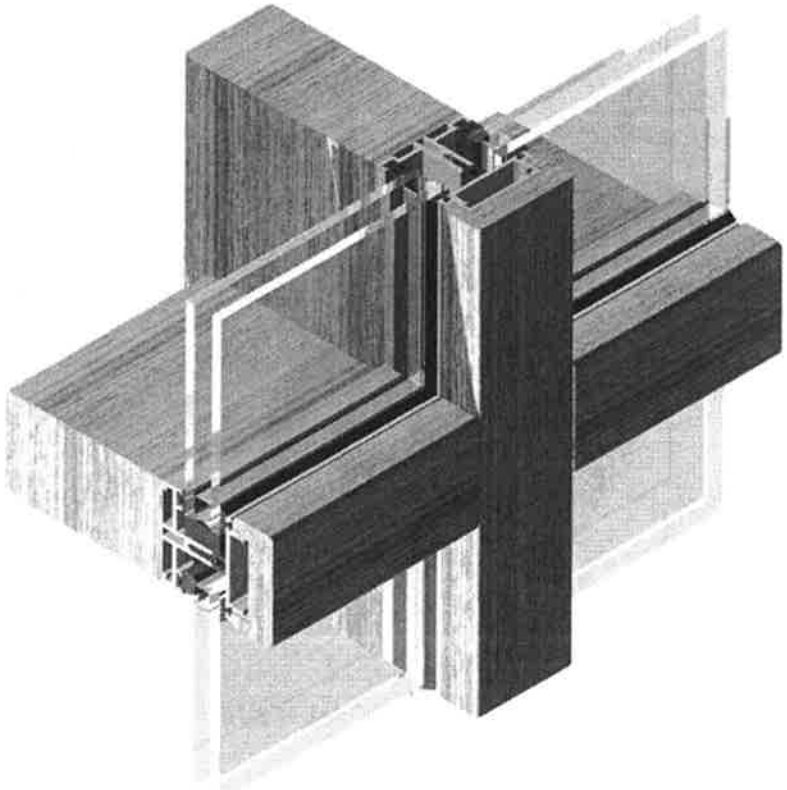
5% in recycle.

The Education and Research arm of the Building and Construction Authority

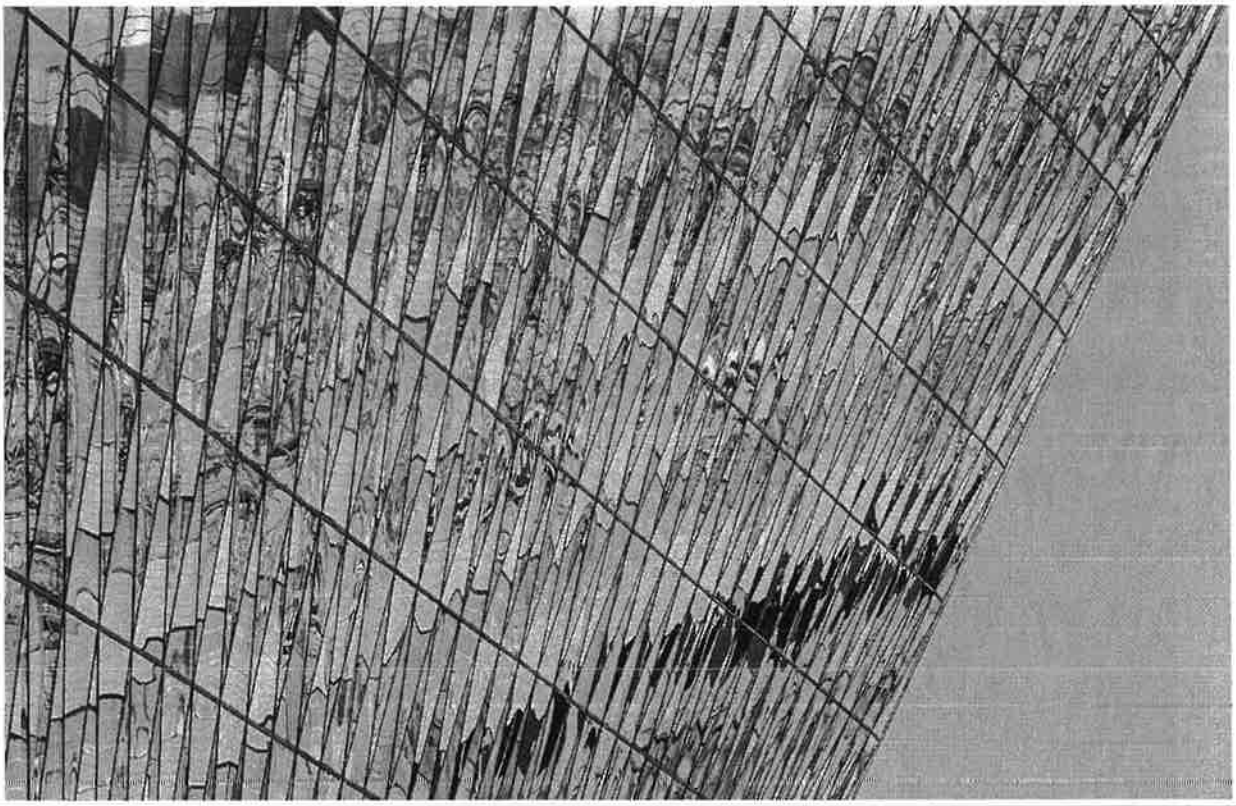
Impact on the Environment



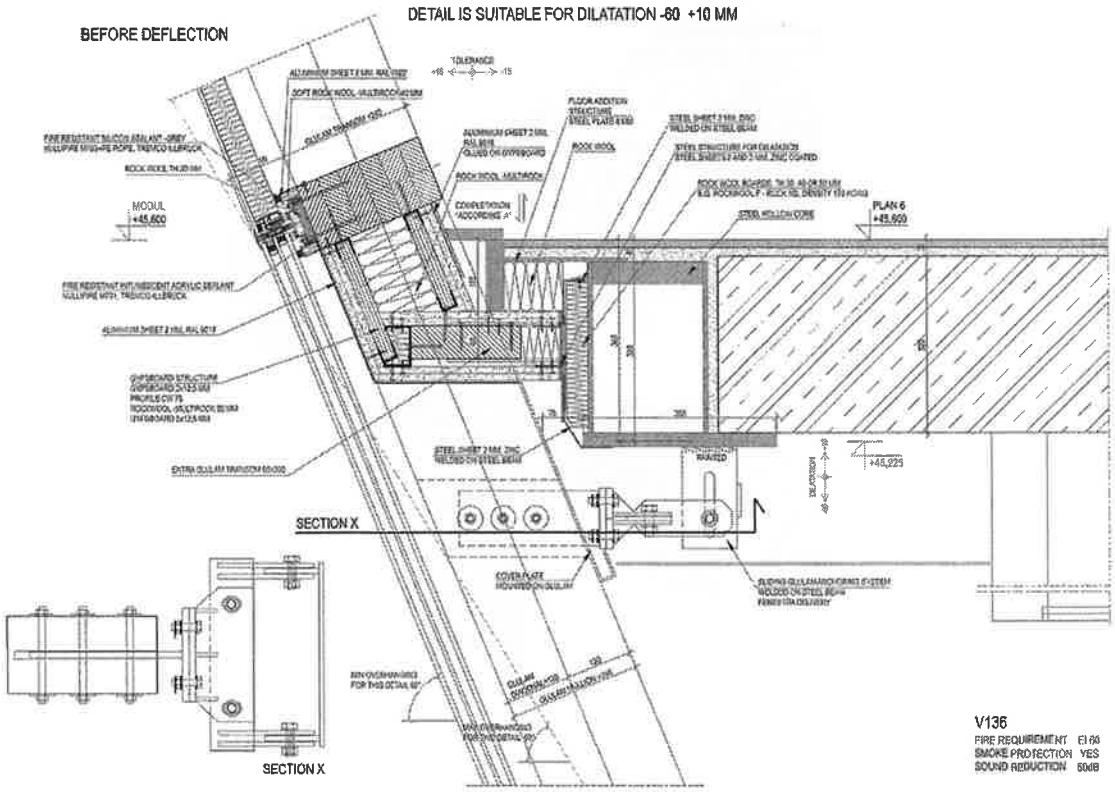
Impact on the Environment



Impact on the Environment

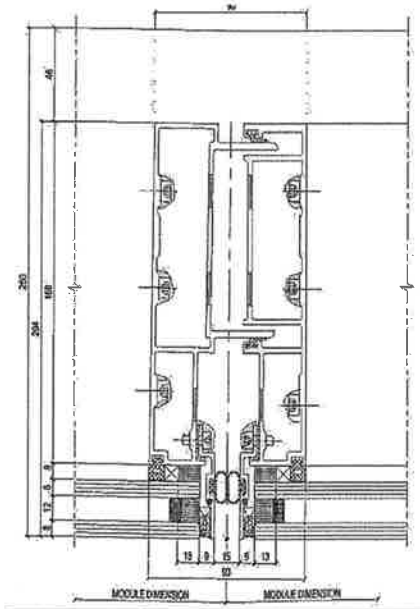


Impact on the Environment

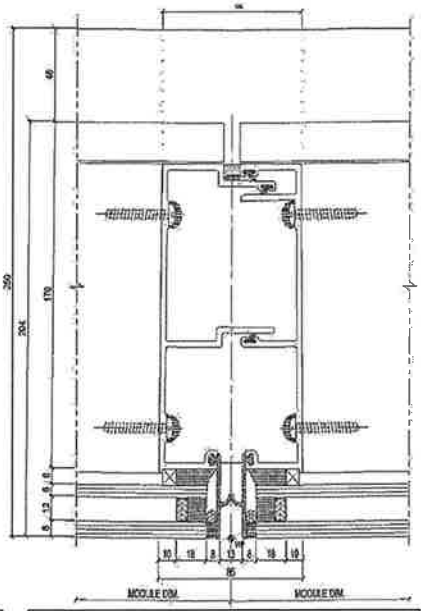


Impact on the Environment

- Optimise framing system



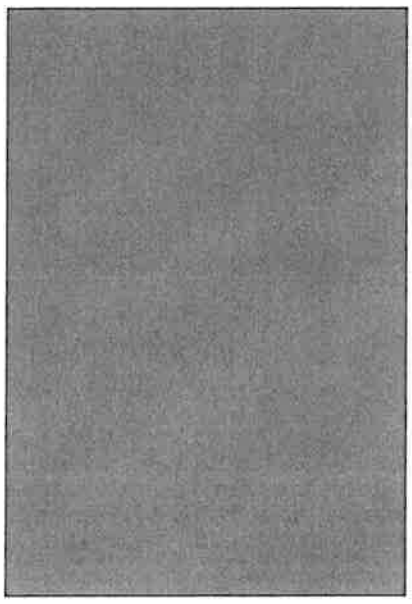
Contractor design: 250t Al.



Optimal design: 130t Al.

Impact on the Environment

- Optimise materials, minimise wastage



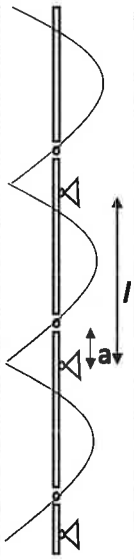
Typical glass stock sheet sizes:

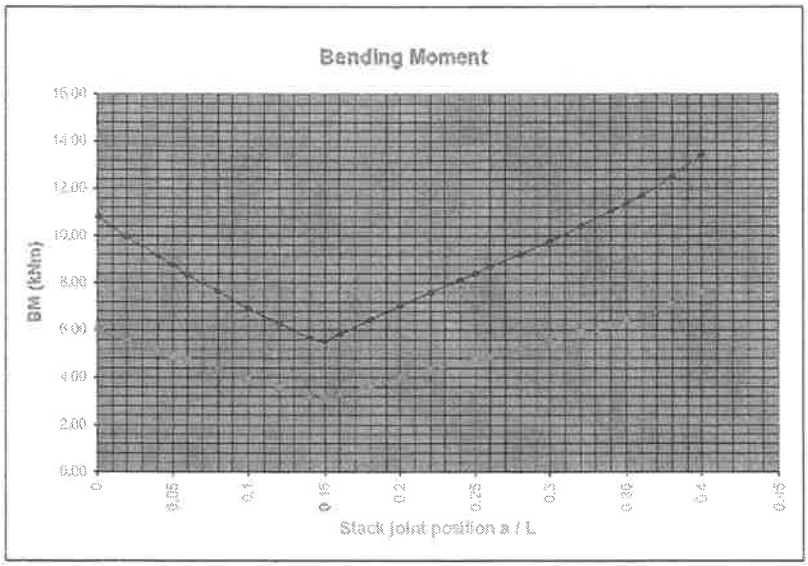
6.0m x 2.4m or 6.0m x 3.0m

3.66m x 2.44m or 5.1m x 3.12m

Impact on the Environment



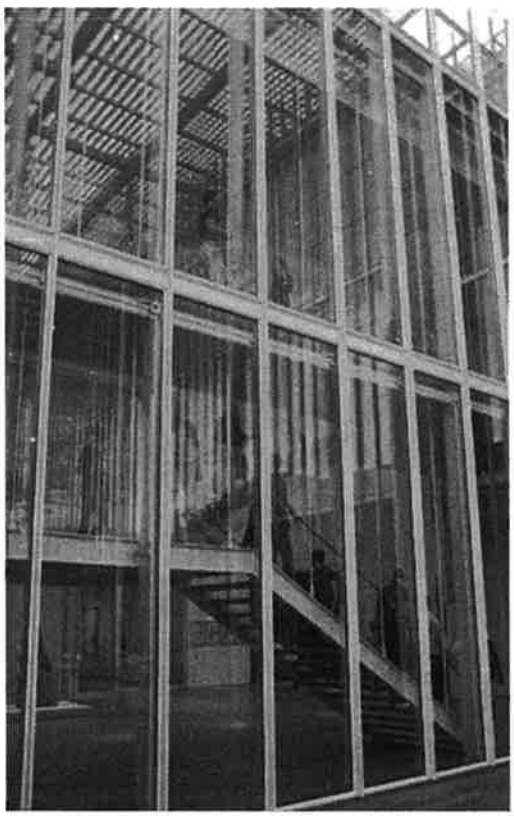


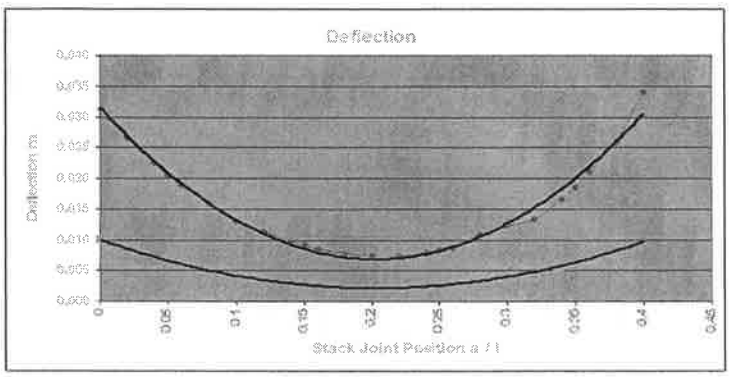


Moment = $$M = \frac{aw(l-a)}{2}$$

Optimum stack joint position = $$\frac{a}{l} = \frac{1}{2} - \frac{Sin45°}{2} = 0.146$$

Impact on the Environment





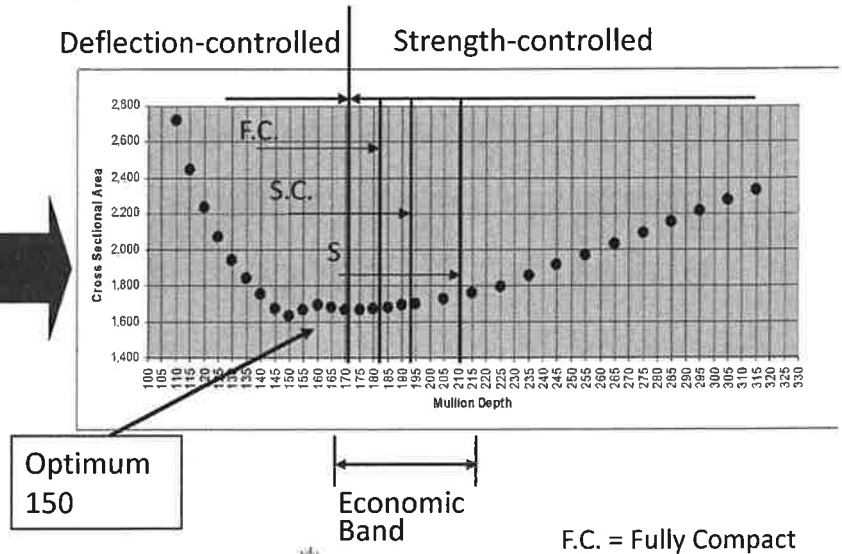
Optimum Stack Joint Position a/l = 0.21

Optimised Framing

Design Optimisation



Peaks occur at classifications of members



F.C. = Fully Compact
S.C. = Semi-Compact
S = Slender

BCA ACADEMY

Impact on the Environment

- Use recycled and/or recyclable materials where possible (glass, aluminium, steel, some plastics)
- Electric power represents about 20% to 40% of the cost of producing aluminium (15±0.5 kWh/kg)

Impact on the Environment

- Recycling requires only five percent of the energy used to produce aluminium from ore
- E.g. Australia is the world's fifth largest producer of aluminium, processing methods use about 10 per cent of national capacity

BCA ACADEMY

Impact on the Environment

- Glass production uses vast amounts of heat
- Use recycled glass cullets to reduce kiln temperature and minimise raw material extraction

Impact on the Environment

- Aluminium frame finishes: anodised, powder-coating, PVDF
- Anodised most eco-friendly, but must contain acid and chromium effluents
- PVDF best performance externally, but high VOC content
- Trade-off between durability and "green" aspect

polyvinylidene fluoride

Impact on the Environment

- Frame / cladding / glass colours
- Urban heat island effect

Impact on the Environment

- Consider façade products that are SGBC-certified





SINGAPORE
GREEN
BUILDING
COUNCIL

GMP Course

Function And Design Of Building Envelopes



School of Graduate Development and Management

BCA ACADEMY

The contents of this document are protected by copyright and other forms of proprietary rights. All rights, title and interest in the contents are owned by, licensed to or controlled ***by BCA*** *and shall not be reproduced, republished, uploaded, posted, transmitted or otherwise distributed in any way, without the prior written permission of BCA. Modification of any of the contents or use of the contents for any other purpose will be a violation of BCA's copyright and other intellectual property rights. No part of the course may be recorded, reproduced or transmitted in any form or by any means, without the express written permission of the course organiser.*

The reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply BCA's endorsement, recommendation, or favouring by BCA.

Building Skin as a Responsive Skin

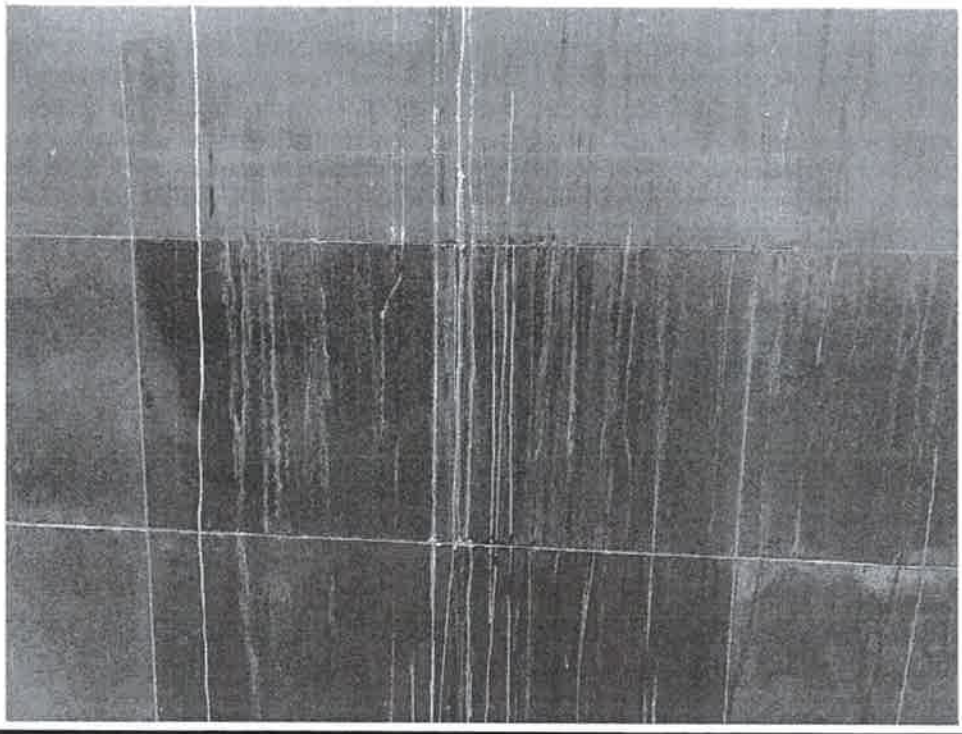
The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

BCA ACADEMY

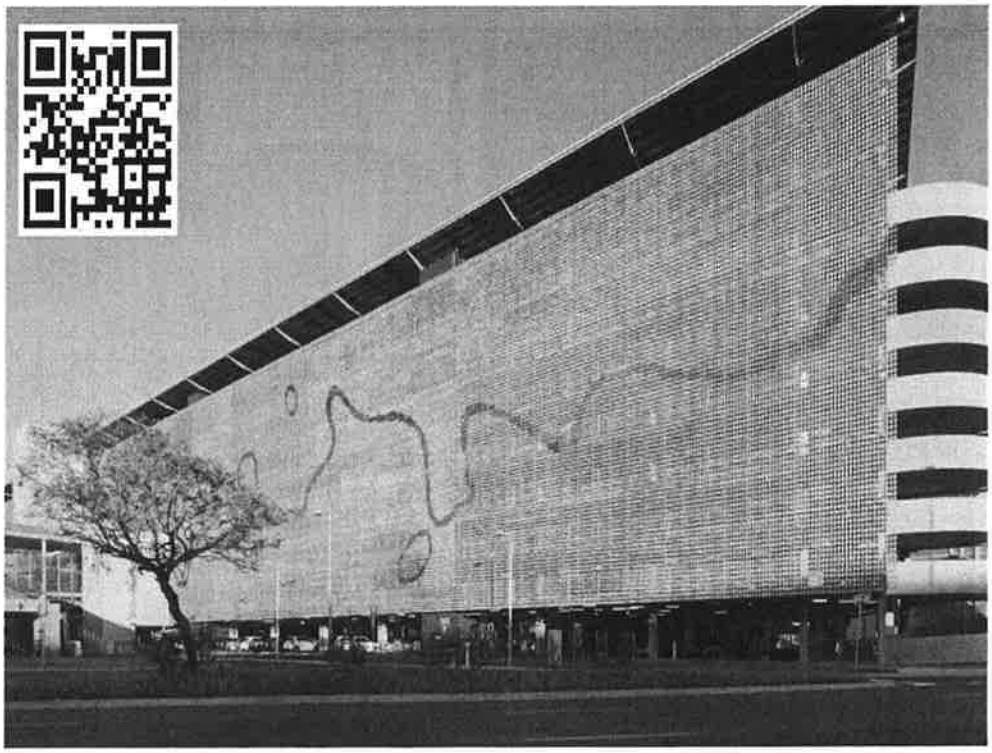
Building Skin as a Responsive Skin

- Pollution



Building Skin as a Responsive Skin

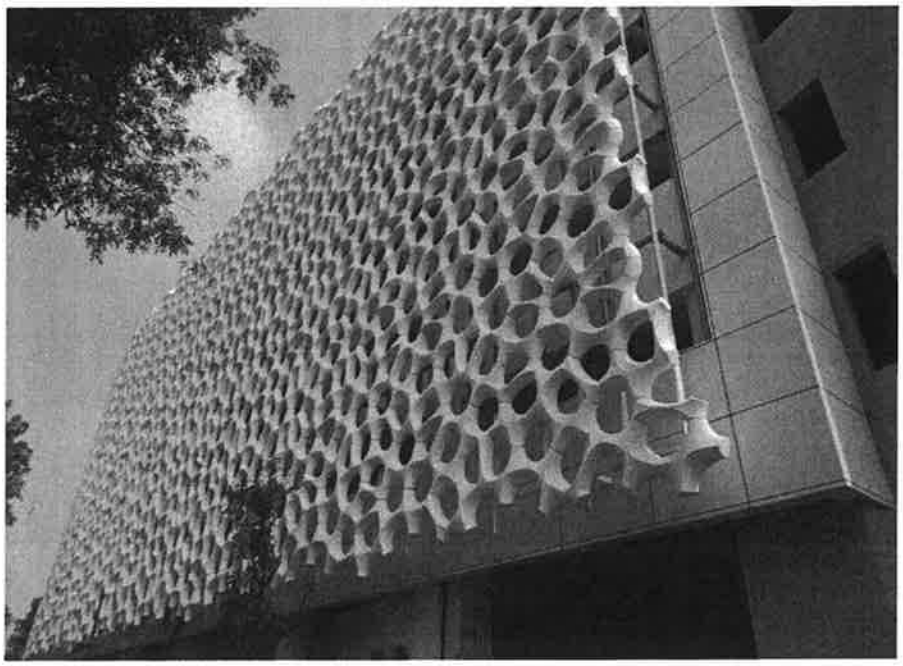
- Kinetic Façades Producing Energy



BCA ACADEMY

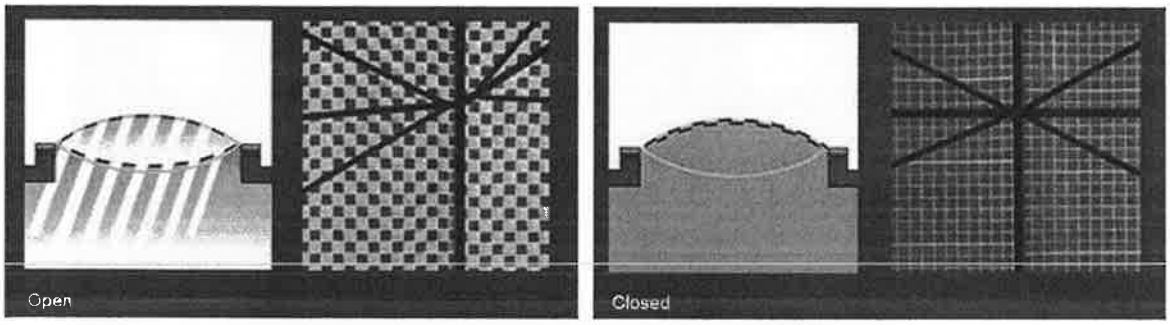
Building Skin as a Responsive Skin

- Smog-Eating Concrete



Building Skin as a Responsive Skin

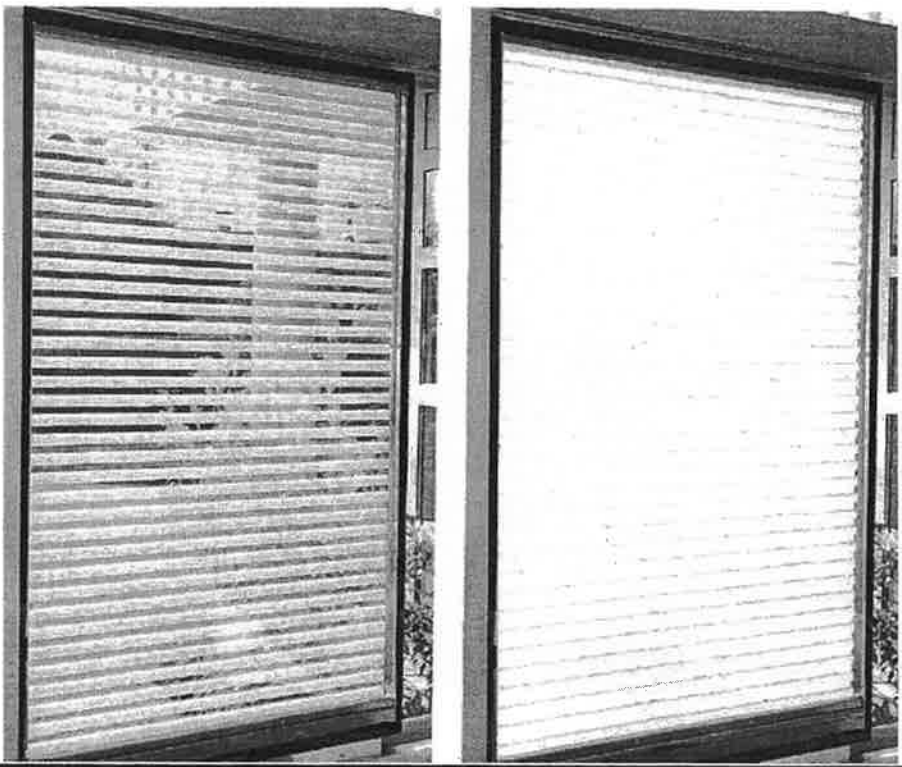
- Intelligent ETFE





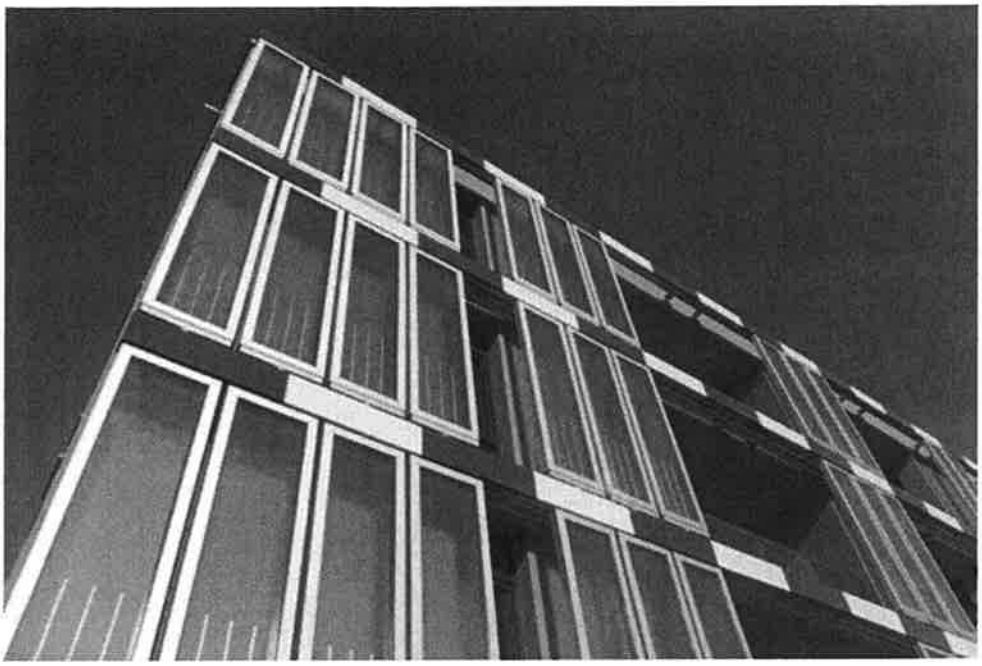
Building Skin as a Responsive Skin

- Reactive Glass



Building Skin as a Responsive Skin

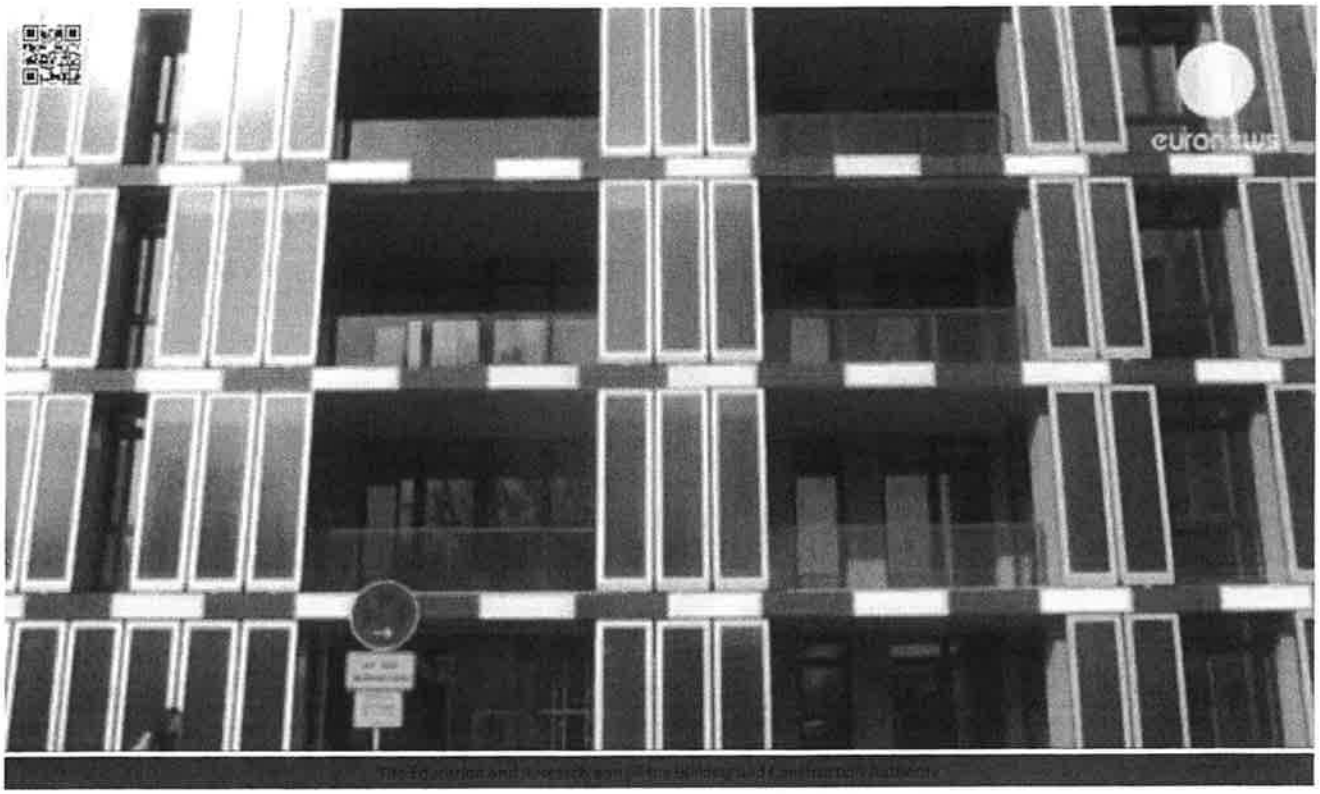
- Bio-glass



BCA ACADEMY

Building Skin as a Responsive Skin

- Bio-glass



Building Skin as a Responsive Skin

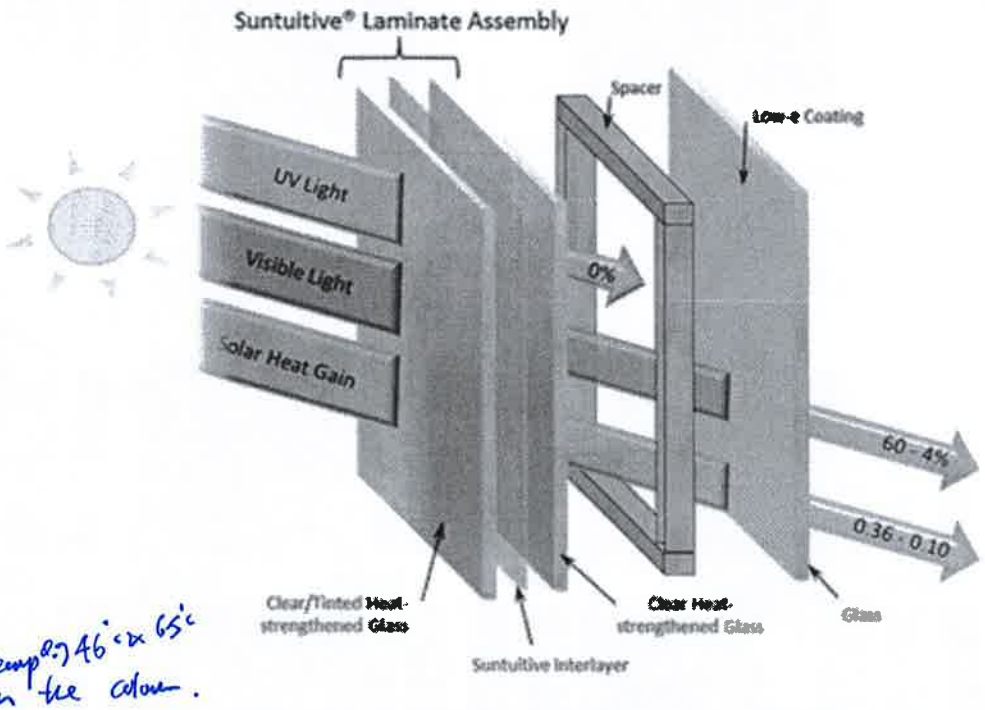
- Electrochromic glass

Change colour



Building Skin as a Responsive Skin

- Thermochromic glass



Transition temp: 46°C to 65°C that soften the colour.

outside glass should be tinted

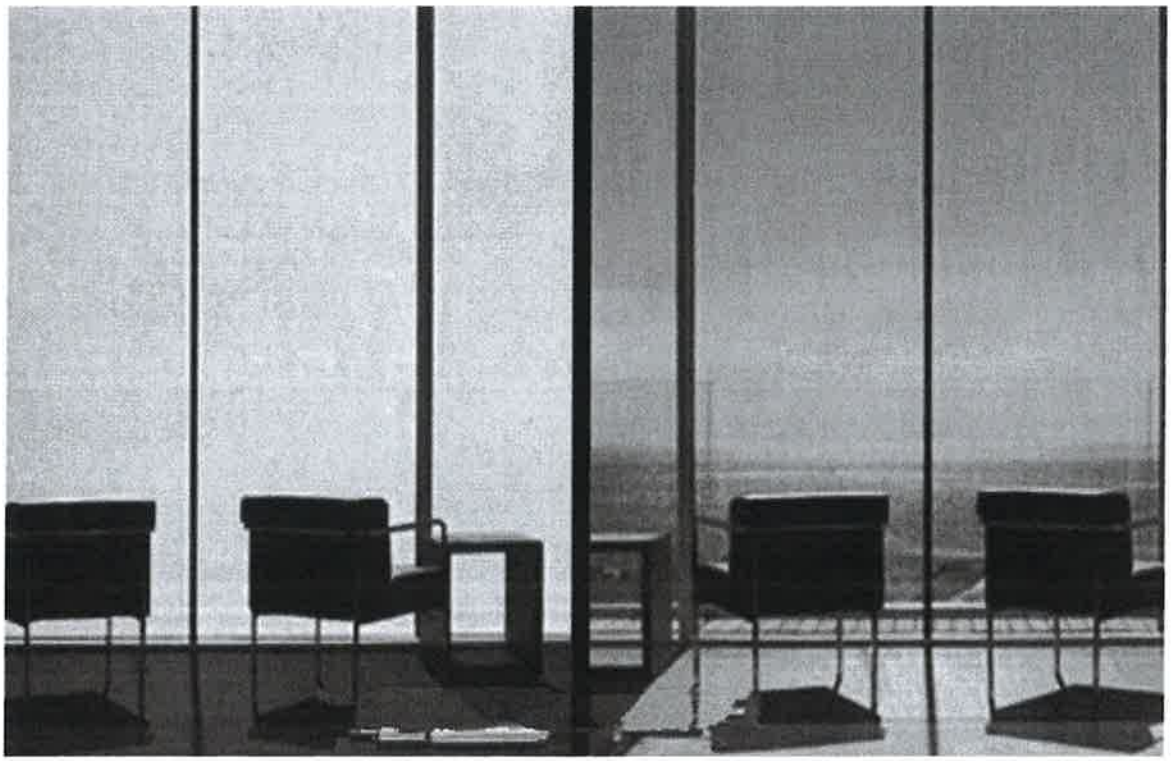
Building Skin as a Responsive Skin

- Thermochromic glass



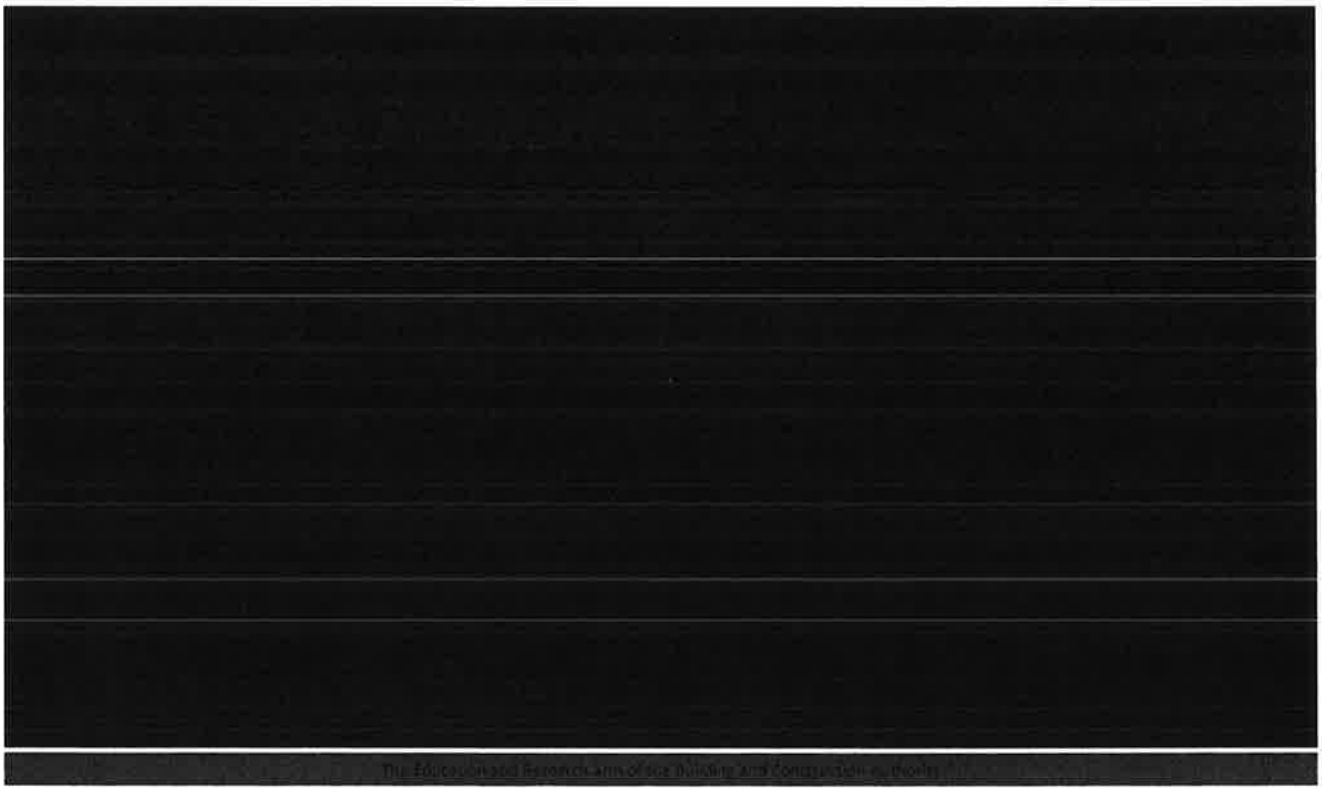
Building Skin as a Responsive Skin

- Photochromic glass (Transitions Glass)



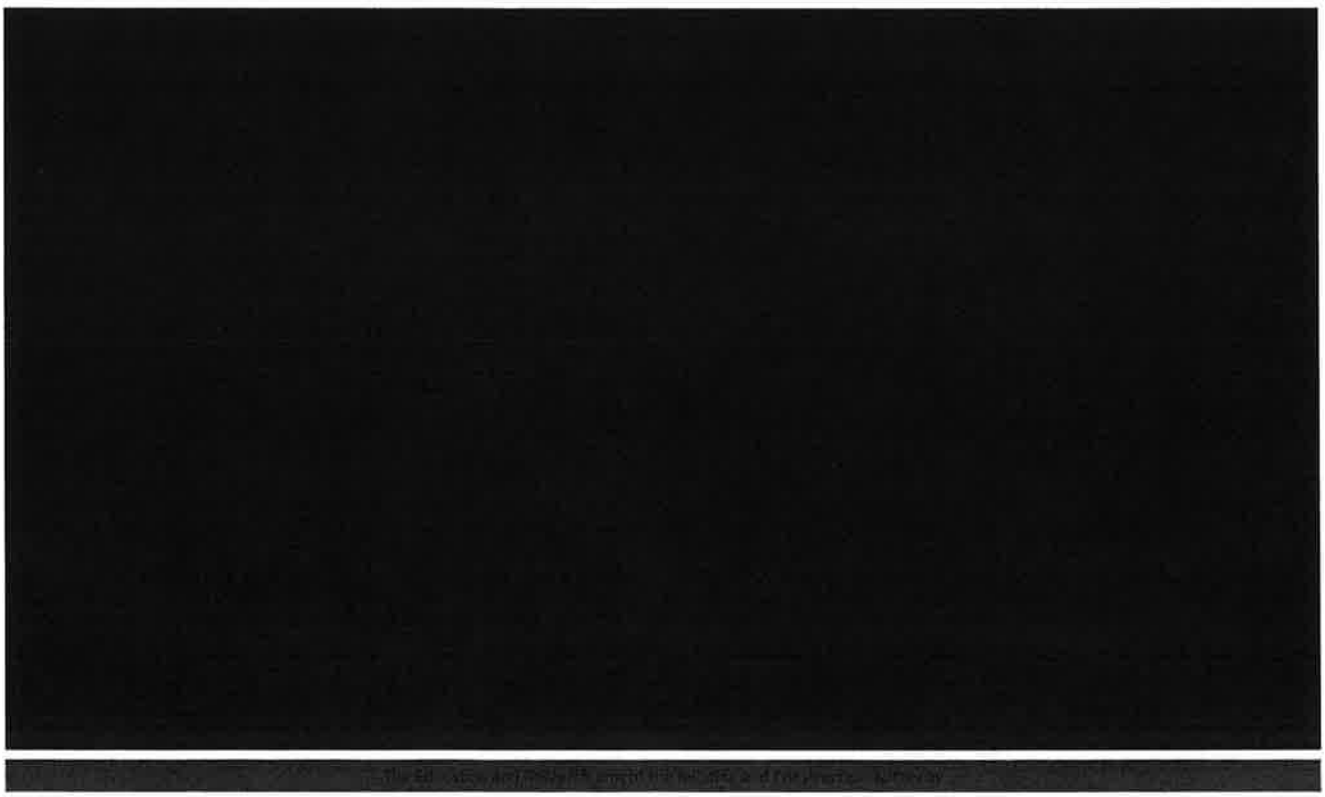
Building Skin as a Responsive Skin

- Photochromic glass



Building Skin as a Responsive Skin

- Responsive screens



Building Skin as a Responsive Skin

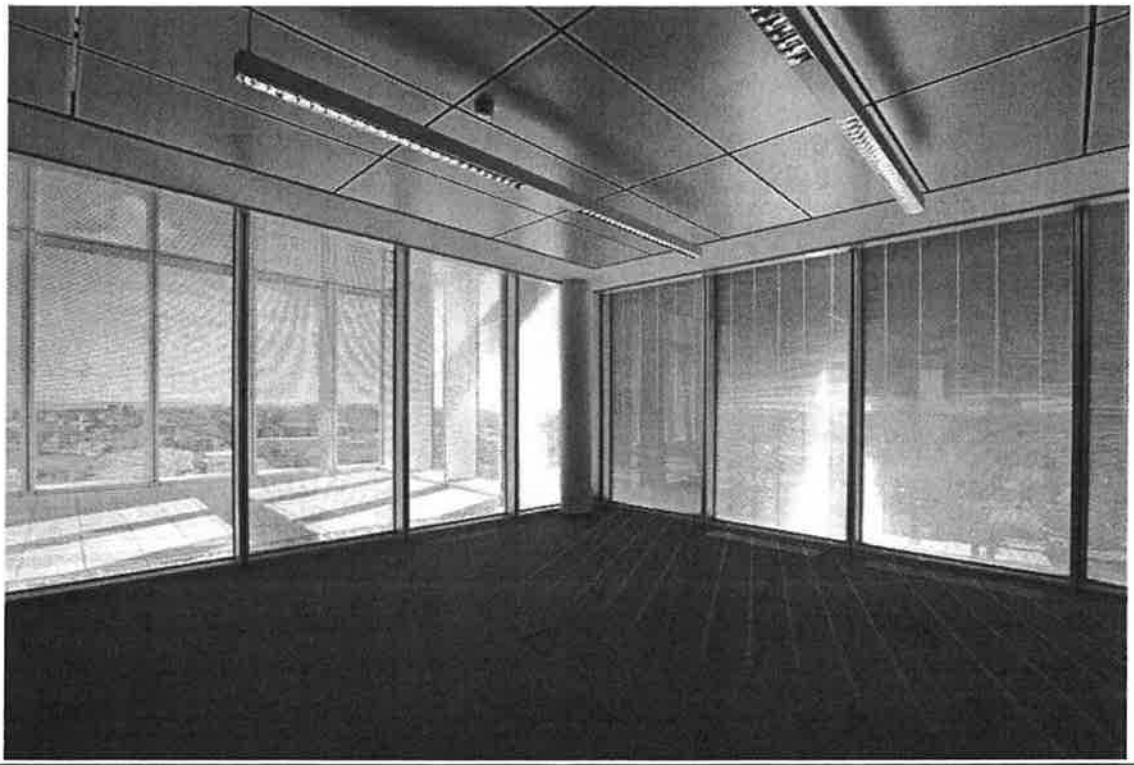
- Mobile sunshades



BCA ACADEMY

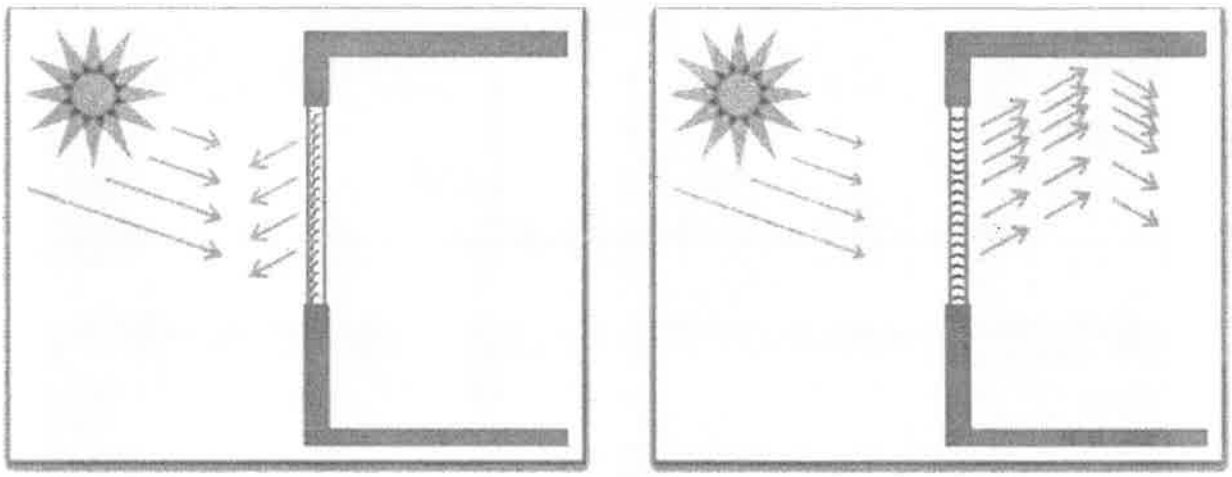
Building Skin as a Responsive Skin

- Mobile sunshades



Building Skin as a Responsive Skin

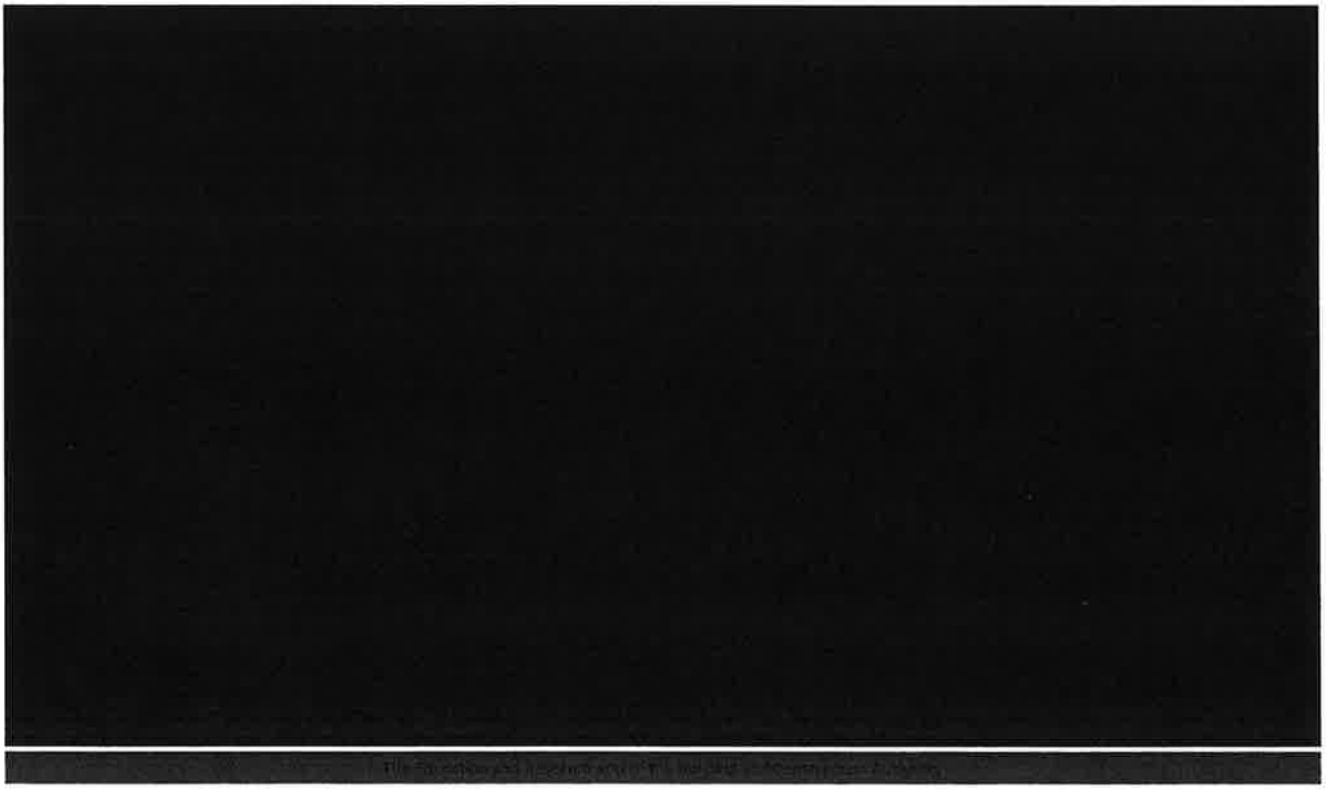
- Mobile sunshades



BCA ACADEMY

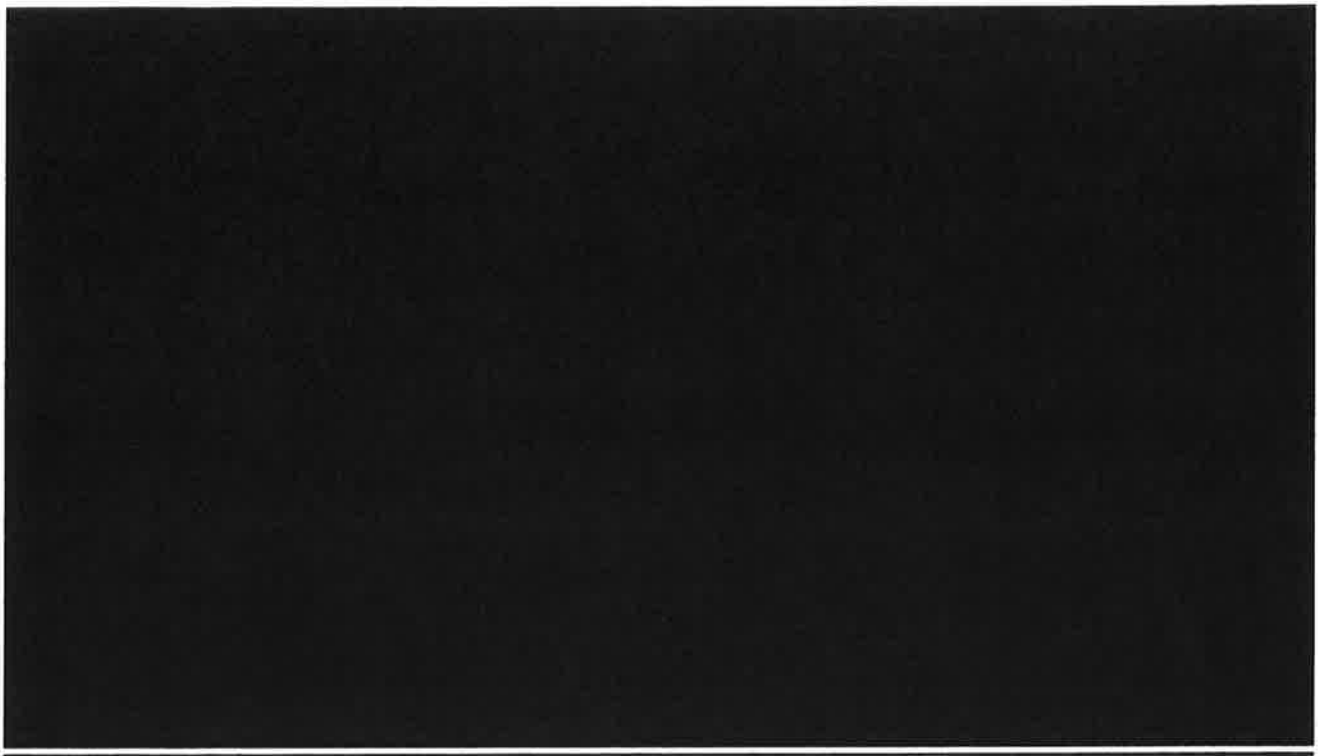
Building Skin as a Responsive Skin

- Mobile sunshades



Building Skin as a Responsive Skin

- Electrochromic glass



BCA ACADEMY

Sustainable Design Considerations

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

Sustainable Design Consideration

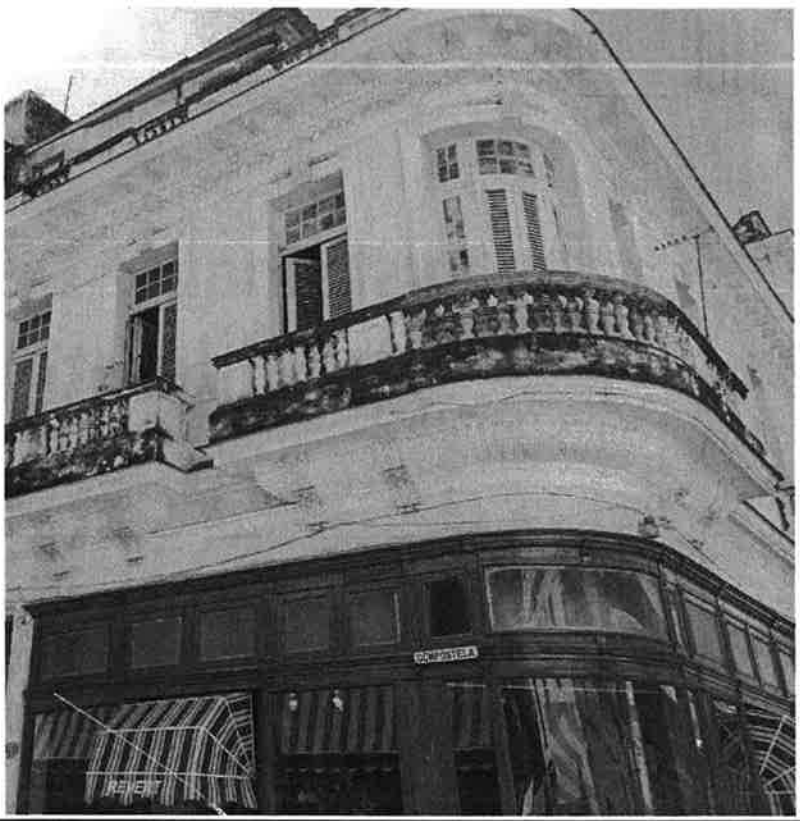
- Moisture control and biological contamination



BCA ACADEMY

Sustainable Design Consideration

- Moisture control and biological contamination



Sustainable Design Consideration

- Moisture control and biological contamination



BCA ACADEMY

Sustainable Design Consideration

- Moisture control and biological contamination



Magnesium oxide chloride MOC Magnesium oxychloride Pre-cast wall.

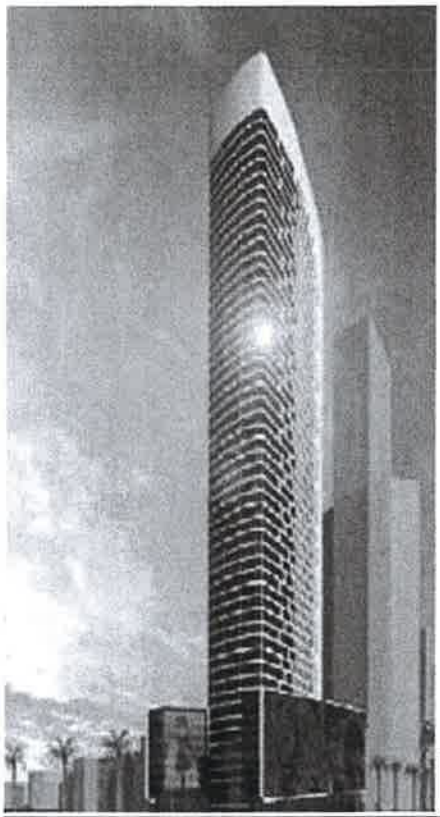
Sustainable Design Consideration

- Use materials certified by SGBC or SEC
- Better environmental management throughout lifespan of product
- Reduced environmental footprint

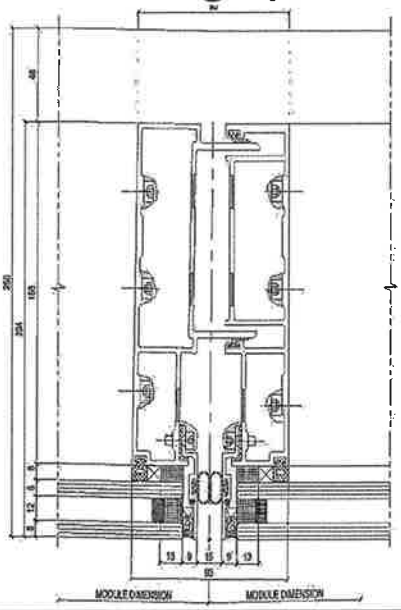
Sustainable Design Consideration

- Maximise use of recycled and recyclable materials
- Reduce façade materials

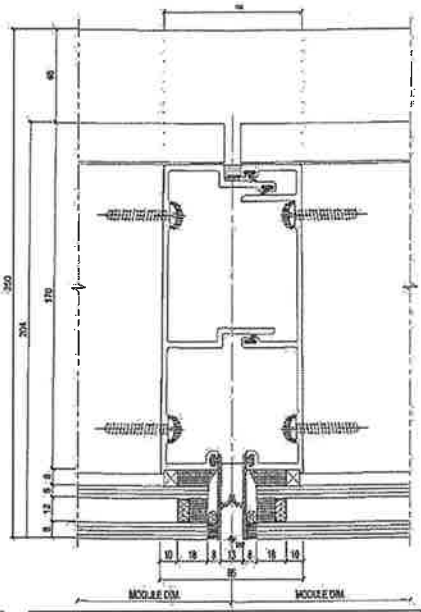
Optimising Resources in Façades



- Use bespoke system, optimise framing system, materials



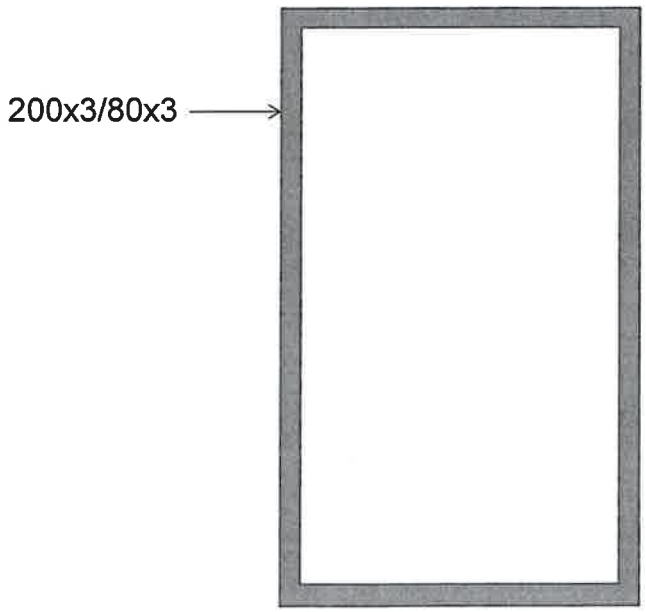
Contractor design: 250t Al.

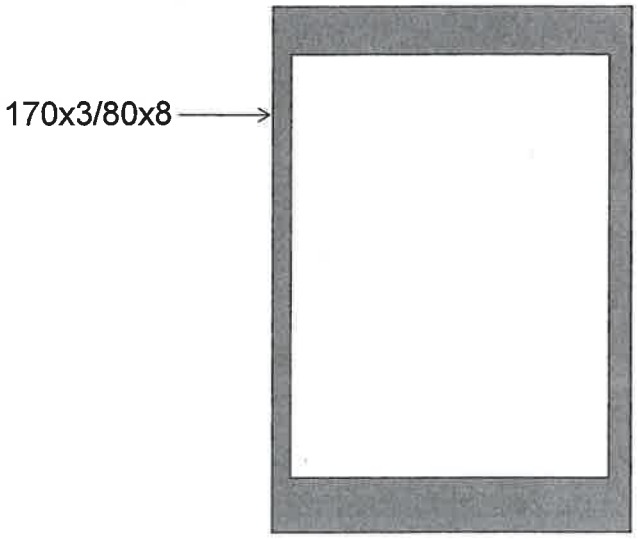


Optimal design: 130t Al.

Optimising Resources in Façades

- Use bespoke system, optimise framing system, worked example

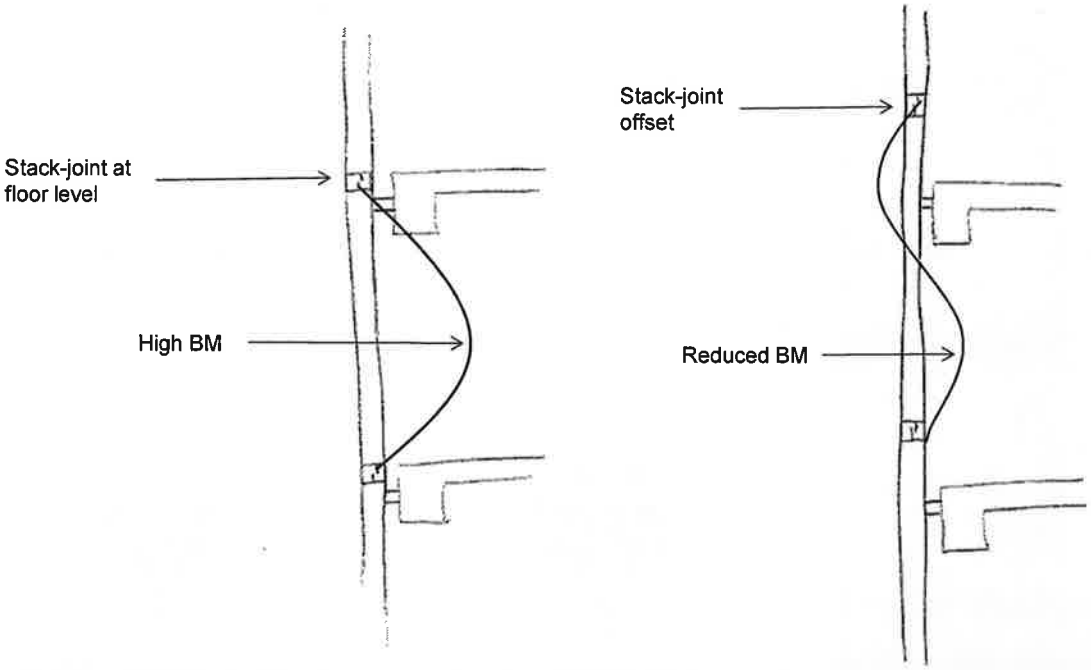




50% more

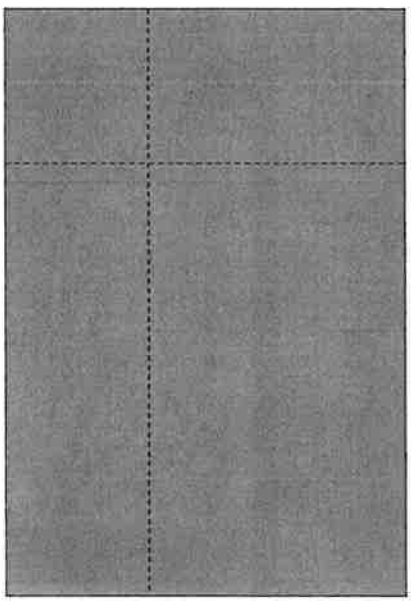
Optimising Resources in Façades

- Optimise member layout, reduce section size



Optimising Resources in Façades

- Optimal use of materials, most efficient modulations



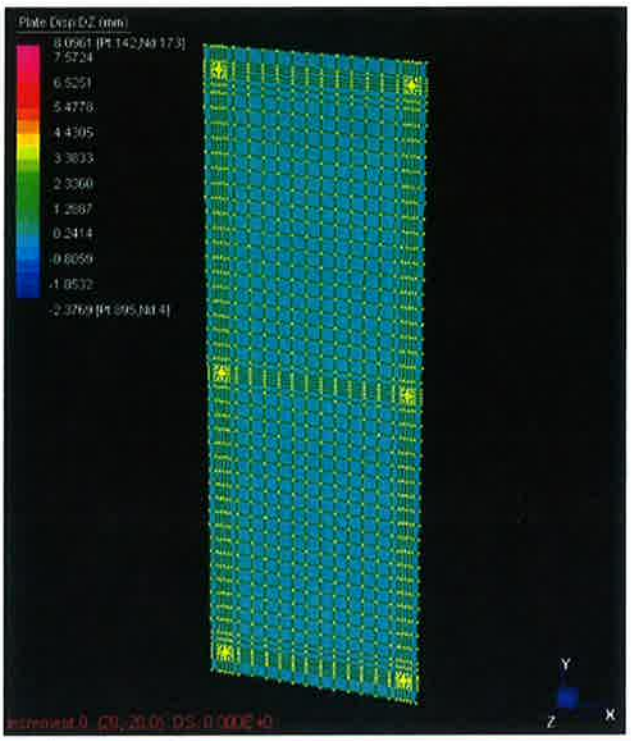
Typical glass stock sheet sizes:

6.0m x 2.4m or 6.0m x 3.0m

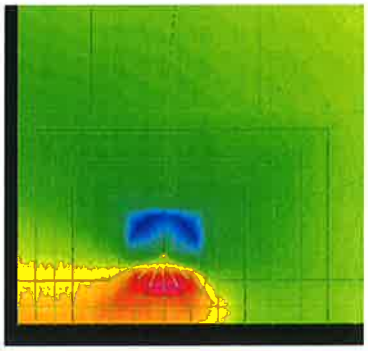
3.66m x 2.44m or 5.1m x 3.12m

Sustainable Design Consideration

- Optimise thickness and sizes







Sustainable Design Consideration

- Recycle façade materials
- Glass, steel and aluminium can be fully recylced

Optimising Resources in Façades

Use recycled and/or recyclable materials where possible (glass, aluminium, steel, some plastics)

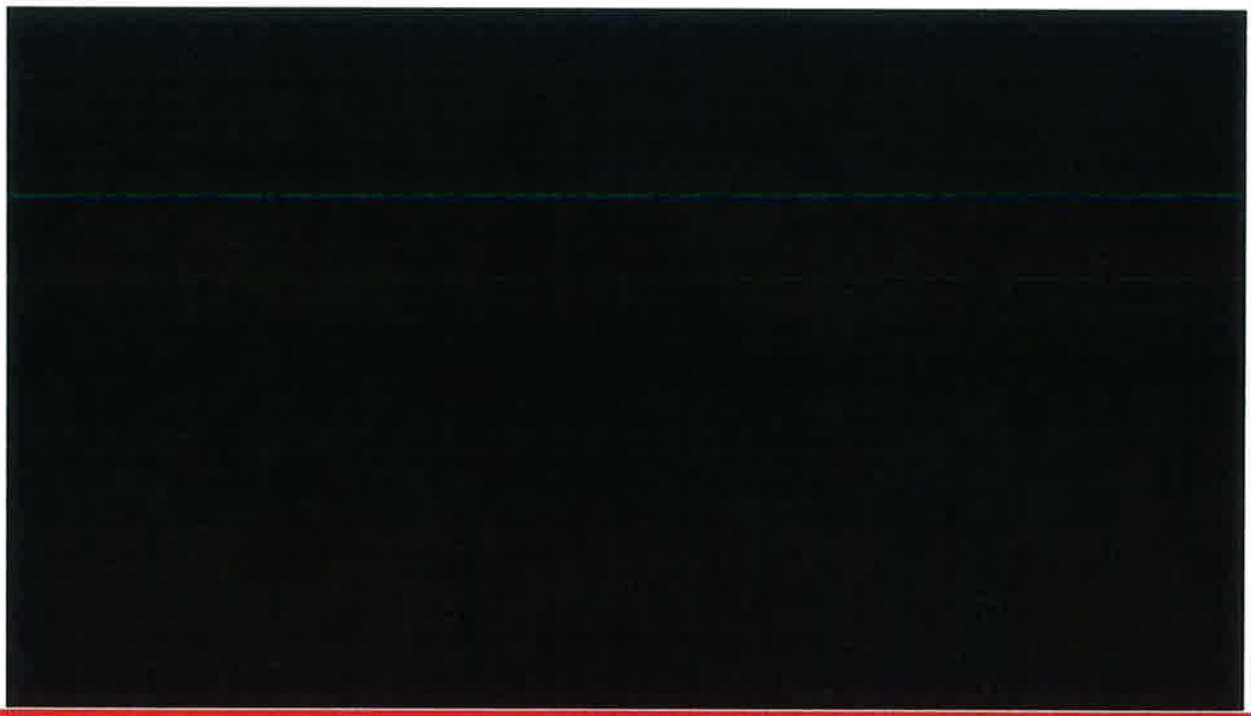
Electric power represents about 20% to 40% of the cost of producing aluminium (15±0.5 kW.h/kg)

Recycling requires only five percent of the energy used to produce aluminium from ore

Recycling glass (culets) helps lower kiln temperature

Sustainable Design Consideration

- Laminated glass requires special treatment



Optimising Resources in Façades

Use locally or regionally sourced materials (lower carbon footprint) – Reduces transport energy

Sustainable Design Consideration

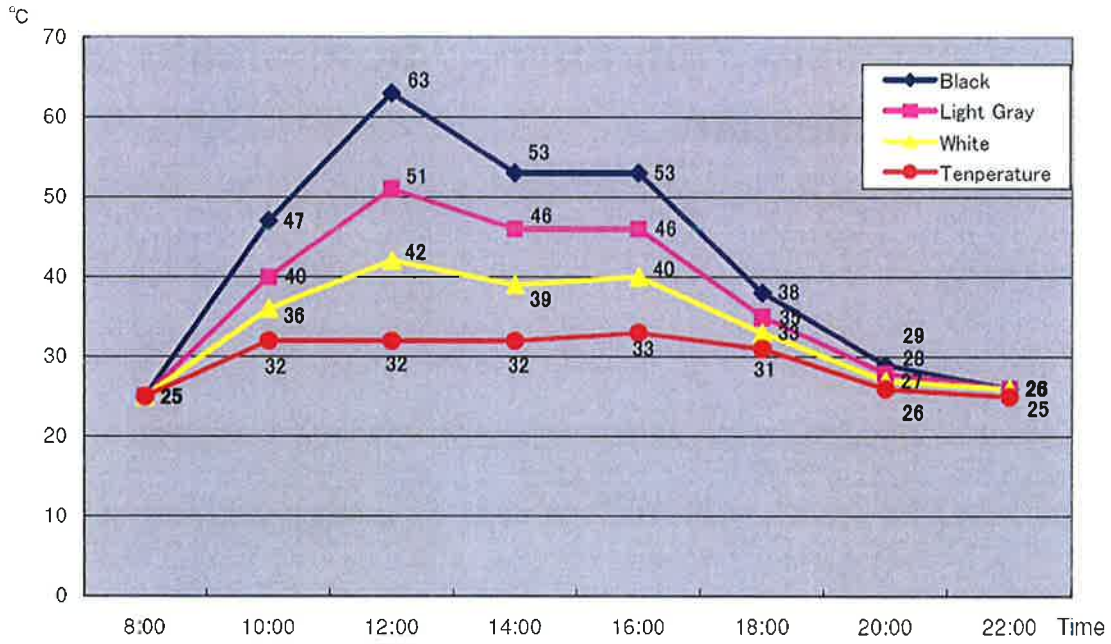
- Maintainability / durability / accessibility to maximise lifespan

Sustainable Design Consideration

- Choice of finishes:
- Aluminium coatings: anodised, powder-coating, PVDF
- Anodised most eco-friendly
- PVDF best performance externally
- Trade-off between durability and "green" aspect

Sustainable Design Consideration

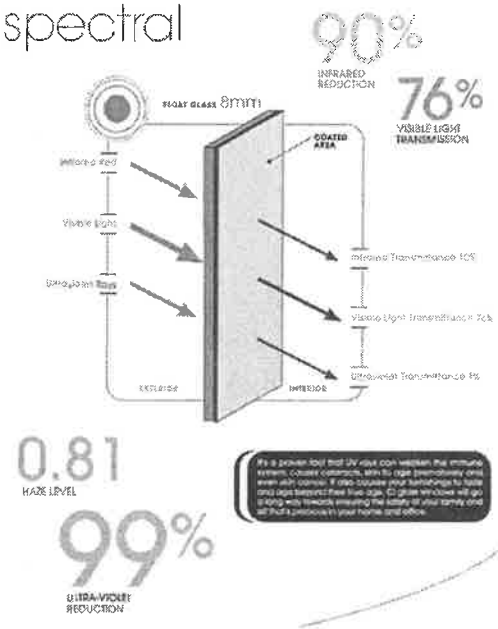
Use right colour / reflectivity



Sustainable Design Consideration

Heat reducing paints for opaque areas

(both solid walls and metal cladding)

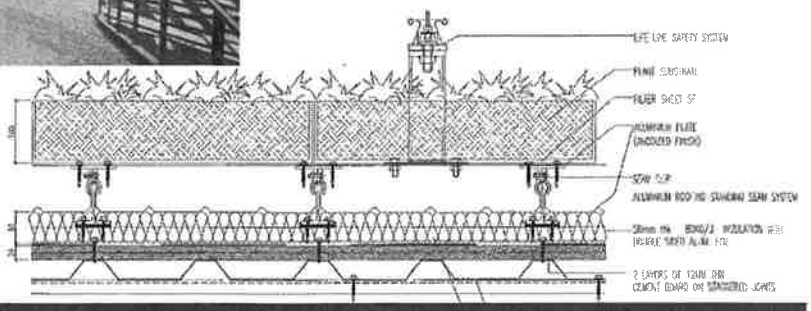




Optimising Resources in Façades

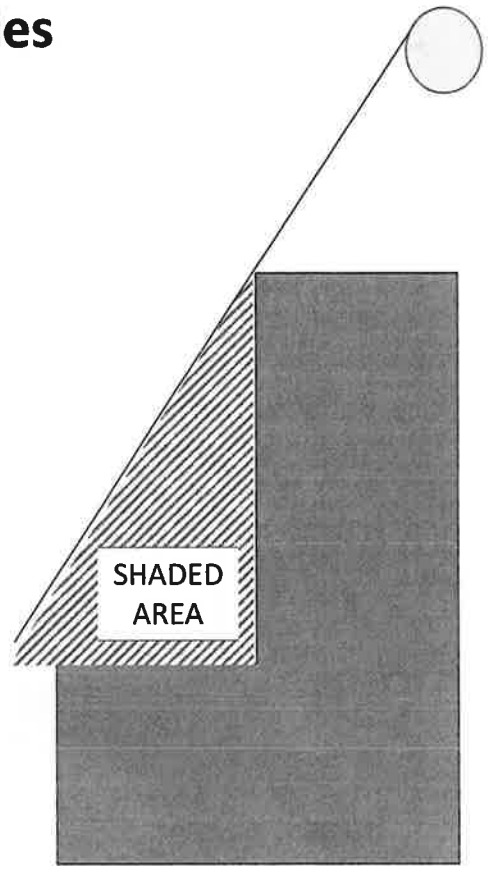
Use greenery to reduce heat, improve acoustics and overall working environment





Optimising Resources in Façades

ETTV doesn't address important factors (self-shading, occupant comfort) – Energy modelling is a more comprehensive approach



BCA ACADEMY

Façade Systems and Materials

The Education and Research arm of the Building and Construction Authority

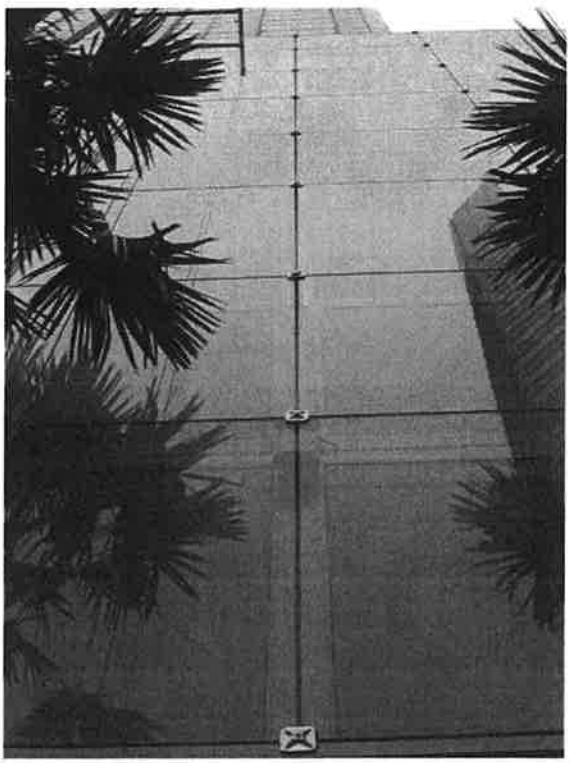
The Education and Research arm of the Building and Construction Authority

Façade Systems and Materials

- Different façade systems = different considerations

Point fixings





Point fixings



4 Sides Cappings





2 Sides Cappings





No Cappings

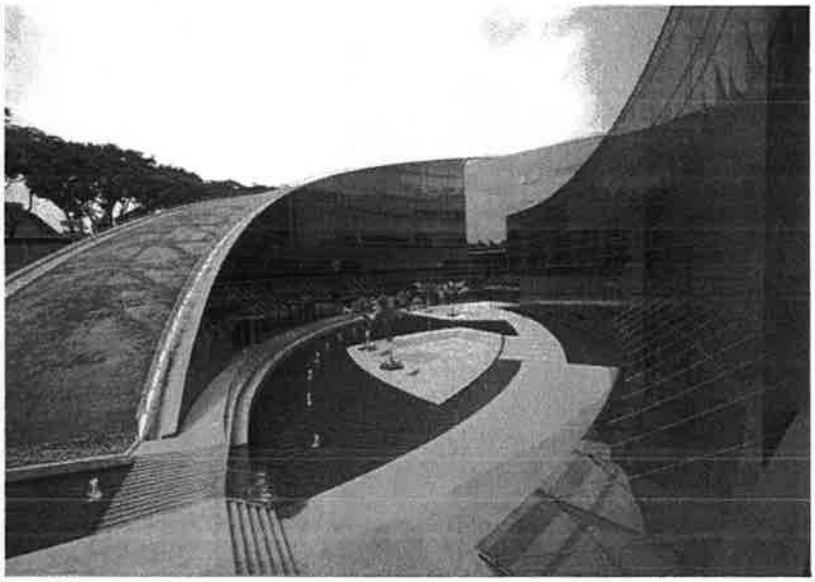




Not allowed now.

No Cappings

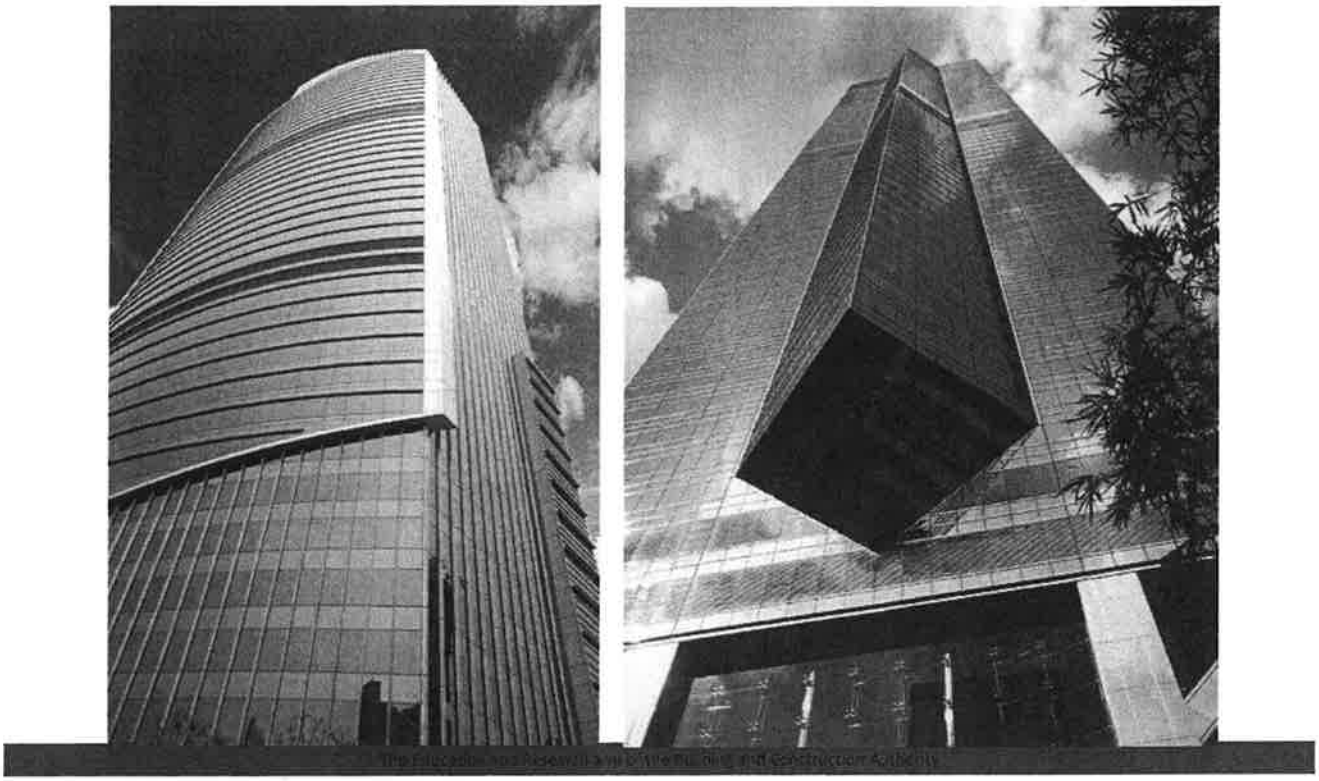




Glass Infills

- Heat-treated for strength or safety
- Double-glazed for thermal and acoustic insulation
- Laminated for safety or acoustic insulation
- Solid or patterned ceramic frit
- Clear or tinted
- Coated for increased reflectivity or thermal performance
- Other options (wired, fire-rated, patterned, etc.)

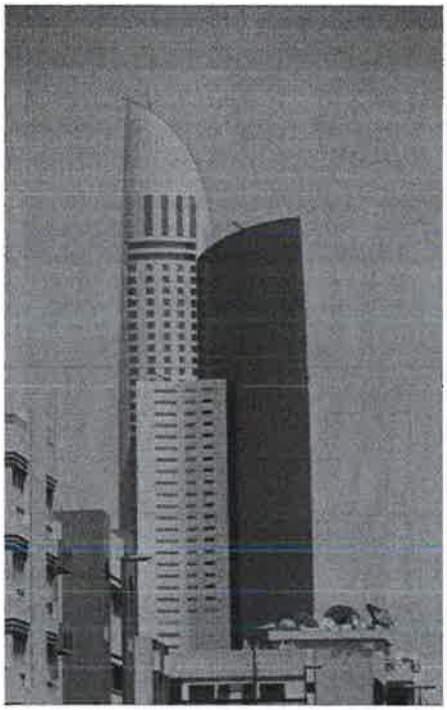
Glass Infills

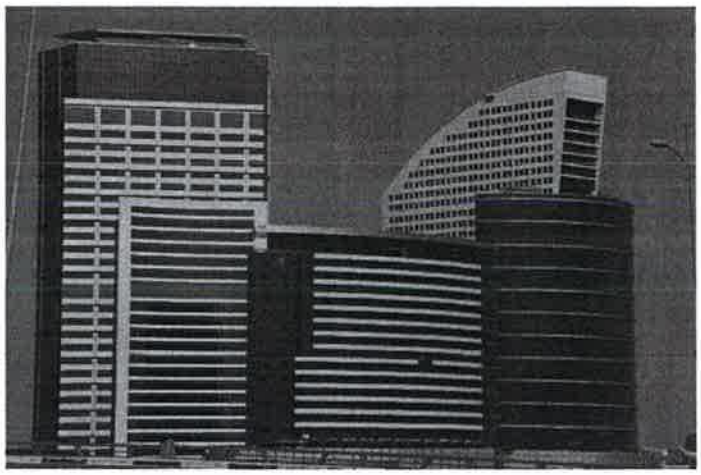


Metal Panel Infills

- Solid or composite aluminium
- Solid or composite stainless steel
- Composite titanium
- Vitreous enamel steel
- Composite copper (natural or pre-patina)

Metal Panel Infills





Stone Panel Infills

- Granite is most common and most suitable
- Marble not recommended externally
- Only hard limestone used externally (thicker)
- Care required for sandstones
- Other stones possible (slate, travertine, etc.)

Stone Panel Infills





Types of Aluminium Surface Finishes

- Anodising
- Powder coating
- PVDF coating

powder coating – internal
– external (super durable)

PVDF – externally.

Anodised Finish

- Oldest technology
- Simplest and most ecologically friendly
- Gives natural metal look
- Limited range of available colours, dull finish
- Difficult field touch-ups
- Requires brushing to eliminate die lines

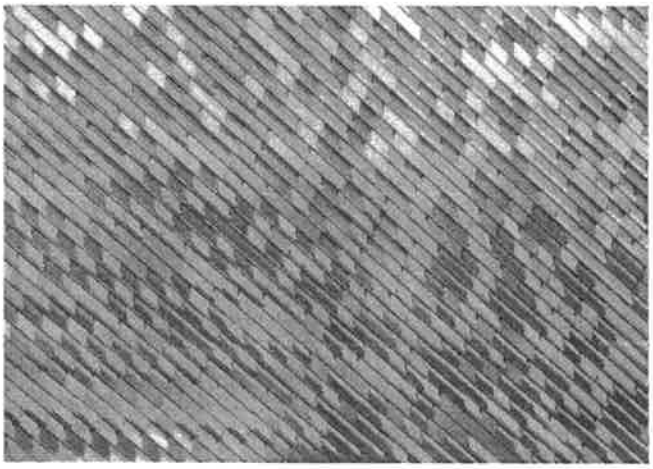
The Copyright and Restrictions of the Building and Construction Authority

BCA ACADEMY

Anodised Finish





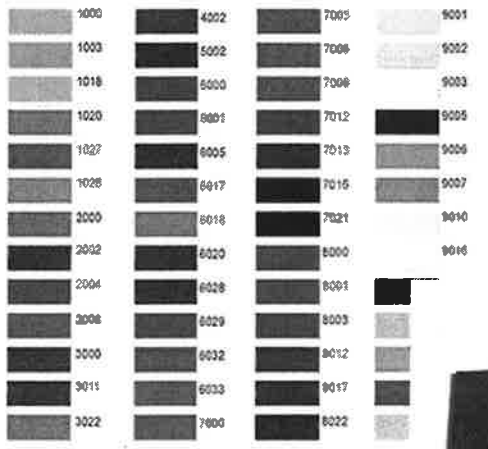


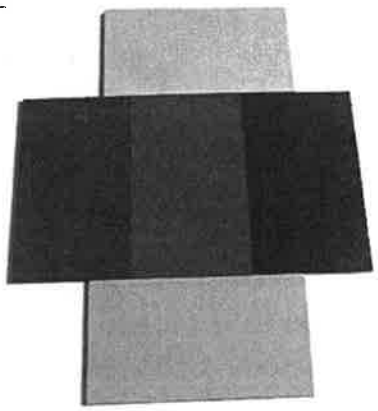
The Copyright and Restrictions of the Building and Construction Authority

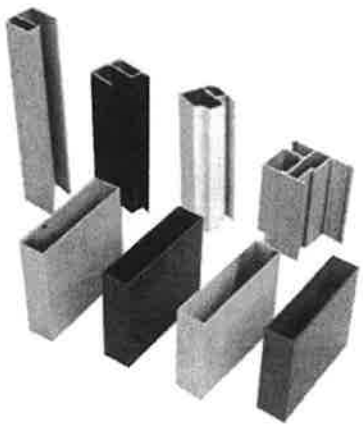
Powder-Coated Finish

- Coloured polyester powders sprayed onto surfaces
- Baked in oven to fix to surface
- Limited resistance to UV exposure
- Large range of available solid colours
- Limited in terms of metallic colours
- Easy field touch-ups
- Covers die lines naturally, no pre-treatment required

Powder-Coated Finish







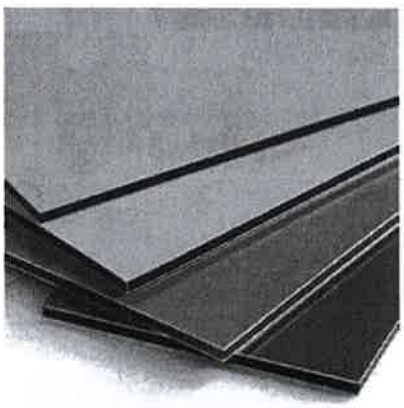
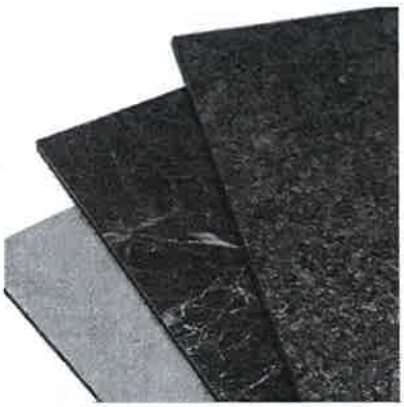
PVDF-Coated Finish

- Inorganic liquid PVDF sprayed onto surfaces
- Baked in oven to fix to surface
- Excellent resistance to UV exposure
- Non-stick, easy cleaning
- Large range of available solid and metallic colours
- Colour-matching difficult for field touch-ups
- Covers die lines naturally, no pre-treatment required

Polyvinylidene fluoride

BCA ACADEMY

PVDF-Coated Finish



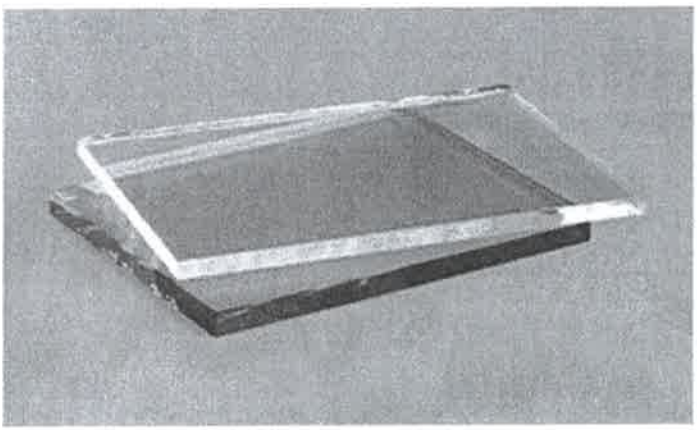

Glass Types

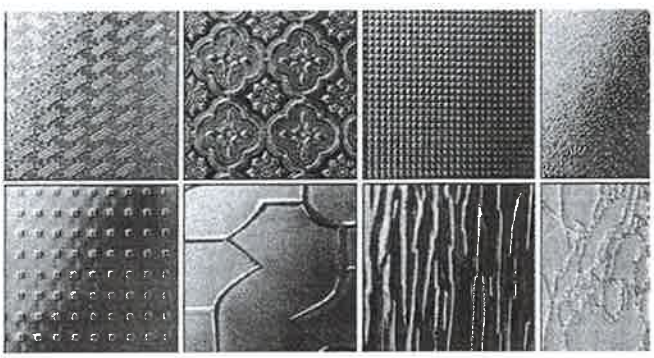
The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

Façade Systems and Materials

Float Glass





Patterned Glass

Float glass - Raw Glass.

Façade Systems and Materials



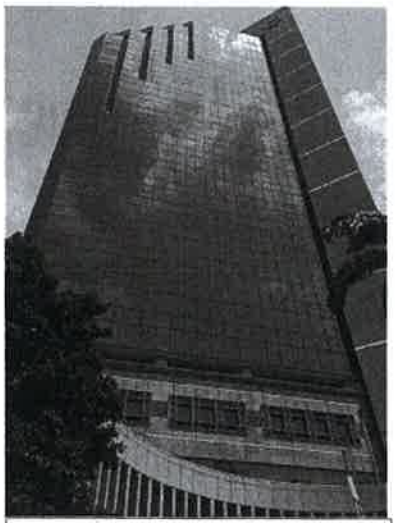
Wired Glass



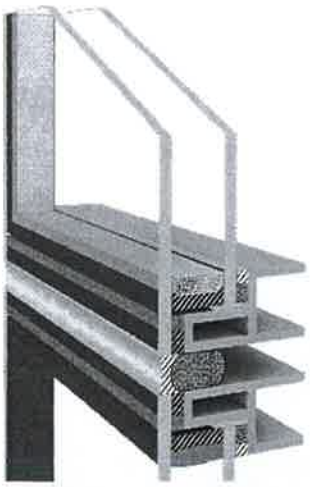
Sheet Glass

Façade Systems and Materials

Reflective Glass



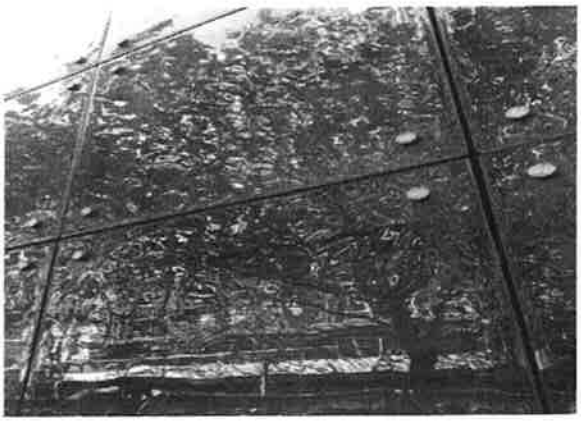
IRAS Building
Singapore



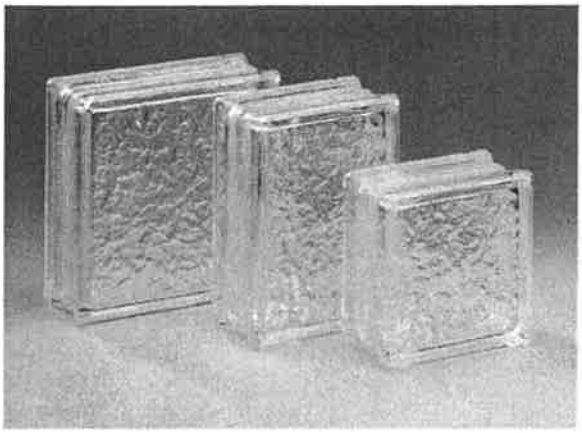
Insulating Glass

Desiccant

Façade Systems and Materials



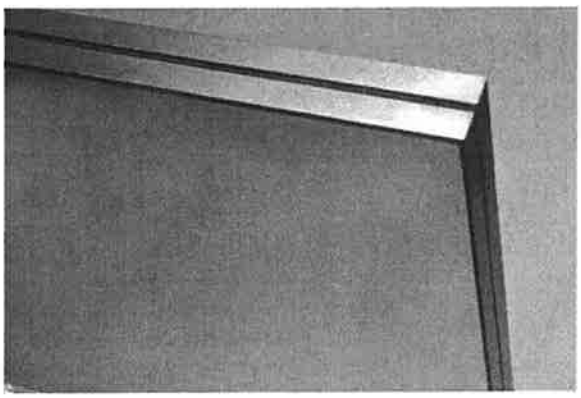
Cast Glass



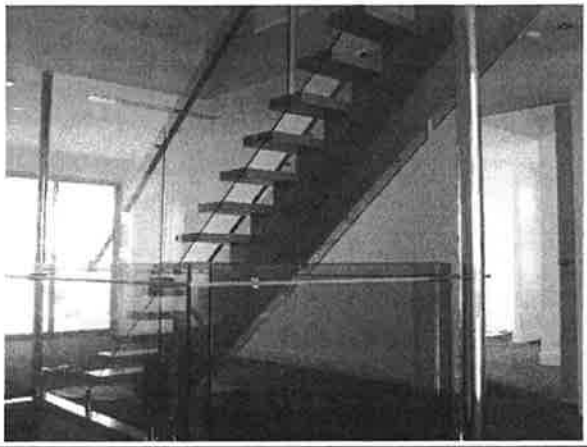
Glass Bricks

BCA ACADEMY

Façade Systems and Materials



Laminated Safety Glass



Toughened Safety Glass

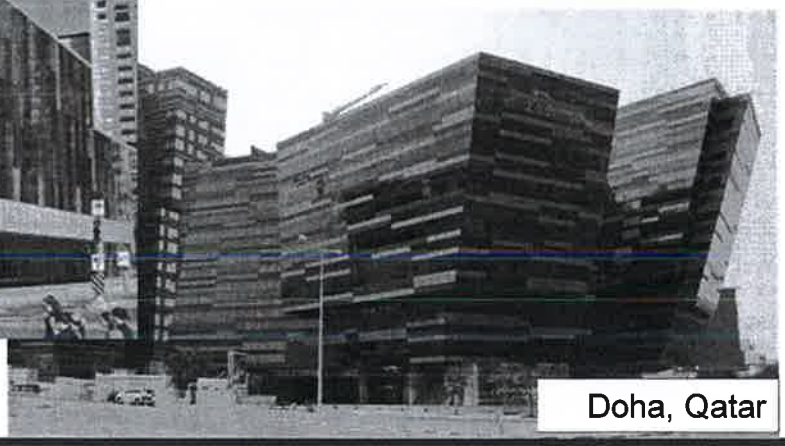
Façade Systems and Materials

Tinted Glass





Palais des Congrès
Montreal, Canada



Doha, Qatar

Façade Systems and Materials

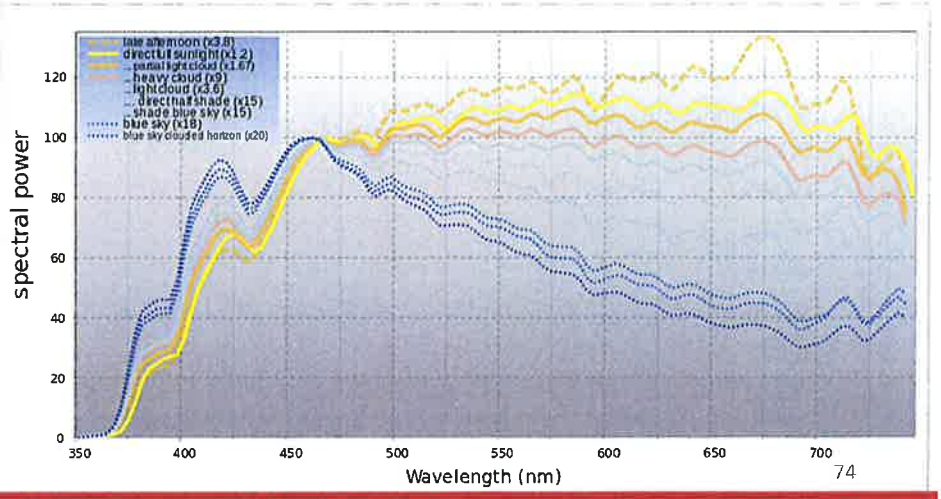
- Different glass types can be mixed in multiple combinations
- Glass thicknesses can also be mixed
- Typical thicknesses 3mm, 4mm, **5mm**, **6mm**, **8mm**, **10mm**, **12mm**, 15mm, 16mm, 19mm, 22mm, 25mm

3mm 4mm glass – Distortion / Bubble

Glass Performance

Visual Spectrum

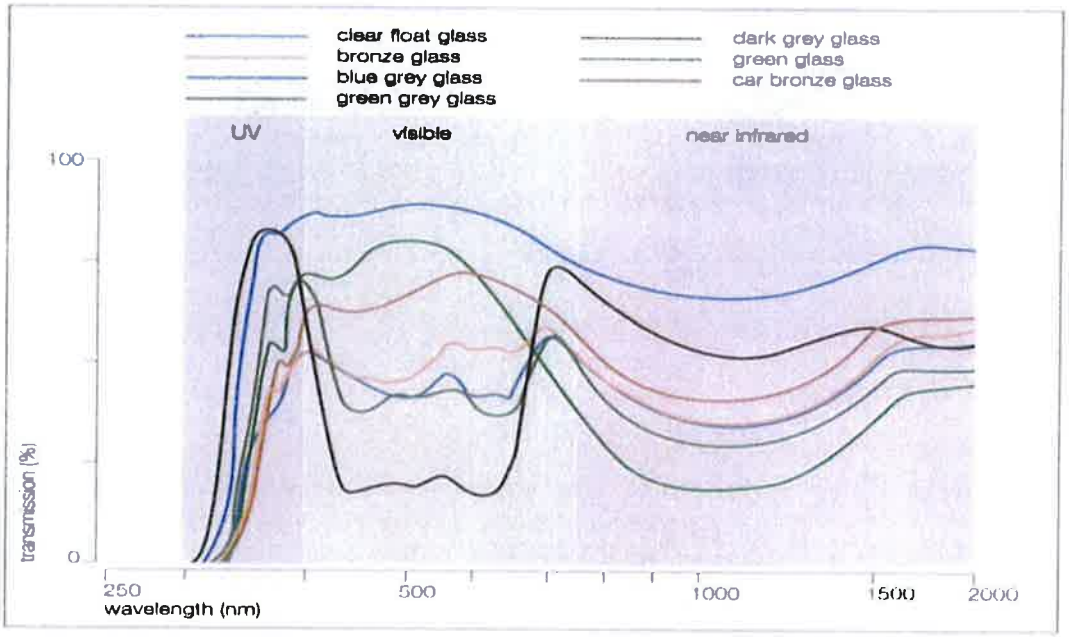
- 50% solar energy in infrared
- 48% solar energy in visible
- 2% solar energy in UV



IAFRARG - Robert Hecht

Visual Light Transmittance

- Varies with tint, thickness and other treatments (frit, coating, etc.)

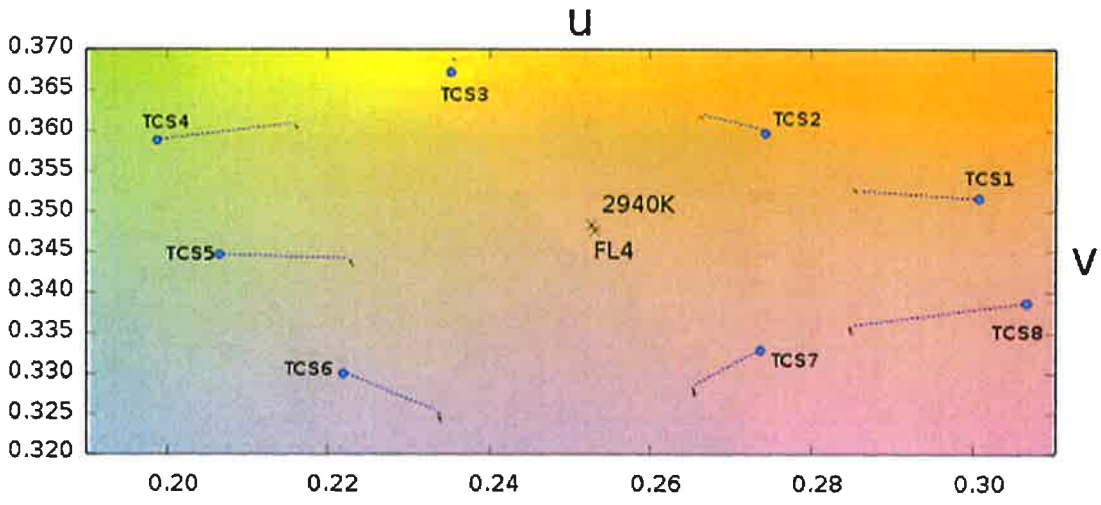


blue green
Green Grey
Green

Green is the best Blue and Best

Visual Light Transmittance

- Colour rendition index
- Quality of light



Visual Light Transmittance

- Typical values of VLT

Glass Tint	Colour Purity	Light Transmission	Infrared Transmission	Total Transmission
Clear Glass	1%	85%	70%	84%
Green Glass	4%	76%	25%	61%
Car Bronze Glass	7%	71%	48%	69%
Architectural Bronze Glass	7%	71%	48%	69%
Architectural Gray/Green Glass	6%	42%	40%	58%
Architectural Gray/Blue Glass	6%	41%	42%	61%
Dark Gray Glass	3%	18%	58%	57%

c P = 1% = cal 99%.

Visual Light Transmittance

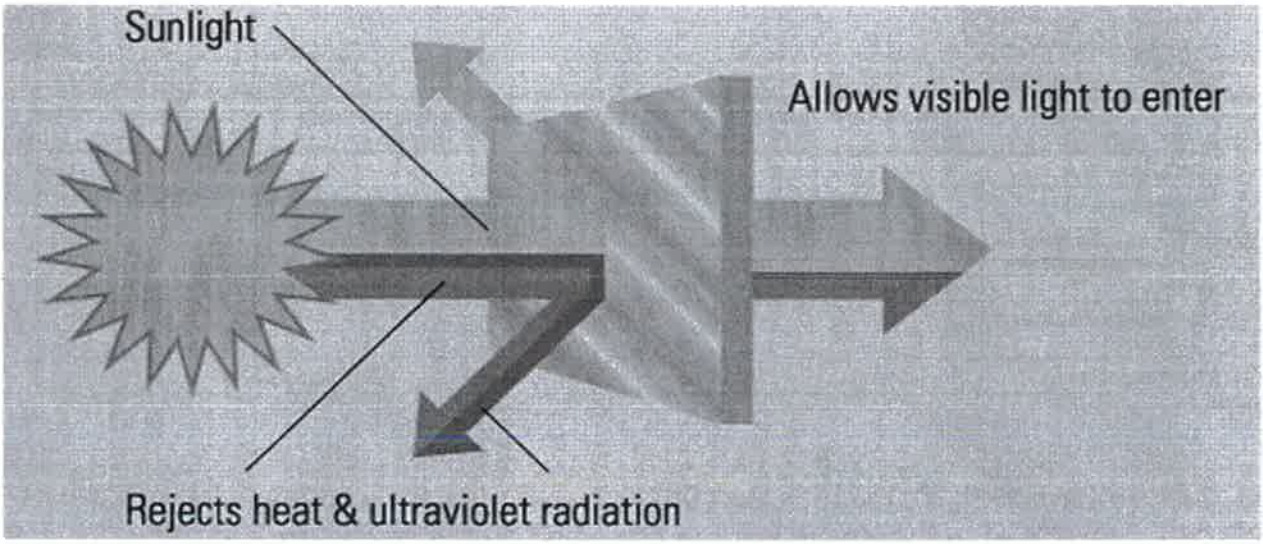
- VLT not directly related to thermal performance (U-value and SC)
- Lower VLT does not equate lower SC!
- Understanding LSG ratio

LSG - light to solar gain

grey glass - 0.6 to 0.9
clear glass - 1.1

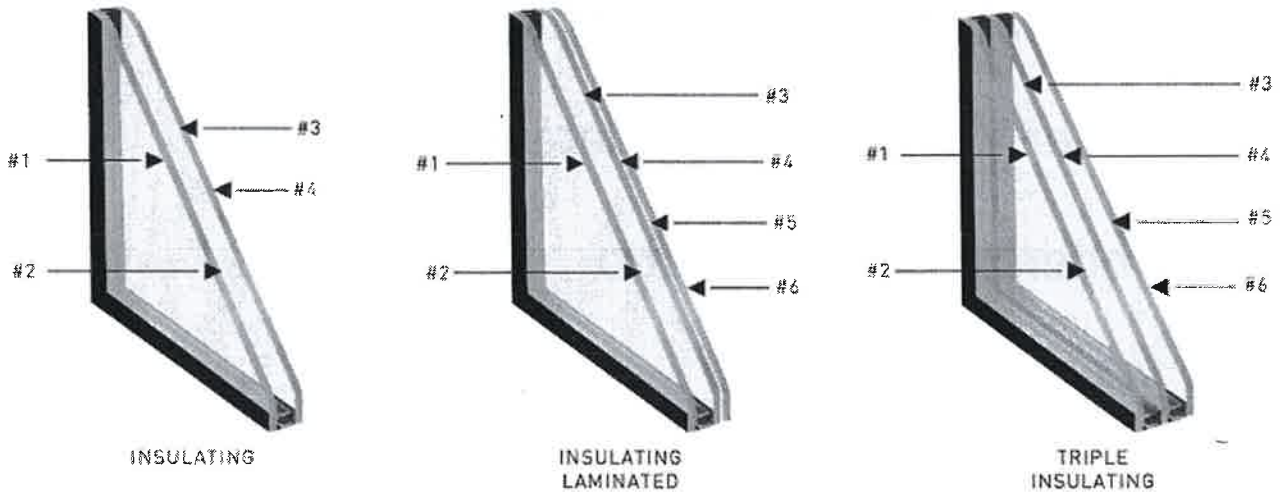
Glass Performance

Low-Emissivity Glass



Glass Performance

- Glass surfaces



- In the tropics, best solar performance is achieved when coating is applied to #2 surface

If outside is laminated, then coating is at #4.

Glass Performance

Product Code	Glass Construction	Silk-Screening	Argon	Transmittance Visible	Transmittance UV	Reflectance Exterior	Reflectance Interior	U-Value Winter	U-Value Summer	SHGC	LSG
Azuria	1/4" (6mm) Monolithic	No Silk-Screening	No	68%	42%	7%	7%	5.79	5.28	0.52	1.31
Blue-Green	1/4" (6mm) Monolithic	No Silk-Screening	No	75%	32%	7%	7%	5.79	5.22	0.62	1.21
Bronze	1/4" (6mm) Monolithic	No Silk-Screening	No	53%	24%	6%	6%	5.79	5.22	0.63	0.84
Clear	1/4" (6mm) Monolithic	No Silk-Screening	No	88%	62%	8%	8%	5.79	5.22	0.82	1.07
CrystalGray	1/4" (6mm) Monolithic	No Silk-Screening	No	65%	34%	6%	6%	5.85	5.28	0.67	0.97
EverGreen	1/4" (6mm) Monolithic	No Silk-Screening	No	66%	14%	6%	6%	5.79	5.22	0.53	1.25
Graphite	1/4" (6mm) Monolithic	No Silk-Screening	No	61%	37%	6%	6%	5.79	5.22	0.67	0.91
Gray	1/4" (6mm) Monolithic	No Silk-Screening	No	44%	24%	6%	6%	5.79	5.28	0.58	0.76
Green	1/4" (6mm) Monolithic	No Silk-Screening	No	76%	29%	7%	7%	5.85	5.28	0.61	1.25
Optigray	1/4" (6mm) Monolithic	No Silk-Screening	No	63%	33%	6%	6%	5.85	5.28	0.65	0.97
Optiwhite	1/4" (6mm) Monolithic	No Silk-Screening	No	91%	85%	8%	8%	5.79	5.22	0.90	1.01
Pacifica	1/4" (6mm) Monolithic	No Silk-Screening	No	42%	15%	5%	5%	5.85	5.28	0.49	0.86
Solarblue	1/4" (6mm) Monolithic	No Silk-Screening	No	56%	31%	6%	6%	5.85	5.28	0.61	0.92
Starphire	1/4" (6mm) Monolithic	No Silk-Screening	No	91%	87%	8%	8%	5.85	5.28	0.90	1.01

Green better than grey

BCA ACADEMY

Glass Performance

Product Code	Glass Construction	Silk-Screening	Argon	Transmittance Visible	Transmittance UV	Reflectance Exterior	Reflectance Interior	U-Value Winter	U-Value Summer	SHGC	LSG
VS2-20	1/4" (6mm) Monolithic	No Silk-Screening	No	17%	5%	18%	32%	4.88	4.26	0.30	0.57
VS3-08	1/4" (6mm) Monolithic	No Silk-Screening	No	4%	2%	14%	37%	4.32	3.58	0.23	0.17
VS3-14	1/4" (6mm) Monolithic	No Silk-Screening	No	7%	4%	12%	38%	4.54	3.86	0.26	0.27
VS3-20	1/4" (6mm) Monolithic	No Silk-Screening	No	10%	5%	10%	32%	4.88	4.26	0.31	0.32
VS4-08	1/4" (6mm) Monolithic	No Silk-Screening	No	5%	1%	17%	37%	4.32	3.58	0.23	0.22
VS4-14	1/4" (6mm) Monolithic	No Silk-Screening	No	8%	3%	14%	38%	4.54	3.86	0.27	0.30
VS4-20	1/4" (6mm) Monolithic	No Silk-Screening	No	12%	4%	11%	31%	4.88	4.26	0.31	0.39
VS6-20	1/4" (6mm) Monolithic	No Silk-Screening	No	17%	5%	18%	32%	4.88	4.26	0.31	0.55
VS7-20	1/4" (6mm) Monolithic	No Silk-Screening	No	16%	5%	18%	32%	4.88	4.26	0.29	0.55
VS8-14	1/4" (6mm) Monolithic	No Silk-Screening	No	10%	2%	20%	37%	4.54	3.86	0.26	0.38
VS8-20	1/4" (6mm) Monolithic	No Silk-Screening	No	15%	2%	15%	32%	4.88	4.26	0.30	0.50
VS19-14	1/4" (6mm) Monolithic	No Silk-Screening	No	10%	4%	19%	38%	4.54	3.86	0.27	0.37
VS19-20	1/4" (6mm) Monolithic	No Silk-Screening	No	15%	6%	15%	32%	4.88	4.26	0.31	0.48
VS26-08	1/4" (6mm) Monolithic	No Silk-Screening	No	5%	2%	20%	37%	4.32	3.58	0.23	0.22

The Education and Research arm of the Building and Construction Authority

Glass Performance

Product Code	Glass Construction	Silk-Screening	Argon	Transmittance		Reflectance		U-Value		SHGC	LSG
				Visible	UV	Exterior	Interior	Winter	Summer		
Azuria	1" (25mm) Insulating	No Silk-Screening	No	61%	33%	10%	13%	2.67	2.78	0.39	1.56
Blue-Green	1" (25mm) Insulating	No Silk-Screening	No	67%	26%	12%	14%	2.67	2.78	0.50	1.34
Bronze	1" (25mm) Insulating	No Silk-Screening	No	47%	19%	8%	12%	2.67	2.78	0.50	0.94
Clear	1" (25mm) Insulating	No Silk-Screening	No	79%	46%	14%	14%	2.67	2.78	0.70	1.13
CrystalGray	1" (25mm) Insulating	No Silk-Screening	No	58%	27%	10%	13%	2.67	2.78	0.55	1.05
EverGreen	1" (25mm) Insulating	No Silk-Screening	No	58%	11%	10%	13%	2.67	2.78	0.40	1.45
Gray	1" (25mm) Insulating	No Silk-Screening	No	39%	17%	7%	12%	2.67	2.78	0.45	0.87
Green	1" (25mm) Insulating	No Silk-Screening	No	66%	24%	11%	13%	2.67	2.78	0.50	1.36
Opalwhite	1" (25mm) Insulating	No Silk-Screening	No	83%	74%	15%	15%	2.67	2.78	0.83	1.00
Starphire	1" (25mm) Insulating	No Silk-Screening	No	84%	77%	15%	15%	2.67	2.78	0.82	1.02
VE1-2M	1" (25mm) Insulating	No Silk-Screening	No	70%	10%	11%	12%	1.70	1.48	0.38	1.84
VE1-42	1" (25mm) Insulating	No Silk-Screening	No	37%	16%	19%	14%	1.76	1.65	0.32	1.16
VE1-45	1" (25mm) Insulating	No Silk-Screening	No	39%	10%	7%	28%	1.70	1.48	0.29	1.34
VE1-48	1" (25mm) Insulating	No Silk-Screening	No	47%	20%	17%	11%	1.76	1.65	0.39	1.24

Glass Performance

Product Code	Glass Construction	Silk-Screening	Argon	Transmittance		Reflectance		U-Value		SHGC	LSG
				Visible	UV	Exterior	Interior	Winter	Summer		
Azuria	1" (25mm) Insulating	50% V175	No	38%	17%	16%	34%	2.67	2.78	0.30	1.27
Blue-Green	1" (25mm) Insulating	50% V175	No	42%	13%	18%	34%	2.67	2.78	0.38	1.11
Bronze	1" (25mm) Insulating	50% V175	No	30%	9%	11%	34%	2.67	2.78	0.38	0.79
Clear	1" (25mm) Insulating	50% V175	No	49%	23%	23%	35%	2.67	2.78	0.50	0.98
CrystalGray	1" (25mm) Insulating	50% V175	No	36%	14%	14%	34%	2.67	2.78	0.40	0.90
EverGreen	1" (25mm) Insulating	50% V175	No	37%	6%	15%	34%	2.67	2.78	0.31	1.19
Gray	1" (25mm) Insulating	50% V175	No	25%	10%	9%	34%	2.67	2.78	0.35	0.71
Green	1" (25mm) Insulating	50% V175	No	41%	11%	17%	34%	2.67	2.78	0.36	1.14
Starphire	1" (25mm) Insulating	50% V175	No	53%	27%	24%	37%	2.67	2.78	0.57	0.93
VE1-2M	1" (25mm) Insulating	50% V175	No	44%	5%	22%	26%	1.70	1.48	0.26	1.69
VE1-42	1" (25mm) Insulating	50% V175	No	23%	8%	27%	18%	1.76	1.65	0.22	1.05
VE1-45	1" (25mm) Insulating	50% V175	No	24%	5%	21%	33%	1.70	1.48	0.21	1.14
VE1-48	1" (25mm) Insulating	50% V175	No	29%	10%	26%	17%	1.76	1.65	0.26	1.12
VE1-85	1" (25mm) Insulating	50% V175	No	47%	13%	23%	30%	1.76	1.65	0.37	1.27

Glass Performance

- http://exprover.saint-gobain-glass.com.im-extra-web2-natpub.sgg.lbn.fr/sites/exprover.saint-gobain-glass.com.im-extra-web2-natpub.sgg.lbn.fr/files/How%20to%20install%20CALUMEN.pdf
- Calumen II: Dedicated glass performance calculator for Saint-Gobain Glass

The information and research work of the Building and Construction Authority

Glass Performance

- http://www.viracon.com/search-by-performance
- http://construct.ppg.com
- http://www.yourglass.com/configurator/gb/en/toolbox/configurator/main.html

Remember to select "METRIC"!

The information and research work of the Building and Construction Authority

Cladding Performance

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

BCA ACADEMY

Cladding Performance

- Most cladding systems do not offer much thermal performance without additional insulation
- Difference between sealed system and rain-screen system

Cladding Performance

- An uninsulated solid brick wall with a thickness of 225mm value will have a U-value of 2.70 W/m^2.˚K
- By comparison, double glazing with low-e will typically have a U-value of below 1.80 W/m^2.˚K

Cladding Performance

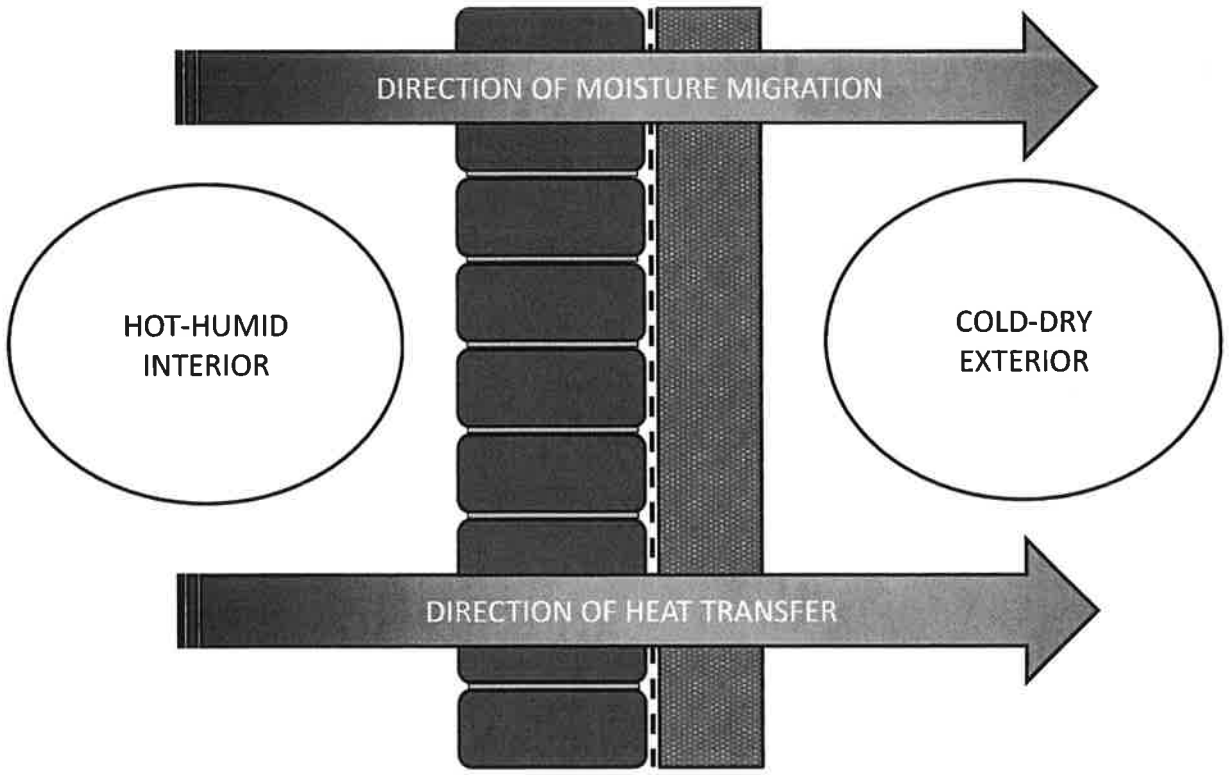
- Location of insulation
- Condensation risk assessment to BS5250 and BS EN ISO 13788
- Vapour barrier placement

Cladding Performance – Cold Climate

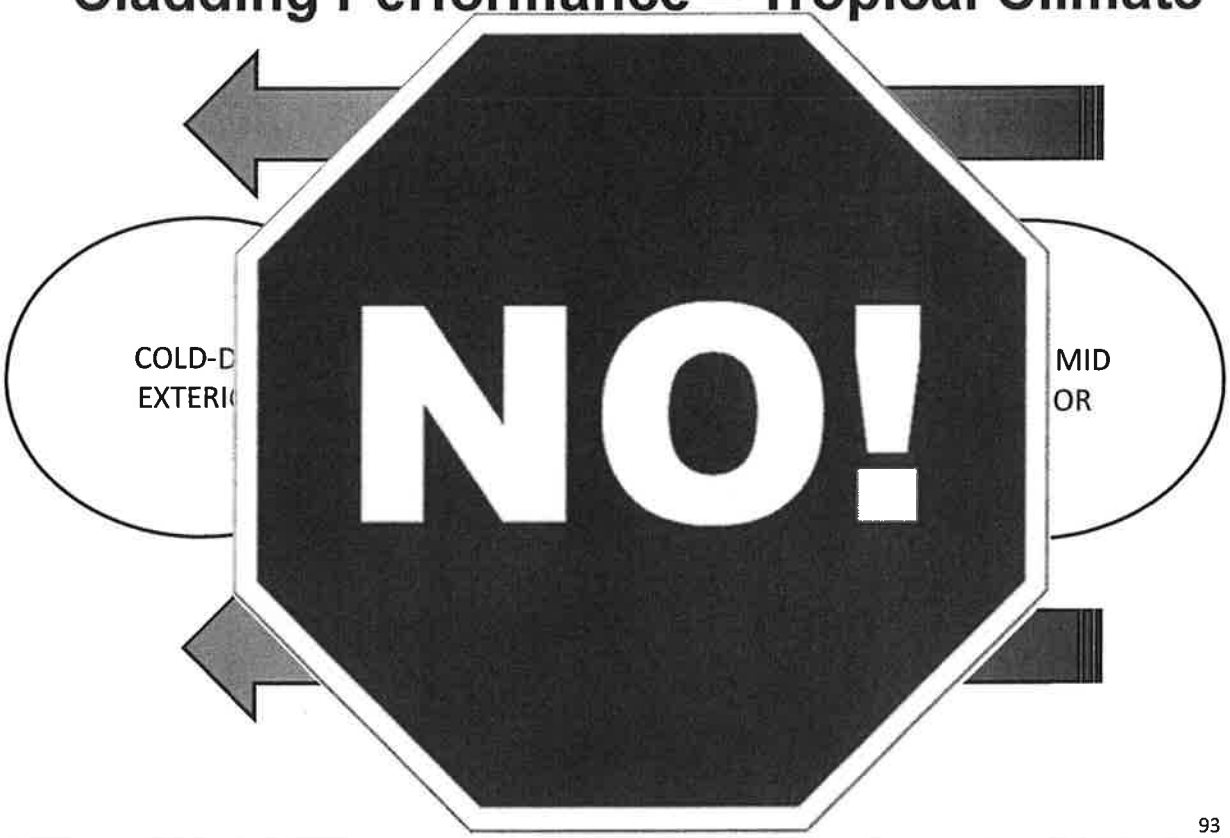


BCA ACADEMY

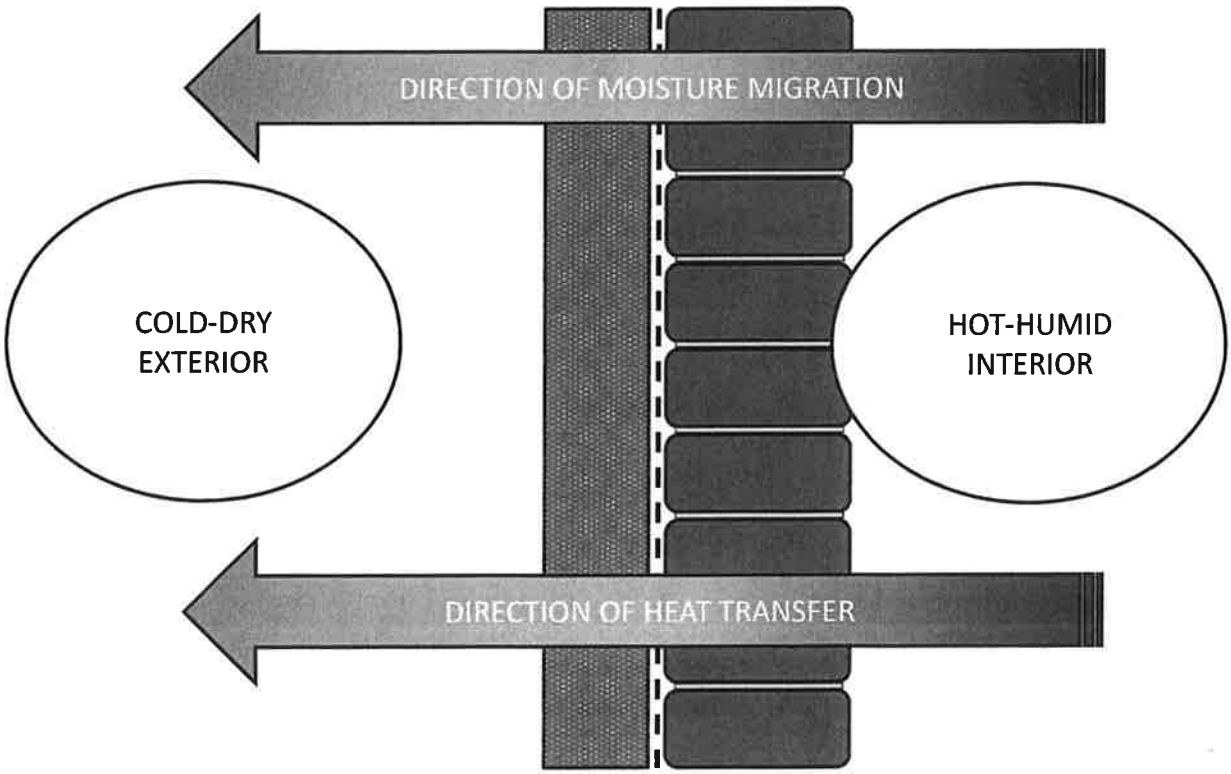
Cladding Performance – Cold Climate



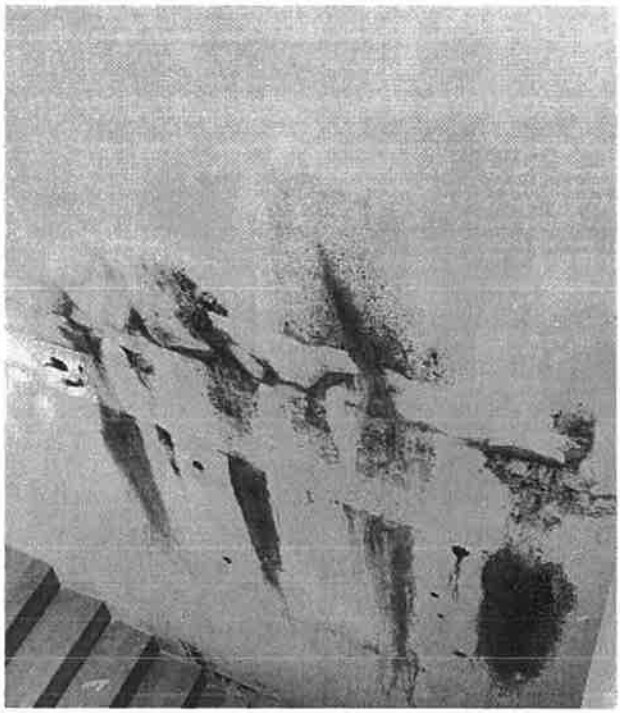
Cladding Performance – Tropical Climate

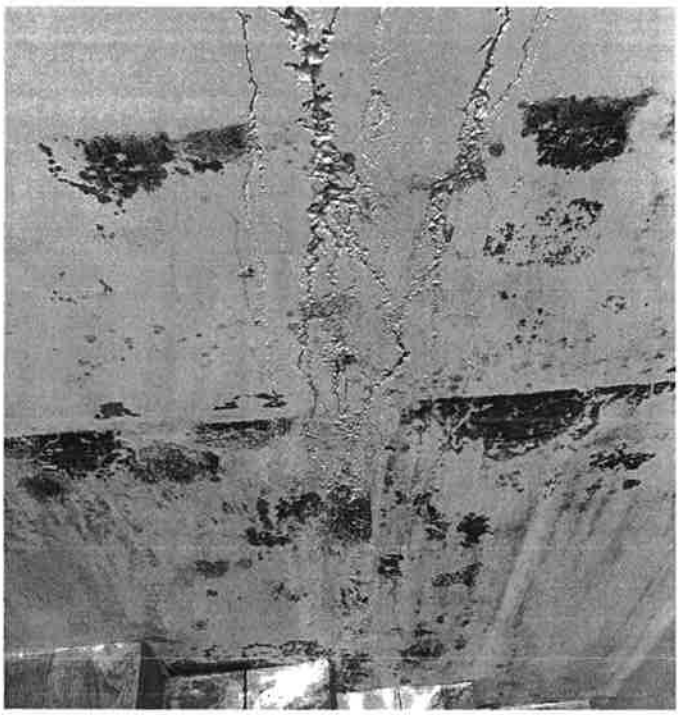


Cladding Performance – Tropical Climate

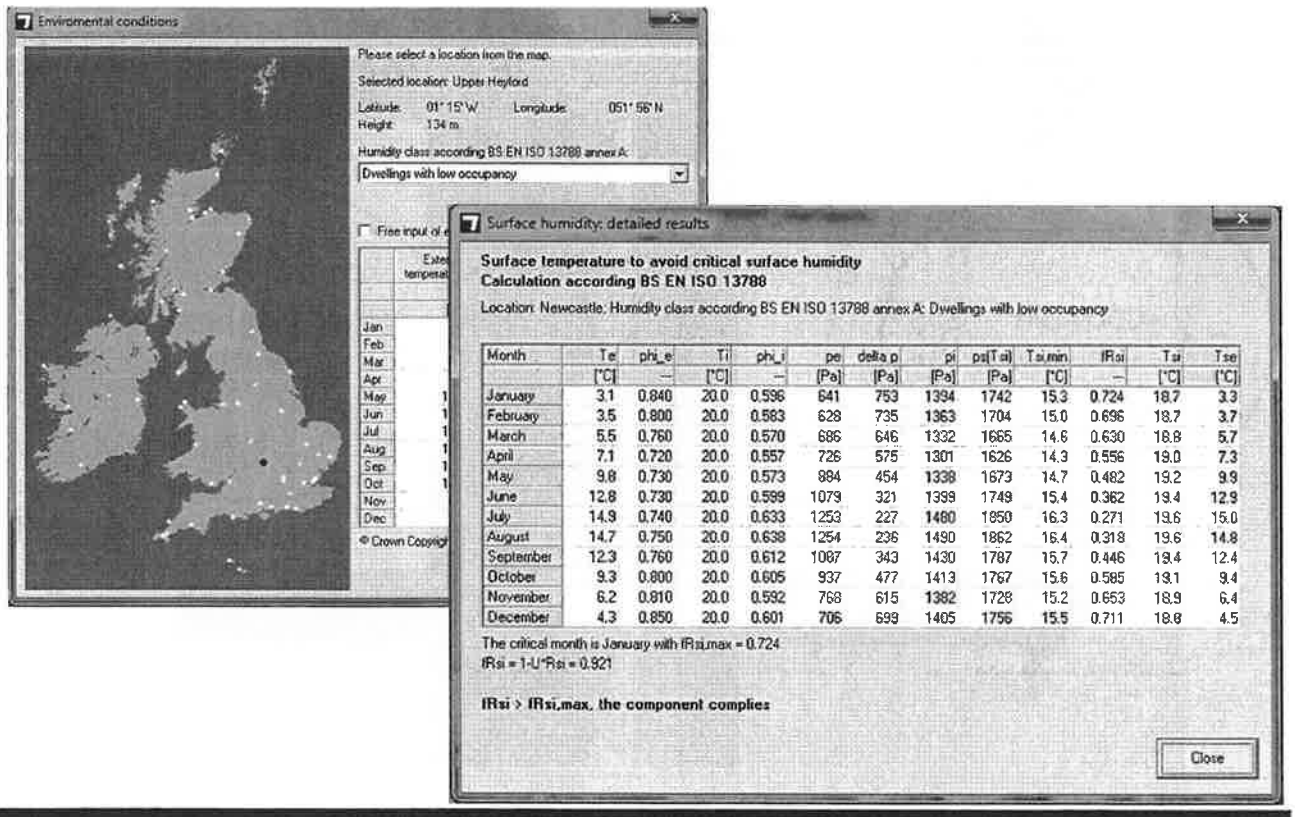


Cladding Performance

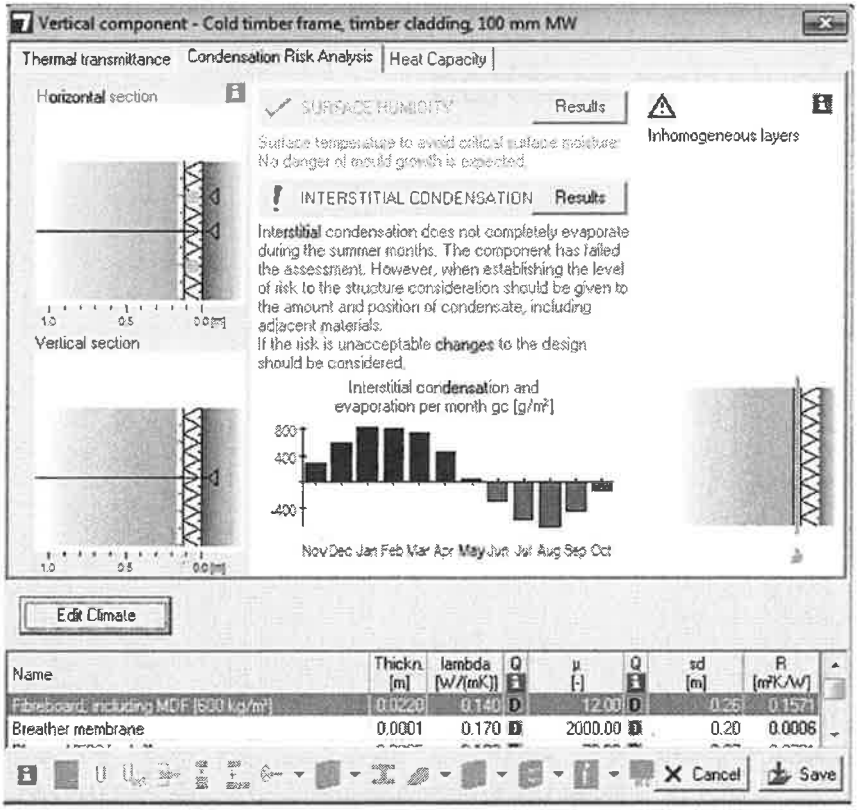




Cladding Performance



Cladding Performance



BCA ACADEMY

Cladding Performance

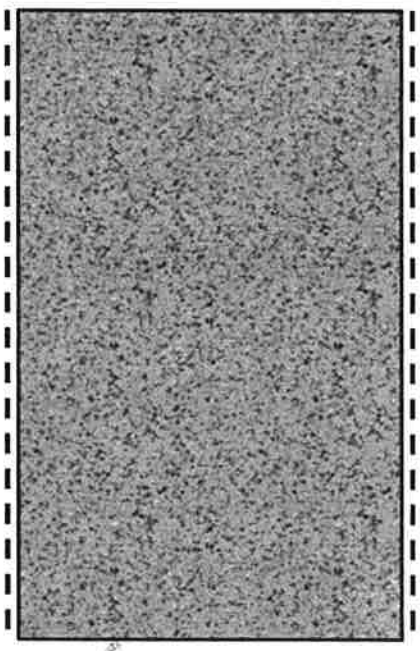
- Type of insulation
- Thickness matters more than density

Cladding Performance

- U-value calculation method
- **Exercise time!**

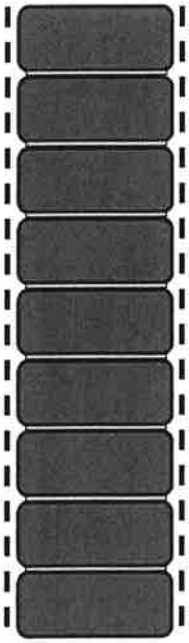
Cladding Performance

- U-value calculation for 400mm thick RC wall



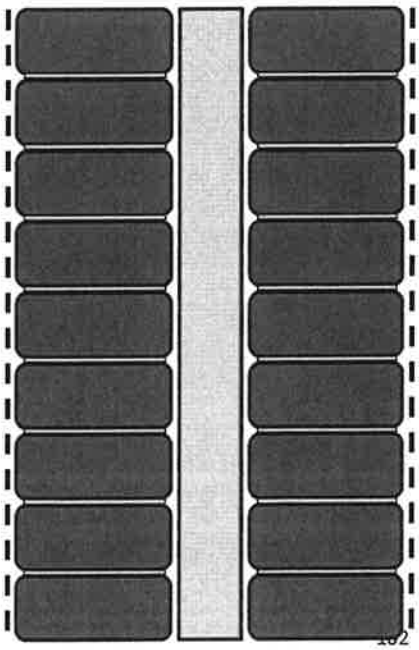
Cladding Performance

- U-value calculation for uninsulated 100mm thick brick wall



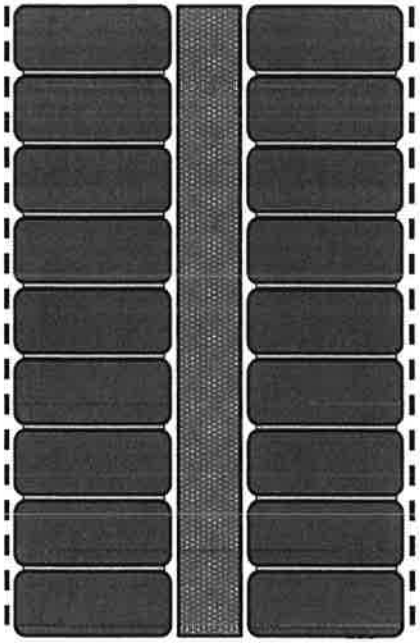
Cladding Performance

- U-value calculation for uninsulated 250mm thick cavity brick wall
- 2 layers of 100mm bricks
- 50mm thick of air space



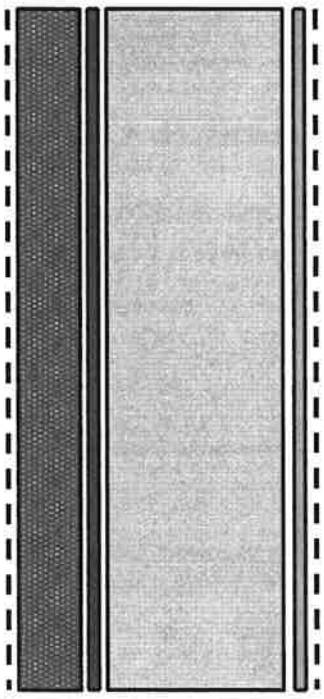
Cladding Performance

- U-value calculation for insulated 250mm thick cavity brick wall
- 2 layers of 100mm bricks
- 50mm thick of XPS insulation



Cladding Performance

- U-value calculation for typical spandrel glass make-up
- 8mm thick glass
- 100mm air space
- 2mm aluminium
- 50mm thick, 40kg/m^3 mineral wool insulation

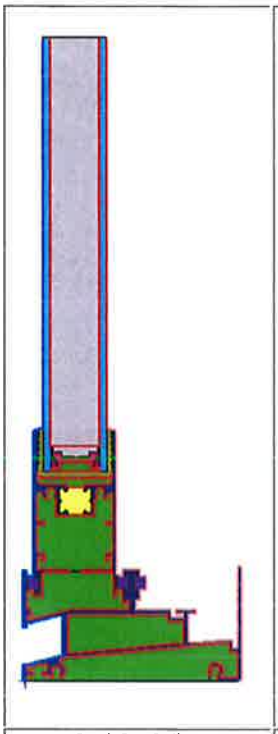


System Performance

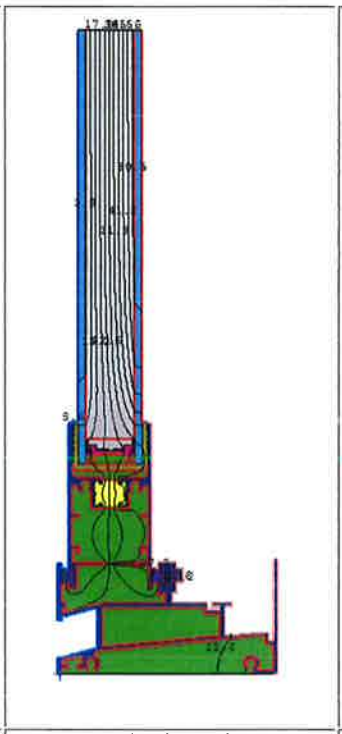
System Performance

- Calculations for complex system, particularly glazed frames?
- LBNL THERM – model two-dimensional heat-transfer effects in building components https://windows.lbl.gov/software/therm/therm.html

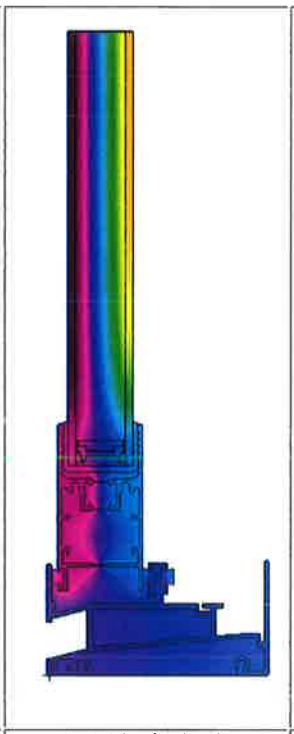
System Performance



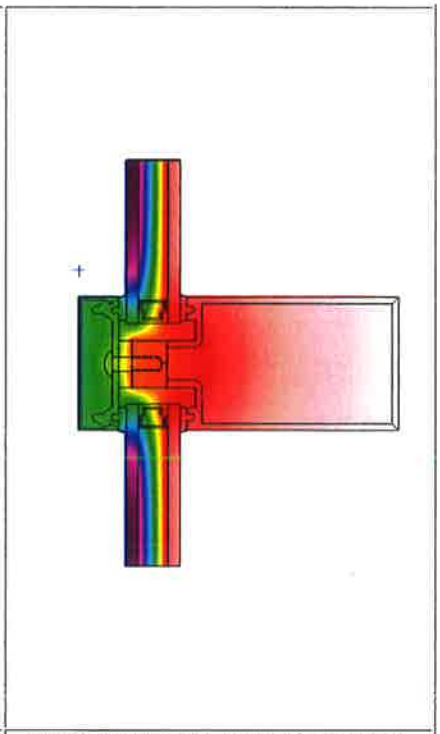
Sample Cross Section
(Aluminum Slider Window Frame)



Sample Isotherm Results
(Aluminum Slider Window Frame)



Sample Color Infrared Results
(Aluminum Slider Window Frame)



Sample Curtainwall with Bolt Cross Section with Infrared Results

BCA ACADEMY

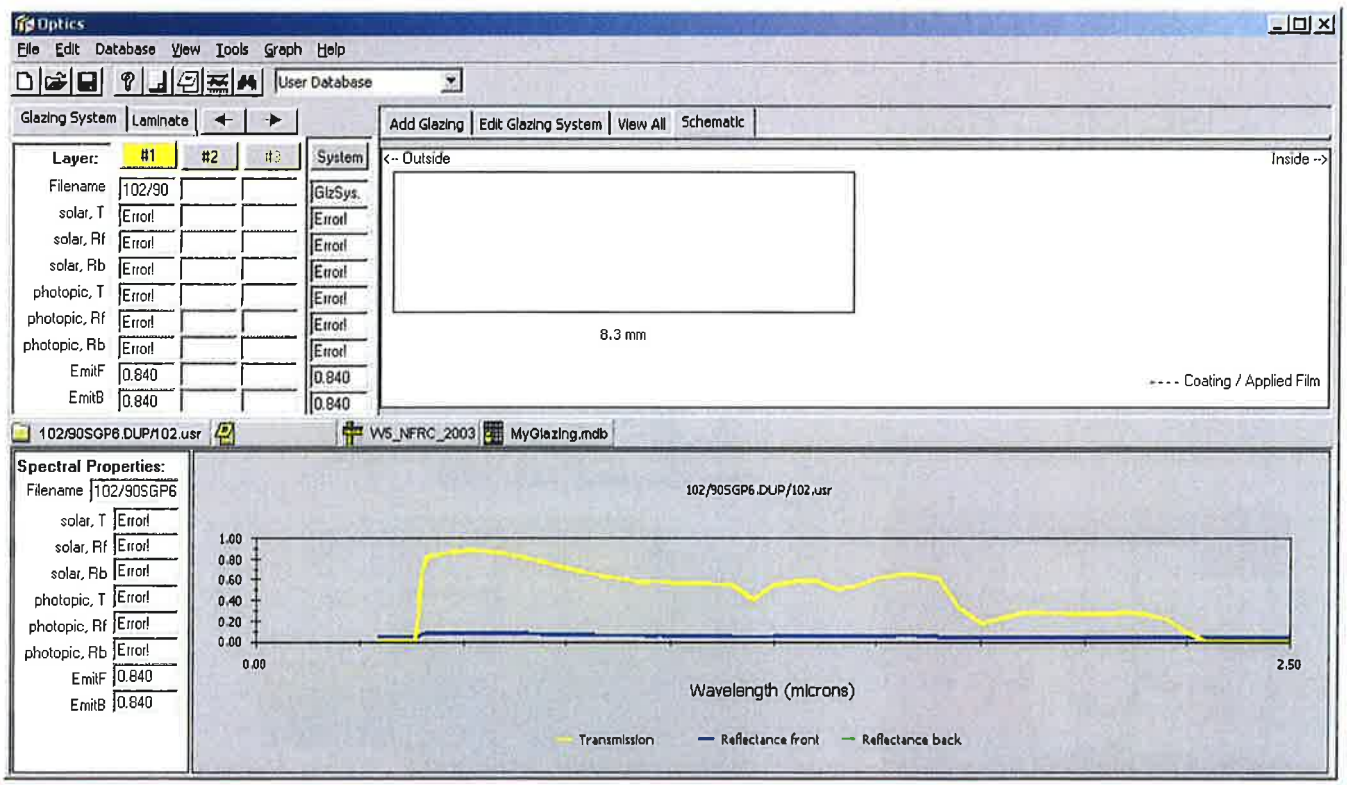
System Performance

- Calculations for complex system, particularly glazed assemblies?
- LBNL Window – analyse products made from any combination of glazing layers, gas layers, frames, spacers, and dividers https://windows.lbl.gov/software/window/window.html

System Performance

- Calculations for complex system, particularly glazed assemblies?
- LBNL Optics – Measurement and calculation of the optical properties of glazing materials, multilayer systems of glazing, and shading attachments
  http://windowoptics.lbl.gov

System Performance

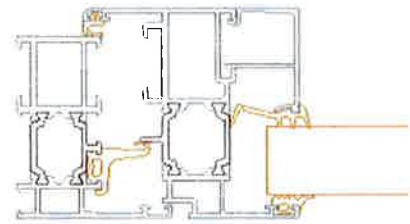


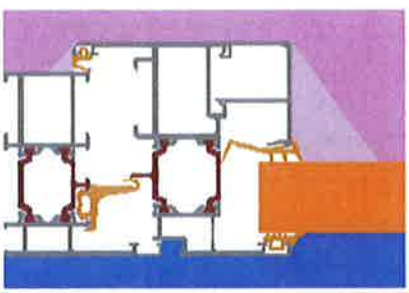
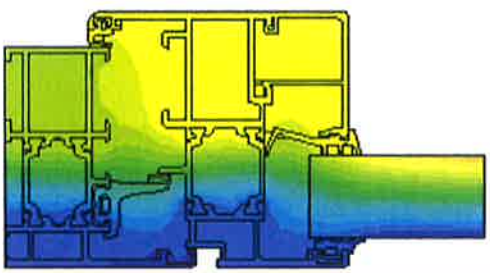
System Performance

- Calculations for complex system, particularly glazed assemblies?
- LBNL IGDB – Optical data for hundreds of standard glazing products. Spectral transmittance and reflectance is measured in a spectrophotometer and contributed to the IGDB by the manufacturers of the products http://windowoptics.lbl.gov/data/igdb

System Performance

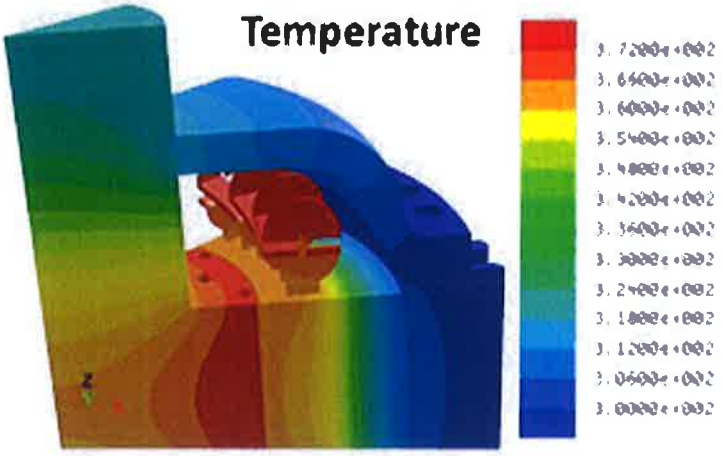
- Other options?
- Physibel Bisco http://www.physibel.be/v0n2bi.htm



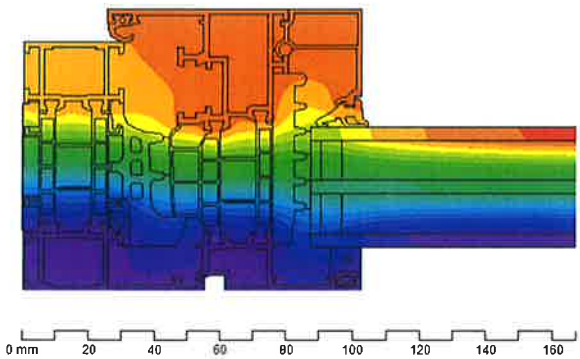
System Performance

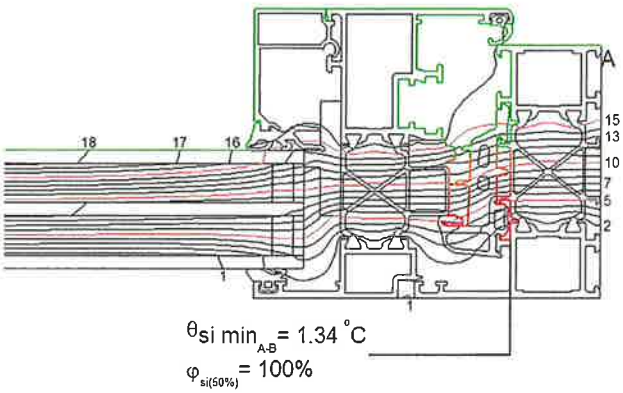
- Other options?
- ANSYS
  http://www.ansys.com/products/structures/thermal-analysis



System Performance

- Other options?
- Infomind: Flixo
  http://www.flixo.com





1:1.8

Material λ[W/(m·K)] ε

System Performance

Standards adapted

LBNL: THERM 5.2	Physibel: BISCO 8.0w	ANSYSÂ: Ansysâ	Infomind: Flixo
BS EN ISO 10077-2 ISO 15099	BS EN ISO 10077-2	-	BS EN ISO 10077-2

System Performance

Input data

	LBNL: THERM 5.2	Physibel: BISCO 8.0w	ANSYSÂ: Ansysâ	Infomind: Flixo
Geometry of cross section	Almost any shape	Any shape	Any shape	Any shape
Importing a cross section	bmp or dxf file as underlay (has to be overdrawn as polygons)	bmp file colour filled without material border. Each colour corresponds to a material or a boundary condition	iges files imported as line drawing	dxf or SVG file as underlay
	dxf file can be converted automatically if in correct format, but material must be defined	dxf file can be converted into coloured bmp file using BISCO-DXF utility	dxf file can be converted automatically if in correct format	dxf file can be converted automatically
Material thermal conductivity database	ASHRAE (USA) BS EN ISO 10077-2	BS EN ISO 10077-2 BS EN 12524 DIN 4108-4 IEA Annex XIV NBN NEN ONORM PHYSIBEL SBR	None as standard, must be created	BS EN ISO 10077-2 BS EN 12524 BS EN 673 BS EN ISO 6946 DIN 4108-4
	Can be extended	Can be extended		Can be extended

System Performance

- More detailed comparison, including outputs, extensions and costs
  http://www.cwct.co.uk/thermal/software/software.htm

GMP Course

Daylighting



School of Graduate Development and Management

BCA ACADEMY

The contents of this document are protected by copyright and other forms of proprietary rights. All rights, title and interest in the contents are owned by, licensed to or controlled ***by BCA*** *and shall not be reproduced, republished, uploaded, posted, transmitted or otherwise distributed in any way, without the prior written permission of BCA. Modification of any of the contents or use of the contents for any other purpose will be a violation of BCA's copyright and other intellectual property rights. No part of the course may be recorded, reproduced or transmitted in any form or by any means, without the express written permission of the course organiser.*

The reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply BCA's endorsement, recommendation, or favouring by BCA.

What is Daylight?

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

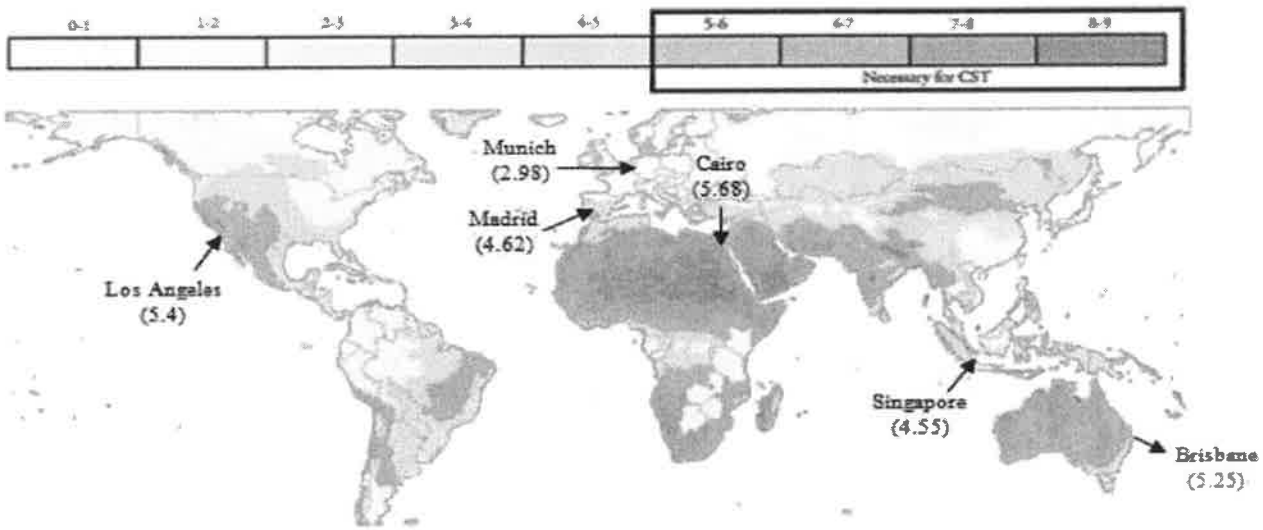
BCA ACADEMY

Definitions

- Singapore's annual average solar insolation is 1,663 kWh/m^2, which is equivalent to receiving 4.55 peak sun hours/day.
- There is an average of 2,064 hours of sunlight per year (of a possible 4,383) with an average of 5:39 of sunlight per day.
- It is sunny 47.1% of daylight hours. The remaining 52.9% are likely cloudy or with shade, haze or low sun intensity.

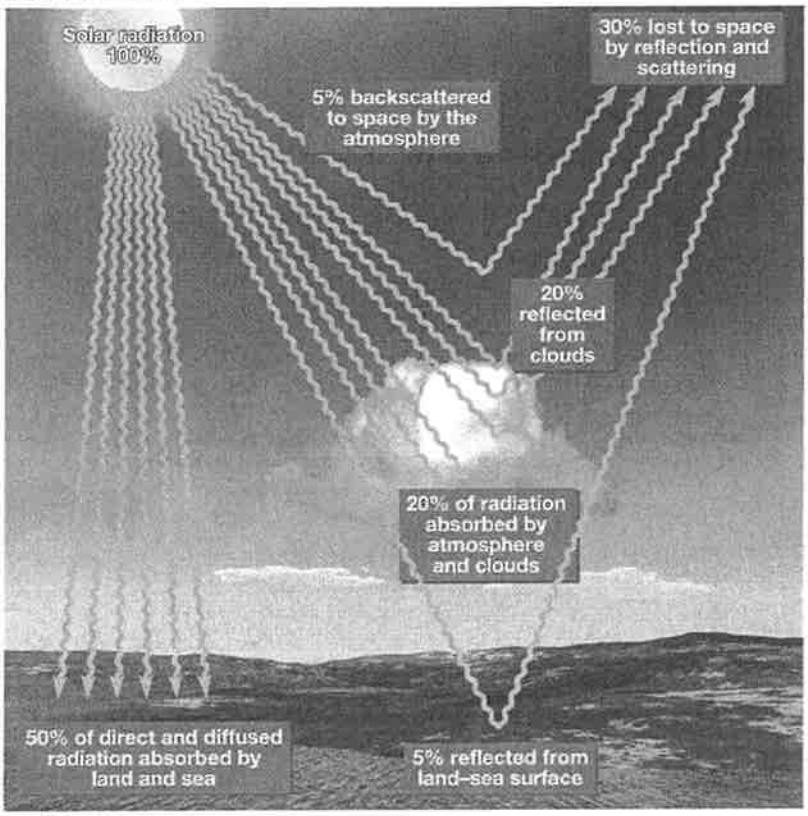
Definitions

Global peak sun hours



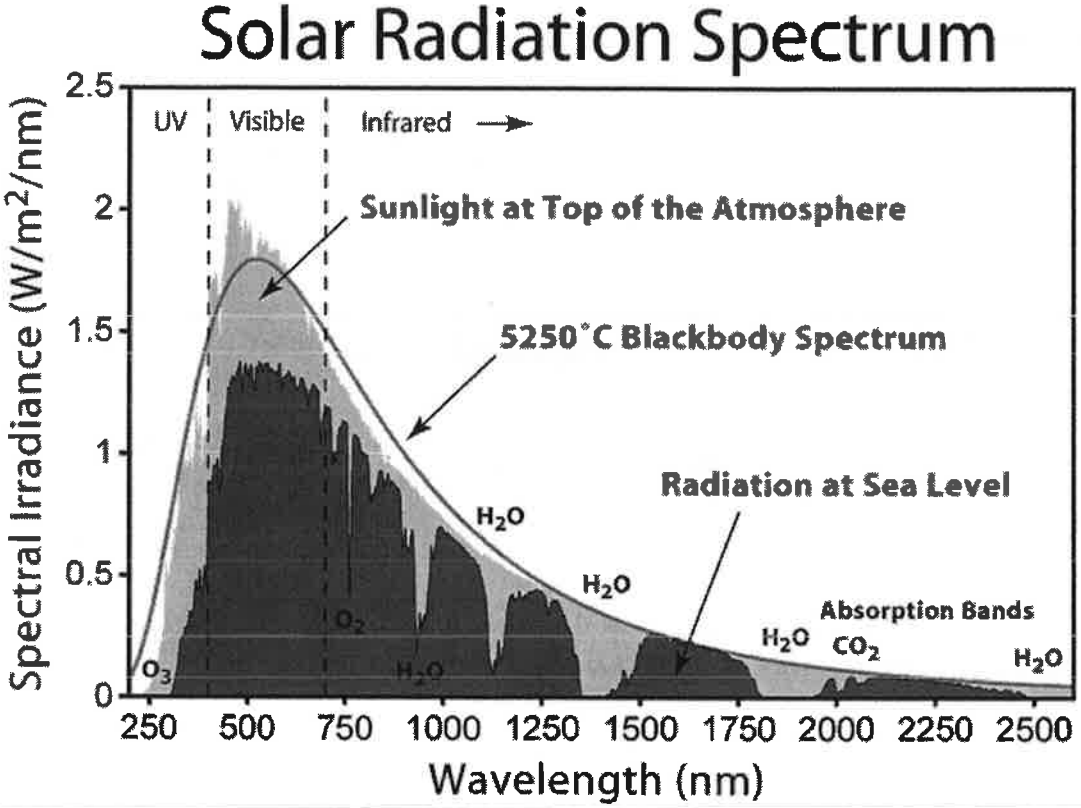
Source: World Resources Institute, NASA Surface Meteorology and Solar Energy

Definitions



© 2013 Pearson Education, Inc.

Definitions



Definitions

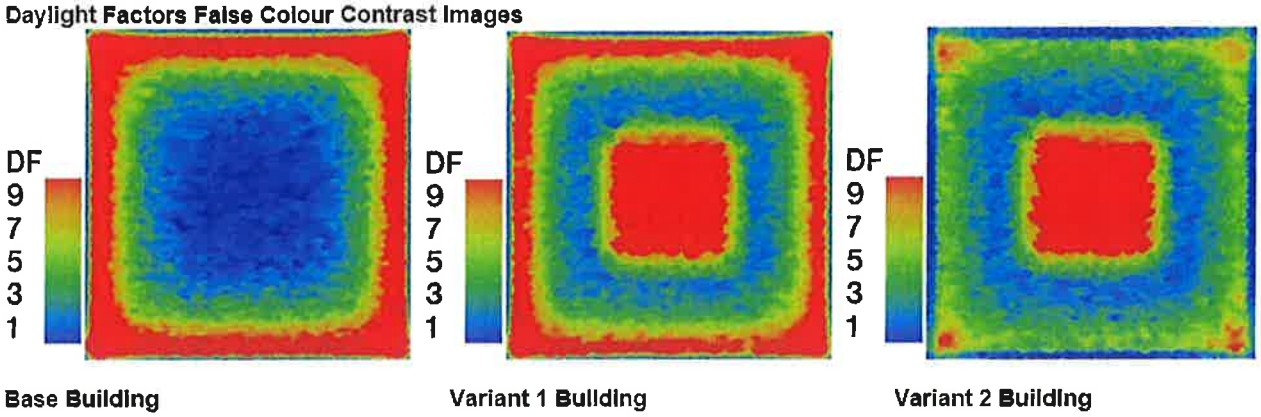
- Luminance describes the measurement of the amount of light emitting, passing through or reflected from a particular surface from a solid angle (in cd/m²)
- Relates to glare assessment

Definitions

- Illuminance describes the measurement of the amount of light falling onto (illuminating) and spreading over a given surface area (in lux)
- Target illuminance values are set for different types of buildings and occupancies

Definitions

- Daylight Factor: In architecture, daylight factor is the ratio of the light level inside a structure to the light level outside the structure. It is defined as: DF = $(E_i / E_o) \times 100\%$



Benefits and Issues

BCA ACADEMY

Benefits and Issues

- Effect on artificial lighting
- Effects on occupants
- Glare issues
- Reflectivity issues
- Effects on heat loading

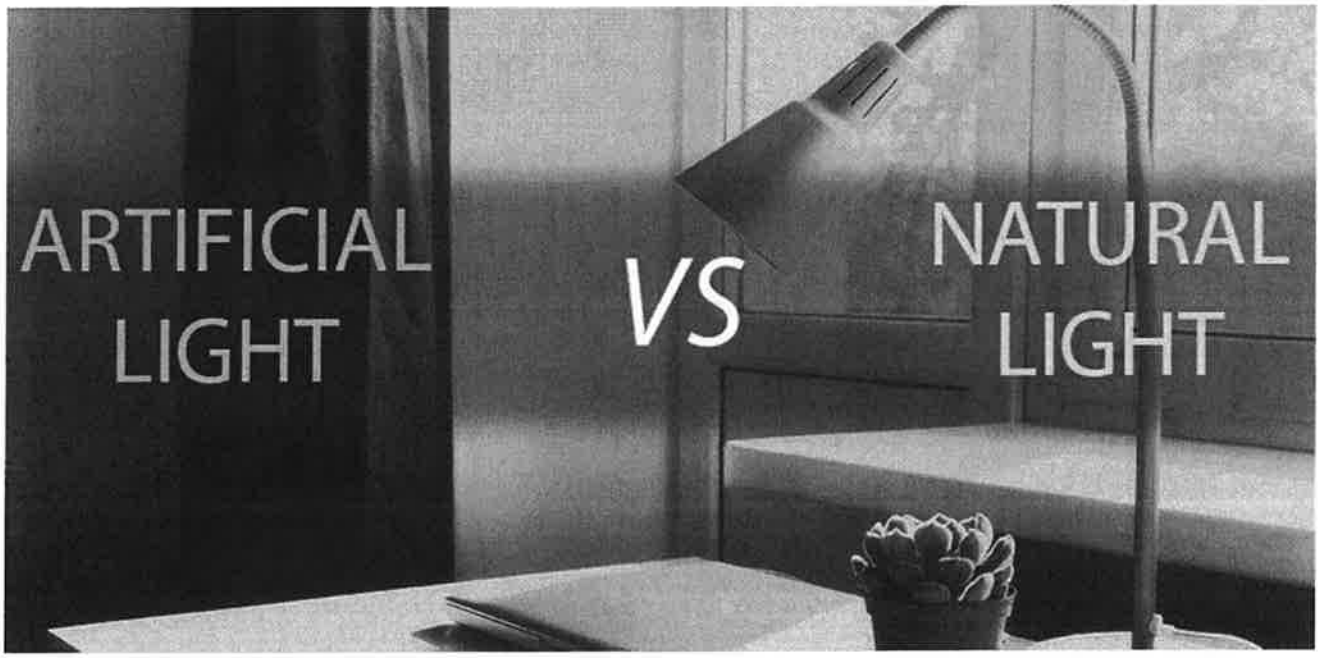
The Education and Research arm of the Building and Construction Authority

Benefits and Issues

- Effects on building aesthetics
- Fading of colours
- Colour rendition

Benefits and Issues

- Effect on artificial lighting



Benefits and Issues

- Sun exposure lowers blood pressure
- Sun exposure improves bone health
- Sun exposure improves brain function
- Sun exposure eases mild depression
- Sun exposure improves sleep quality
- Sun exposure lessens Alzheimer's symptoms

Benefits and Issues

- Effect on indoor plants





Benefits and Issues

- Effect on indoor plants



Benefits and Issues

- May cause glare



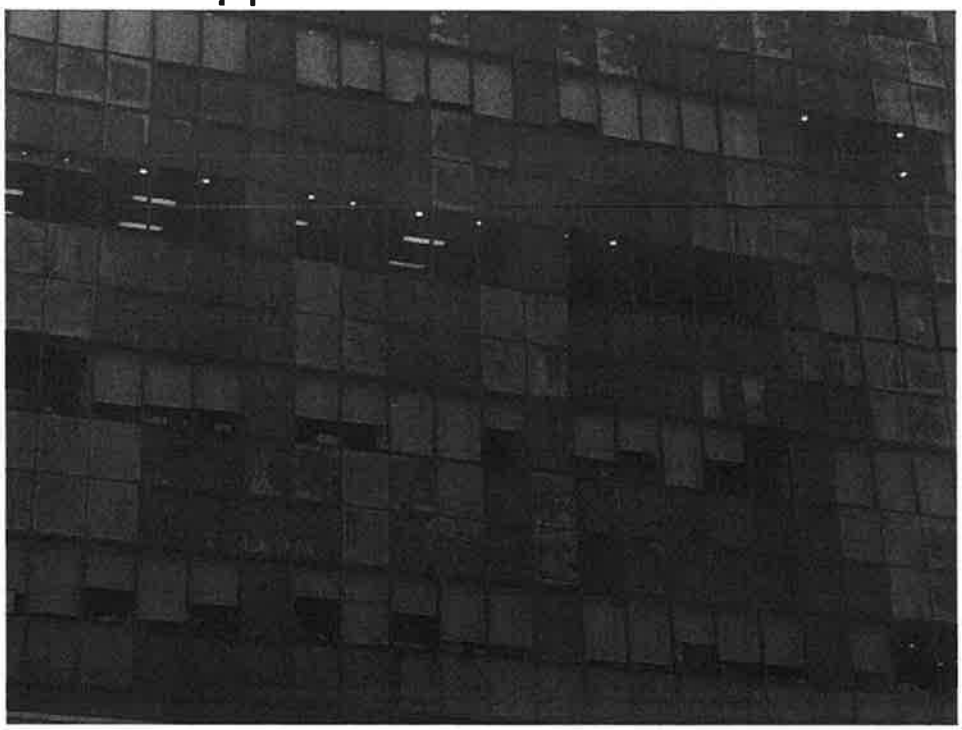
Benefits and Issues

- Checkered appearance



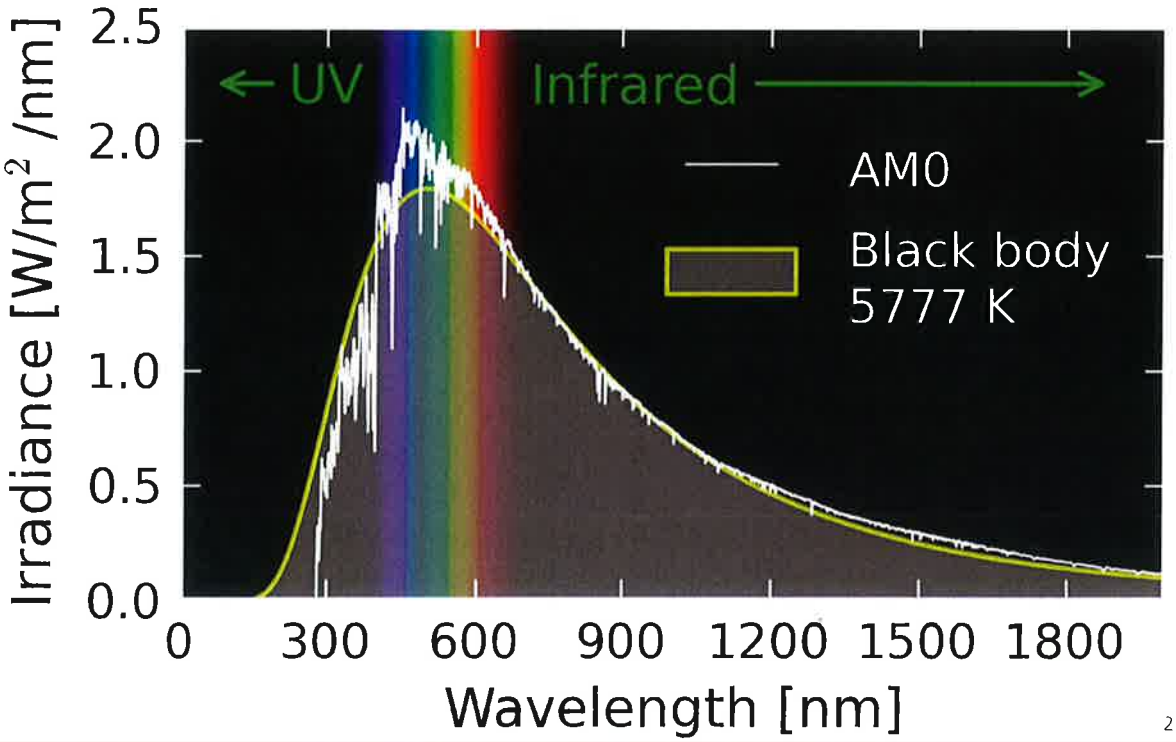
Benefits and Issues

- Checkered appearance



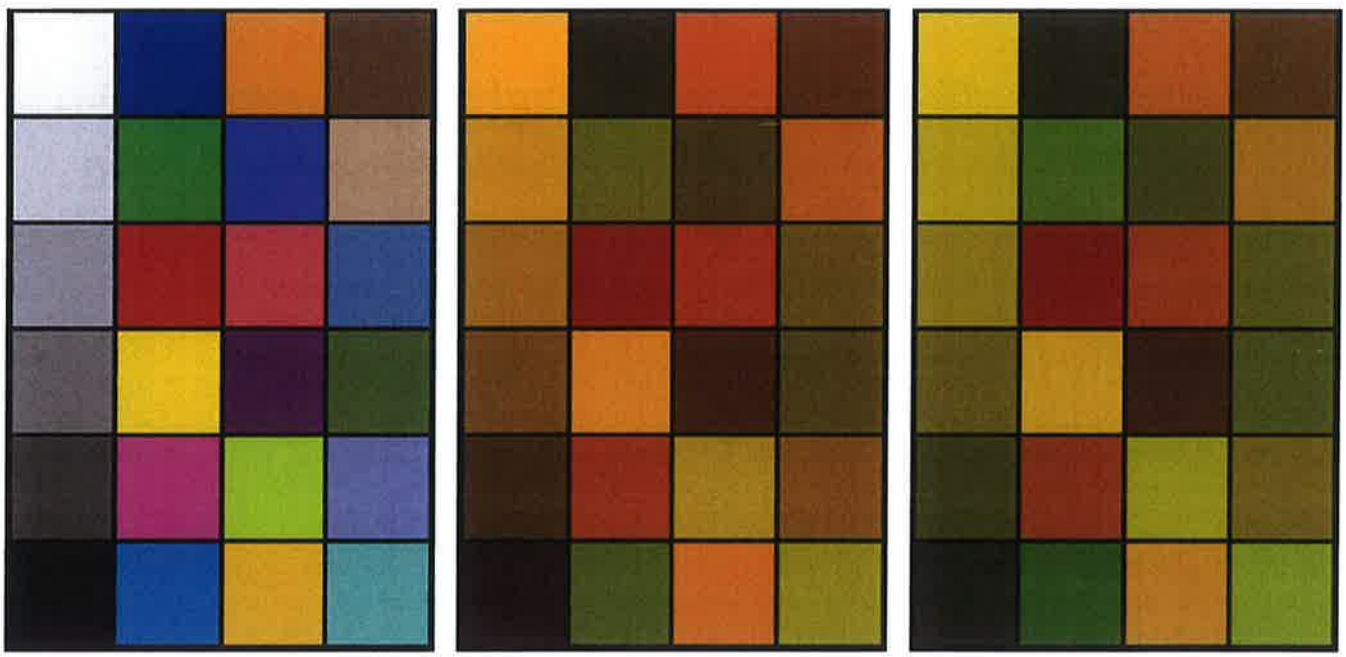
Benefits and Issues

- Heat loading



Benefits and Issues

- Colour rendering



Benefits and Issues

- Colour rendering

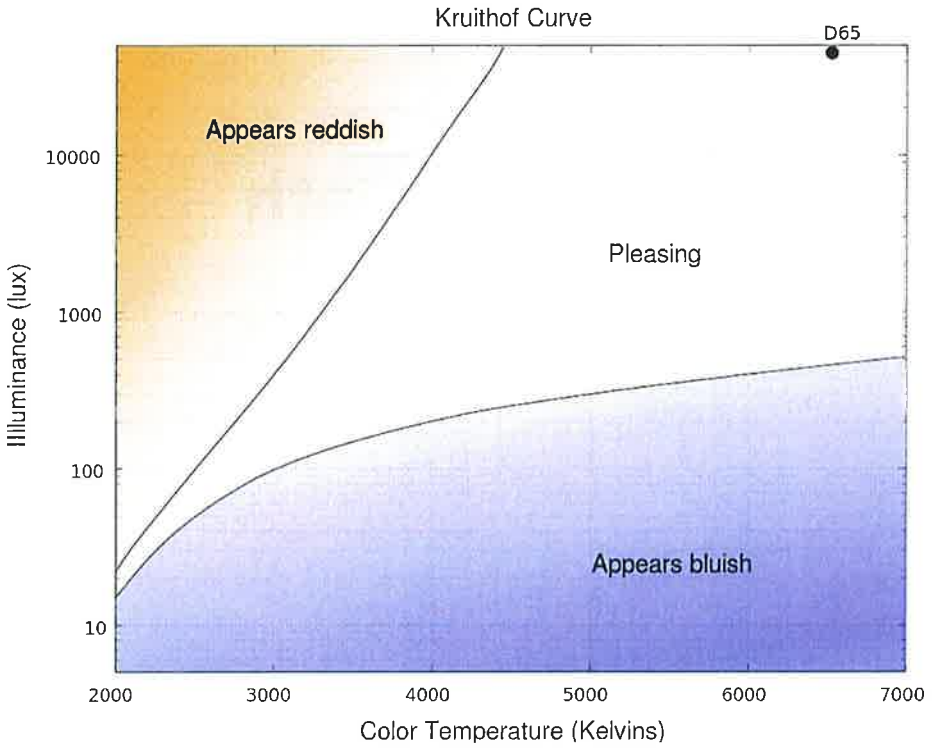


Benefits and Issues

- Colour rendering – Healthier source
- Physical effects: lack of daylight can suppress melatonin hormone that cause drowsiness and fatigue
- Psychological effects: ability to sense the outdoors, secure feeling

Benefits and Issues

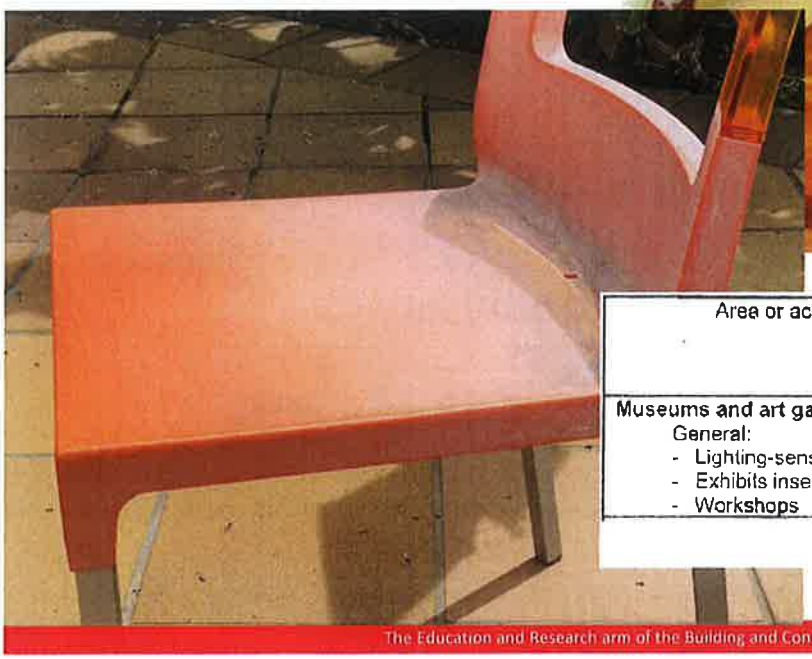
- Colour rendering – A slight digression



Benefits and Issues

- Colour fading





Area or activity	Illuminance (Lux)	
	Range	Recommended design value
Museums and art galleries:		
General:		
- Lighting-sensitive exhibits	100 - 200	150
- Exhibits insensitive to light	200 - 500	300
- Workshops	300 - 750	500

Singapore CP 38

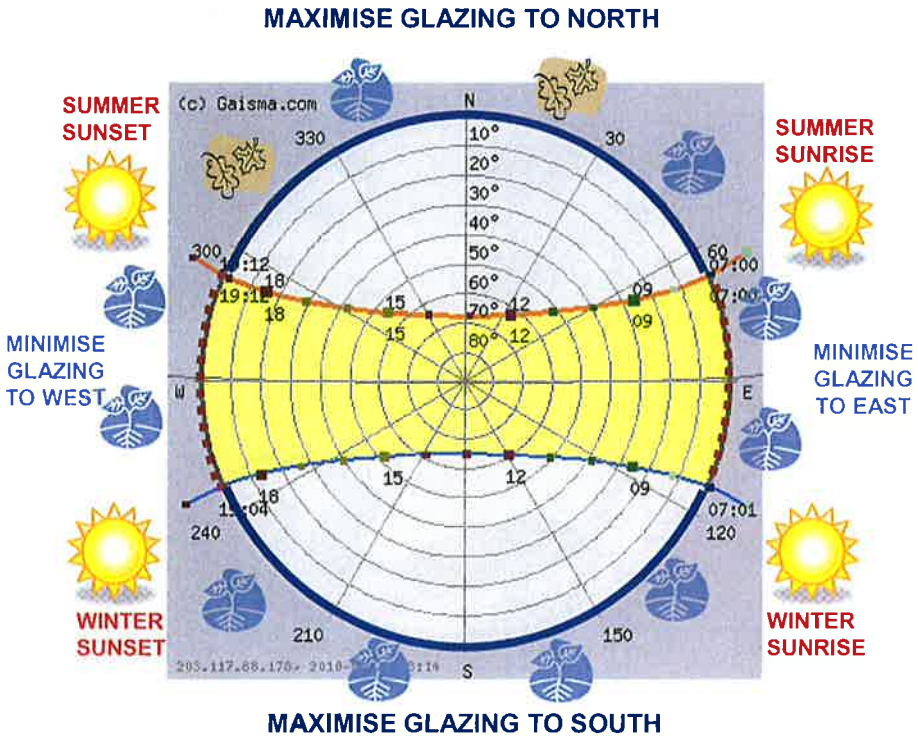
Solar Sun Path

BCA ACADEMY

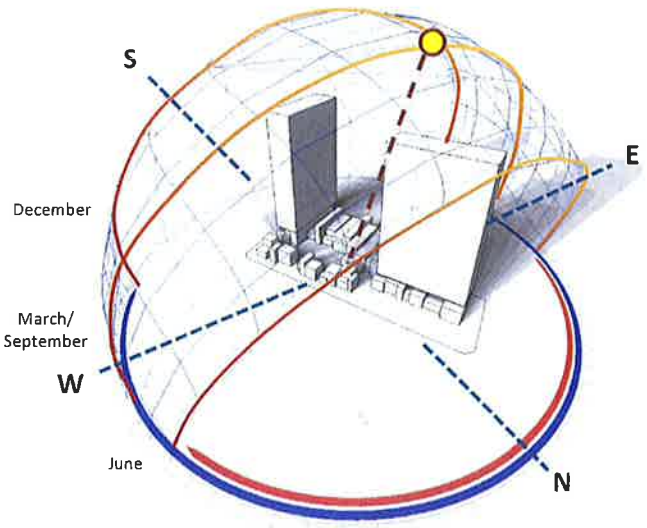
Solar Sun Path

- Plot of the sun's path across the sky
- Dependent on building location
- Used as basis for daylight analysis
- Used as basis for shading analysis
- Used as basis for reflectivity studies

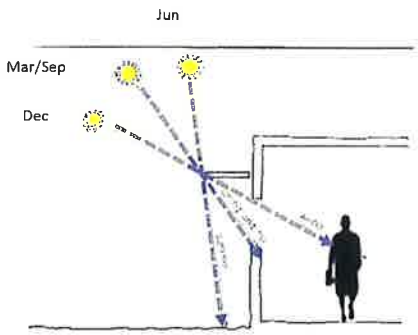
Solar Sun Path

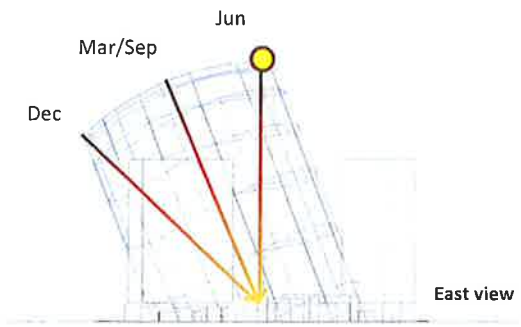


Solar Sun Path

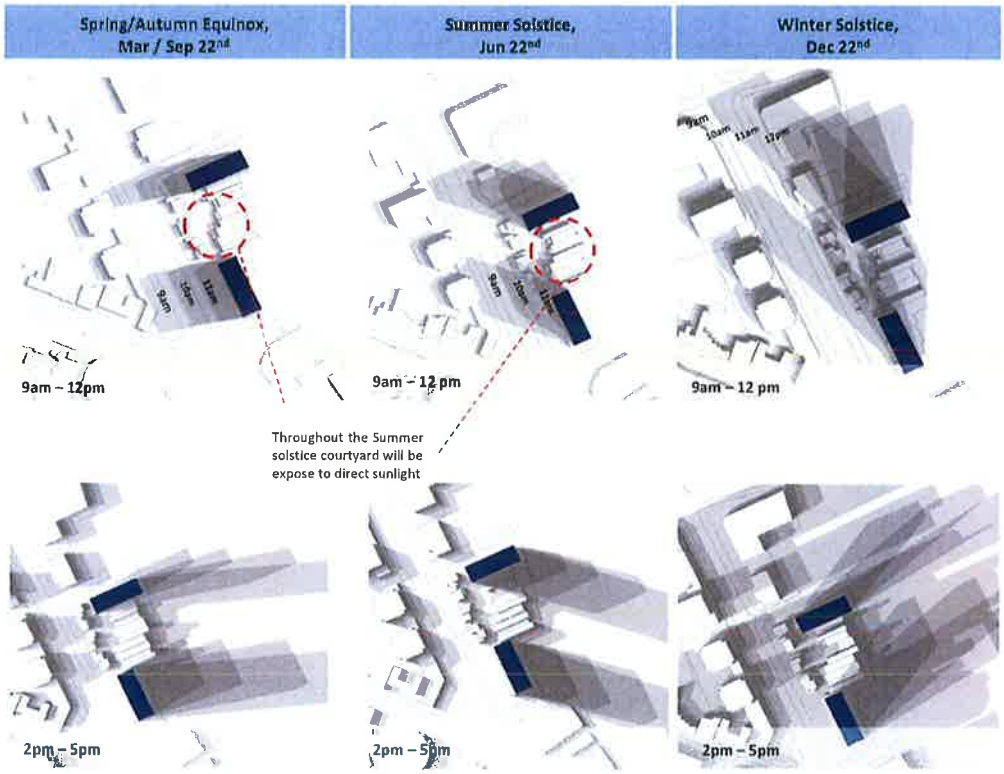


Sunpath Diagram

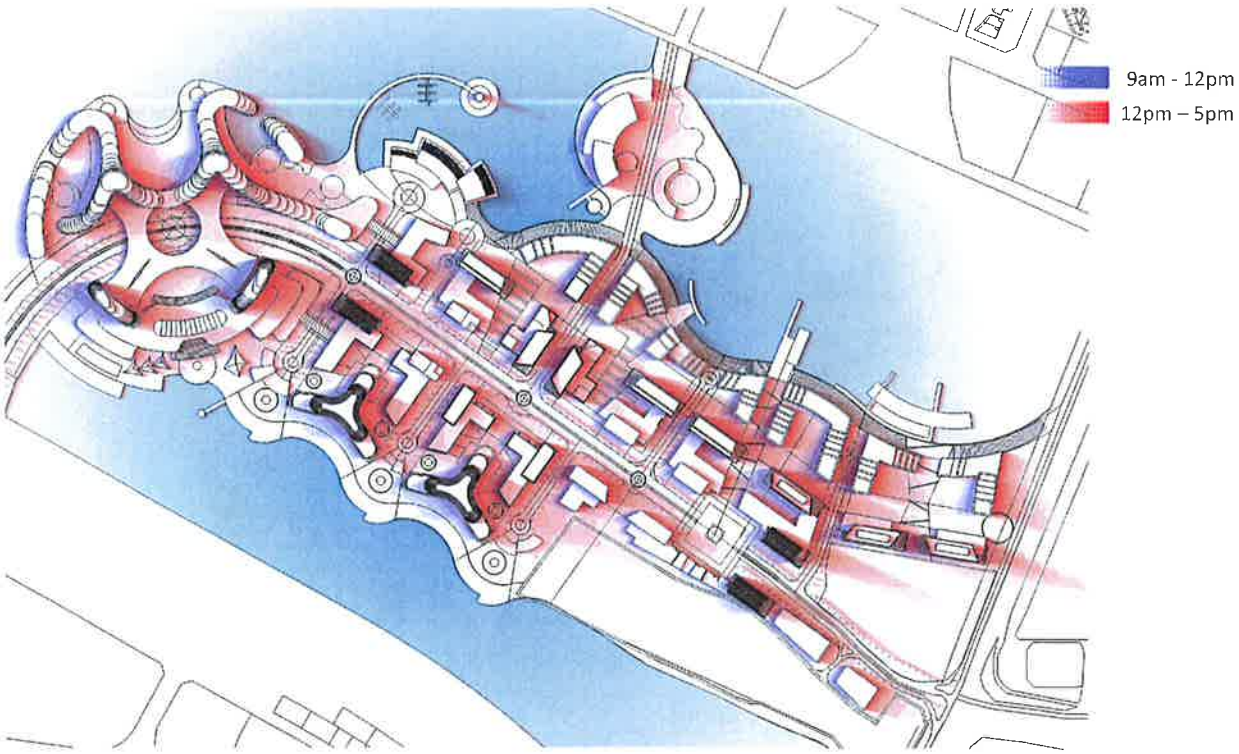




Solar Sun Path

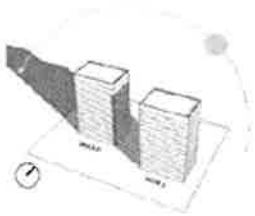


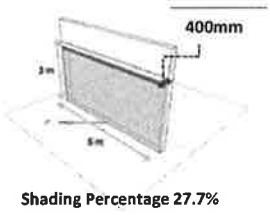
Solar Sun Path



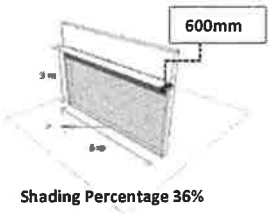
Masterplan Level

Solar Sun Path

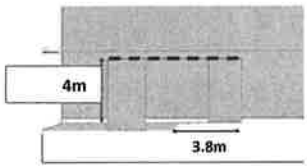


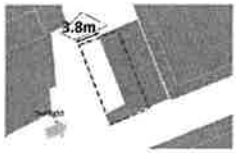


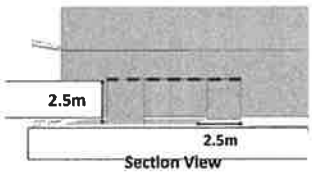
Shading Percentage 27.7%



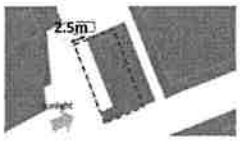
Shading Percentage 36%







Section View



Plan View

BCA ACADEMY

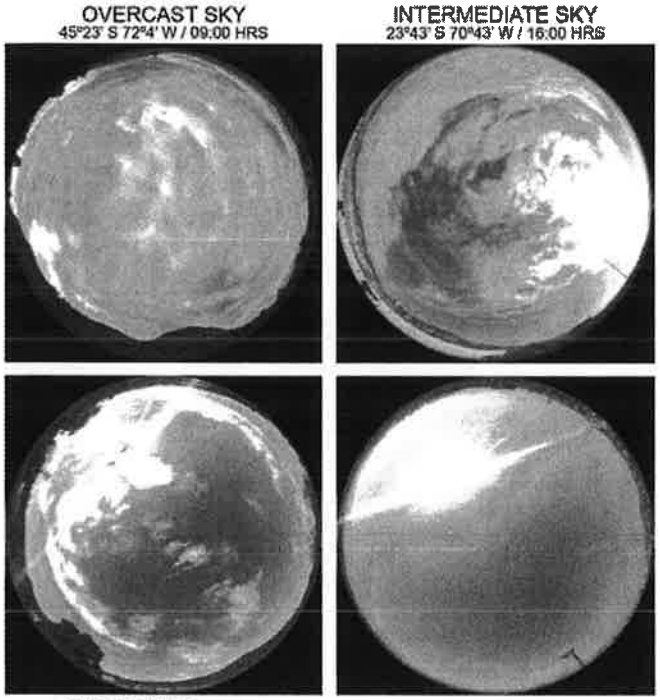
Daylight Performance

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

Maximising Daylight in Interior

- CIE Standard Skies



Maximising Daylight in Interior

- Clear sky: the luminance varies over both altitude and azimuth. It is brightest around the sun and dimmest opposite it. The brightness of the horizon lies in between those two extremes

- Intermediate sky: hazy variant of the clear sky. The sun is not as bright as with the clear sky and the brightness changes are not as drastic

Maximising Daylight in Interior

- Overcast sky: luminance changes with altitude. At the zenith, it is three times brighter than at the horizon. It is used for Daylight Factor.
- Uniform sky : characterised by a uniform luminance that does not change with altitude or azimuth. It is used for Right of Light cases.

BCA ACADEMY

Maximising Daylight in Interior

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

Maximising Daylight in Interior

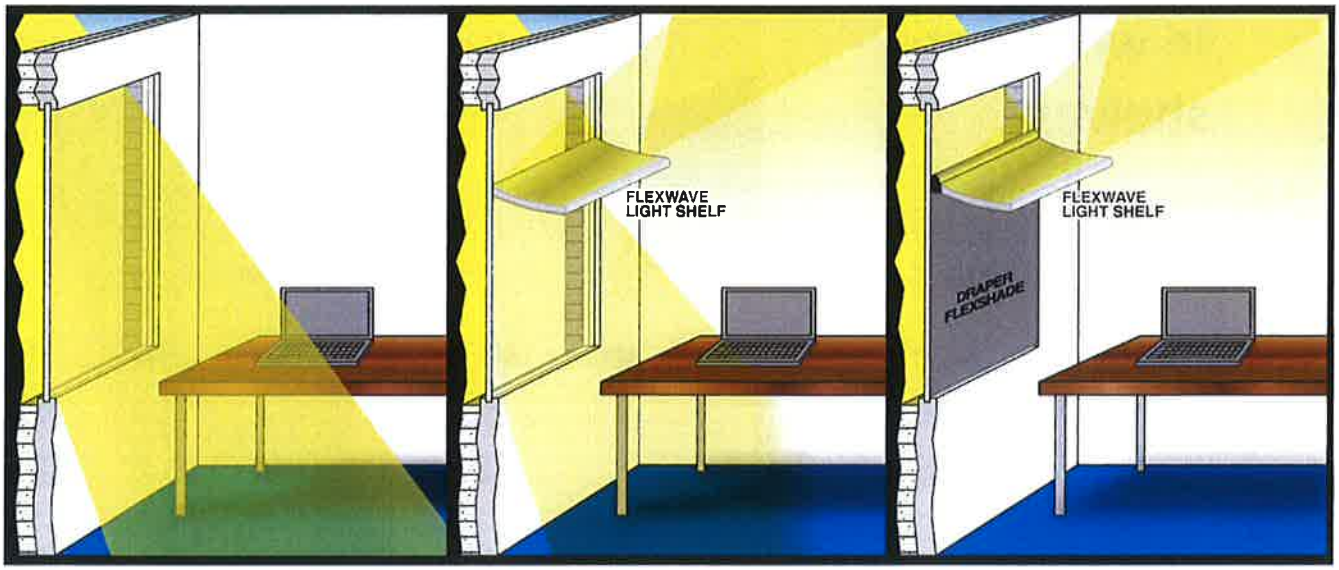
- Adjust WWR
- Adjust VLT
- Adjust building orientation
- Adjust external shading elements

Maximising Daylight in Interior

- Use spectrally selected low-e glass to filter out the non-visible spectrum and to allow through the visible spectrum
- Reflective glass can have low SC value to reject heat, but it also rejects the visible light
- Tinted glass can have low SC value to reject heat, but it also rejects the visible light, and also builds up absorbed heat (glass becomes hot to the touch)

Minimise Glare and Heat from Daylight

- Bring daylight in with light shelves



http://www.draperinc.com/images/windowshades/flexwave_3panel.jpg

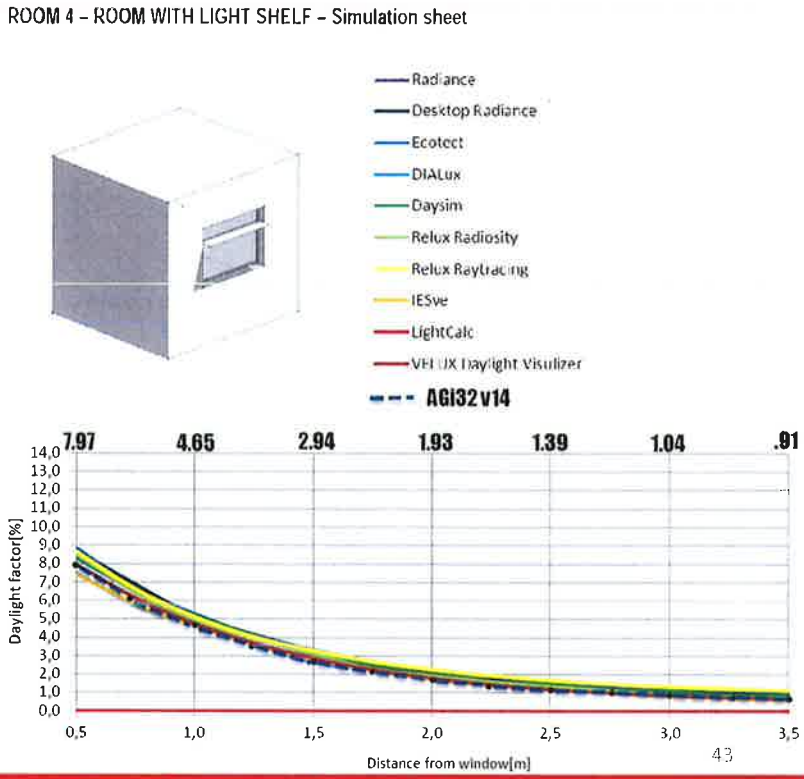
Minimise Glare and Heat from Daylight



- Bring daylight in with light shelves

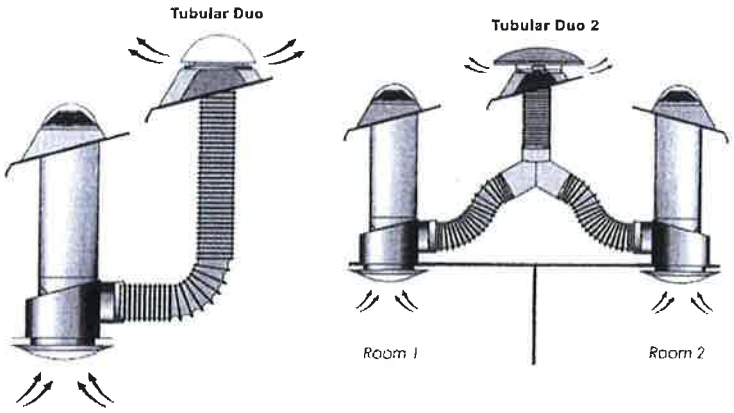
Minimise Glare and Heat from Daylight

- Bring daylight in with light shelves

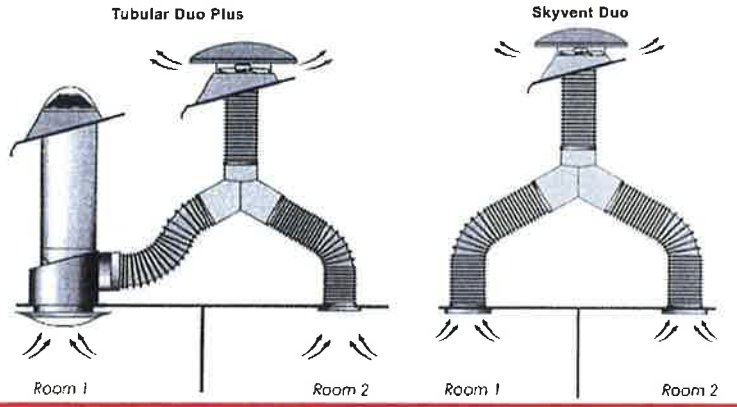


BCA ACADEMY

Minimise Glare and Heat from Daylight

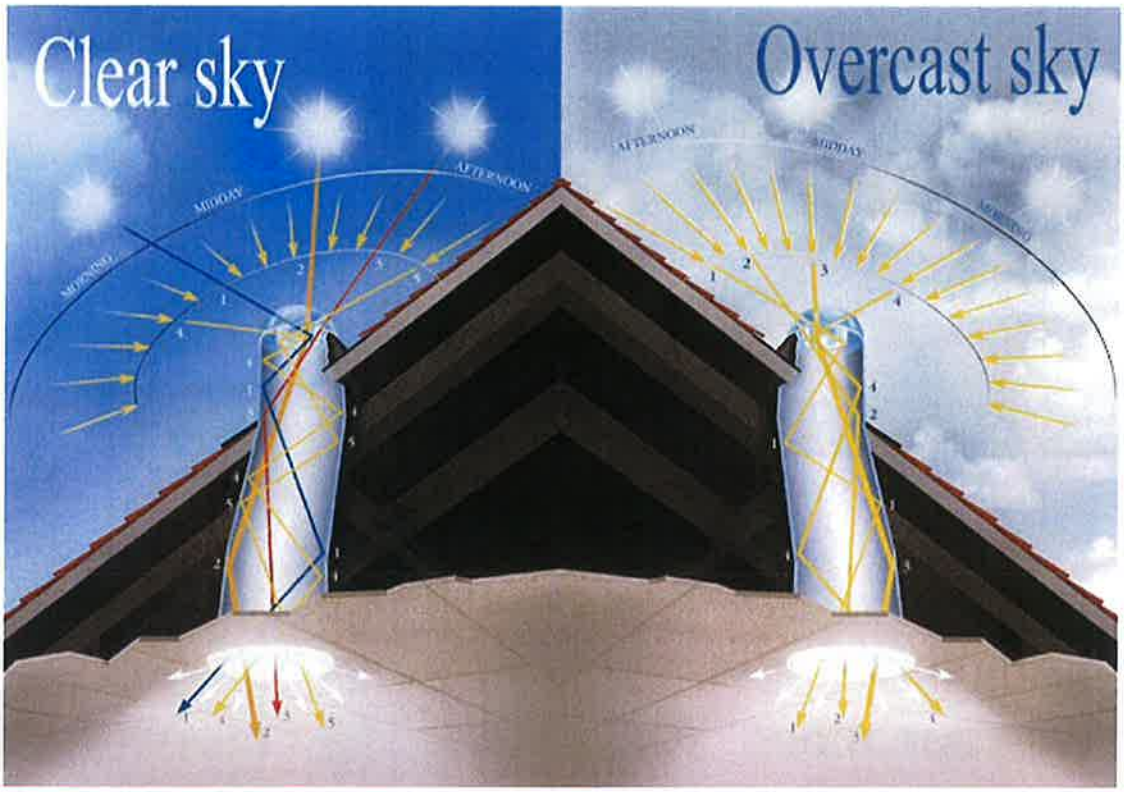


- Bring daylight in with sun pipes



The Education and Research arm of the Building and Construction Authority

Minimise Glare and Heat from Daylight



BCA ACADEMY

Minimise Glare and Heat from Daylight



- Bring daylight in with sun pipes

Minimise Glare and Heat from Daylight

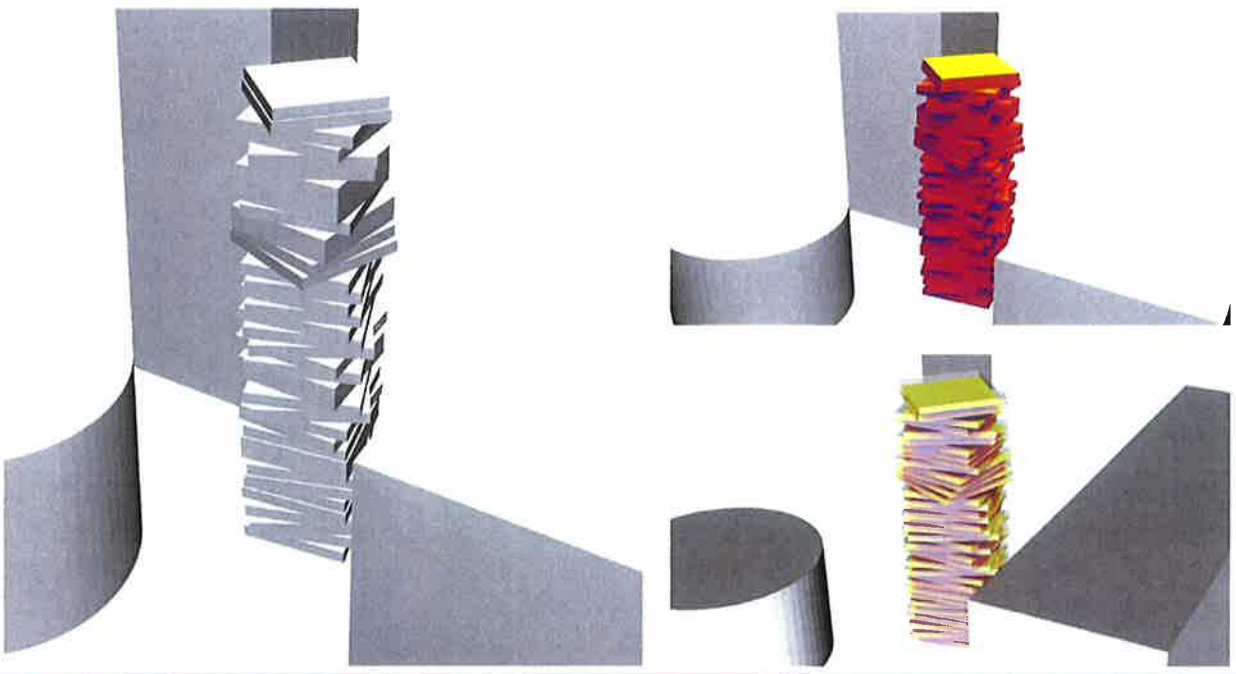




- Bring daylight in with sun pipes

Maximising Daylight in Interior

- Self-shading analysis

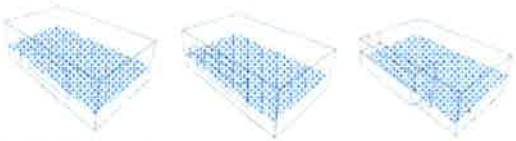


Maximising Daylight in Interior

Option 1
No Shading Devices

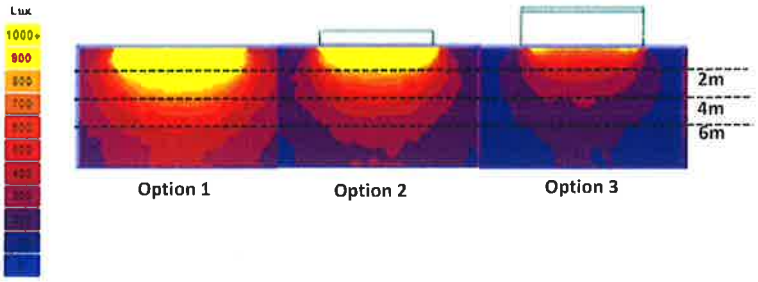
Option 2
Horizontal Shading Devices

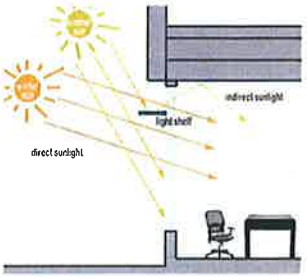
Option 3
Balcony as Shading Devices



West Facing Facade

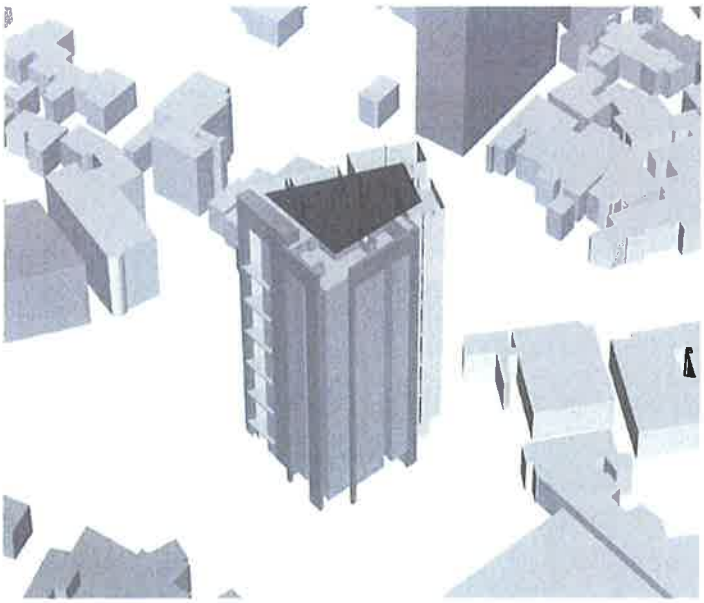
Sky Condition	: Overcast Sky
Work Plane Height	: 0.7m
Date/ Time	: 22 June, 1300





Maximising Daylight in Interior

- Light wells

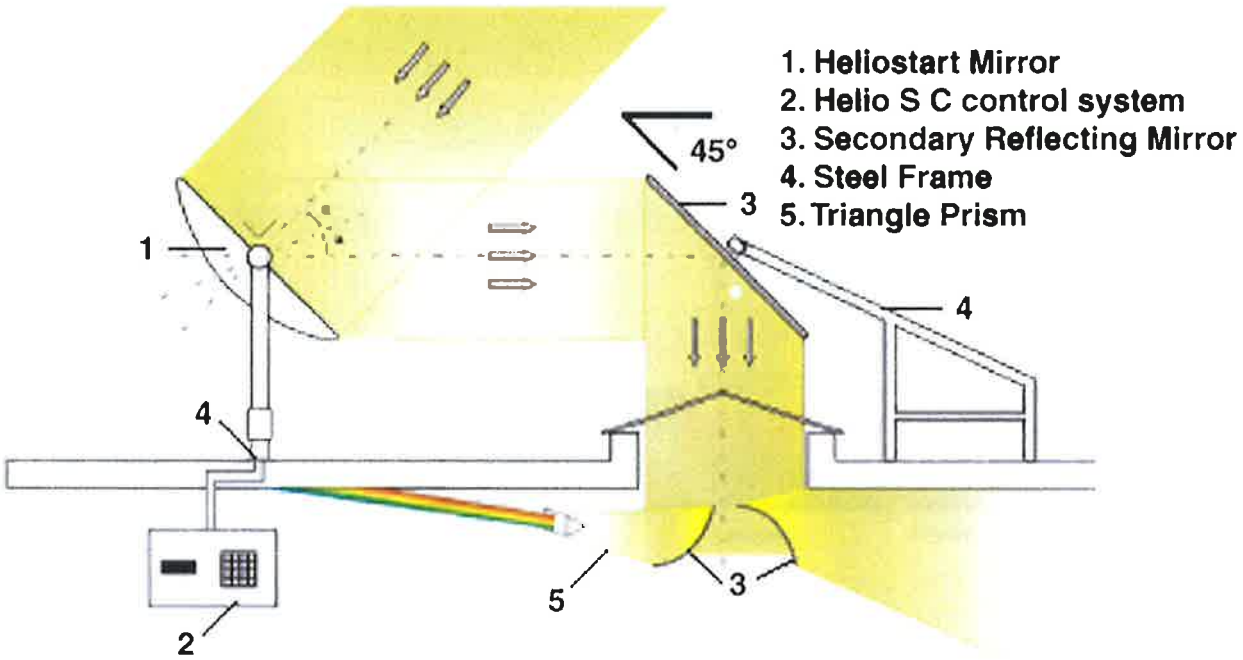






Maximising Daylight in Interior

- Solar reflectors / Heliostats



BCA ACADEMY

Maximising Daylight in Interior

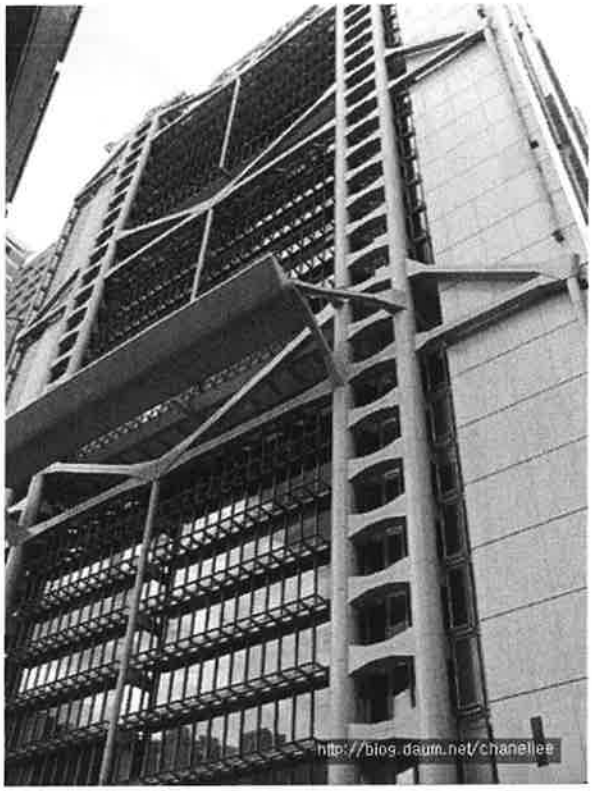
- Solar reflectors / Heliostats



The Education and Research arm of the Building and Construction Authority

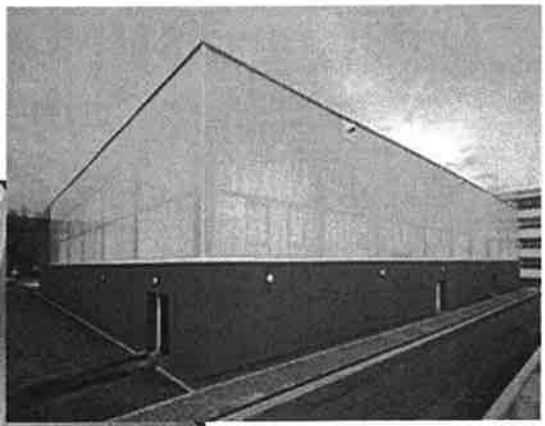
Maximising Daylight in Interior

- Solar scoops



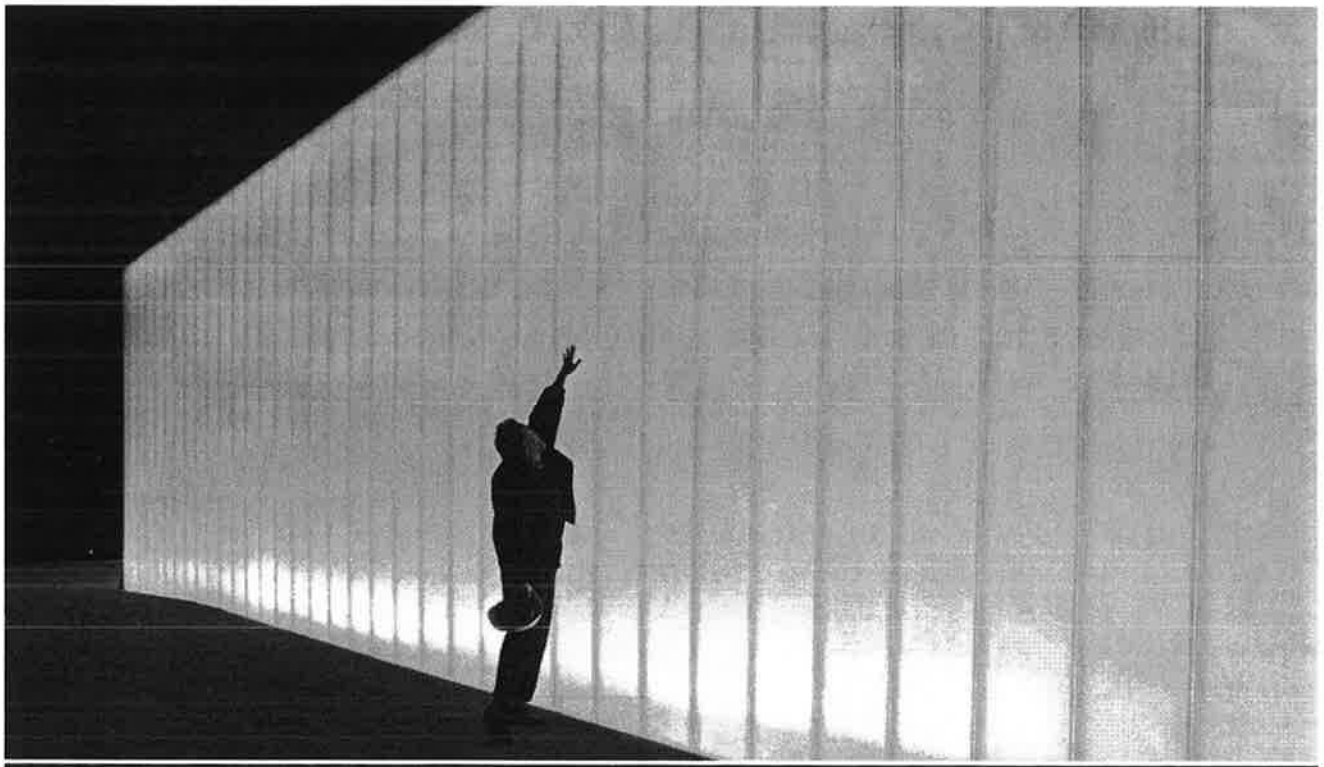
Maximising Daylight in Interior

- Diffuse daylight



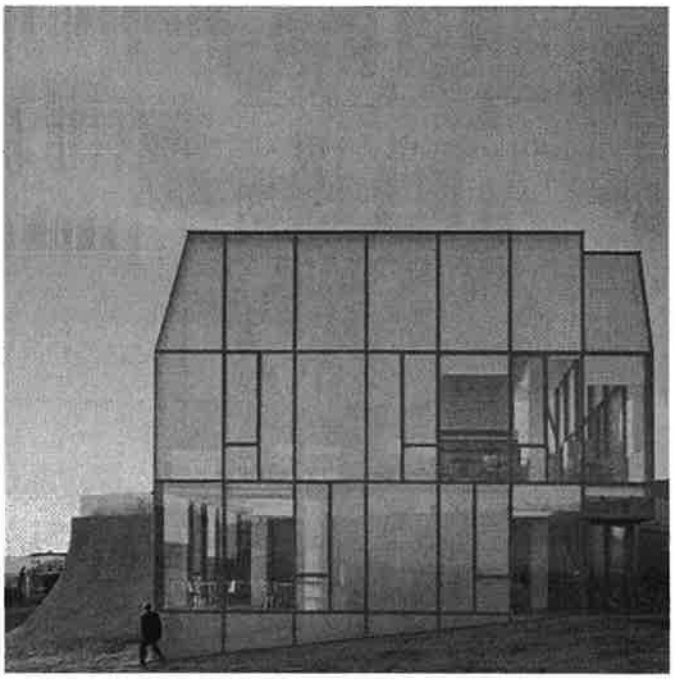


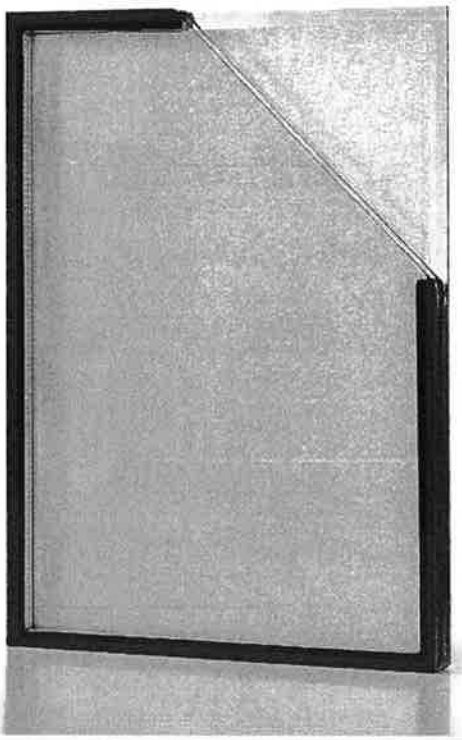
Maximising Daylight in Interior



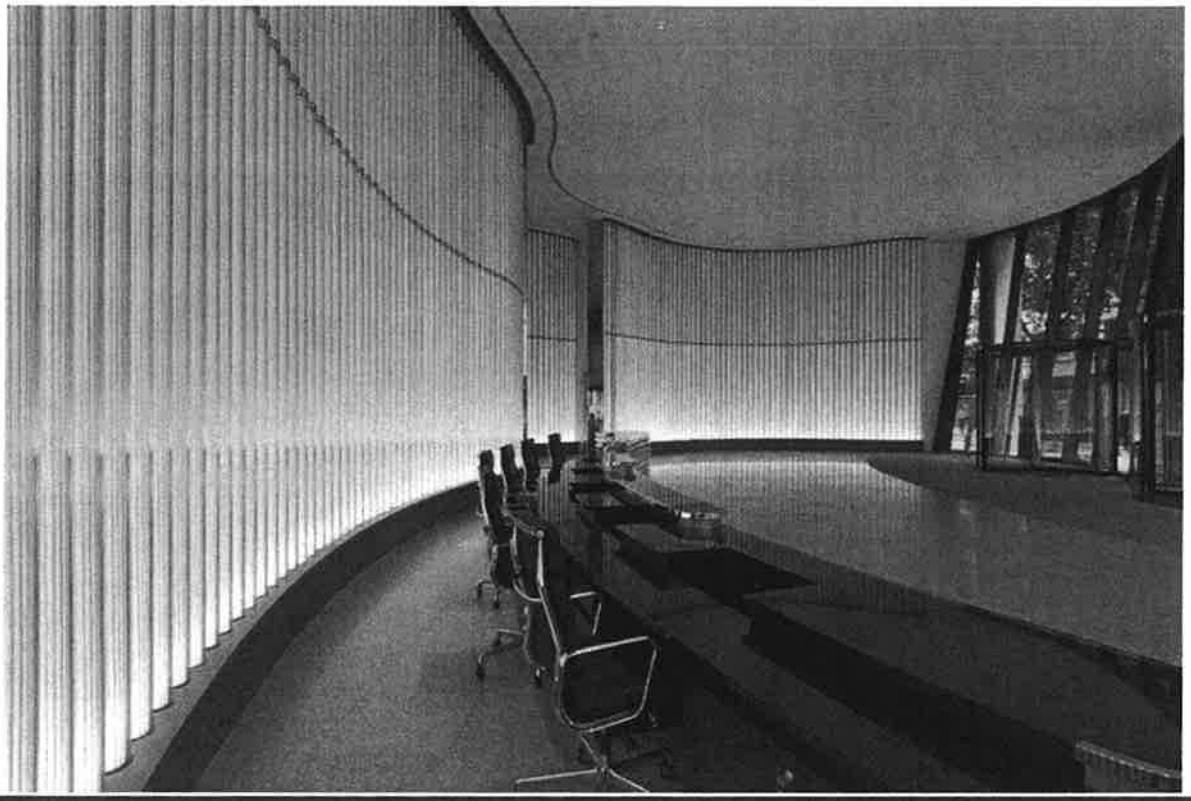
Maximising Daylight in Interior

- Diffuse daylight –Capillary





Maximising Daylight in Interior



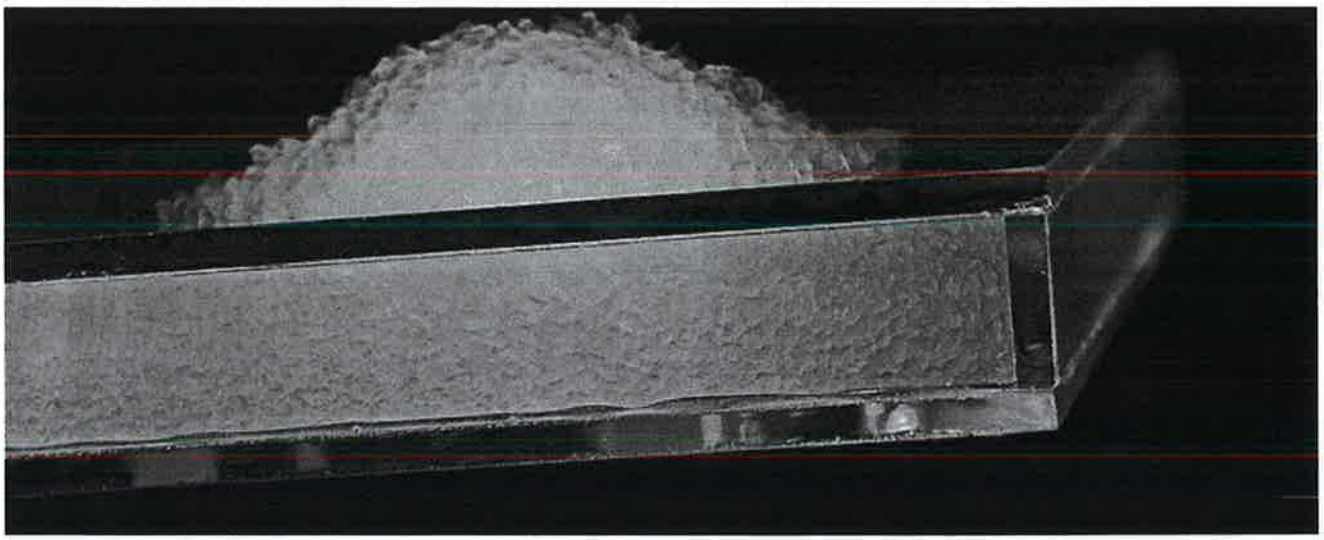
Maximising Daylight in Interior

- Diffuse daylight + Insulation



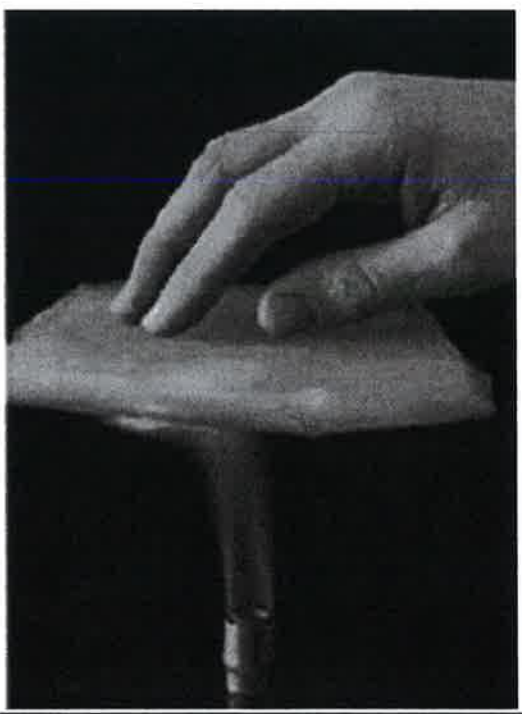
Maximising Daylight in Interior

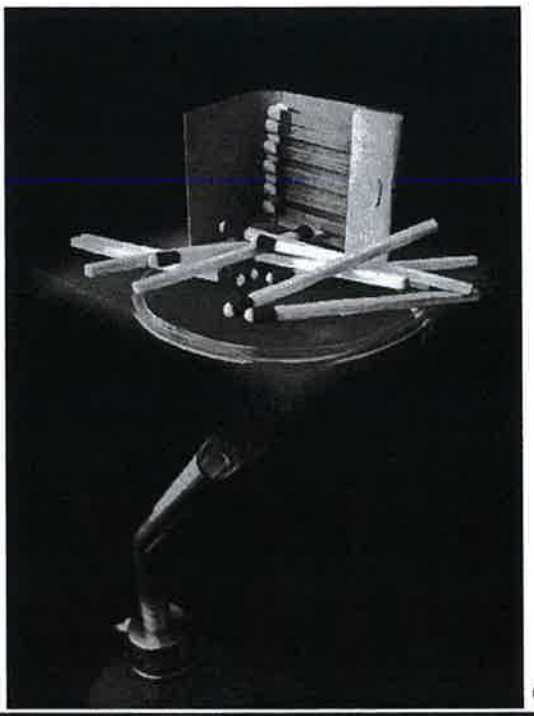
- Diffuse daylight + Insulation



Maximising Daylight in Interior

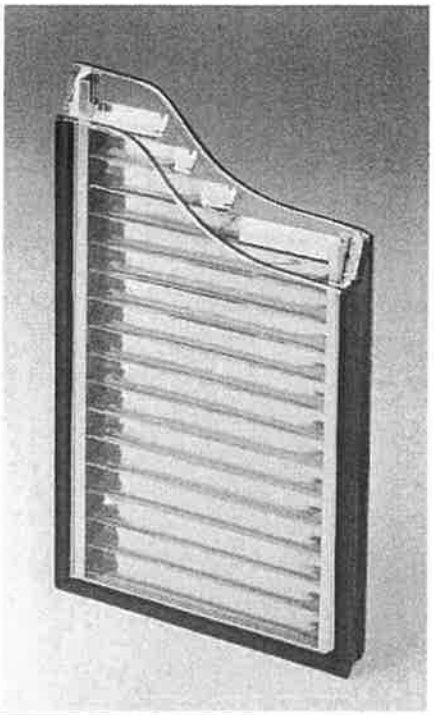
- Diffuse daylight + Insulation

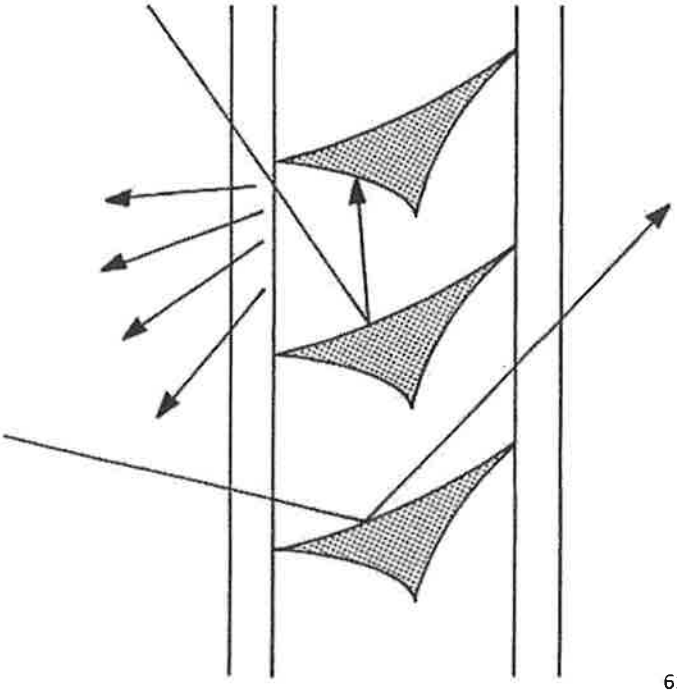




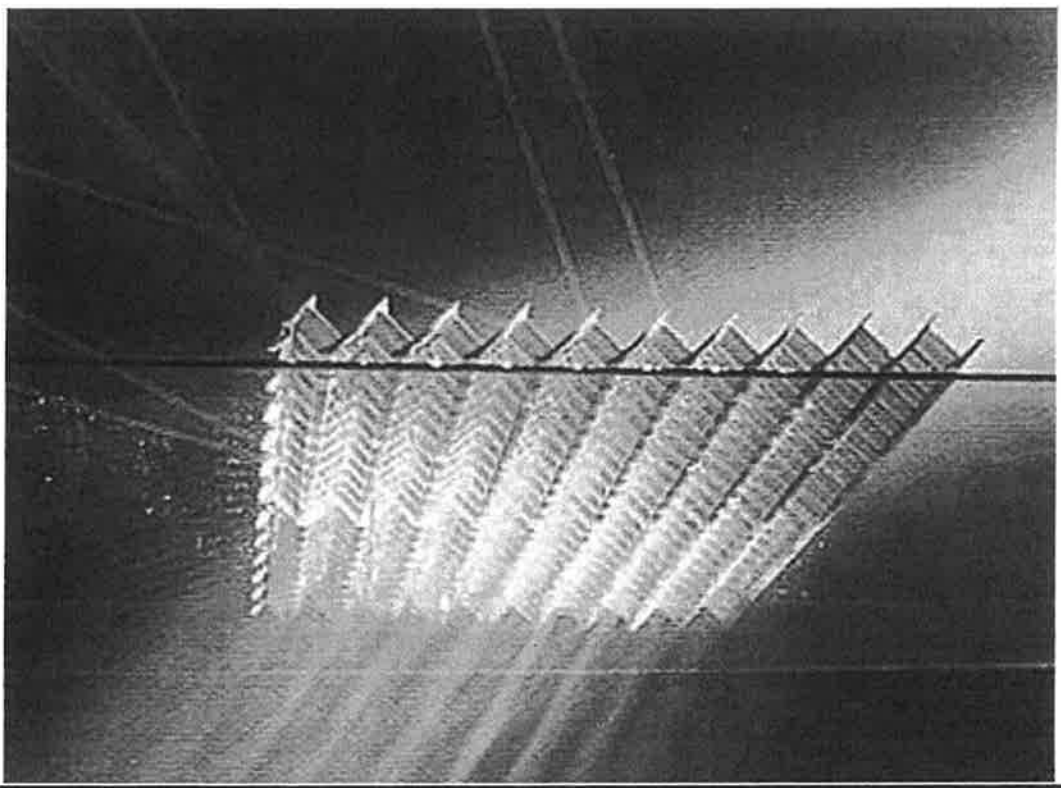
Maximising Daylight in Interior

- Built-in Prismatic Reflectors

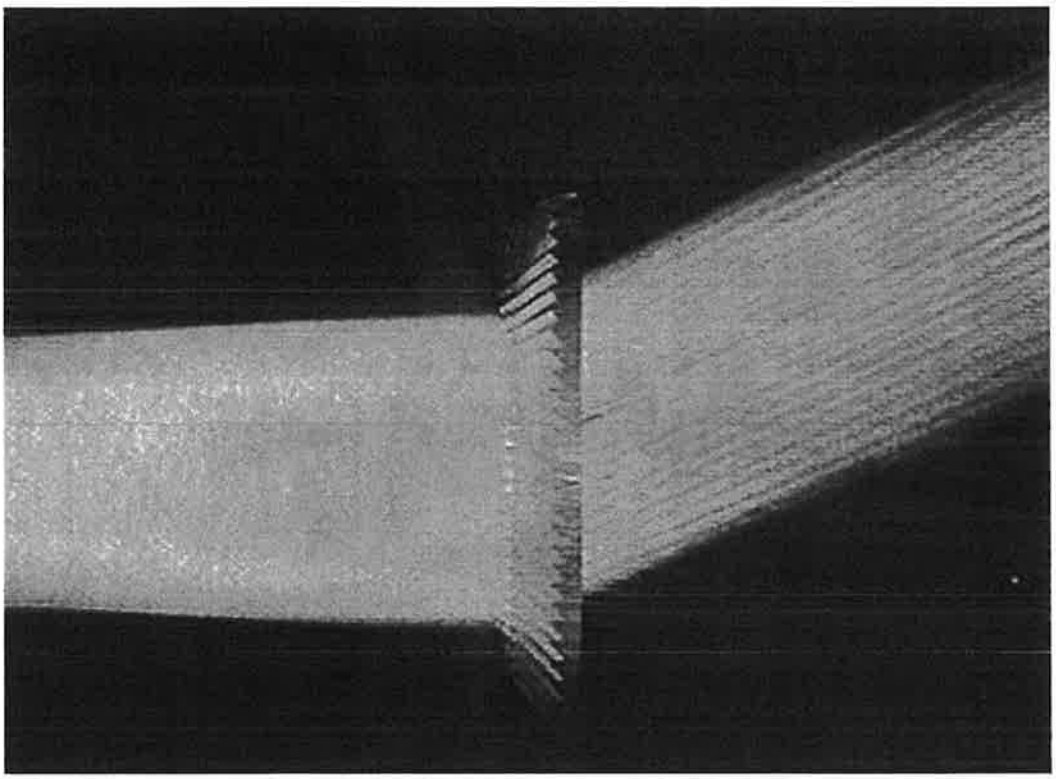




Maximising Daylight in Interior

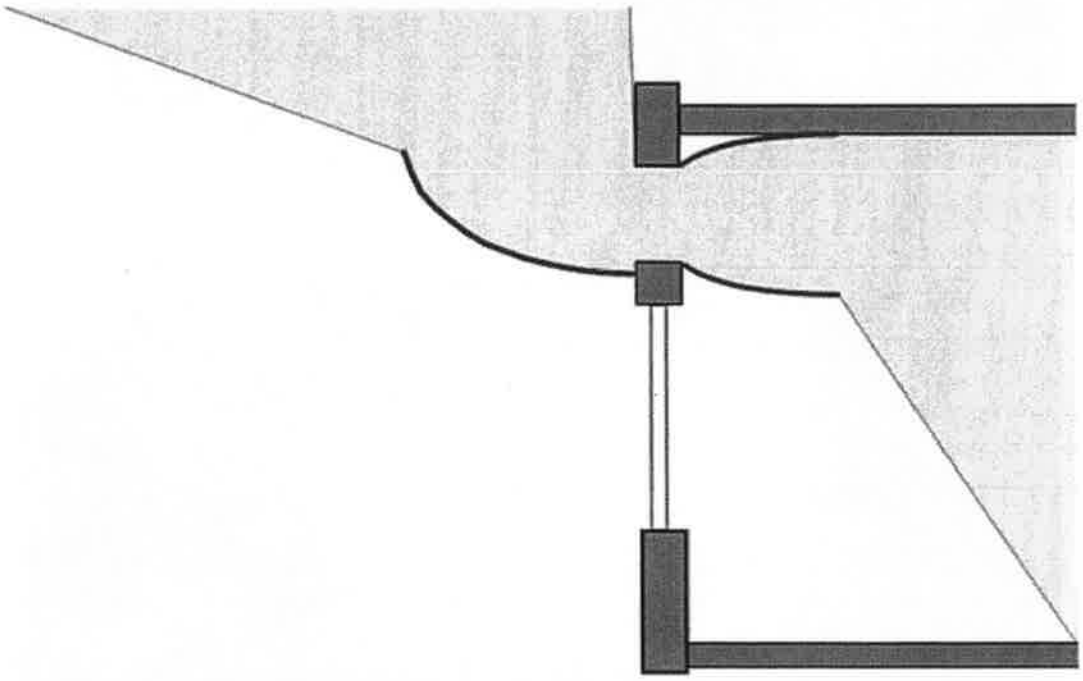


Maximising Daylight in Interior

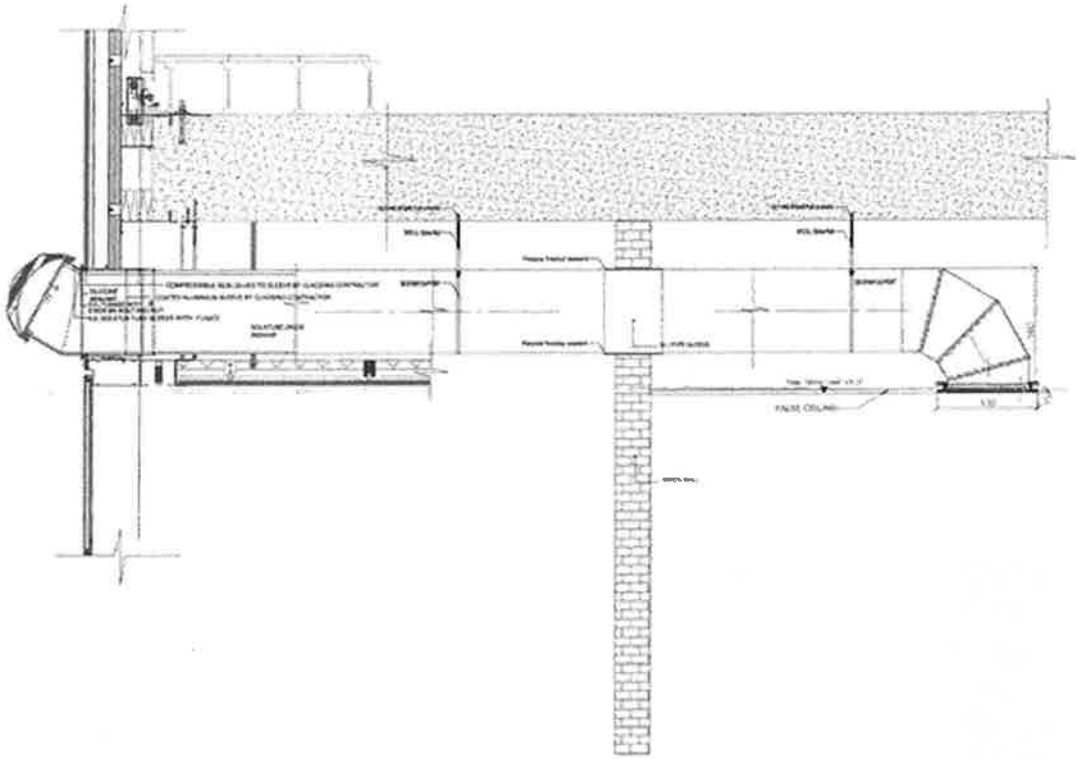


Maximising Daylight in Interior

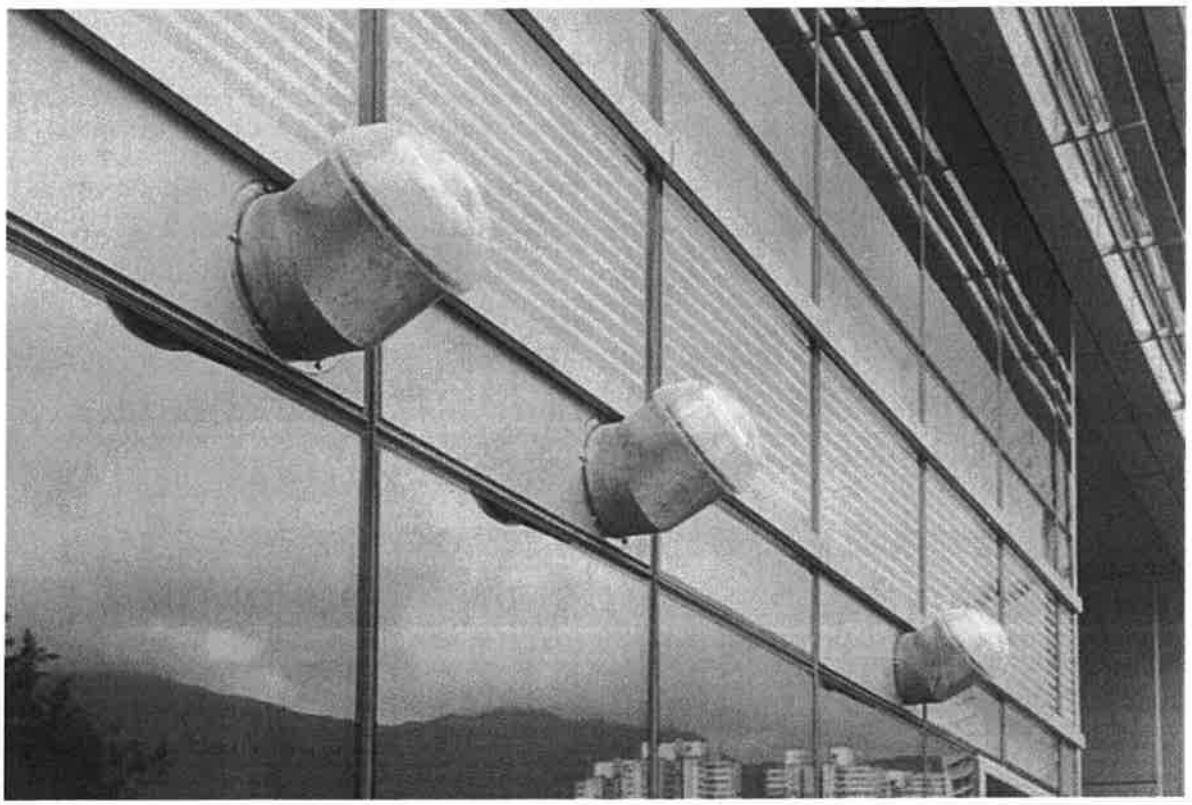
- Anidolic Light Systems



Maximising Daylight in Interior

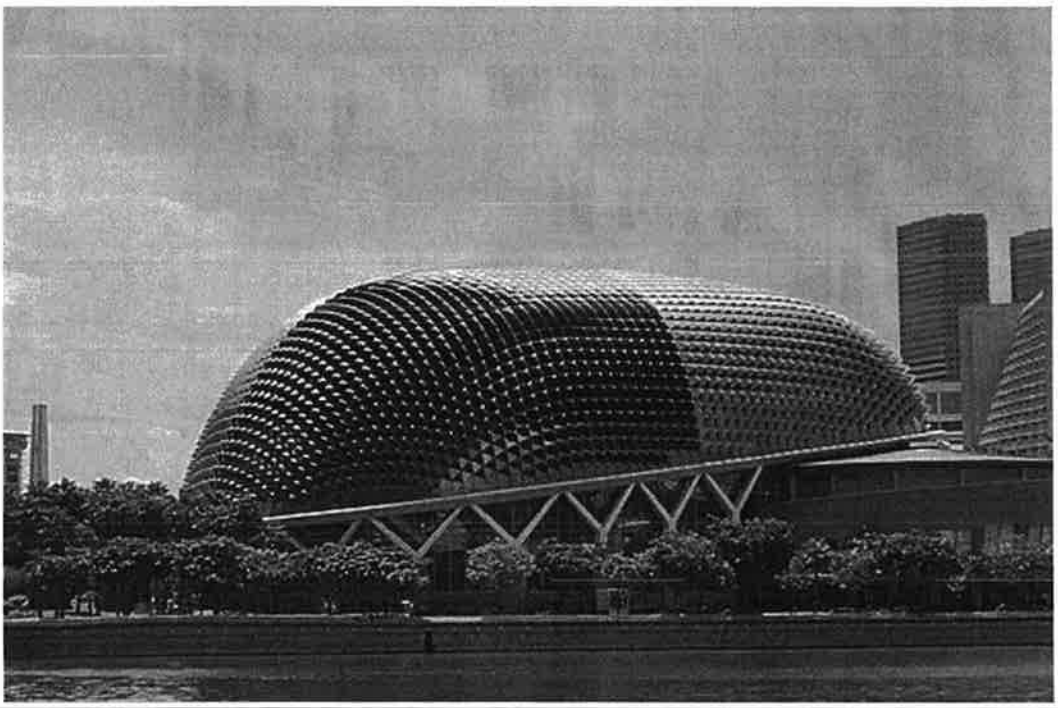


Maximising Daylight in Interior



Maximising Daylight in Interior

- Optimised sunshades



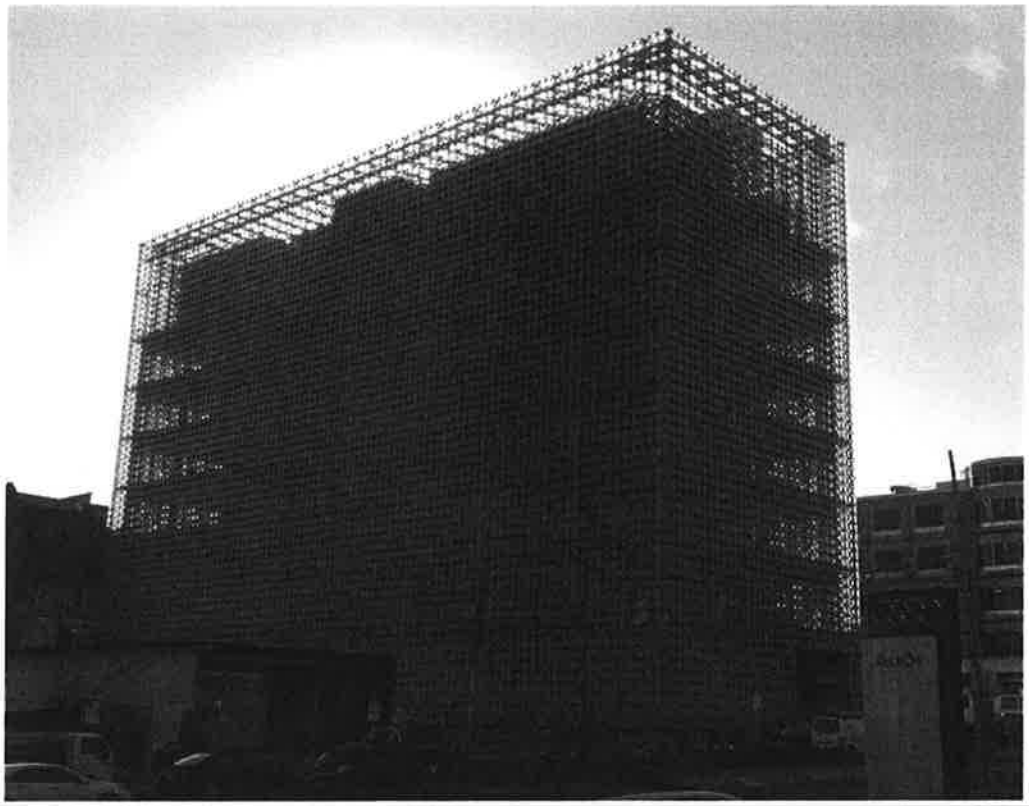
Maximising Daylight in Interior

- Optimised sunshades



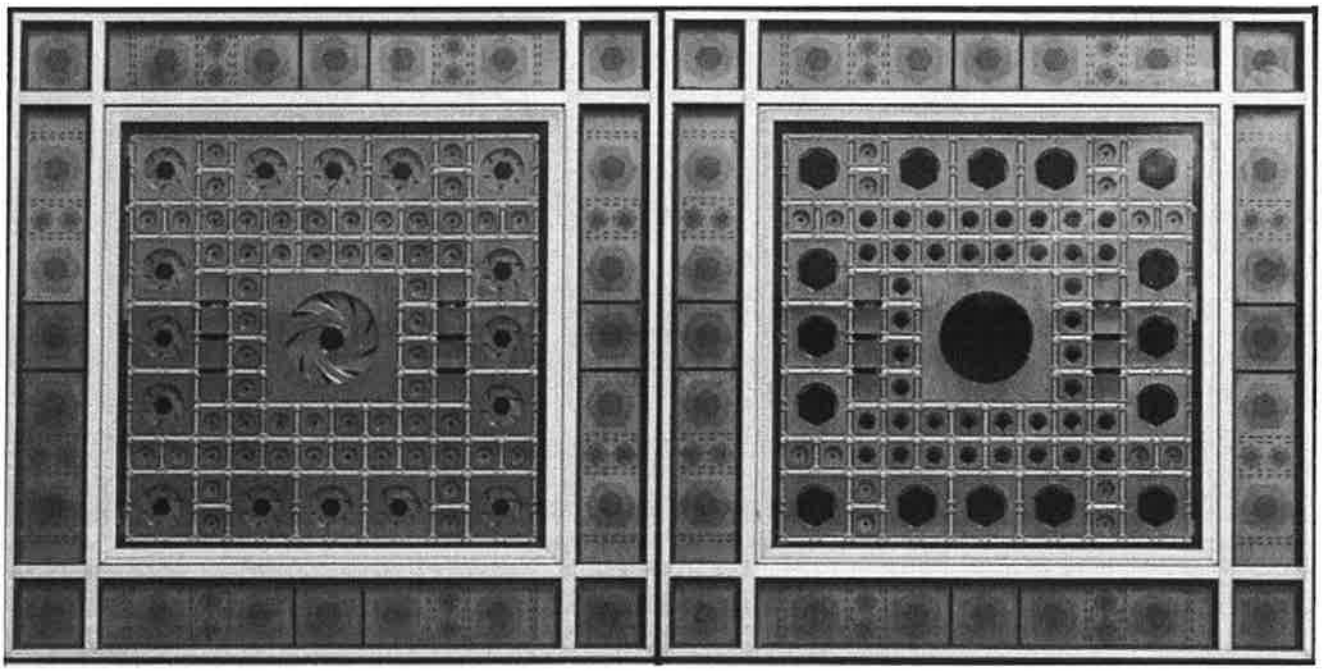


Maximising Daylight in Interior

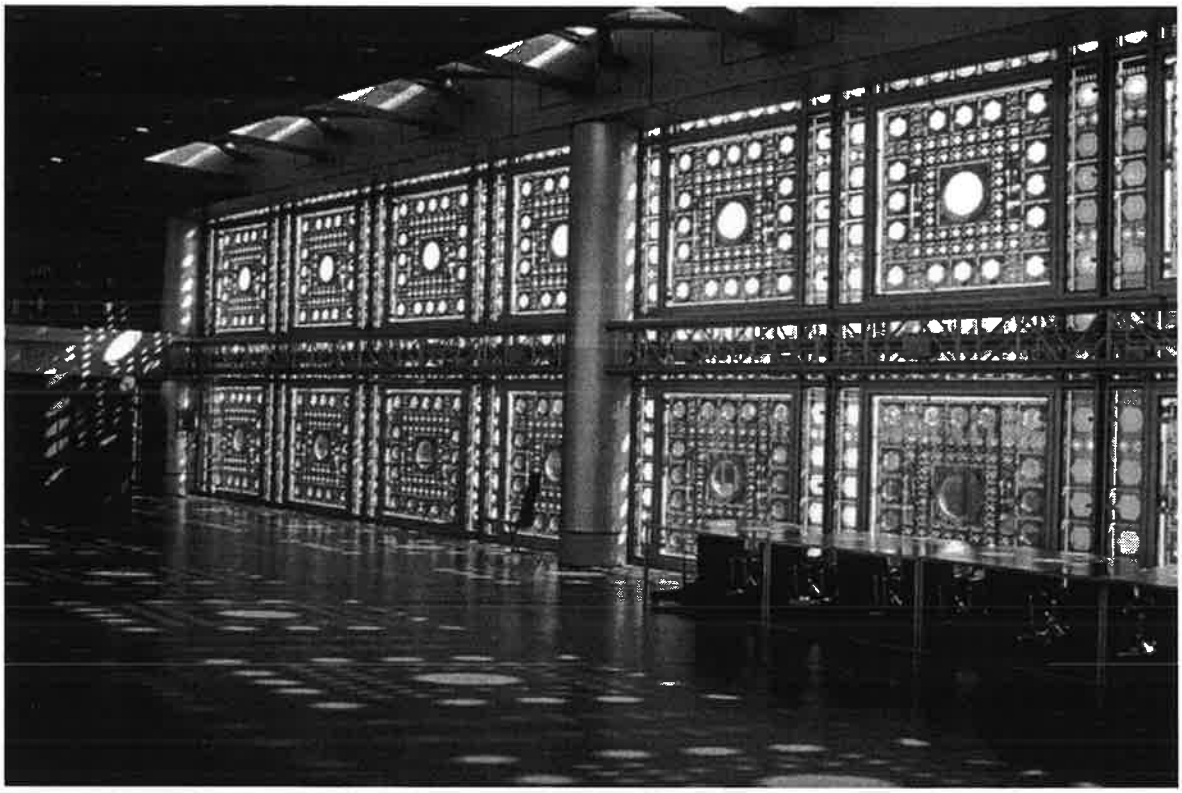


Maximising Daylight in Interior

- Dynamic sunshades



Maximising Daylight in Interior



Maximising Daylight in Interior

- Recessed Windows



Maximising Daylight in Interior

- Daylight Reflectors



Daylighting and GreenMark

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

GM RB 2016

- Section 1.01d (i) BIM

Also referred to as social BIM or collaborative BIM, integrative BIM refers to the use of a coordinated BIM modelling framework that harmonises the various disciplines' designs in a 3D environment, to facilitate the co-ordinated spatial design and reduce clashes during construction. Integrative BIM models can also be used to form the base models for various building performance simulations, the results of which can be used to further optimise the building design. Many performance plug-ins are being developed that can evaluate building energy use, façade heat gains and ETTV, lighting and daylighting analysis, as well as natural ventilation performance.

1 point for the use of BIM for environmental analysis, building performance simulation and clash detection purposes.

GM RB 2016

- Section 4.01b Contaminants

iii) Indoor Air Quality in Wet Areas

Up to 2 points can be scored with provision of adequate natural ventilation and daylighting in wet areas such as kitchens, bathrooms and toilets. Fumes from stove(s) should be adequately ventilated to exterior, instead of spreading to other occupied spaces.

Points scored based on the % of applicable areas with such provision:

- 1 point for 50% to 90% of applicable areas
- 2 points for ≥ 90% of applicable areas

GM RB 2016

- Section 4.02a Lighting

Criteria	Points
(i) Daylight in residential units	3
(ii) Potential Overlighting and daylight control measures	0.5
(iii) Daylighting in common areas	1.5
TOTAL	5

i) Daylight in residential units

Up to 3 points can be scored for encouragement of effective daylighting and potential for visual discomfort mitigation strategies in residential units; in bedrooms, living room, family room and study room.

Two methods are available for evaluating and reporting of daylight provision:

- Simplified Daylit Area Matrix
- Full simulation – refer to Simulation guideline

GM RB 2016

- Section 4.02a Lighting

<u>For Exemplary Daylit Dwelling Design</u>

Each Residential units to meet $DA_{200lux,\ 50\%}$ minimum in 75% (exclude area with overlighting) of applicable area to qualify in the count of number of residential units are daylit.

$$\frac{\text{Total Residential Units meet the daylit requirment}}{\text{Total Number of Units}} \times 100\% \times 3 \text{ points}$$

<u>For Acceptable Daylit Dwelling Design</u>

Each Residential units to meet $DA_{200lux,\ 50\%}$ minimum in 60% (exclude area with overlighting) of applicable area to qualify in the count of number of residential units are daylit.

$$\frac{\text{Total Residential Units meet the daylit requirement}}{\text{Total Number of Units}} \times 100\% \times 2 \text{ points}$$

GM RB 2016

- Section 4.02a Lighting

ii) Potential Overlighting and daylight control measures

0.5 point can be scored for usage of simple strategies to allow building occupants to adjust their environment to reduce discomfort overlighting during certain times of the day, whilst allowing effective daylight to enter functional areas.

Provision of any of the following strategies for at least 90% of residential units with overlighting:

- Blinds and Screens
- Light shelf
- Glazing treatments (Variable opacity glazing, bi-level glazing)

Note: for projects using simulation method; the strategies used for overlighting mitigation must be shown in simulation that it is effective in mitigation.

BCA ACADEMY

GM RB 2016

- Section 4.02a Lighting

iii) Daylighting in common areas

Up to 1.5 points can be scored by prorating the number of daylit transient common spaces with daylighting controls against the total number of applicable spaces. Applicable areas include i) staircases, ii) corridors and lift lobbies and iii) carparks.

GM RB 2016

- Section 4.02c Wellbeing

i) Biophilic Design

Up to 1 point can be scored for including elements of nature in comfortable spaces to nurture the human-nature relationship is important for the health and happiness of the building users. We see the value of greenery in improving our quality of life. This indicator aims to facilitate even more accessible greenery to further enhance the building occupant and user's environment, and overall wellbeing.

0.5 point shall be awarded for the provision of at least 3 elements of nature in common areas.

a) Daylighting and natural ventilation
b) Water features
c) Extensive greenery (eg. high GPR, roof gardens, green wall)
d) Fauna, beyond insect species (e.g. birds, fish, amphibians, native wildlife)
e) Natural landscape and ecosystems (e.g. eco-pond, natural planting with matured trees)

GM NRB 2015

- Section 4.02a Lighting

(i) Effective Daylighting and Potential for Visual Discomfort

Effective daylighting for common areas – 2 points

Up to 2 points can be scored by prorating the number of daylit transient common spaces with daylighting controls against the total number of applicable spaces. The applicable areas are toilets, staircases, corridors, lift lobbies, atriums and carparks.

GM NRB 2015

▪ Section 4.02a Lighting

Effective daylighting for occupied spaces – 4 points

Method	Percentage of occupied spaces with access to effective daylighting (3 points)	Effective Mitigation of Overlit Areas (1 point)
Pre-Simulated Daylight Availability Tables: Simplified method for standard designs to guide concept stage design in identifying design strategies for optimised daylight design. Daylight Simulation: Performance-based method for non-standard/ complex designs.	Points can be scored as follows based on the percentage of total occupied areas that can achieve the specific Daylight Autonomy (DA) requirement of $DA_{N\ by50\%}$ (without overlighting), as outlined in the *Green Mark NRB: 2015 Technical Guide and Requirements Annex B: Effective Daylighting Simulation and Pre-Simulated Daylight Availability Tables Methodology and Requirements.* Effectively daylit areas shall be integrated with automated lighting controls.	1 point can be scored for the adoption of suitable mitigation strategies for overlit spaces. 1 point can be scored where mitigation measures to effectively address overlighting are included into the simulation model in accordance with *Annex B.*

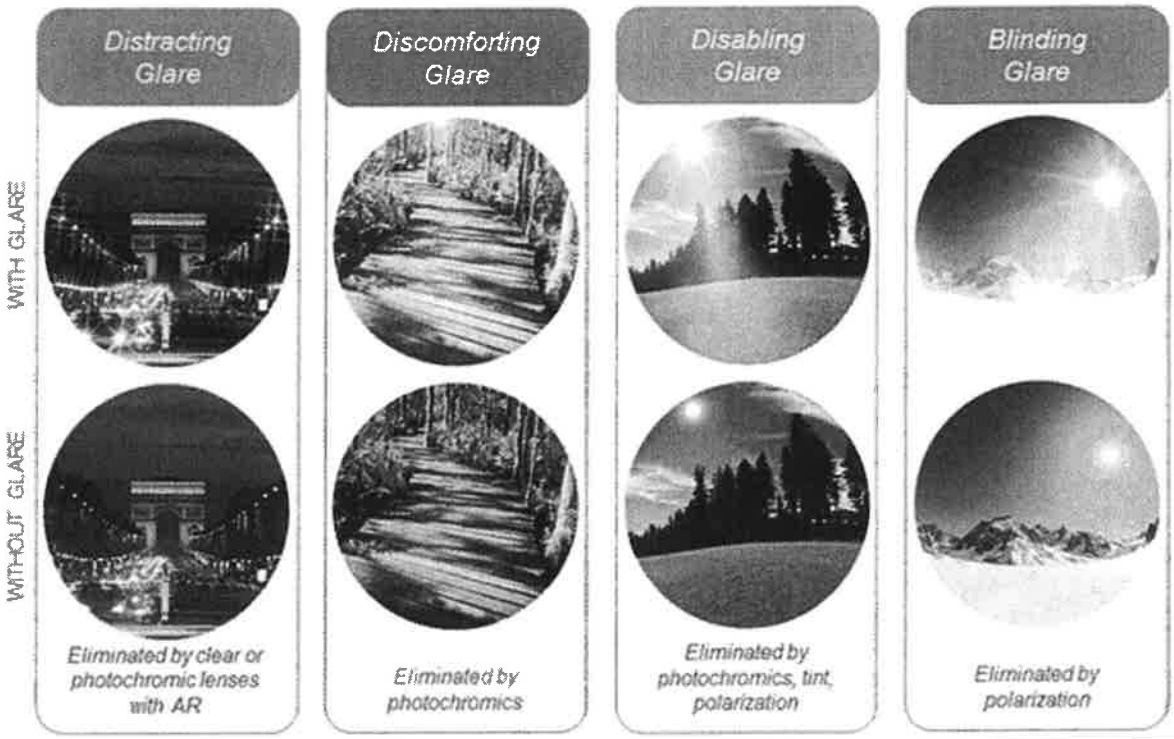
Percentage	Points
15 to < 35 %	0.5
35 to < 55 %	1
55 to < 75 %	2
≥75%	3

Glare Definitions

The Education and Research arm of the Building and Construction Authority

Definitions

Four types of glare



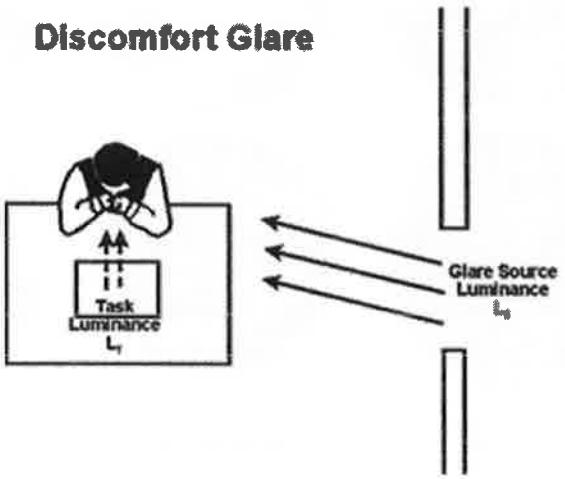
BCA ACADEMY

Definitions

- Glare: The glass portion of a façade transmits abundant daylight to the interior. Therefore, the glass surface may have much higher luminance than the surrounding walls and spandrel portions of the façade.
- If there is high contrast between two or more visual scenes, glare will occur.

Definitions

- Glare above a certain level (luminance is greater than the eye can adapt to) will cause discomfort for the observers ("discomfort glare"). It can also become noticeable after a period of time.



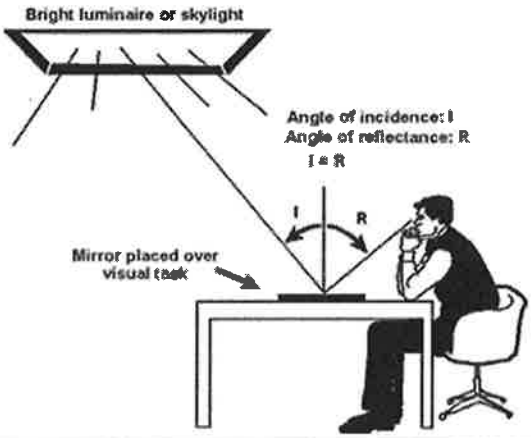
Definitions



Definitions

- If contrast level / glare is even higher, observers may lose the ability to see surrounding objects ("disability glare"). The effect is usually an immediate one, and can even be painful.

Disability Glare



Definitions



Definitions

- Generally accepted metric for disability glare is L_{seq}, the equivalent veiling luminance
- L_{seq} provides a measure of the luminance that is equivalent to the veil of light a person experiences due to scattered light captured through the eye
- Disability glare reduces the contrast of the object your are trying to see

Definitions

$$C = \frac{\left(L_{Background} + L_{seq}\right) - \left(L_{Object} + L_{seq}\right)}{L_{Background} + L_{seq}}$$

$$C = \frac{L_{Background} + L_{Object}}{L_{Background} + L_{seq}}$$

Definitions

- Different computations exist for assessing L_{seq}
- Basic formula are all similar

$$L_{SEQ} = \frac{k \cdot E_{gl}}{\theta^n}$$

- k is a multiplier that is age-dependent
- E_{gl} is the illuminance o f the glare source
- θ is the angle of the glare source from the line of sight

Definitions

- Several metrics exist for glare assessment:
- UGR – Unified Glare Rating
- CGI – CIE Glare Index
- DGI – Daylight Glare Index
- VCP – Visual Comfort Probability
- CBE – Cumulative Brightness Evaluation
- Glare Control Mark

Definitions

- Only DGI was developed to consider the presence of large glare sources, such as a bright sky seen through a window; however, it is not considered to be reliable when direct sunlight or specular reflections are present in the field of view
- CGI and UGR, developed by the CIE, were developed from existing glare studies at the time and did not include direct human studies in their derivation

Definitions

- VCP is only valid for electric light sources of typical-size that are ceiling mounted and have uniform luminance
- DGI, CGI and UGR evaluate in a range where greater than 28-31 = intolerable glare, and less 13-18 = glare is not perceptible
- VCP evaluates in a numerical range from 0 to 100,specifying a percentage of people who would feel comfortable under similar lighting circumstances (mostly used in North America)

Below 19 ✓ m

Definitions

- Glare is typically expressed as the ratio of the size, location and luminance of glare sources in a field of vision when compared to the average luminance not inclusive of the glare source

$$Glare = \sum_{i=1}^{n} \frac{L_{s,i}^{exp}\,\omega_{s,i}}{L_b^{exp}\,P_i^{exp}}$$

Definitions

- DGI correlates the source luminance, size and position in the field of view against background luminance and a small percentage of the source luminance which compensates for additional eye adjustment to the visible luminance

$$DGI_N = 8 \times \log_{10} 0.25 \sum_{i=1}^{n} \frac{L_{exterior,i}^2 \Omega_{s,i}}{L_{adapt} + 0.07\left(\sum_{i=1}^{n} \omega_{s,i} L_{window,i}^2\right)^{0.5}}$$

L_{adapt}	adaptation luminance (cd/m^2)
$L_{exterior}$	average exterior luminance (cd/m^2)
L_{window}	average window luminance (cd/m^2)
ω	solid angle of the glare source (sr)
Ω	solid angle of a viewing hemisphere subtended by glare sources (sr)

Definitions

- CIE Glare Index was an attempt bto develop a formula that took into account all peer-reviewed glare research in order to be used as a standard glare index adopted by the CIE

$$CGI = C_1 \times \log_{10} C_2 \frac{\left(1 + \frac{E_d}{500}\right)}{E_d + E_i} \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{P^2}$$

- Values lower than 13 are imperceptible, and greater than 28 are intolerable

Definitions

- UGR is an amalgamation of the European Glare Index and the Luminance Limiting Curve methods

$$UGR = 8 \cdot \log\left(\frac{0.25}{L_{Background}}\right)\sum_{n}\left(\frac{L^2\omega}{p^2}\right)$$

where

L = *Luminance of the luminous area*

ω = *size of the luminous area*

p = *Guth position index*

$L_{Background}$ = *Background Luminance*

n = *number of luminaires*

Definitions

- Computational evaluation produces very similar data for the DGI, CGI and UGR
- Only valid conditions where direct sunlight will not enter the space and where the window can be considered as a medium-sized source of contrast-based glare
- CGI is the most robust of the three metrics as it consistently predicts a higher likelihood of discomfort, thereby representing a worst-case comfort scenario.

BCA ACADEMY

Definitions

- CGI is the most robust of the three metrics as it consistently predicts a higher likelihood of discomfort, thereby representing a worst-case comfort scenario. As DGI requires geometrically complex information and has had no conclusive user validation studies performed, its use is not recommended as of now

Minimise Glare and Heat from Daylight

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

BCA ACADEMY

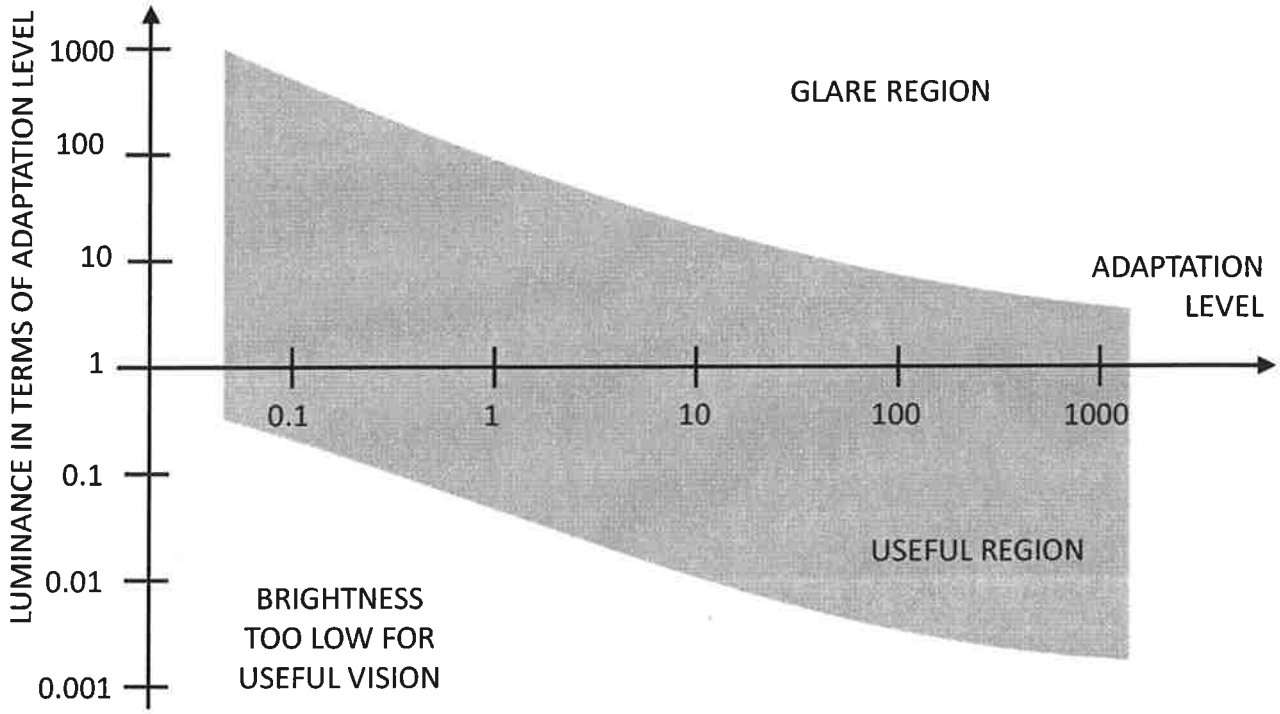
Minimise Glare and Heat from Daylight

- Limit luminance of the glare source
- Screen light source
- Increase luminance of the background to the source
- Adjust the size of the glare source
- Position of the source from the observer viewing direction (eye direction)
- Effect of internal finishes on glare

Minimise Glare and Heat from Daylight

- Useful Daylight Index: percentage of the occupied times in a year when daylight levels are 'useful' for the occupant, i.e. neither too dark (<100 lux) nor too bright (>2000 lux).

Minimise Glare and Heat from Daylight

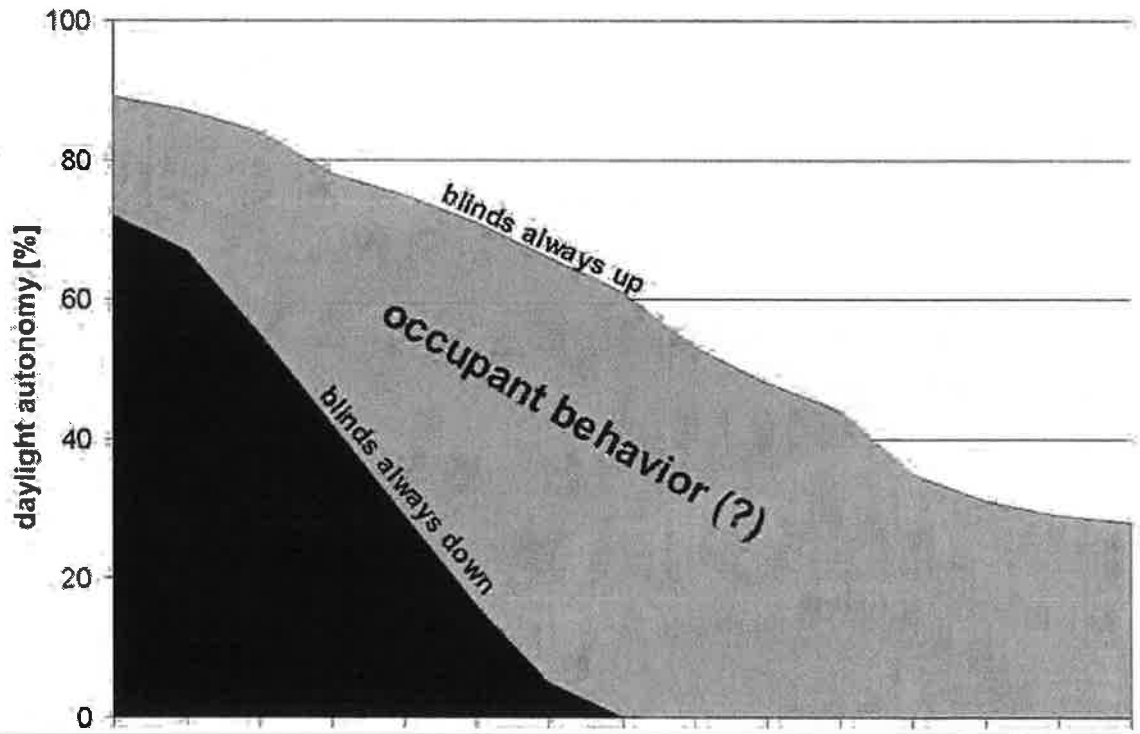


Minimise Glare and Heat from Daylight

- Daylight Autonomy: percentage of the occupied times in a year when a minimum illuminance threshold is met by daylight alone

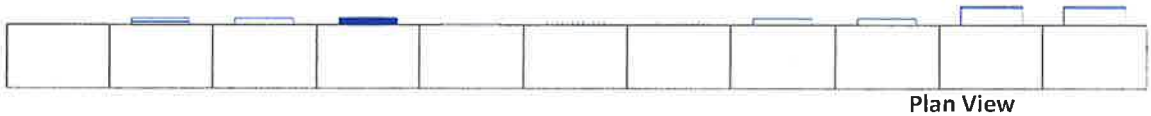
BCA ACADEMY

Minimise Glare and Heat from Daylight



Minimise Glare and Heat from Daylight

1	2	3	4	5	6	7	8	9	10	11
Non-shading	Double Horizontal	Single Horizontal	Trellis	Louvres	Fins	Slanted Fins	Slanted Horizontal	Horizontal & Vertical	Balcony (top)	Balcony (bottom, no shading)



Plan View



Elevation View



Perspective View

BCA ACADEMY

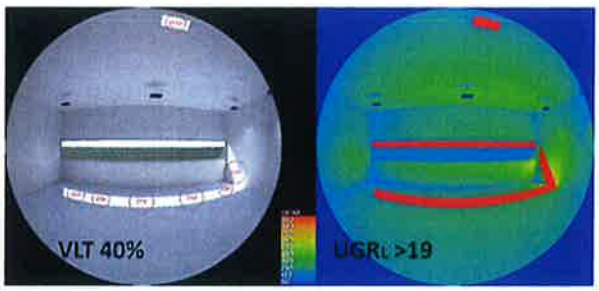
Minimise Glare and Heat from Daylight

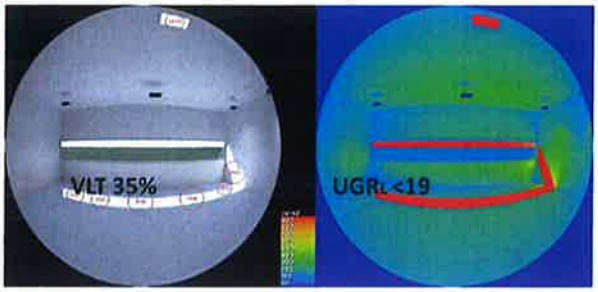


SS 531 : Part 1 : 2006

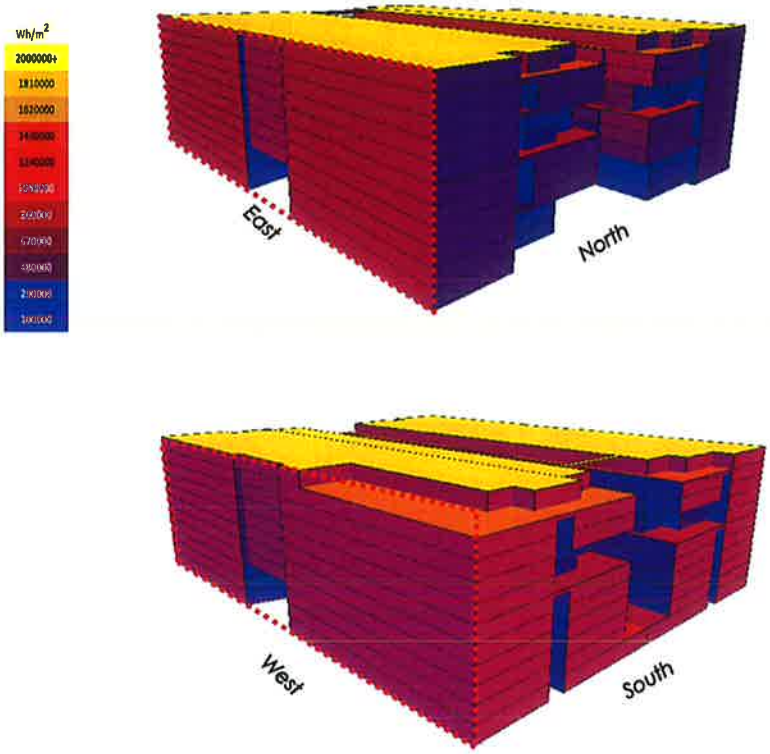
Type of interior, task or activity	$\overline{E_m}$ lux	UGR_L	R_a
22. Offices			
Writing, typing, reading, data processing	500	19	80

UGR_L : The maximum allowable design Unified Glare Rating value for the lighting installation.





Minimise Glare and Heat from Daylight



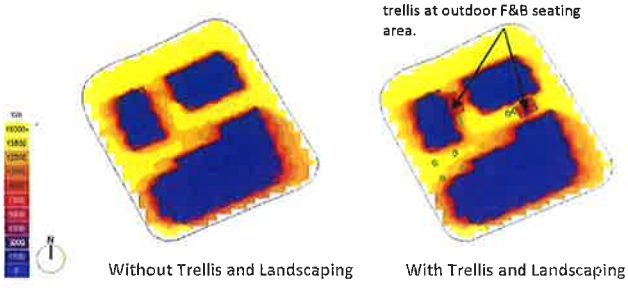
Minimise Glare and Heat from Daylight

Identify façade with highest solar radiation

Passive Design	Active Design
▫ Building Orientation	▫ Building Cooling System
▫ Building Massing	▫ Blinds
▫ Shading Devices	
▫ Window and Wall Ratio	
▫ Landscape	
▫ Glass Performance (U-value, SC, VLT)	

Incident Solar Radiation Analysis

Significant reduction in solar radiation with addition of trellis at outdoor F&B seating area.

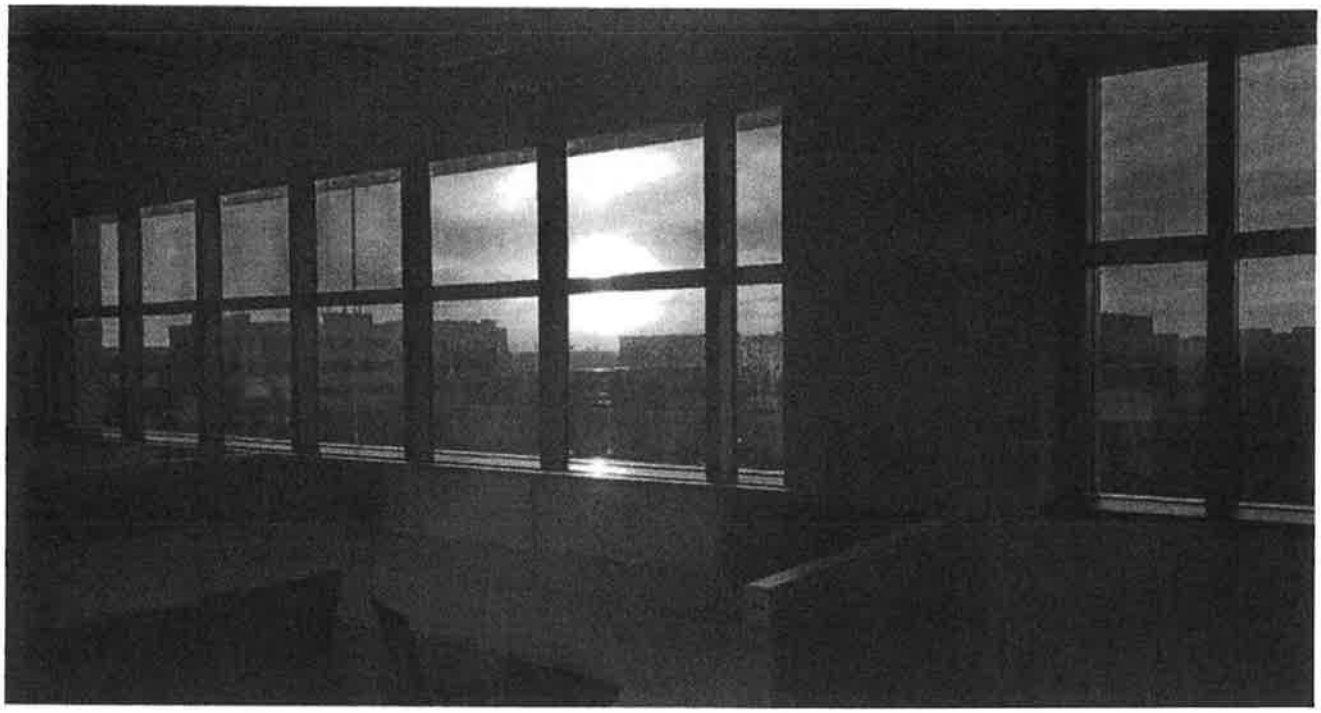


Without Trellis and Landscaping

With Trellis and Landscaping

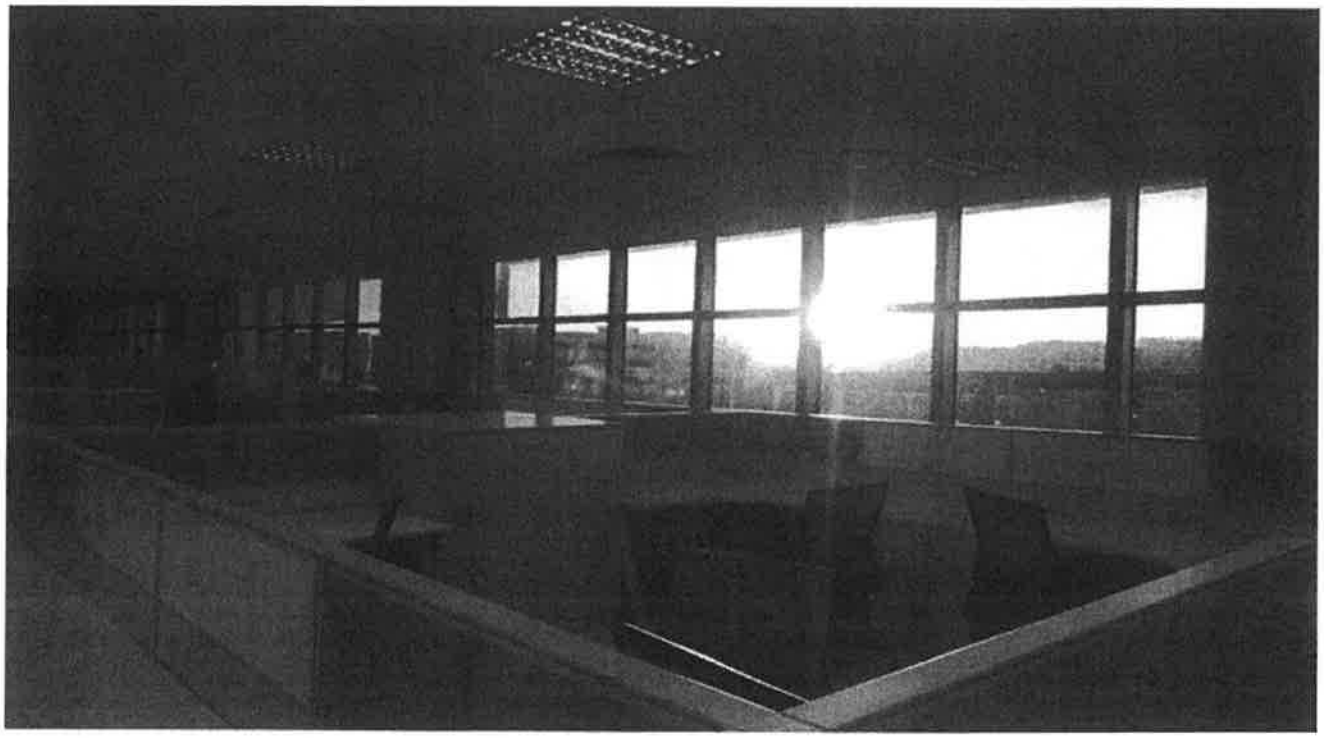
Summer solstice (Jun 22nd)

Minimise Glare and Heat from Daylight



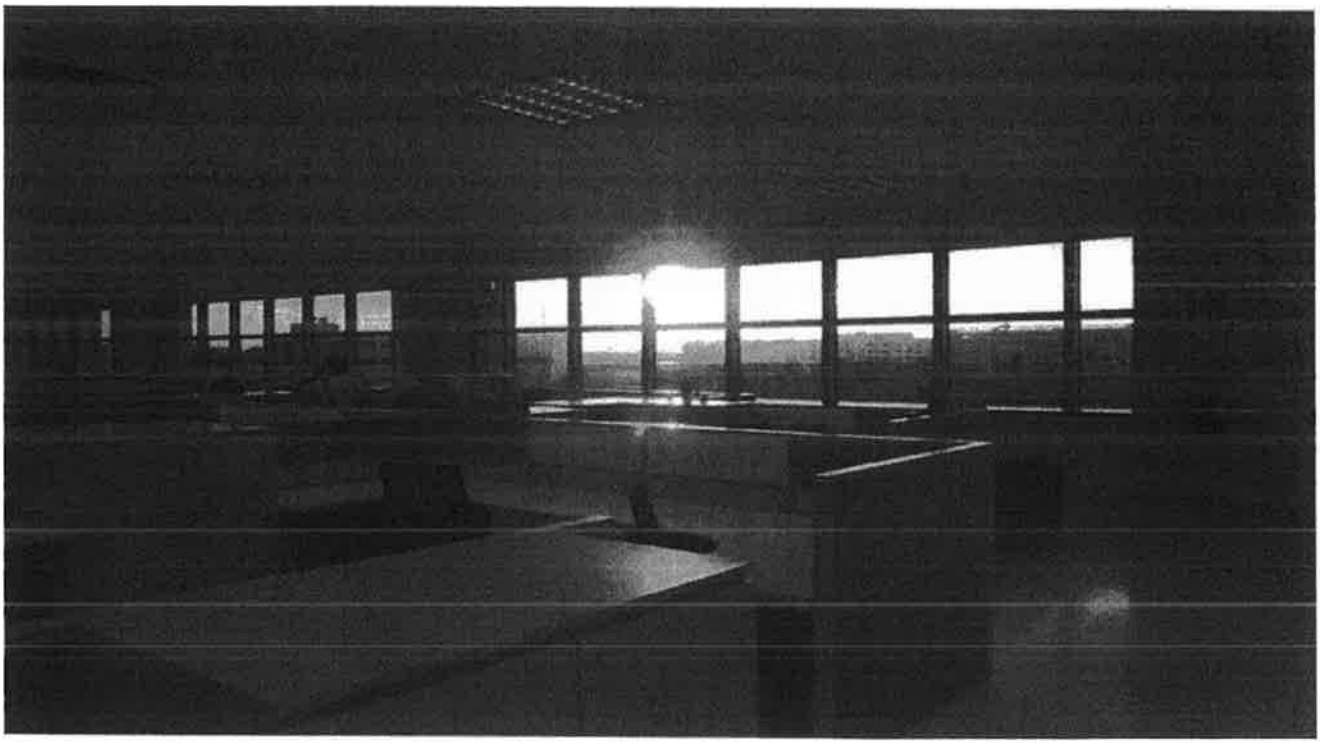
© Building and Construction Authority

Minimise Glare and Heat from Daylight



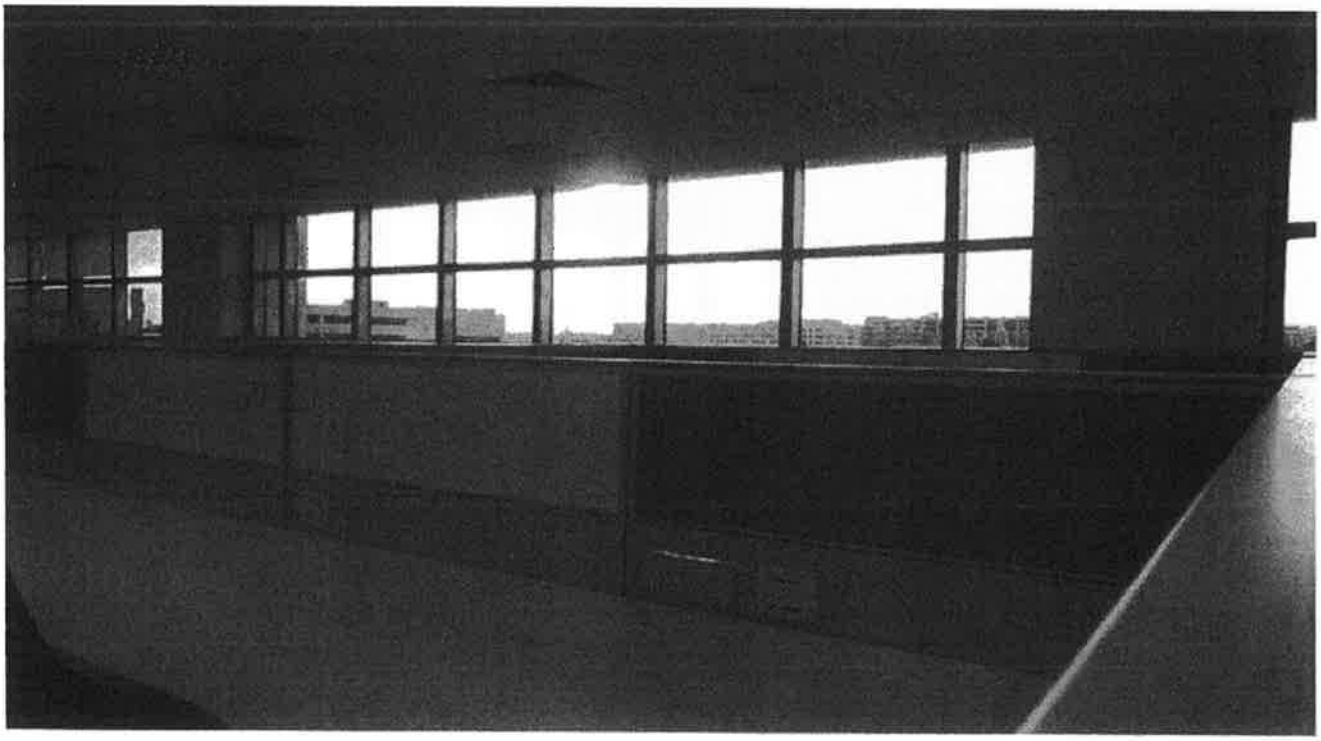
© Building and Construction Authority

Minimise Glare and Heat from Daylight



BCA ACADEMY

Minimise Glare and Heat from Daylight



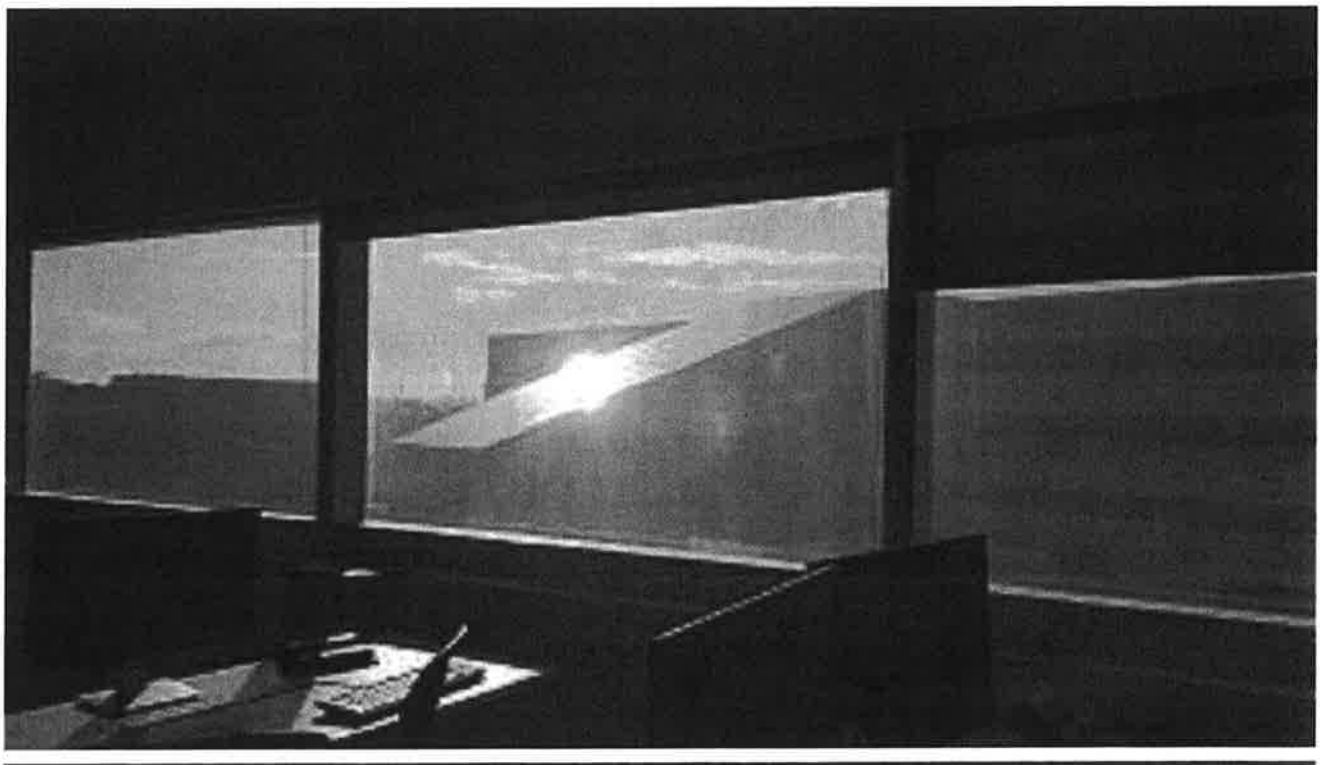
BCA ACADEMY

Minimise Glare and Heat from Daylight



BCA ACADEMY

Minimise Glare and Heat from Daylight



The Educational Research arm of the Building and Construction Authority

Minimise Glare and Heat from Daylight







Minimise Glare and Heat from Daylight

Zone	Region	DGI	UGR
Discomfort zone	intolerable	>28	>28
	just intolerable	28	28
	uncomfortable	26	25
	just uncomfortable	24	22
Comfort zone	acceptable	22	19
	just acceptable	20	16
	noticeable	18	13
	just perceptible	16	10

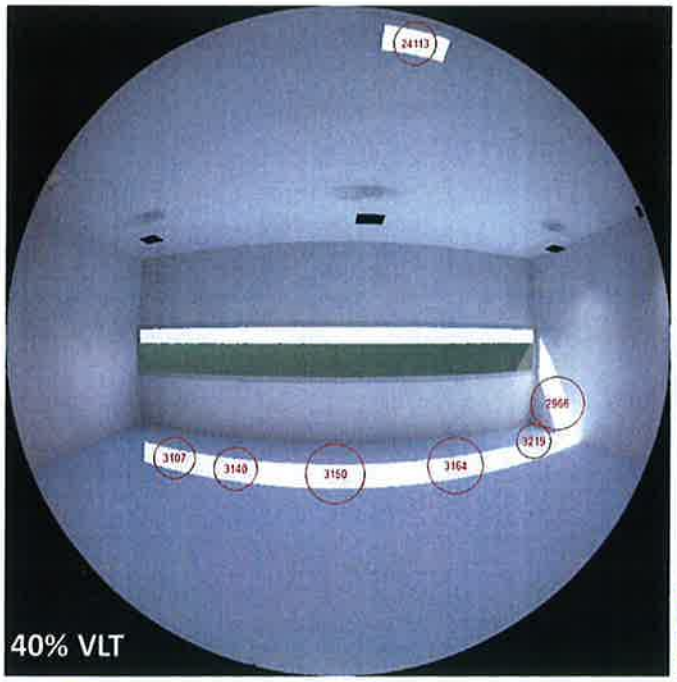
Glare regions and their related glare index

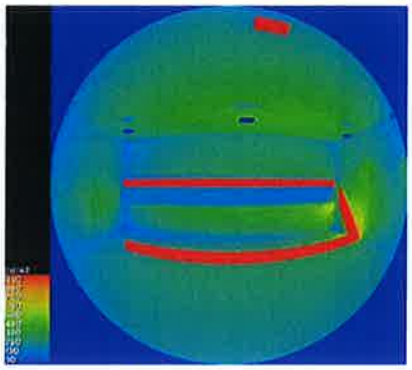
SS 531 : Part 1 : 2006

Type of interior, task or activity	$\overline{E_m}$ lux	UGR_L	R_a
22. Offices			
Writing, typing, reading, data processing	500	19	80

UGR_L: The maximum allowable design UGR value for the lighting installation

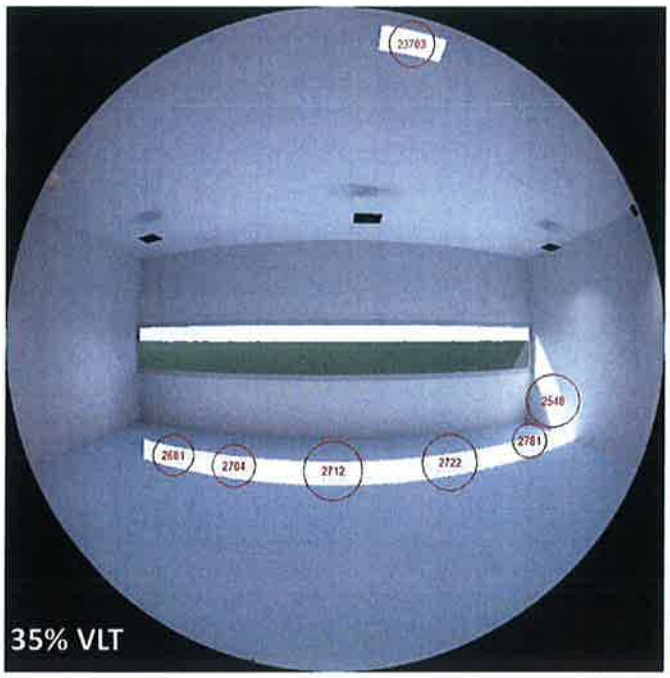
Minimise Glare and Heat from Daylight

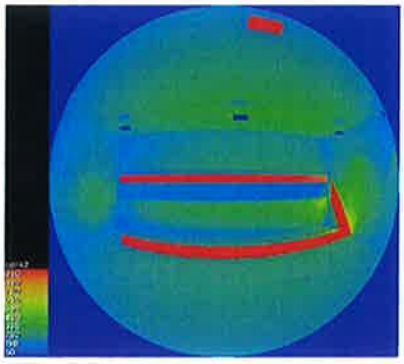




	Glare Threshold = 2208.91 cd/m² resolution = 250 Dec22_1600_ss.sky												
Angle	60	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
UGR	13.70	14.99	15.99	16.71	17.37	17.91	18.30	18.75	19.04	19.32	19.26	19.08	18.50

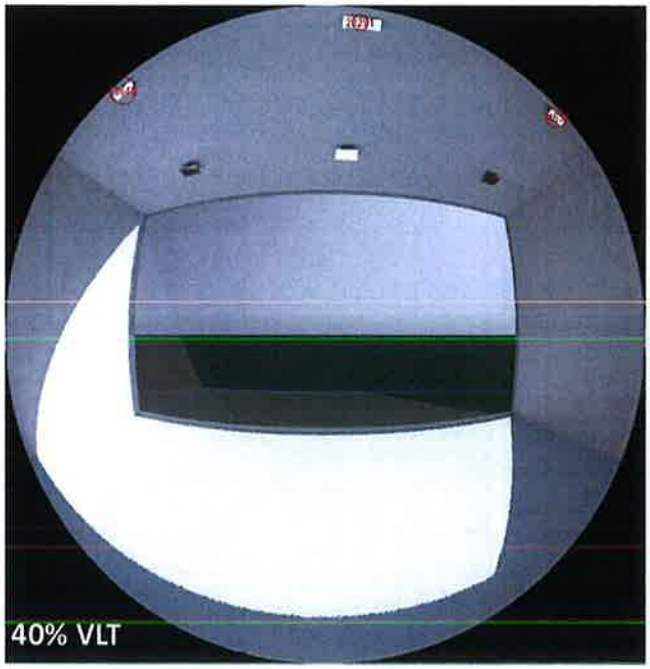
Minimise Glare and Heat from Daylight

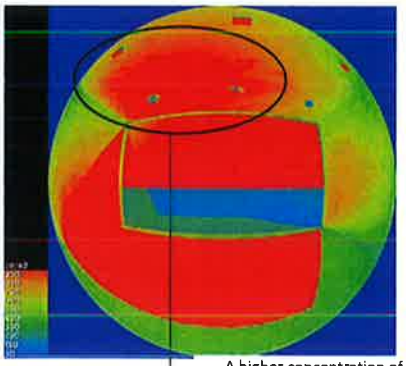




	Glare Threshold = 2005.13 cd/m² resolution = 250 Dec22_1600_ss.sky												
Angle	60	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
UGR	13.10	14.41	15.45	16.21	16.90	17.46	17.88	18.33	18.62	18.90	18.83	18.65	18.09

Minimise Glare and Heat from Daylight

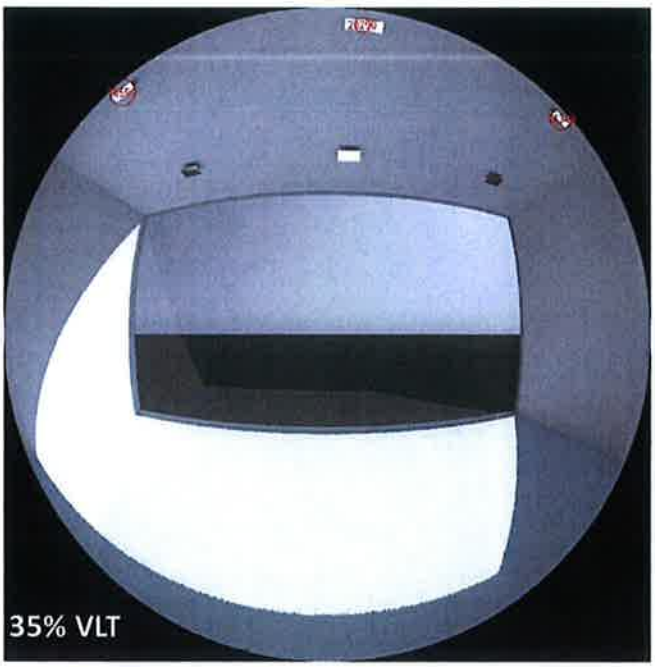


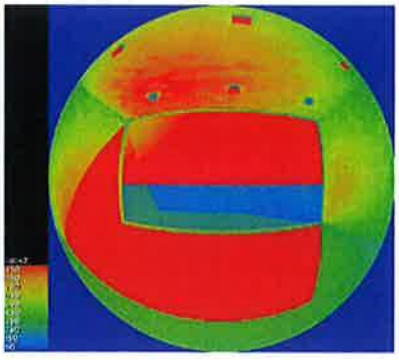


A higher concentration of light on the ceiling which resulting the uniformity of the lux level in the room. Hence, resulting in a lower UGR value compare to the 35% VLT model.

	Glare Threshold = 7962.51 cd/m²	resolution = 250	Dec22_1000_ss.sky										
Angle	60	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
UGR	6.87	6.40	5.58	4.50	3.30	2.40	1.98	2.31	3.26	4.45	5.75	6.82	7.51

Minimise Glare and Heat from Daylight



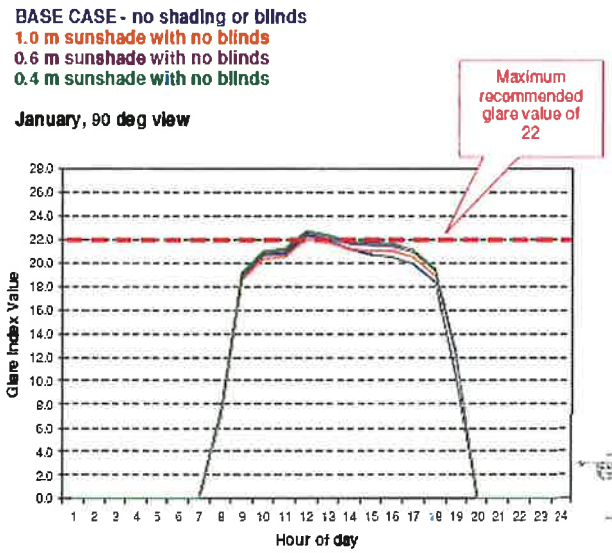


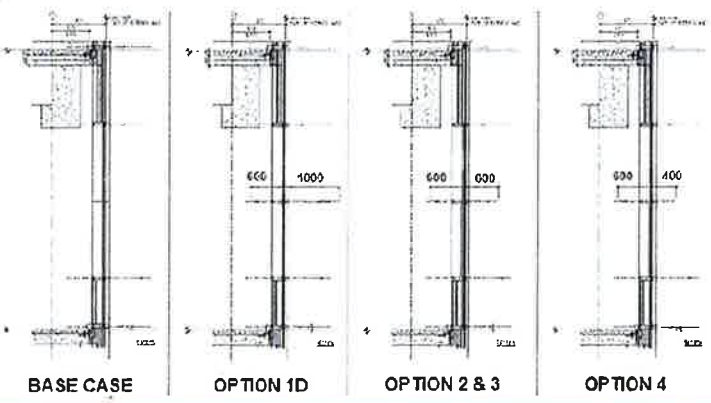
	Glare Threshold = 6943.34 cd/m²	resolution = 250	Dec22_1000_ss.sky										
Angle	60	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
UGR	7.40	6.93	6.11	5.02	3.82	2.91	2.48	2.80	3.76	4.96	6.28	7.38	8.10

Minimise Glare and Heat from Daylight

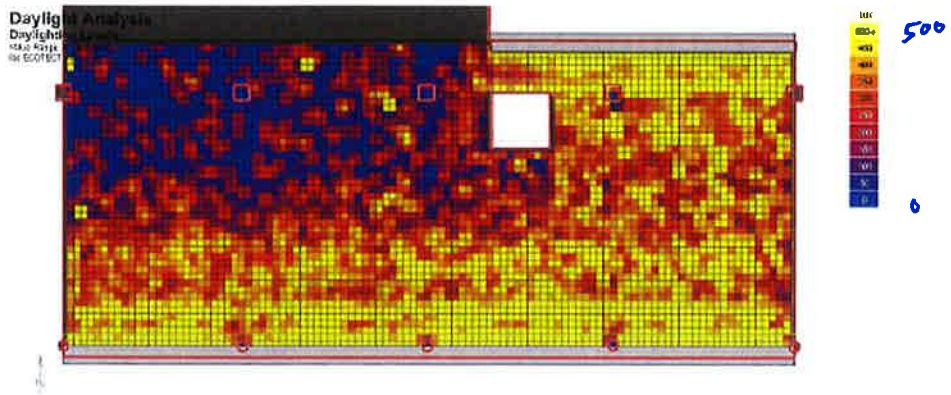
- Importance of floor finishes
- Importance of wall finishes
- Balancing natural daylight with artificial lighting

Optimising Shading Devices





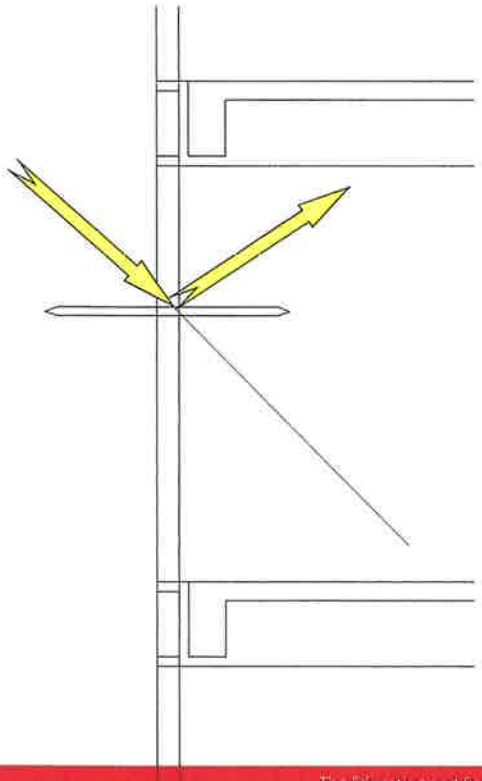
Optimising Shading Devices



Daylight levels measured at desk height - 800mm above finished floor level.
Blinds are considered to be fully open.

Illuminance range (Lux)	Percentage of floor area above range
0 - 50	100.0
50 - 100	84.3
100 - 150	76.0
150 - 200	65.7
200 - 250	59.2
250 - 300	52.4
300 - 350	46.7
350 - 400	42.9
400 - 450	39.7
450 - 500	34.6

Maximise Daylight Penetration



1. Light shelves
2. Lower VLT below, higher above
3. Shape and colour of ceiling also matter

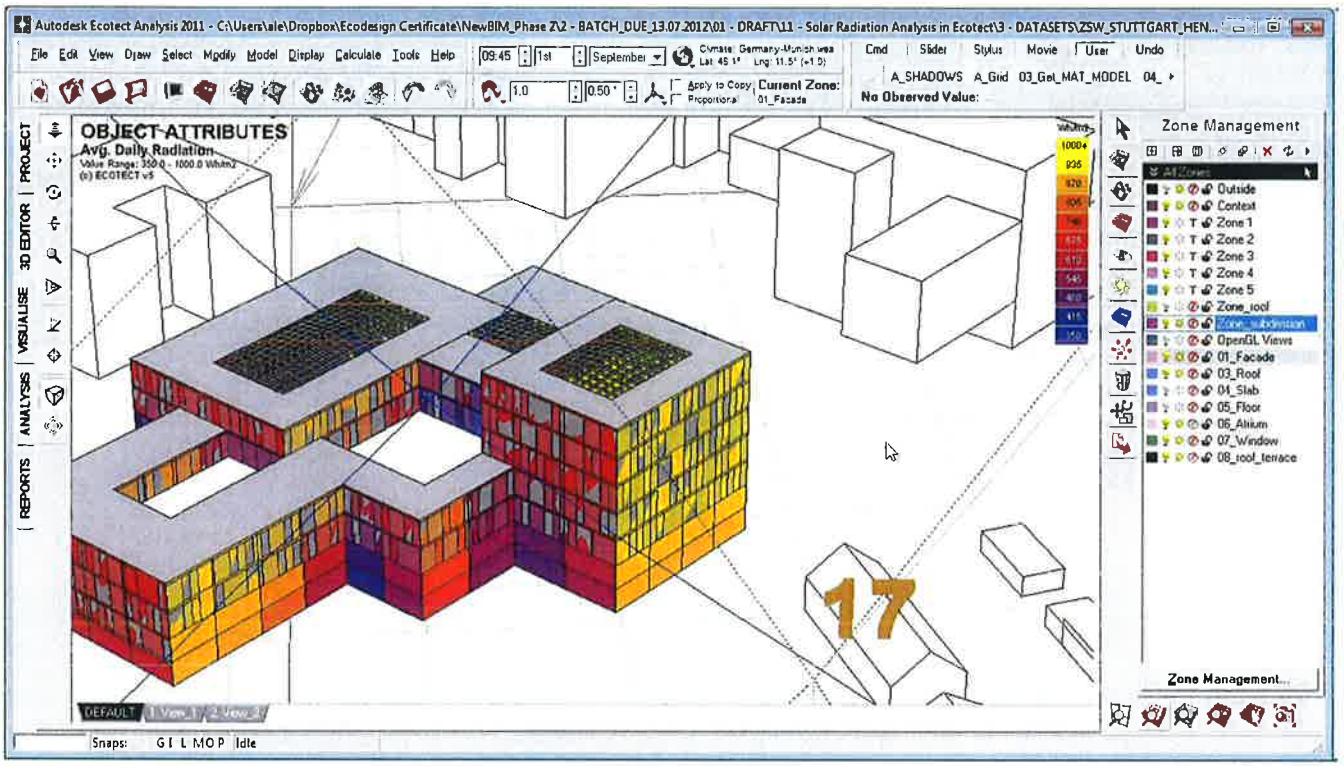
Simulation Software

BCA ACADEMY

Simulation Software

- Ecotect Analysis - Discontinued
- Popular, easy and quick to use
- Results are sometimes questionable
- Best to consider other options

Simulation Software



BCA ACADEMY

Simulation Software

- Radiance – Suite of programs for the analysis and visualisation of lighting in design
- Calculated values include spectral radiance (i.e. luminance + color), irradiance (illuminance + color) and glare indices
- Free software developed by LBNL

The Education and Research arm of the Building and Construction Authority

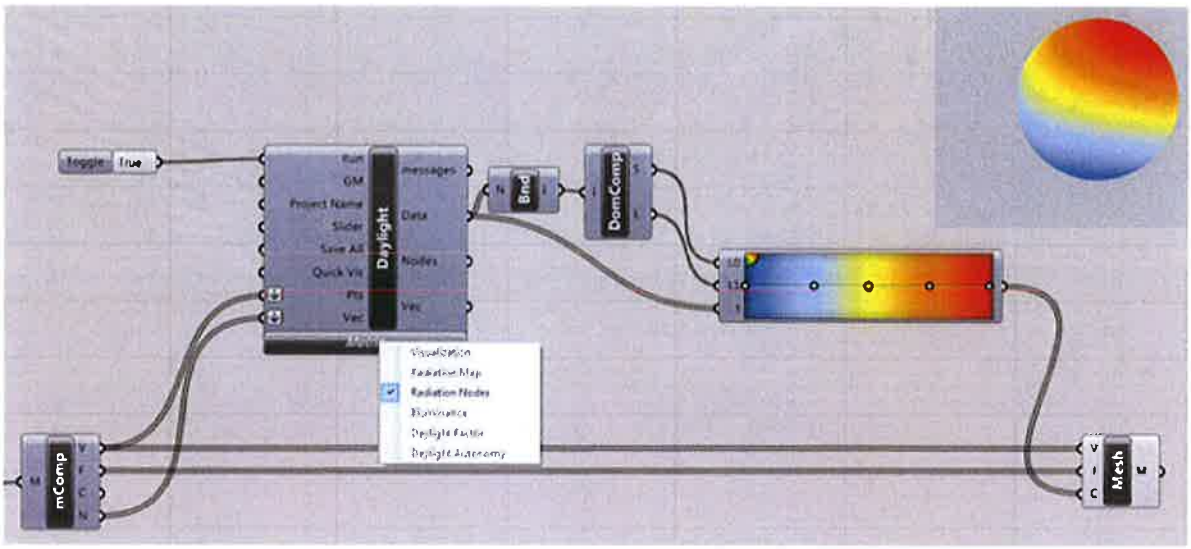
Simulation Software



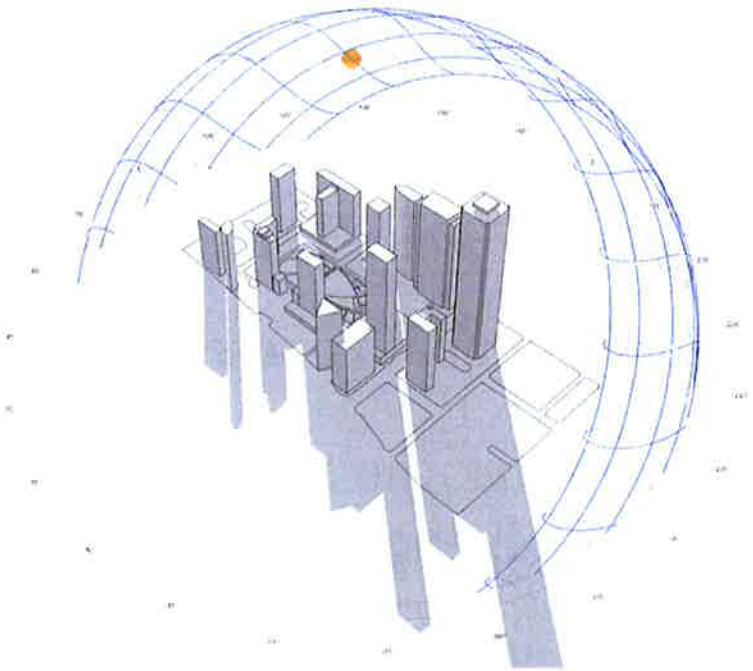
Simulation Software

- DIVA for Rhino
- Highly optimized daylighting and energy modeling plug-in
- Very powerful sunpath and shadow analysis
- Only software that can simulate arbitrary numbers of independently operated shades
- Works with Radiance to create physically accurate renderings

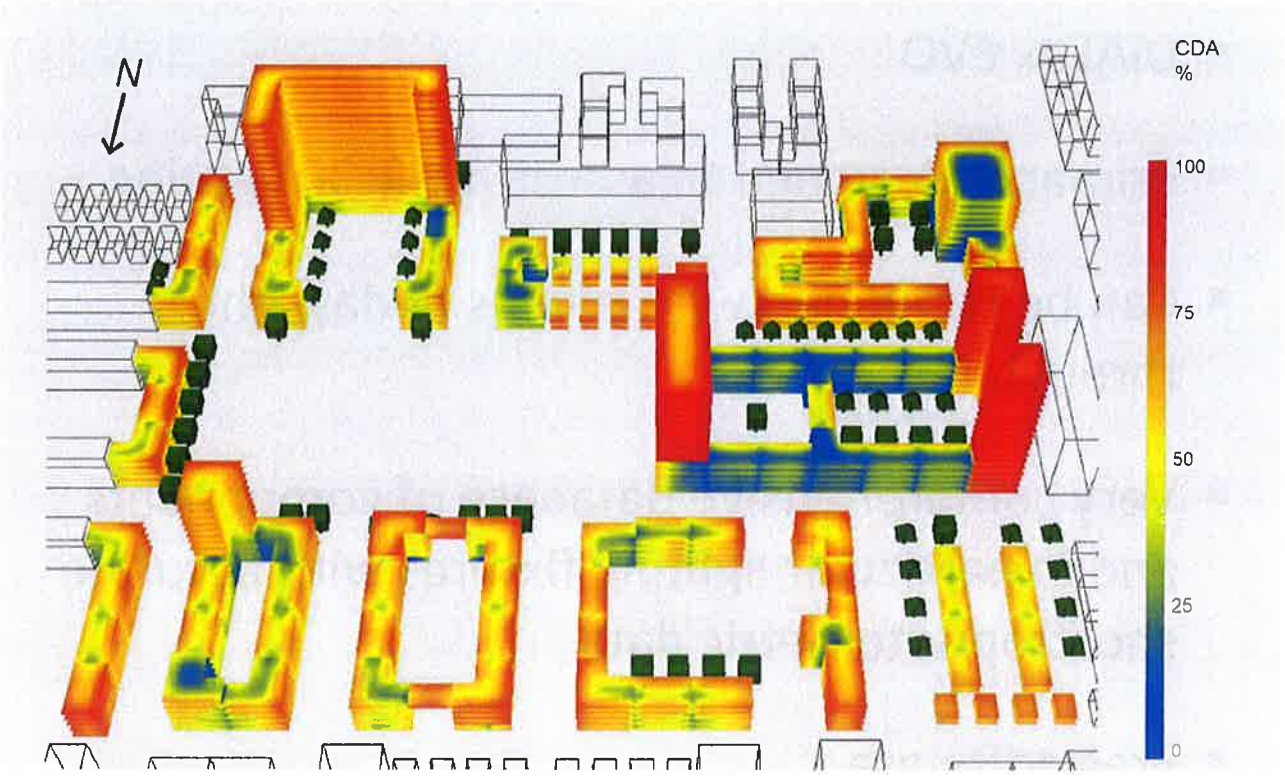
Simulation Software



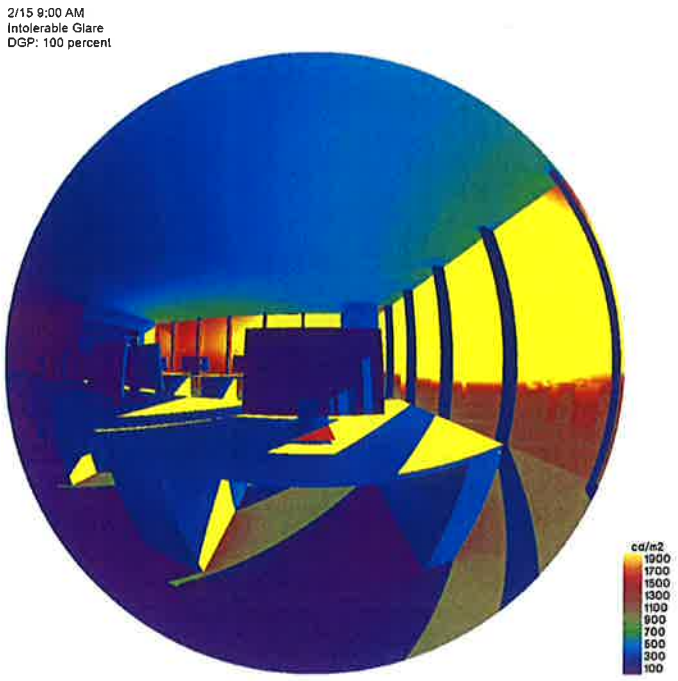
Simulation Software



Simulation Software



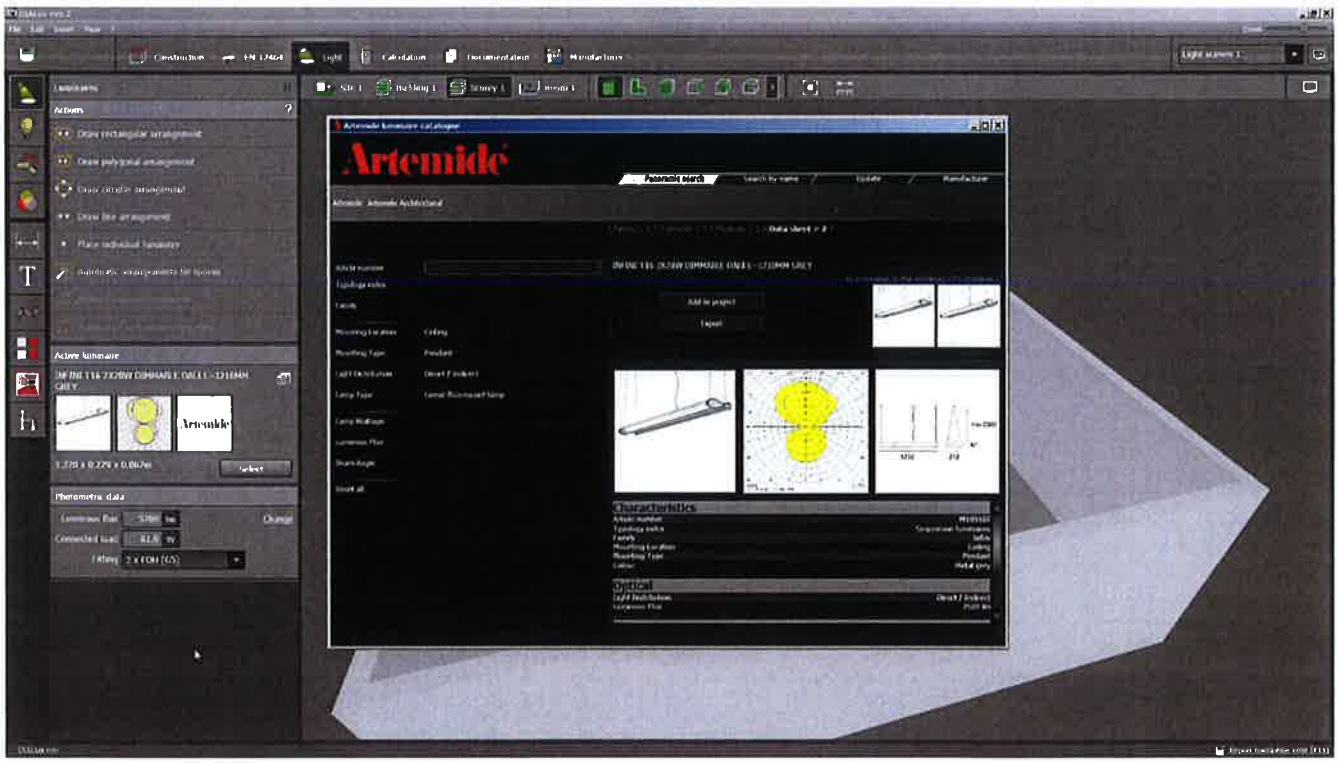
Simulation Software



Simulation Software

- DIALux EVO
- Primarily designed to assess artificial lighting
- Can be combined with effects of daylight through façade
- Very comprehensive database of components and in particular lighting fixtures with accurate spectrophotometric data
- Free software

Simulation Software



Simulation Software



BCA ACADEMY

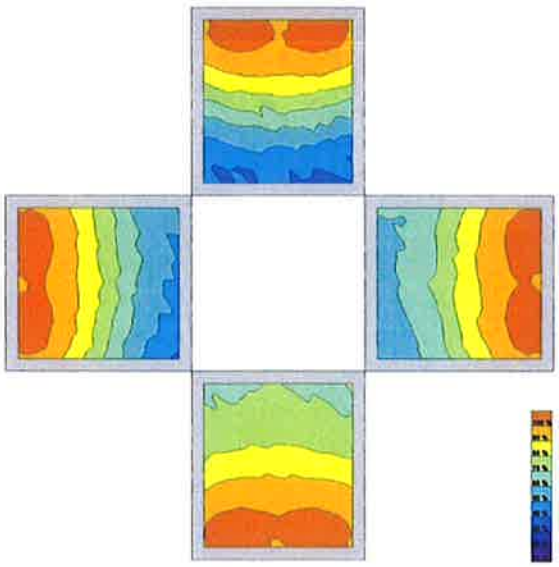
Simulation Software



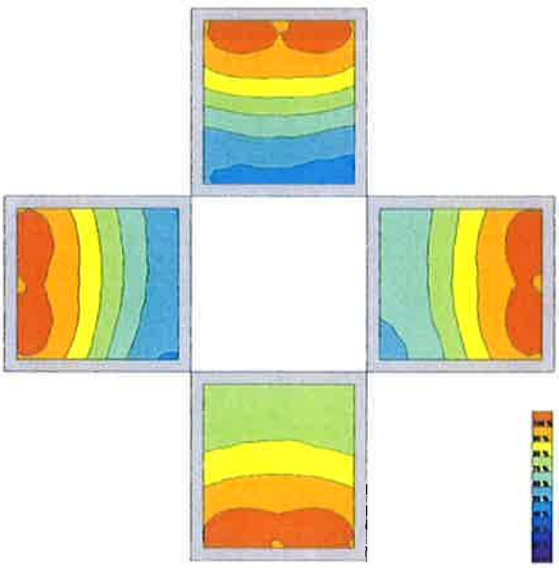
Simulation Software

- LICASO
- Computes workplane illuminance for every daylit hour of every day for an entire yearIntegrates with Revit
- Free software

Simulation Software

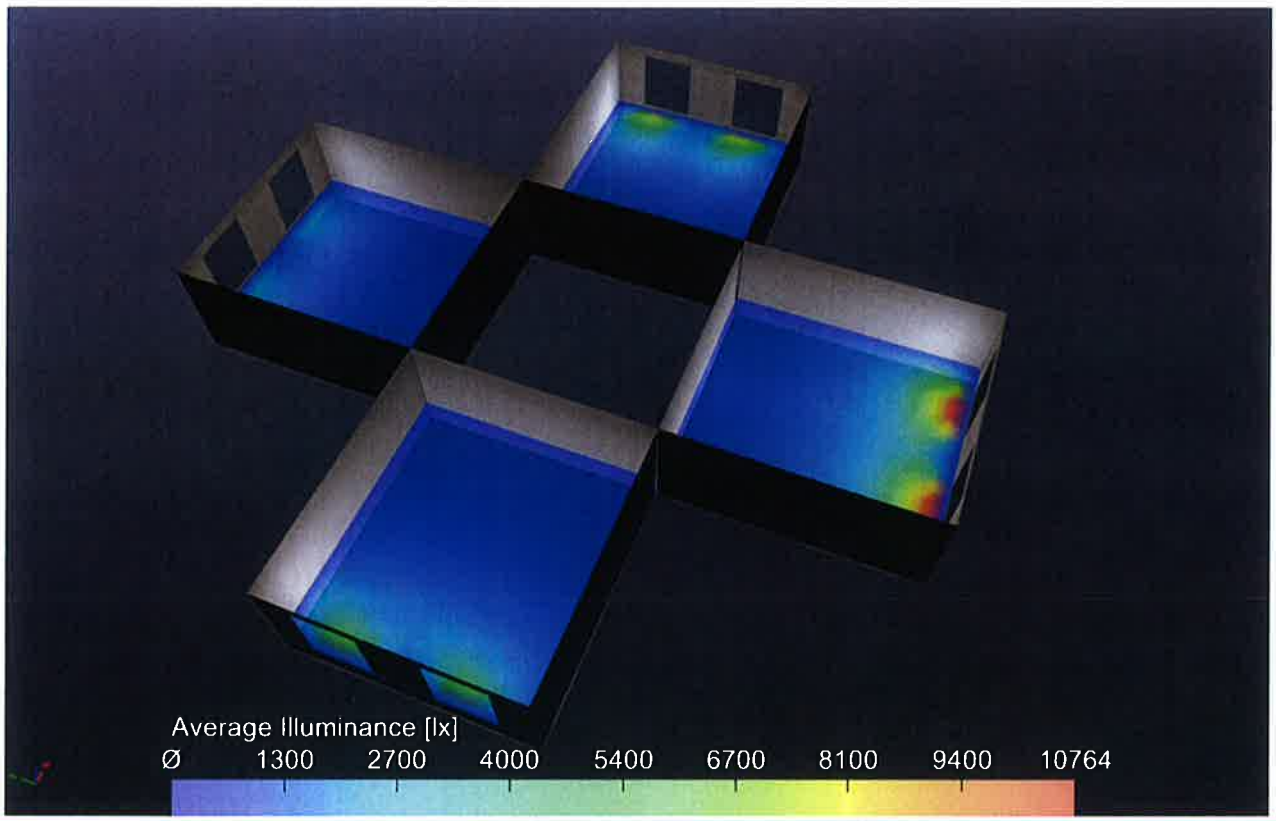


-aa	0.1
-ab	5
-ad	1000
-ar	300
-as	20



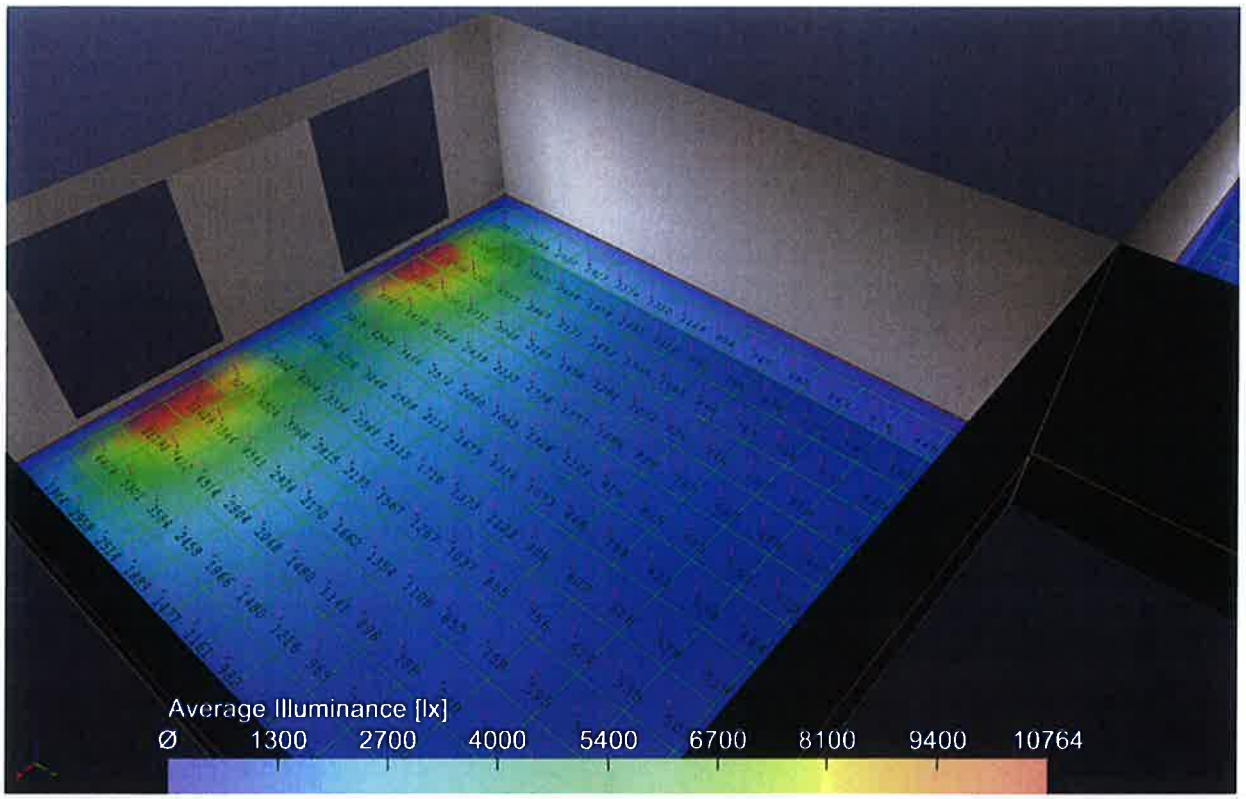
-aa	0.1
-ab	7
-ad	5000
-ar	300
-as	500

Simulation Software



BCA ACADEMY

Simulation Software

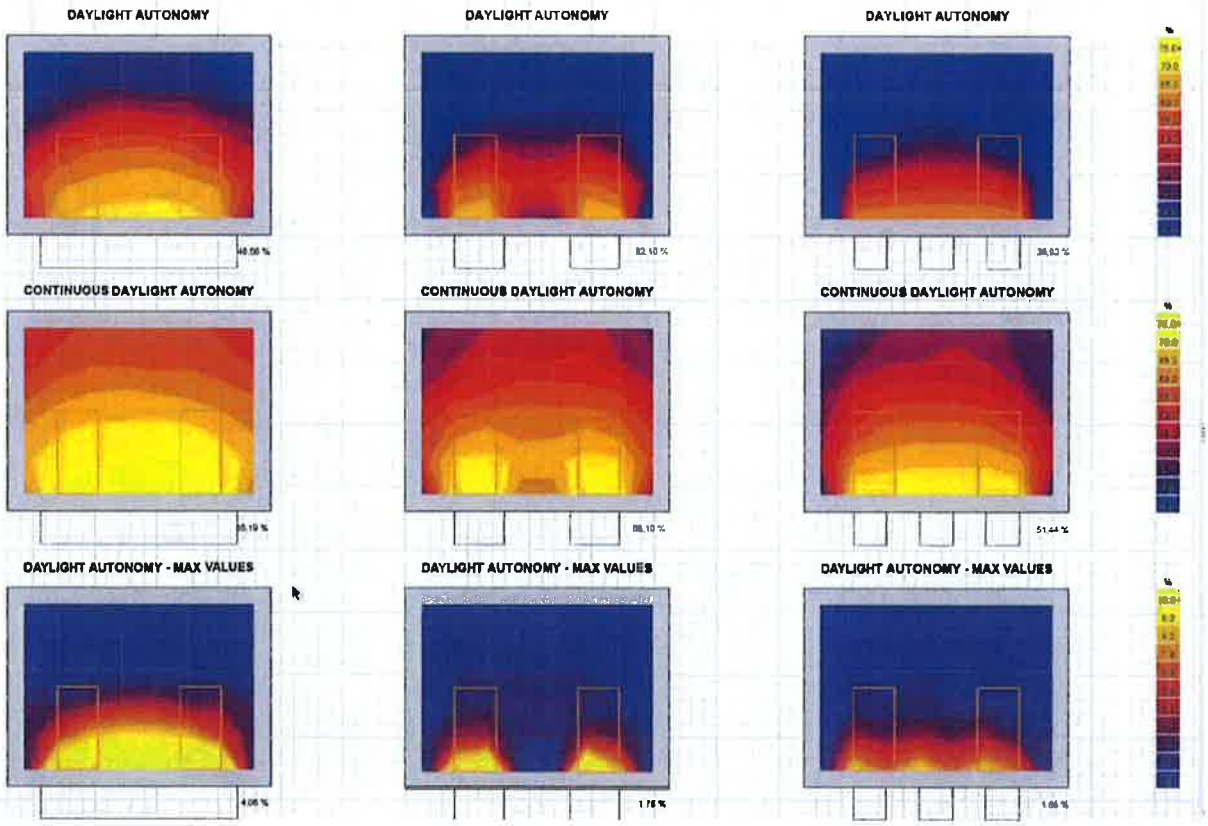


The Education and Research arm of the Building and Construction Authority

Simulation Software

- DaySim
- Similar to LICASO –models the annual amount of daylight in and around buildings
- Can be directly coupled with thermal simulation engines such as EnergyPlus, eQuest and TRNSYS
- GUIs can call it from within Rhino and SketchUp
- Free software

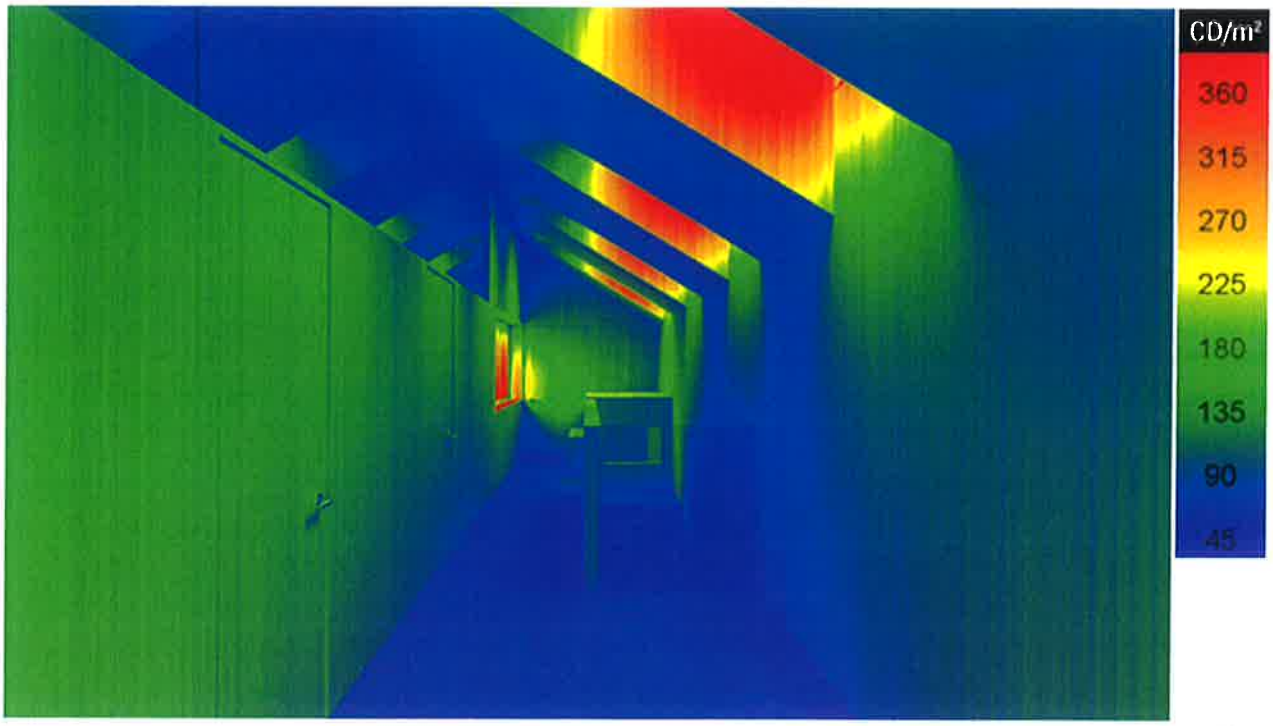
Simulation Software



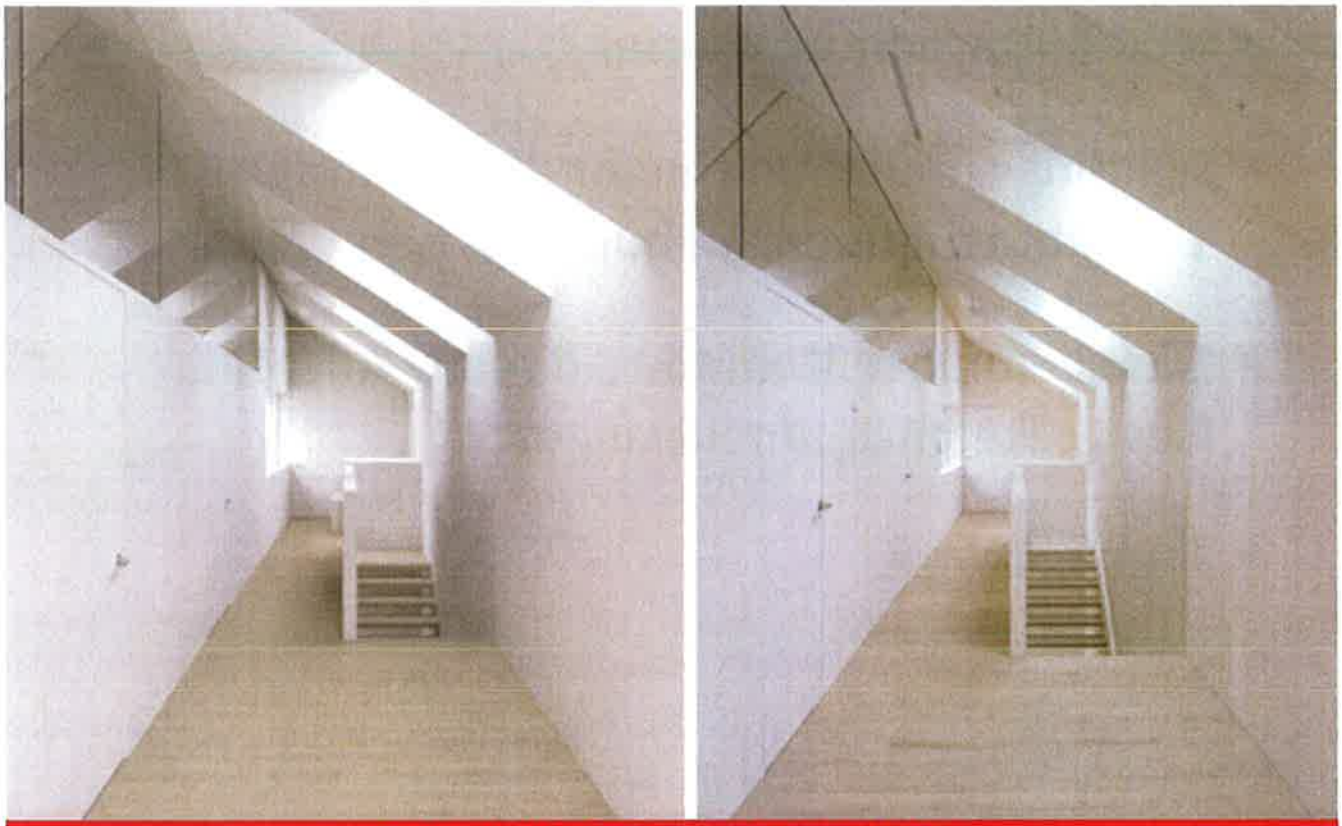
Simulation Software

- VELUX Daylight Vizualiser
- Lighting simulation tool for the analysis of daylight conditions in buildings
- Simply import 3D models directly Autocad, Revit, SketchUp, Archicad, etc.
- Free software

Simulation Software



Simulation Software



GMP Course

Efficient Building Envelope Design



School of Graduate Development and Management

BCA ACADEMY

The contents of this document are protected by copyright and other forms of proprietary rights. All rights, title and interest in the contents are owned by, licensed to or controlled ***by BCA*** *and shall not be reproduced, republished, uploaded, posted, transmitted or otherwise distributed in any way, without the prior written permission of BCA. Modification of any of the contents or use of the contents for any other purpose will be a violation of BCA's copyright and other intellectual property rights. No part of the course may be recorded, reproduced or transmitted in any form or by any means, without the express written permission of the course organiser.*

The reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply BCA's endorsement, recommendation, or favouring by BCA.

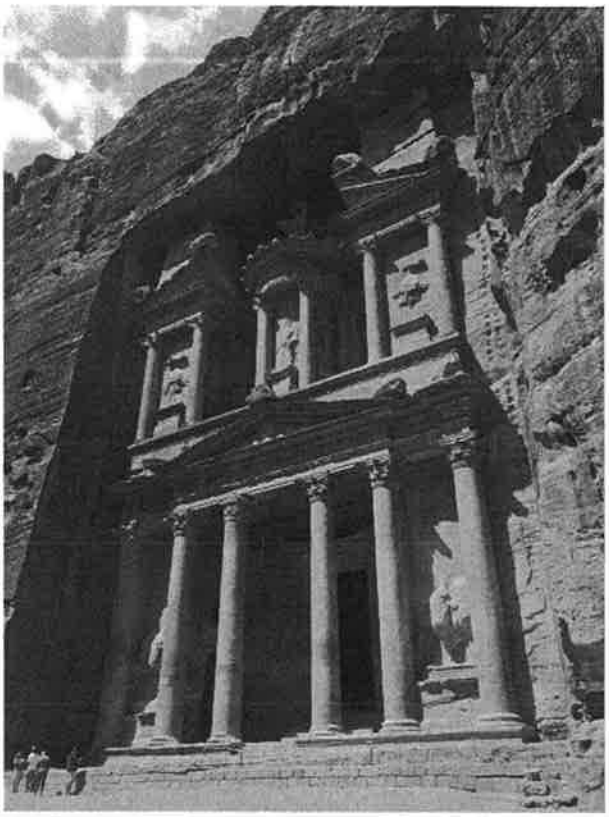
Types of Walls, Fenestrations, Glass and Shading Devices

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

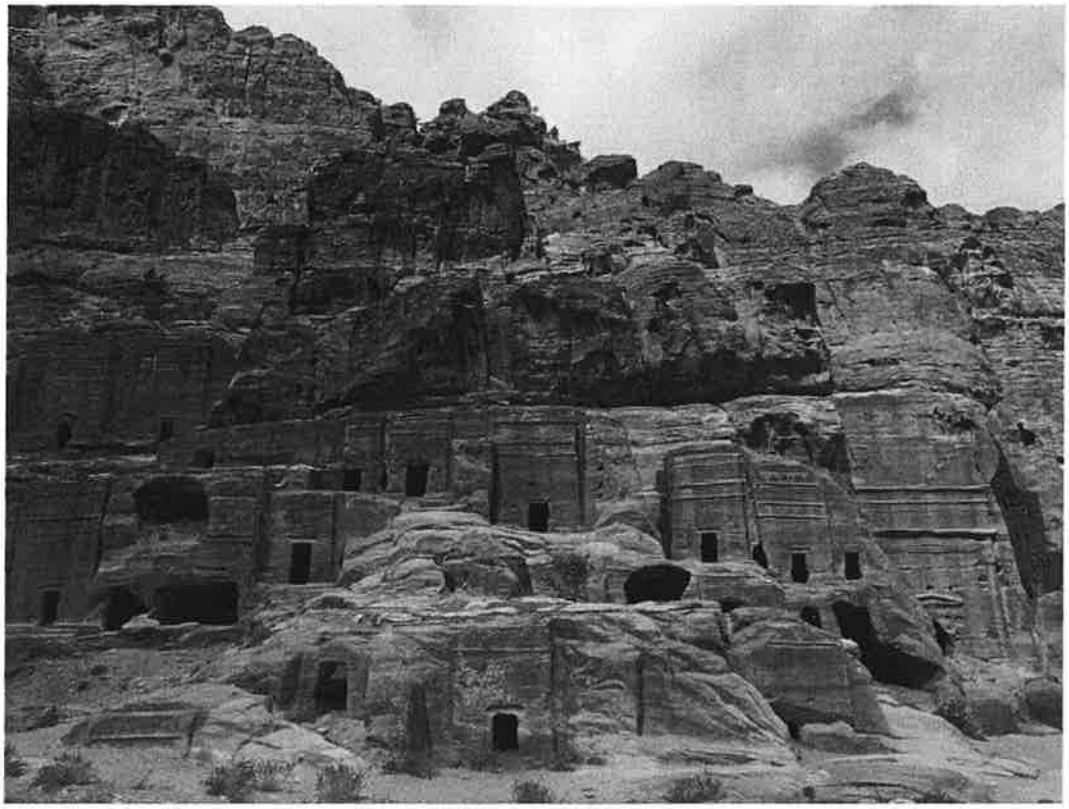
The Education and Research arm of the Building and Construction Authority

Types of Façades



The Education and Research arm of the Building and Construction Authority

Types of Façades



BCA ACADEMY

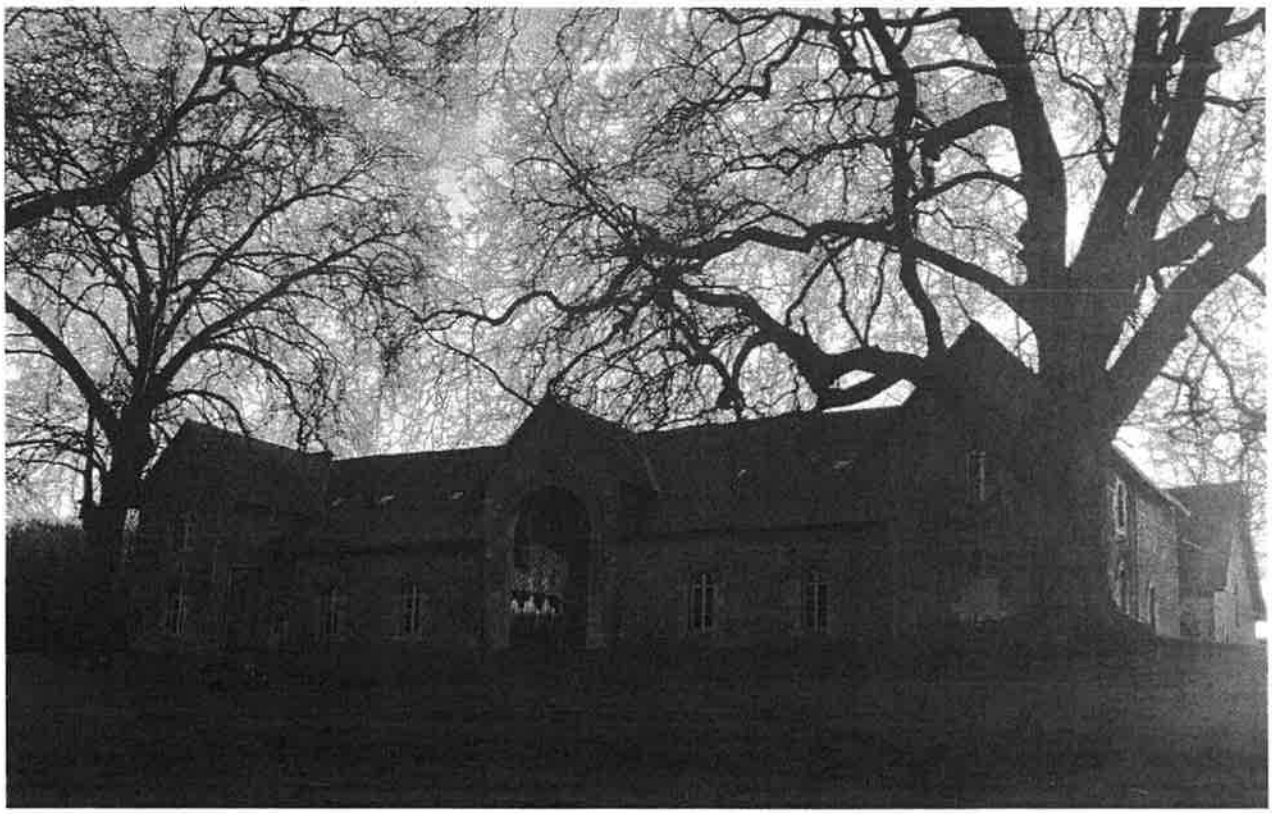
Types of Façades



Types of Façades



Types of Façades



Types of Façades



BCA ACADEMY

Types of Façades



Types of Façades



BCA ACADEMY

Types of Façades



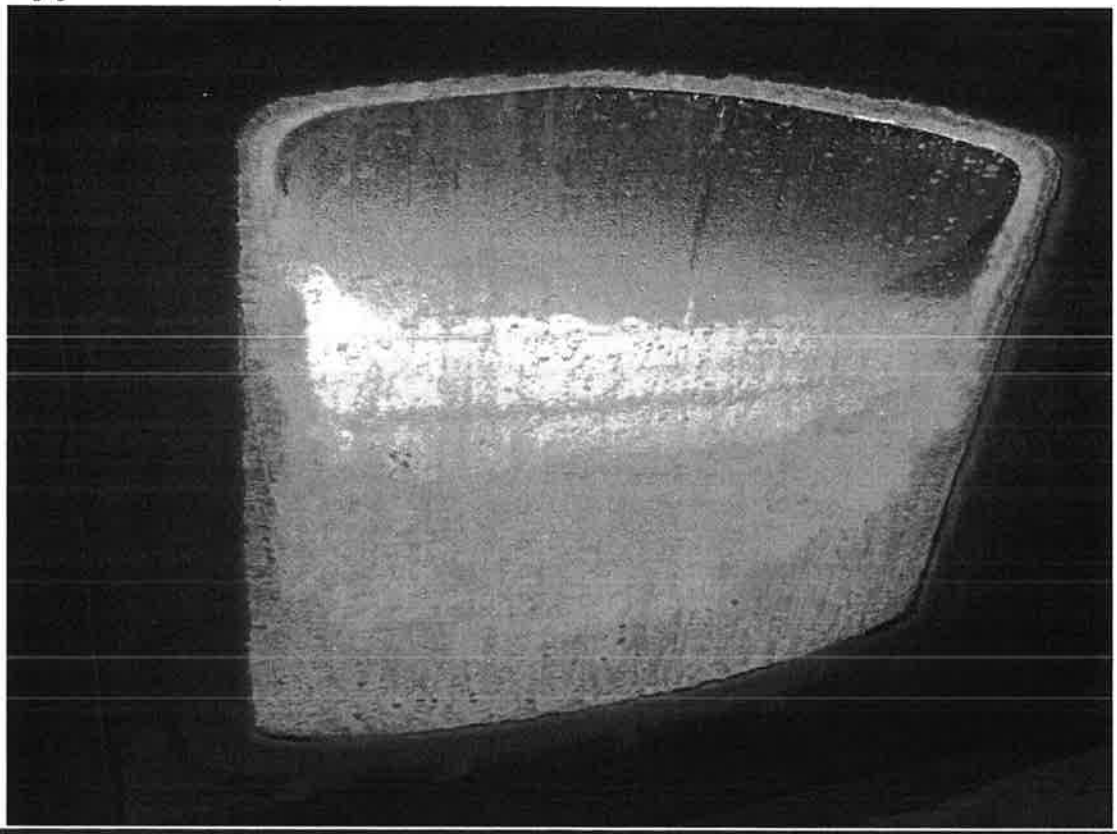
Types of Façades



Types of Façades

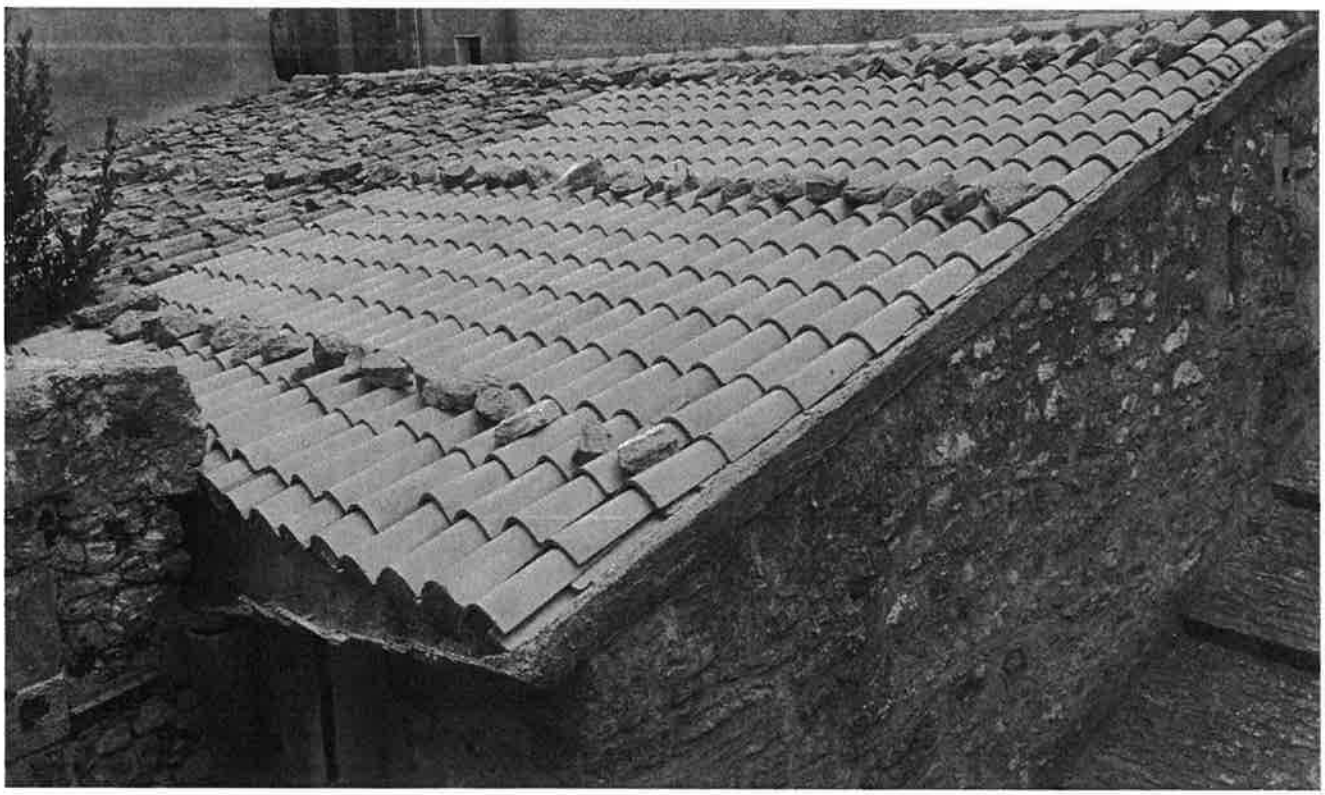


Types of Façades



BCA ACADEMY

Types of Façades



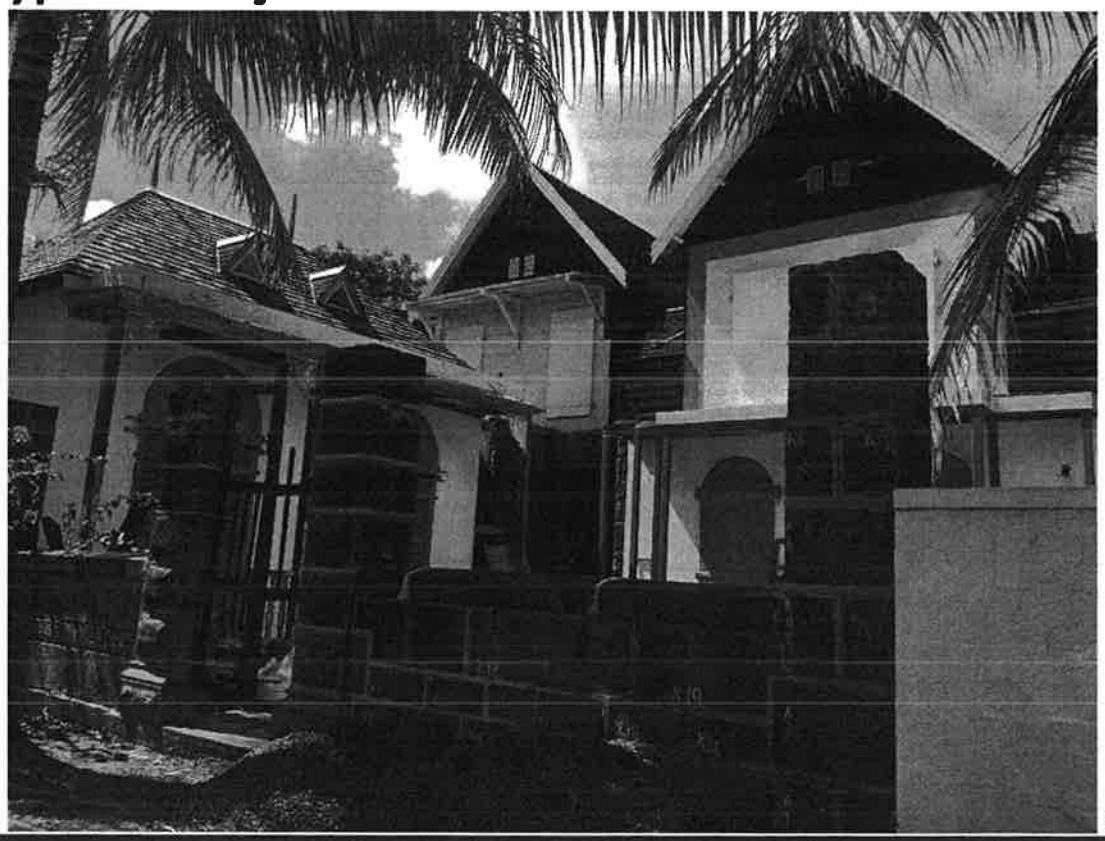
Types of Façades



Types of Façades



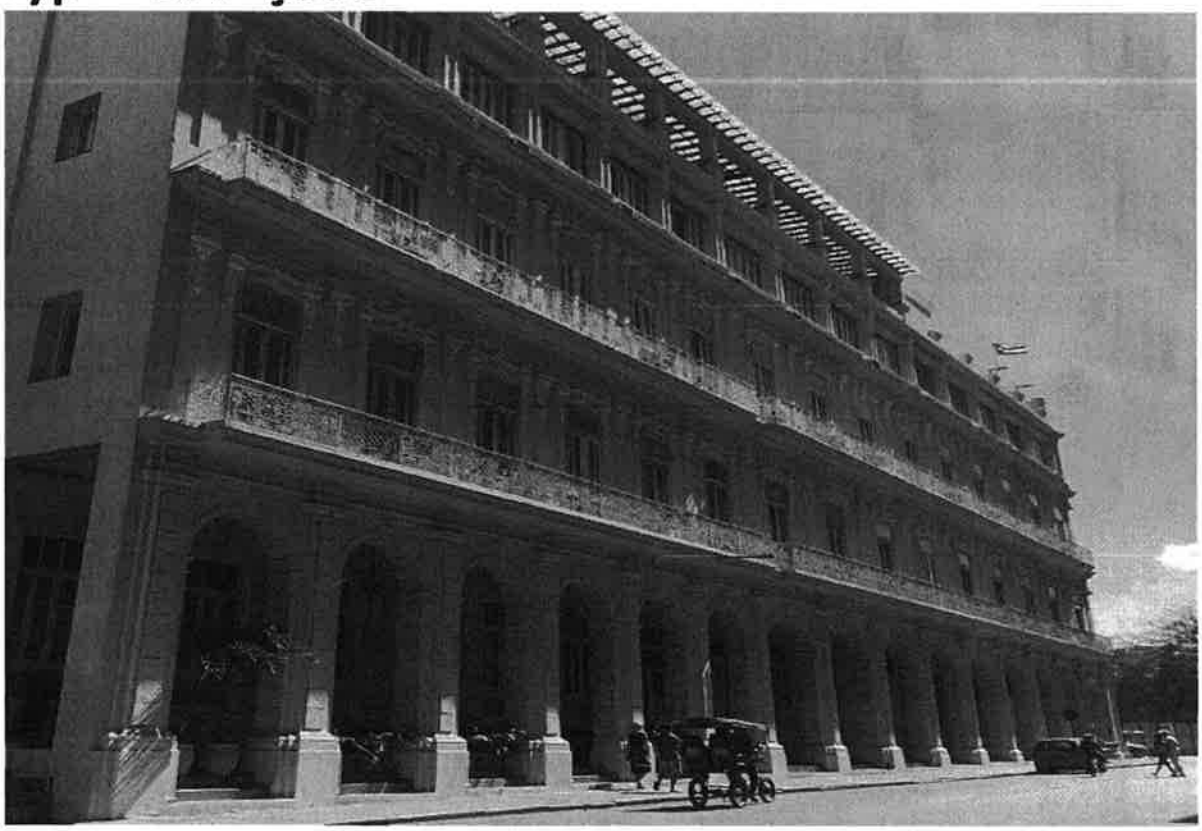
Types of Façades



This material is the property of the Building and Construction Authority

BCA ACADEMY

Types of Façades



Types of Façades



BCA ACADEMY

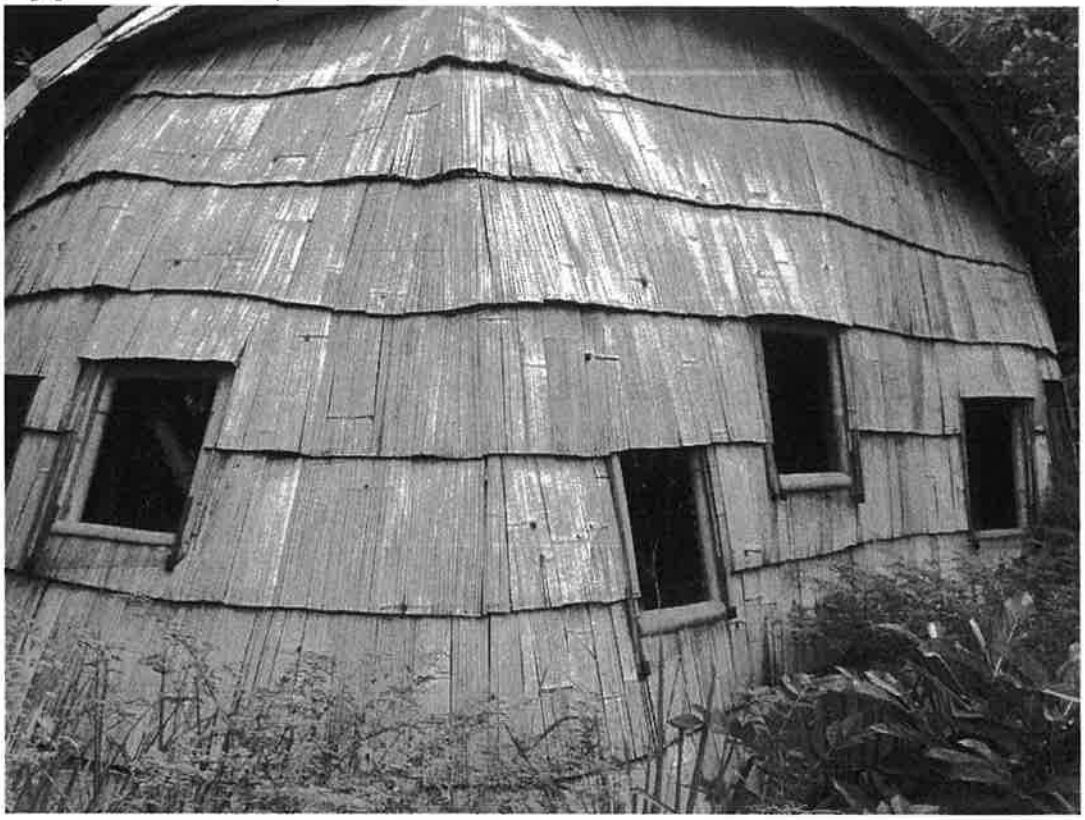
Types of Façades



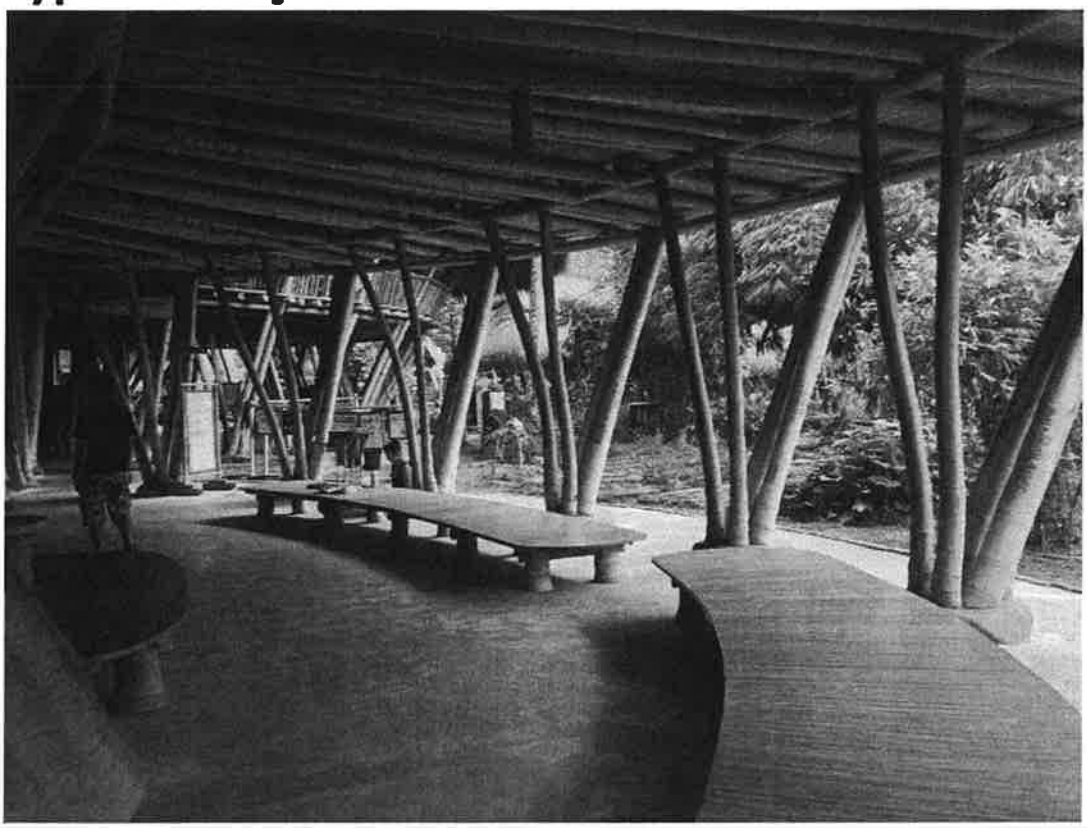
Types of Façades



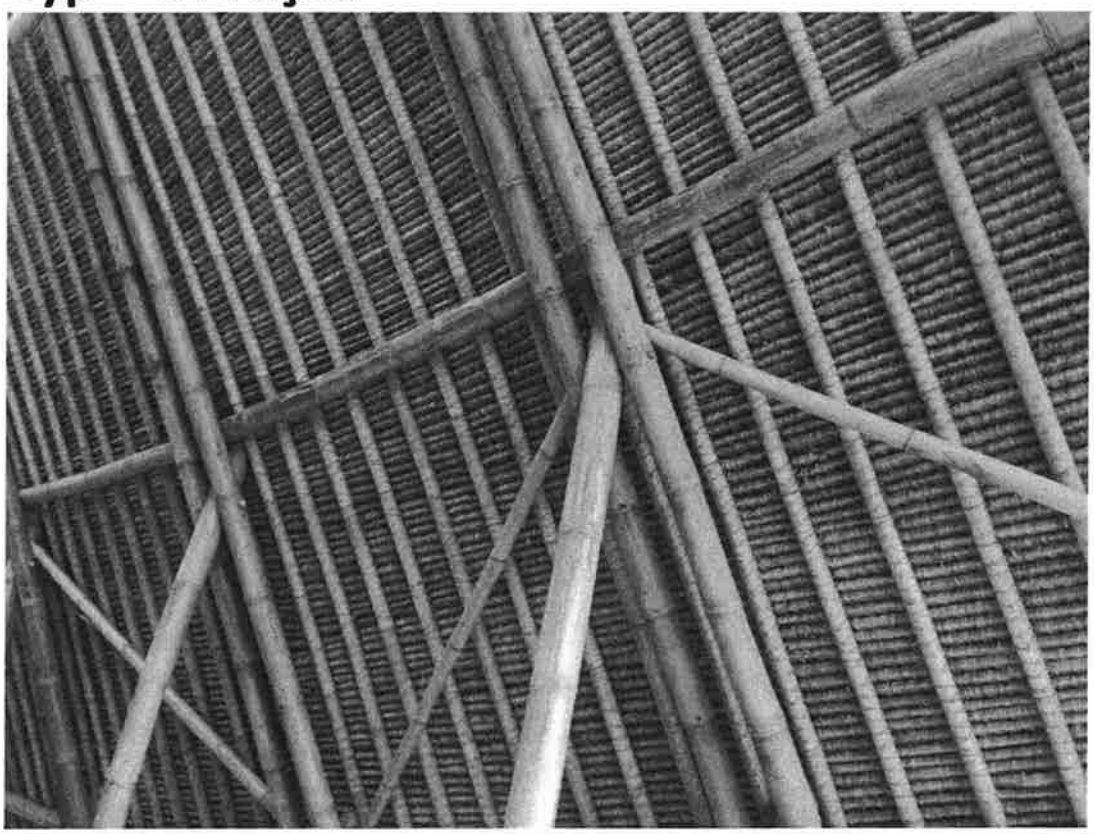
Types of Façades



Types of Façades



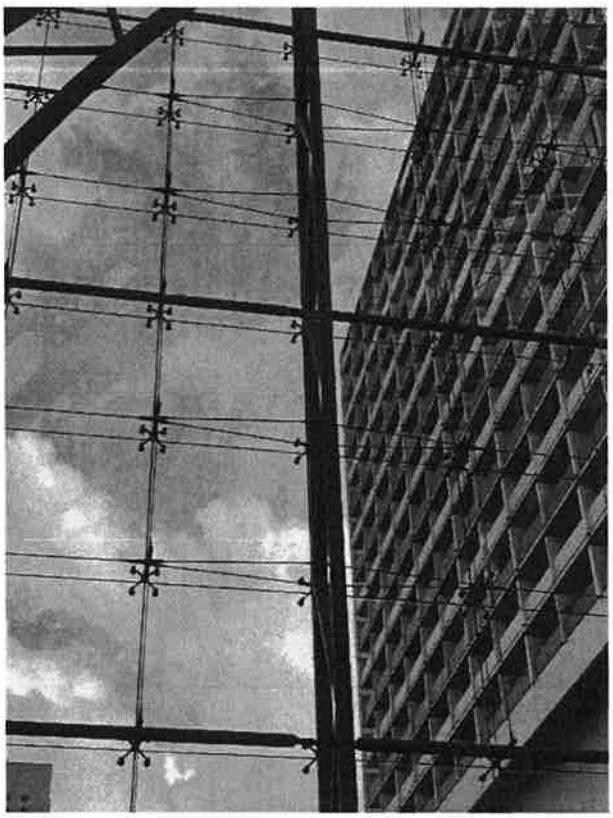
Types of Façades



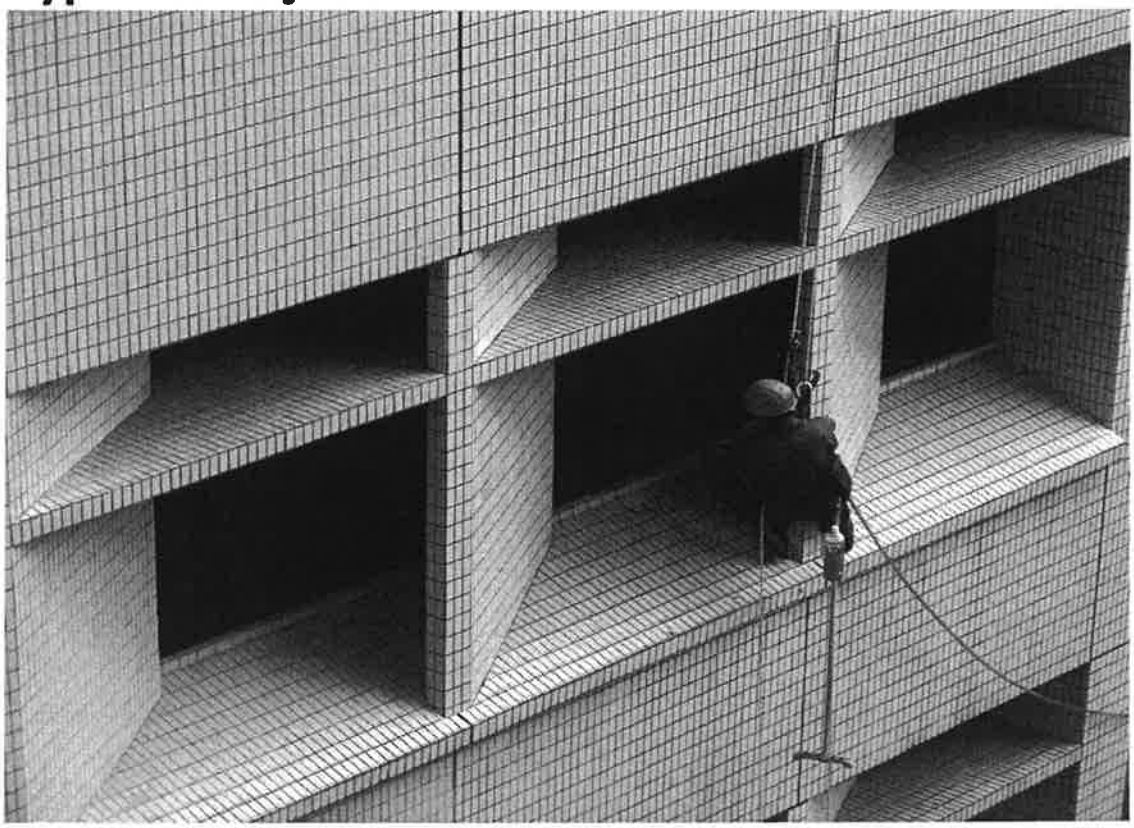
Types of Façades



Types of Façades



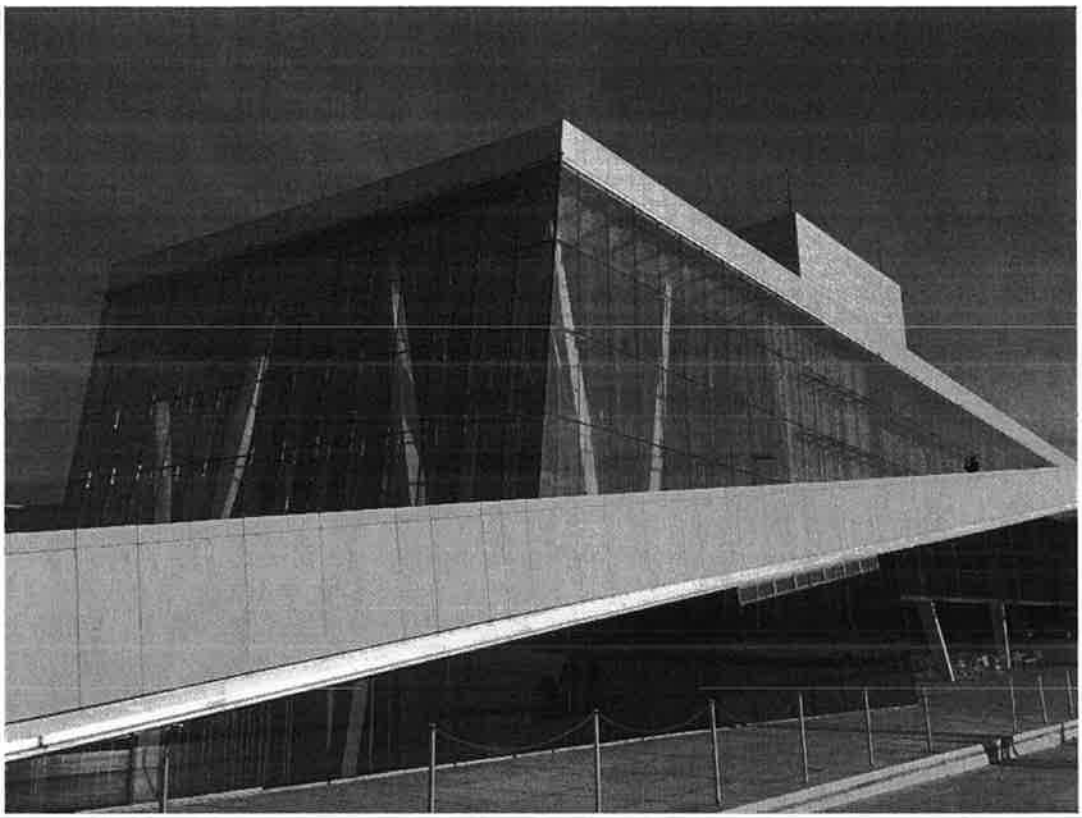
Types of Façades



Types of Façades



Types of Façades

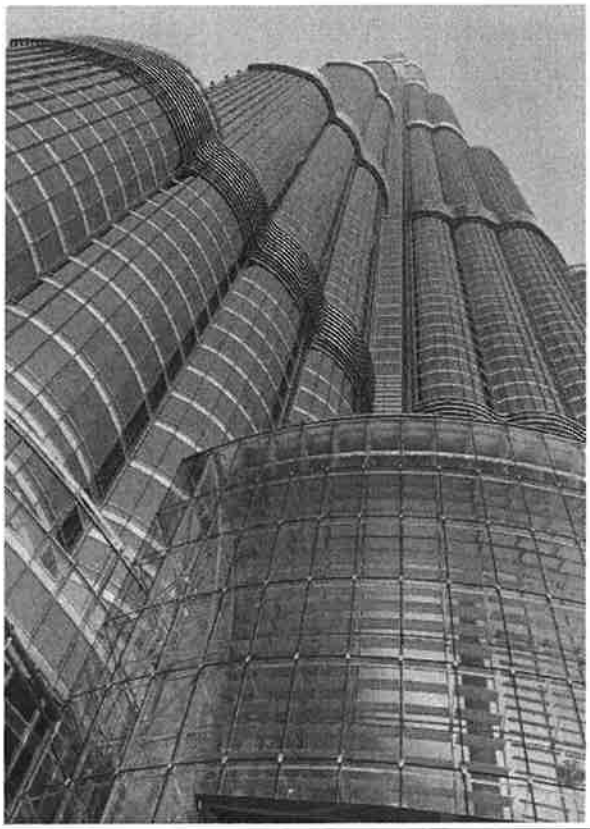


BCA ACADEMY

Types of Façades



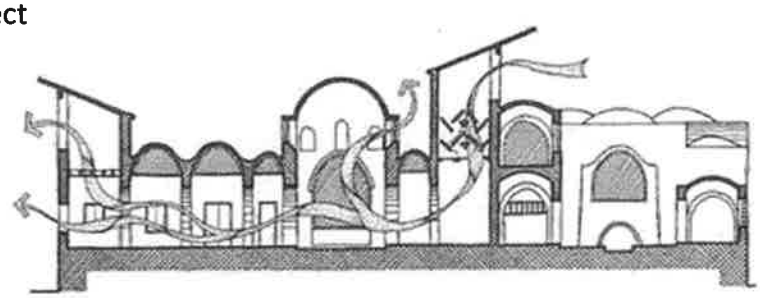
Types of Façades



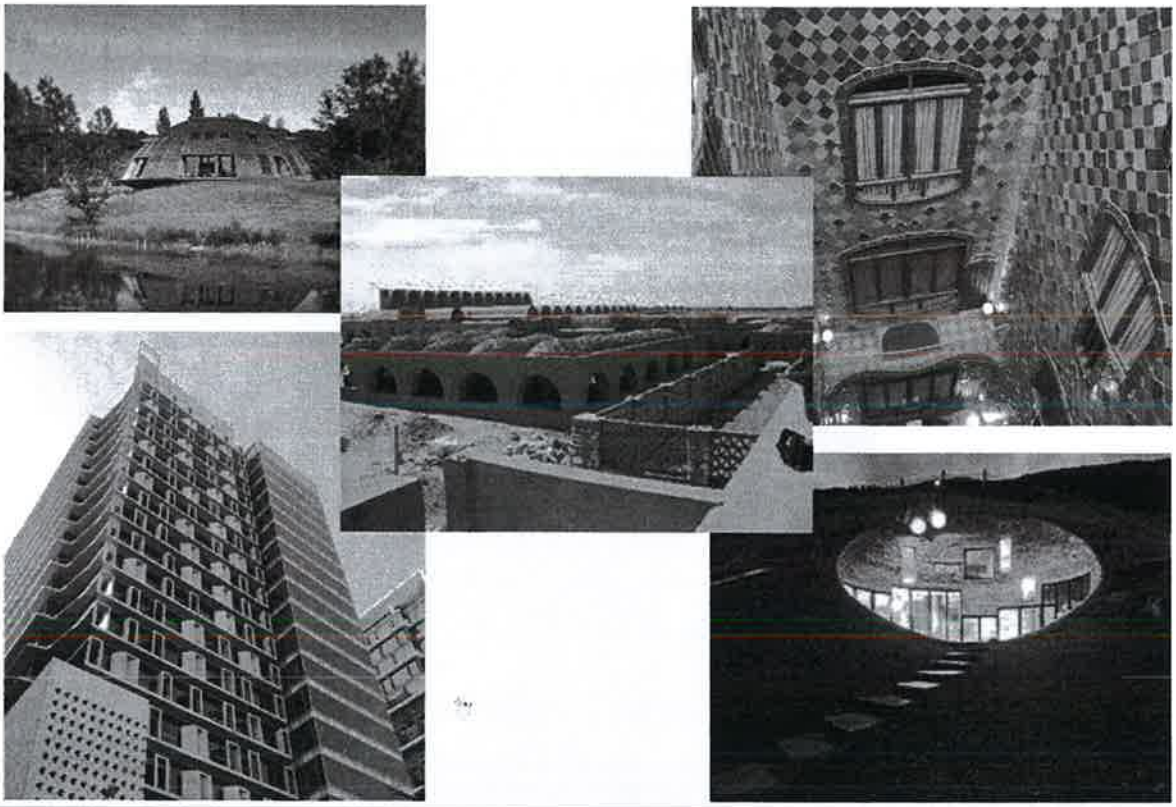
Types of Façades

"Before investing or proposing new mechanical solutions, traditional solutions in vernacular architecture should be evaluated and then adopted or modified and developed to make them compatible with modern requirements"

...Hassan Fathy, Egyptian architect

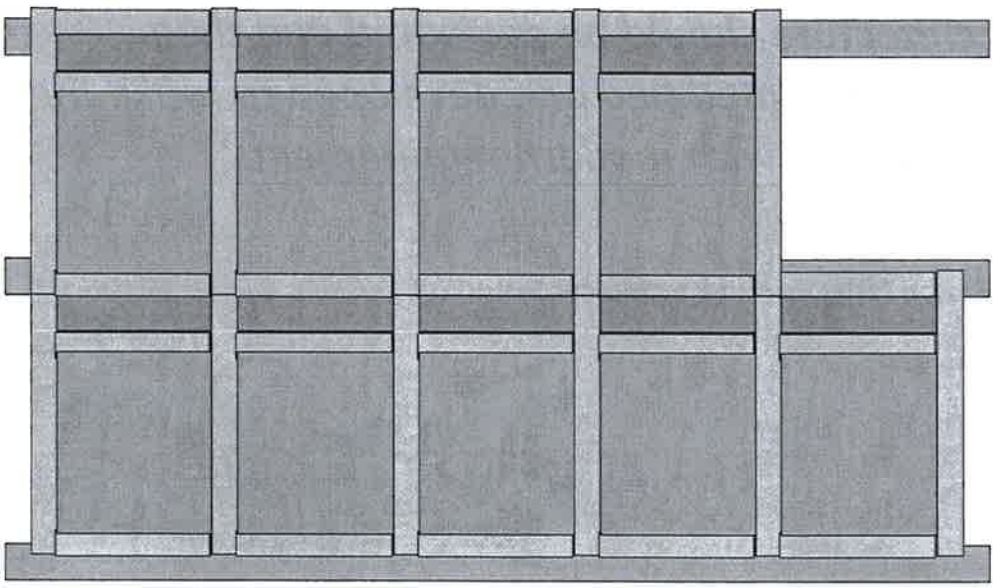


Modern Take On Vernacular Solutions



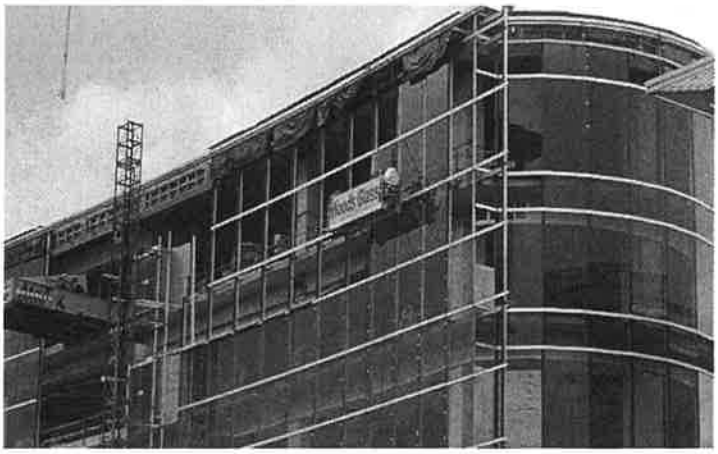
Types of Walls, Fenestrations, Glass and Shading Devices

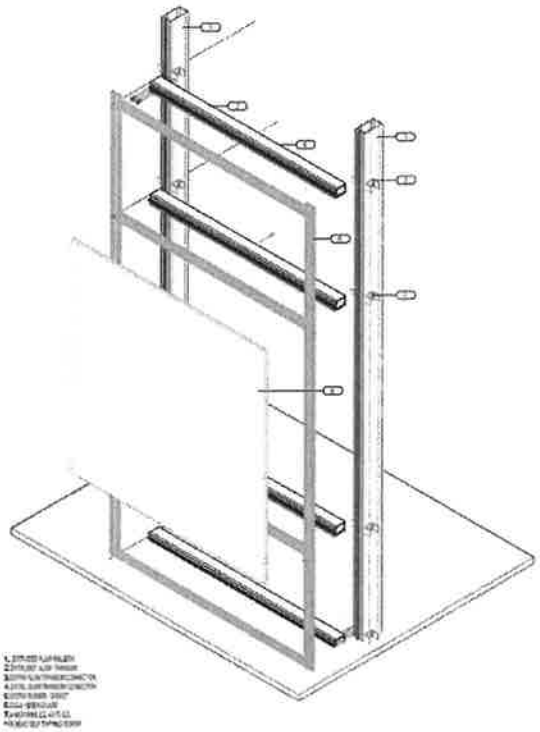
- Stick curtain wall



Types of Walls, Fenestrations, Glass and Shading Devices

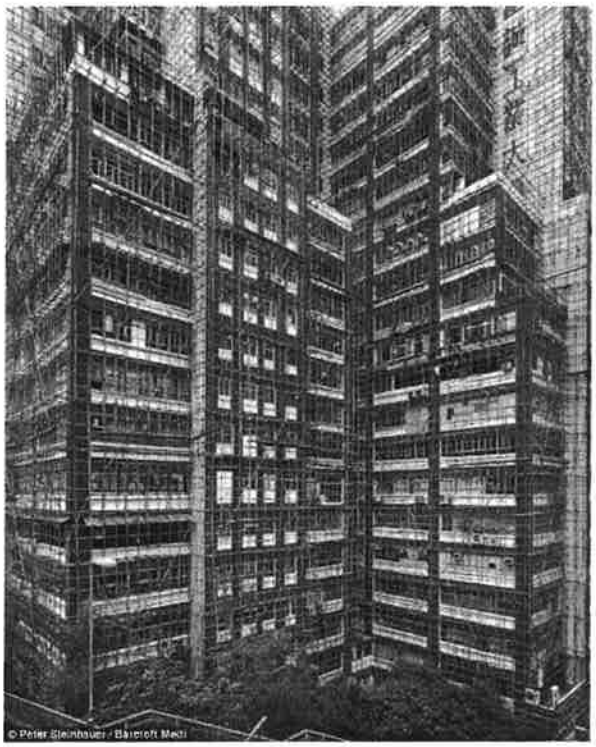
- Stick curtain wall





BCA ACADEMY

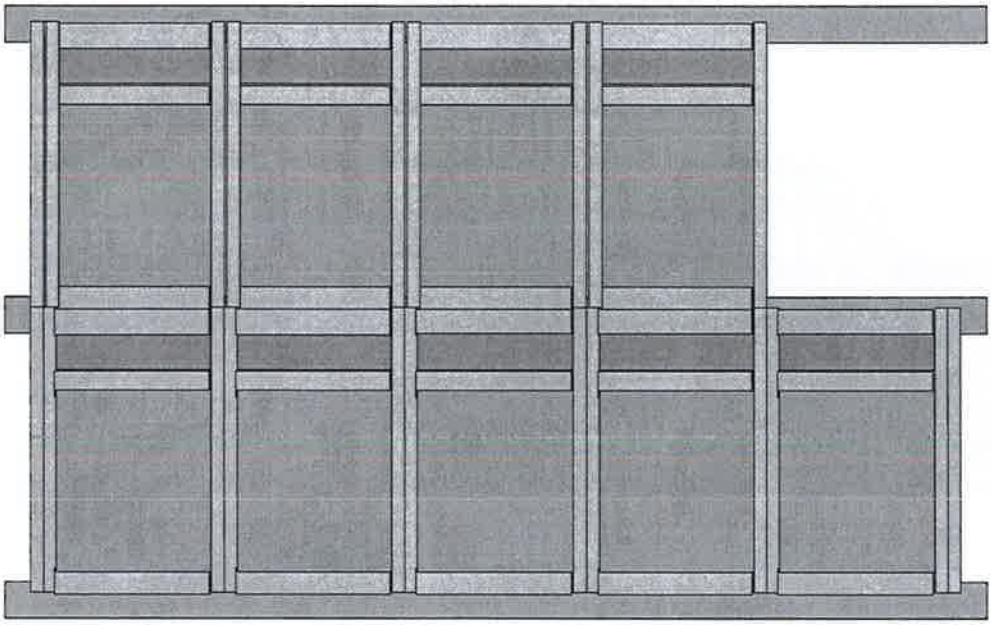
Types of Walls, Fenestrations, Glass and Shading Devices





Types of Walls, Fenestrations, Glass and Shading Devices

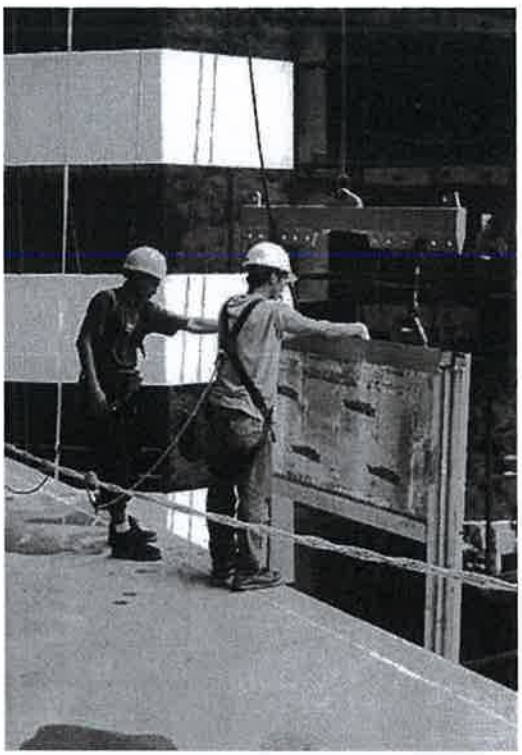
- Unitised curtain wall



parapet glazing Panel.

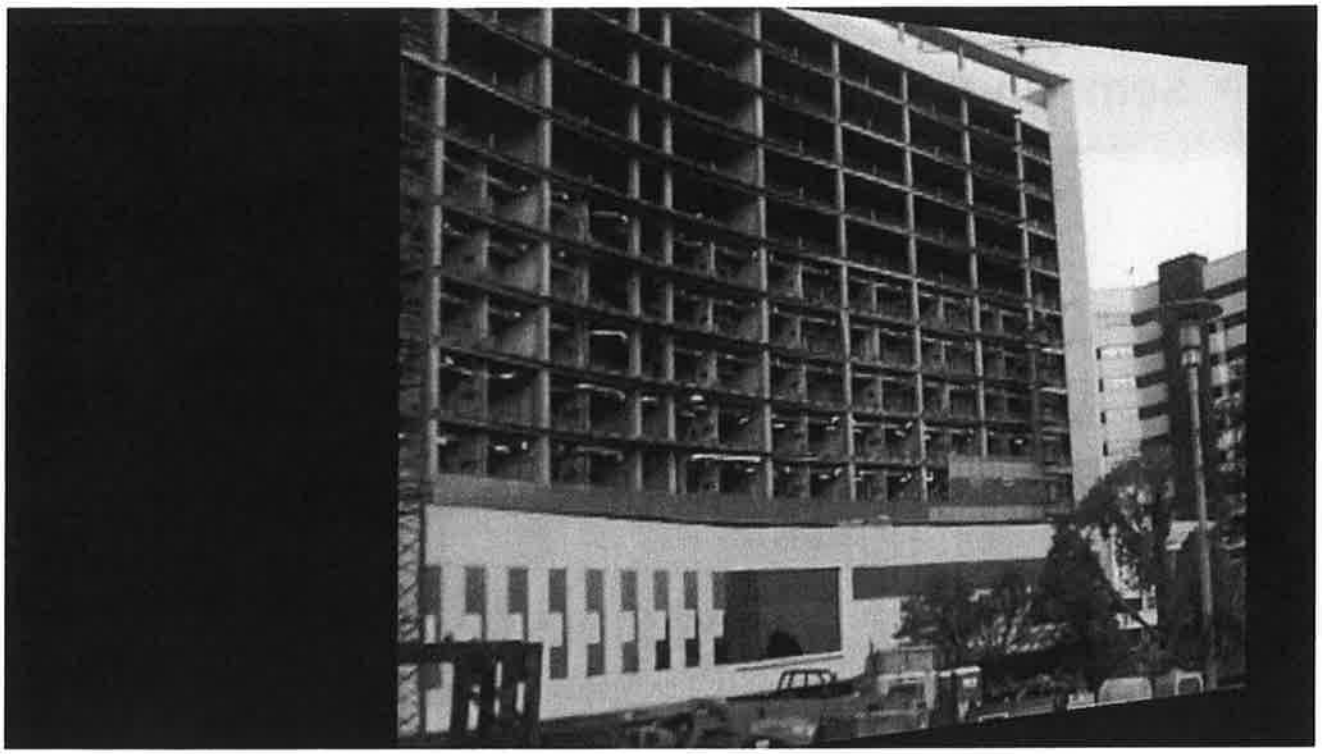
Types of Walls, Fenestrations, Glass and Shading Devices

- Faster installation
- Better QA/QC
- No external access required



BCA ACADEMY

Types of Walls, Fenestrations, Glass and Shading Devices



BCA ACADEMY

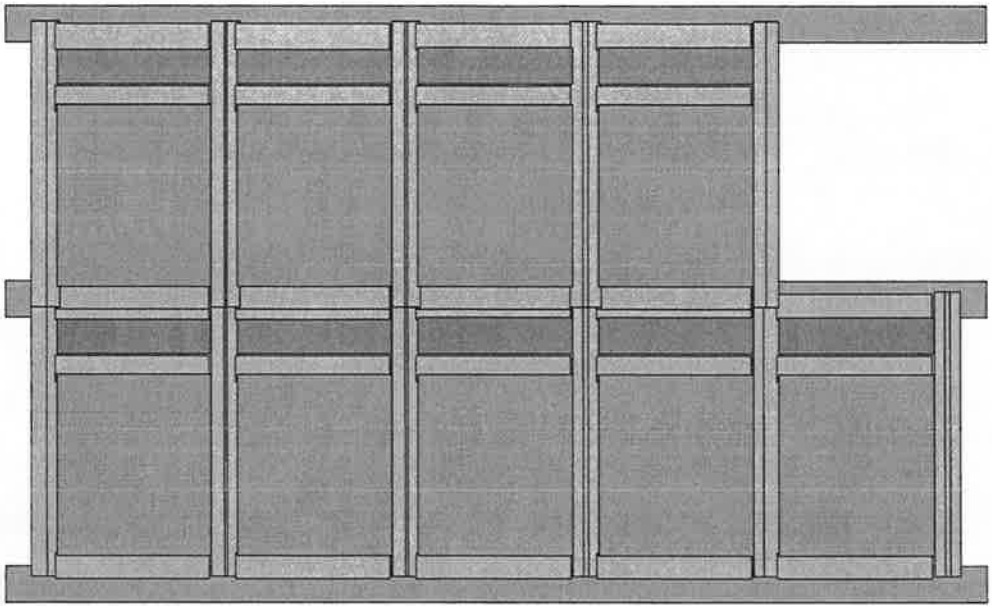
Types of Walls, Fenestrations, Glass and Shading Devices

- Ultimate step – Self-installing unitised façade



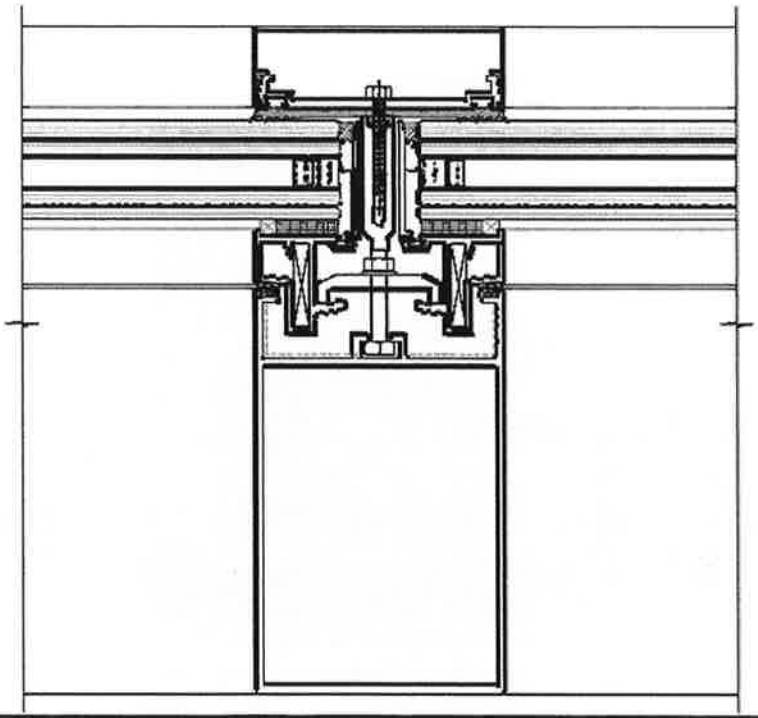
Types of Walls, Fenestrations, Glass and Shading Devices

- Semi-unitised curtain wall

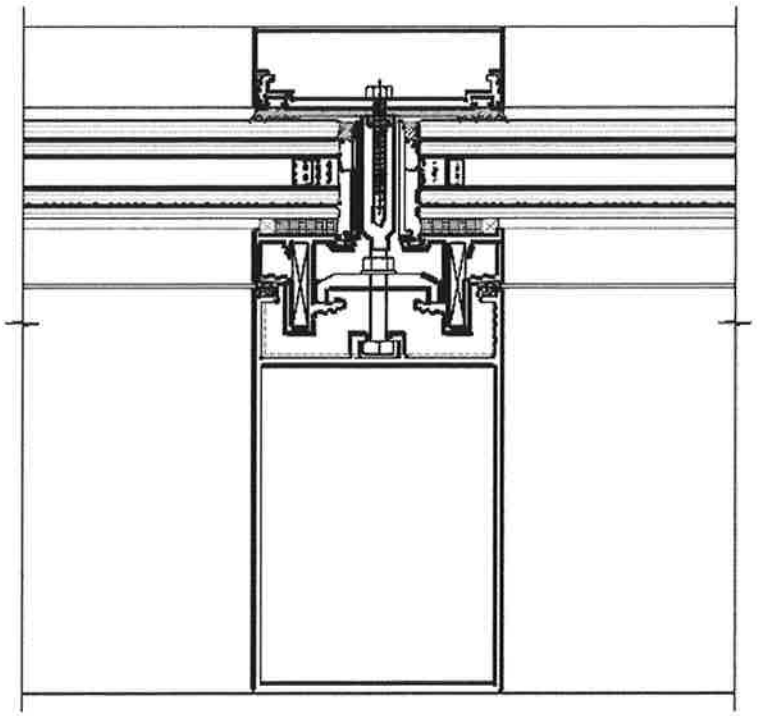


Types of Walls, Fenestrations, Glass and Shading Devices

- Semi-unitised curtain wall

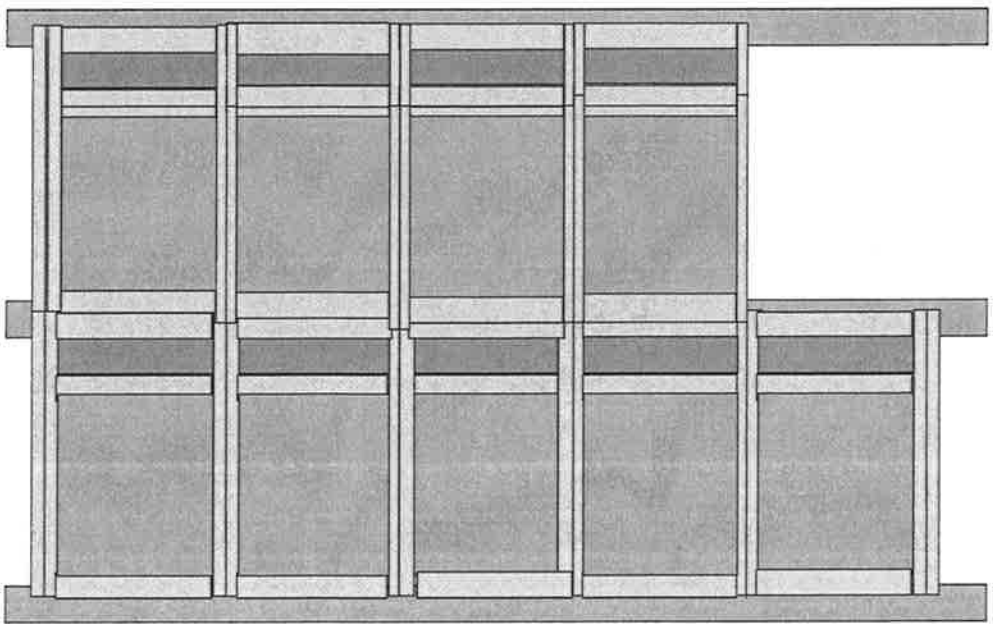


Semi-Unitised Curtain Walls



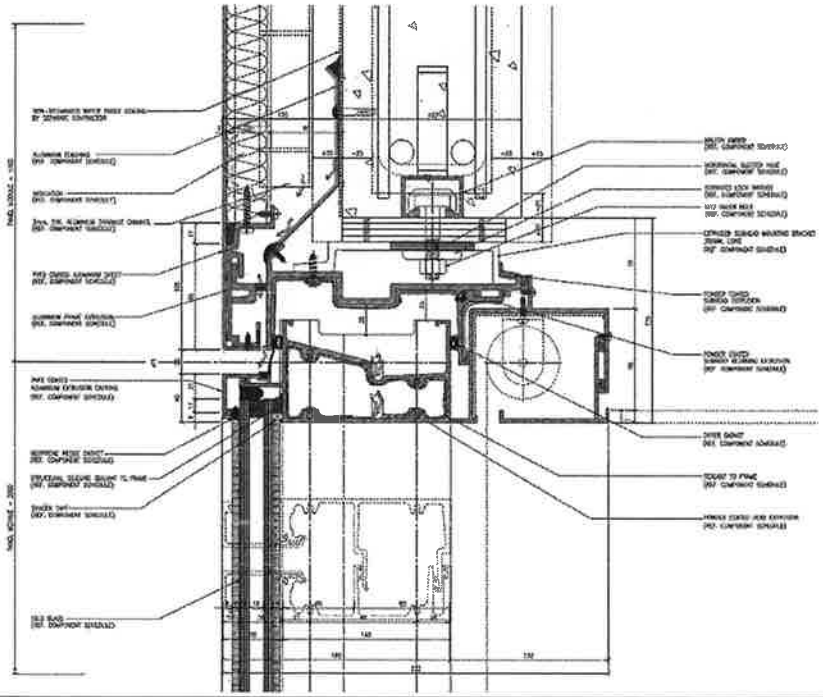
Types of Walls, Fenestrations, Glass and Shading Devices

- Ribbon curtain wall



Types of Walls, Fenestrations, Glass and Shading Devices

- Ribbon curtain wall



BCA ACADEMY

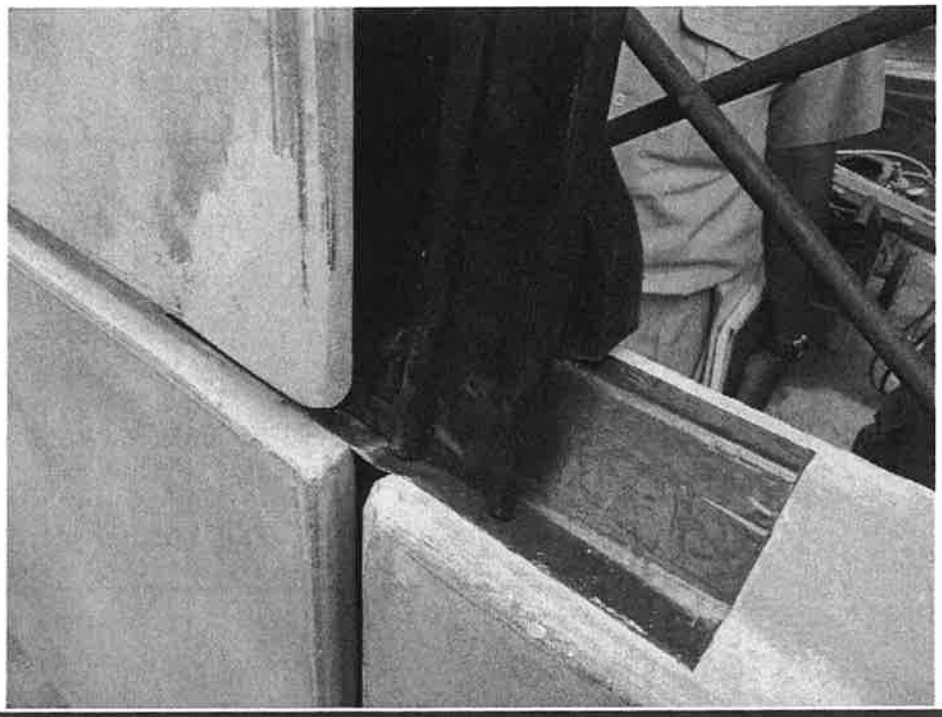
Types of Walls, Fenestrations, Glass and Shading Devices

- Precast concrete cladding and windows



Types of Walls, Fenestrations, Glass and Shading Devices

- Precast concrete cladding and windows



BCA ACADEMY

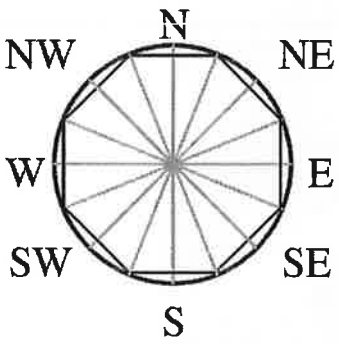
Impact from Geometry and Location, and Façade Characteristics

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

Impact from Geometry and Location, and Façade Characteristics

- Effect of façade orientation



Pitch Angle	Orientation							
	N	NE	E	SE	S	SW	W	NW
70°	1.17	1.33	1.47	1.35	1.21	1.41	1.56	1.38
75°	1.07	1.23	1.37	1.25	1.11	1.32	1.47	1.28
80°	0.98	1.14	1.30	1.16	1.01	1.23	1.39	1.20
85°	0.89	1.05	1.21	1.07	0.92	1.14	1.31	1.11
90°	0.80	0.97	1.13	0.98	0.83	1.06	1.23	1.03
95°	0.73	0.90	1.05	0.91	0.76	0.99	1.15	0.96
100°	0.67	0.83	0.97	0.84	0.70	0.92	1.08	0.89
105°	0.62	0.77	0.90	0.78	0.65	0.86	1.01	0.83
110°	0.59	0.72	0.83	0.72	0.61	0.80	0.94	0.78
115°	0.57	0.67	0.77	0.67	0.58	0.75	0.87	0.73
120°	0.55	0.63	0.72	0.63	0.56	0.71	0.81	0.69

BCA ACADEMY

Impact from Geometry and Location, and Façade Characteristics

- Effect of building location

TD_{eq} = equivalent temperature difference (K)

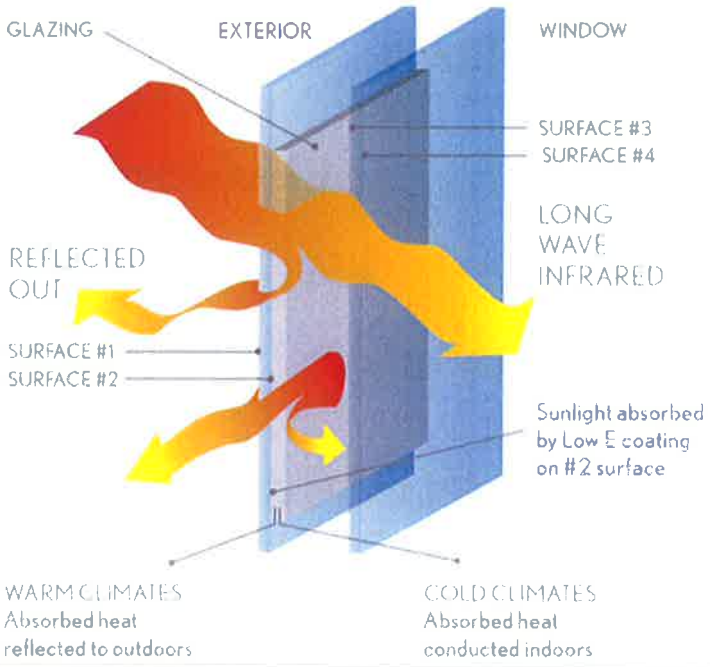
DT = temperature difference between interior and exterior (K)

SF = solar factor of fenestration (W/m^2)

	Singapore	Malaysia	Thailand	Philippines	Jamaica	Hong Kong
Latitude (city)	1° 20' N Singapore	3° 7' N Kuala Lumpur	13° 41' N Bangkok	14° 35' N Manila	17° 56' N Kingston	22° 18' N Hong Kong
Year adopted	1979	1989	1992	1993	1992	1995
Status	Mandatory	Voluntary	Mandatory	Voluntary	Mandatory	Mandatory
OTTV limits for walls (W/m^2)	45	45	45	48	55.1 - 67.7	Tower: 35 Podium: 80
OTTV limits for roof (W/m^2)	45 (max. U-value if no skylights)	25 (max. U-value if no skylights)	25 (max. U-value if no skylights)	Max. U-value if no skylights	20	(average for walls and roof)
TD_{eq} for walls (K)	10 - 15	19.1 α	9 - 18	12.65 α (office) 5.4 α (hotel)	varies with α	1.4 - 7.5
TD_{eq} for roof (K)	16 - 24	16 - 24	12 - 32	---	varies with α	7.9 - 18.6
DT for walls (K)	5	neglected	5	3.35 (office) 1.10 (hotel)	varies by location	neglected
DT for roof (K)	5	neglected	5	---	varies by location	neglected
Average SF for walls (W/m^2)	130	194	160	161 (office) 142 (hotel) 151 (store)	372	160
Average SF for roof (W/m^2)	320	488	370	---	435	264
Consider exterior shading?	Yes	Yes	Yes	No	Yes	Yes
Daylighting credits?	No	Yes (10% or 20%)	N/A	Yes (10%)	Yes (7.5% or 30%)	No

Impact from Geometry and Location, and Façade Characteristics

- Radiant heat from glass



BCA ACADEMY

Heat Transfer Fundamentals

The Education and Research arm of the Building and Construction Authority

Heat Transfer Fundamentals

- Heat exchanges follow 3 mechanisms
- Convection = air flows
- Conduction = across façade material (heat gradient)
- Radiation = infrared rays
- Each mechanism requires different control methods

BCA ACADEMY

Heat Transfer Fundamentals

- Understanding convection:
- Air flow through perimeter of windows and doors
- Air circulation within IGUs with large gaps

The Education and Research arm of the Building and Construction Authority

Heat Transfer Fundamentals

- Understanding conduction:
- Corresponds to what is commonly referred to as good or poor "heat conductor"

Heat Transfer Fundamentals

- Understanding radiative heat:
- Corresponds to IR radiation
- Can be direct or indirect

Heat Transfer Fundamentals

- How to minimise heat transfers?

BCA ACADEMY

Heat Transfer Fundamentals

- Convection = air movement across façade
- Should be minimised, guidelines provided in SS212 and CP96
- Need for proper seals, minimal air infiltration and exfiltration

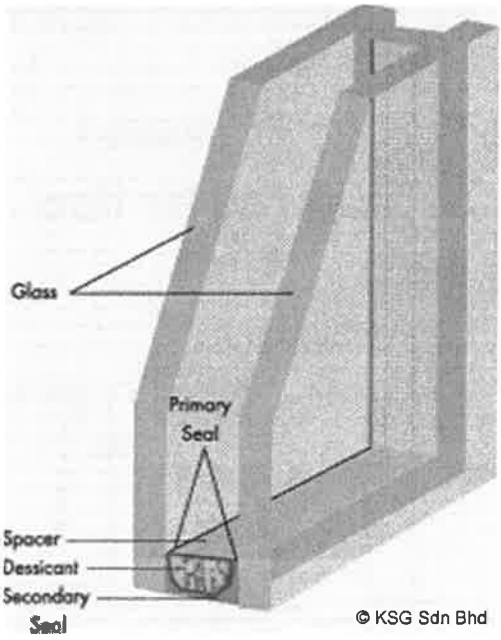
SS212 window CP96 curtain wall

Heat Transfer Fundamentals

- Conduction = heating or cooling of separating medium (wall, glass, etc.)
- Little difference between inside and outside, not most critical in Singapore climate
- Only small influence on ETTV locally
- Can be critical on overseas projects

BCA ACADEMY

Heat Transfer Fundamentals



- Can use IGUs (low U-value)
- For improved performance, use gas fills (Ar, Xe, etc.)
- Low-e glass also lowers U-value slightly

Heat Transfer Fundamentals

Inert Gas Fills

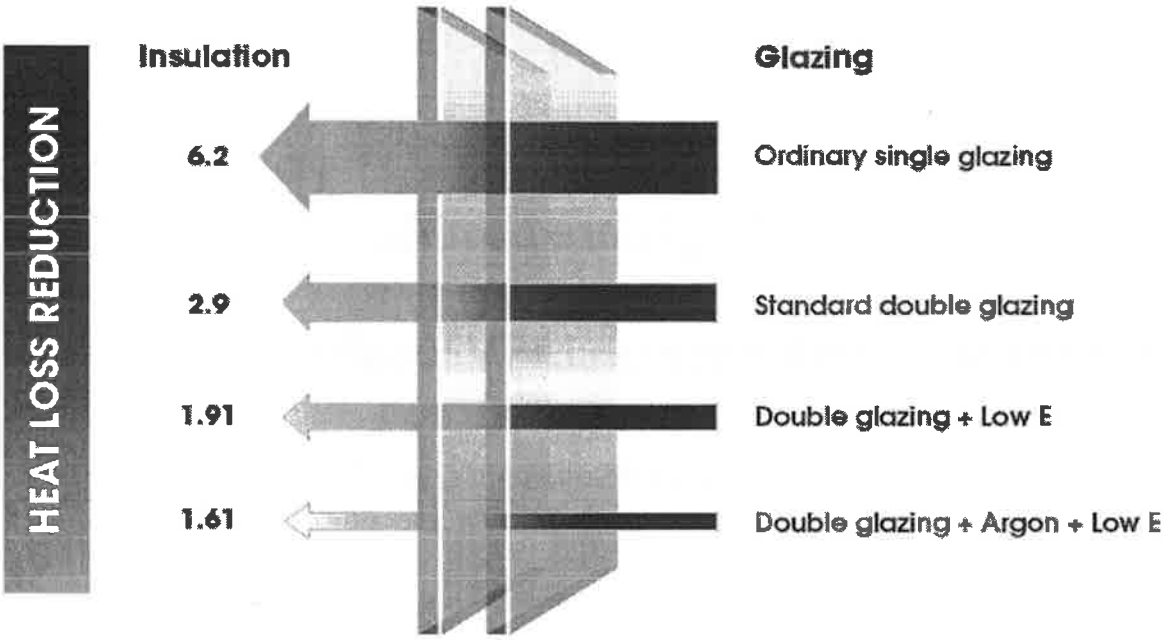
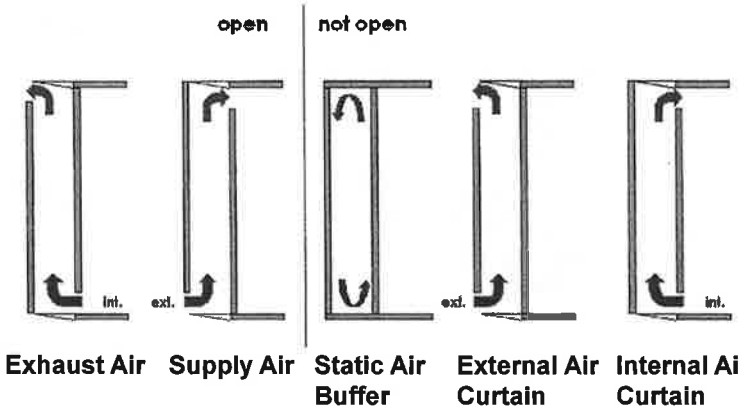


Image © www.festive.co.nz

Heat Transfer Fundamentals

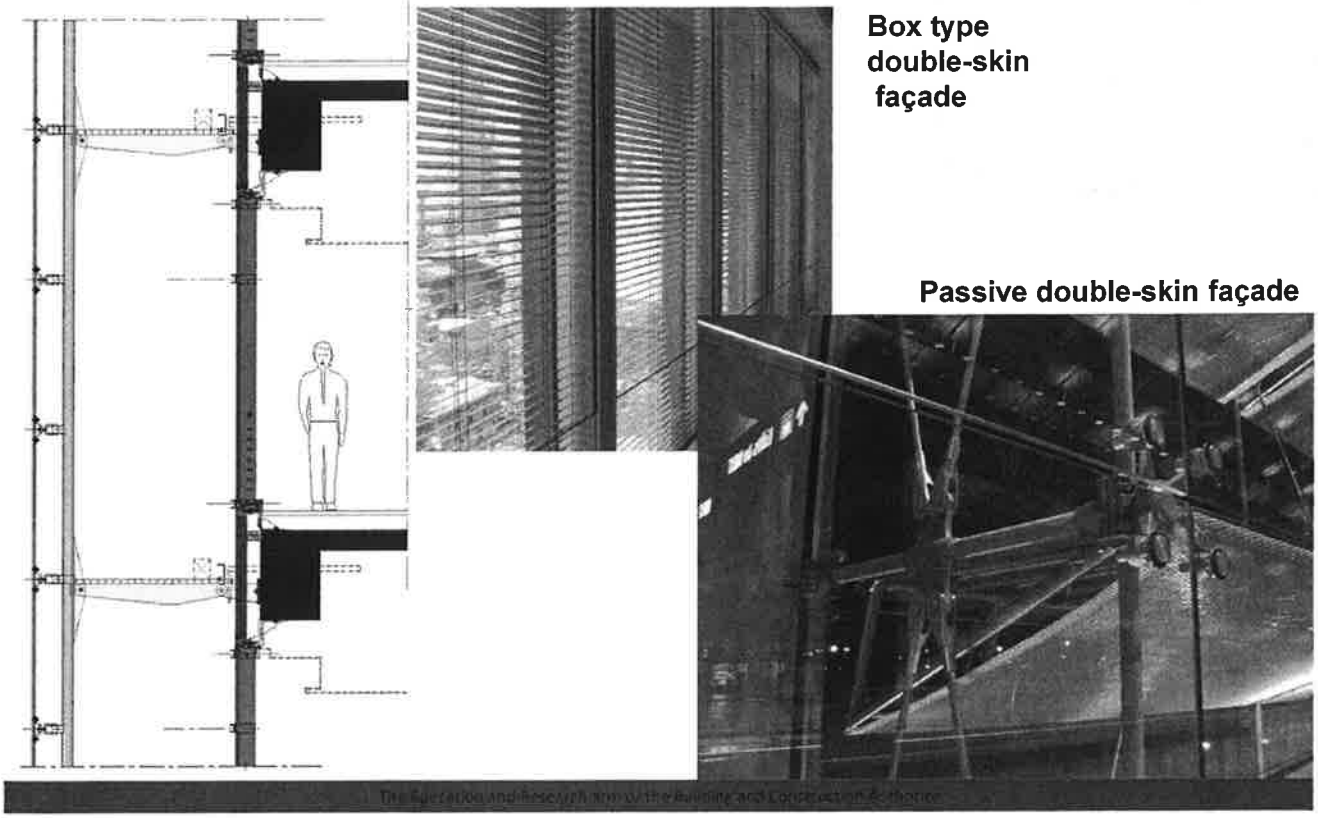


- Can also use double-skin façade
- DSF can be active or passive, with natural or forced air flow



AdPuC

Heat Transfer Fundamentals



Box type double-skin façade

Passive double-skin façade

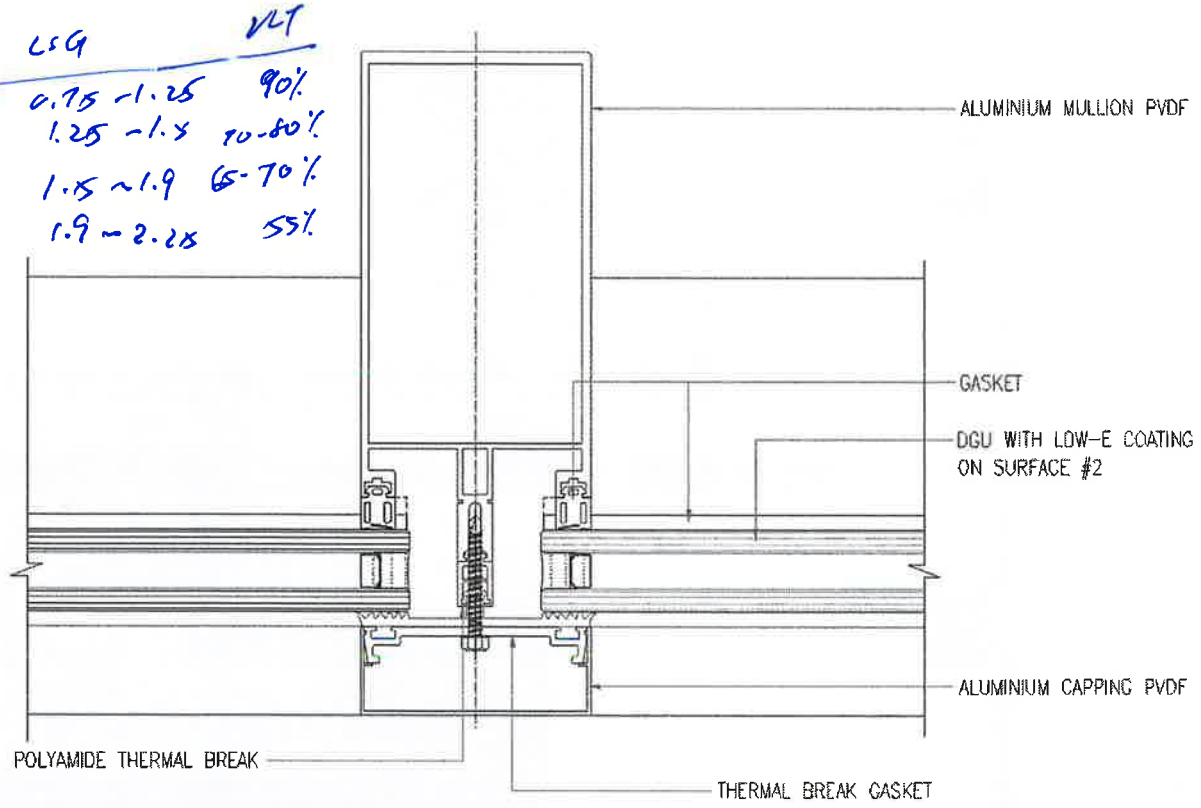
BCA ACADEMY

Heat Transfer Fundamentals

- Metal frames also conduct heat
- Can use thermally-broken system to minimise effect
- Not very relevant locally, better suited to continental or dry-hot climate

Heat Transfer Fundamentals

type	LSG	VLT
mono	0.75 – 1.25	90%
low E1	1.25 – 1.5	70-80%
low E2	1.5 – 1.9	65-70%
low E3	1.9 – 2.25	55%



Light to solar gain VLT visual light transmittance

$LSG = \frac{VLT}{SHGC} = \frac{0.3}{0.16} = 2.$

BCA ACADEMY

Heat Transfer Fundamentals

- More important in local climate, with high IR intensity
- Most influential on ETTV computations
- Controlled by glass SC / SHGC, which measures IR transmittance
- Indirect relationship between SC and visible light transmittance

$SHGC = \frac{IR(in)}{IR(incident)}$

$SC = \frac{SHGC(glass)}{SHGC(3mm\ clear)}$. Solar Heat Gain coefficient — Direct solar heat gain 0 → 1.

$SHGC = SC \times 0.87$

Heat Transfer Fundamentals

- Old approach = use of tinted or reflective glass (not targeted, problematic), limit vision areas
- Architectural trend to have maximum vision area
- Current preference for glass as clear as possible
- Contradiction between aesthetics and green requirements

BCA ACADEMY

Heat Transfer Fundamentals



- Possible to build in internal blinds, but heat already inside building
- Can result in "checker board" look

Heat Transfer Fundamentals

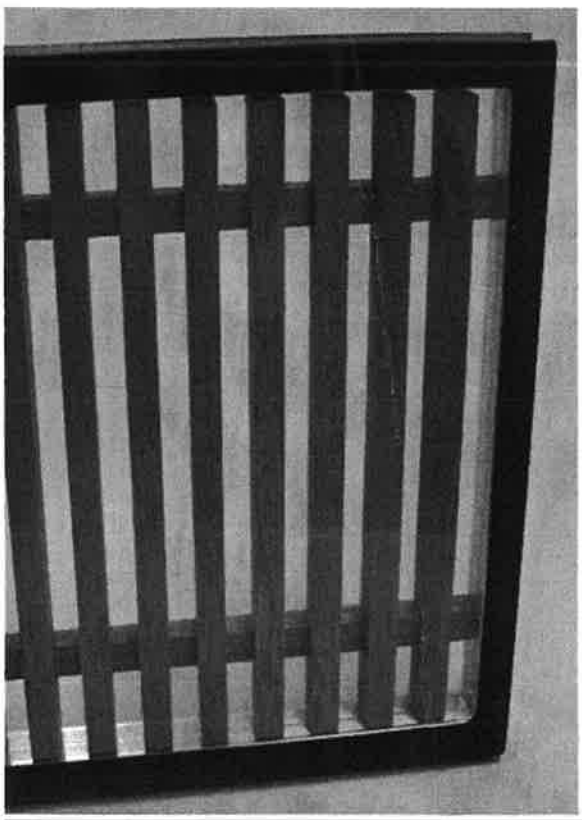


- Can build external shading device, but costly, hard to maintain, visually strong, not effective at all angles



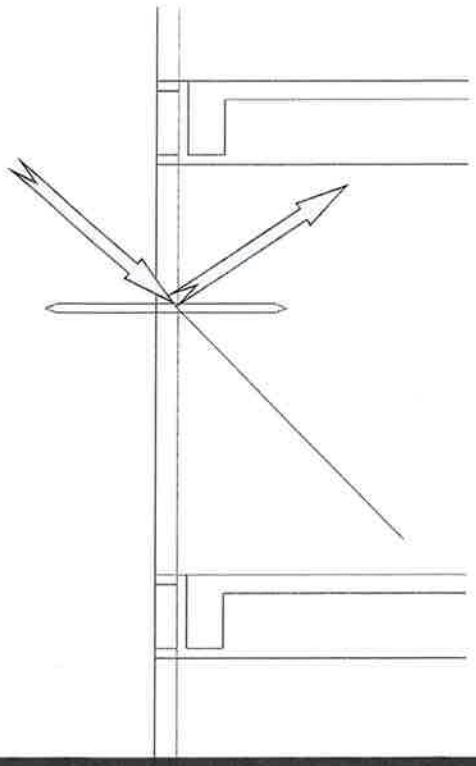
BCA ACADEMY

Heat Transfer Fundamentals



- Can use glass with built-in shading device, but expensive, and same issue as external louvers
- Mechanically operated versions available, but difficult to maintain

Heat Transfer Fundamentals

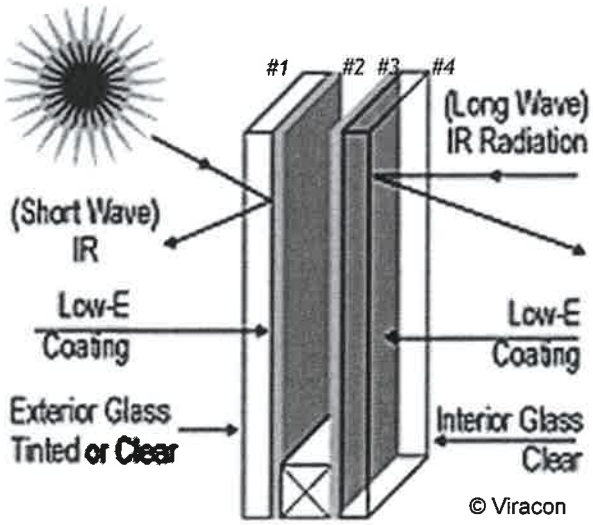


- Blinds and louvers not selective, also block out visible light
- Can adopt a light-shelf system instead, depending on local regulations and building layout

Soft coating → Add on later. Needed to be protected.
Hard coating → Fuse into the glass. - Protected by glass.
1st general low E - performance not good.

BCA ACADEMY

Heat Transfer Fundamentals



- Low-emissivity glass can give all glass look, with good solar performance
- Reflects IR with minimal effect on visible light
- Different coating and surface depending on climate

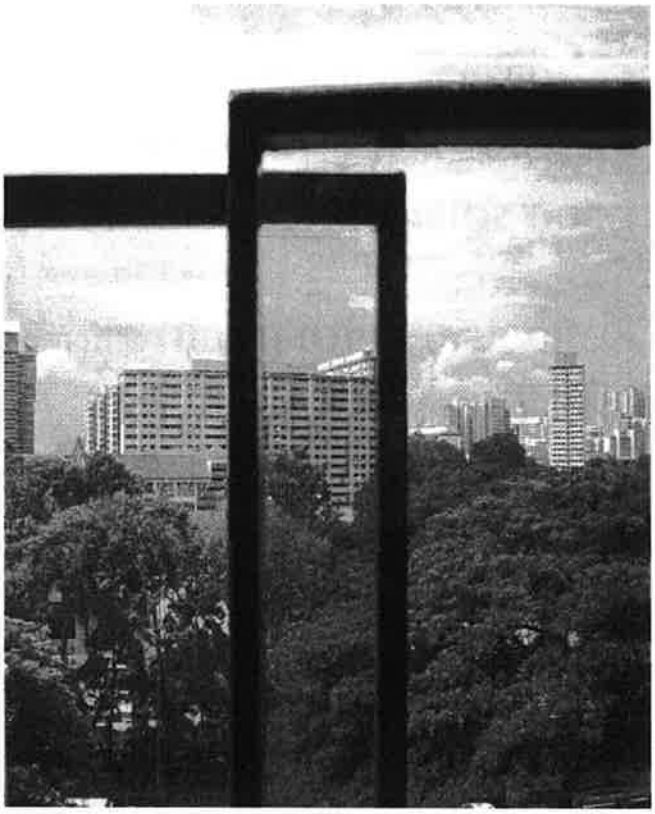
not coating surface #2
coating surface #3

DVB polyvinyl butyl low E - to protect silver coating by using Double glazing.

Heat Transfer Fundamentals

- Low-e coating typically requires DGUs (soft coat)
- Can consider hard-coated low-e glass for specific areas (entrances, etc.)
- Soft-coated low-e performs better than hard-coated low-e, but not always possible to adopt

Heat Transfer Fundamentals



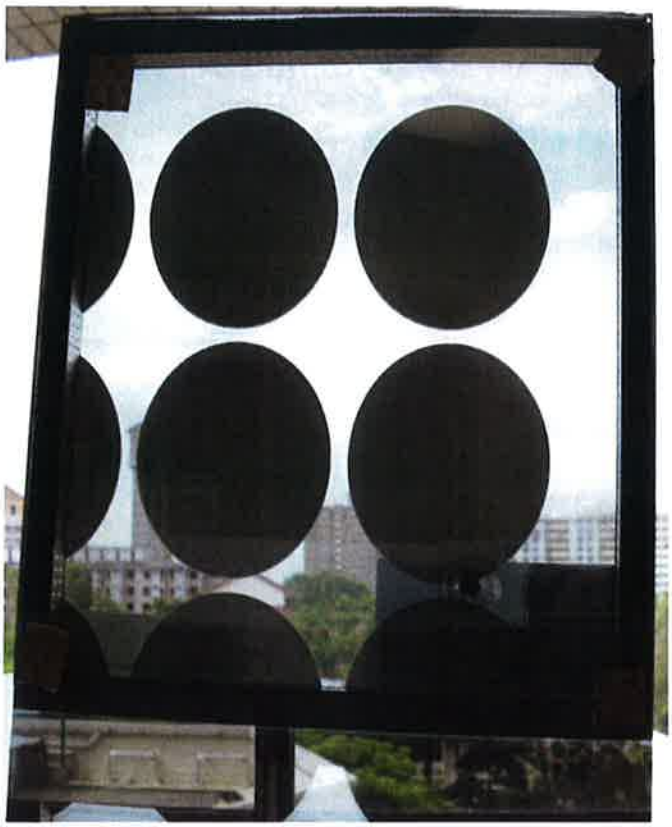
- Left: clear DGU, VLT=80%, SC=0.85
- Right: clear DGU with low-e coating, VLT=52%, SC=0.32

Heat Transfer Fundamentals

- Possible to use ceramic frit coating
- Cuts out glare and radiative heat
- Highly flexible colours and patterns
- Can be visually distracting

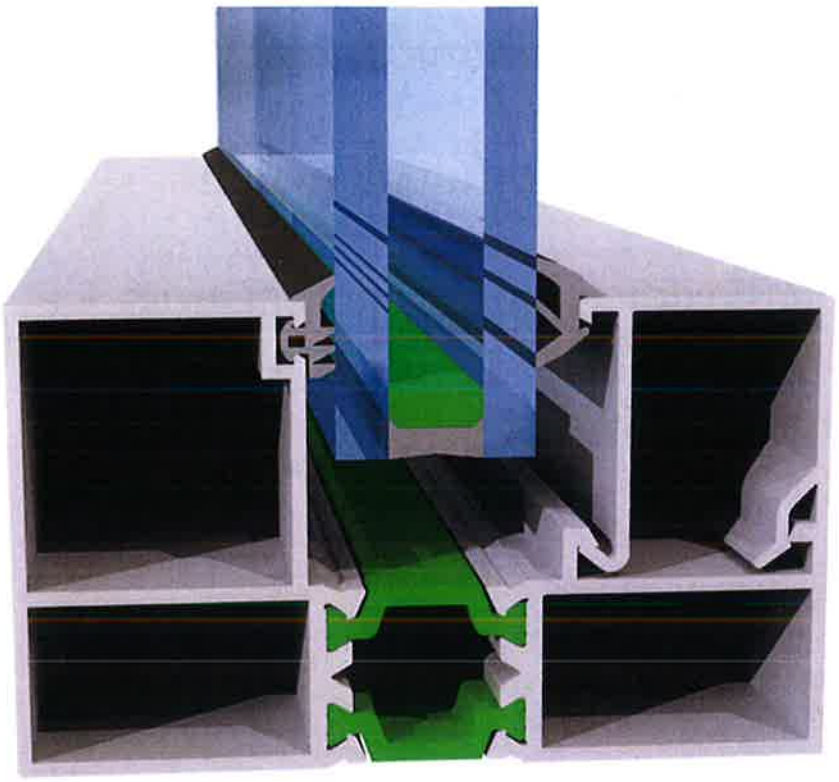
BCA ACADEMY

Heat Transfer Fundamentals



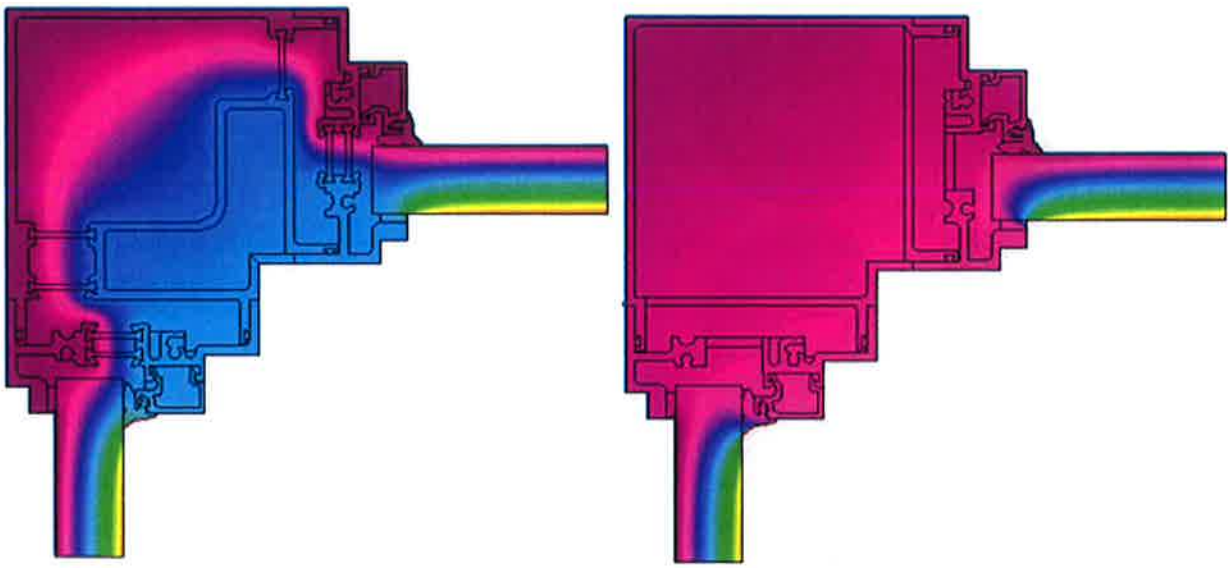
- Large dot ceramic frit pattern (about 60% coverage)

Thermally-Broken Frames



BCA ACADEMY

Thermally-Broken Frames



The Education and Research arm of the Building and Construction Authority

Need to Assess ROI



Option	Glass	HVAC Cost	Façade Cost *	TOTAL COST *
Option 1	SC of 0.34; U-Value of 1.80 W/m² °K	$ 5,500,000.00	$ 7,475,200	**$ 12,975,200.00**
Option 2	SC of 0.34; U-Value of 5.10 W/m² °K	$ 5,870,000.00	$ 7,539,440	**$ 13,409,440.00**
Option 3	SC of 0.40; U-Value of 1.80 W/m² °K	$ 5,670,000.00	$ 7,349,640	**$ 13,019,640.00**
Option 4a	SC of 0.40; U-Value of 5.10 W/m² °K	$ 6,040,000.00	$ 7,008,000	**$ 13,048,000.00**
Option 4b	SC of 0.40; U-Value of 5.10 W/m² °K	$ 6,040,000.00	$ 6,894,120	**$ 12,934,120.00**
Option 5	SC of 0.70; U-Value of 5.10 W/m² °K	$ 6,790,000.00	$ 6,716,000	**$ 13,506,000.00**
Option 6	SC of 0.43; U-Value of 6.12 W/m² °K	$ 6,230,000.00	$ 7,008,000	**$ 13,238,000.00**

Image credit: RTKL

BCA ACADEMY

ETTV and RETV Equations

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

Definitions

- U-value: Measures how effective a material is an insulator. The lower the U-value is, the better the insulator [$W/m^2.^\circ K$]
- R-value: Measures how effective a material is an heat conductor. The higher the R-value, the greater the insulating effectiveness [$m^2.^\circ K/W$]
- k-value: thermal conductivity. It is the property of a material to conduct heat [$m.^\circ K/W$]

Definitions

- SHGC: fraction of incident solar radiation admitted through glass, both directly transmitted and absorbed and subsequently released inward. SHGC is expressed as a number between 0 and 1.
- SC: ratio of solar gain passing through a glass unit to the solar energy which passes through 3mm clear glass. Commonly between 0 and 1 (can be slightly higher than 1).

Definitions

- g-value: coefficient commonly used in Europe to measure the solar energy transmittance of glass. G-value is expressed as a number between 0 and 1 (or as a percentage).
- RHG: The total heat gain through glass for a specific set of conditions. This value considers indoor/outdoor air temperature differences and the effect of solar radiation. It is not used for direct computations, but as comparison tool.

Radiation Heat Gain

ETTV Equation

- Base equation for single façade type

$$ETTV = 12(1 - WWR)U_w + 3.4(WWR)U_f + 211(WWR)(CF)(SC)$$

where

ETTV	:	envelope thermal transfer value (W/m^2)
WWR	:	window-to-wall ratio (fenestration area / gross area of exterior wall)
U_w	:	thermal transmittance of opaque wall ($W/m^2\,^oK$)
U_f	:	thermal transmittance of fenestration ($W/m^2\,^oK$)
CF	:	correction factor for solar heat gain through fenestration
SC	:	shading coefficients of fenestration

ETTV Equation

- Base equation for multiple façade types

$$ETTV = \frac{12(A_{w1} \times U_{w1} + A_{w2} \times U_{w2} + \ldots + A_{wn} \times U_{wn})}{A_o} +$$

$$\frac{3.4(A_{f1} \times U_{f1} + A_{f2} \times U_{f2} + \ldots + A_{fn} \times U_{fn})}{A_o} +$$

$$\frac{211(A_{f1} \times SC_{f1} + A_{f2} \times SC_{f2} + \ldots + A_{fn} \times SC_{fn})(CF)}{A_o}$$

where

A_{w1}, A_{w2}, A_{wn}	:	areas of different opaque wall (m^2)
A_{f1}, A_{f2}, A_{fn}	:	areas of different fenestration (m^2)
A_o	:	gross area of the exterior wall (m^2)
U_{w1}, U_{w2}, U_{wn}	:	thermal transmittances of opaque walls ($W/m^2\,^oK$)
U_{f1}, U_{f2}, U_{fn}	:	thermal transmittances of fenestrations ($W/m^2\,^oK$)
$SC_{f1}, SC_{f2}, SC_{fn}$	:	shading coefficients of fenestrations

BCA ACADEMY

ETTV Equation

- Overall ETTV for multiple façade types

$$ETTV = \frac{A_{o1} \times ETTV_1 + A_{o2} \times ETTV_2 + \ldots + A_{on} + ETTV_n}{A_{o1} + A_{o2} + \ldots + A_{on}}$$

where

A_{o1}, A_{o2}, A_{on} : gross areas of the exterior wall for each orientation (m^2)

ETTV Equation

- Applies to non-residential building. The maximum allowable ETTV depends on the type of certification
- Maximum for all buildings = 50W/m^2
- Maximum for GM Platinum buildings = 38W/m^2
- Maximum for GM GoldPlus buildings = 40W/m^2
- Maximum for GM Gold buildings = 45W/m^2

This Educational Presentation is the property of the Building and Construction Authority

RTTV Equation

- Applicable to air-conditioned building is provided with skylight (single type)

$$RTTV = 12.5(1-SKR)U_r + 4.8(SKR)U_s + 485(SKR)(CF)(SC)$$

where

RTTV : roof thermal transfer value (W/m^2)
SKR : skylight ratio of roof (skylight area / gross area of roof)
U_r : thermal transmittance of opaque roof (W/m^2 K)
U_s : thermal transmittance of skylight area (W/m^2 K)
CF : solar correction factor for roof
SC : shading coefficient of skylight portion of the roof

This Educational Presentation is the property of the Building and Construction Authority

RTTV Equation

- Applicable to air-conditioned building is provided with skylight (multiple types)

$$RTTV = \frac{12.5(A_{r1} \times U_{r1} + A_{r2} \times U_{r2} + ... + A_{rn} \times U_{rn})}{A_o} + \frac{4.8(A_{s1} \times U_{s1} + A_{s2} \times U_{s2} + ... + A_{sn} \times U_{sn})}{A_o} + \frac{485(A_{s1} \times SC_{s1} + A_{s2} \times SC_{s2} + ... + A_{sn} \times SC_{sn})(CF)}{A_o}$$

where

A_{r1}, A_{r2}, A_{rn}	:	areas of different opaque roof (m^2)
A_{s1}, A_{s2}, A_{sn}	:	areas of different skylight (m^2)
A_o	:	gross area of roof (m^2)
U_{r1}, U_{r2}, U_{rn}	:	thermal transmittances of opaque roofs ($W/m^2 K$)
U_{s1}, U_{s2}, U_{sn}	:	thermal transmittances of skylights ($W/m^2 K$)
$SC_{s1}, SC_{s2}, SC_{sn}$	:	shading coefficient of skylights

RTTV Equation

- Applicable to air-conditioned building is provided with skylight (multiple types)

$$RTTV = \frac{A_{o1} \times RTTV_1 + A_{o2} \times RTTV_2 + ... A_{on} \times RTTV_n}{A_{o1} + A_{o2} + ... + A_{on}}$$

where

A_{o1}, A_{o2}, A_{on} :gross areas of the roof for each section (m^2)

RETV Equation

- Base equation for single façade type

$$RETV = 3.4(1-WWR)U_w + 1.3(WWR)U_f + 58.6(WWR)(CF)(SC)$$

where

RETV	:	residential envelope transmittance value (W/m^2)
WWR	:	window-to-wall ratio (fenestration area/gross area of exterior wall)
U_w	:	thermal transmittance of opaque wall (W/m^2 K)
U_f	:	thermal transmittance of fenestration (W/m^2 K)
CF	:	correction factor for solar heat gain through fenestration
SC	:	shading coefficients of fenestration

The Knowledge and Research Arm of the Singapore Construction Authority

RETV Equation

- Base equation for multiple façade types

$$RETV = \frac{3.4(A_{w1}\times U_{w1} + A_{w2}\times U_{w2} + \ldots + A_{wn}\times U_{wn})}{A_o} +$$

$$\frac{1.3(A_{f1}\times U_{f1} + A_{f2}\times U_{f2} + \ldots + A_{fn}\times U_{fn})}{A_o} +$$

$$\frac{58.6(A_{f1}\times SC_{f1} + A_{f2}\times SC_{f2} + \ldots + A_{fn}\times SC_{fn})(CF)}{A_o}$$

where

A_{w1}, A_{w2}, A_{wn}	:	areas of different opaque walls (m^2)
A_{f1}, A_{f2}, A_{fn}	:	areas of different fenestrations (m^2)
A_o	:	gross area of the exterior wall (m^2)
U_{w1}, U_{w2}, U_{wn}	:	thermal transmittances of opaque walls (W/m^2 K)
U_{f1}, U_{f2}, U_{fn}	:	thermal transmittances of fenestrations (W/m^2 K)
SC_{f1}, SC_{f2}, SC_{fn}	:	shading coefficients of fenestrations

The Knowledge and Research Arm of the Singapore Construction Authority

RETV Equation

- Base equation for multiple façade types

$$RETV = \frac{A_{o1} \times RETV_1 + A_{o2} \times RETV_2 + \ldots + A_{on} + RETV_n}{A_{o1} + A_{o2} + \ldots + A_{on}}$$

where
A_{o1}, A_{o2}, A_{on} : gross areas of the exterior wall for each orientation (m^2)

RETV Equation

- Exemption from actual computation if...

$WWR_{Bldg} < 0.3$ and $SC^1_{facade} < 0.7$

or

$WWR_{Bldg} < 0.4$ and $SC^1_{facade} < 0.5$

or

$WWR_{Bldg} < 0.5$ and $SC^1_{facade} < 0.43$

where

WWR : Window to wall ratio

SC : Shading coefficient of fenestration = SC_{Glass} X $SC_{shading\ device}$

Note: This is applicable to buildings with external masonry walls.

[1] Each SC of the facade must not exceed the prescribed value.

Strategies to Lower ETTV and RETV

The Education and Research arm of the Building and Construction Authority

The Education and Research arm of the Building and Construction Authority

BCA ACADEMY

Strategies to Lower ETTV and RETV

- Add sunshades
- Different types for different orientations
- Optimal size/length

Strategies to Lower ETTV and RETV

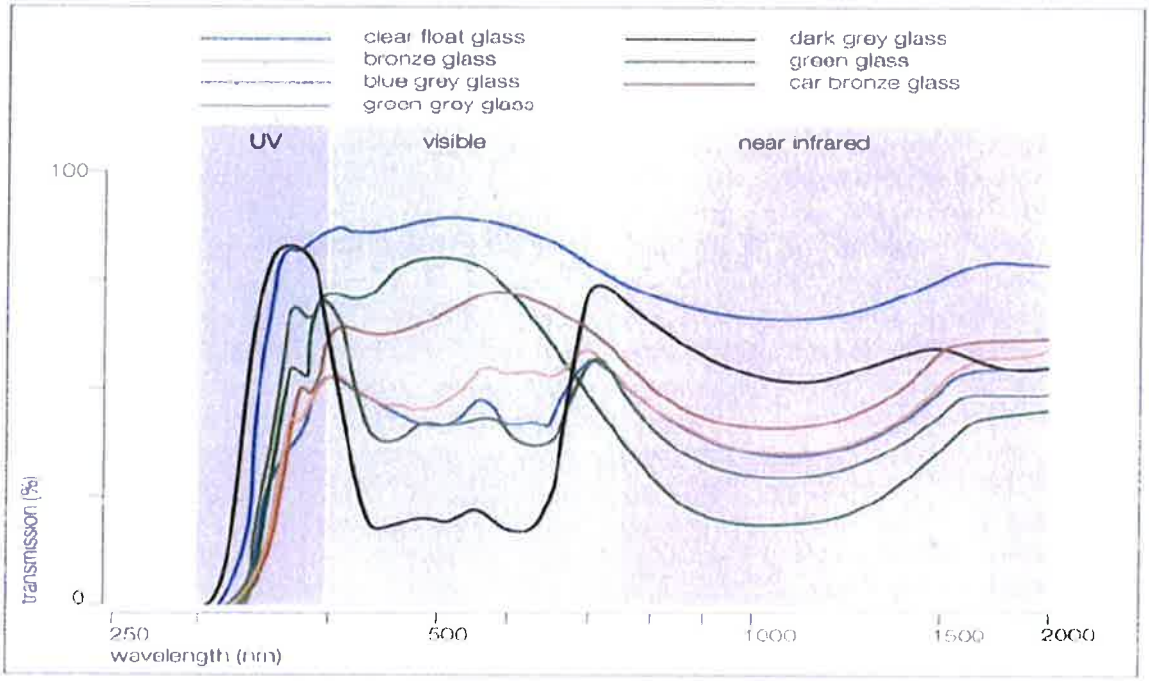
- Reduce WWR (more solid walls, enlarged spandrels)
- Insulate walls

BCA ACADEMY

Strategies to Lower ETTV and RETV

- Reduce glass SC by adding frit, tinted glass or more layers of silver in low-e
- Must strike a balance with daylight transmission
- Concept of LSG (light-to-solar gain ratio)

Strategies to Lower ETTV and RETV



LSG / SELECTIVITY = VLT / SHGC

SHGC = 0.87 x SC

BCA ACADEMY

Strategies to Lower ETTV and RETV

- Optimise East and West elevations preferentially
- Adjust performance for each elevation; spend where it counts

The Education and Research arm of the Building and Construction Authority

Practical Exercises

Strategies to Lower ETTV and RETV

- Practical application exercise: compute U-value of wall assembly

Strategies to Lower ETTV and RETV

- Practical application exercise: compute ETTV of simple façade

BCA ACADEMY

Strategies to Lower ETTV and RETV

- Practical application exercise: effect of orientation

Strategies to Lower ETTV and RETV

- Practical application exercise: effect of WWR

Strategies to Lower ETTV and RETV

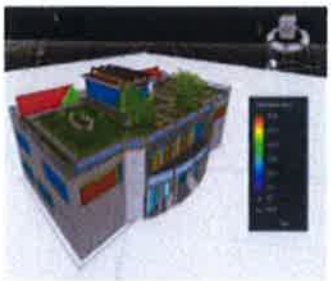
- Practical application exercise effect of SC versus U-value

Strategies to Lower ETTV and RETV

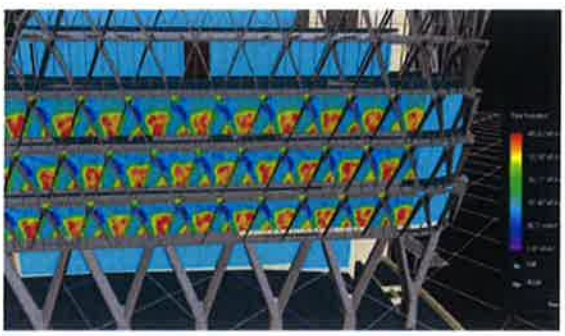
- Practical application exercise: effect of sunshades

Automated ETTV Computation

- BIM HVACTool



Sunpath and solar radiation analysis

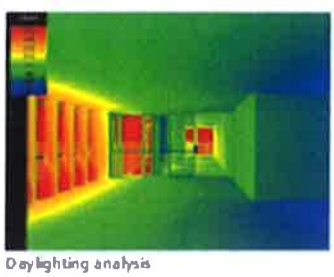




Detailed solar insolation analysis



Shadow analysis



Daylighting analysis

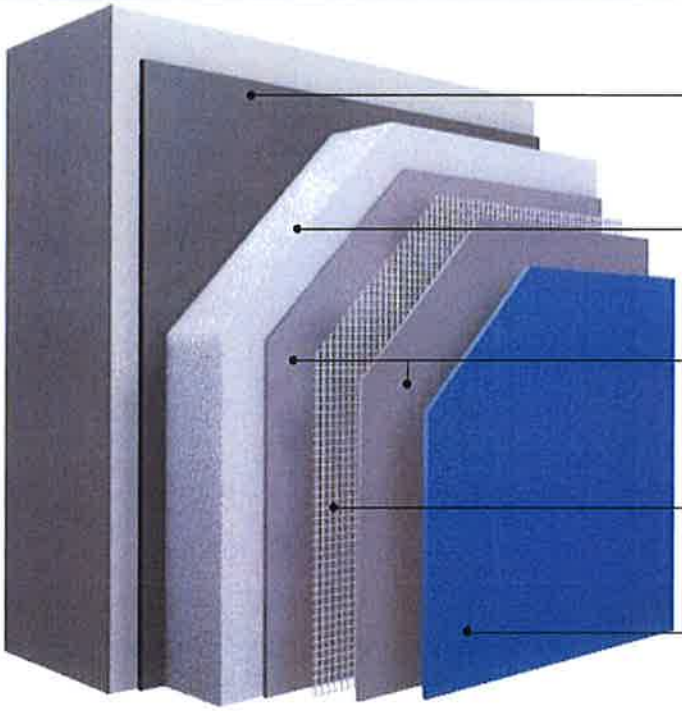
Innovative Façades

BCA ACADEMY

Innovative Façades

- Energy-Saving
- Water-Saving
- Indoor Environment Quality
- Other Environmental Considerations

Insulating Plaster for Solid Rendered Walls



Bonding: Sto-ADH-B

Mineral bound adhesive mortar. High adhesive strength on mineral, organic and non-elastic substrates.

Insulation: Sto EPS Board

Insulation board made from expanded polystyrene foam. CFC-free, of limited combustibility and shrinkage-free.

Reinforcing coat: StoArmat Classic

Organically bound, ready-to-use reinforcing coat. Highly elastic, low-stress, crack-proof and resistant to mechanical stress.

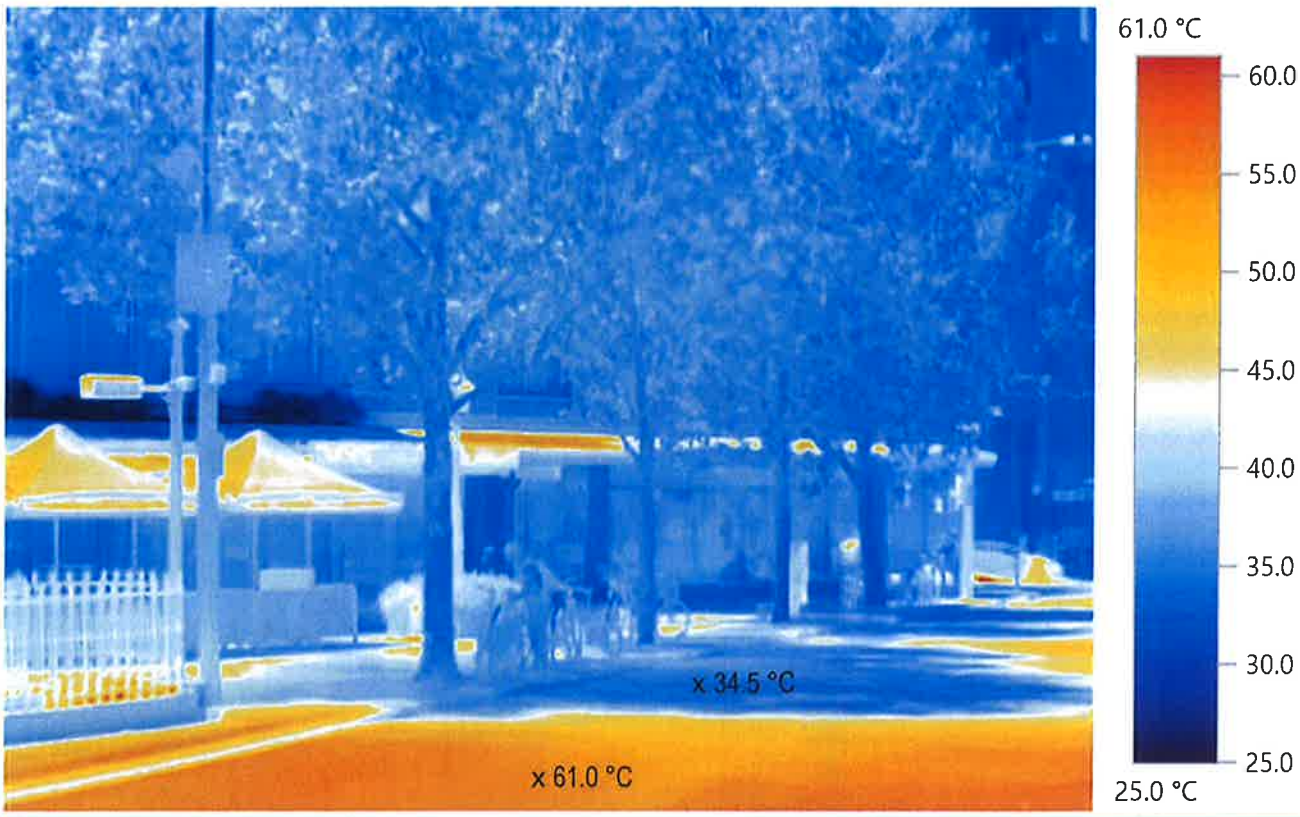
Reinforcing mesh: Sto Glass Fibre Mesh

Easy to install, meets the very highest requirements for crack and shock resistance.

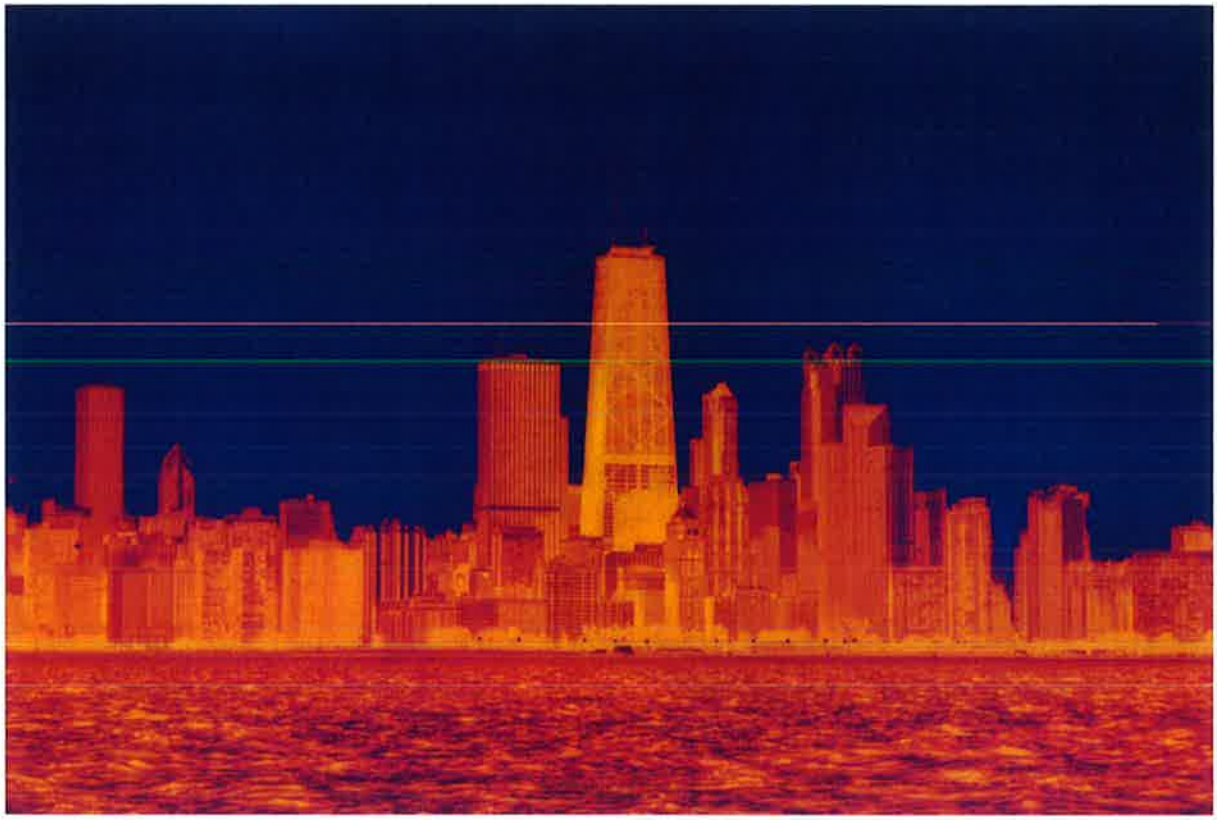
Top coat: Stolit, StoSilco

Organically bound, cement-free, ready-to-use finishing plasters for all substrates. Highly weather resistant, minimal susceptibility to soiling, highly elastic, resistant to mechanical stress. Film-conserved for enhanced resistance to micro-organisms (algae, fungus). Tintable according to the StoColor System.

Anti-Urban Heat Island Film

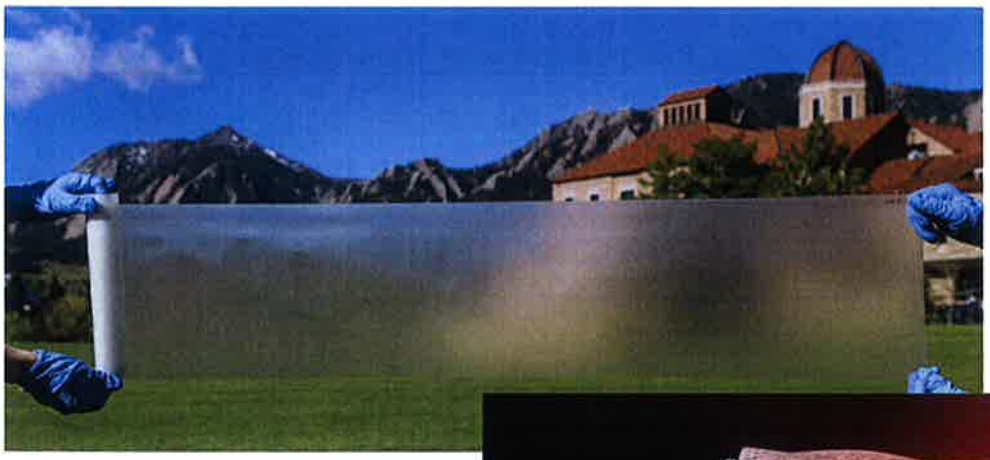


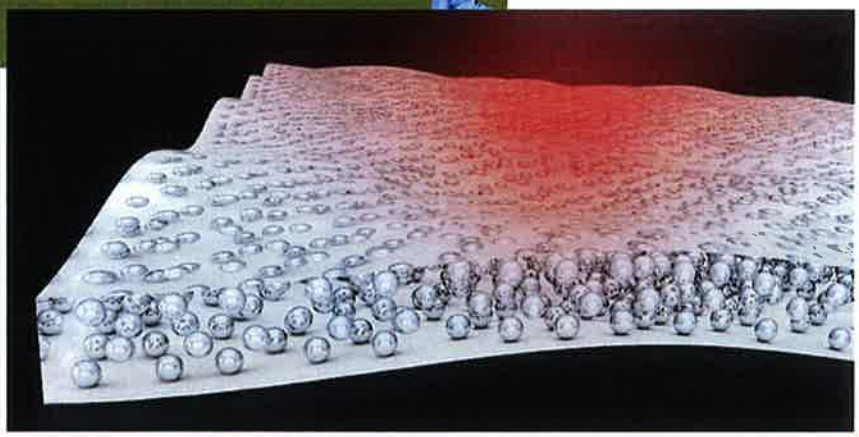
Anti-Urban Heat Island Film



BCA ACADEMY

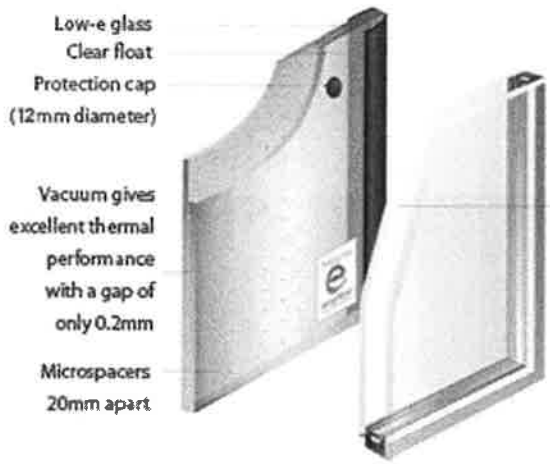
Anti-Urban Heat Island Film

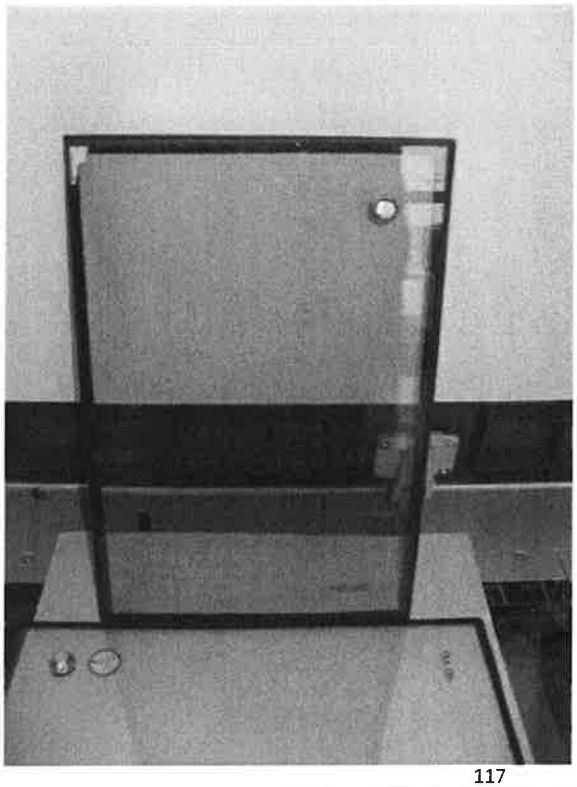




The Education and Research arm of the Building and Construction Authority

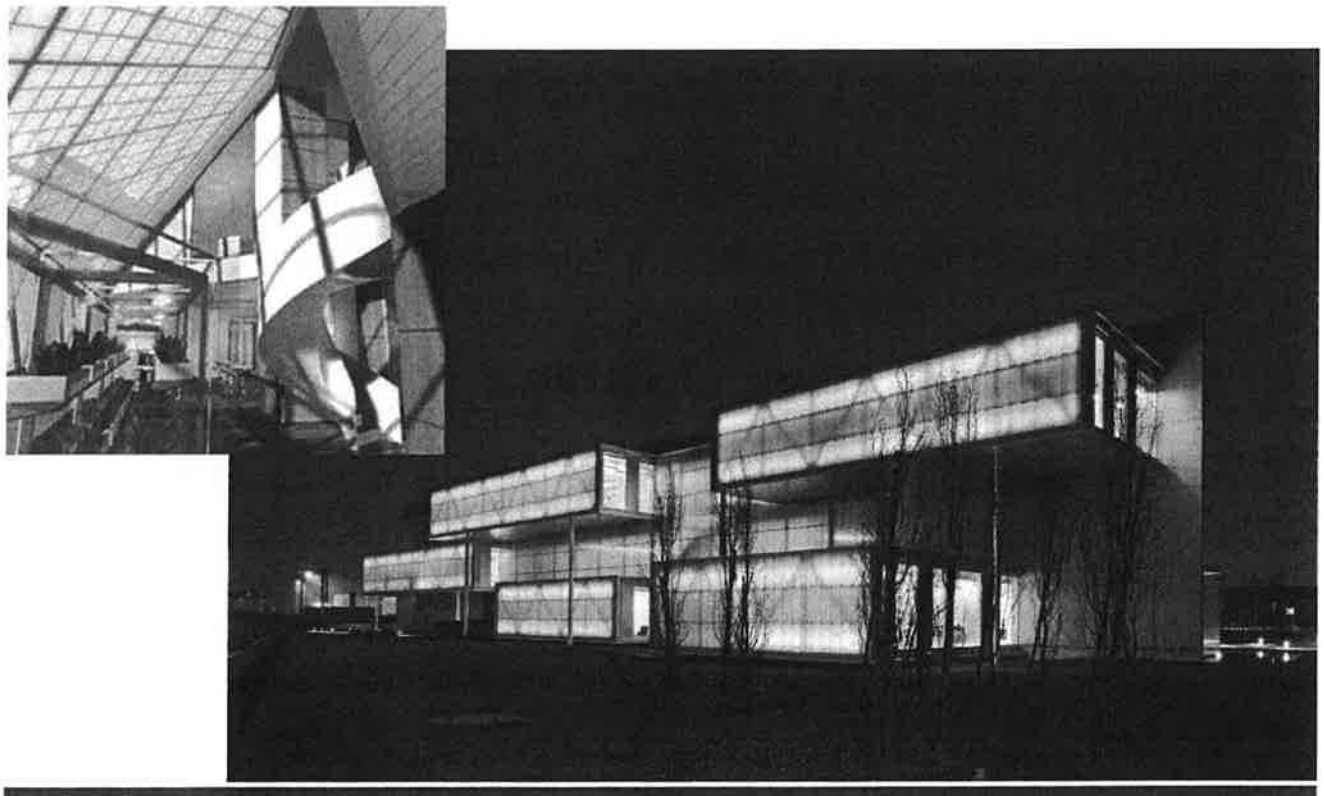
Vacuum-Insulated Panels





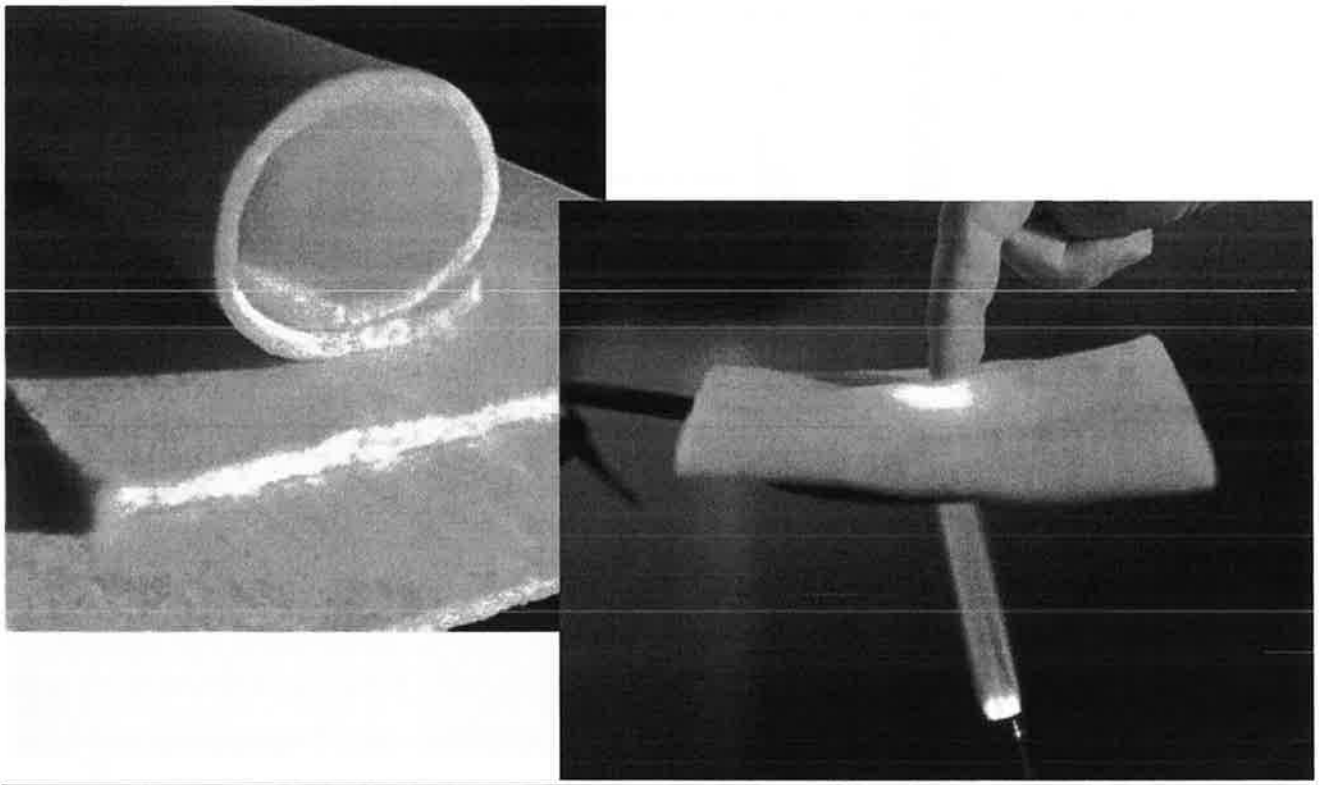
U = 0.5

Aerogel Glass For Roof Lights

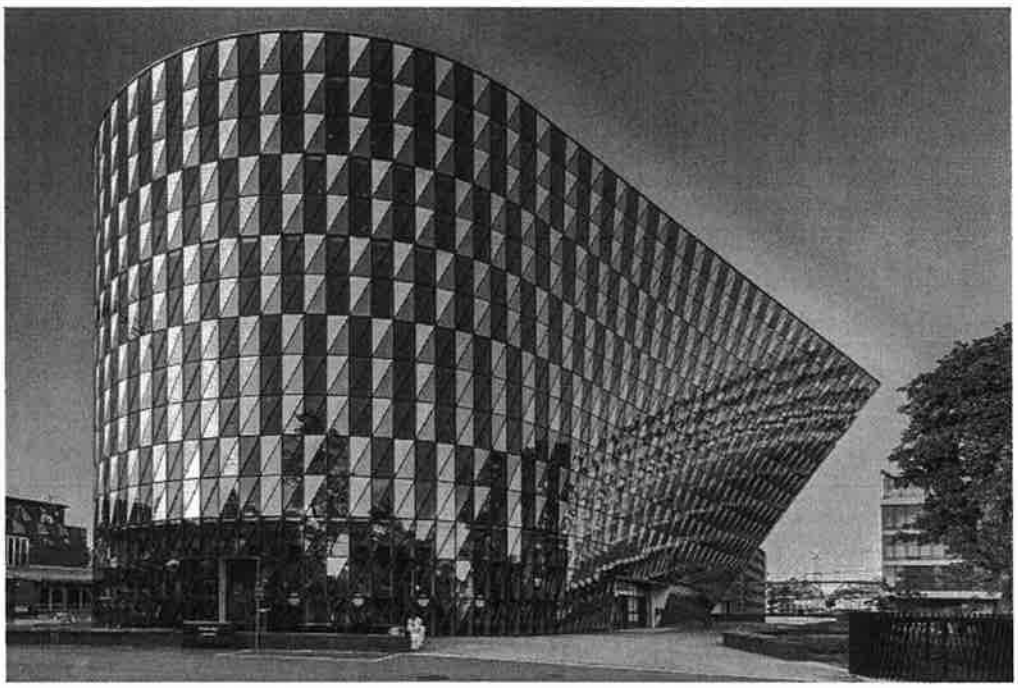


U = 0.1

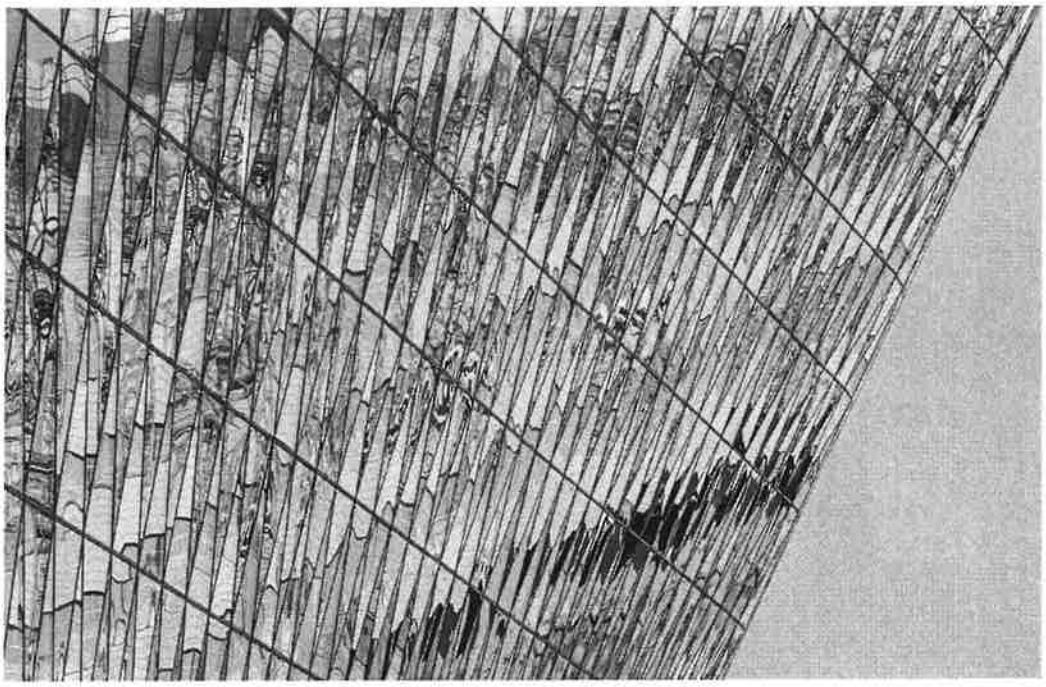
Aerogel Glass For Roof Lights



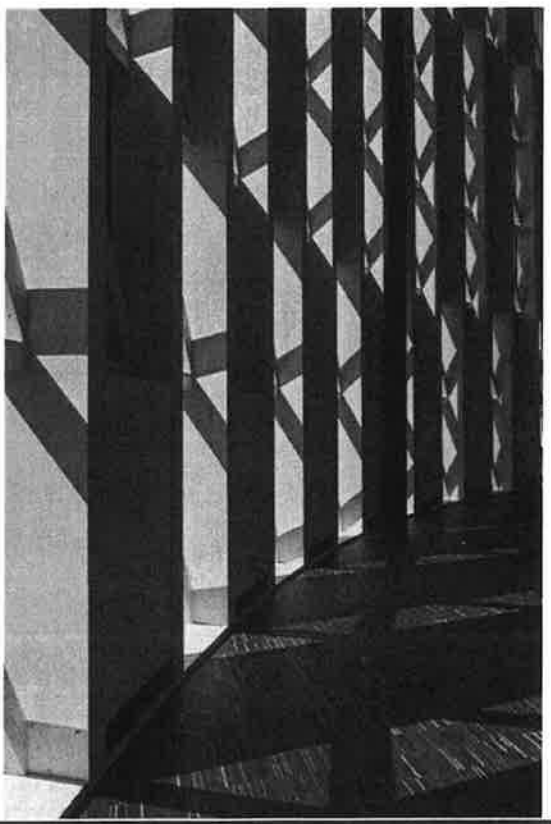
Timber-Framed Curtain Wall



Timber-Framed Curtain Wall



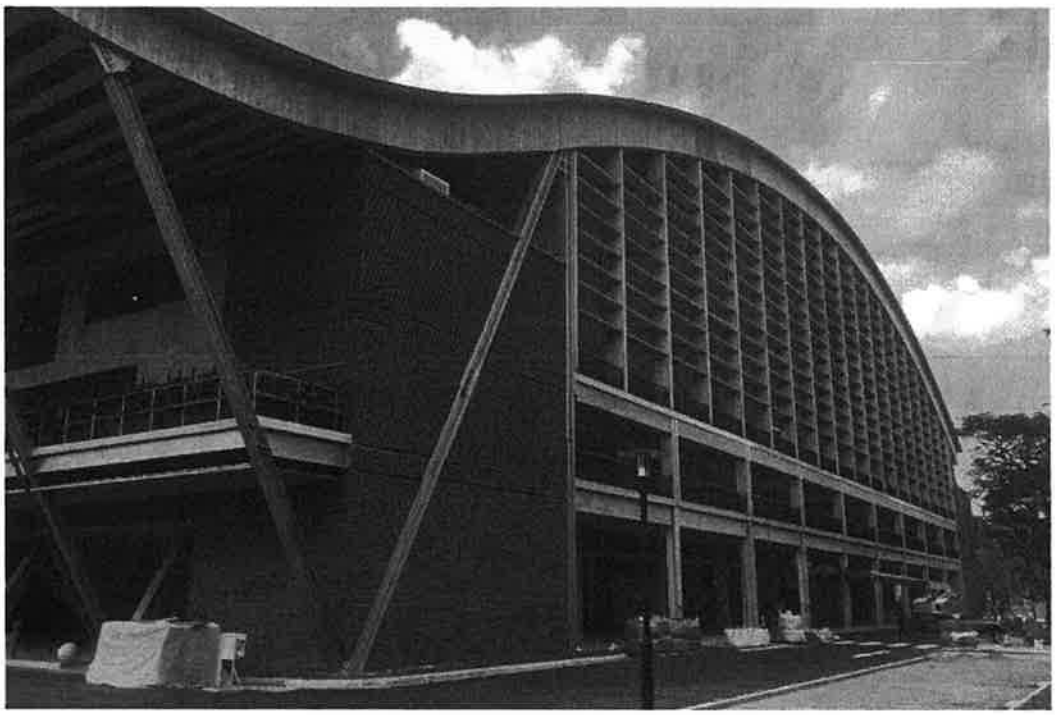
Timber-Framed Curtain Wall



Timber-Framed Curtain Wall



Timber-Framed Curtain Wall

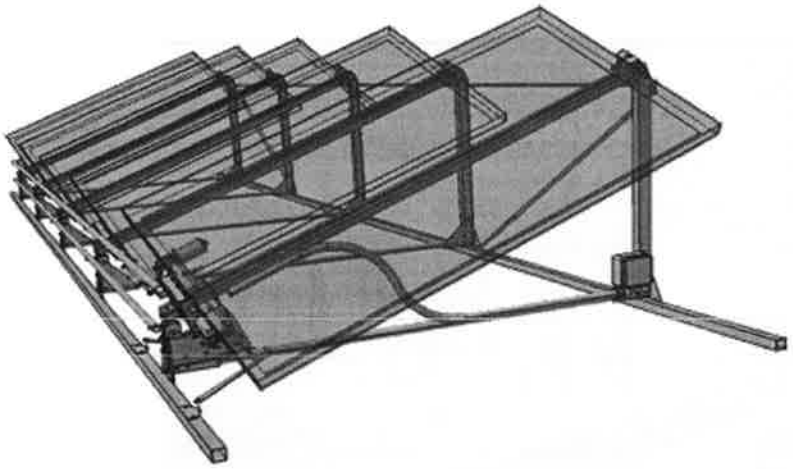


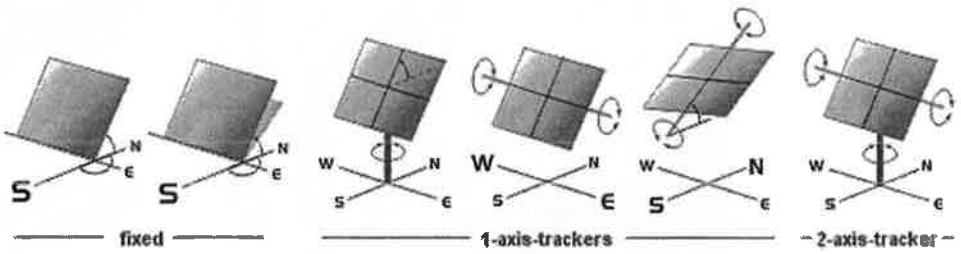
Timber-Framed Curtain Wall



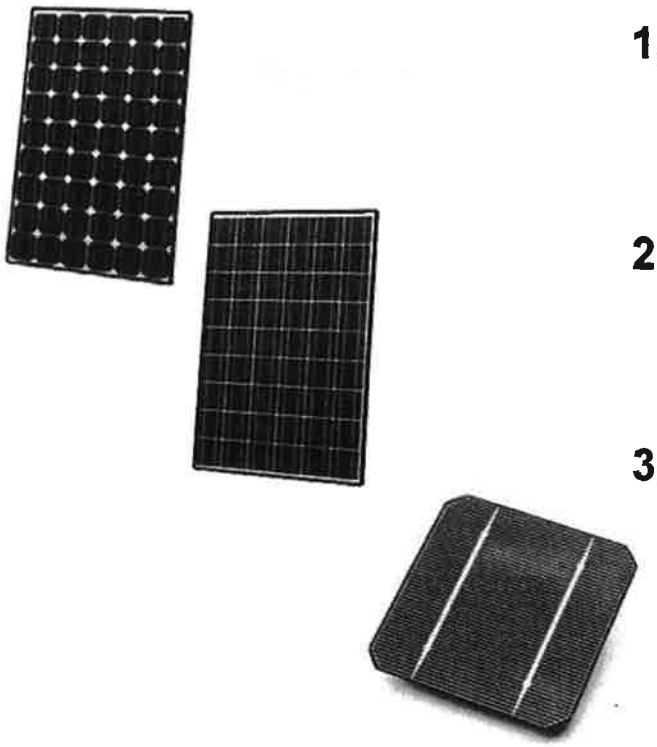
Energy-Generating Façades

Solar-Tracking PV Modules



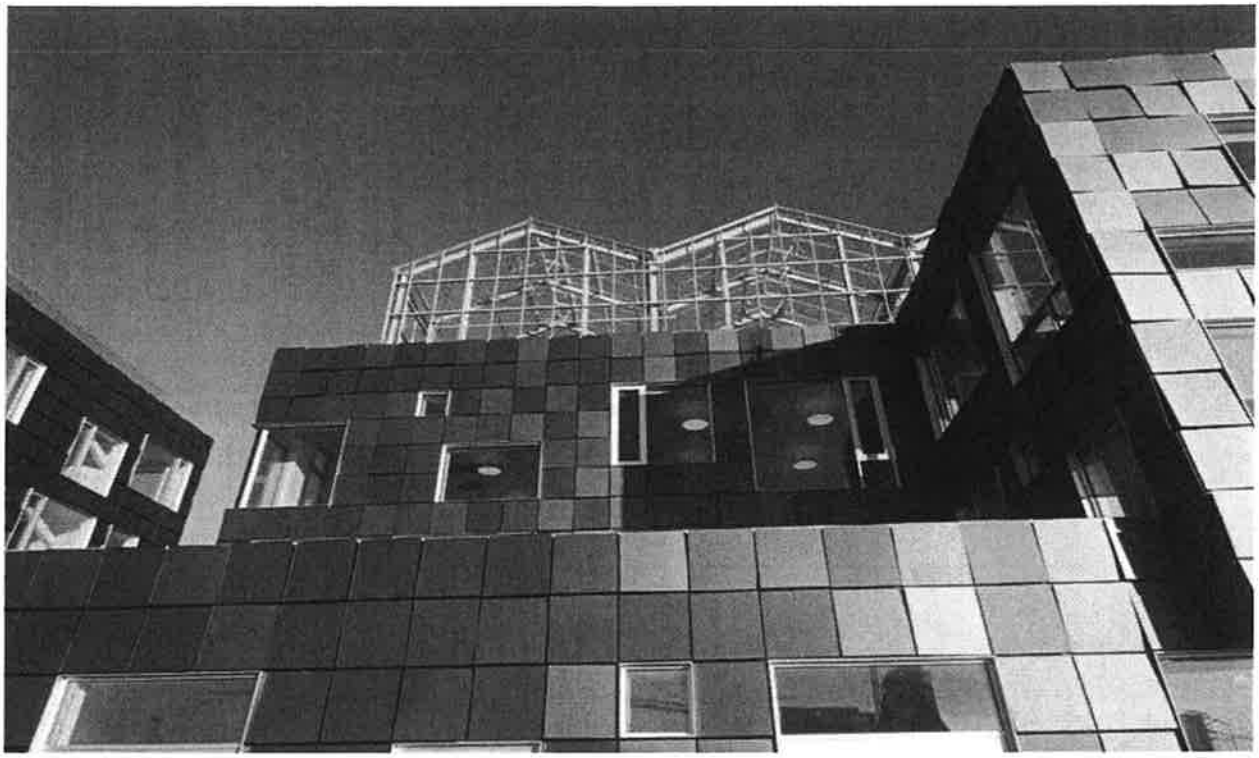


Solar-Tracking PV Modules

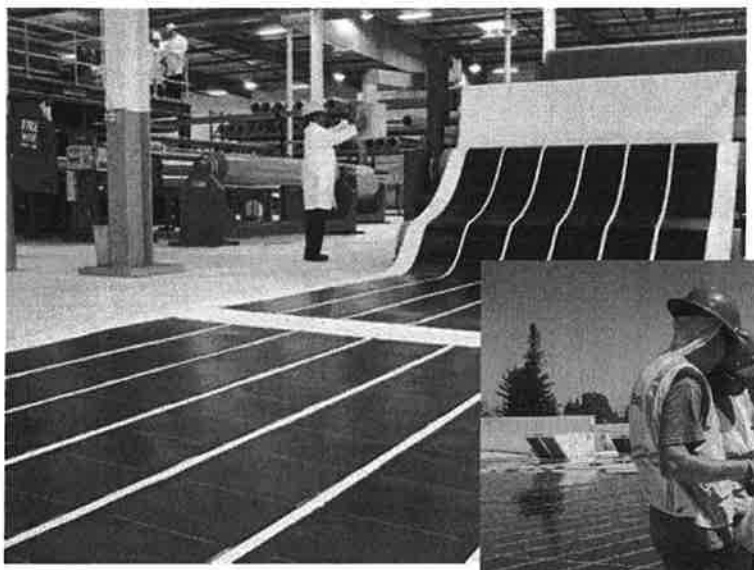


1. Mono-crystalline (high cost, high efficiency)
2. Poly-crystalline (medium cost, average efficiency)
3. Amorphous (low cost, low efficiency)

BIPV Façades



Thin Film Façades

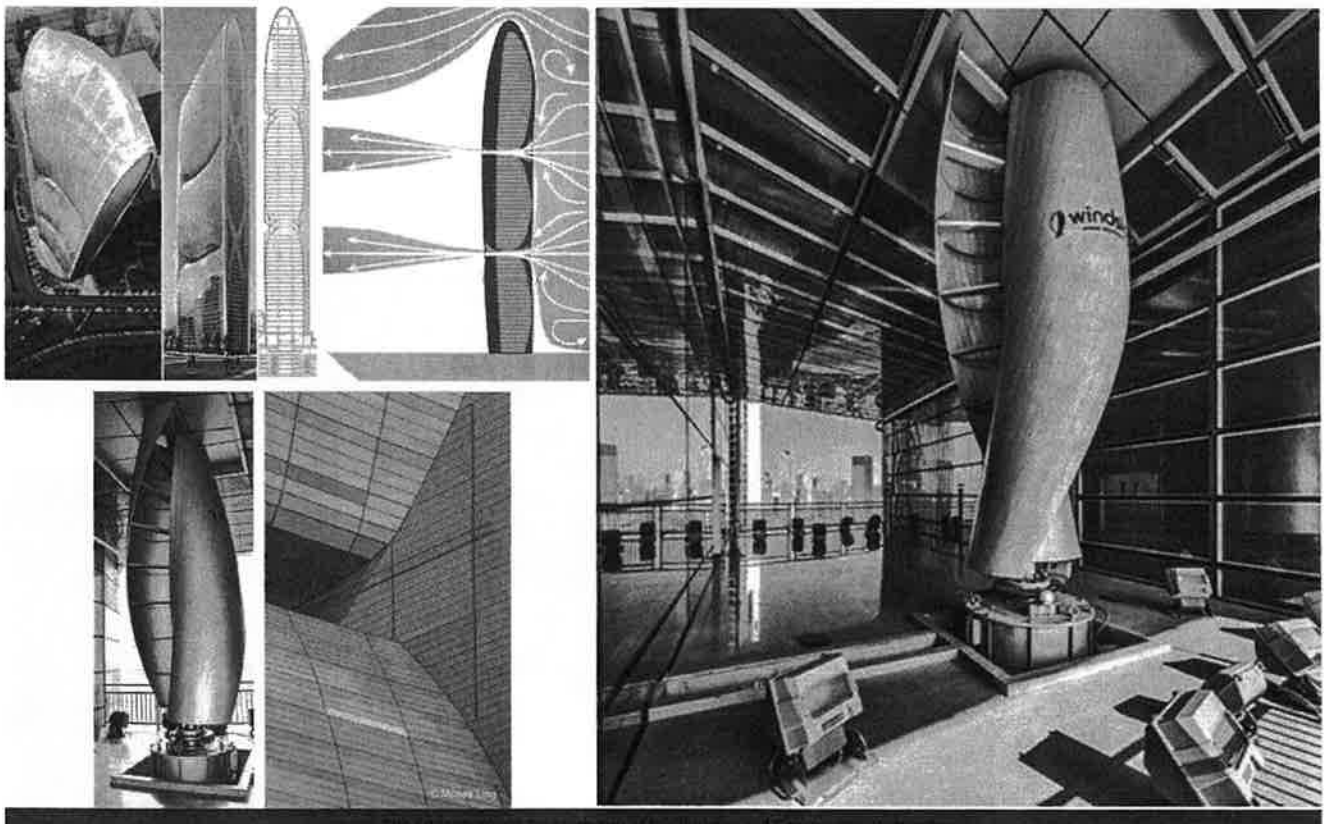




Thin Film Façades

	Crystalline (Mono and Multi Silicon) Panels 1st Generation 93% of Market	Thin Film (a-Si and non silicon) Panel (Amorphous) 2nd Generation 7% of Market	Screen Printed (Thin Film non silicon Organic) 3rd Generation PV
Capitalization	Very High ($B)	Very High ($XXM)	Low ($XM)
Raw Material	Constrain	Non-constrain	Non-constrain
Process	Very Long	Long	Very Short
Factory and Headcount	3 Different Factories	Low Capacity, Big space and Large Headcount	High Capacity, small space and low headcount
Cell Efficiency	11 - 15%	5 - 9%	8 - 12%
Cost Per Watt	US$5.00	US$5.00	Less than US$2.50

Wind Turbine Façades



Thermally-Broken Curtain Wall

Existing Method of calculating ETTV

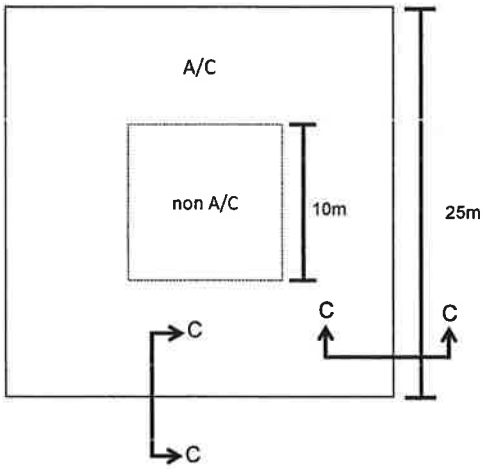
Recap of the ETTV Formula:

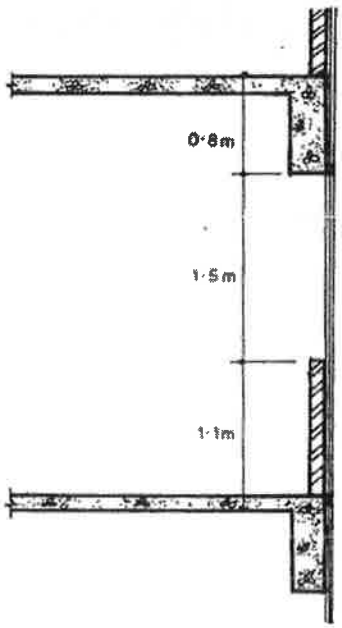
$$ETTV = \frac{12(A_w \times U_w) + 3.4(A_f \times U_f) + 211 \times CF(A_f \times SC_f)}{A_o}$$

Where,

ETTV	:	Envelope Thermal Transmittance Value (W/m^2)
A_w	:	Area of Opaque Wall (m^2)
A_f	:	Area of Fenestration (m^2)
A_o	:	Gross area of the exterior wall (m^2)
U_w	:	Thermal Transmittance of opaque wall (W/m^2K)
U_f	:	Thermal Transmittance of fenestration (W/m^2K)
CF	:	Correction factor for Solar Heat Gain Through fenestration
SC_f	:	Shading Coefficient of Fenestration

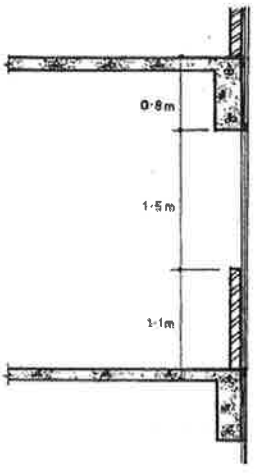
Existing Method of calculating ETTV



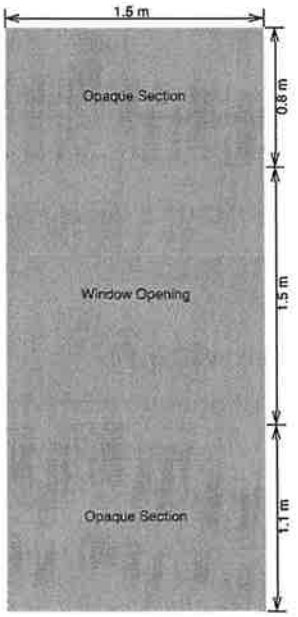


SECTION C – C

Existing Method of Calculating ETTV



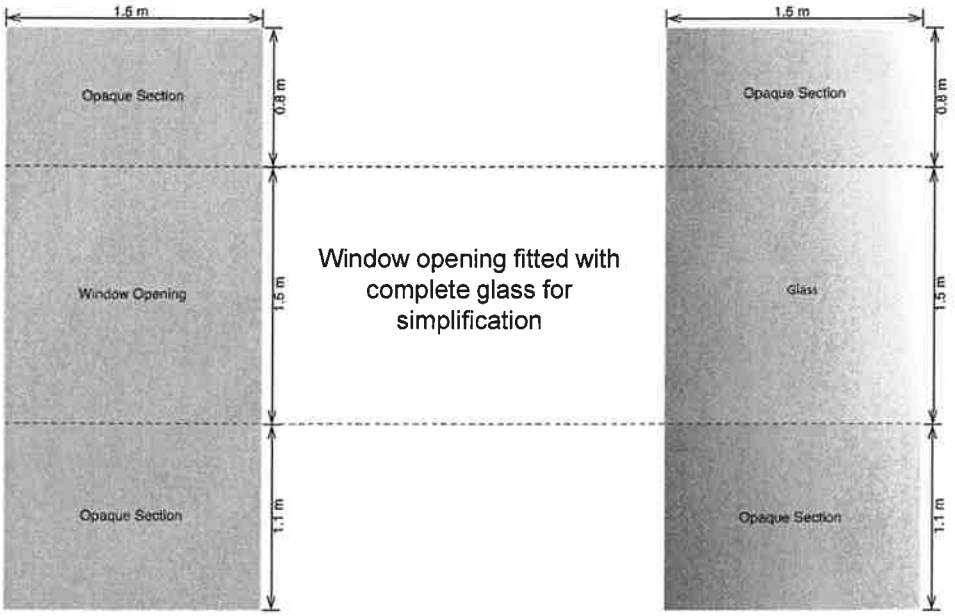
SECTION C – C



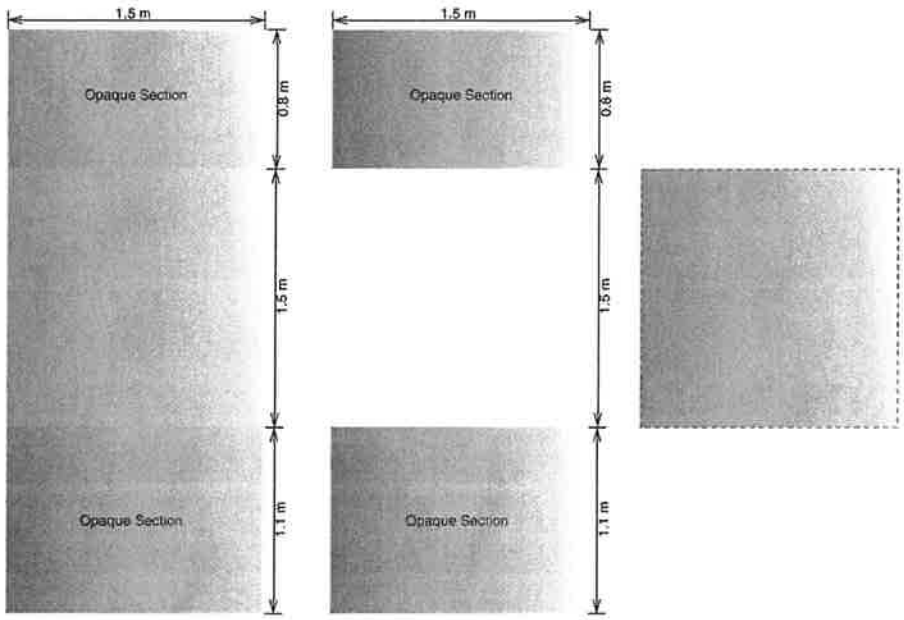
Taking a wall section to be 1.5m wide

- Unitised Curtain Wall

Fenestration considers only glazing



Fenestration considers only glazing



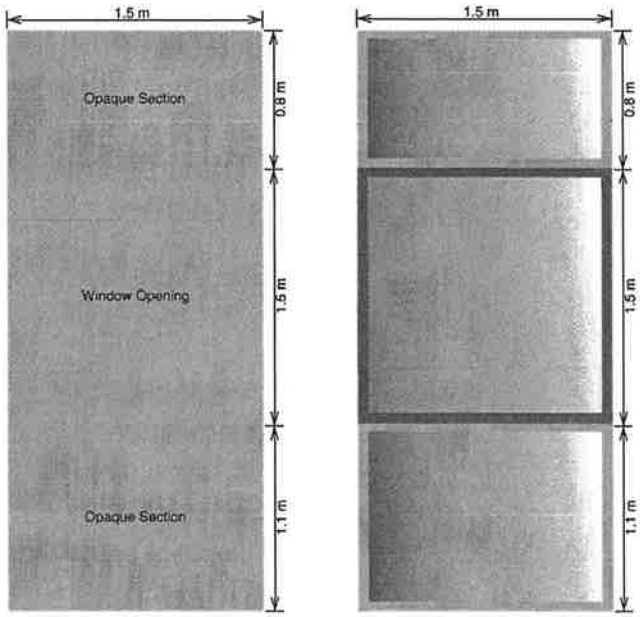
Methodology:

- Assumed glazing thermal properties as the entire fenestration's properties
  - $U_g = U_f$
  - $SC_g = SC_f$
- Neglected the frame's contribution to the entire fenestration's thermal properties

Does this method of application give a realistic ETTV value ?

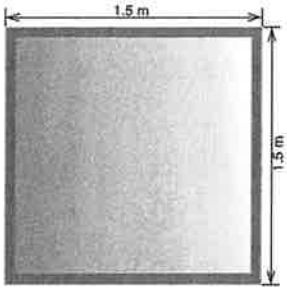


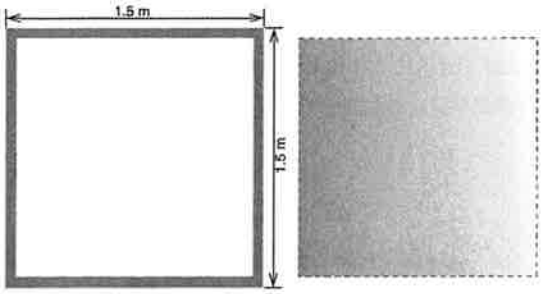
What if – Fenestration considers frame & glazing



- Wall section to be 1.5m wide
- Simulating a unitized curtain wall system consisting of:
  - Non-vision portion
  - Vision Portion
- Window opening consisting of frame and glazing for the vision portion

What if – Fenestration considers frame & glazing





Thermal performance of entire fenestration to be considered in the window opening:

1. Frame; and
2. Glazing

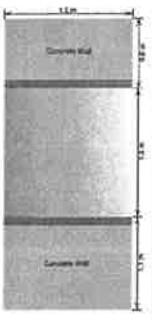
Frame Properties:
U_{frame} – U value of frame
$SHGC_{frame}$ – SHGC value of frame

Glazing Properties:
$U_{glazing}$ – U value of glazing
$SC_{glazing}$ – SC value of glazing

Fenestration Properties:
U_f – U value of fenestration
SC_f – SC value of fenestration

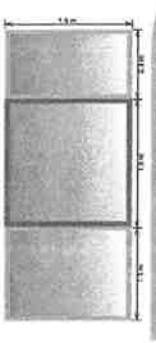
Which method gives a more realistic value of the ETTV?





Existing Method

Using glazing properties as overall fenestration performance

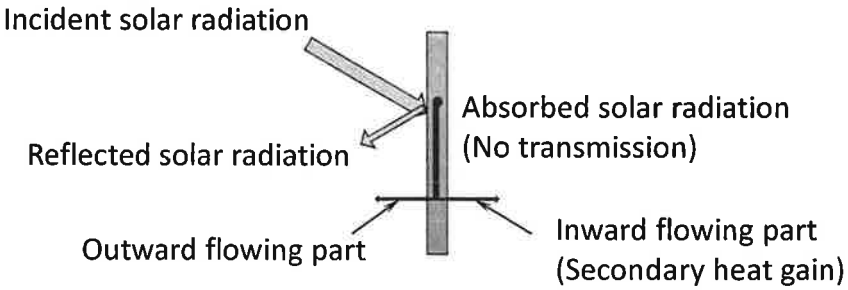


Enhanced Method

Using both frame and glazing properties to determine the overall fenestration performance

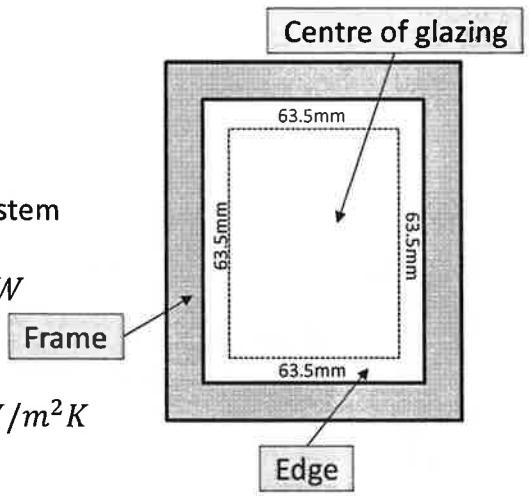
Shortcoming of ETTV: Solar Heat Gain through Frames

- Although there is no directly transmitted solar radiation through frames, the frame Solar Heat Gain Coefficient, , is ≠ 0.$SHGC_{fr}$
- Solar radiation is absorbed by the frame and released into the indoor space as secondary heat gain



Overall U-value of a fenestration system comprises of 3 key components (ISO 15099)

: overall thermal transmittance of fenestration system ()$U_f W/m^2K$
: thermal transmittance of centre of glazing ()$U_{cg} W/m^2K$
: thermal transmittance of frame ()$U_{fr} W/m^2K$
: thermal transmittance of edge of glazing ()$U_{eg} W/m^2K$
: centre of glazing area ()$A_{cg} m^2$
: frame area ()$A_{fr} m^2$
: edge of glazing area ()$A_{eg} m^2$
: total projected fenestration area ()$A_f m^2$



Solar Heat Gain through Frames

- Frame Solar Heat Gain Coefficient, , can be calculated with the following equation (ISO 15099)$SHGC_{fr}$

$$SHGC_{fr} = \alpha_{fr} \frac{U_{fr}}{\frac{A_{fr,w}}{A_{fr}} h_{ex}}$$

$$h_{ex} = h_{cv,ex} + h_{r,ex}$$

- is directly proportional to and thus dependent on$SHGC_{fr}$
  1. Solar absorptance of the outer frame surface,
  2. U-value of the frame,

BCA ACADEMY

Solar Heat Gain through Frames

- The overall of a fenestration system can be calculated with the following equation (ISO 15099)$SHGC_f$

Relationship between SC and SHGC

: overall solar heat gain coefficient of fenestration : solar heat gain coefficient of glazing$\mathrm{SHGC_f}\mathrm{SHGC}_g$

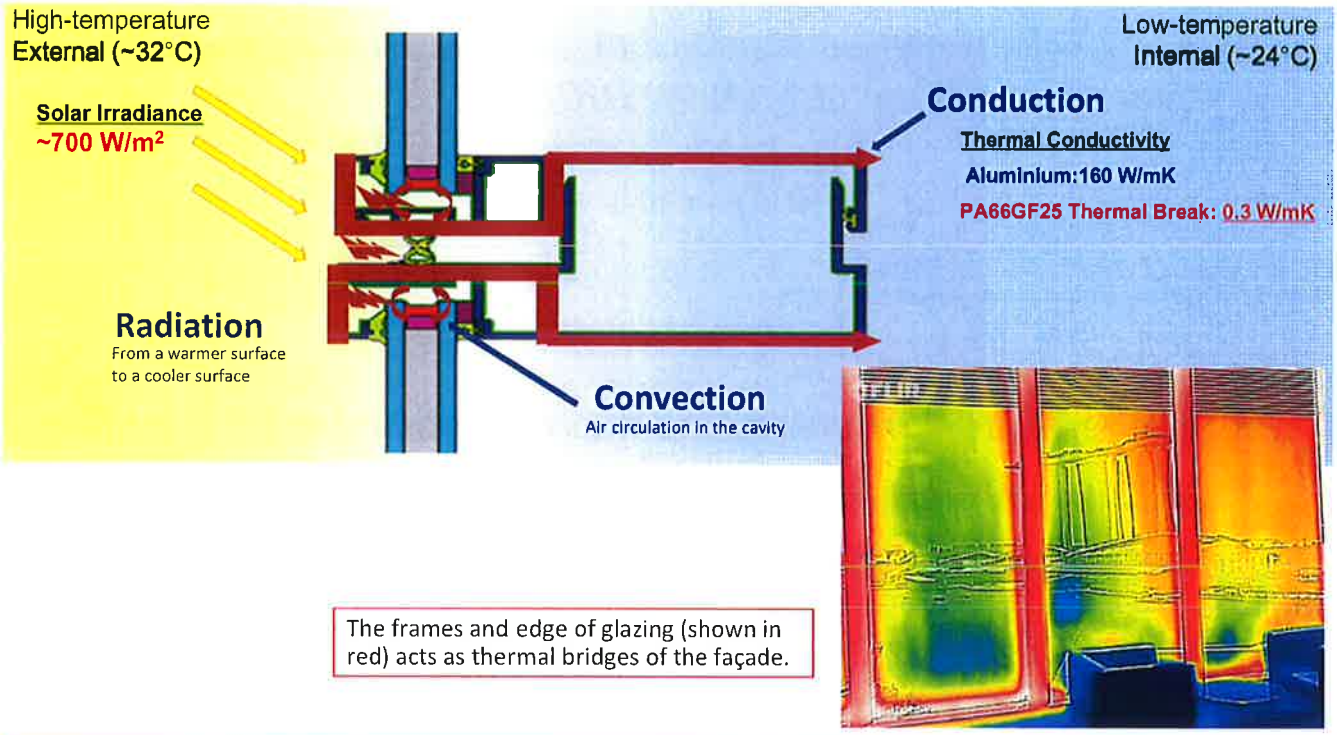
: solar heat gain coefficient of frame SHGC_{fr}

: glazing area ()$\mathrm{A}_g m^2$

: frame area ()$\mathrm{A}_{fr} m^2$

: total projected fenestration area ()

Frame Heat Transfer Mechanism

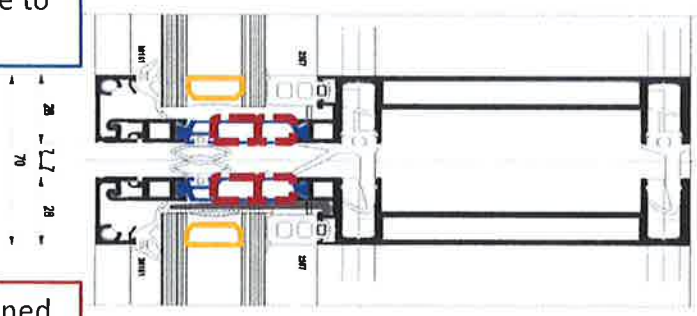


The frames and edge of glazing (shown in red) acts as thermal bridges of the façade.

Improving U-value of Frame and Edge of Glazing

Thermal break reduces the conduction heat flow from the outer frame to the inner frame

Warm Edge Spacer improves the thermal transmittance at the edge of glass

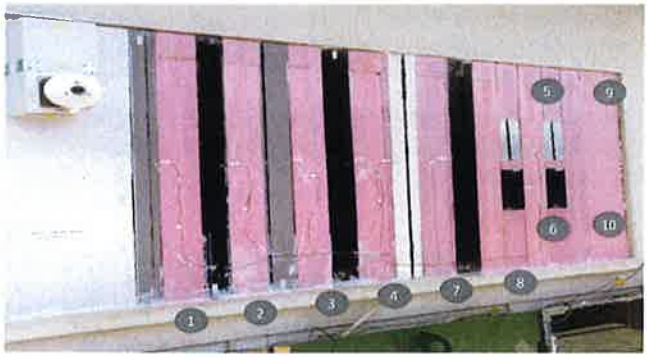


Thermal break designed with hollow chambers can break up convection heat transfer in frame cavities

Thermally broken curtain wall system

Validation of Thermal Break Performance

- Heat flux sensors are used to monitor the frame samples shown below



Source: Pilot study on the energy saving potential of thermally-broken aluminium frames in tropical climates by SERIS

1	No thermal break, light color	AL_LC
2	No thermal break, dark color	AL_DC
3	With low performance thermal break, light color	TBL_LC
4	With low performance thermal break, dark color	TBL_DC
5	With moderate performance thermal break, light color	TBM_LC
6	With moderate performance thermal break, dark color	TBM_DC
7	With high performance thermal break, light color	TBH_LC
8	With high performance thermal break, dark color	TBH_DC
9	No thermal break, light color	Spare part
10	No thermal break, dark color	Spare part

Validation of Thermal Break

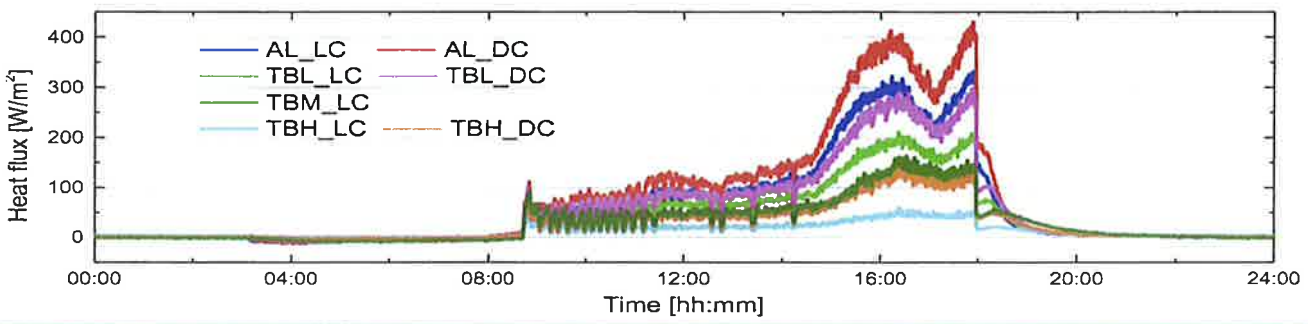


Light colour aluminium (AL_LC)

Dark colour Aluminium (AL_DC)

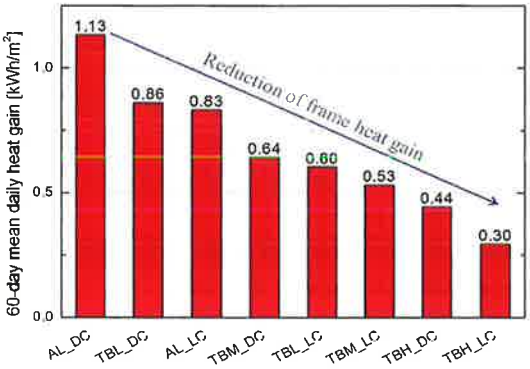
Light colour With low performance thermal break (TBL_LC)

Black With low performance thermal break (TBH_LC)



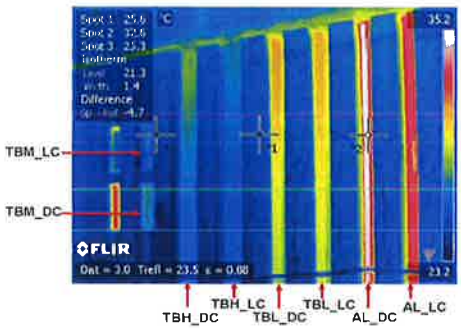
Validation of Thermal Break Performance

Frame Mean Daily Heat Gain



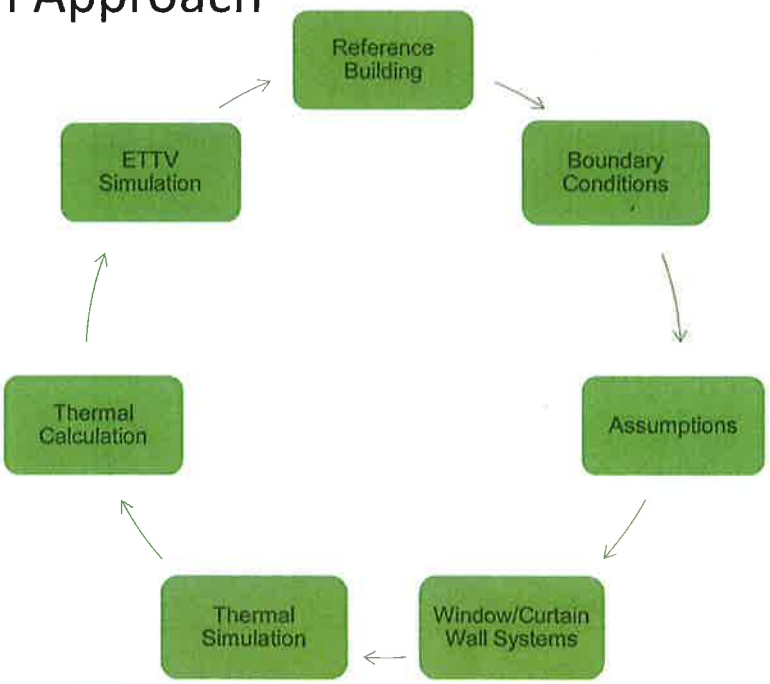
Source: Pilot study on the energy saving potential of thermally-broken aluminium frames in tropical climates by SERIS

- Results showed that frame heat gain is correlated to its U-value, and outer surface solar absorptance,
- Thermal break effectively reduces frame heat gain and thus reduces the indoor frame surface temperature



Analysis of the impact on ETTV values using enhanced method of calculation

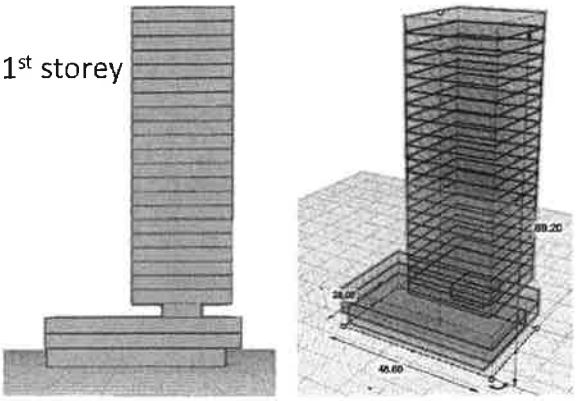
Simulation Approach



Reference Building

- Office Building as described in Appendix D of BCA's "Code on Envelope Thermal Performance for Building"

Type	: Office Building
Storey	: 25
External Shading	: Podium 1st storey
	SC(South) = 0.68
	SC(East) = 0.58
Fenestration Area (A_f)	: 3,654 m^2
Total Envelope Area (A_0)	: 8,295 m^2
Mean WWR (A_f/A_0)	: 0.44

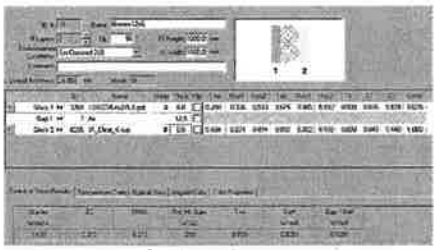


Boundary Condition

Boundary Conditions for Simulation	
Indoor Temperature, T_{in}	24 °C
Outdoor Temperature, T_{out}	32 °C
Solar Irradiance	783 W/m^2
Convective & Radiative Heat Transfer Coefficient Interior, $H_{c,in}$	8 W/m^2k
Convective & Radiative Heat Transfer Coefficient Exterior, $H_{c,ex}$	22 W/m^2k

Assumptions

1. ETTV Simulation Variables:
   1. Glass Properties
   2. Non-Thermally Broken Curtain Wall Systems
   3. Thermally Broken Curtain Wall Systems



e.g. of LBNL WINDOW Library with glass properties

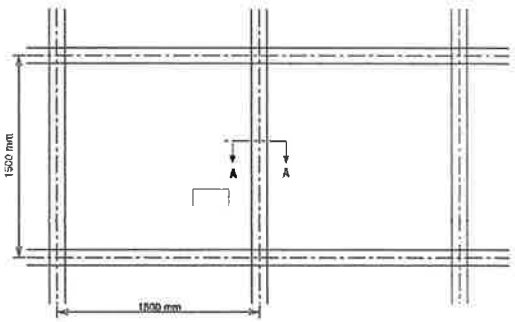
2. Curtain wall systems assumed to have similar transom (horizontal) & mullion (vertical) profile sections.
   - *Simulation of heat transfer through curtain wall system is still valid.*



3. Thermal simulation is made only to vision portion of the building envelope.

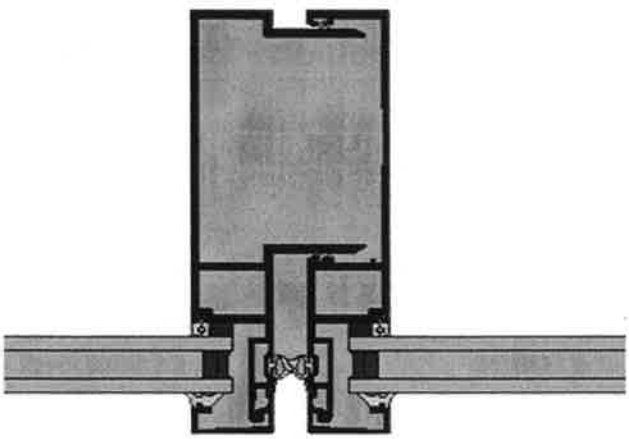
4. Glazing systems & properties are taken from Lawrence Berkeley National Laboratory WINDOW library for thermal simulation.
   - *Curtain wall system 1:* *6mm / low-e / 12mm air / 6mm*
   - *Curtain wall system 2:* *8mm single glazed*

Curtain wall systems



Curtain Wall 1 (CW1)

Type	: Unitised Curtain Wall
System	: 100 mm System
Depth	: 175 mm
Frame-Window-Ratio	: 13.7%
Level	: 2nd and 3rd Storey; 5th to 25th Storey



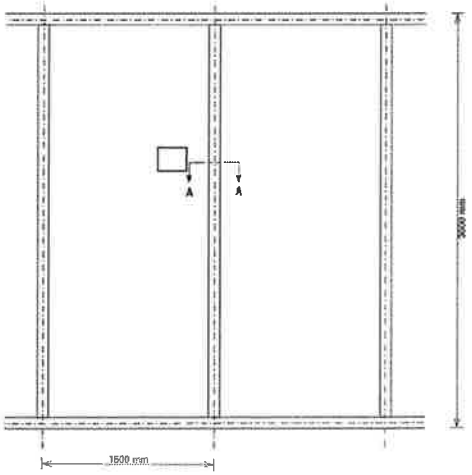
Non-Thermal Break System Profile Section A-A

Glass Configuration

6 mm / low-e / 12 mm air / 6 mm

Aluminium Spacer

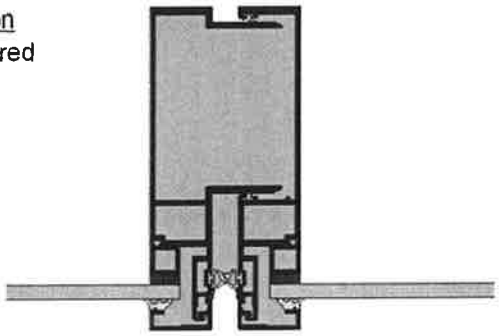
Curtain wall systems



Curtain Wall 2 (CW2)

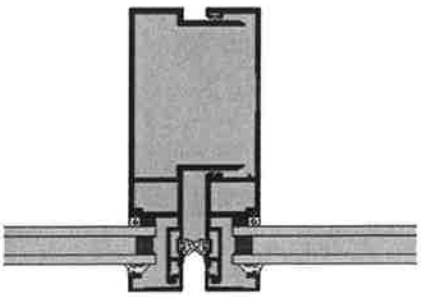
Type	: Unitized Curtain Wall
System	: 100 mm System
Depth	: 175 mm
Frame-Window-Ratio	: 9.9%
Level	: Podium (1st Storey)

Glass Configuration
8mm Clear Tempered

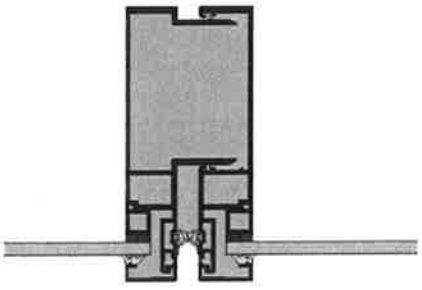


Non-Thermal Break System Profile Section A-A

Curtain wall systems



Non-Thermal Break System Profile



Non-Thermal Break System Profile

Thermal Performance – CW1		
Description	***Units***	
Frame U-value	W/m^2K	13.95
Edge U-value	W/m^2K	2.31

Thermal Performance – CW2		
Description	***Units***	
Frame U-value	W/m^2K	15.19
Edge U-value	W/m^2K	5.40

Thermal Calculation

Determining fenestration properties through calculation:

- Frame Total Solar Energy Transmittance (i.a.w ISO 15099)

$$\tau_{fr} = \alpha_{fr} \frac{U_{fr}}{\frac{A_s}{A_f} h_{ex}}$$

- Total Solar Energy Transmittance (i.a.w ISO 15099)

$$\tau_s = \frac{\sum \tau_g A_g + \sum \tau_{fr} A_{fr}}{A_f}$$

- U-value of complete fenestration (i.a.w ISO 15099)

$$U_w = \frac{(U_g \times A_g) + (U_f \times A_f) + (U_{edge} \times A_{edge})}{A_w}$$

Glazing vs. complete fenestration properties

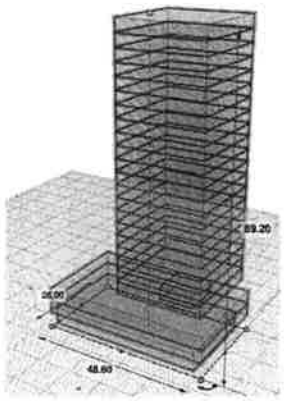
Curtain Wall 1 –Unitized Curtain Wall				
	Units	Frame + glazing considered	Only glazing considered	Differences
$U_{fenestration}$	*W/m²K*	3.61	1.88	91.3 %
$SHGC_{fenestration}$	-	0.28	0.28	-1.4 %
$SC_{fenestration}$	-	0.32	0.33	-1.4 %

Curtain Wall 2 – Unitized Curtain Wall				
	Units	Frame + glazing considered	Only glazing considered	Differences
$U_{fenestration}$	*W/m²K*	6.53	5.60	16.5 %
$SHGC_{fenestration}$	-	0.48	0.50	-4.4 %
$SC_{fenestration}$	-	0.55	0.57	-4.4%

There are significant differences in the fenestration properties

ETTV Simulation & Calculation

- Formula: $ETTV = \frac{12(A_w \times U_w) + 3.4(A_f \times U_f) + 211 \times CF(A_f \times SC_f)}{A_o}$

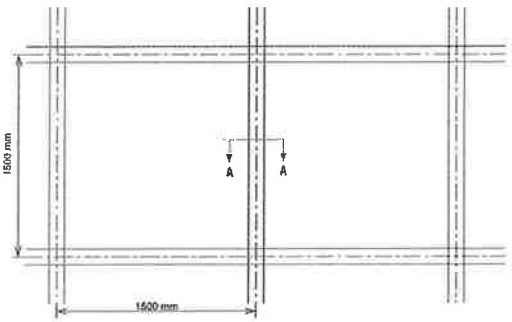


	South	East	North	West	Overall ETTV
Existing Method – Only Glazing Considered	35.67	40.96	33.60	42.39	47.1
Enhanced Method – Frame + Glazing Considered	38.11	42.80	35.64	44.61	49.08

4.2% performance over-predicted

Values calculated using the existing method is not representative of actual performance

Curtain wall systems

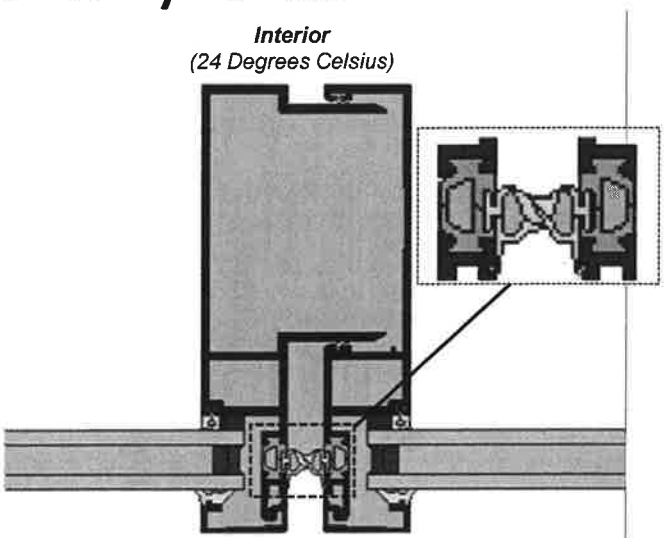


Curtain Wall 1 (CW1)

Type	: Unitised Curtain Wall
System	: 100 mm System
Depth	: 175 mm
Frame-Window-Ratio	: 13.7%
Level	: 2nd and 3rd Storey, 5th to 25th Storey

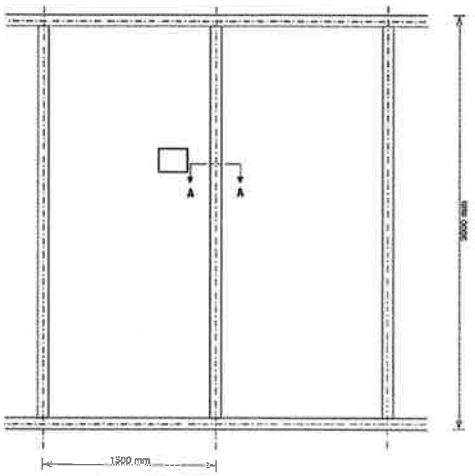
Glass Configuration

6 mm / low-e / 12 mm air / 6 mm Aluminium Spacer



Thermal Break System Profile Section A-A

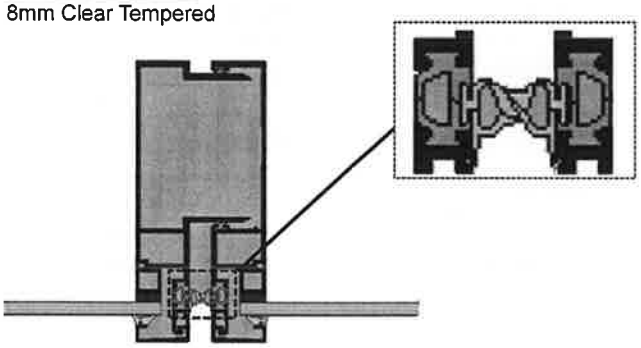
Curtain wall systems



Curtain Wall 2 (CW2)

Type	: Unitized Curtain Wall
System	: 100 mm System
Depth	: 175 mm
Frame-Window-Ratio	: 9.9%
Level	: Podium (1st Storey)

Glass Configuration
8mm Clear Tempered



Thermal Break System Profile Section A-A

Thermal Simulation – Curtain wall

Comparison of Thermal Performance – CW1

Description	Units	Frame + glazing considered	Thermally broken frame + glazing considered
Frame U-value	W/m^2K	13.95	6.60
Edge U-value	W/m^2K	2.31	2.04

Note: Curtain Wall 1 refers to Double Glazed Unitised Curtain Wall

Approximately **46.9%** improvement in $U_{frame} + U_{edge}$ Value

Comparison of Thermal Performance – CW2

Description	Units	Frame + glazing considered	Thermally broken frame + glazing considered
Frame U-value	W/m^2K	15.19	8.19
Edge U-value	W/m^2K	5.40	5.34

Note: Curtain Wall 2 refers to Single Glazed Unitised Curtain Wall

Approximately **34.3%** improvement in $U_{frame} + U_{edge}$ Value

Non Thermally Broken vs. Thermally Broken System

Curtain Wall 1 –Unitized Curtain Wall				
	Units	Frame + glazing considered	Thermally broken frame + glazing considered	Improvements
$U_{fenestration}$	W/m^2K	3.61	2.56	29.1%
$SHGC_{fenestration}$	-	0.28	0.26	6.6%
$SC_{fenestration}$	-	0.32	0.30	6.6%

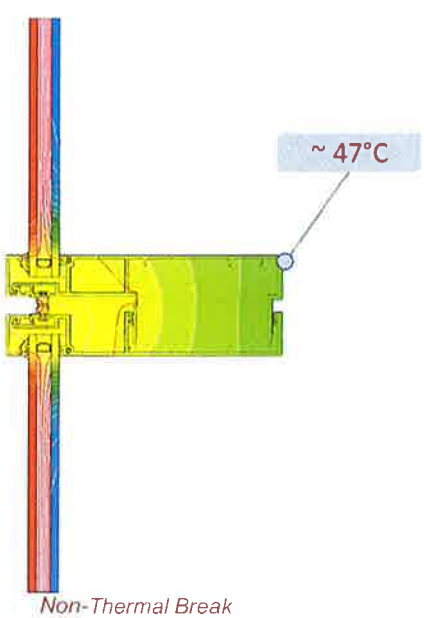
Note: Curtain Wall 1 refers to Double Glazed Unitised Curtain Wall

Curtain Wall 2 – Unitized Curtain Wall				
	Units	Frame + glazing considered	Thermally broken frame + glazing considered	Improvements
$U_{fenestration}$	W/m^2K	6.53	5.83	10.6%
$SHGC_{fenestration}$	-	0.48	0.46	2.7%
$SC_{fenestration}$	-	0.55	0.53	2.7%

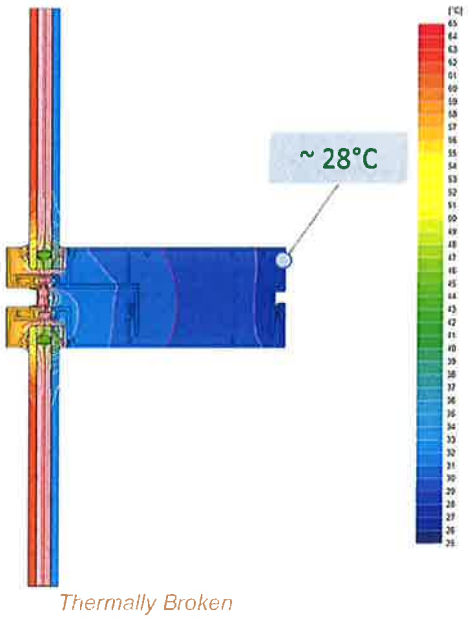
Note: Curtain Wall 2 refers to Single Glazed Unitised Curtain Wall

BCA ACADEMY

Non-Thermally-Broken vs. Thermally-Broken System



Non-Thermal Break System Profile



Thermally Broken System Profile

The Education and Research arm of the Building and Construction Authority

Non-Thermally-Broken vs. Thermally-Broken System

Curtain Wall 1 – Unitized Curtain Wall				
	Units	Frame + Glazing	Thermally Broken Frame + Glazing	Only Glazing
$U_{fenestration}$	W/m^2K	3.61	2.56	1.88
$SHGC_{fenestration}$	-	0.28	0.26	0.28
$SC_{fenestration}$	-	0.32	0.30	0.33
Curtain Wall 2 – Unitized Curtain Wall				
	Units	Frame + Glazing	Thermally Broken Frame + Glazing	Only Glazing
$U_{fenestration}$	W/m^2K	6.53	5.83	5.60
$SHGC_{fenestration}$	-	0.48	0.46	0.50
$SC_{fenestration}$	-	0.55	0.53	0.57

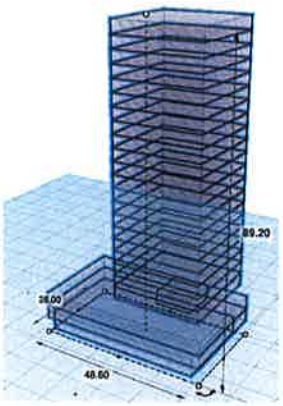
Enhanced Method – using overall fenestration properties (incl. frame & glazing)

Existing Method – using glazing properties

ETTV Simulation & Calculation

- Formula: $$ETTV = \frac{12(A_w \times U_w) + 3.4(A_f \times U_f) + 211 \times CF(A_f \times SC_f)}{A_o}$$

ETTV calculated with glazing properties only does not account for the heat gain through the entire fenestration.

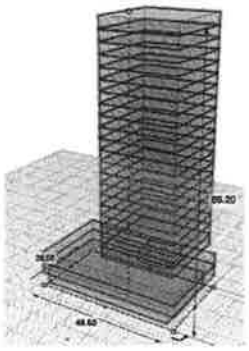


	South	East	North	West	Overall ETTV
Existing Method – Only glazing considered	35.67	40.96	33.60	42.39	47.1
Enhanced Method – Frame + Glazing Considered	38.11	42.80	35.64	44.61	49.08
Enhanced Method – Thermally Broken Frame + Glazing considered	35.37	39.70	33.29	41.31	45.65

Thermally broken systems improves the overall ETTV by approx. 7%

ETTV Simulation & Calculation

Annual Fenestration Heat Gains					
	Units	Non-Thermally Broken	Thermally Broken	Heat Gain Reduction	Improvements
Conduction Heat Gain	MWh	220.7	184.2	36.5	-16.5%
Solar Heat Gain	MWh	615.8	544.5	71.3	-11.6%
Total Heat Gain	MWh	836.5	728.7	107.8	-12.9%



~13%
reduction in CO_2 emission

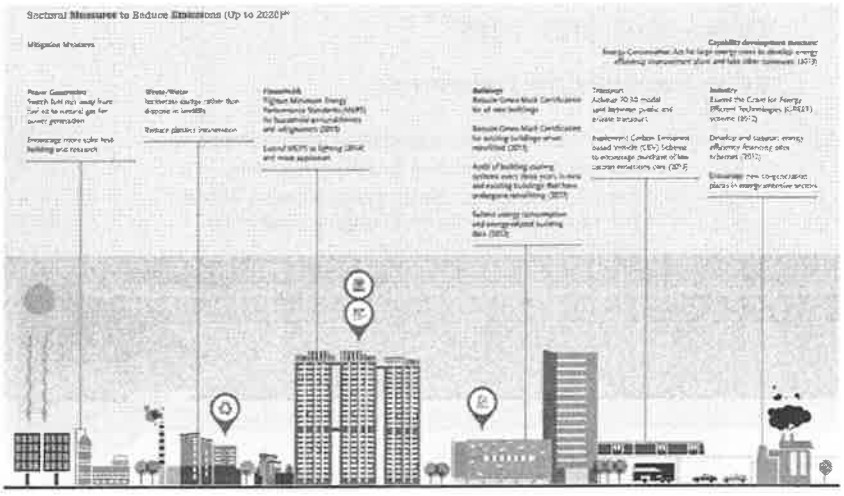
For a fenestration area of 3,654 m^2 ,

	Units	Non-Thermally Broken	Thermally Broken
Annual CO_2 Emission	kg	92,324	80,427

Assumption: Based on total cooling design system efficiency of 0.9 kW/RT and Grid Emission Factor of 0.4313 kg/kWh

Ecological Benefits – Reduction in CO_2 Emissions

- Increasing global annual mean surface temperature
- Higher annual temperatures > heat stresses > greater use of air-conditioning > increasing energy demand > increasing carbon emission
- Reduce the 2030 emission intensity by 36% from 2005 levels



Building Sector to contribute 11-16% in emissions reduction by 2020

Which method gives a more realistic value of the ETTV?



Existing Method

Using glazing properties as overall fenestration performance



Enhanced Method

Using both frame and glazing properties to determine the overall fenestration performance

BCA Green Mark Rewards the Use of Thermal Break in Façades

Green Mark NRB: 2015

1.03A Tropical Façade Performance

- A maximum of 3 points can be scored for façade performance:
  - 1 point for meeting notional façade performance
  - 1 point (up to 2 points) can be scored for every 5% heat load reduction of the envelope and solar insolation reduction against notional façade

1.03A THERMAL BRIDGING (ADVANCE GREEN EFFORT)

1 point can be scored for the use of SGBP certified thermal break / insulation profile achieving < 6.0 W/m2K, for > 80% of external facades adjoining air-conditioned interiors

Overall Weighted Values	Industrial Buildings	Other building types
Weighted Window U-Value	5.4 W/m²K	2.8 W/m²K
Weighted Wall U-Value	1.5 W/m²K	0.7 W/m²K
Overall Envelope U-value	2.4 W/m²K	1.6 W/m²K
Window-to-Wall Ratio (Each façade)	0.2	0.4
Total Effective Glass Shading Coefficient ($SC_1 \times SC_2$)	0.6	0.4
Roof U-Value	1.1 W/m²K	0.8 W/m²K
Sky light/ Roof window U-Value	4.3 W/m²K	2.2 W/m²K
RTTV (where there are sky lights for AC areas)	50 W/m²K	50 W/m²K

Looking Ahead

- Enhanced ETTV/RETV formulation by June 2018
- Validation of formulation using BCA Skylab



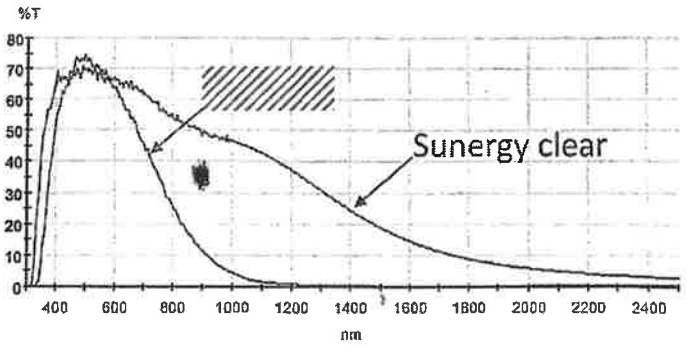
Nano-coated Glass

AGC Sunergy Clear

	EN410	NFRC	
VLT	67%	68%	67%
UVT	39%	46%	43%
SC	0.69	0.69	0.67

	EN410	NFRC
VLT	68%	68%
UVT	14%	14%
SC	0.58	0.57

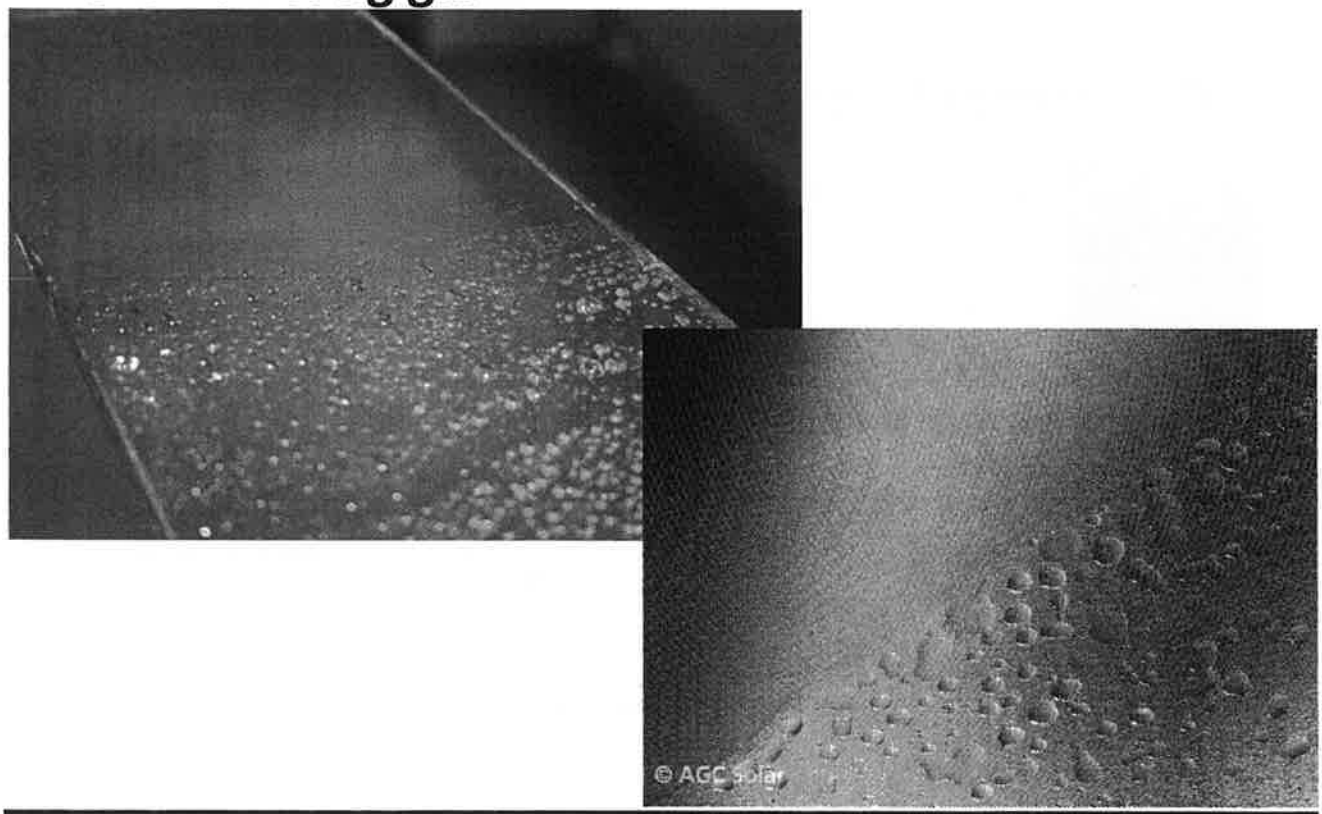
- DC Data for coating on 6mm clear float glass substrate
- NFRC 100-2010 using Window 6.3
- From AGC specifications



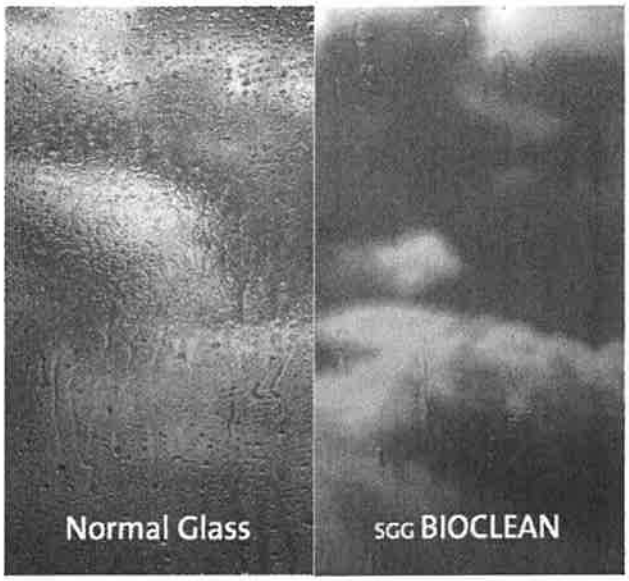
Self-cleaning glass

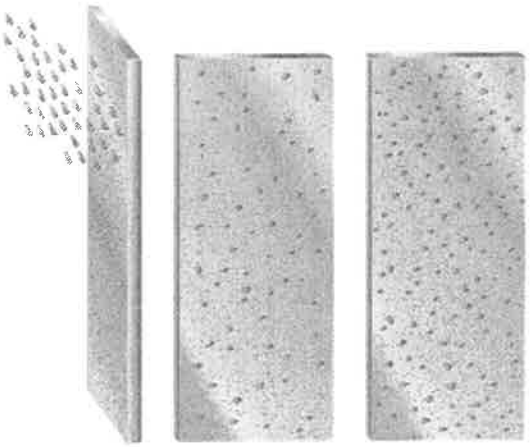


Self-cleaning glass



Self-cleaning glass



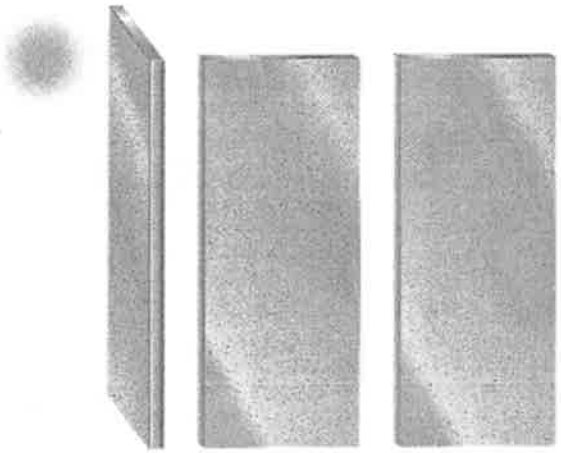


Normal Glass

Dirty water marks and grime gather on the window.

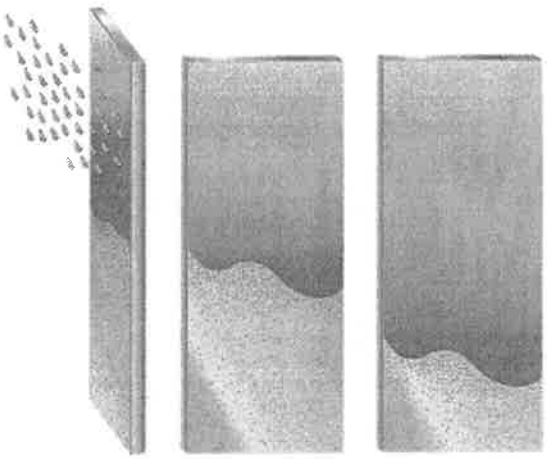
BCA ACADEMY

Self-cleaning glass



SGG BIOCLEAN - Step 1 : Photocatalysis

Exposure to the UV rays present in daylight triggers the decomposition of organic dirt and causes the surface of the glass to turn hydrophilic.

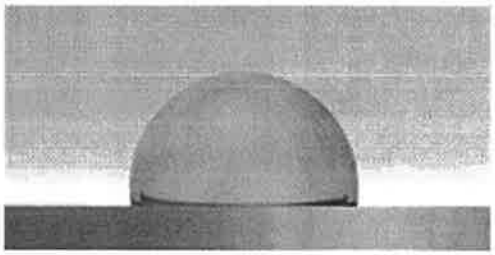


SGG BIOCLEAN - Step 2 : Hydrophilic Action

Water (or rain) forms a sheet of water across the surface of the glass and rinses away broken-down organic dirt and mineral material.

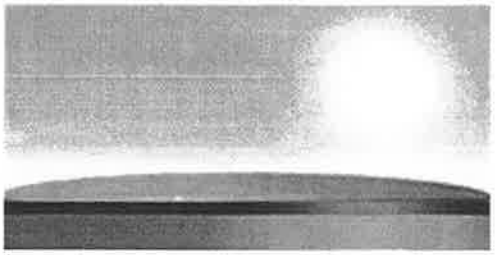
Self-cleaning coating: The principle

hydrophobic



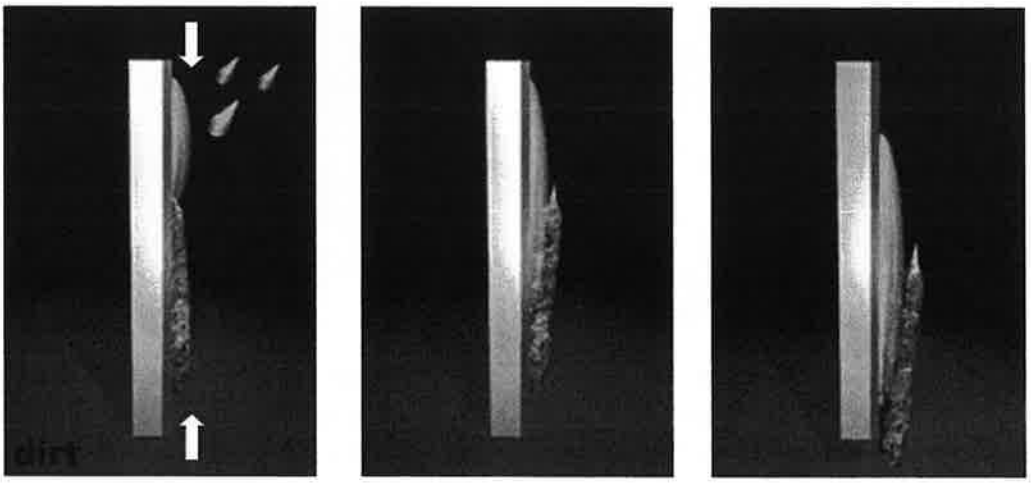
standard tile with drop of water

hydrophilic



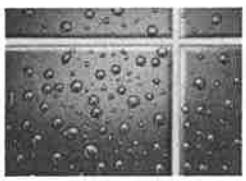
Hydrotect coated tile:
Effects of light relax the water surface.
A film of water is formed.

Self-cleaning coating : The principle



Self-cleaning coating: The principle

Conventional tile

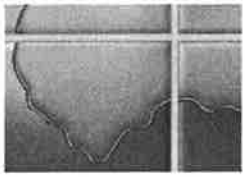


Water drops form....

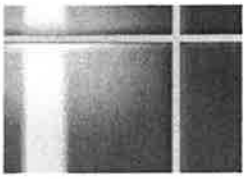


...and dirt is left on the surface

Hydrotect-coated tile



The water spreads as a thin film on the surfaces and washes down dirt...

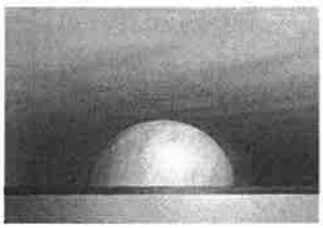


...which can then be easily removed. Result: a clean surface.

BCA ACADEMY

Self-cleaning coating: The principle

Oil...



Oil drop on Hydrotect tile



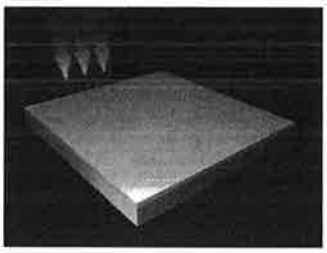
Oil drop slowly peels off



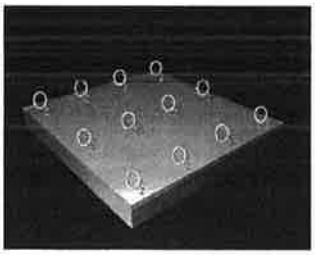
Oil drop detaches itself

Self-cleaning coating: The principle

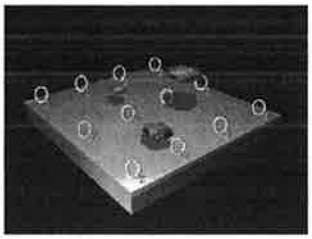
Bacteria...



Hydrotect: The light activates the oxygen



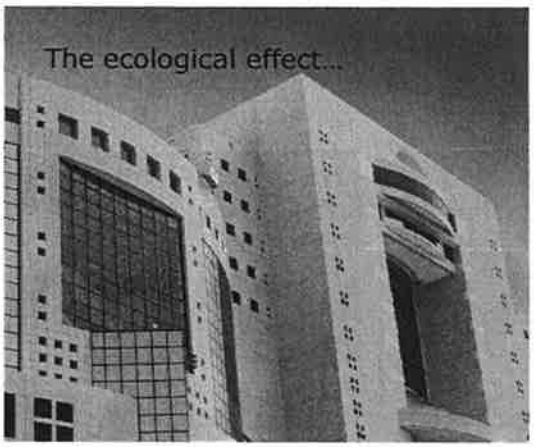
Activated oxygen



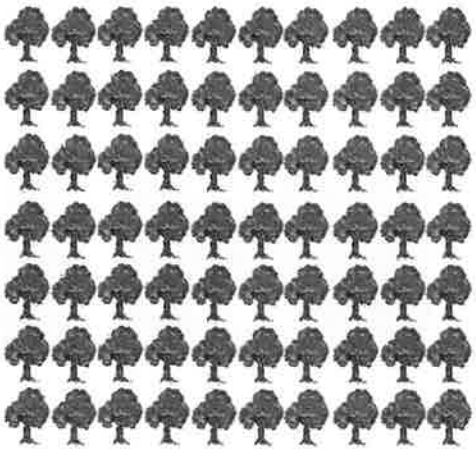
Bacteria are decomposed

BCA ACADEMY

Self-cleaning coating: The principle



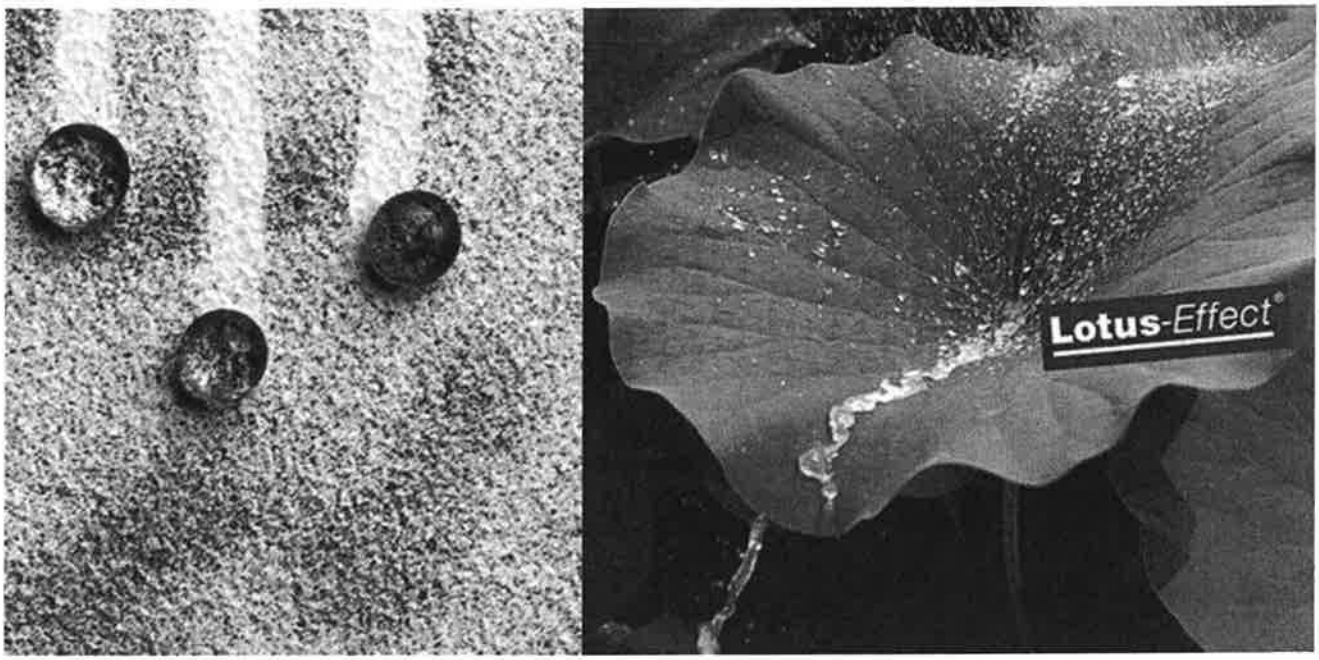
=



1000m² Hydrotect façade surface

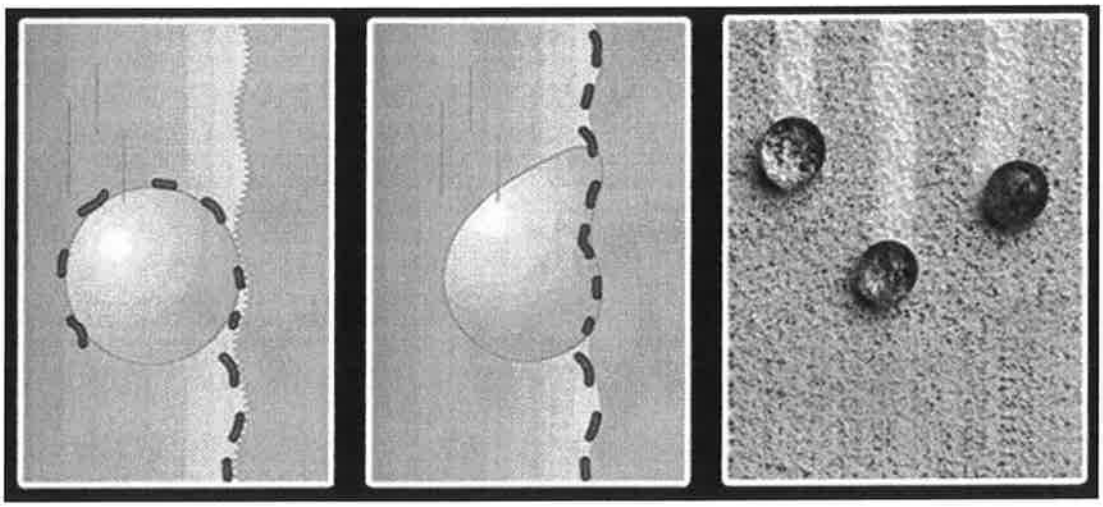
70 medium-sized deciduous trees

Hydrophyllic Paint for Solid Rendered Walls

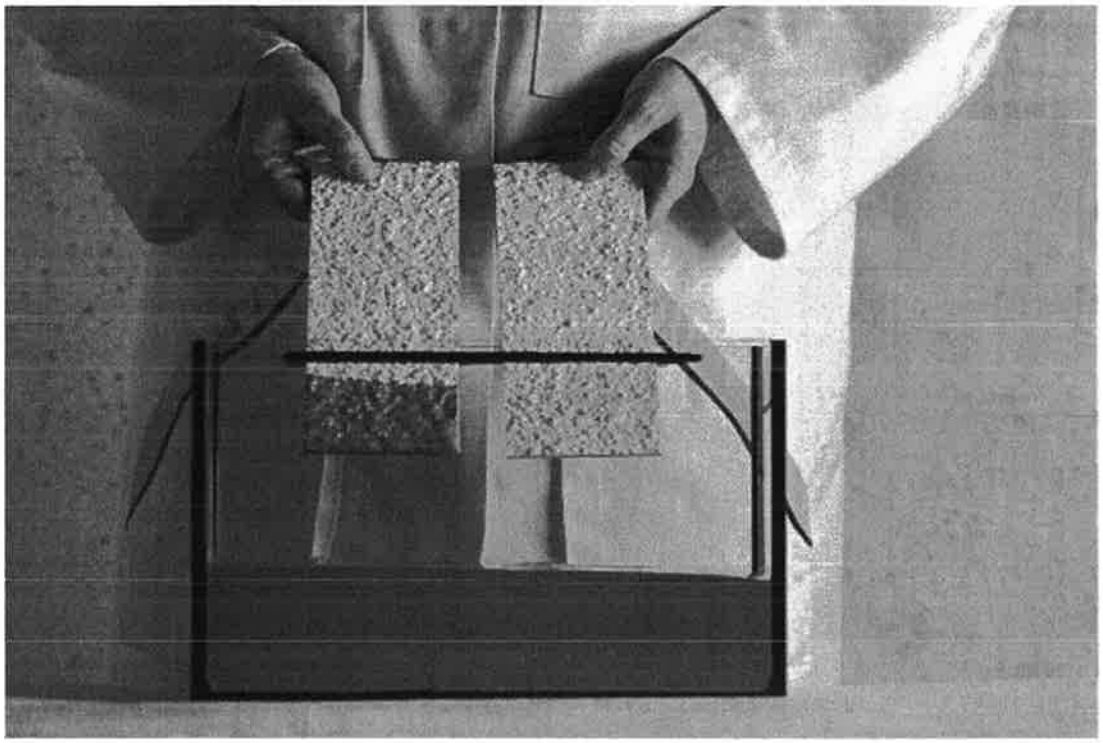


BCA ACADEMY

Hydrophyllic Paint for Solid Rendered Walls

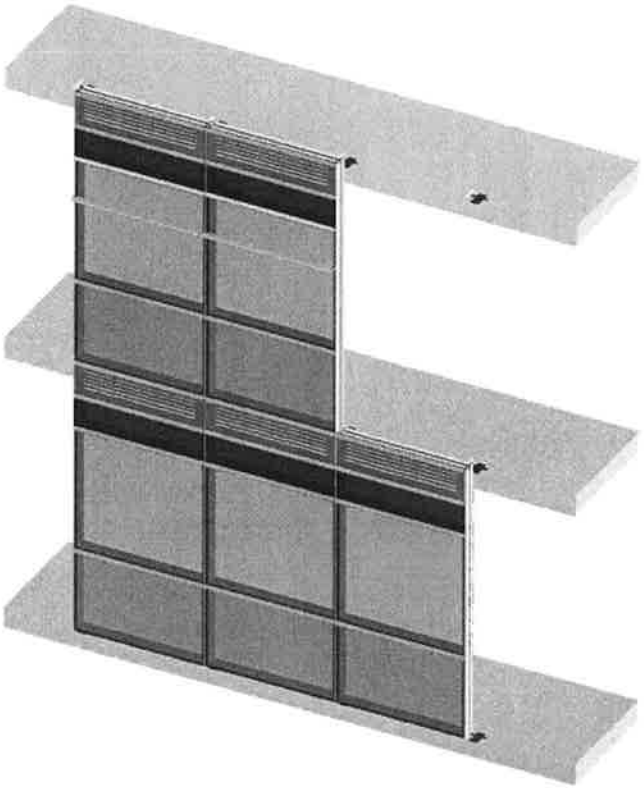


Hydrophyllic Paint for Solid Rendered Walls



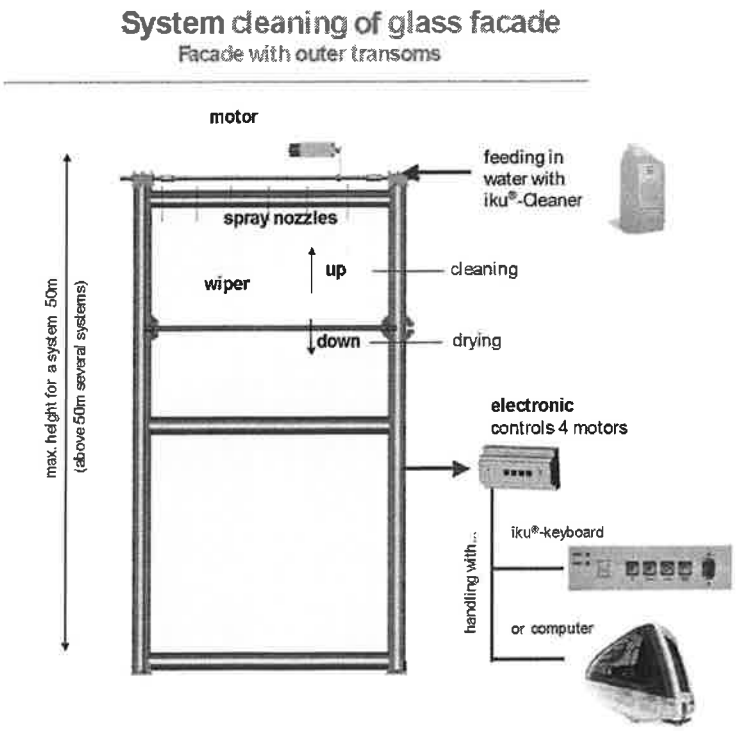
Hydrophyllic Paint for Solid Rendered Walls

Self-cleaning Façade



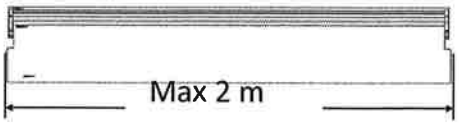
Unitised system including self-cleaning

Self-cleaning Façade

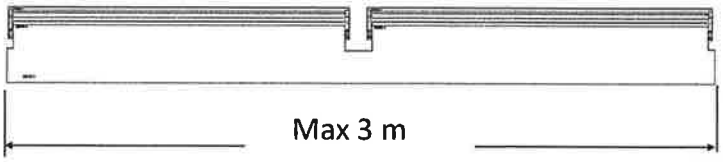


Self-cleaning Façade

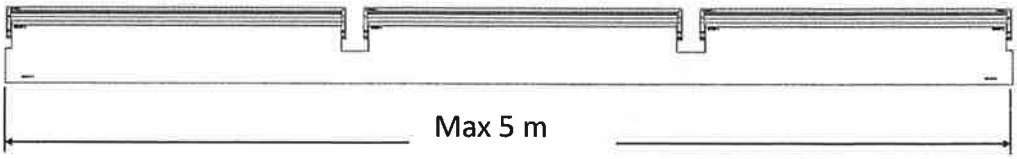
1-Field Wiper



2-Field Wiper



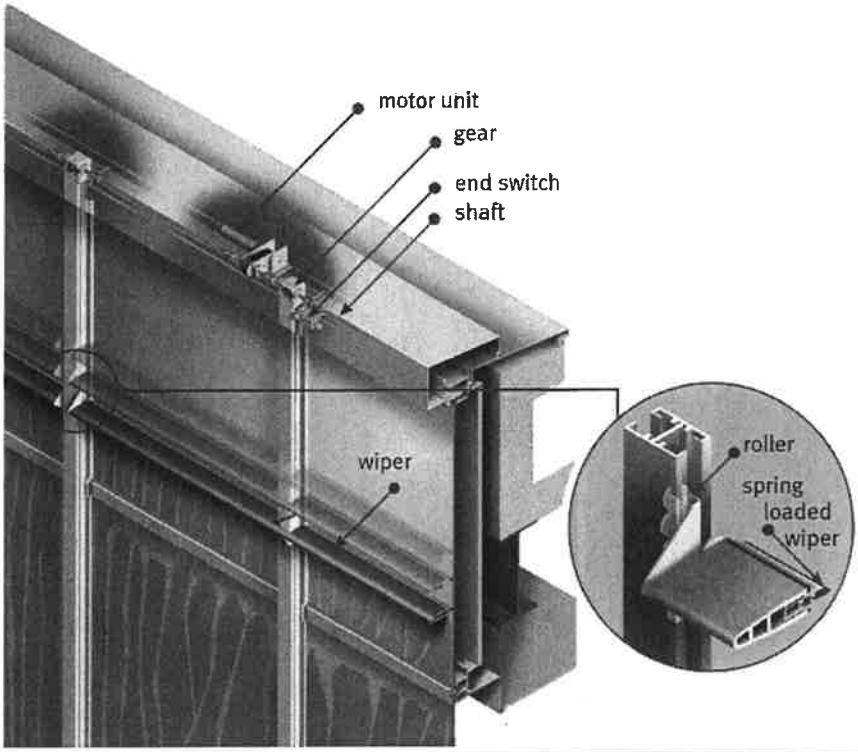
3-Field Wiper



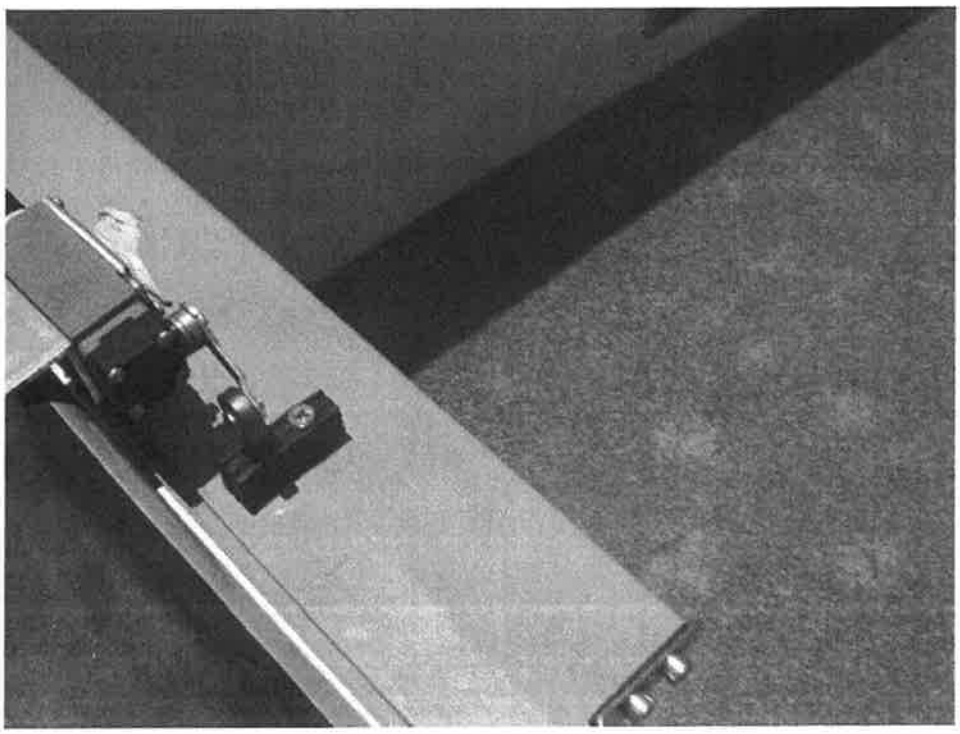
Self-cleaning Façade



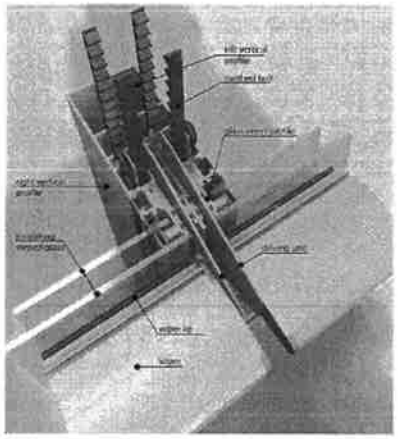
Self-cleaning Façade: traditional cover cap system

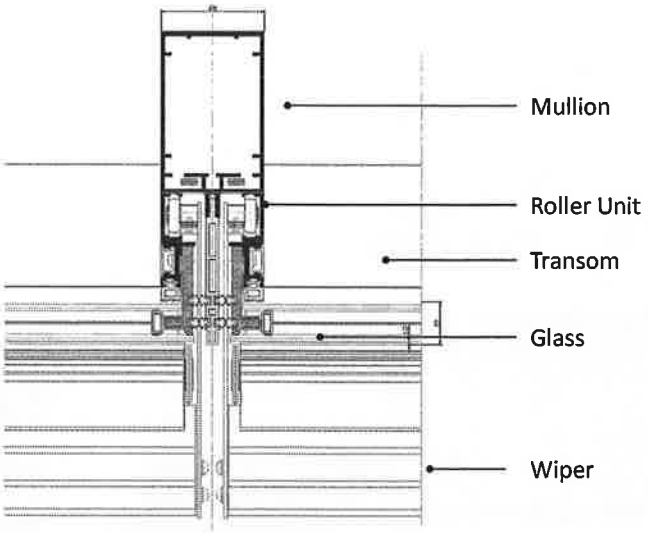


Self-cleaning Façade



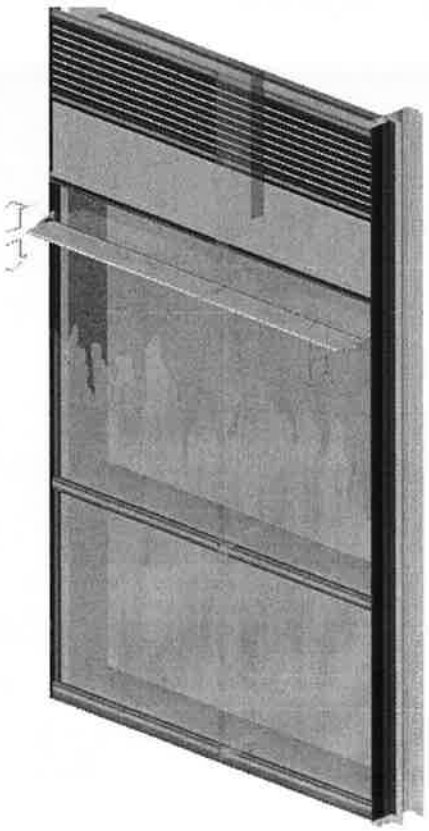
Self-cleaning Façade



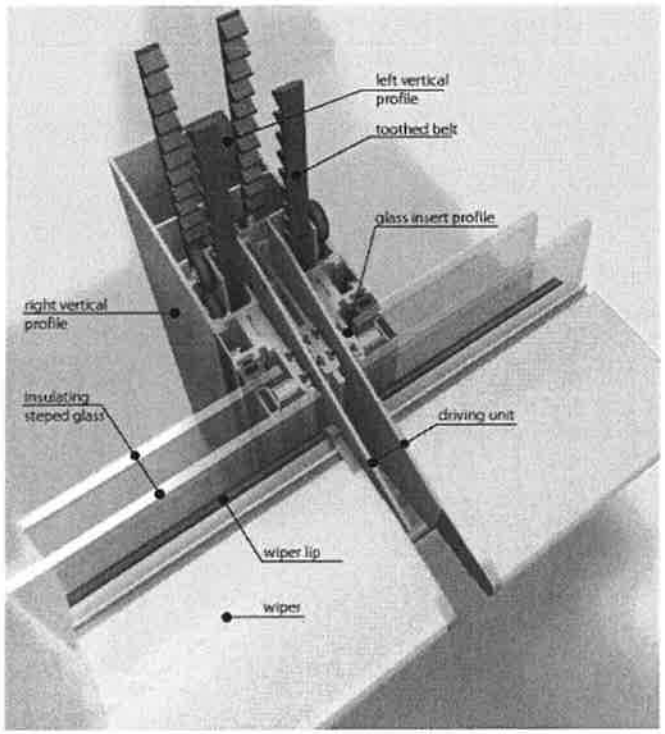


Horizontal section

Self-cleaning Façade

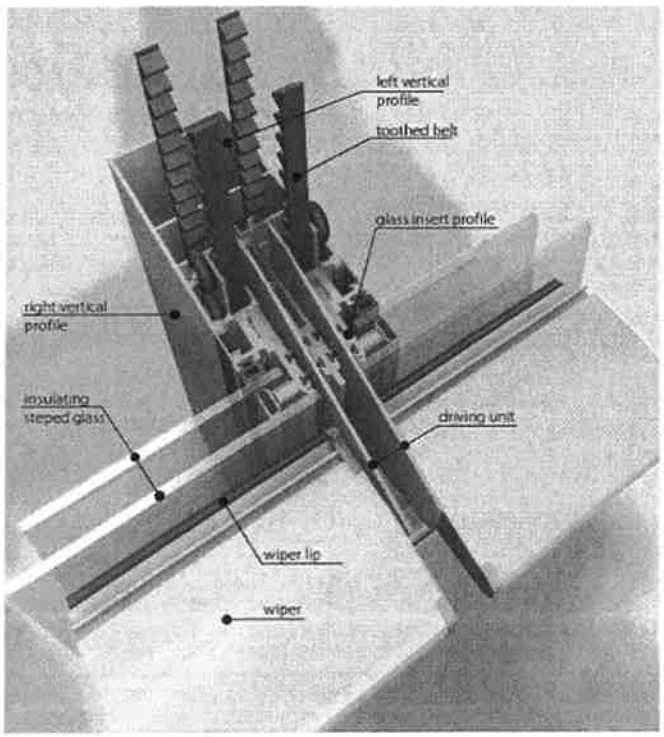


Self-cleaning Façade



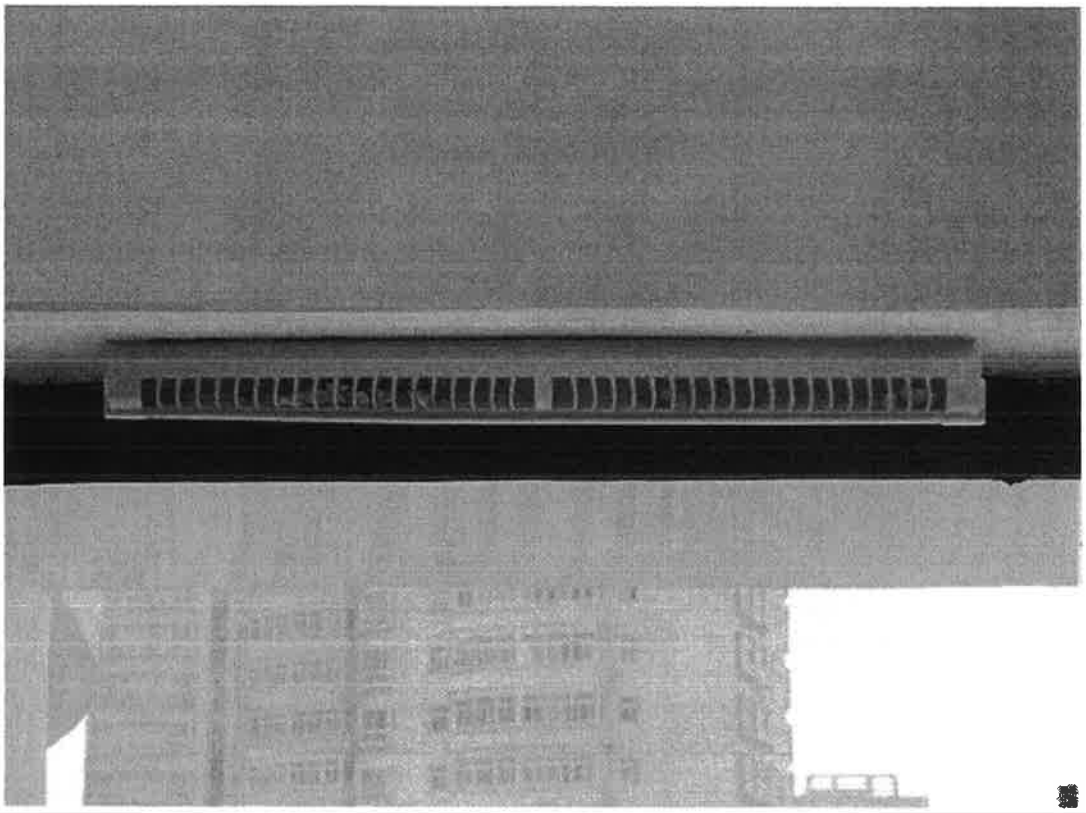
The Building and Construction Authority

Self-cleaning Façade

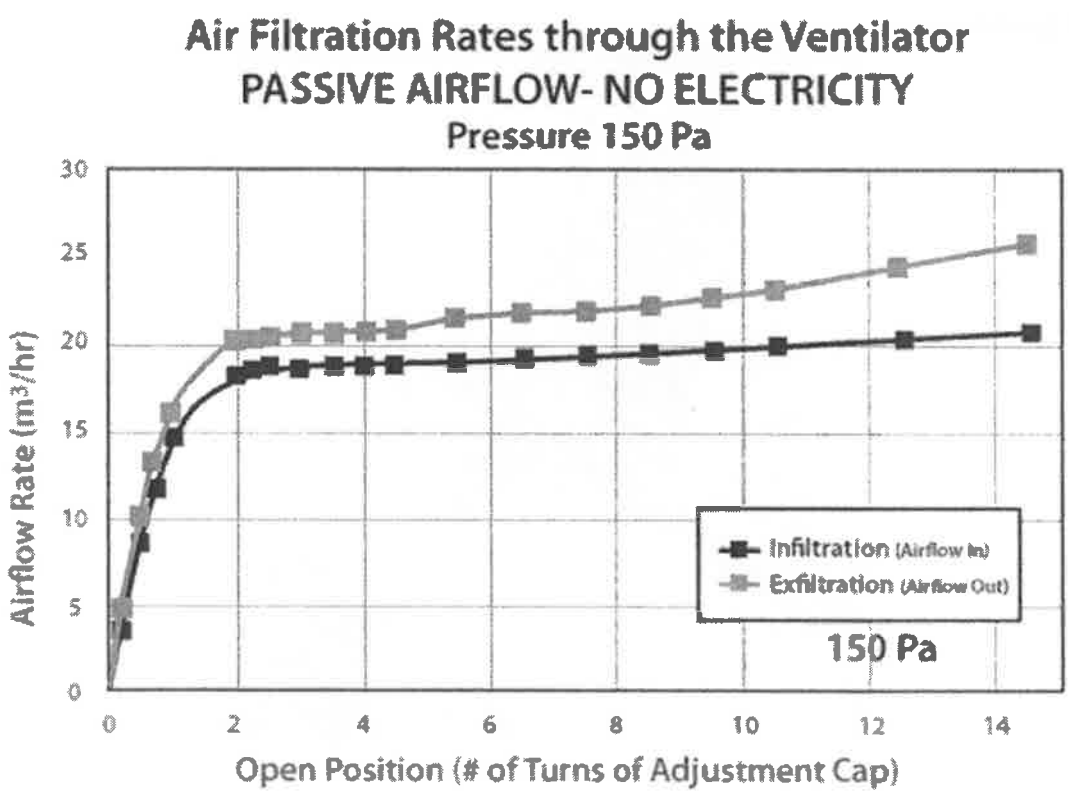


The Building and Construction Authority

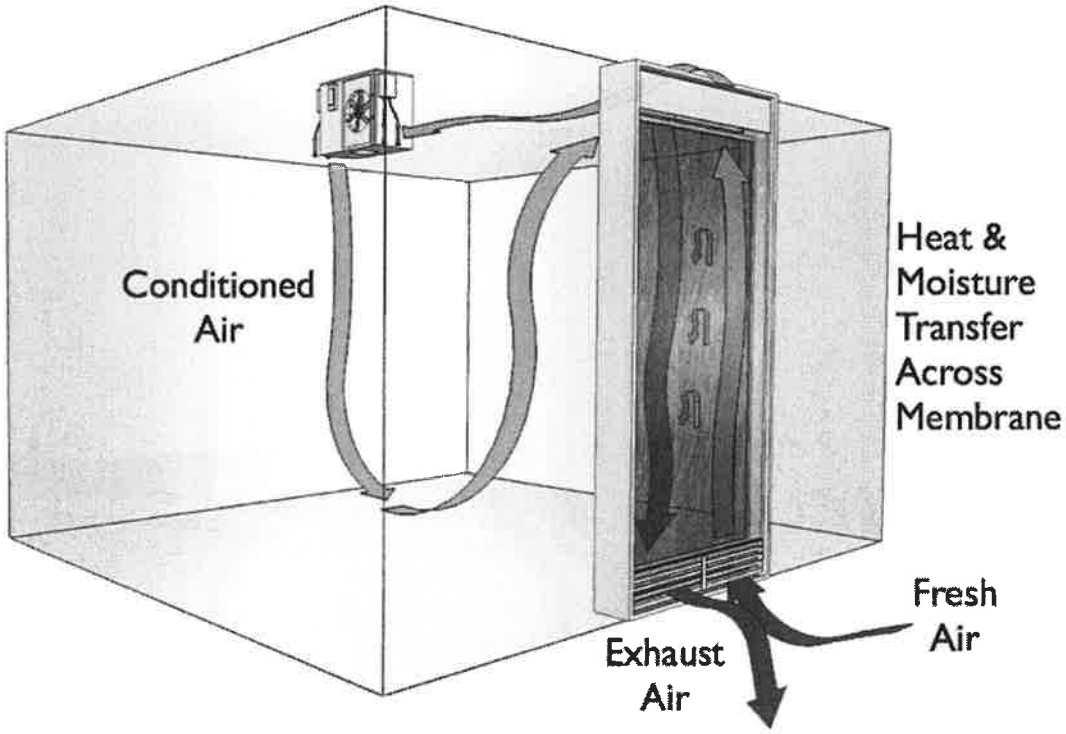
Air-filtering trickle vent



Air-filtering trickle vent

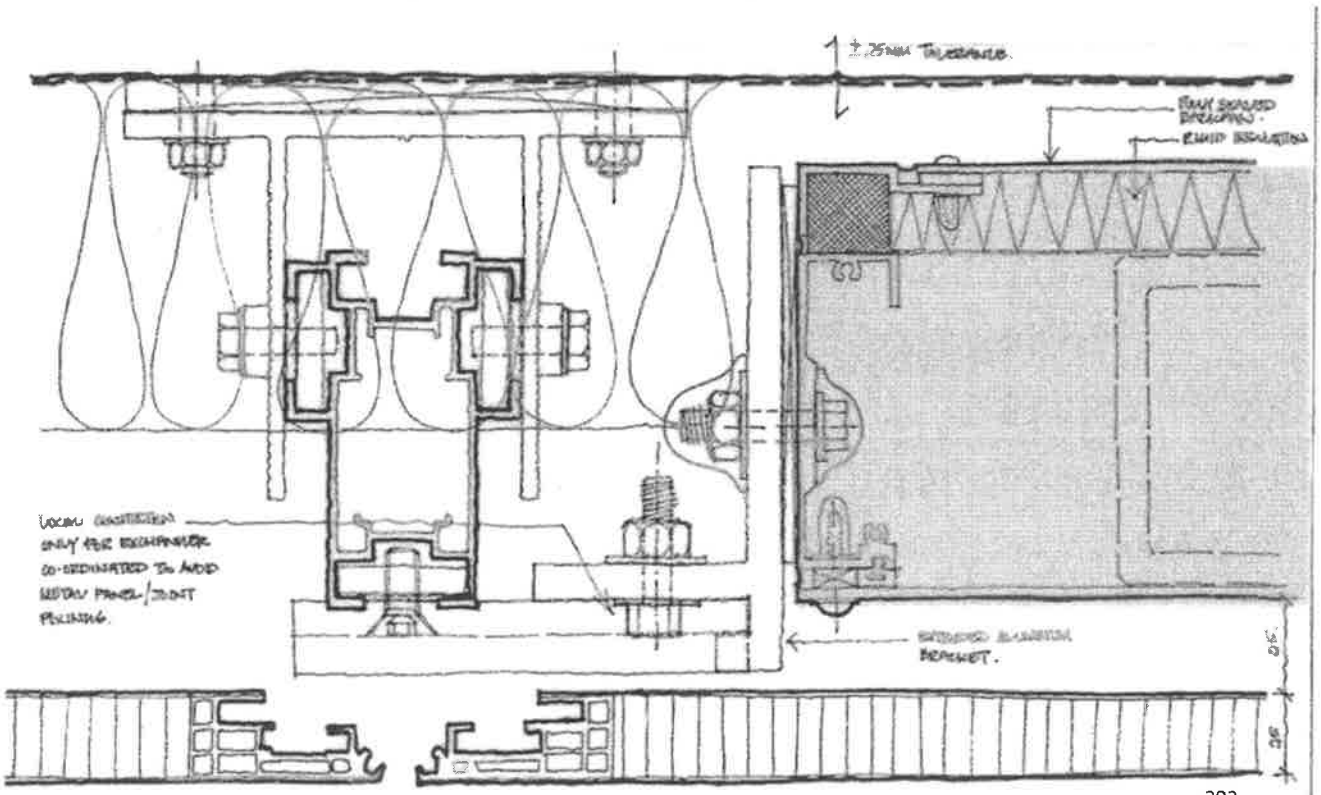


Heat-exchanger in cladding



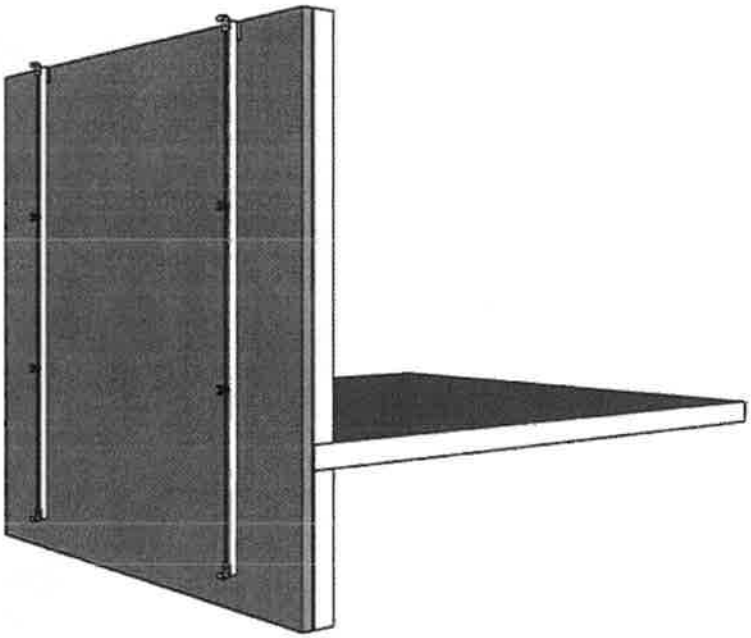
BCA ACADEMY

Heat-exchanger in cladding



Heat-exchanger in cladding

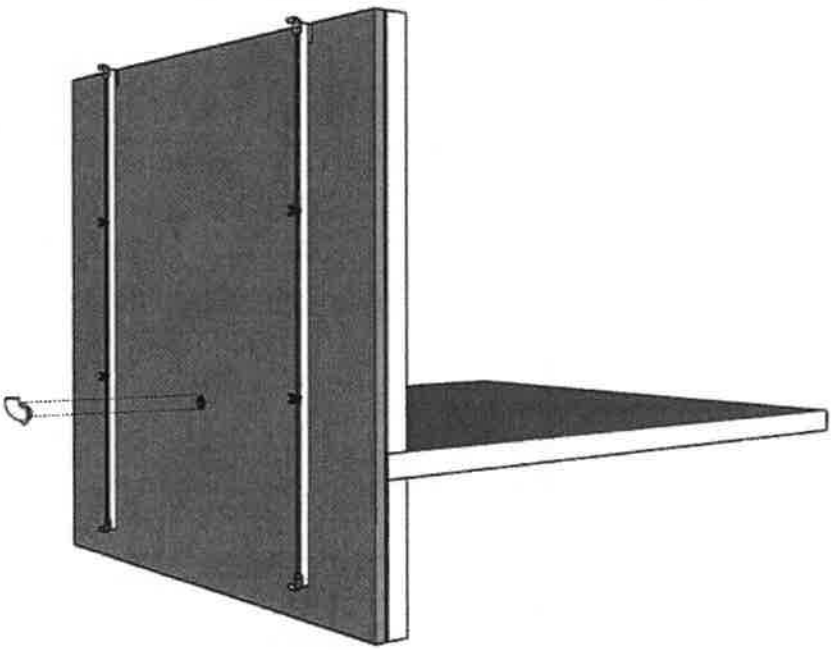
INSTALLATION SEQUENCE



BCA ACADEMY

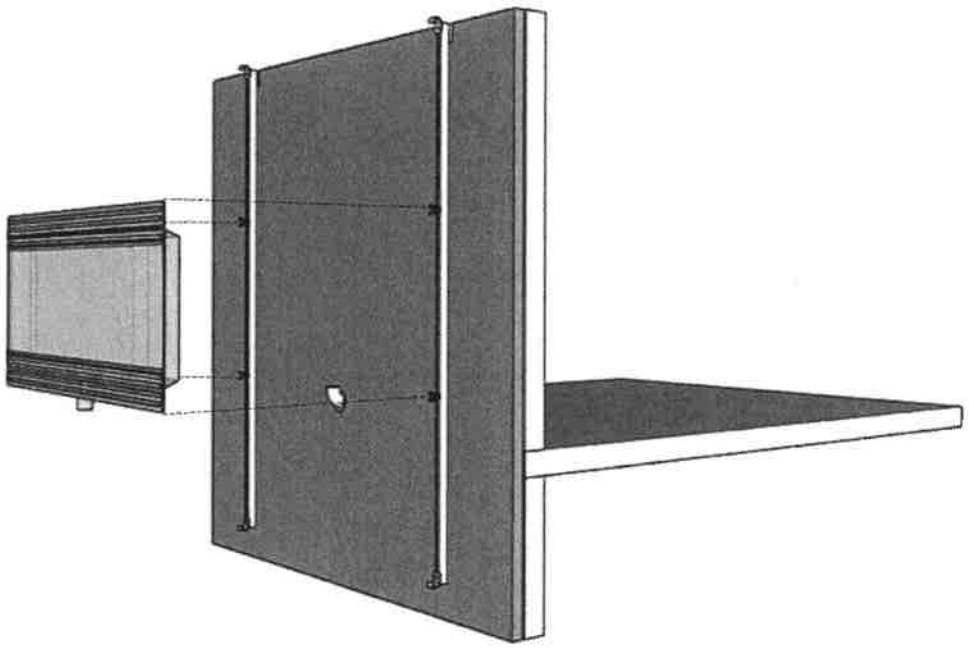
Heat-exchanger in cladding

INSTALLATION SEQUENCE



Heat-exchanger in cladding

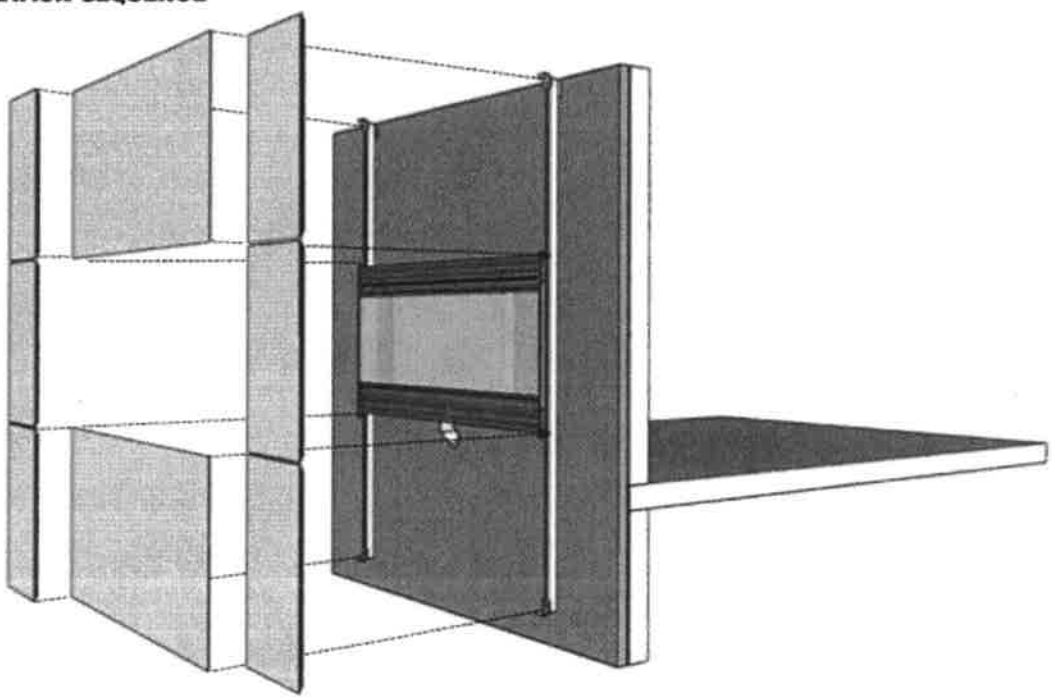
INSTALLATION SEQUENCE



BCA ACADEMY

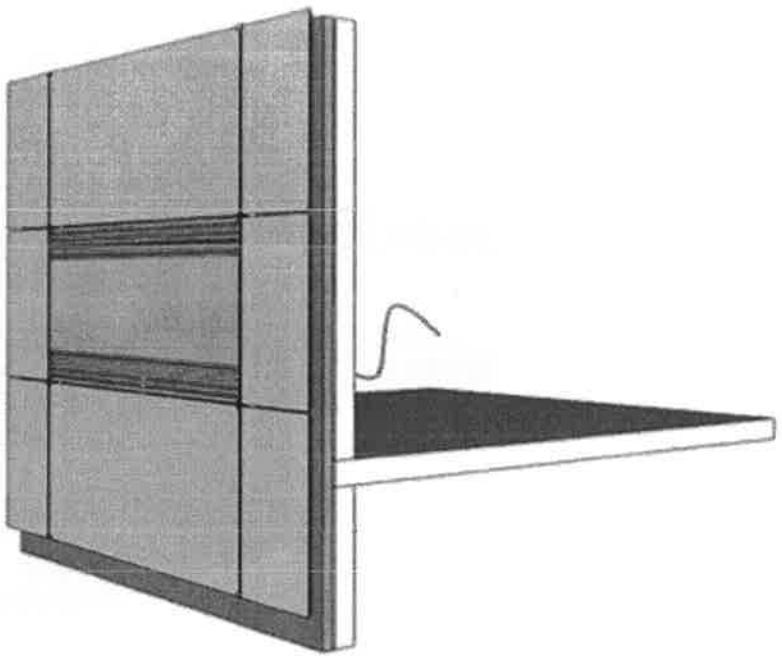
Heat-exchanger in cladding

INSTALLATION SEQUENCE



Heat-exchanger in cladding

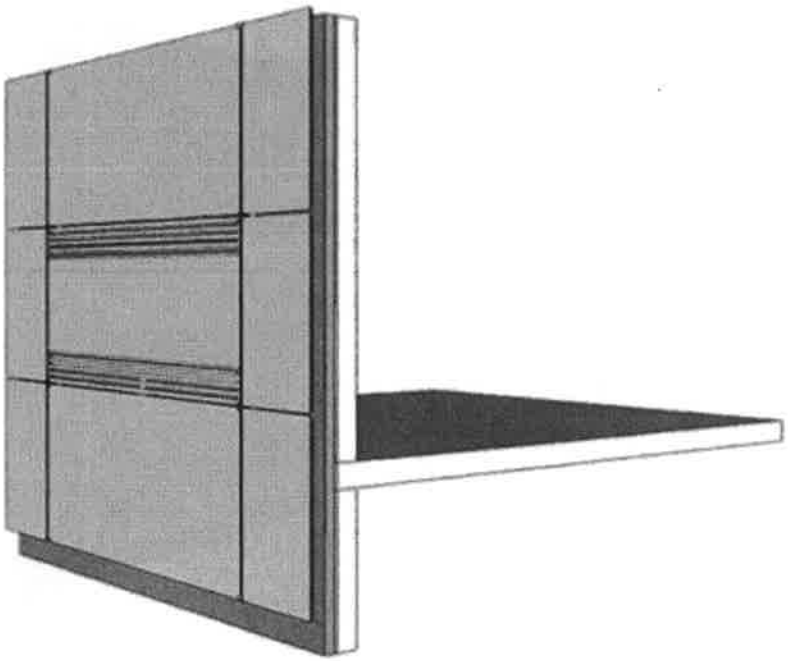
INSTALLATION SEQUENCE



The Education and Research arm of the Building and Construction Authority

Heat-exchanger in cladding

INSTALLATION SEQUENCE



The Education and Research arm of the Building and Construction Authority

Heat-exchanger in cladding

ADVANTAGES AND BENEFITS

- AIR CONDITIONING ENERGY USE REDUCTION
- PEAK COOLING LOAD REDUCTION
- SMALLER AIR CON SYSTEM REQUIRED
- REDUCED CONDENSATON AND RISK OF MOULD
- IMPROVED INDOOR AIR QUALITY
- BETTER VENTILATION ZONING CONTROL
- INCREASED NET LETTABLE AREA
- FAÇADE AESTHETIC IMPROVEMENT

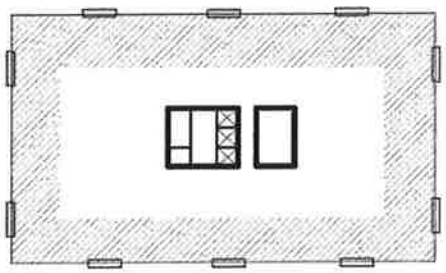
	ENERGY USE REDUCTION			PEAK COOLING REDUCTION	HUMIDITY CONDENSATION REDUCTION
	cooling	fans	TOTAL		
OFFICE	46%	4%	46%	44%	31%
SCHOOL	27%	1%	28%	30%	32%
RESIDENCE	39%	0%	44%	45%	29%
HOSPITAL	32%	1%	33%	35%	34%

Heat-exchanger in cladding

RETURN ON INVESTMENT

- Single office building floor plate
- Total floor area = 3960 sq. m.
- Perimeter zone area= 1608 sq. m.

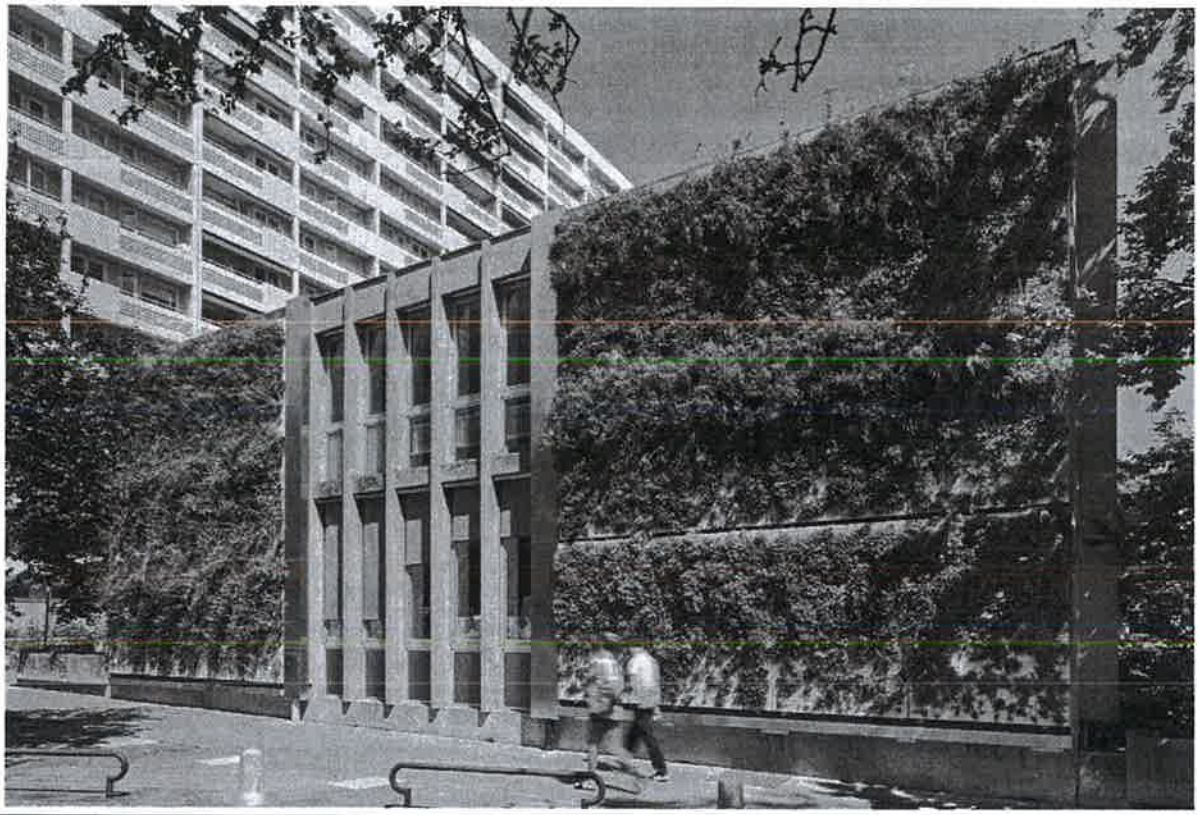
Add 10 AirFlow™ Panels to serve perimeter zone.



< Reduced Air Con System Capacity >	<deduction>
< Reduced Perimeter Zone Ductwork >	<deduction>
< Eliminated ERV >	<deduction>
< Eliminated 10 Rain Screen Panels >	<deduction>
Added 10 AirFlow™ Panels	addition
Net Cap-Ex to Project	X
Annual Avoided Electrical Purchase	Y
ROI (5-year)	positive

Note:
generic model showing overall cap-ex balance.
Specific projects to be tested in this format.

Bio-Concrete



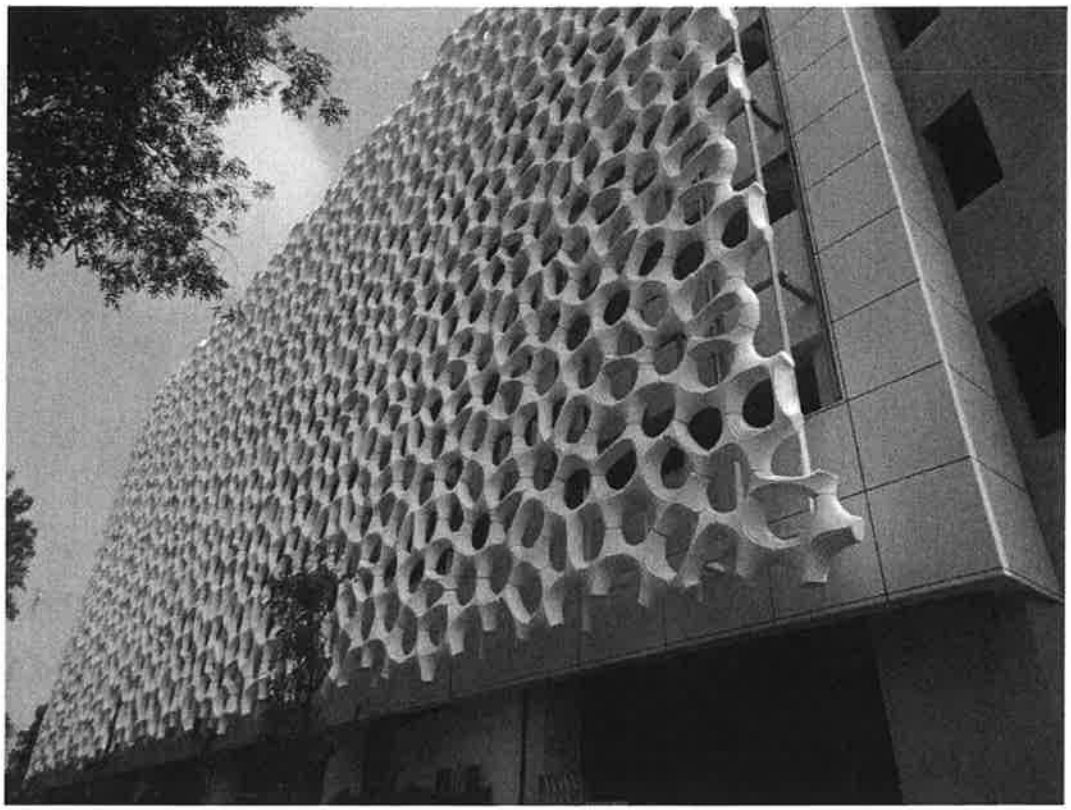
Creabeton

BCA ACADEMY

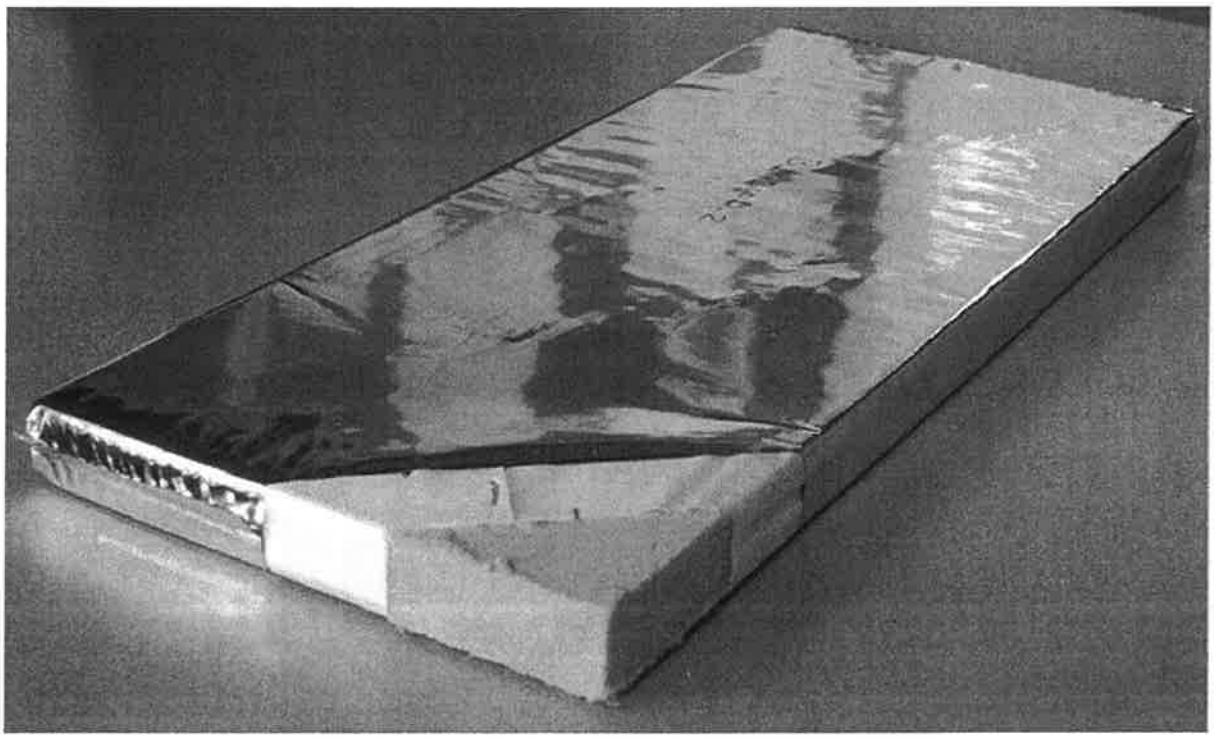
Bio-Concrete



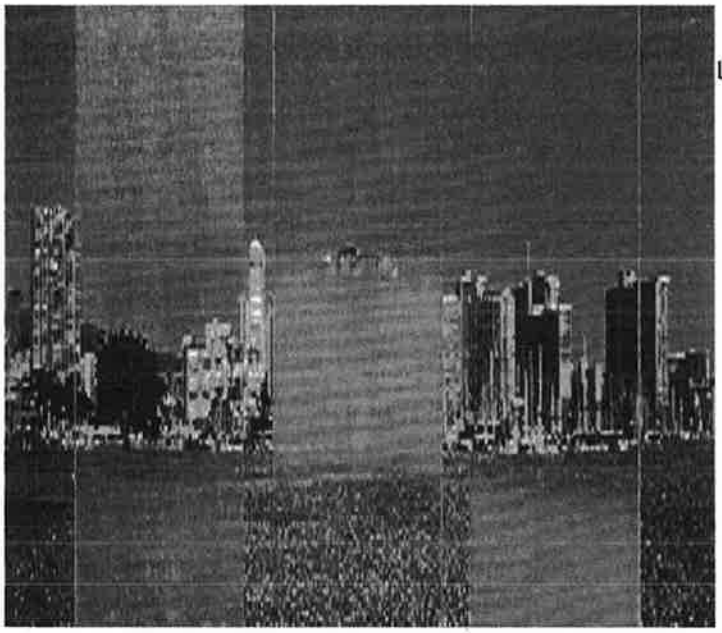
Haze-Filtering Concrete Concrete



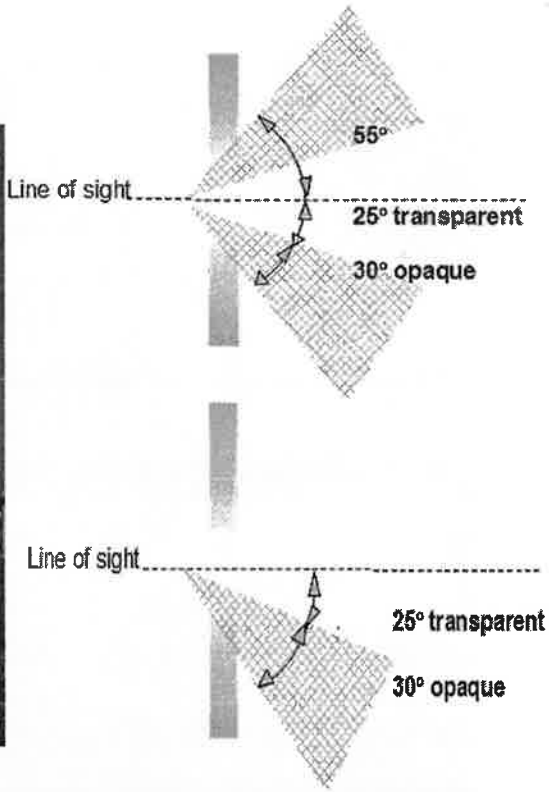
Hyper-insulation - VIPs



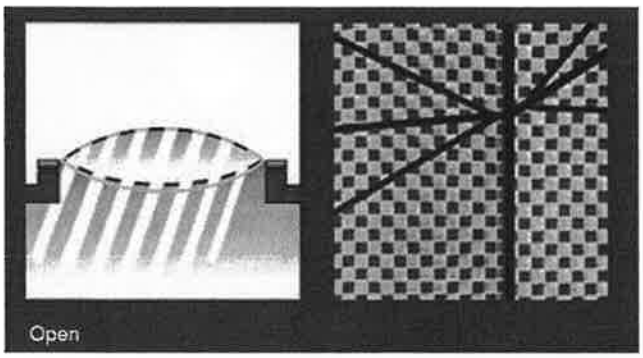
Angle-Selective Glass

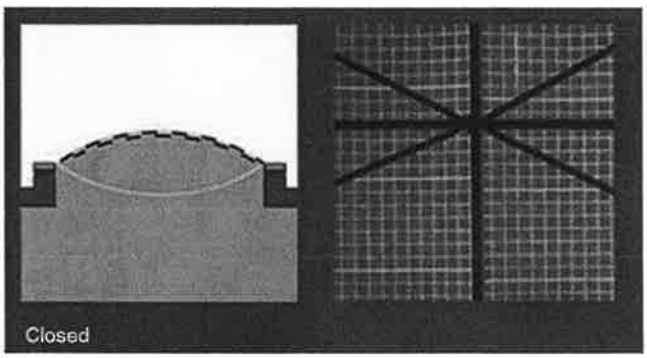


Images © www.cyberglasstrade.com



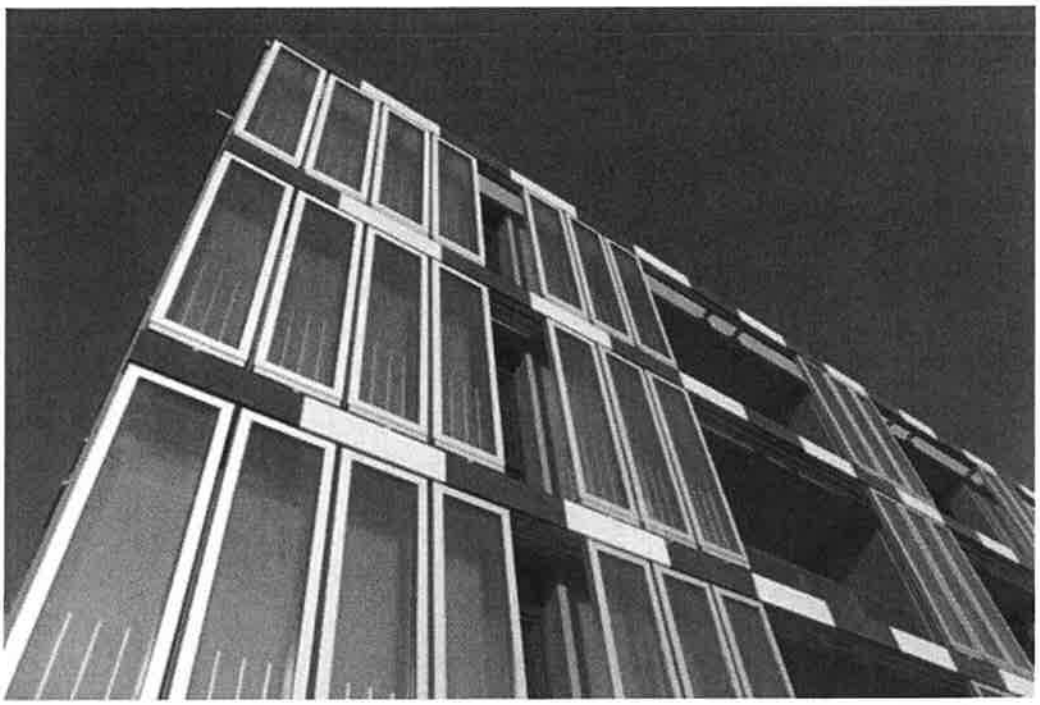
Intelligent ETFE







Bio-Glass



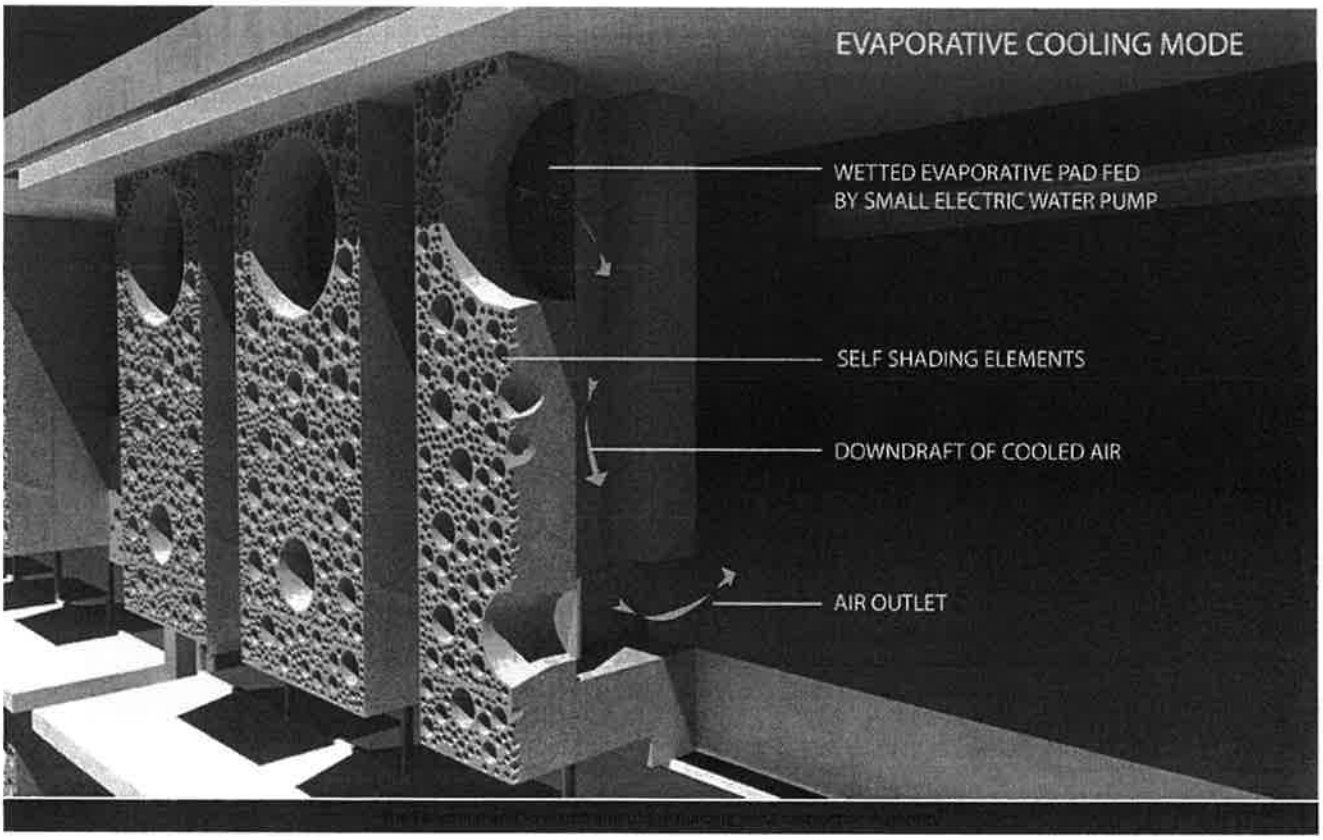
BCA ACADEMY

Bio-Glass



Electrochromic Glass

Evaporative Cooling Façade



Evaporative Cooling Façade

