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Carbon footprint of façades: significance of glass

Findings from the life cycle assessment of 16 façade typologies & 18,000 design simulations

Tom Patterson Theatre, Ontario, Canada

COOL-LITE SKN 076 II on Diamont

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Understanding the relationship between embodied carbon and operational performance is key to making targeted decisions to reduce emissions across supply chains and design processes.

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Delivered in partnership: Arup and Saint-Gobain Glass

This research has been delivered by Arup and Saint-Gobain Glass in partnership. Through this collaboration the combined team was able to draw on unique expertise, detailed datasets, industry context, and existing analysis tools to explore the life cycle carbon impact of glass within façades.

Contents

Foreword

Graham Dodd
Arup Fellow
ARUP

As a key component of façades, glass and glazing units have a primary role to play in the reduction of whole life carbon of the built environment.

The quality and performance characteristics required of glass in modern buildings is complex and integral to the long-term operational performance of the building. However, the embodied carbon associated with the production, installation, and replacement contributes to the embodied carbon footprint of the façade.

For building envelopes, it is critical that operational and embodied carbon are considered in parallel. Improving the thermal performance of the envelope often involves adding more material, leading to an increased embodied carbon.

The picture is more complex when glazing is considered in isolation. The thermal insulation and solar heat protection properties of the glazing depend not only on the extent of glazing, but also upon the choice of coatings, width of the Insulating Glazing Unit (IGU) cavity, and the presence of gas within the IGU.

Understanding the relationship between embodied carbon and operational performance is key to making targeted decisions to reduce emissions across supply chains and design processes.

The first part of the study focused on understanding the variability in embodied carbon for different façade designs, and considered a number of typologies, materials, and design variables such as shading. The whole life embodied carbon of facades was found to vary significantly depending on the façade typology used.

The second part of the study focused on evaluating the embodied carbon of unitised curtain wall systems and their impact on a building’s operational demand. We investigate the influence that different design and material decisions have. A unitised curtain wall façade system was selected as the focus for this step, based on the prevalence of use for both residential and commercial properties in the UK and Europe.

The results of this study demonstrate the challenge which is ahead; we must, as an industry, embrace the complexity of understanding low-carbon design and manufacturing solutions within the context of each individual project we undertake.

Foreword

Even if climate change is not new (let us be reminded that the landmark Bruntland report was published 35 years ago!), interest in this topic has grown rapidly over the past couple of years. Since the Paris Agreement (2016), the publication of two major reports have shaken up the building industry: the LETI study and the RIBA 2030 Climate Challenge. Both set embodied carbon thresholds for buildings.

At Saint-Gobain, we have made a commitment to achieve zero net carbon emissions by 2050. We follow a clear roadmap towards the decarbonisation of our business by paying attention to the two sides of this coin: embodied & operational carbon.

On operational carbon, we continue to innovate and improve the performance of our coatings to reduce energy consumption during building use: less cooling, less heating, less artificial lightning.

On embodied carbon, Saint-Gobain Glass was the first glass manufacturer to publish EPDs in 2011. Since then we have continued to innovate. We have added the carbon footprint (GWP: A1-A3) to our glazing configurator, CalumenLive, as a means of making the environmental impact of glass choices more visible.

What was missing for us was understanding the “carbon” relationship between glass and facades. Where are we in terms of embodied carbon per m^2 of façade? What about the impact of the different façade typologies and different design choices, such as window wall ratio and choice of shading system? What is the impact of glass? How much could low carbon glass be a solution for façade decarbonisation?

We are delighted to have had the opportunity to partner with Arup on this study. The results of this important work are a key building block in bringing understanding and visibility to this topic. We believe it is just the beginning. More building life cycle assessments will be needed to fine-tune the most comfortable and sustainable façades of the future.

We hope you enjoy the reading!

Bruno Mauvernay
Managing Director
Business Unit Glass Facade

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Key Outcomes

Through the exploration of a range of façade designs, this analysis has made the following key observations:

- The embodied carbon of a façade will vary significantly depending on the system type and design. For the 16 facades studied, the embodied carbon (A1 – A5, B4 and C1 – C4) ranged from 160 to 520 $kgCO_2e/m^2$ of façade.
- Glass is unique in its ability to provide daylight into our buildings. It is a significant contributor to the embodied carbon of facades (often second only to aluminium) and the percentage contribution may increase as other industries decarbonise. The contribution of glass varies significantly with façade typology (in this study, from 26 to 60%).
- One key factor leading to glass's embodied carbon contribution over the life of the structure is the service life of IGUs (30 years), and thus the requirement for replacement of IGUs within the lifetime of the façade. In reality, it is not very common for glazing alone to be replaced, particular for commercial buildings. Instead, whole facades are more commonly replaced.
- No single solution for an 'optimal' unitised curtain wall (UCW) façade with regards to whole life carbon (WLC) was observed. To make informed decisions in terms of embodied and operational carbon, assessment of design options against the specific needs of a project is required.
- Due to the wide variation in carbon impact that different façade systems, and different designs for unique façade systems have, designers have a wide scope, and responsibility, to take informed approaches to minimise whole life carbon. This may be achieved through systematically performing complete life cycle assessments at a building level as a part of the design process.
- To achieve this, the industry must unite and be transparent, to ensure that necessary data and guidance is provided to equip designers, and manufacturers, to understand their scope for influence.
- Many façade/building design variables influence both operational performance and embodied carbon, sometimes in tension. Understanding these influences and the 'carbon payback period' of design choices can influence carbon outcomes.
- Glass coatings present an effective way to reduce whole life carbon: they have an improved 'return on investment' when compared to external shading and internal blinds, due to their negligible impact on the embodied carbon (approximately 1 $kgCO_2e/m^2$), and relatively high positive impact on the operational carbon, reducing solar gains, heating requirements and need for artificial lighting. The optimal shading solution in terms of operational carbon will depend on the orientation of the building.
- More generally, the embodied and operational carbon benefits of design decisions in terms of must be balanced; there is a need to understand the trade-offs made with each design decision.

Introduction

From operational to embodied carbon

The global built environment sector is the source of almost 40% of global energy-related carbon emissions[1]. Until recently, little attention has been paid to the carbon impacts of the construction and refurbishing of buildings, with the majority of focus on their operational performance. Global decarbonisation trajectories indicate that the industry needs to reduce these emissions by 50% by 2030 if it is to reach net zero by mid-century and achieve the climate goals of the Paris Agreement.

Reduction in operational energy carbon emissions of buildings has occurred through more stringent energy codes, greater energy efficiency in design briefs, and shifts towards renewable energy production both on-and off site. As the performance of buildings has improved, the proportional contribution of embodied carbon compared to operational carbon is increasing.

While operational carbon (OC) can continue to be optimised throughout the life of the building, embodied carbon (EC) is ‘locked in’ once building construction is complete. Architecture 2030[2] predict that if no change is made between now and 2040, embodied carbon will be responsible for nearly 60% of total new construction emissions.

In particular, ‘upfront carbon’, associated with raw material supply, production of construction materials, and construction, must rapidly be reduced.

To create a net zero built environment, embodied carbon must sit at the forefront of designers’ minds. Baselines and targets for embodied carbon reductions are being established by many organisations in the UK and EU, and across the world, with C40 Cities recording 144 policies and actions introduced globally in 2021 alone.[3]

The Royal Institute of British Architects (RIBA) 2030 Climate Challenge Targets state designers should be reducing embodied carbon of the building by at least 50 – 70% before offsetting by 2030. For commercial offices, this entails a reduction of whole life cycle embodied carbon to less than 750 $kgCO_2/m^2$ [4].

The London Energy Transformation Initiative (LETI) Climate Emergency Design Guide embodied carbon targets provide important context for what new buildings may aim to achieve by 2030. For commercial offices, LETI targets reducing upfront embodied carbon to less than 350 $kgCO_2/m^2$ [5].

It can be concluded from the literature[4] that the façade accounts for 10-20% of the building’s embodied carbon footprint. It is clear from studies conducted across industry that the carbon footprints of buildings are still above these thresholds.

[1] Global carbon emissions from buildings and construction were 37% of total emissions in 2019. Source: ‘2021 Global Status Report for Buildings and Construction’, Global Alliance for Buildings and Construction

[2] Architecture 2030 https://architecture2030.org/embodied-carbon-actions/

[3] Growing number of policies to tackle embodied emissions © C40 Clean Construction Policy Explorer. Retrieved 01/07/2021

[4] RIBA 2030 Climate Challenge V2 (2021)

[5] Proportion of façade in the total building carbon footprint: (a) LETI’s Climate Emergency Design Guide embodied carbon targets, 2020 : 16%; (b) Whole-life carbon: Facades (https://www.building.co.uk/whole-life-carbon-facades/5078620.article), 2015 : from 8 to 21 %; (c) Net-zero buildings Where do we stand? Arup & WBCSD, 2021: 19%; (d) Embodied Carbon – Understanding the impact of real estate (https://www.britishland.com/sites/british-land-corp/files/press-release/pdf/embodied-carbon-real-estate.pdf) : 11%

The role of glass

Performance versus environmental impact

Glazing is essential to building façades; it provides us with natural light and a connection to the outdoors, and contributes to the management of heating and cooling. The quality and performance characteristics required of glass in modern buildings is complex and integral to the long-term operational performance of the building. However, the embodied carbon associated with the production, installation, and replacement of glazing (typically at least once in the lifetime of a 60 year building) contributes to the carbon footprint of the façade.

Materials sustainability is about striking the right balance between performance benefits, architectural aspirations, client requirements, and the environmental and social impacts of the design solution, material selection and specification this demands. An approach that examines the full life cycle of the material should be used to minimise overall impact whilst at the same time maximising the performance benefits it affords.

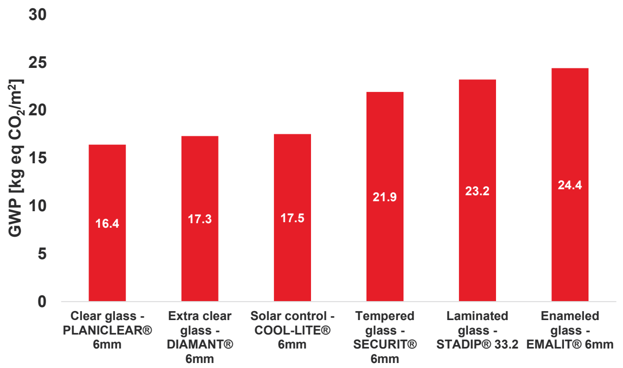
Decisions made about the selection, specification and manufacture of a product often have consequential results for other properties. For example, to produce glass with very high aesthetic control, intense quality control and more requirements on the input material are often required, reducing the amount of cullet that can be used. However, increasing cullet content is a key way to reduce the upfront embodied carbon of glass products.

Making an insulated glass unit

The embodied carbon associated with the production of an insulated glazing unit is comprised of the carbon associated with several material selection and design choices that are made about the unit, including:

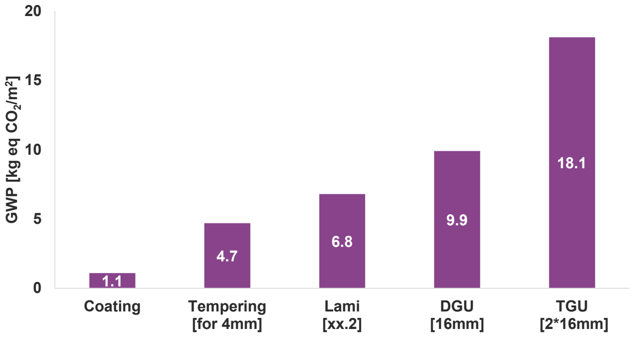
- The thickness of the glass
- The raw materials and processing of the float glass selected
- Heat treatments applied
- The material and energy of lamination
- The material and energy of any coatings applied
- The material and energy required to produce the Insulated Glazing Unit (spacer, sealant, dessicant).

The graphs on the right present the embodied carbon associated with select Saint-Gobain Glass products and processes. After thermal treatment processes, heat soak testing is typically conducted to minimise the risk of spontaneous breakage due to the presence of nickel sulphide inclusions. It is noted that the data presented on the right does not include the embodied carbon associated with this process.



EC associated with glass products

© Saint-Gobain Glass EPD 2021, GWP [kg eq CO_2/m^2 of glass pane], A1-A3 (except for EMALIT, EPD 2016)



Glass transformation processes (excluding glass production)

© Saint-Gobain Glass. EPD 2021, GWP [$kgCO_2e/m^2$ of glass pane], A1-A3 - without glass impact

The influence of glass on the life-cycle carbon of façades

Understanding the way in which material and design choices influence embodied carbon and operational performance outcomes is key to identifying the actions which will contribute most significantly to reducing the whole-life carbon of façades/ buildings.

The aim of this project was to understand how the different elements of façade build-ups contribute individually to the overall, or whole life, carbon footprint of a façade and building.

Whilst some carbon-reduction strategies can be led by design teams, through selection of lower carbon material palettes or designing lower carbon systems, at some point, a limit is reached and further reductions must be delivered by materials manufacturers decarbonising their products. Both of these actions are required urgently to reduce our industry's environmental impact.

This study sought to determine the degree of influence that glazing units have within façades. Design variables have been selected and studied to explore potential ways designers can influence/reduce whole life carbon. By clearly understanding the role of glass within the wider system, Saint-Gobain Glass, Arup, and the wider industry, can be better informed in determining their roadmaps for decarbonisation.

The project has been delivered in two parts, described in more detail in the next sections:

1. Glass contribution to systems
   Understanding the carbon footprint of a number of façade typologies, including the contribution of glass.
2. Influence of design choices
   Investigating the influence of particular design choices on the embodied carbon and operational performance of a façade system through a Parametric unitised curtain wall case study.

Tours Duo, Paris, France
COOL-LITE SKN 065, SKN 076, XTREME 60/28, STBS
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Selection of emission factors

Influence of decarbonisation of other materials

The results of life cycle embodied carbon analyses are highly sensitive to the emission factors selected for each material or product.

In this analysis, emission factors have been selected to be representative of the European supply chain, with data taken from a combination of LCA databases presenting industry average values, including EcoInvent and product specific Environmental Product Declarations (EPDs).

Many players within material supply chains are focusing on decarbonizing their material production, such that the emission factors associated with certain materials are dramatically reducing. One example of this is the aluminium market. By increasing the recycled content of aluminium and using renewable energy supplies in production, the embodied carbon associated with production can be dramatically reduced. Across the market, a range of products are still available, from fossil fuel powered virgin material supplies, through to renewable energy powered high recycled material supplies.

Depending on which product/emissions factor is selected, the proportional impact that glass has to the total system will vary.

Using the three emission factors for aluminium presented below, we find that the proportional contribution that glass has to the total embodied carbon of a façade system shifts from:

11% → 20%

As other material supply chains are already beginning to decarbonize, it is becoming increasingly important that the glass industry does so too.

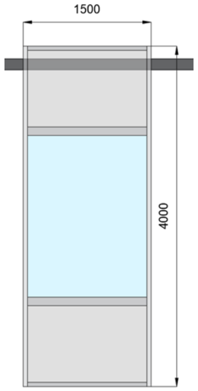
For the purposes of this study, we used the 78% pre-consumer recycled content product, as this is closest to the European average.

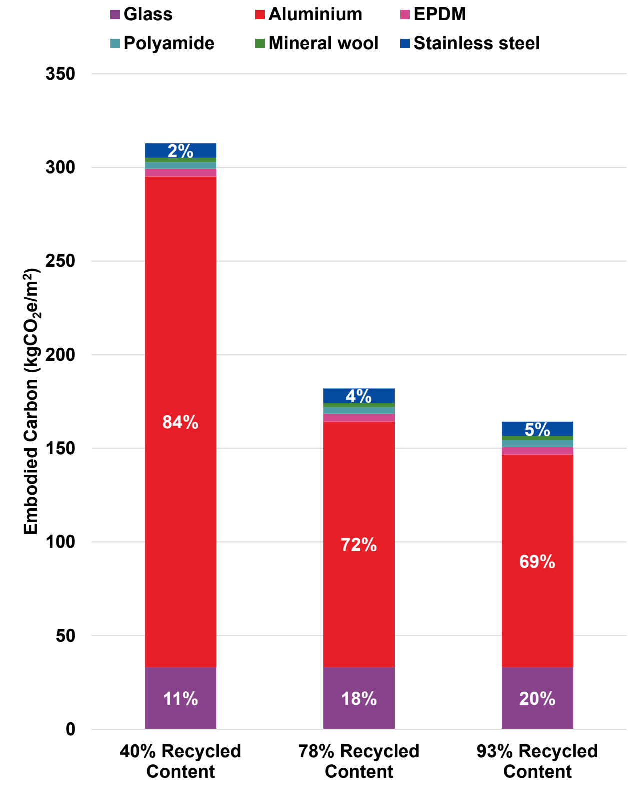
Recycled content	kgCO$_2$e/kg
40% pre-consumer recycled content [1]	16.42
78% pre-consumer recycled content [2]	7.00
93% pre-consumer recycled content [3]	5.72

[1] Ecoinvent 3.7.1, Aluminium alloy, AlMg3 {GLO}| market for | APOS, U & Section bar extrusion, aluminium {GLO}| market for | APOS, U

[2] S-P-02973 For Aluminium Profiles Produced By Hydro Extrusion Spain S.A.U.Navarra

[3] S-P-03015 For Aluminium Profiles Produced By Hydro Aluminium Extrusion Portugal Haep S.A. Avintes





Influence of de-carbonisation of aluminium on the EC of WT-02

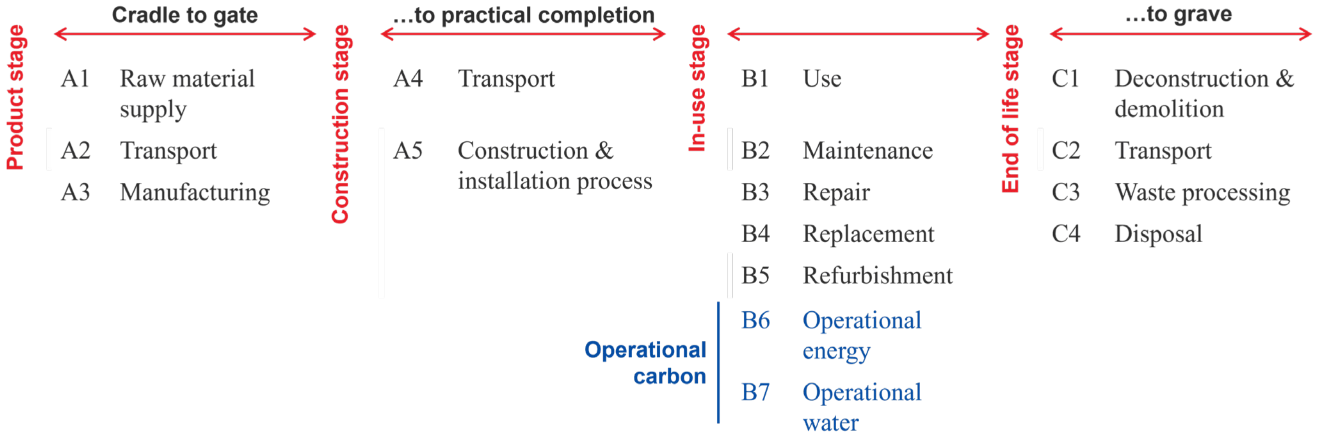
A1 – A3 (kgCO$_2$e/m^2)
All the recycled content is from pre-consumer sources.

Introduction to life cycle assessment

Life cycle assessment (LCA) is an environmental systems analysis and accounting method for assessing the environmental impacts of any product or service over its lifetime. It is a systematic and quantitative approach, in which the value chain of a product or service being assessed is mapped from cradle to grave (i.e. incorporating process steps from extraction of resources, transport/logistics, manufacture and assembly, energy supply, use of the product or service and end-of-life).

Steps 1 and 2 of this study work within the LCA framework established by EN 15978.

EN 15978 provides calculation rules for the assessment of the environmental performance of new and existing buildings. The standard splits the building lifecycle down into distinct modules with A1-A5, B1-5 & C1-C4 covering embodied carbon. The calculation mainly consists of multiplying volumes of materials by Environmental Product Declarations (EPD) emission factors.



Life cycle assessment stages of an asset

Key terminology

Key sustainability definitions

Carbon dioxide equivalent emissions (CO_2e) represents an equal GHG emissions quantum. It is commonly use since carbon dioxide is the major component of GHG emissions (burning of fossil fuels, waste, biological materials, emissions from chemical reactions).

The Carbon Payback Period may be defined as the time over which the benefits on a building's operational carbon offset the burden associated with an increased embodied carbon associated with a particular design decision.

Decarbonisation refers to measures through which a business sector, government entity, or other organisation is able to reduce its CO_2e.

Embodied carbon refers to a quantity of CO_2e associated with the materials used to construct and maintain a building throughout its lifespan (material extraction, manufacture, construction, demolition and end of life).

An emission factor is a value which attempts to represent the quantity of pollutants released into the atmosphere by a particular activity, process or action. Typically, emission factors are expressed in terms of equivalent kilograms of carbon dioxide released into the atmosphere for a defined unit quantity of a product.

An Environmental Product Declaration is an independently verified and registered document that communicates clear and comparable information about the whole life environmental impact of a product on the basis of a life cycle assessment.

Fossil fuels are hydrocarbon-containing materials such as coal, formed underground from the remains of decomposing biological matter. When burned, these fuels release carbon dioxide and other greenhouse gases into the atmosphere.

Global Warming Potential (GWP) is a measure of how much energy the emissions of 1 tonne of a gas will absorb over a given period of time, relative to the emissions of 1 tonne of carbon dioxide (CO_2). The GWP is measure in $kgCO_2e$ (carbon equivalent). The GWP measure was developed to allow comparisons of the global warming impacts of different gases. On an environmental product declaration, the GWP impact indicator presents the $kgCO_2e$ associated with a functional unit of the product through the defined lifecycle stages.

Carbon offsetting is a process by which carbon dioxide emissions arising from human activity is compensated for through participation in schemes designed to make an equivalent reduction of carbon dioxide equivalent emissions in the atmosphere. While offsetting carbon emissions may in some contexts render a particular activity 'carbon neutral', it is important to note that this is not a robust alternative to making true reductions in the carbon emissions made by humans and our activities.

Operational carbon refers to the quantity of CO_2e associated with the heating, cooling, and energy use of the building (for example, artificial lighting).

Renewable energy is energy which comes from natural sources or processes that are constantly replenished.

Upfront carbon is the embodied CO_2e associated with raw material supply, production of construction materials, transportation to site and construction.

Whole Life Cycle Assessment (WLCA) is a method to quantify both embodied and operational carbon emissions of an asset over its life cycle.

Key terminology *cont.*

Key acronyms and abbreviations

Al	Aluminium
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	Carbon dioxide
CLT	Cross laminated timber
CW	Curtain wall
CWCT	Centre for Window and Cladding Technology
DGU	Double glazed unit
DSF	Double skin facade
EC	Embodied carbon
EPD	Environmental Product Declaration
GRC	Glass reinforced concrete
GWP	Global warming potential
IGU	Insulating glazing unit
LCA	Life cycle assessment
LETI	London Energy Transformation Initiative
OC	Operational carbon
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
SFS	Steel framing system
StickCW	Stick curtain wall
TGU	Triple glazed unit
UCW/UniCW	Unitised curtain wall
WLC	Whole life carbon
WWR	Window/wall ratio

Glass Contribution to Systems

Step 1: Understanding the carbon footprint of a number of façade typologies, including the contribution of glass

Glass contribution to systems

Scope

The key goal of this first study was to understand the proportional contribution of glass and other materials to the embodied carbon of different façade systems.

16 façade systems were studied. This set of façade typologies, selected by Arup and Saint-Gobain Glass in collaboration, are considered representative indicators of the current market in the UK and EU.

The 16 façade systems included the following broad typologies:

- Unitised curtain wall systems
- Stick curtain wall systems
- Handset systems
- Deep and narrow cavity double skin systems
- Rainscreen systems.

LCA stages A1 – A5, B4 and C1 – C4 were included in this scope. Full details of the methodology and assumptions made in defining these are presented in the appendices to this report.

Methodology

The methodology utilised in this assessment is an internal Arup method based on EN 15978:2011 and aligned with the guidance of RICS. Full details of are given in the Appendix. The Centre for Window & Cladding Technology (CWCT) are currently working on developing a standardised methodology for the embodied carbon assessment of facades and cladding.

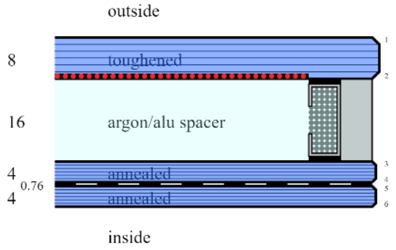
Sufficient design detail was developed for the 16 façade systems investigated in order to calculate the quantities of material present for the functional unit of 1m² of façade.

Different façade typologies and designs will achieve different thermal, solar, daylight and acoustic performance. Care must hence be taken in directly comparing typologies in terms of their cradle-to-grave embodied carbon only, as this may not consider whether the façade typology is suitable for the technical requirements of the scenario or project. The façades studied have different performance according to their configuration. A 3D comparison diagram is provided of the results to contextualise each typology of both its embodied carbon, and also its energy performance (U-value, g-value).

Appropriate emission factors were gathered from a number of industry accepted sources, including the EcoInvent database, Environmental Product Declarations for products considered to be appropriately indicative of the industry, and the Inventory of Embodied Carbon and Energy.

Emission factors for glazing units were provided by Saint-Gobain Glass.

Coating 🟥
Glass substrate 🟦
PVB interlayer ▬

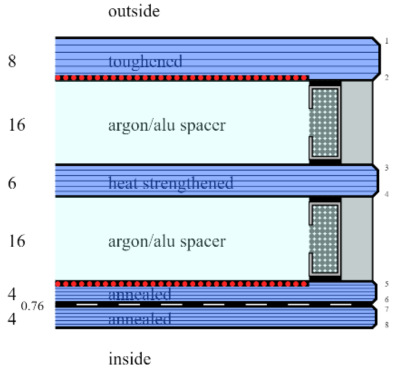


Double glazed unit (DGU)

Build-up: 8T-16-44.2

Total Embodied Carbon

A1 - A3: 71 $kgCO_2eq/m^2$
A + C: 73 $kgCO_2eq/m^2$

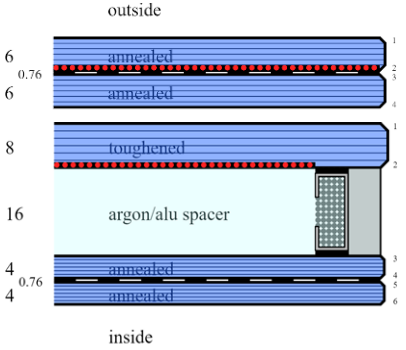


Triple glazed unit (TGU)

Build-up: 8T-16-6-16-44.2

Total Embodied Carbon

A1 - A3: 96 $kgCO_2eq/m^2$
A + C: 98 $kgCO_2eq/m^2$



Double Skin Facade (DSF)

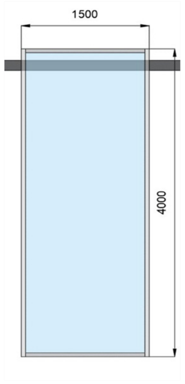
Build-up: 66.2 + 8T-16-44.2

Total Embodied Carbon

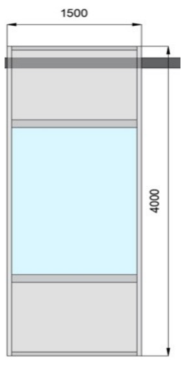
A1 - A3: 116 $kgCO_2eq/m^2$
A + C: 119 $kgCO_2eq/m^2$

Facade system selection

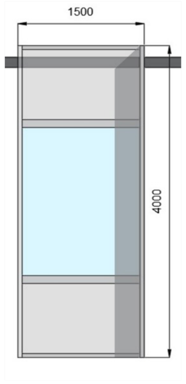
16 façade typologies were selected to represent the breadth of European and United Kingdom façade design.



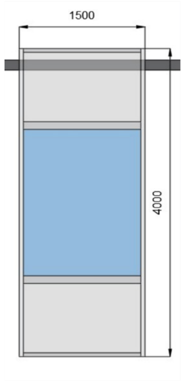
1. Al Unitised CW
100% DGU



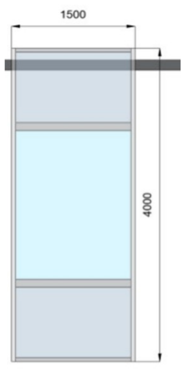
2. Al Unitised CW, Al cladding
50% DGU



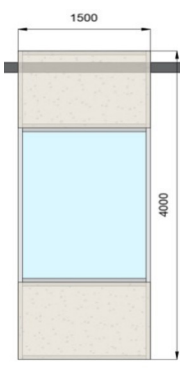
3. Al Unitised CW, Al cladding
50% DGU, Al fins



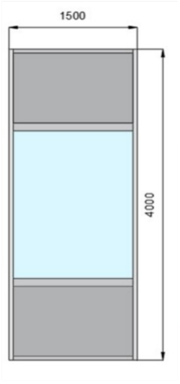
4. Al Unitised CW, Al cladding
50% TGU



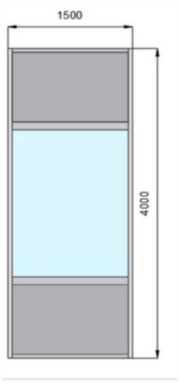
5. Al Unitised CW, shadow box
50% DGU



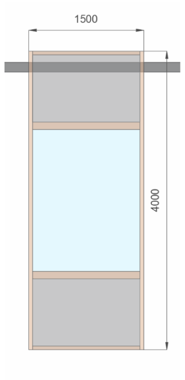
6. Al Unitised CW, GRC cladding
50% DGU



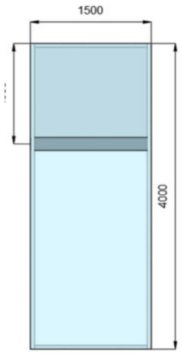
7. Al StickCW, Al cladding
50% DGU



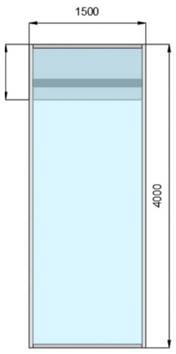
8. Steel StickCW, Al cladding
50% DGU



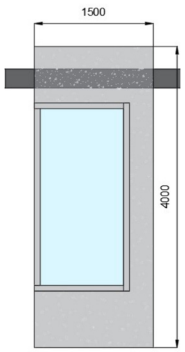
9. Timber StickCW, Al clad.
50% DGU



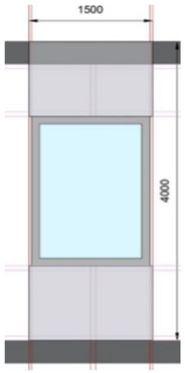
10. Deep cavity Double Skin Facade
100% SGU + DGU



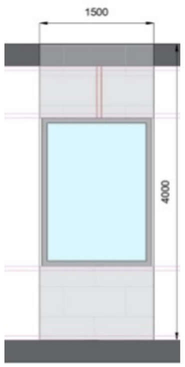
11. Narrow cavity Double Skin Facade
100% SGU + DGU



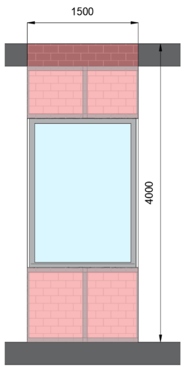
12. Precast Concrete
50% DGU



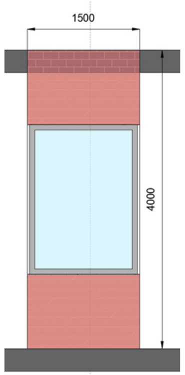
13. Al Rainscreen on SFS
50% DGU



14. Handset Stone on SFS
50% DGU



15. Handset Brick on SFS
50% DGU



16. Handset Brick on CLT
50% DGU

Facade systems comparison

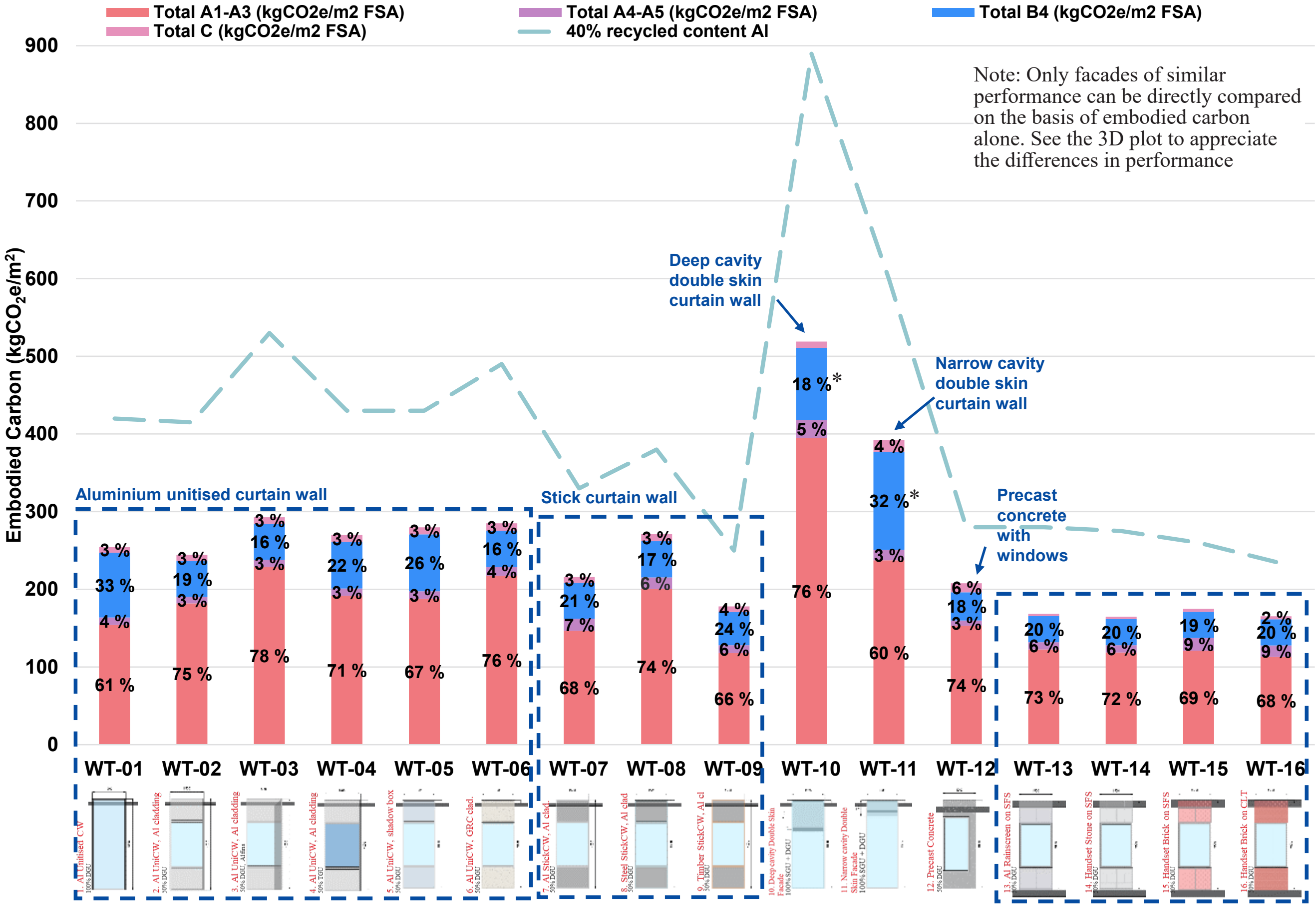
Embodied carbon over façade life cycle

The diagram on the right shows the total embodied carbon for each façade system from cradle-to-grave (stages A to C) over a 60 year lifetime, in terms of each LCA stage.

The embodied carbon of a façade will vary significantly depending on the system type and design. For the 16 facades studied, the embodied carbon (A1 – A5, B4 and C1 – C4) ranged from 160 to 520 kgCO₂e/m² of façade.

The cradle-to-gate stages (A1 – A3) represent the majority contribution to the embodied carbon of the façade. The second largest contribution is stage B4, which represents the replacement of the glazing after 30 years in service, as is the typical LCA assumption. WT-10 (Deep cavity Double Skin Facade, 100% Single + DGU) had the largest overall cradle-to-grave embodied carbon, followed by WT-11 (Narrow cavity double skin façade, 100% Single + DGU) and WT-01 (Aluminium Unitised Curtain Wall, 100% DGU).

Over the page, we see 3D projection of the same data, with each façade typology sorted into a band of thermal (‘U-value’) and solar (‘solar gains’) performance. This can be used to give an indication of the way in which these facades may perform in operation.

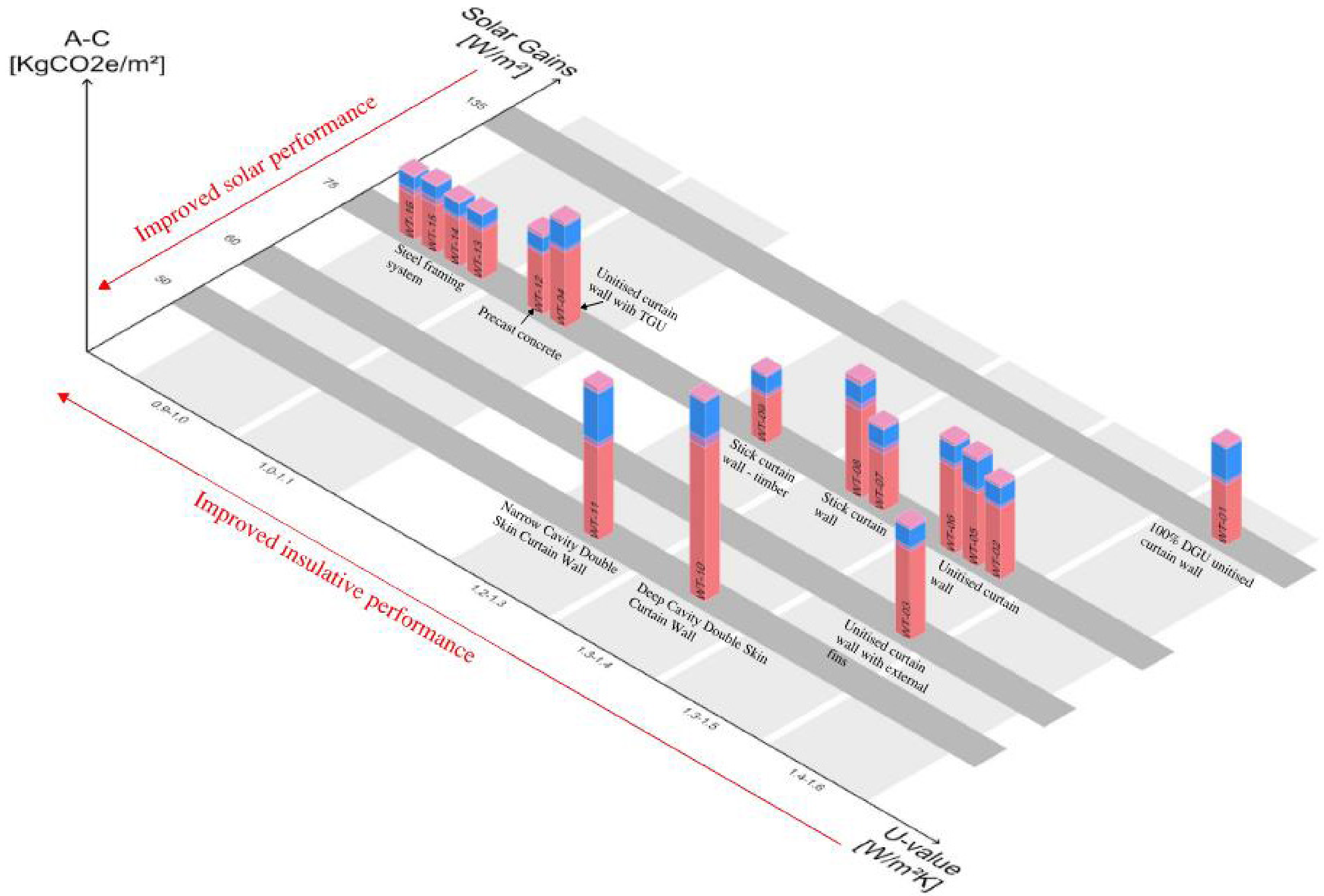


Note: Only facades of similar performance can be directly compared on the basis of embodied carbon alone. See the 3D plot to appreciate the differences in performance

Embodied carbon by stage

A1-A5, B4, C (kgCO₂e/m²) – 78% pre-consumer recycled content Aluminium

* The service life of the inner double glazed unit and outer laminated pane was defined as 30 years. If detailed to enable replacement of the inner IGU without affecting the outer laminate, the service life of the laminate could potentially be extended to 60 years, reducing the overall carbon impact during the B4 stage.



When considering the cradle-to-grave embodied carbon of these typologies, we must also ensure that we are comparing facades with similar performance characteristics – for example, it is more reasonable to directly compare WT-02 to WT-05 than it is to compare WT-02 to WT-11.

The design of a façade system considers a variety of design parameters and considerations beyond cost and embodied carbon. Changing any one aspect of the design of a façade necessarily impacts upon its performance in terms of parameters such as thermal insulation, solar control, daylight, acoustic performance, safety and aesthetics.

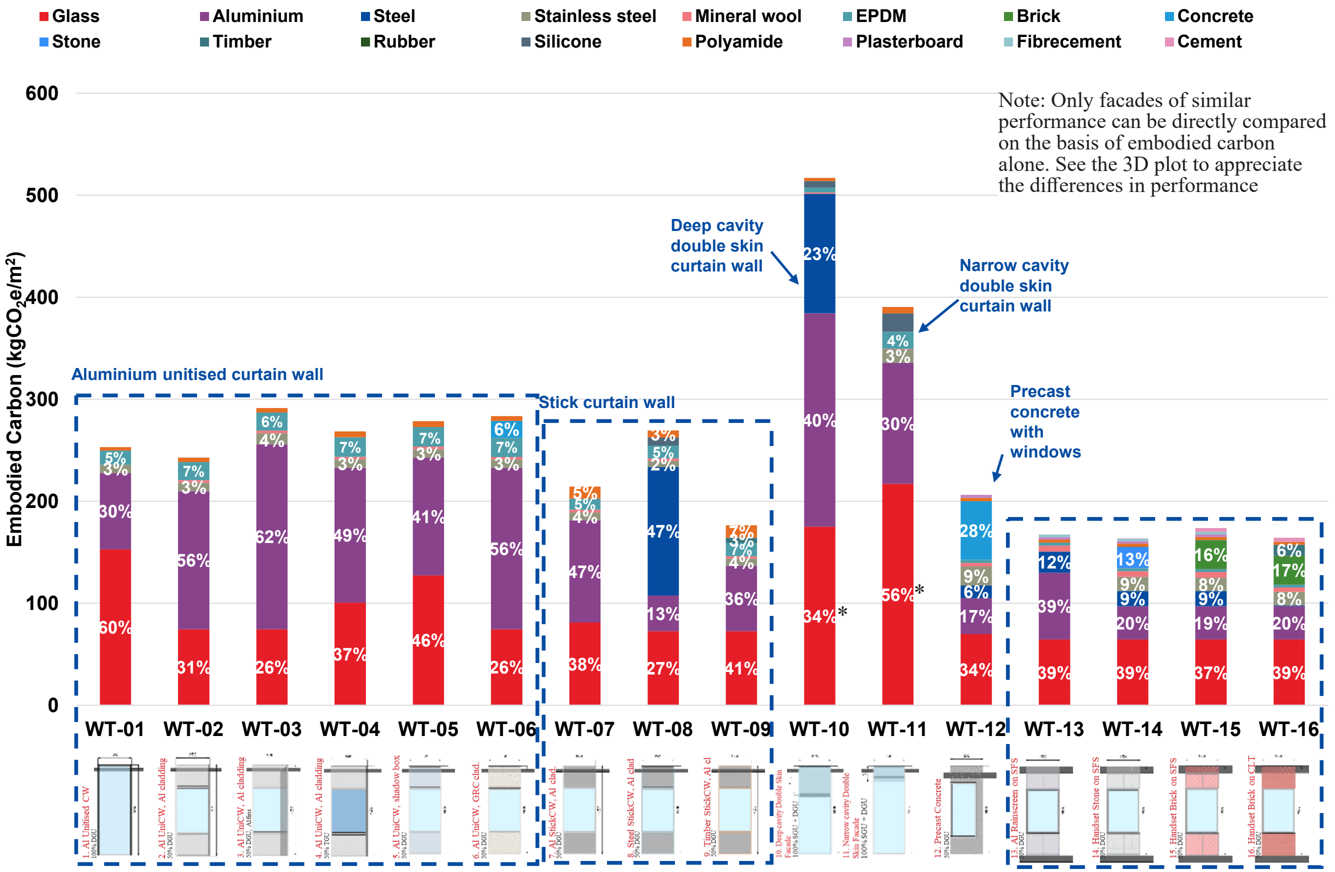
Step 1 focused on evaluating the embodied carbon of systems, and parameters influencing operational performance (e.g. use of solar control) were fixed. The systems defined could have been selected to achieve better solar control through use of a coating with a lower g-value and or use of triple glazing units. The influence of different design parameters on both embodied carbon and operational performance was subsequently considered in Step 2.

Material contribution

The diagram on the right shows the total embodied carbon for each façade system from cradle-to-grave (stages A to C) over a 60 year lifetime, brown down by material components.

It can be seen that for the 50% DGU aluminium unitised curtain wall systems (WT-02 to WT-09), in most cases, the aluminium utilised for the framing represents the majority contribution, with glass representing a close second.

In this study, aluminium with a pre-consumer recycled content of 78% has been utilised. It is anticipated that aluminium and other materials will continue to decarbonise over time. As this occurs, the percentage contribution of glass will increase.



Note: Only facades of similar performance can be directly compared on the basis of embodied carbon alone. See the 3D plot to appreciate the differences in performance

Embodied carbon by material

A1-A5, B4, C (kgCO₂e/m²) – 78% pre-consumer recycled content Aluminium
* The service life of the inner double glazed unit and outer laminated pane was defined as 30 years. If detailed to enable replacement of the inner IGU without affecting the outer laminate, the service life of the laminate could potentially be extended to 60 years, reducing the overall carbon impact during the B4 stage.

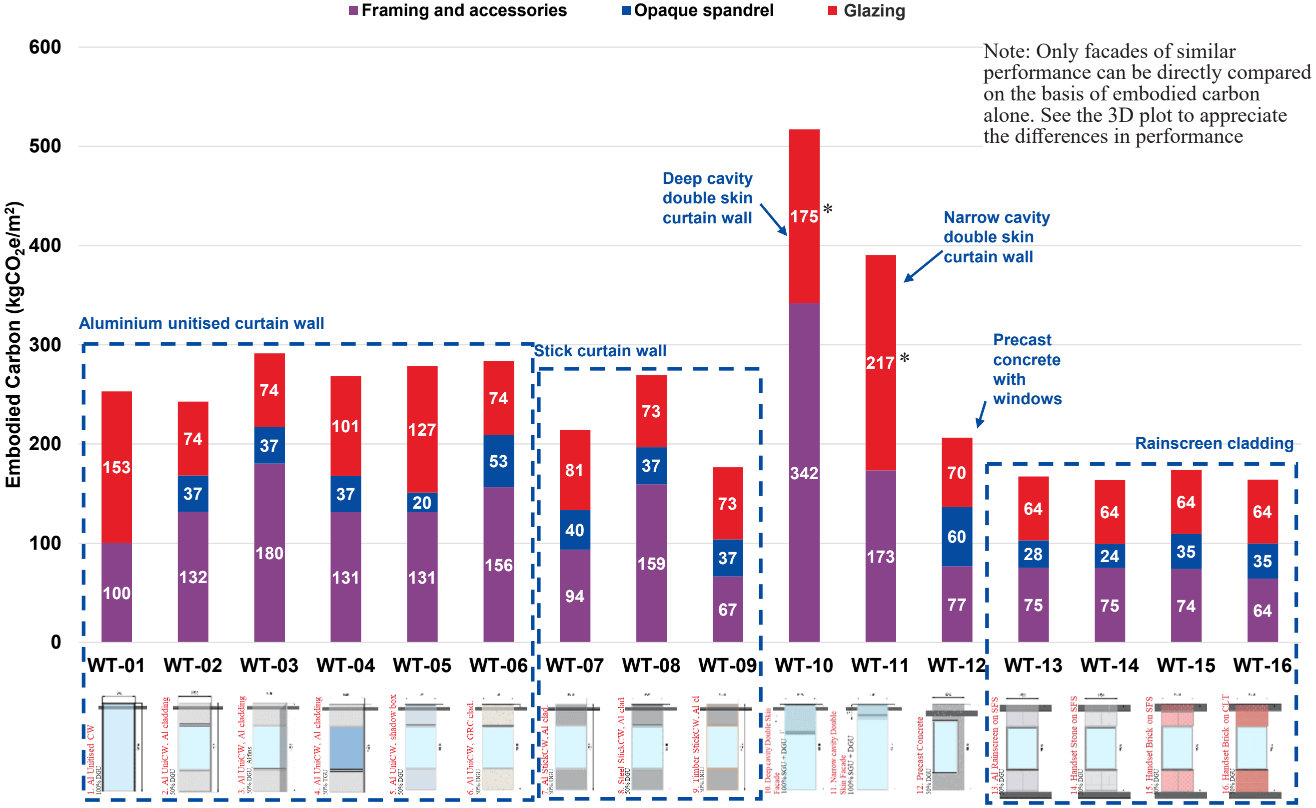
Contribution of framing, opaque spandrels and glazing

The diagram on the right shows the total embodied carbon for each façade system from cradle-to-grave (stages A to C) over a 60 year lifetime, as a comparison of framing and accessory components, the opaque spandrel material, and the glazing.

It can be seen that in the majority of cases, the framing and accessory components (e.g. fins) represent the highest overall percentage contribution to the embodied carbon of the system.

It is important to note a number of limitations of this simplified breakdown:

- The values shown are in terms of kgCO₂e per square metre of façade.
- WT-03 is the only design included in this dataset with external fins, which inflate the contribution of the 'framing & accessories' classification.
- WT-10 and WT-11, have a negligible (<2 kgCO₂e/m²) opaque spandrel contribution associated with insulation.



Note: Only facades of similar performance can be directly compared on the basis of embodied carbon alone. See the 3D plot to appreciate the differences in performance

Contribution of framing, opaque spandrels and glazing

A1-A5, B4, C (kgCO₂e/m²) – 78% pre-consumer recycled content Aluminium
* The service life of the inner double glazed unit and outer laminated pane was defined as 30 years. If detailed to enable replacement of the inner IGU without affecting the outer laminate, the service life of the laminate could potentially be extended to 60 years, reducing the overall carbon impact during the B4 stage.

Conclusions

A number of observations can be made about the way in which glass contributes to the embodied carbon of different façade systems:

- The embodied carbon of a façade will vary significantly depending on the system type and design. For the 16 facades studied, the embodied carbon (A1 – A5, B4 and C1 – C4) ranged from 160 to 520 $kgCO_2e/m^2$ of façade.
- Glass as a material is a major contributor to the embodied carbon of façades (often second only to aluminium), and we can anticipate that this percentage contribution may increase as other materials and industries continue the decarbonisation process.
- The percentage embodied carbon contribution of glass to the façade as a whole can vary significantly depending on the façade typology selected (in this study, from 26 to 60%).
- One key factor leading to glass's embodied carbon contribution over the life of the structure is the service life of Insulated Glazing Units (IGUs) (30 years), and thus the requirement for replacement of IGUs within the lifetime of the façade.

It is intended that the 16 façade typologies selected represent the breadth of European and United Kingdom façade design.

Szervita Square Building, Budapest, Hungary
COOL-LITE XTREME Silver II
© Sz. Nagy Judit

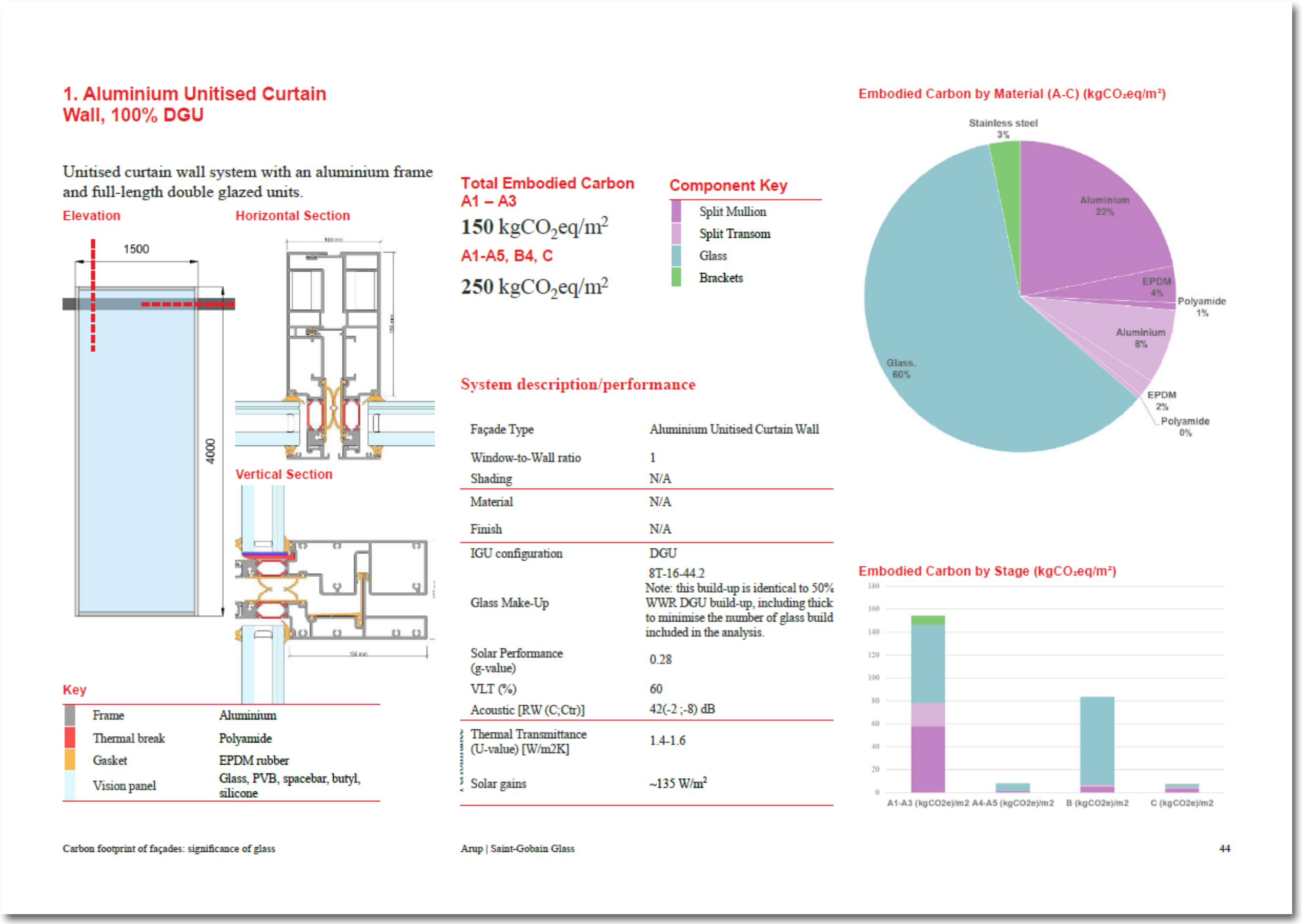
Facade systems comparison

Embodied carbon over façade life cycle

The complete results of this study are presented in the Appendix of this report.

For each façade system the following information is provided:

- A summary overview of the façade typology modelled.
- Three key sketches (elevation, horizontal section, vertical section) describing the configuration of the system and the materials included.
- Results of the LCA, including:
  - The total embodied carbon for both cradle-to-gate (A1 – A3) and cradle-to-grave (A1-A5, B4, C),
  - The percentage quantity of the different materials in the system by material and component mass,
  - The percentage embodied carbon (A1-A5, B4, C) of the different materials in the system.
  - The calculated embodied carbon of the system by life cycle stage.



1. Aluminium Unitised Curtain Wall, 100% DGU

Unitised curtain wall system with an aluminium frame and full-length double glazed units.

Key

▨	Frame	Aluminium
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
▢	Vision panel	Glass, PVB, spacebar, butyl, silicone

Total Embodied Carbon A1 – A3

150 $kgCO_2eq/m^2$

A1-A5, B4, C

250 $kgCO_2eq/m^2$

Component Key

🟪	Split Mullion
▨	Split Transom
🟦	Glass
🟩	Brackets

System description/performance

Façade Type	Aluminium Unitised Curtain Wall
Window-to-Wall ratio	1
Shading	N/A
Material	N/A
Finish	N/A
IGU configuration	DGU
Glass Make-Up	8T-16-44.2 Note: this build-up is identical to 50% WWR DGU build-up, including thick to minimise the number of glass build included in the analysis.
Solar Performance (g-value)	0.28
VLT (%)	60
Acoustic [RW (C;Ctr)]	42(-2 ;-8) dB
Thermal Transmittance (U-value) [W/m2K]	1.4-1.6
Solar gains	~135 W/m²

Embodied Carbon by Material (A-C) ($kgCO_2eq/m^2$)

Embodied Carbon by Stage ($kgCO_2eq/m^2$)

Carbon footprint of façades: significance of glass   Arup | Saint-Gobain Glass   44

Design Choices

Step 2: Investigating the influence of particular design choices on the embodied carbon and operational performance of a façade system

Step 2:
Assessing the impact of design

Exploring Unitised Curtain Walls

The key goal of this second study was to evaluate the embodied carbon and operational demand for a given façade system, and investigate the influence that different design and material decisions have. A unitised curtain wall façade system was selected as the focus for this step, based on the prevalence of use for both residential and commercial properties in the UK and Europe.

Through investigating the embodied and operational implications of a series of differing design solutions, consideration was given to questions including:

- How can designers reduce whole life carbon through the design of façades?
- Does an optimal (lowest whole life carbon) Unitised Curtain Wall design exist?
- Where should the glass industry focus investment in product design and production process improvements to make the biggest impact overall?

Embodied carbon stages A1 – A5, B4, and C1 – C4 were included in this scope. Operational heating demand, cooling demand, electricity demand and daylight factor were calculated as a part of the operational carbon scope.

Full details on the methodology and assumptions made in defining these are presented in the coming slides and given in the appendix.

A parametric approach

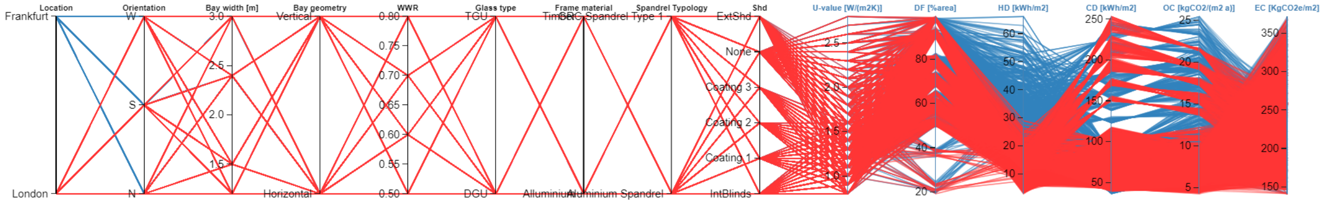
This study has considered a range of variable parameters that influence both the embodied and operational carbon of a unitized curtain wall and building.

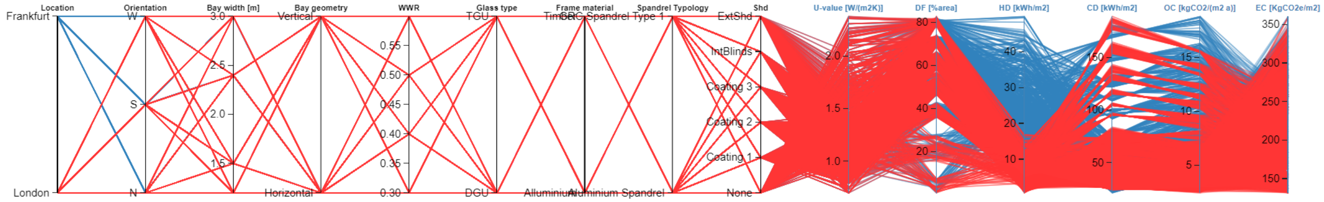
Every combination of these variable parameters results in a different façade configuration, with a different quantity of constituent materials (influencing embodied carbon) and a different system performance (e.g. U value, g value, influencing operational carbon).

Based on the variables defined, over 9000 simulations were run for each of the commercial and residential building models. This is visually presented below using an in-house Arup tool called Parameterspace.

The dataset developed is extensive (over 18,000 simulations) and detailed analysis has the potential to uncover a large number of insights. For the purposes of this study and report, insights focus on the following themes:

- Influence of window-wall ratio
- Influence of different solar control solutions
- Optimising for a single solution



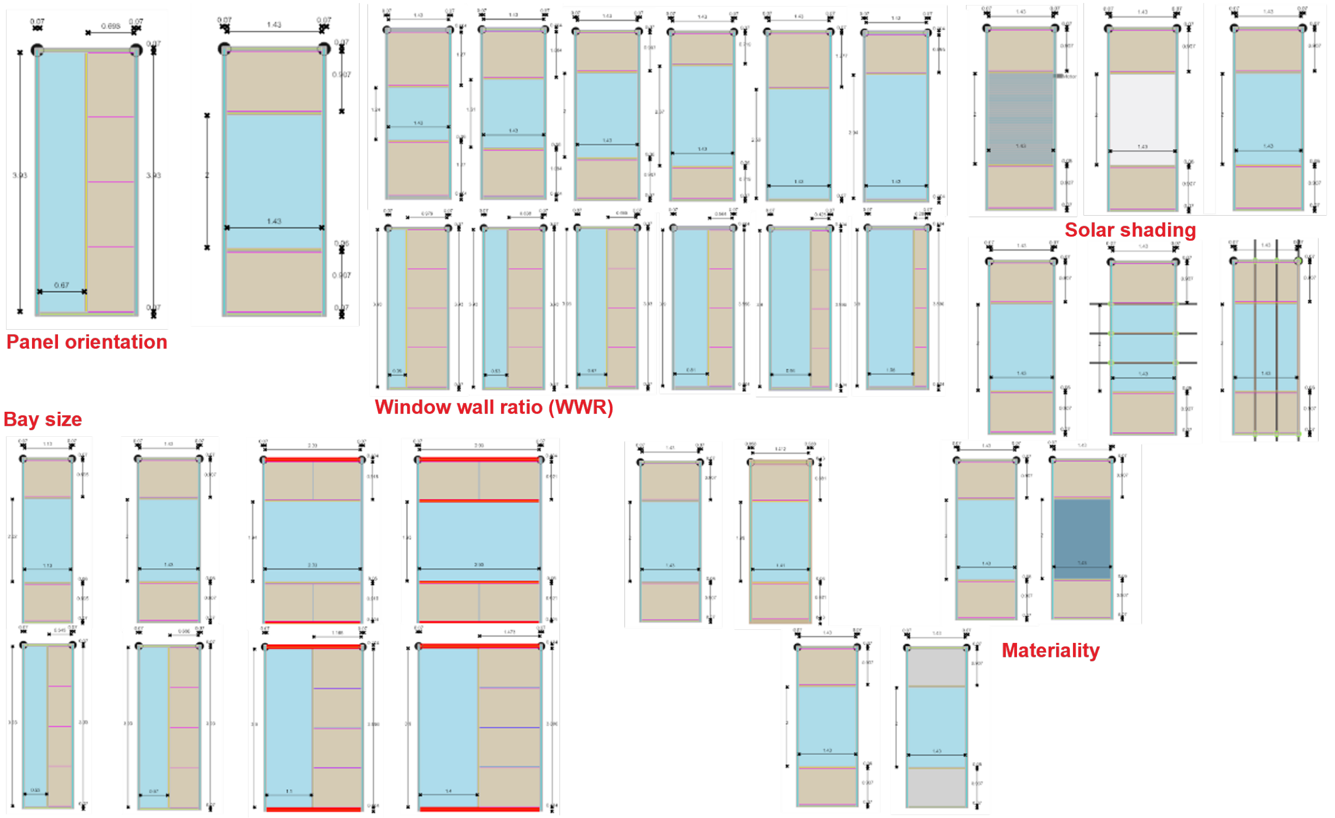


Step 2:
Study parameters

Embodied carbon considerations

There are many parameters/considerations that contribute to a façade's design, even when only considering a single façade system, in this instance a unitised curtain wall. For the purposes of this study, we have simplified the variable parameters based on some key design assumptions, but there is still a great number of possible variations based on the variables defined. The images to the right summarise the variable parameters for this study:

- Panel orientation: vertical; horizontal
- Bay size: 1.2m; 1.5m; 2.4m; 3m
- WWR: 30%; 40%; 50%; 60%; 70%; 80%
- Solar shading:
  - None;
  - Coated glass;
  - Internal venetian blinds,
  - External fins (north elevation: none; south elevation: horizontal; east/ west elevation: vertical)
- Materiality:
  - IGU: DGU, TGU;
  - Frame material: aluminium, timber;
  - Spandrel material: GRC, aluminium


Panel orientation

Window wall ratio (WWR)

Solar shading

Bay size

Materiality

Summary of variable parameters for this study

Step 2:
Study parameters *cont.*

Operational carbon considerations

Particular attention must be paid to the scope and bounding of the operational carbon model utilized. By necessity, a number of assumptions must be made about the building modelled.

The operational performance was estimated for a sample room with WxDxH of 4x5x4m.

The results of the analysis are based on very specific assumptions that influence the operational energy and related carbon emissions of the building, completely separate from the façade design. These are listed in the appendix to this report.

The variation of some of these assumptions (e.g. the ratio between cooling and heating efficiency, the occupancy density, the temperature setpoints) can influence drastically the results and produce very different outcomes.

Therefore, the results of the operational analysis can be considered representative only of the sample room described by these assumptions and they cannot be applied to and generalised for any other building.

Variable parameters

The variable operational carbon parameters for the study were:

- Building use: commercial; residential
- Location: Frankfurt; London
- Façade orientation: North; South; West
- U-value: dependent on panel build-up
- Visible light transmission (VLT): dependent on shading / glass build-up

Solar shading (g-value):

- None (no coating, no shading);
- Coated glass (3 types - COOL-LITE® XTREME 70/33, COOL-LITE® XTREME 61/29, COOL-LITE® XTREME 50/22);
- Internal venetian blinds with COOL-LITE® XTREME 70/33;
- External fins with COOL-LITE® XTREME 70/33.

Note, both the internal venetian blind and external fixed fin scenarios also have a solar control coating applied. This is reflective of standard practice in mature markets, as it is unlikely that non-coated glass would be used.

Outputs

The operational performance was estimated in terms of:

- Thermal transmittance (U-value) in W/m^2.K
- Percentage of floor area in good daylight (DF) in % per sqm of floor area
- Heating demand (HD) in kWh per sqm of floor area
- Cooling demand (CD) in kWh per sqm of floor area
- Electricity demand (ED) in kWh per sqm of floor area
- Operational carbon emissions (OCE) in kgCO$_2$e per sqm of façade
- Embodied carbon emissions (ECE) in kgCO$_2$e per sqm of façade

Step 2
Results

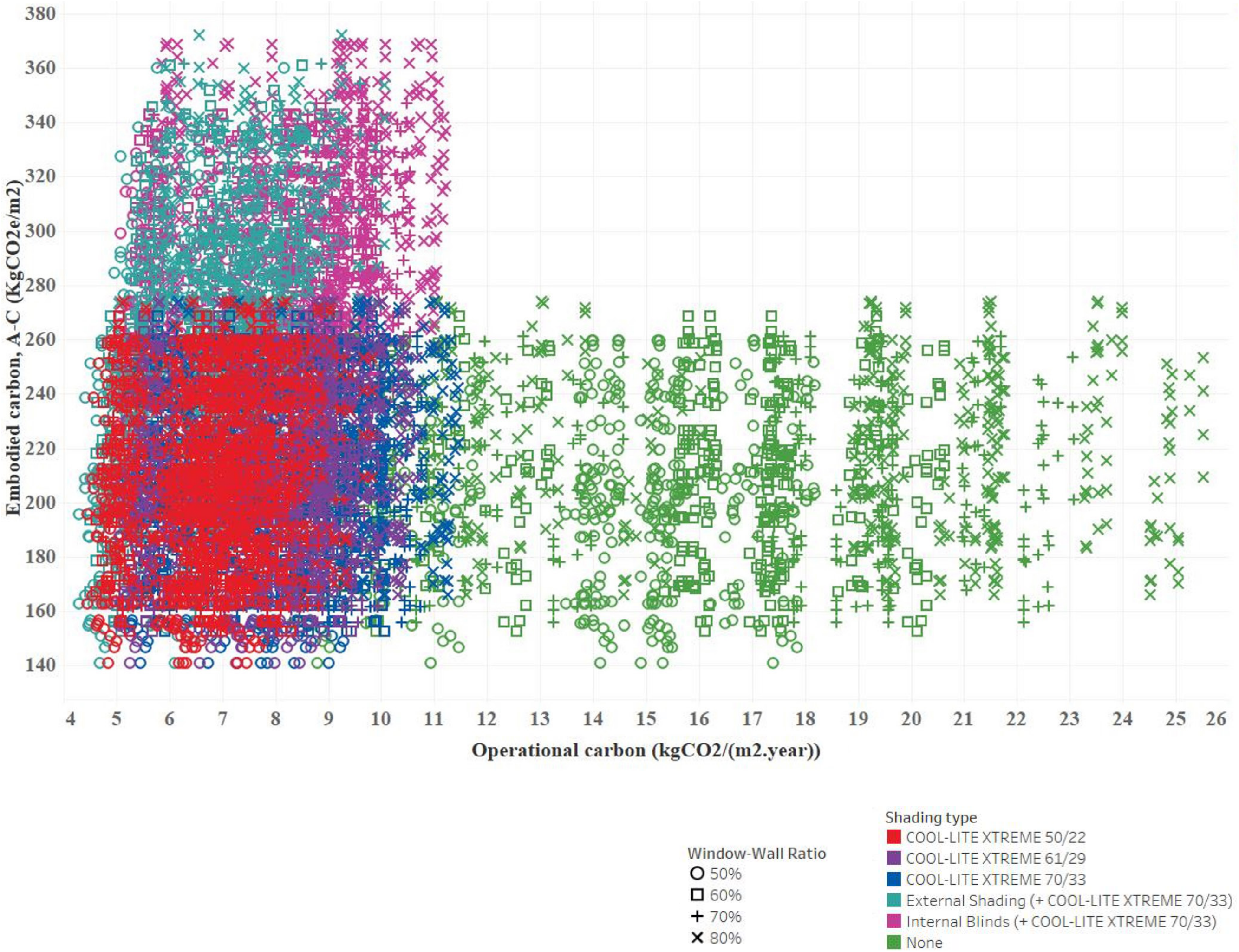
Exploring key insights

This page shows all 9216 results for the commercial building simulation plotted according to the calculated embodied carbon and annual operational carbon for each façade design. Façades closer to the origin have both lower embodied carbon (A1-A5, B4, C) and lower annual operational carbon.

The façade simulations with no shading solution at all show the worst operational carbon performance. The façade simulations with external shading or internal blinds (both in combination with COOL-LITE XTREME 70/33) show the highest embodied carbon values.

Some of the trends observed are significantly influenced by the design assumptions and study parameters defined. Care should be taken in generalising any of the results.

Note: both internal venetian blind and external fixed fin scenarios also have a solar control coating applied. This is reflective of standard practice in mature markets, as it is unlikely that non-coated glass would be used.



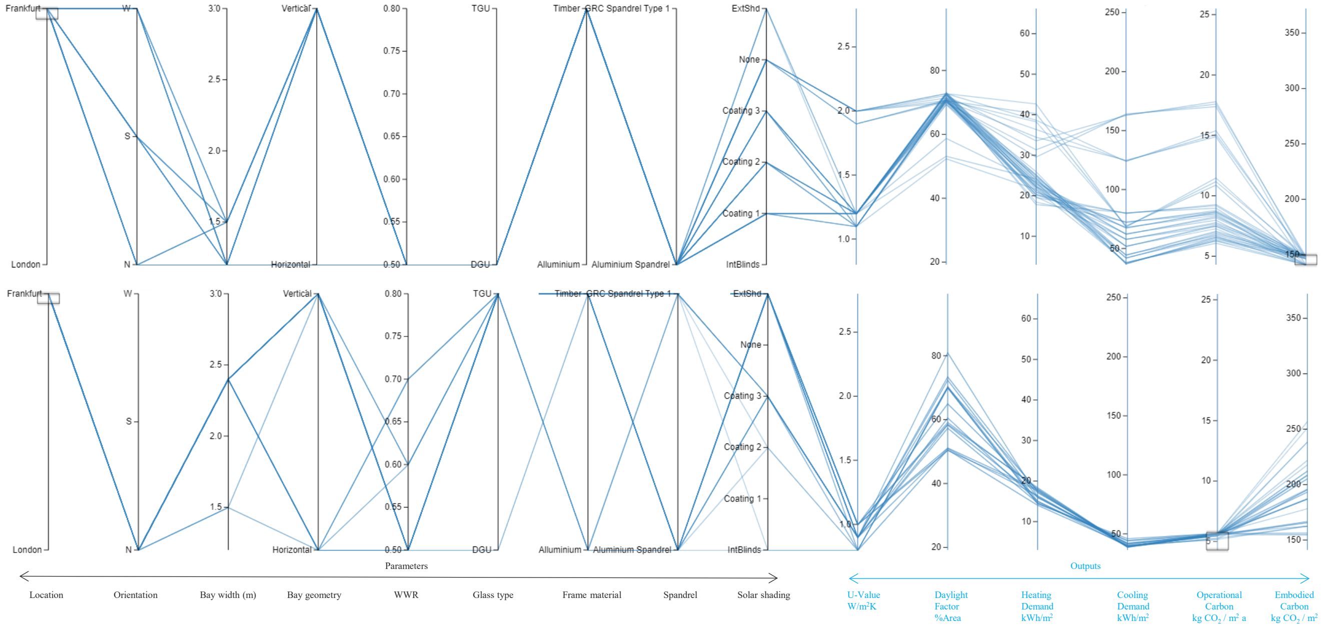
Embodied carbon and annual operational carbon results for the commercial building simulation

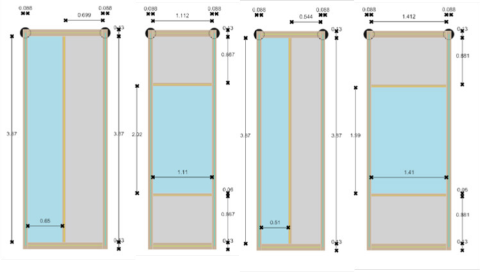
Does an optimal configuration exist?

Optimising for embodied carbon and operational carbon

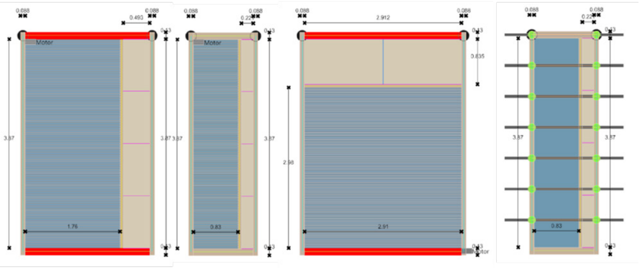
At project outset, we sought to understand whether architects are likely to converge on certain façade typologies, if they are to optimise designs based on whole life carbon. Based on our parametric analysis, it does not appear that this will be the case. Due to the complexity of façade/building design, the large number of variables that influence the design, and accordingly the embodied and operational carbon, it appears impossible to identify a unique set of parameters that will lead to the lowest whole life carbon design for all project scenarios.

On the right you can see a visualisation of the lowest embodied carbon solutions (top) for Frankfurt and the lowest operational carbon solutions (bottom). Below that, we identify the four facade designs with the lowest and highest whole life embodied carbons. In the table, we see the upfront carbon and annual operational carbon associated with these designs. If we were to optimise for these values, different façade solutions would have been identified.





		Embodied carbon A-C (kgCO2/m^2)	Embodied carbon A1-A3 (kgCO2/m^2)	Operational carbon (kgCO2/(m^2.a)
Lowest Embodied carbon (A-C)	1: Timber frame, Aluminium spandrel, coated glass, 1.5m, 50% WWR, vertical, DGU	141	80	7.74
	2: Timber frame, Aluminium spandrel, coated glass, 1.2m, 50% WWR, horizontal, DGU	146.6	81.2	7.84
	3: Timber frame, Aluminium spandrel, coated glass, 1.2m, 50% WWR, vertical, DGU	148.8	84.9	7.87
	4: Timber frame, Aluminium spandrel, coated glass, 1.5m, 50% WWR, horizontal, DGU	150.9	82.4	7.77
Highest Embodied carbon (A-C)	5: Aluminium frame, GRC spandrel, Int shading; 2.4m, 80% WWR, vertical, TGU	367.7	188.4	9.62
	6: Aluminium frame, GRC spandrel, Int shading; 1.2m, 80% WWR, vertical, TGU	368.7	203	9.36
	7: Aluminium frame, GRC spandrel, Int shading; 3.0m, 80% WWR, horizontal, TGU	369.2	186.9	9.66
	8: Aluminium frame, GRC spandrel, Ext shading; 1.2m, 80% WWR, vertical, TGU	372.2	268.8	6.55



Highest and lowest embodied carbon (A-C) solutions from the dataset, with relevant operational carbon results also shown.

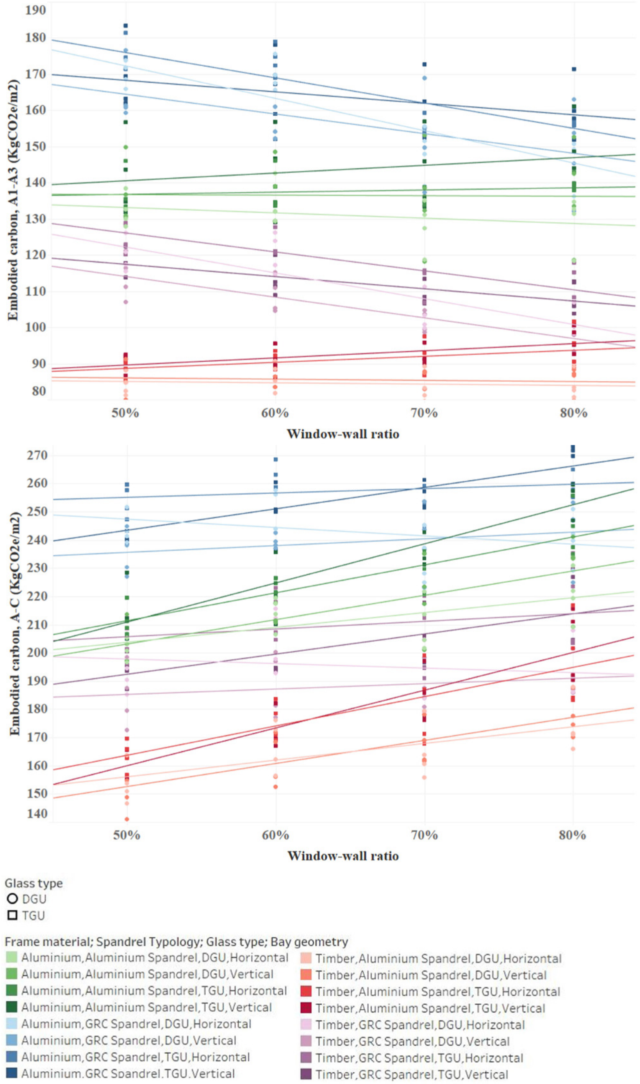
Results
Window-wall ratio

Embodied carbon - the influence of boundary conditions

In general as we increase the window-wall ratio, the upfront embodied carbon (A1-A3) reduces. This can generally be explained by the fact that the glazing has a lower embodied carbon than the opaque build up – as such, as the proportion of area of the glazing increases and opaque area decreases, the embodied carbon is reduced.

However, in general, if we consider later life cycle stages as well, in particular Stage B (replacement of components), we see the opposite trend: as the WWR increases, the embodied carbon increases as well. This is due to the fact that whilst the majority of the façade is considered to have a 60 year life, the insulated glazing unit is considered to have a 30 year life, and accordingly must be replaced once through this study period.

In reality, it is not very common for glazing alone to be replaced, particularly for commercial buildings. Instead, whole facades are more commonly replaced and one could argue that the whole life embodied carbon analysis is under-representing the more realistic scenario.

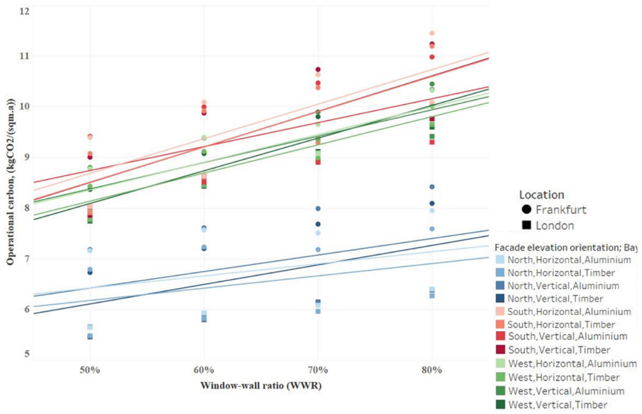


Comparison between the trends seen for Upfront embodied carbon (A1-A3) [Top] and Whole life embodied carbon (A-C) [Bottom]

Relationship between WWR and operational carbon

Perhaps unsurprisingly, as the WWR increases, we find that the operational carbon for the notional building also increases. This is due to the decreased thermal insulation ability of transparent glazing components compared to opaque materials (i.e., the u-value for glass is typically higher than that of opaque panel materials).

Results would be expected to vary significantly for different building types and locations, for instance, in hotter locations where cooling is more critical. This study has focused on carbon, but there are many factors which are also key considerations; glass is unique in its nature as an extremely durable material which also provides access to daylight into our buildings.



Relationship between WWR and embodied carbon for a range of façade designs

Step 2
Window-wall ratio cont.

A system by system analysis is required to gain true insight

Taking a closer look we see that in reality, this trend is variable across different designs, and it is not linear. Different design assumptions/designs influence this trend in different ways. In the plot on the right, we see four different simulations, showing different trends, from top to bottom:

- 1.2m bay size, Aluminium frame, GRC spandrel, TGU, Horizontal configuration

For the 1.2m bay size, we see that as we increase from 50 to 60% WWR, we see a reduction in embodied carbon. This can be explained by the reduced area of the higher impact GRC spandrel, replaced by the lower impact TGU. At 70%, we see a substantial drop in carbon. This is due to the design shifting to a single spandrel, accordingly, with removal of one transom and the associated embodied carbon. From 70 to 80% WWR we see a slight increase again, as thicker glass is required for this larger panel size, and the relative embodied carbon of the increased glazing area outweighs the embodied carbon of the reduced GRC spandrel area.

- 3m bay size, Aluminium frame, GRC spandrel, TGU, Horizontal configuration.

Whilst we see a similar trend from 60 to 80% WWR ratio for a 3m bay size module, between 50 to 60%, we see the reverse trend. For this larger bay size, as the WWR increases from 50 to 60%, a thicker glazing configuration is required and the aluminium frame profile also increases. This outweighs the embodied carbon associated with the reduced GRC area and accordingly we see a minor increase in embodied carbon.

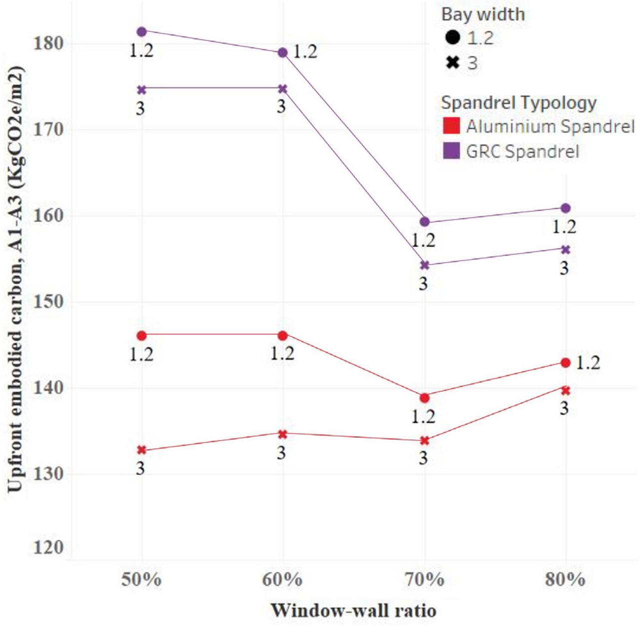
- 1.2m bay size, Aluminium frame, Aluminium spandrel, TGU, Horizontal configuration

The aluminium spandrel has a lower embodied carbon than the GRC, and is very similar to that of the glazing build-up. Accordingly, between 50-60% there is negligible change in carbon as the relative areas shift. Otherwise we see the same trend as for the first system.

- 3m bay size, Aluminium frame, Aluminium spandrel, TGU, Horizontal configuration;

In this final system, with each increase in WWR, the thickness of the glass build-up increases, outweighing the reduction in carbon associated with reduction in the area of the spandrel panel, leading to a total increase in carbon from 50% to 80% WWR.

Analysis of this very large dataset has reinforced that it's a complicated exercise! But we must embrace this complexity and carry out carbon modelling on all projects, early in the design, if we are to decarbonise our buildings.



Four selected simulations showing variation in trend of embodied carbon with increasing WWR

A1-A3 (kgCO_2e/m^2)

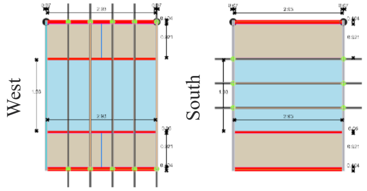
Step 2
Window-wall ratio cont.

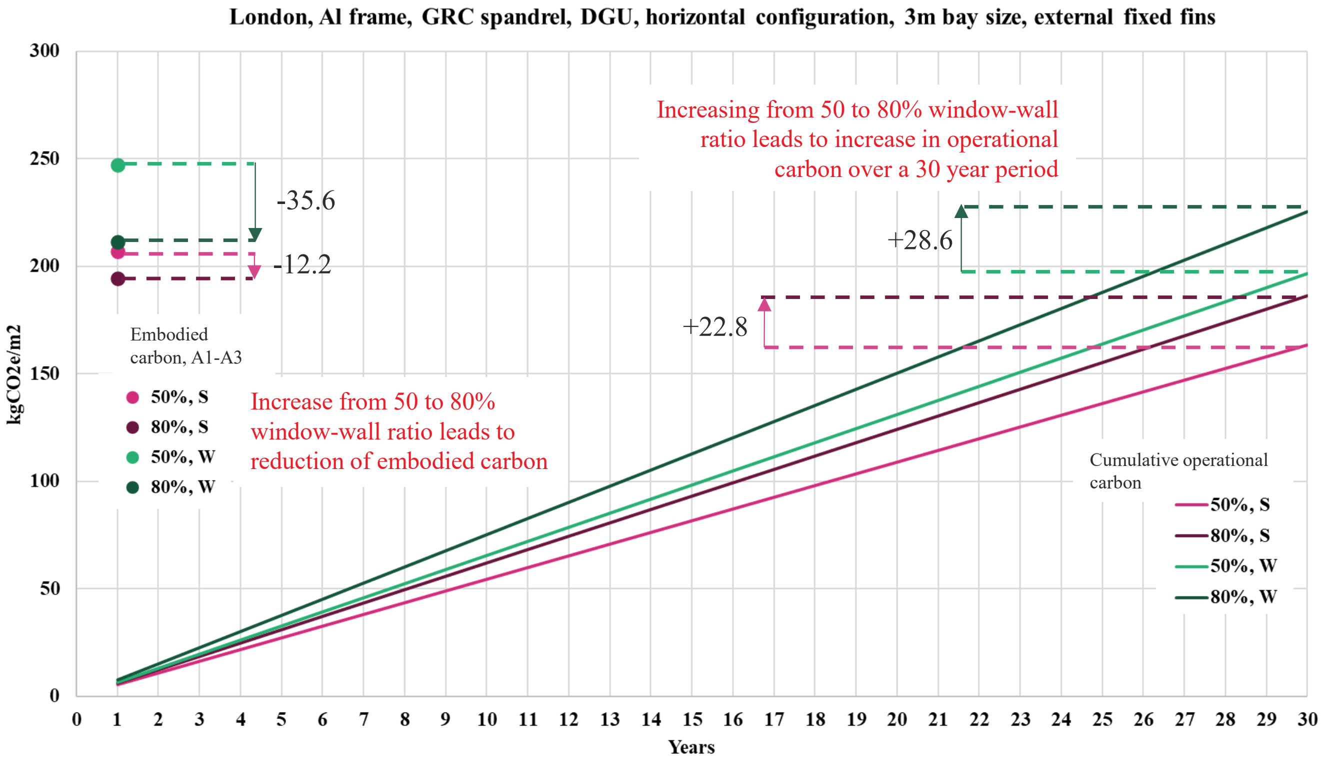
A whole life view

With a general trend in our data that the embodied carbon decreases as the WWR increases, whilst the operational carbon increases as the WWR increases, it is clear that the embodied and operational impacts must be considered hand in hand to understand the whole life carbon impact of increasing (or decreasing) the WWR.

This page shows, for one façade simulation, how the embodied and operational impacts of increasing from 50% to 80% WWR compare. Looking at both South and West orientations, we find that for the West orientation, the embodied carbon savings outweigh the operational losses by increasing the WWR, whilst for the South, the operational losses outweighs the embodied savings. This analysis has crudely considered a linear projection of the annual operational carbon, i.e. it has not taken into account grid decarbonisation. In addition, this analysis excludes the reality that the coating selected would likely also change when the WWR is altered (e.g. g value could be lower for higher WWR).

Note: This is a single example and does not present a trend that can be generalised across the dataset.





(Above) Comparing embodied gains with operational losses of increasing WWR; (Left) Graphic presentation in the variation in external fin design by changing the orientation of the façade

Results
Solar control

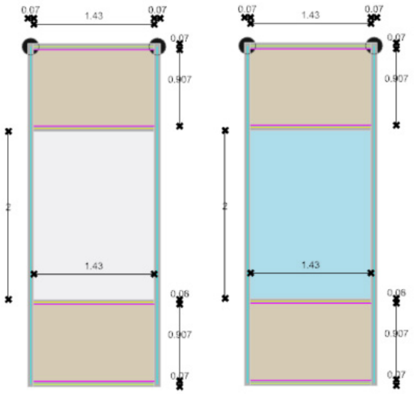
Variable parameters: types of solar control

Broadly, four types of solar control were considered in the study:

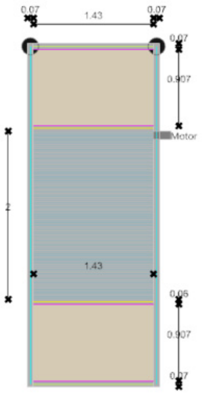
- No coating (considered only to develop a baseline for comparison of operational carbon)
- Three types of solar control coating:
  - COOL-LITE® XTREME 70/33
  - COOL-LITE® XTREME 61/29
  - COOL-LITE® XTREME 50/22
- Internal venetian blinds: Aluminium
- External fixed fins: Aluminium fins (North orientation – no fins; South orientation – horizontal fins; West and East orientation – vertical fins)

Key assumptions:

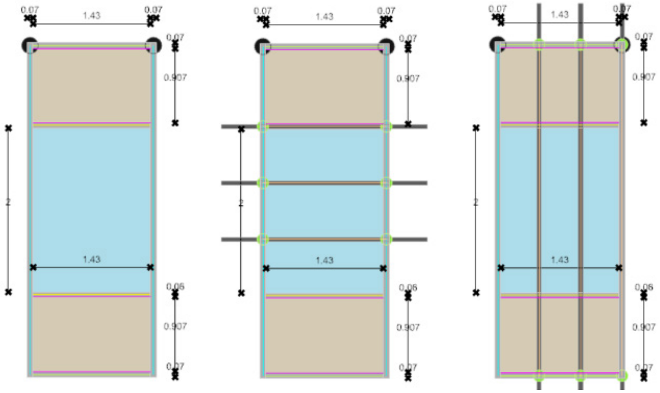
- The embodied carbon associated with the different solar control coatings is assumed to be equivalent
- Both internal venetian blind and external fixed fin scenarios also have a solar control coating applied. This is reflective of standard practice in mature markets, as it is unlikely that non-coated glass would be used. COOL-LITE® XTREME 70/33 has been used.



No coating (left); Coating (right)



Internal venetian blinds



External fixed fins: North orientation – no fins; South orientation – horizontal fins; West and East orientation – vertical fins

The carbon impact of each shading solution varies depending on the configuration of the facade unit. As the WWR and bay size varies, the number of external fins (in the case of the horizontal configuration will vary), and the area of internal shading will vary. The orientation of the facade will also have a significant impact in the case of the external fins.

In the instance shown in the figure above [Bay size: 1.5m; WWR: 50%; DGU; Frame: Aluminium; Spandrel Technology: GRC], the following carbon per unit of facade is attributed to each shading type. If the WWR or bay size were to change, the impact associated with each system would also vary.

Solar control type	kgCO$_2$e/m^2 of unit facade
Solar control coating	1.1
Internal venetian blinds	21.8
External fixed fins:	
West/East	90.9
South	39.3

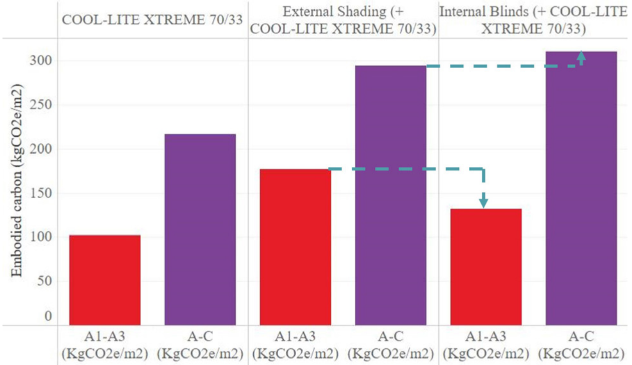
Results
Solar control *cont.*

Embodied carbon: Internal blinds vs external fins

The influence of the embodied carbon boundary conditions we select is again clear when we compare the use of internal venetian blinds and external fixed fins for shading.

The diagram on the right shows the embodied carbon results for a single simulation. When we look at the A1 – A3 stage (red), we can see that the internal blinds result is more than 50 kgCO₂/m² less than the external fins result.

In isolation, this would perhaps indicate that internal blinds are the overall lower embodied carbon solution compared to external fins. However, when we consider the whole life cycle (A1-A5, B4, C), we see that this trend is in fact reversed. Over the whole life, there are cases where the embodied carbon of the internal blinds exceeds that of the external fins. This trend is due to the influence of component replacement over the whole life of the façade. While the external fins have been assumed to not be replaced over the life of the façade (60 years), the internal blinds have a service life of 20 years and are hence replaced twice during this time.



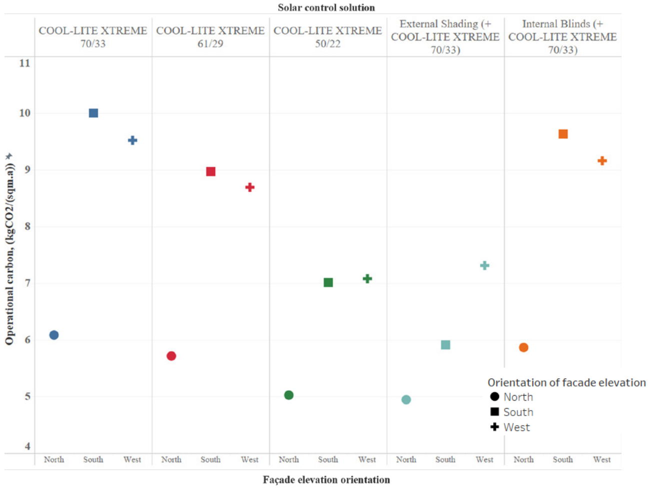
The influence of boundary conditions on the use of blinds vs fins

Graph shows data for the following simulation: London, West orientation, 3m bay size, 80% WWR, Timber frame, Aluminium spandrel. Impact includes DGU.

Operational carbon impact of solar shading solutions

The graphic on the right shows the annual operational carbon associated with the different shading solutions studied for a single simulation. We can make the following observations:

- The use of external shading makes a greater impact on the operational carbon of the façade than the use of internal blinds (for the blinds product selected for the study), both in combination with a solar control coating. However, it is important to note here that in reality, for reasons of glare control, it is unlikely that external shading would be used independent of internal shading control (which is rarely used as a complete solar control solution). In all scenarios a solar control coating is assumed.
- In some cases, coatings are independently able to achieve similar operational carbon outcomes to external shading and internal blind solutions. For example, the performance of coating COOL-LITE® XTREME 50/22 on the West orientation is similar to the performance of external shading (with COOL-LITE® XTREME 70/33) for this orientation. However, this same performance is not seen for the same coating when compared to external shading on the southern orientation.
- The optimal shading solution for a façade will depend on which orientation of the building is being considered.



Impact of different shading solutions on operational carbon

Graph shows data for the following simulation: Commercial building, London, Timber frame, Aluminium spandrel, TGU, bay size 3m, 80% WWR

Conclusions and Recommendations

Conclusions

Glass plays a significant, and potentially increasing, role

The proportion of embodied carbon associated with glass varies quite significantly from system to system, in this study, ranging from:

26-60%

These high values identify a significant opportunity, and responsibility, for the glass industry to support designers in reducing the embodied carbon of their projects.

As other industries continue their decarbonisation journeys, it can be anticipated that the percentage contribution of glass to the embodied carbon of facades may increase. This makes clear the importance of the glass industry undertaking its own decarbonisation journey.

Variations in design can significantly influence whole life carbon

Beyond the variation from system to system seen from the results of Step 1, the Step 2 results further highlight the significant scope of influence that designers have to change the Whole Life Carbon (WLC) of their designs. Even for a single façade type, in this instance, unitised curtain walling, and with a limited materials palette (2 frame materials and 2 spandrel panels), the range in both embodied carbon and annual operational carbon is great.

Of course we must remember that there are many building level variables that will also influence the façade design, bringing further complexity.

We must embrace complexity: a detailed analysis is required

In analysing over 18,000 façade simulations (for residential and commercial models), we find that there is no simple answer to the optimal UCW façade with regards to WLC. The lowest embodied carbon façade for one orientation may not be the lowest scenario for another, and may not be lowest operational carbon solution either.

We have identified some trends, for instance when considering whole life boundary conditions for embodied carbon (e.g. A1-A5, B4, C), there is a critical Window-wall ratio where internal blinds become the higher carbon option as compared to external shading. However, even for these high level trends, there is variation between systems/designs, and a closer look is required to determine what is occurring for a specific façade design. To make truly informed decisions in terms of embodied and operational carbon, assessment of design options against the specific needs of a project is required.

Embodied carbon and annual operational carbon results for the commercial building simulation, excluding simulations with no solar control

Conclusions

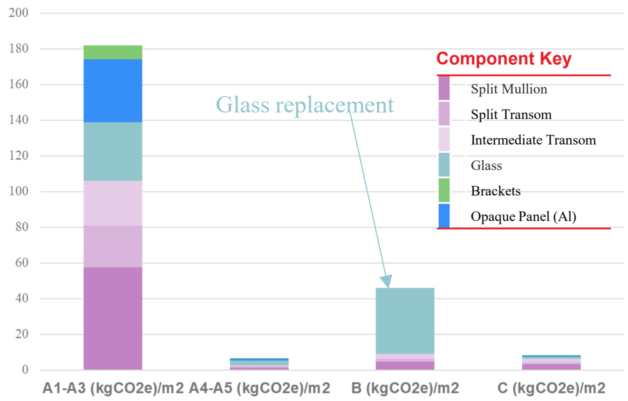
Material selection must be informed by data

It is our responsibility as designers and engineers to consider circular economy principles and material selection from the very beginning of the design process of our projects. This requires a change in how we work, what materials we choose and how we influence our client’s choices in material selection and design decisions. Provision of data from suppliers can help designers be informed as possible when selecting materials and designing systems.

Increasing the IGU service life would reduce whole life carbon

Through both the step 1 and step 2 analysis, it is clear that the replacement of the IGU through the life of the façade has a significant impact to whole life embodied carbon – in the example on the right, it accounts for 15% of the embodied carbon. Considering upfront carbon alone (i.e without the replacement of the DGU), we find that increasing window-wall ratio is generally favourable. The opposite is true considering the whole life.

In reality, renovation projects where windows and glazing framing are replaced, but the remaining system frame is maintained, are not typical. More commonly, the façade as a whole is replaced.



Embodied Carbon by Stage (kgCO$_2$eq/m^2)

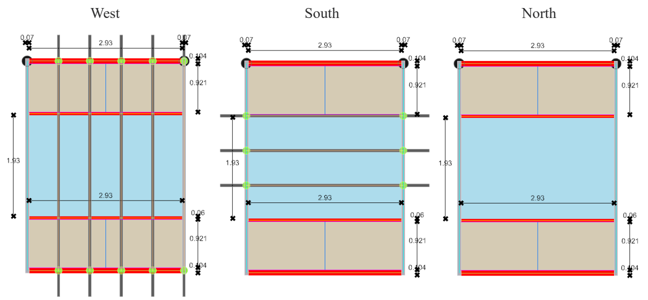
Results for Aluminium Unitised Curtain Wall, Aluminium Cladding, 50% WWR, DGU

Designing with façade orientation in mind

Some trends observed in the dataset are influenced by variables such as the orientation of the façade face. A trend observed in our dataset for a particular scenario is a reduction in embodied carbon associated with an increase in window-wall ratio, a trend which has further complexity emerging from the interaction between WWR and operational carbon for the building. This operational carbon is in turn varied depending on the orientation of the facade.

Similarly, we see a variation in embodied carbon for different external fin orientations associated with different compass orientations of the façade.

The industry should consider the ways in which both embodied carbon and operation carbon can be influenced by design choices made with consideration of each individual façade face.



The variation in external fin design by changing the orientation of the façade

Conclusions

Understanding trade-offs of design decisions

It is clear that the embodied carbon and operational carbon impacts must be considered hand in hand to understand the whole life carbon impact of increasing (or decreasing) the WWR.

Design decisions for particular projects made in the pursuit of reducing operational carbon must be considered in the context of embodied carbon impacts. Conversely, decisions made to reduce the embodied carbon of the façade must consider the operational carbon impacts of these choices.

These decisions are also time based – what is the climate crisis impact of a carbon saving today, compared to a saving that pays off in five years time? Metrics such as the carbon payback period – the time taken to ‘pay off’ an increase in embodied carbon which leads to an annual operational carbon benefit – may also be important considerations.

Operational results cannot be generalised

The results of the analysis are based on very specific assumptions that influence the operational energy and related carbon emissions of the building, completely separate from the façade design.

The variation of some of these assumptions (e.g. the ratio between cooling and heating efficiency, the occupancy density, the temperature setpoints) can influence drastically the results and produce very different outcomes.

Therefore, the results of the operational analysis are only specific of the sample room analysed and cannot be applied to and generalised for any other building.

This study presents a methodology for how operational carbon impact of façades can be evaluated to determine whole life carbon.

Appendix 1

Step 1: Understanding the carbon footprint of a number of façade typologies, including the contribution of glass

Glass contribution to systems

Step 1: Understanding the carbon footprint of a number of façade typologies, including the contribution of glass

This appendix presents the complete results of the first stage of the study as follows:

- Consideration of the 16 façades in comparison in terms of: percentage contribution of components; percentage contribution of glass and other materials; percentage contribution of glazed and opaque sections.
- Assumed performance criteria for the 16 façades.
- Individual design details and results for each façade in terms of life cycle stages and percentage contribution of materials.

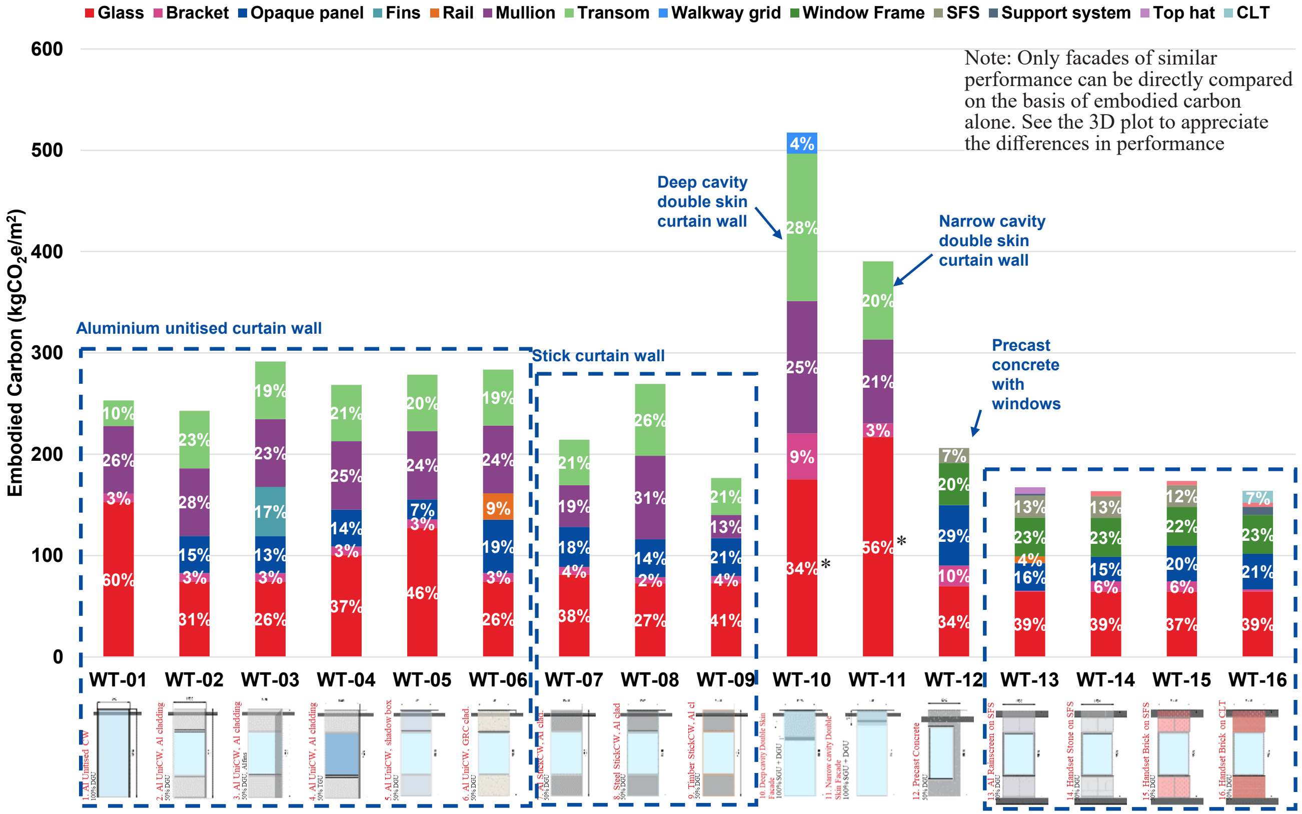
Facade systems comparison *cont.*

Component contribution

The diagram on the right shows the total embodied carbon for each façade system from cradle-to-grave (stages A to C) over a 60 year lifetime, as a comparison of the different components which make up each system.

It can be seen that for the majority of systems, the glass represents the highest percentage contribution of any individual component.

Note that for WT-05 (Aluminium Unitised Curtain Wall, Shadow Box, 50% DGU), the opaque panel component is an insulated shadow box with a glass spandrel.



Note: Only facades of similar performance can be directly compared on the basis of embodied carbon alone. See the 3D plot to appreciate the differences in performance

Embodied carbon by component type

A1-A5, B4, C (kgCO$_2$e/m^2) – 78% pre-consumer recycled content Aluminium

* The service life of the inner double glazed unit and outer laminated pane was defined as 30 years. If detailed to enable replacement of the inner IGU without affecting the outer laminate, the service life of the laminate could potentially be extended to 60 years, reducing the overall carbon impact during the B4 stage.

Facade systems comparison

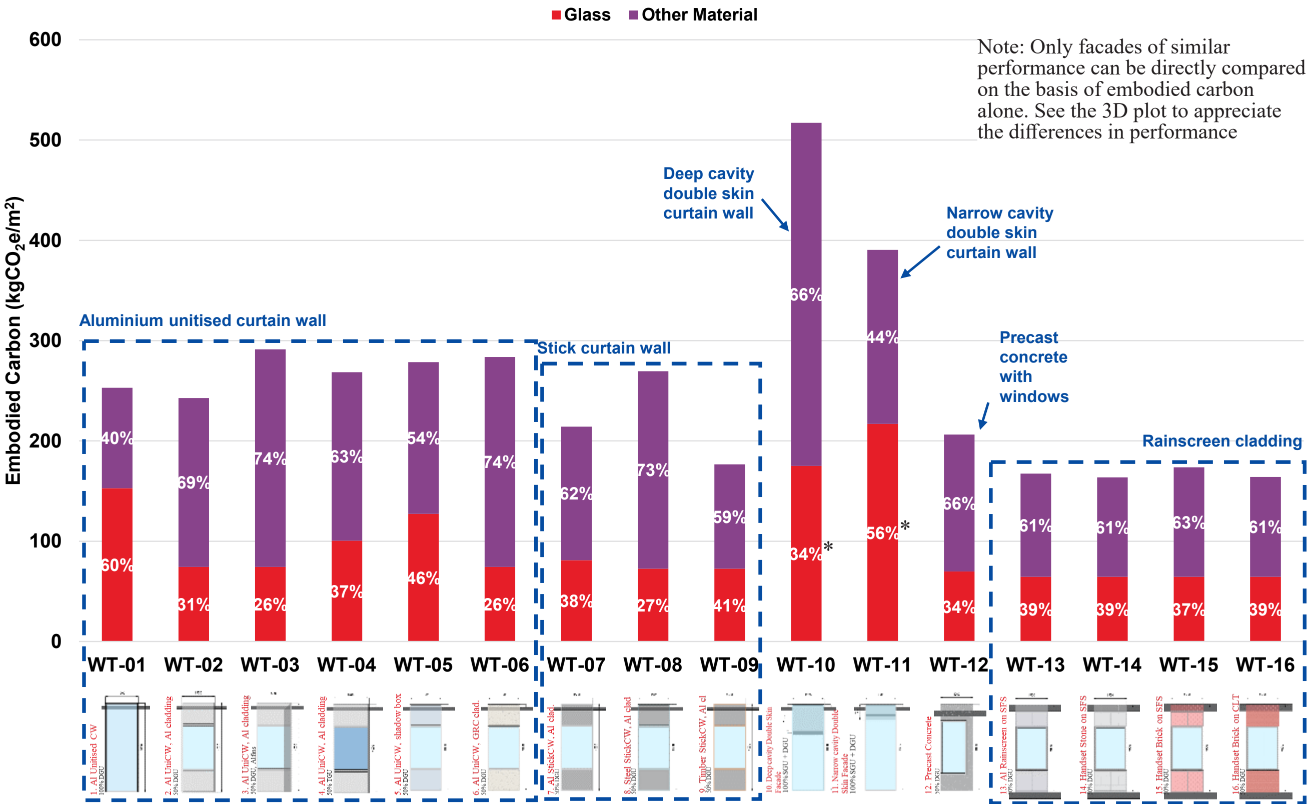
Percentage of glass vs other material

The diagram on the right shows the total embodied carbon for each façade system from cradle-to-grave (stages A to C) over a 60 year lifetime as a comparison of the amount of glass material to the amount of other material used in the design.

The percentage contribution of glass to the embodied carbon of the systems ranges from 26 to 60 percent. The percentage contribution of glass is influenced by factors including:

The amount of glass in the façade – WT-01, which consists of a 100% window/wall ratio double glazed unit, has the highest percentage glass contribution, as the amount of glass is very high while the amount of other materials is low.

The emission factors associated with other materials – materials which require a smaller amount of carbon to produce will have smaller emission factors, and thus may have a lower contribution even when there is a large amount of this material present.



Note: Only facades of similar performance can be directly compared on the basis of embodied carbon alone. See the 3D plot to appreciate the differences in performance

Embodied carbon: percentage of glass vs other material

A1-A5, B4, C ($kgCO_2e/m^2$) – 78% pre-consumer recycled content Aluminium
* The service life of the inner double glazed unit and outer laminated pane was defined as 30 years. If detailed to enable replacement of the inner IGU without affecting the outer laminate, the service life of the laminate could potentially be extended to 60 years, reducing the overall carbon impact during the B4 stage.

				Module		Opaque Area		Glazing					System Performance			
Wall Type	Façade Type	Window-to-Wall ratio	Shading	Typical width (m)	Typical height (m)	Material	Finish	IGU configuration	Glass Make-Up (T=tempered) All with XTREME 61/29 coating	Solar Performance (g-value)	VLT (%)	Acoustic RW (C;Ctr)	Thermal Transmittance U-value (W/m2K)	Solar Radiation	Air tightness	Weather tightness
WT-1	Aluminium Unitised Curtain Wall	1	N/A	1.5	4	N/A	N/A	DGU	8T-16-44.2	0.29	60	42(-2 ;-8) dB	1.4-1.6	~135 W/m2	Class A4	Class R7
WT-2	Aluminium Unitised Curtain Wall	0.5	N/A	1.5	4	Aluminium cladding	Anodised	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	1.3-1.5	~75 W/m2	Class A4	Class R7
WT-3	Aluminium Unitised Curtain Wall	0.5	Vertical Al fins 400mm	1.5	4	Aluminium cladding	Anodised	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	1.3-1.5	~60 W/m2	Class A4	Class R7
WT-4	Aluminium Unitised Curtain Wall	0.5	N/A	1.5	4	Aluminium cladding	Anodised	TGU	8T-16-6-16-44.2	0.27	55	41(-1 ;-5) dB	0.9-1.1	~75 W/m2	Class A4	Class R7
WT-5	Aluminium Unitised Curtain Wall	0.5	N/A	1.5	4	Insulated shadow box	Glass	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	1.3-1.5	~75 W/m2	Class A4	Class R7
WT-6	Aluminium Unitised Curtain Wall	0.5	N/A	1.5	4	GRC cladding	N/A	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	1.3-1.5	~75 W/m2	Class A4	Class R7
WT-7	Aluminium Stick System Curtain Wall	0.5	N/A	1.5	4	Aluminium panels	Anodised	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	1.3-1.4	~75 W/m2	Class A4	Class R7
WT-8	Steel Stick System Curtain Wall	0.5	N/A	1.5	4	Aluminium panels	Anodised	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	1.3-1.4	~75 W/m2	Class A4	Class R7
WT-9	Timber Stick System Curtain Wall	0.5	N/A	1.5	4	Aluminium panels	Anodised	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	1.2-1.3	~75 W/m2	Class A4	Class R7
WT-10	Deep cavity Double Skin Façade	1	N/A	1.5	4	N/A	N/A	S+DGU	66.2 + 8T-16-44.2			41(-3 ;-7) dB*	1.3-1.4	~50 W/m2	Class A4	Class R7
WT-11	Narrow cavity Double Skin Façade	1	N/A	1.5	4	N/A	N/A	S+DGU	66.2 + 8T-16-44.2			41(-3 ;-7) dB*	1.2-1.4	~50 W/m2	Class A4	Class R7
WT-12	Precast Concrete System	0.5	N/A	1.5*	4	Precast concrete	Concrete	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	1.0-1.1	~75 W/m2	N/A	Class 9A
WT-13	Aluminium Rainscreen (SFS backing)	0.5	N/A	1.5*	4	Aluminum	Anodised	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	0.9-1.0	~75 W/m2	N/A	Class 9A
WT-14	Hand Set Stone (SFS backing)	0.5	N/A	1.5*	4	Stone	Stone	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	0.9-1.0	~75 W/m2	N/A	Class 9A
WT-15	Handset brick (SFS backing)	0.5	N/A	1.5*	4	Brick	N/A	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	0.9-1.0	~75 W/m2	N/A	Class 9A
WT-16	Handset brick (CLT backing)	0.5	N/A	1.5*	4	Brick	N/A	DGU	8T-16-44.2	0.29	60	41(-3 ;-7) dB	0.9-1.0	~75 W/m2	N/A	Class 9A

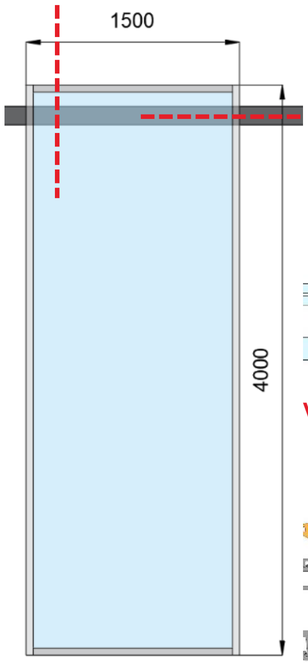
* This value represents the double glazed unit only. Understanding the holistic acoustic performance of the double skin system is complex and depends on the framing design.

Facade system performance criteria

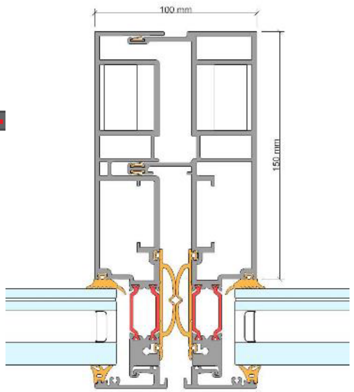
For Step 1: Glass contribution to systems

1. Aluminium Unitised Curtain Wall, 100% DGU

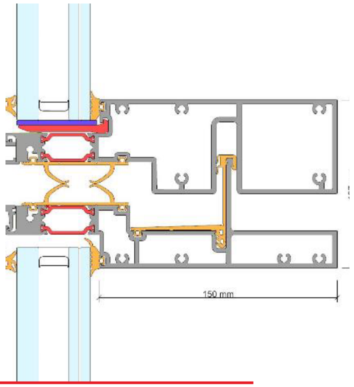
Elevation



Horizontal Section



Vertical Section



Key

■	Frame	Aluminium
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
□	Vision panel	Glass, PVB, spacebar, butyl, silicone

Total Embodied Carbon A1 – A3

150 kgCO$_2$eq/m^2

A1-A5, B4, C

250 kgCO$_2$eq/m^2

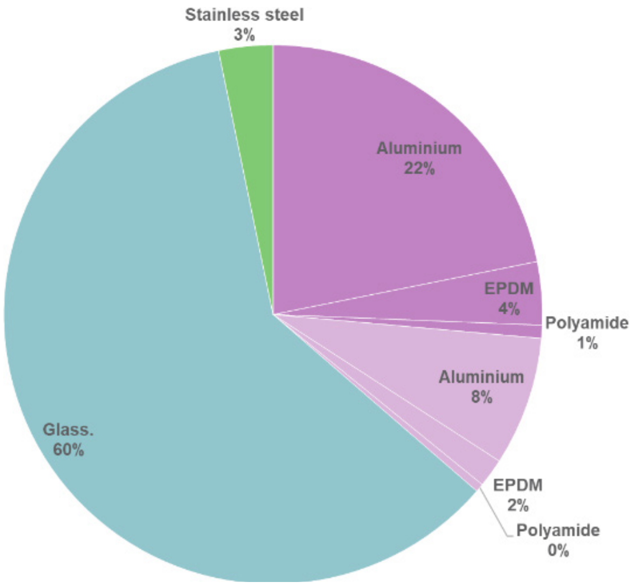
Component Key

🟪	Split Mullion
🟪	Split Transom
🟦	Glass
🟩	Brackets

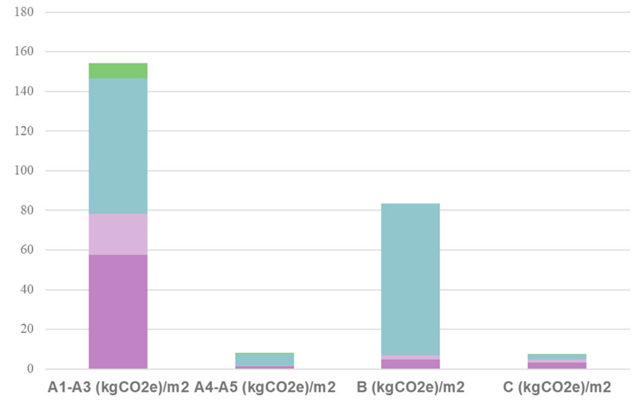
System description/performance

Façade Type	Aluminium Unitised Curtain Wall
Window-to-Wall ratio	1
Shading	N/A
Material	N/A
Finish	N/A
IGU configuration	DGU
Glass Make-Up	8T-16-44.2 Note: this build-up is identical to 50% WWR DGU build-up, including thick to minimise the number of glass build included in the analysis.
Solar Performance (g-value)	0.28
VLT (%)	60
Acoustic [RW (C;Ctr)]	42(-2 ;-8) dB
Thermal Transmittance (U-value) [W/m2K]	1.4-1.6
Solar gains	~135 W/m^2

Embodied Carbon by Material (A-C) (kgCO₂eq/m²)

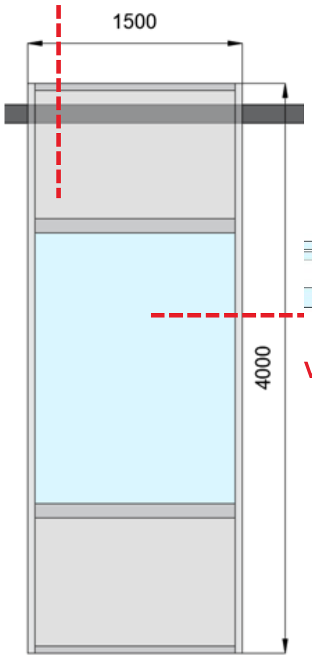


Embodied Carbon by Stage (kgCO₂eq/m²)

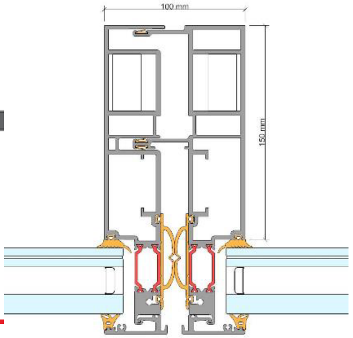


2. Aluminium Unitised Curtain Wall, Aluminium Cladding, 50% DGU

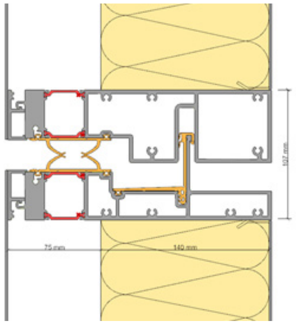
Elevation



Horizontal Section



Vertical Section



Key

⬛	Frame	Aluminium
⬛	Opaque panel	Aluminium
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
⬜	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool

Total Embodied Carbon A1 – A3

180 kgCO$_2$eq/m^2

A1-A5, B4, C

240 kgCO$_2$eq/m^2

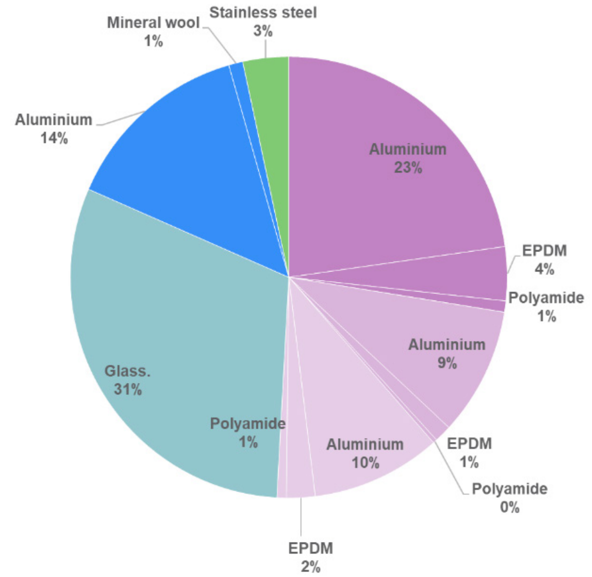
Component Key

🟪	Split Mullion
🟪	Split Transom
🟪	Intermediate Transom
🟦	Glass
🟩	Brackets
🟦	Opaque Panel (Al)

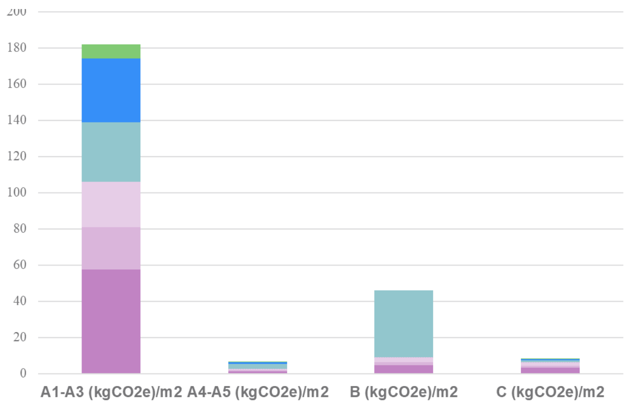
System description/performance

	Façade Type	Aluminium Unitised Curtain Wall
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Aluminium cladding
	Finish	Anodised
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	1.3-1.5
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) kgCO$_2$eq/m^2)

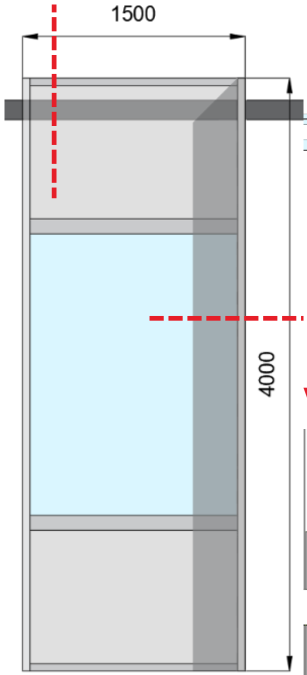


Embodied Carbon by Stage (kgCO$_2$eq/m^2)

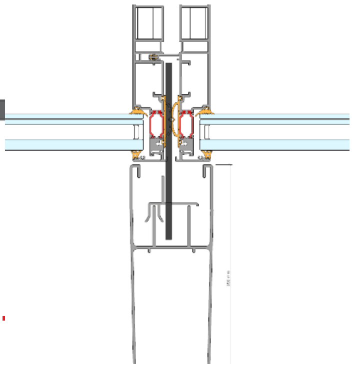


3. Aluminium Unitised Curtain Wall, Aluminium Cladding & Vertical Fins, 50% DGU

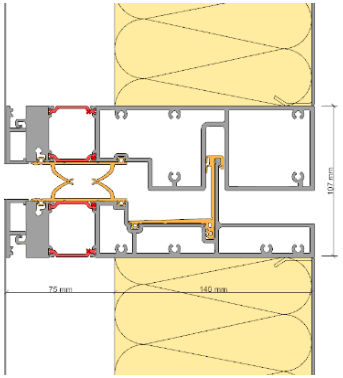
Elevation



Horizontal Section



Vertical Section



Key

■	Frame	Aluminium
■	Opaque panel	Aluminium
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
⬜	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool

Total Embodied Carbon

A1 – A3

230 kgCO$_2$eq/m^2

A1-A5, B4, C

290 kgCO$_2$eq/m^2

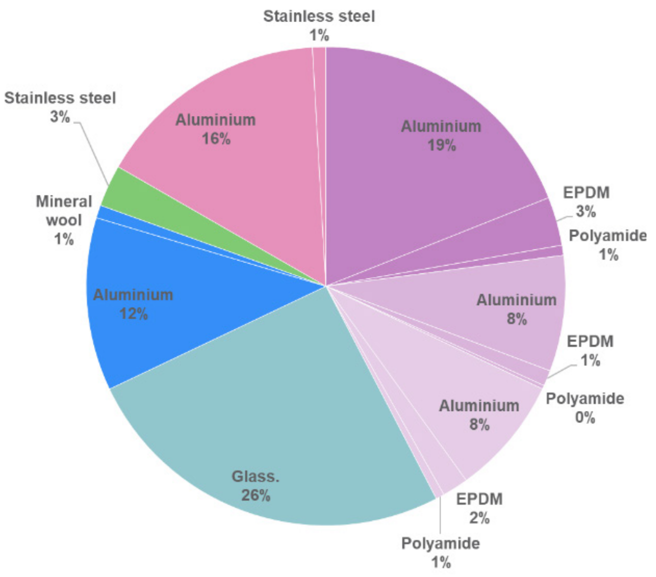
Key

🟪	Split Mullion
🟪	Split Transom
⬜	Intermediate Transom
🟦	Glass
🟩	Brackets
🟦	Opaque Panel (Al)
🟥	Fins (400mm deep)

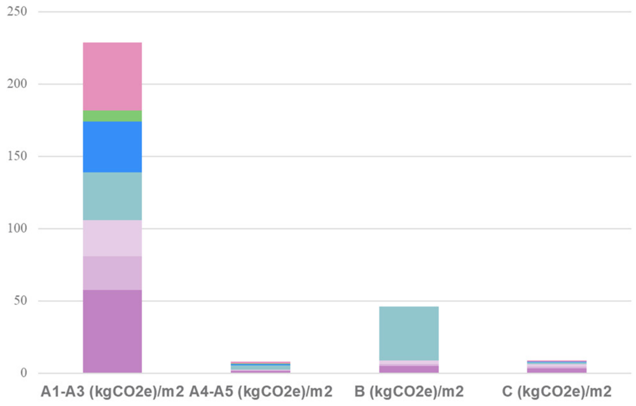
System description/performance

Façade Type	Aluminium Unitised Curtain Wall
Window-to-Wall ratio	0.5
Shading	Vertical aluminium fins, 400mm dee
Material	Aluminium cladding
Finish	Anodised
IGU configuration	DGU
Glass Make-Up	8T-16-44.2
Solar Performance (g-value)	0.28
VLT (%)	60
Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
Thermal Transmittance (U-value) [W/m2K]	1.3-1.5
Solar gains	~60 W/m^2

Embodied Carbon by Material (A-C) kgCO₂eq/m²)

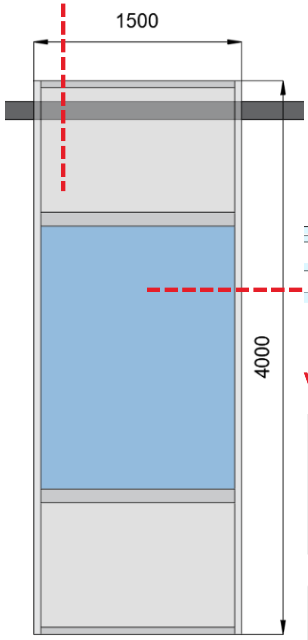


Embodied Carbon by Stage (kgCO₂eq/m²)

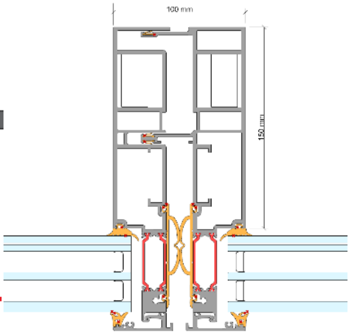


4. Aluminium Unitised Curtain Wall, Aluminium Cladding, 50% TGU

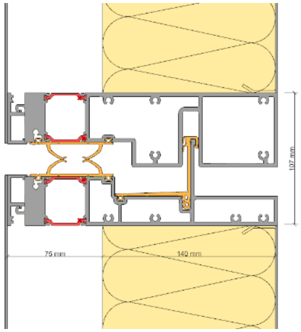
Elevation



Horizontal Section



Vertical Section



Key

⬛	Frame	Aluminium
⬛	Opaque panel	Aluminium
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
⬜	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool

Total Embodied Carbon A1 – A3

190 $kgCO_2eq/m^2$

A1-A5, B4, C

270 $kgCO_2eq/m^2$

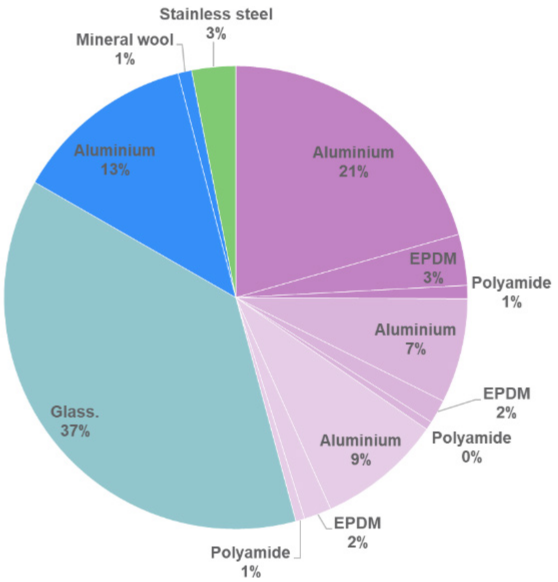
Key

🟪	Split Mullion
🟪	Split Transom
⬜	Intermediate Transom
🟦	Glass
🟩	Brackets
🟦	Opaque Panel (Al)

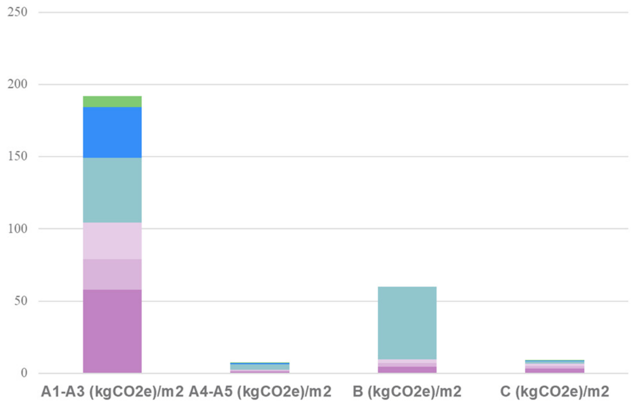
System description/performance

	Façade Type	Aluminium Unitised Curtain Wall
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Aluminium cladding
	Finish	Anodised
Glazing	IGU configuration	TGU
	Glass Make-Up	8T-16-6-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-1 ;-5) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	0.9-1.1
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) $kgCO_2eq/m^2$

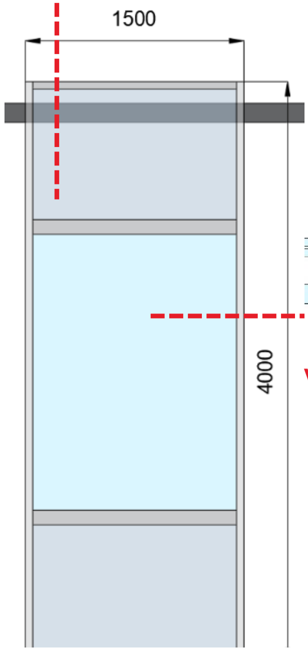


Embodied Carbon by Stage ($kgCO_2eq/m^2$)

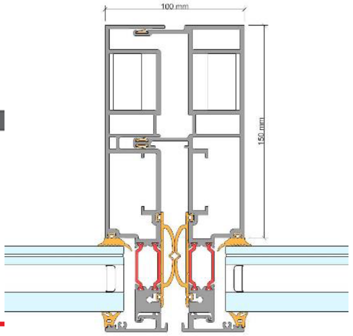


5. Aluminium Unitised Curtain Wall, Insulated Shadow Box, 50% DGU

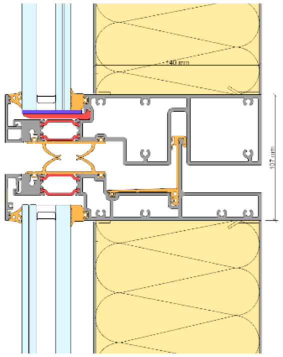
Elevation



Horizontal Section



Vertical Section



Key

⬛	Frame	Aluminium
⬜	Opaque panel	Insulated shadow box with glazed spandrel
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
⬜	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool

Total Embodied Carbon

A1 – A3

190 $kgCO_2eq/m^2$

A1-A5, B4, C

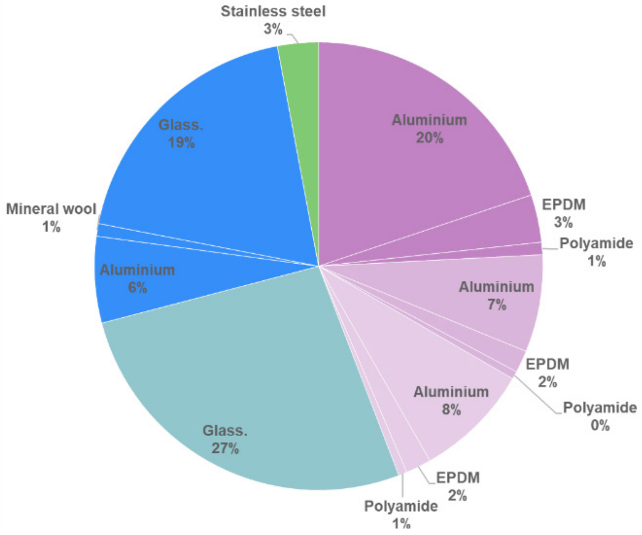
280 $kgCO_2eq/m^2$

🟪	Split Mullion
🟪	Split Transom
🟪	Intermediate Transom
🟦	Glass
🟩	Brackets
🟦	Opaque Panel (ISB)

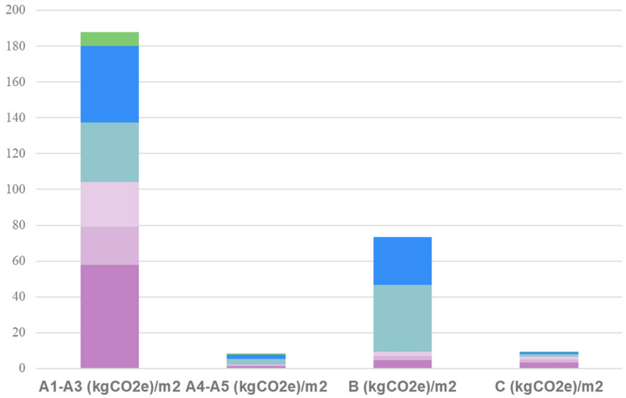
System description/performance

	Façade Type	Aluminium Unitised Curtain Wall
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Insulated shadow box
	Finish	Glass
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	1.3-1.5
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) $kgCO_2eq/m^2$

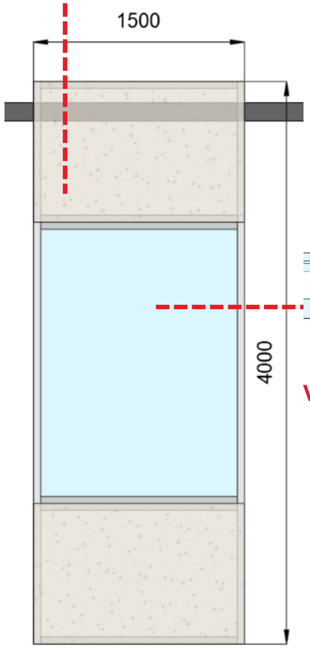


Embodied Carbon by Stage ($kgCO_2eq/m^2$)

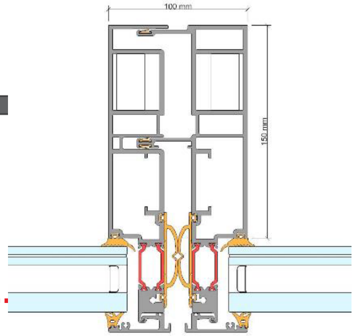


6. Aluminium Unitised Curtain Wall, GRC Cladding, 50% DGU

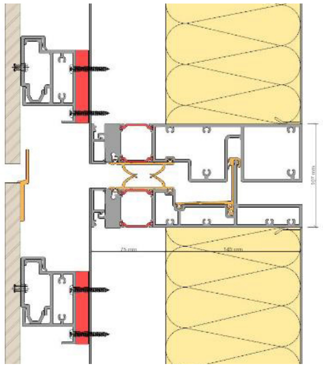
Elevation



Horizontal Section



Vertical Section



Key

⬛	Frame	Aluminium
⬛	Opaque panel	Glass reinforced concrete
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
🟦	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool

Total Embodied Carbon A1 – A3

220 $kgCO_2eq/m^2$

A1-A5, B4, C

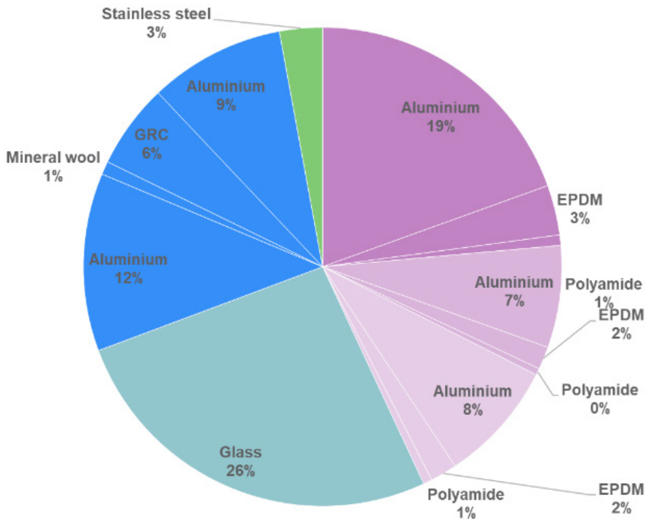
280 $kgCO_2eq/m^2$

🟪	Split Mullion
🟪	Split Transom
🟪	Intermediate Transom
🟦	Glass
🟩	Brackets
🟦	Opaque Panel (Glass Reinforced Concrete)

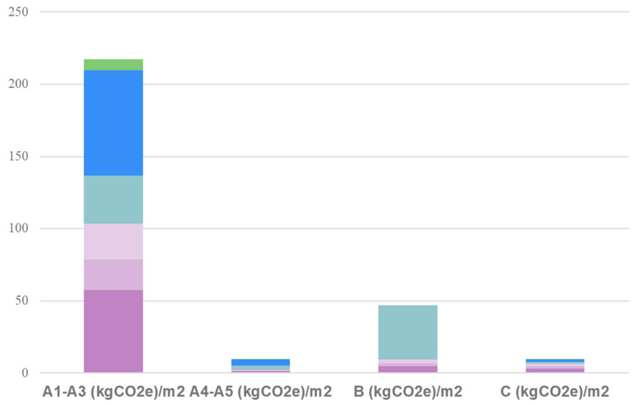
System description/performance

	Façade Type	Aluminium Unitised Curtain Wall
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Glass reinforced concrete cladding
	Finish	Concrete
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	1.3-1.5
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) $kgCO_2eq/m^2$)

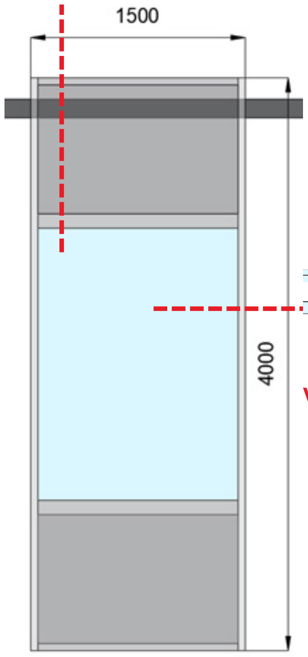


Embodied Carbon by Stage ($kgCO_2eq/m^2$)

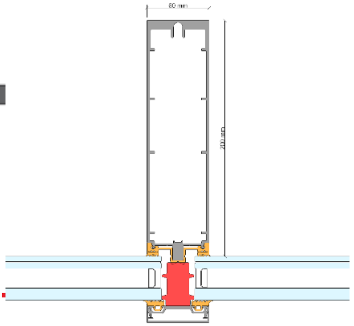


7. Aluminium Stick Curtain Wall, Aluminium Cladding, 50% DGU

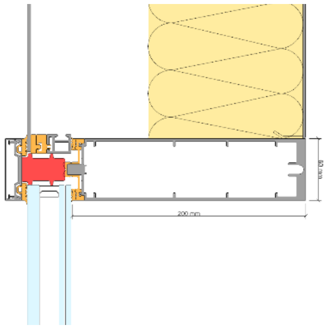
Elevation



Horizontal Section



Vertical Section



Key

■	Frame	Aluminium
■	Opaque panel	Aluminium
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
▢	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool

Total Embodied Carbon

A1 – A3

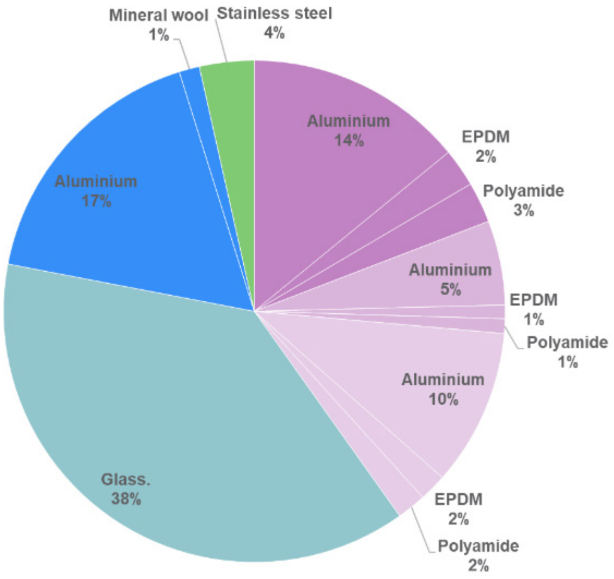
150 $\text{kgCO}_2\text{eq/m}^2$

A1-A5, B4, C

210 $\text{kgCO}_2\text{eq/m}^2$

🟪	Mullion
🟪	Transom
🟪	Intermediate Transom
🟦	Glass
🟩	Brackets
🟦	Opaque Panel (Al)

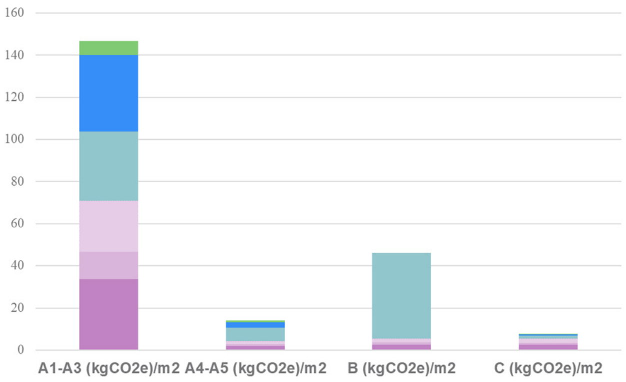
Embodied Carbon by Material (A-C) $\text{kgCO}_2\text{eq/m}^2$)



System description/performance

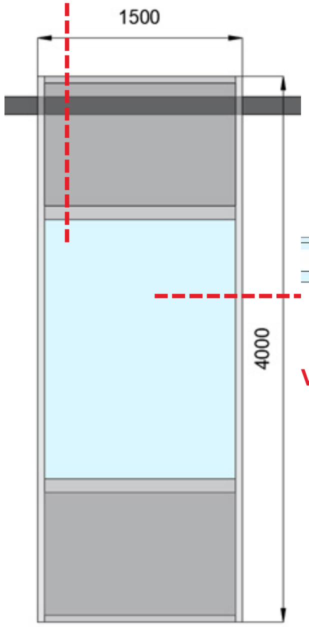
	Façade Type	Aluminium Stick Curtain Wall
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Aluminium
	Finish	Anodised
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	1.3-1.5
	Solar gains	~75 W/m^2

Embodied Carbon by Stage ($\text{kgCO}_2\text{eq/m}^2$)

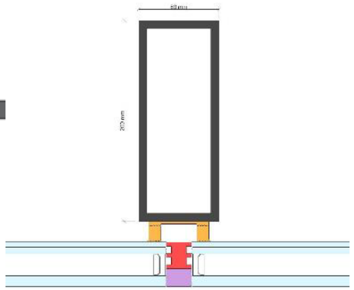


8. Steel Stick Curtain Wall, Aluminium Cladding, 50% DGU

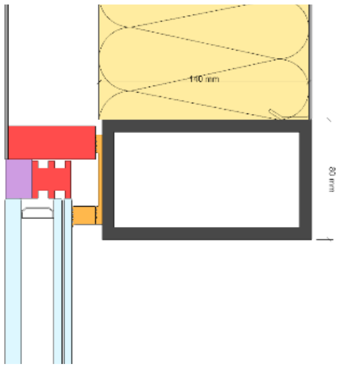
Elevation



Horizontal Section



Vertical Section



Key

⬛	Frame	Steel
▨	Opaque panel	Aluminium
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
⬜	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool
🟪	Sealant	Silicone

Total Embodied Carbon A1 – A3

230 kgCO$_2$eq/m^2

A1-A5, B4, C

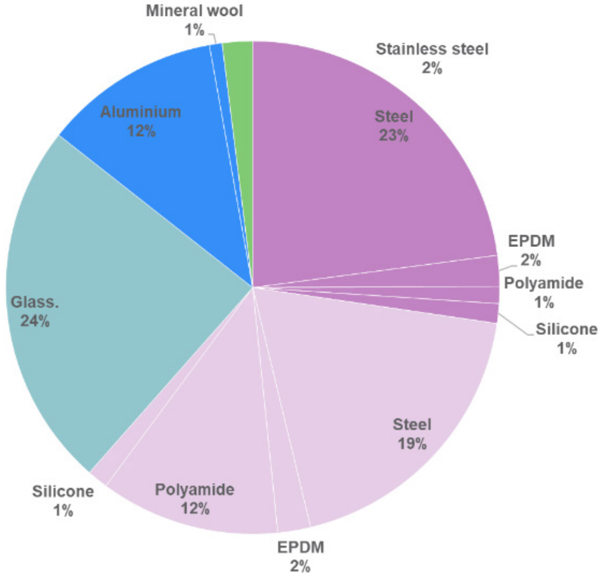
300 kgCO$_2$eq/m^2

🟪	Split Mullion
▨	Split Transom
▩	Glass
🟩	Brackets
🟦	Opaque Panel (Al)

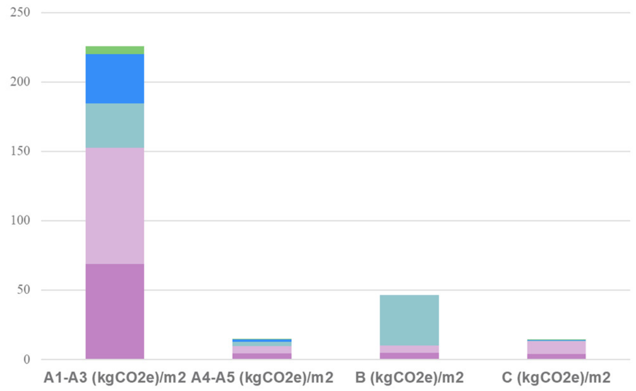
System description/performance

	Façade Type	Steel Stick Curtain Wall
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Aluminium
	Finish	Anodised
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	1.3-1.5
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) kgCO₂eq/m²)

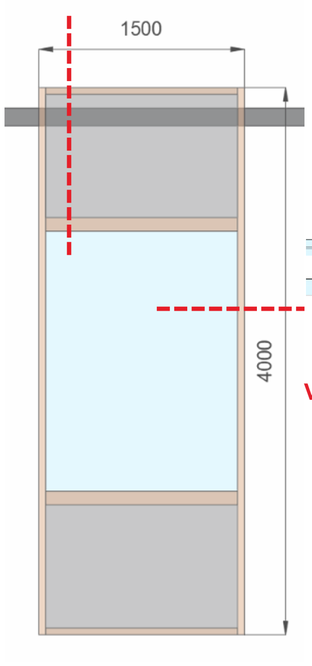


Embodied Carbon by Stage (kgCO₂eq/m²)

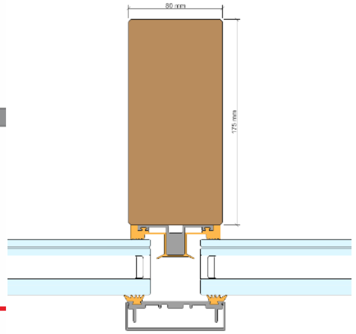


9. Timber Stick Curtain Wall, Aluminium Cladding, 50% DGU

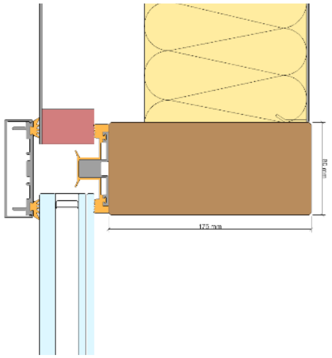
Elevation



Horizontal Section



Vertical Section



Key

⬛	Frame, cup opaque panel	Aluminium
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
⬜	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral Wool
🟫	Frame	Timber

Total Embodied Carbon A1 – A3

$120\ \mathrm{kgCO_2eq/m^2}$

A1-A5, B4, C

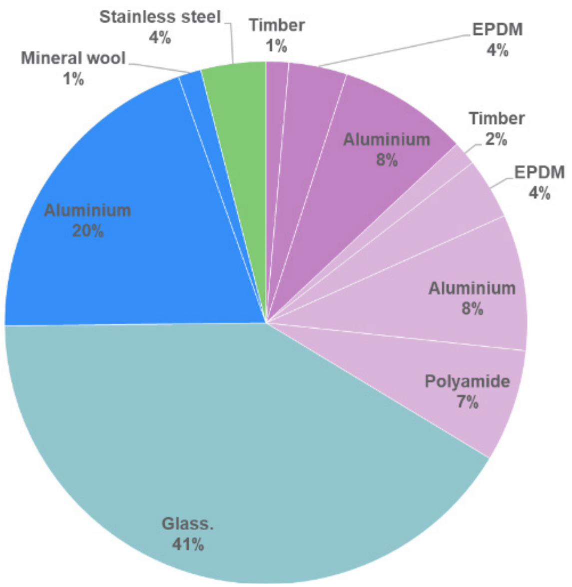
$180\ \mathrm{kgCO_2eq/m^2}$

🟪	Split Mullion
🟪	Split Transom
🟦	Glass
🟩	Brackets
🟦	Opaque Panel (Al)

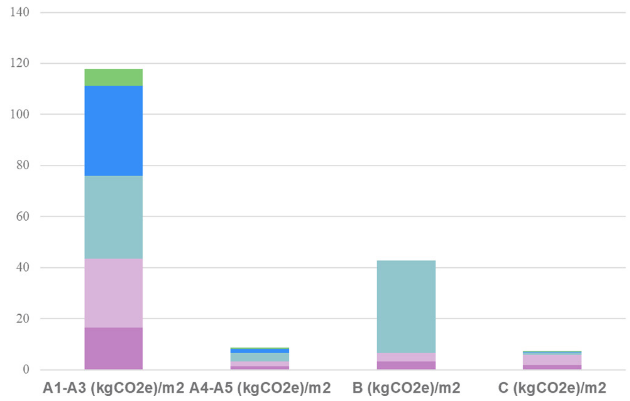
System description/performance

	Façade Type	Timber Stick Curtain Wall
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Aluminium
	Finish	Anodised
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	1.2-1.3
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) ($\mathrm{kgCO_2eq/m^2}$)

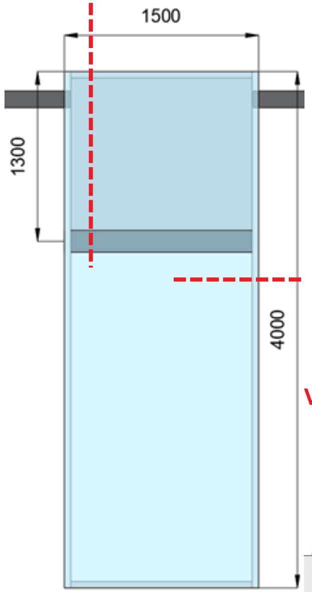


Embodied Carbon by Stage ($\mathrm{kgCO_2eq/m^2}$)

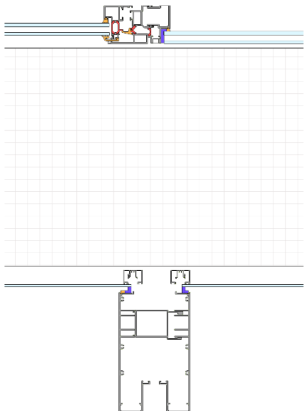


10. Deep Cavity Double Skin Façade, 100% Single + DGU

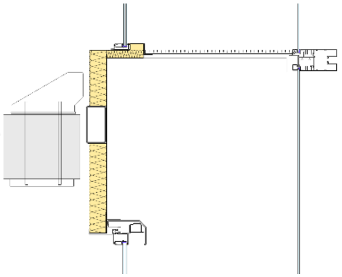
Elevation



Horizontal Section



Vertical Section



Key

■	Frame, opaque panel	Aluminium
■	Structure, brackets	Steel
■	Thermal break	Polyamide
■	Gasket	EPDM rubber
■	Vision panel	Glass, PVB, spacebar, butyl, silicone
■	Insulation	Mineral wool
■	Sealant	Silicone

Total Embodied Carbon A1 – A3

390 kgCO$_2$eq/m^2

A1-A5, B4, C

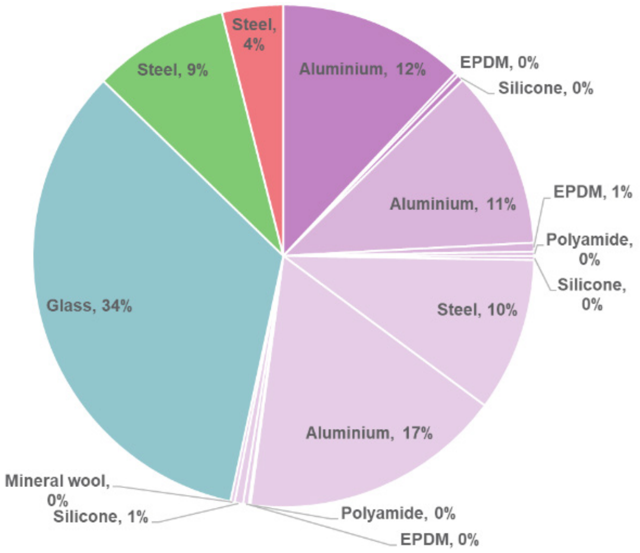
520 kgCO$_2$eq/m^2

🟪	Split Mullion
🟪	Split Transom
🟪	Intermediate Mullion
🟦	Glass
🟩	Brackets
🟥	Walkway grid (steel)

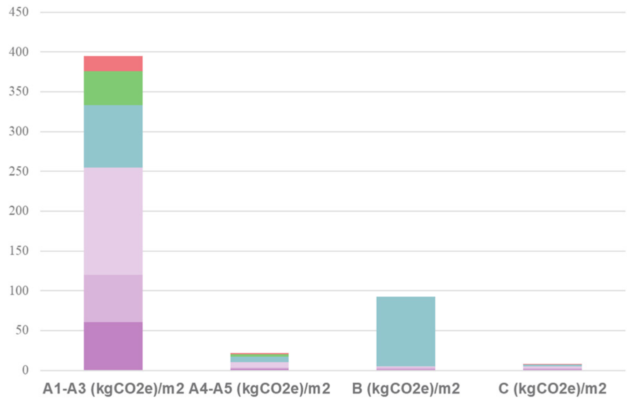
System description/performance

	Façade Type	Double Skin Façade
	Window-to-Wall ratio	1
	Shading	N/A
Opaque	Material	N/A
	Finish	N/A
Glazing	IGU configuration	Single + DGU
	Glass Make-Up	66.2 + 8T-16-44.2
	Solar Performance (g-value)	0.55-0.12
	VLT (%)	70-75
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB This value represents the double glazed unit only.
System Performance	Thermal Transmittance (U-value) [W/m2K]	1.2-1.4
	Solar gains	~50 W/m^2

Embodied Carbon by Material (A-C) (kgCO$_2$eq/m^2)

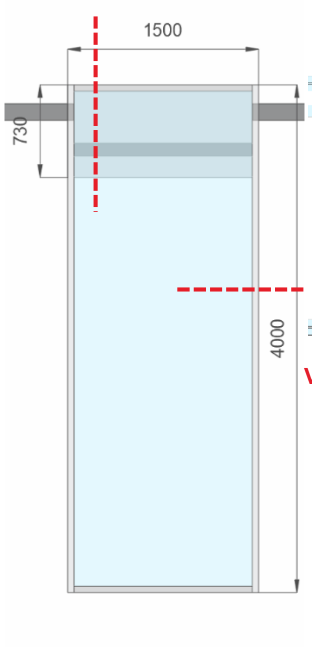


Embodied Carbon by Stage (kgCO$_2$eq/m^2)

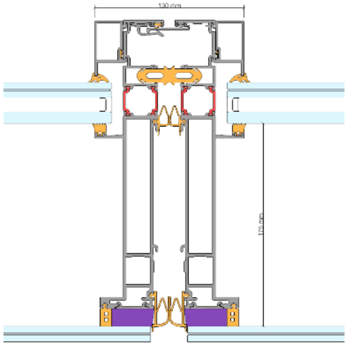


11. Narrow Cavity Double Skin Façade, 100% Single + DGU

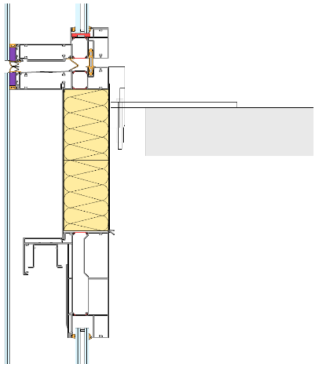
Elevation



Horizontal Section



Vertical Section



Key

■	Frame, opaque panel	Aluminium
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
◻	Vision panel*	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool
🟪	Sealant	Silicone

*The contribution of aluminium blinds has been excluded from the study.

Total Embodied Carbon A1 – A3

$240\ kgCO_2eq/m^2$

A1-A5, B4, C

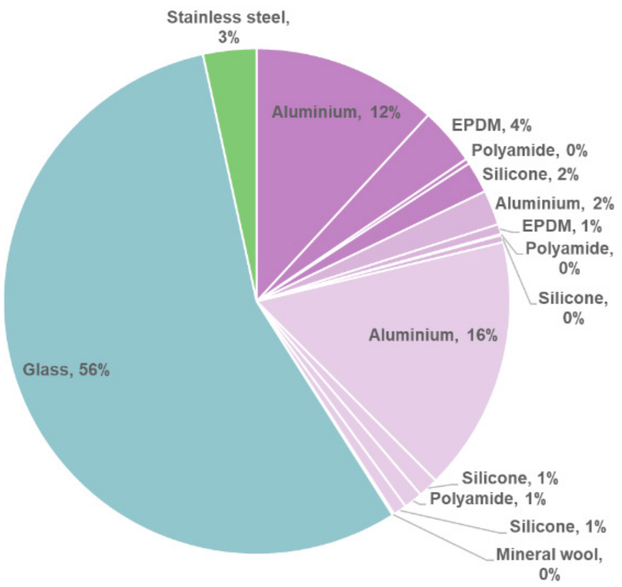
$390\ kgCO_2eq/m^2$

- 🟪 Split Mullion (glass-glass)
- 🟪 Split Mullion (opaq-opaq)
- ◻ Split Transom
- 🟦 Glass
- 🟩 Brackets

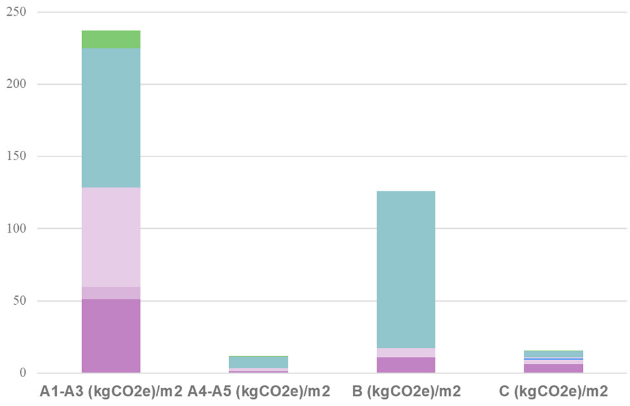
System description/performance

	Façade Type	Aluminium Stick Curtain Wall
	Window-to-Wall ratio	1
	Shading	N/A
Opaque	Material	N/A
	Finish	N/A
Glazing	IGU configuration	Single + DGU
	Glass Make-Up	66.2 + 8T-16-44.2
	Solar Performance (g-value)	0.55-0.12
	VLT (%)	70-5
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB This value represents the double glazed unit only.
System Performance	Thermal Transmittance (U-value) [W/m2K]	1.2-1.5
	Solar gains	~50 W/m^2

Embodied Carbon by Material (A-C) (kgCO₂eq/m²)

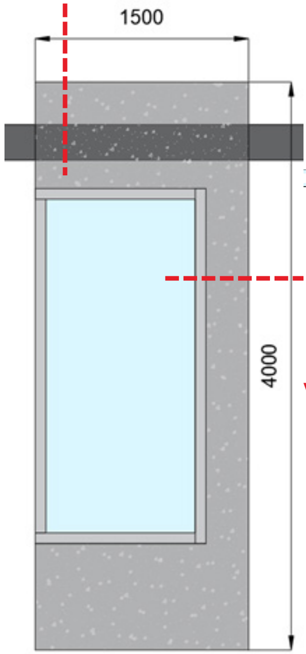


Embodied Carbon by Stage (kgCO₂eq/m²)

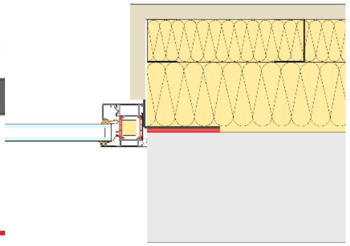


12. Precast Concrete System, 50% DGU

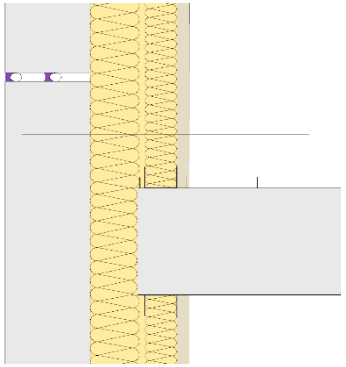
Elevation



Horizontal Section



Vertical Section



Key

⬛	Window frame, flashing	Aluminium
⬜	Precast panel	Precast concrete
🟫	Internal finishes	Plasterboard
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
🟦	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool
🟪	Sealant	Silicone

Total Embodied Carbon A1 – A3

150 kgCO$_2$eq/m^2

A1-A5, B4, C

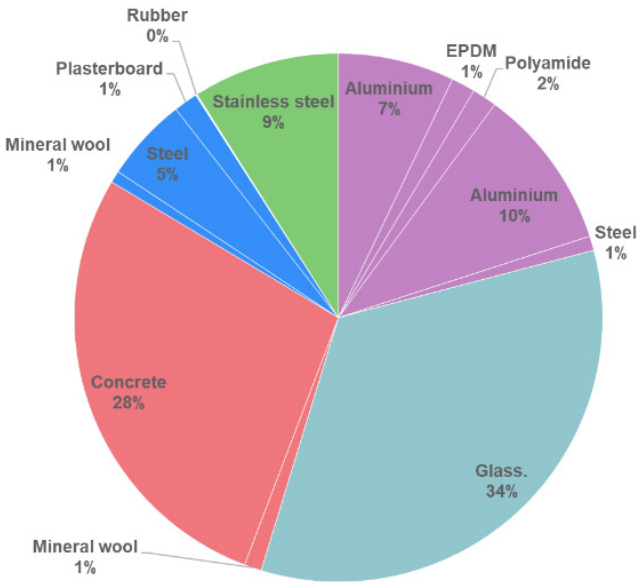
210 kgCO$_2$eq/m^2

🟪	Window Frame
🟦	Glass
🟩	Brackets
🟥	Opaque Panel (Concrete)
🟦	Steel Frame System

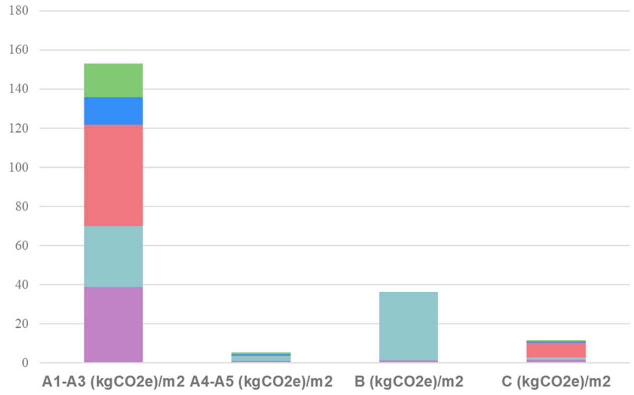
System description/performance

	Façade Type	Precast Concrete System
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Precast Concrete
	Finish	Concrete
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	1.0-1.1
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) (kgCO$_2$eq/m^2)

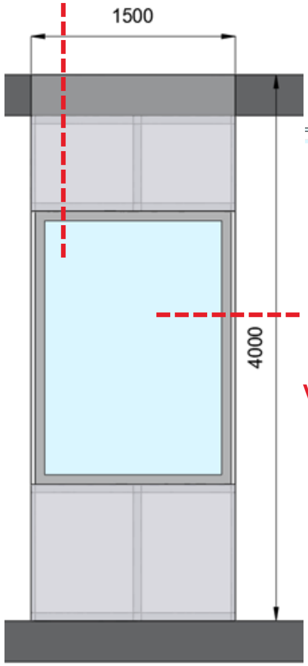


Embodied Carbon by Stage (kgCO$_2$eq/m^2)

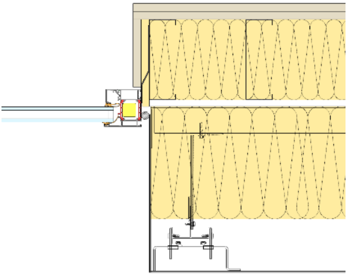


13. Aluminium Rainscreen, Steel Frame System, 50% DGU

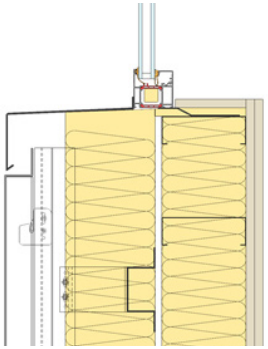
Elevation



Horizontal Section



Vertical Section



Key

▩	Window frame, flashing	Aluminium
■	Studs, rail, brackets	Steel/stainless steel
▨	Internal finishes	Plasterboard
🟥	Thermal break	Polyamide
🟧	Gasket	EPDM rubber
⬜	Vision panel	Glass, PVB, spacebar, butyl, silicone
🟨	Insulation	Mineral wool

Total Embodied Carbon

A1 – A3

120 $kgCO_2eq/m^2$

A1-A5, B4, C

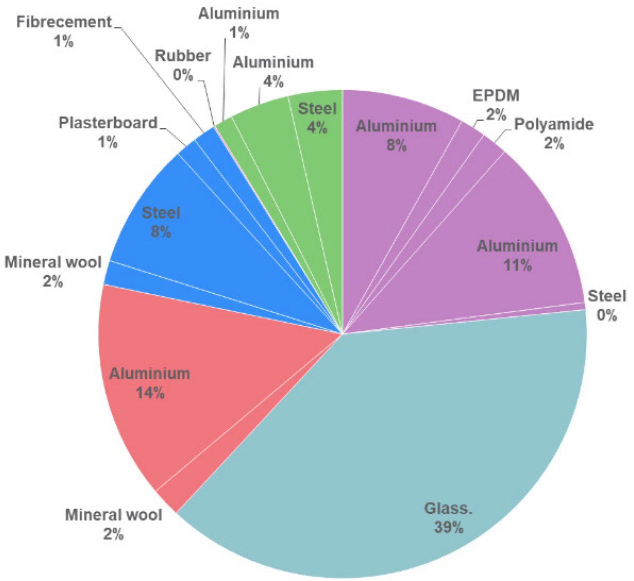
170 $kgCO_2eq/m^2$

🟪	Window Frame
🟦	Glass
🟩	Support System
🟥	Opaque Panel (Al)
🟦	Steel Frame System

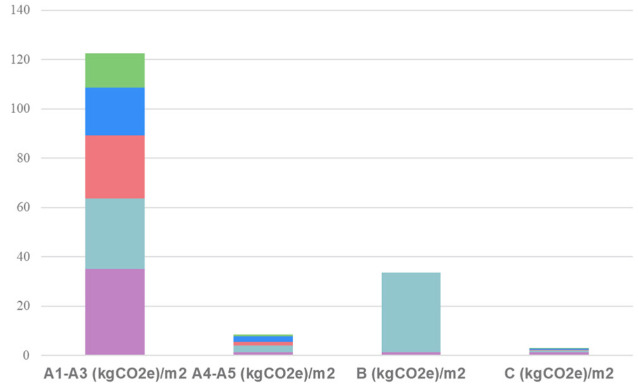
System description/performance

	Façade Type	Aluminium Rainscreen System, SFS
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Aluminium
	Finish	Anodised
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	0.9-1.0
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) ($kgCO_2eq/m^2$)

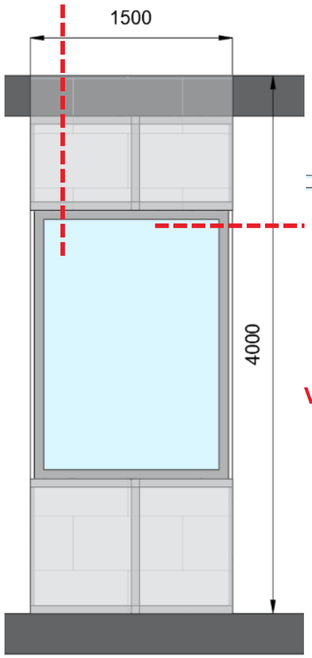


Embodied Carbon by Stage ($kgCO_2eq/m^2$)

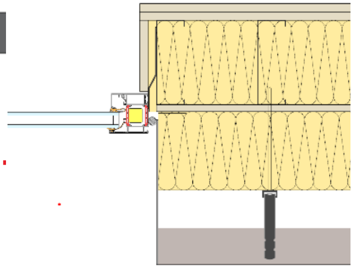


14. Handset Stone, Steel Frame System, 50% DGU

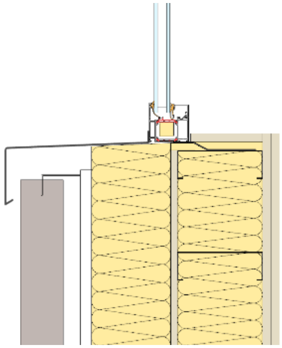
Elevation



Horizontal Section



Vertical Section



Key

■	Window frame, flashing	Aluminium
■	Studs, rail, brackets, ties	Steel/stainless steel
■	Cladding	Stone
■	Internal finishes	Plasterboard
■	Thermal break	Polyamide
■	Gasket	EPDM rubber
■	Vision panel	Glass, PVB, spacebar, butyl, silicone
■	Insulation	Mineral wool

Total Embodied Carbon A1 – A3

120 kgCO$_2$eq/m^2

A1-A5, B4, C

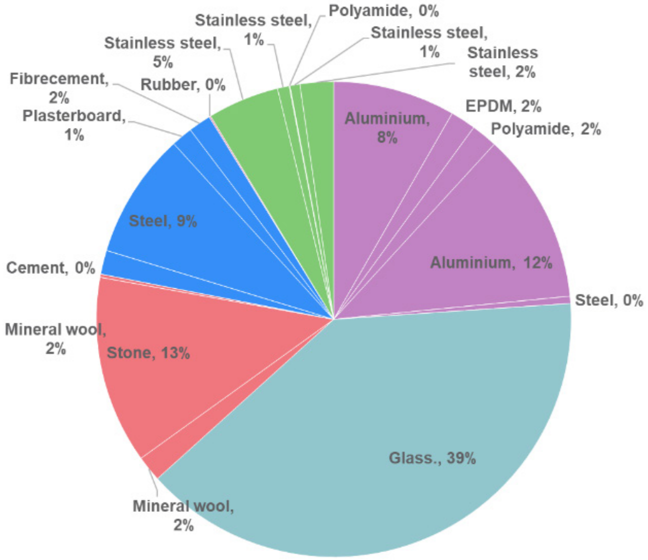
160 kgCO$_2$eq/m^2

🟪	Window Frame
🟦	Glass
🟩	Support System
🟥	Opaque Panel (Stone)
🟦	Steel Frame System

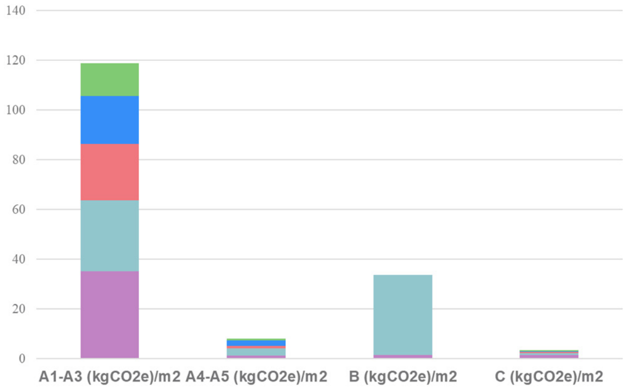
System description/performance

	Façade Type	Handset stone system, SFS backing
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Stone
	Finish	N/A
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	0.9-1.0
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) (kgCO₂eq/m²)

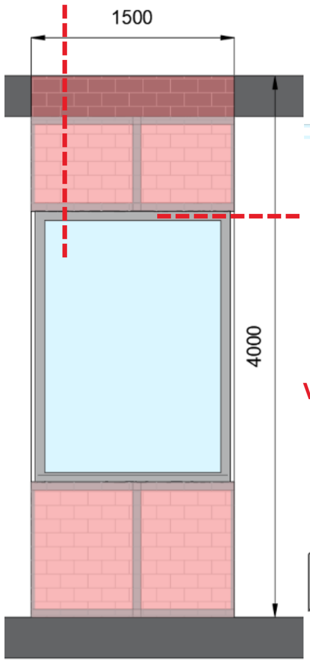


Embodied Carbon by Stage (kgCO₂eq/m²)

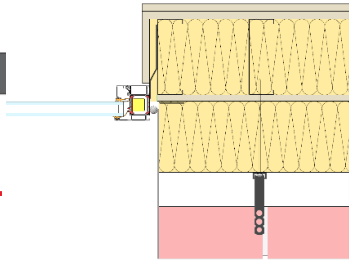


15. Handset Brick, Steel Frame System, 50% DGU

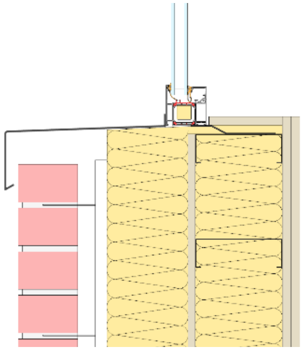
Elevation



Horizontal Section



Vertical Section



Key

■	Window frame, flashing	Aluminium
■	Studs, rail, brackets, ties	Steel/stainless steel
■	Cladding	Brick
■	Internal finishes	Plasterboard
■	Thermal break	Polyamide
■	Gasket	EPDM rubber
■	Vision panel	Glass, PVB, spacebar, butyl, silicone
■	Insulation	Mineral wool

Total Embodied Carbon A1 – A3

120 $kgCO_2eq/m^2$

A1-A5, B4, C

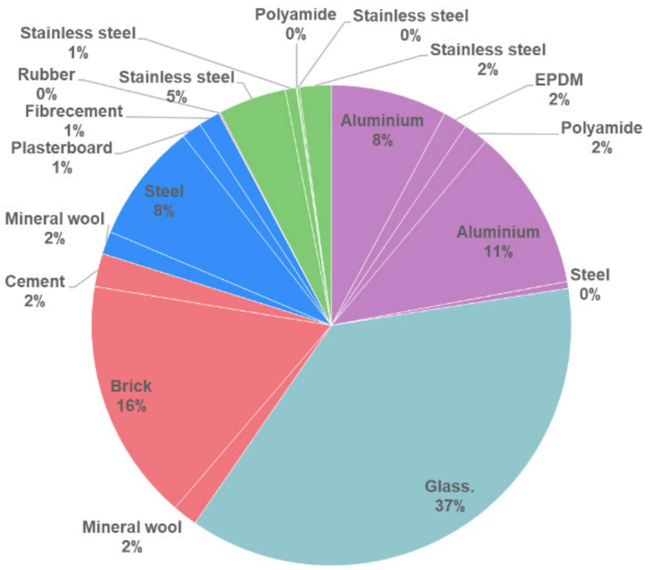
170 $kgCO_2eq/m^2$

🟪	Window Frame
🟦	Glass
🟩	Support System
🟥	Opaque Panel (Brick)
🟦	Steel Frame System

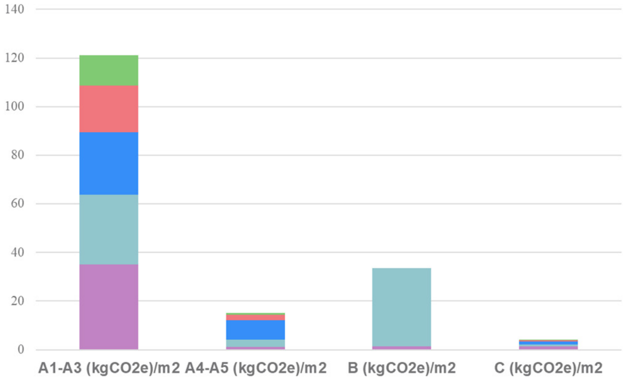
System description/performance

	Façade Type	Handset brick system, SFS backing
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Brick
	Finish	N/A
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	0.9-1.0
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) ($kgCO_2eq/m^2$)

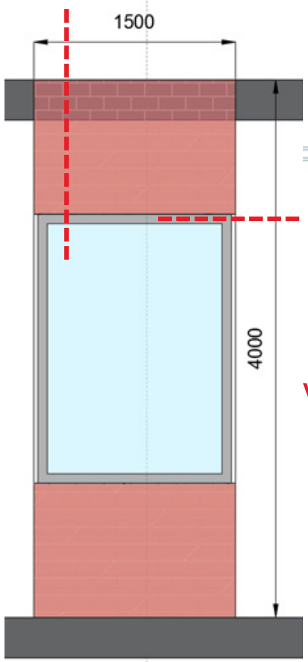


Embodied Carbon by Stage ($kgCO_2eq/m^2$)

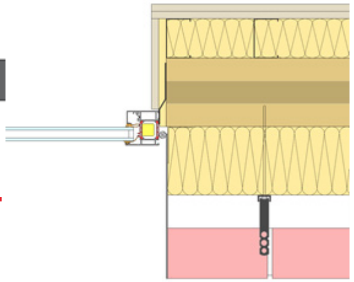


16. Handset Brick, Cross Laminated Timber Backing, 50% DGU

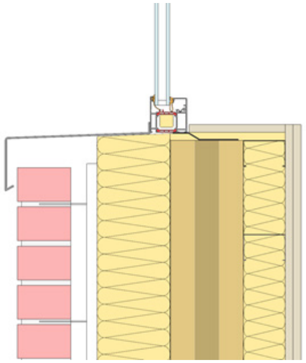
Elevation



Horizontal Section



Vertical Section



Key

■	Window frame, flashing	Aluminium
■	Studs, rail, brackets, ties	Steel/stainless steel
■	Cladding	Brick
■	Internal finishes	Plasterboard
■	Thermal break	Polyamide
■	Gasket	EPDM rubber
■	Vision panel	Glass, PVB, spacebar, butyl, silicone
■	Insulation	Mineral wool
■	Substructure	CLT

Total Embodied Carbon

A1 – A3

110 $\mathrm{kgCO_2eq/m^2}$

A1-A5, B4, C

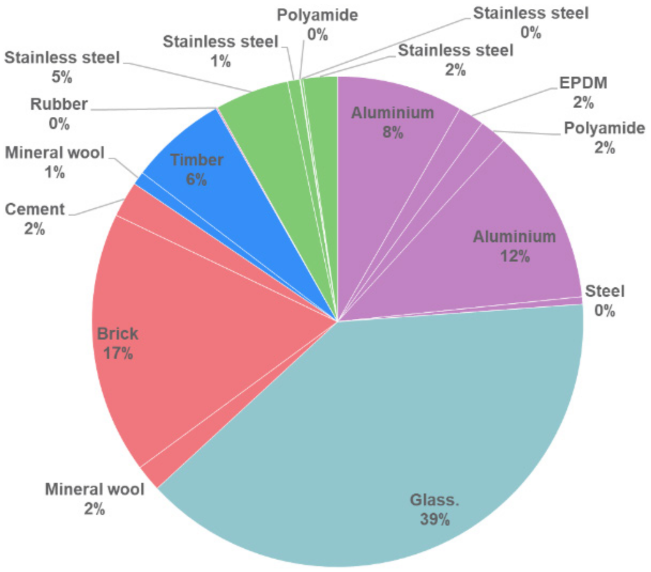
160 $\mathrm{kgCO_2eq/m^2}$

■	Window Frame
■	Glass
■	Support System
■	Opaque Panel (Brick)
■	CLT Backing

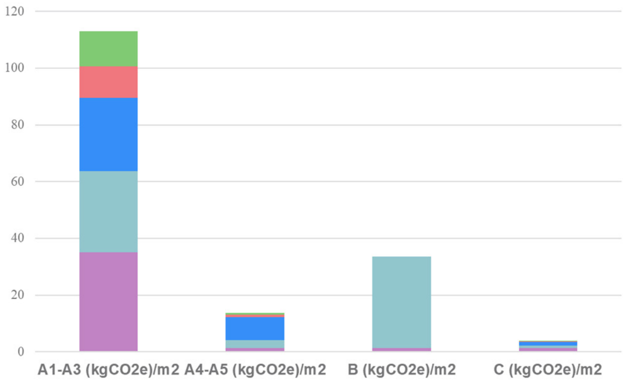
System description/performance

	Façade Type	Handset brick system, CLT backing
	Window-to-Wall ratio	0.5
	Shading	N/A
Opaque	Material	Brick
	Finish	N/A
Glazing	IGU configuration	DGU
	Glass Make-Up	8T-16-44.2
	Solar Performance (g-value)	0.28
	VLT (%)	60
	Acoustic [RW (C;Ctr)]	41(-3 ;-7) dB
System Performance	Thermal Transmittance (U-value) [W/m2K]	0.9-1.0
	Solar gains	~75 W/m^2

Embodied Carbon by Material (A-C) ($\mathrm{kgCO_2eq/m^2}$)



Embodied Carbon by Stage ($\mathrm{kgCO_2eq/m^2}$)



Appendix 2

Study scope, boundaries and assumptions

Performance criteria

General Assumptions

No specific enhancements / rating are considered at this stage regarding:

Fire Performance

Security (blast)

Fixed assumptions:

It is assumed that the insulation material is mineral wool.

All material grades have been assumed where relevant.

Watertightness (Curtain Walling): Class R7

Watertightness (Windows): Class 9A

Air permeability (Curtain Walling): Class A4

Air permeability (Windows): Class 4

Service life of the building: 60 years

Service life of IGU: 30 years

Additional assumptions for Step 1

A mid-rise building with a wind pressure of ~1.8kPa has been assumed.

A typical facade module of 4m high and 1.5m wide.

A west-facing orientation was assumed.

Heat-strengthend laminated glass in both outer & innner panes.

Definitions

Watertightness (Curtain Walling): Classification in accordance with BS EN 12154. Specified performance is valid for any windows and doors in the curtain walling.

Watertightness (Windows): Classification in accordance with BS EN 12208.

Air permeability (Curtain Walling): Classification in accordance with BS EN 12152. At the peak test pressure, the permissible air infiltration rate shall not exceed 1.5 cu.m./hr/m^2 excluding any leakage through opening joints: For windows and doors: At peak test pressure the permissible air infiltration rate through the opening joints shall not exceed 2.0 cu.m/hr/lin.m.

Air permeability (Windows): Classification in accordance with BS EN 12207.

Deflection limits: Under the action of the most onerous combination of loads, deflections of framing members shall not exceed the values given in the Centre for Window and Cladding Technology's Standard for systemised building envelopes. The deflections shall be recovered fully when the loads are removed.

Wind resistance: Refer to section 3.5 and 3.6 of Centre for Window and Cladding Technology's Standard for systemised building envelopes

Thermal transmittance: Overall area weighted average U-value including centre pane U-values, framing U-values, all edge effects, interfaces and thermal bridges. Calculated in accordance with BS EN 12631 and BS EN 10211. Software validated in accordance with Annex D of EN ISO 10077-2.

Service life of the building: Service life of Primary and Secondary façade components as defined in section 7.2 of Centre for Window and Cladding Technology's Standard for systemised building envelopes

Life cycle assessment assumptions

Assumptions, A1 - A3 stages

Factory assembled systems - additional impacts at this stage:

- Transportation of material to the factory: National - 300 km by road
- Factory material wastage emissions (cuttings).

Factory material wastage emissions produced by:

- A1-A3 module + Transport to factory (300 km by road) + transport to waste management (300 km by road) + waste processing impact.

Waste rate per material according to WRAP Net Waste Tool reference:

Material/ product	**WR (waste rate)**
Concrete precast	1%
Brick	20%
Concrete blocks	20%
Stone	10%
Glass	1%
Aluminium frames	1%
Insulation	15%

Factory assembly emissions: Factory energy intensity x grid carbon factor.

Intensity	**Factory energy intensity**
Low intensity	0.1 kWh/kg
Medium intensity	0.15 kWh/kg
High intensity	0.2 kWh/kg

Location	**Grid Carbon Factor, GCF**
UK	0.25 kgCO2e/kWh[1][2]
Europe	0.30 kgCO2e/kWh[1][3]

[1] Data based on Carbon Footprint 2020

[2] Includes both ‘general’ and ‘T&D’ (transmission and distribution emissions)

[3] Based on an average of the countries available

Assumptions, A4 and A5

A4 Transportation of material to site: European manufactured - 1500 km by road. Scaffolding transport not taken into account (similar needs considered across typologies).

A5 Site activities: Based on RICS guidance, 1400kgCO$_2$e/£100k of project value (BRE Meeting Construction 2025 Targets – SMARTWaste KPI p.3, footnote 9)

- Facade installation assumed to represent 10% of the intensity for whole building
- Facade cost assumed to represent 15% of project cost

A5 Site wastage (cuttings):

- Impacts produced by A1-A3 module + Transport to site (1500 km by road) + transport to waste management (300 km by road) + waste processing impact
- Only for site assembled systems
- Waste rate per material according to WRAP Net Waste Tool reference (see table in previous slide)

Site wastage from packaging not taken into account (similar needs considered across typologies)

Life cycle assessment assumptions *cont.*

Assumptions, B1, B2, B3 and B5 stage

B1: Use of the façade system - considered negligible.

B2 and B3: Maintenance and repairs. Due to the significant lack data to support the assessment of these emissions it is proposed to be ignored.

B5: Planned refurbishments of the façade system known at the time of assessment, which are not considered for the present assessment.

Assumptions, B4 stage

Replacement needs across the life span of the building. Considered as follows:

Element	**Replacement frequency**
Glass	30 years
Accessible gaskets and sealants	30 years
Framing	60 years
Sealants and gaskets which are concealed within the system, and which cannot be inspected and replaced without dismantling the envelope system	60 years
Insulation	60 years
Blinds – material	20 years
Blinds – motor	15 years

Assumptions, C1 stage

Refer to assumption for A5 site activities.

Assumptions, C2 stage

Transportation to waste management facilities:
National - 300 km by road

Assumptions, C3-C4 stage

Gaskets, thermal breaks (Rubber, silicone, polyamide):
Ecoinvent defaults for Europe
Glass: SGG values, provided on 17/12/2021 by Julie Vinson and Hadrien Heuclin

Other materials: EPD values

Embodied carbon emission factors

					Emissions factor ($kgCO_2$/kg)		
Material Group	**Material**	**Database / EPD Program**	**Dataset / EPD Title**	**Details**	**(A1-A3)**	**(C3)**	**(C4)**
Aluminium	Aluminium profile	The International EPD System	Aluminium profiles produced by HYDRO Navarra	Anodised finish. 78% recycled content	7.00	0.01	0.00
Aluminium	Aluminium PVDF panel 0,7mm	EPD - European Aluminium	COIL COATED ALUMINIUM SHEET OROFE® Falzip 0,7 mm	Polyvinylidene (PVDF) finish	6.98	0.03	0.00
Gasket	EPDM gasket	Ecoinvent 3.7.1	Synthetic rubber {GLO}| market for | APOS, U	Ethylene propylene diene monomer rubber, ReCiPe 2016 Midpoint (H)_V1.04 calculation methodology	2.79	0.00	3.16
Timber	Cross laminated timber panel^	Institut Bauen und Umwelt e.V.	Cross-laminated timber (X-LAM) Studiengemeinschaft Holzleimbau e.V.		0.34	0.01	0.00
Timber	Laminated timber profile^	Institut Bauen und Umwelt e.V.	Glue laminated timber (glulam) Studiengemeinschaft Holzleimbau e.V.		0.33	0.01	0.00
Brick	Ceramic brick	GlobalEPD	008-004 Clay Facing Bricks "U" masonry units in accordance with EN 771-1		0.26	0.00	0.01
Cement	Cement mortar	GlobalEPD	GrupoPUMA Morteros para albañilería		0.17	-	0.00
Polyamide	Polyamide thermal break	Industry data 2.0	Polyamide (Nylon) 6.6/EU-27	ReCiPe 2016 Midpoint (H)_V1.04 calculation methodology	6.74	0.00	1.38
Rubber	Vapour barrier	EPD - EcoPlatform	ODE Opal membrane		4.58	0.00	0.03
Mineral wool	Mineral wool - stone wool	The International EPD System	Glass Wool Insulation G3 without facing		1.56	-	0.02
Plasterboard	Plasterboard	EPD - Environdec	Regular plasterboard 12.5mm		0.25	0.00	0.02
Fibrecement	Cement board	EPD - IBU	AQUAPANEL® Cement Board Outdoor		0.30	0.00	0.00
Concrete	Precast panel - reinforced concrete	The International EPD System	Precast concrete massive wall		0.17	0.00	0.00
Concrete	Glass fibre reinforced concrete panel	EPD - The Building Information Foundation RTS	Glass fibre reinforced concrete		0.58	0.00	0.00
Stainless steel	Stainless steel profile or fixings	EPD - IBU	Stainless Steel Long Product		2.89	0.00-	
Steel	Hot dipped galvanised steel profile or fixings	The International EPD System	Gyproc steel profiles		2.90	-	0.00
Silicone	Silicone gasket	Ecoinvent 3.7.1	Silicone product {RER}| market for silicone product | APOS, U		3.02	0.00	3.16
Stone	Stone panel	The International EPD System	Natural stone - Silkarstone	1 cm thick rainscreen panel	0.28	-	0.01
Glass	DGU 8T_16_44.2 (50%)	Data provided by Saint Gobain	Data provided by Saint Gobain Glass, based on 2016 data		1.78	0.01-	
Glass	CCF/DSF DGU 66.2 + 8T_16_44.2	Data provided by Saint Gobain	Data provided by Saint Gobain Glass, based on 2016 data		1.65	0.01-	
Glass	66.4 (laminated)*	Data provided by Saint Gobain	Data provided by Saint Gobain Glass, based on 2016 data		1.45	0.02-	
Glass	TGU 8T_16_6_16_44.2	Data provided by Saint Gobain	Data provided by Saint Gobain Glass, based on 2016 data		1.74	0.01-	
Aluminium	Interior venetian blinds, aluminium	INIES	Store vénitien interieur en aluminium manuel	Manual aluminium blinds.	10.76	0.01-	
N/A	Motor for venetian blinds	PEP Ecopassport	Wired motor for outdoor Venetian blind J4 - SOMFY	Motor only.	15.20	0.17-	

*Single laminated panel value utilised in WT-10 and WT-11 for external opaque area not otherwise included in CCF/DSF value.

^Value has been adjusted to exclude the effect of carbon sequestration by timber.

Datasets and emission factors used in the calculations (A1 - A3, C3, C4 stages)

Embodied carbon emission factors *cont.*

Datasets and emission factors used in the calculation (A4 and C2 stages)

Mode	**$gCO_2e/kgkm$**
Road transport emissions, average laden	0.1065

Based on data for average of diesel HGV transport from Department for Business, Energy & Industrial Strategy *Conversion Factors 2021: condensed set (for most users).* https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

Transport scenario	**Road travel (km)**	**Sea travel (km)**	**Reference**
Locally manufactured	50	-	UK government information published 2021
Nationally manufactured	300	-	(RICS, 2017)
European manufactured	1500	-	(RICS, 2017)
Globally manufactured	200	10000	(RICS, 2017)

Embodied carbon emission factors *cont.*

Configuration (DGU / TGU)	Glass make-up	Coating	Nominal thickness	Weight (Kg/m2)	U-value (W/m2K)	Psi value of spacer (W/mK)	Solar Performance (g-value)	VLT (%)	Acoustic RW (C;Ctr)	Embodied Carbon A1-A3 (kgCO$_2$eq/m^2)
DGU	4-16-33.2 COOL-LITE® 0/33 face 2	COOL-LITE® XTREME 70/33	26,8 mm	26 kg/m^2	1,0 W/m^2.K	0.04	0.33	70	36(1;-5)	45.02
DGU	4-16-44.2 COOL-LITE® 70/33 face 2	COOL-LITE® XTREME 70/33	28,8 mm	31 kg/m^2	1,0 W/m^2.K	0.04	0.33	69	37(-2;-6)	50.7
DGU	6-16-44.2 COOL-LITE® 70/33 face 2	COOL-LITE® XTREME 70/33	30,8 mm	36 kg/m^2	1,0 W/m^2.K	0.04	0.33	69	38(-2;-5)	56.4
DGU	8-16-44.2 COOL-LITE® 70/33 face 2	COOL-LITE® XTREME 70/33	32,8 mm	41 kg/m^2	1,0 W/m^2.K	0.04	0.33	69	38(-2;-6)	62.5
DGU	8-16-66.2 COOL-LITE® 70/33 face 2	COOL-LITE® XTREME 70/33	36,8 mm	51 kg/m^2	1,0 W/m^2.K	0.04	0.33	68	42(-2;-6)	73.9
DGU	10-16-66.2 COOL-LITE® 70/33 face 2	COOL-LITE® XTREME 70/33	38,8 mm	56 kg/m^2	1,0 W/m^2.K	0.04	0.32	67	40(-1;-4)	79.59
DGU	6-16-44.2 'naked'	NONE	30,8 mm	36 kg/m^2	2,6 W/m^2.K	0.04	0.76	81	38(-2;-5)	56.4
DGU	6-16-44.2 COOL-LITE® 61/29 in face 2	COOL-LITE® XTREME 61/29	30,8 mm	36 kg/m^2	1,0 W/m^2.K	0.04	0.29	60	38(-2;-5)	56.4
DGU	6-16-44.2 COOL-LITE® 50/22 II in face 2*	COOL-LITE® XTREME 50/22 II	30,8 mm	36 kg/m^2	1,0 W/m^2.K	0.04	0.21	47	38(-2;-5)	56.4
TGU	4-12-4-12-33.2 (XTREME 70/33 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 70/33 + ECLAZ	38,8 mm	36 kg/m^2	0,7 W/m^2.K		0.31	65	34(-2;-5)	62.5
TGU	4-12-4-12-44.2 (XTREME 70/33 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 70/33 + ECLAZ	40,8 mm	41 kg/m^2	0,7 W/m^2.K		0.31	64	37(-2;-6)	68.1
TGU	4-12-5-12-44.2 (XTREME 70/33 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 70/33 + ECLAZ	41,8 mm	43 kg/m^2	0,7 W/m^2.K		0.31	64	37(-2;-6)	71.0
TGU	6-12-4-12-44.2 (XTREME 70/33 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 70/33 + ECLAZ	42,8 mm	46 kg/m^2	0,7 W/m^2.K		0.31	64	40(-2;-5)	73.8
TGU	6-12-5-12-44.2 (XTREME 70/33 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 70/33 + ECLAZ	43,8 mm	48 kg/m^2	0,7 W/m^2.K		0.31	64	38(-2;-5)	76.7
TGU	8-12-4-12-44.2 (XTREME 70/33 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 70/33 + ECLAZ	44,8 mm	51 kg/m^2	0,7 W/m^2.K		0.31	63	38(-1;-4)	79.9
TGU	8-12-5-12-44.2 (XTREME 70/33 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 70/33 + ECLAZ	45,8 mm	53 kg/m^2	0,7 W/m^2.K		0.31	63	?	82.8
TGU	6-12-5-12-66.2 (XTREME 70/33 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 70/33 + ECLAZ	47,8 mm	58 kg/m^2	0,7 W/m^2.K		0.31	63	41(-2;-7)	88.1
TGU	8-12-6-12-55.2 (XTREME 70/33 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 70/33 + ECLAZ	48,8 mm	61 kg/m^2	0,7 W/m^2.K		0.31	63	40(-1;-5)	91.3
TGU	6-12-4-12-44.2 'Naked'	None	42,8 mm	46 kg/m^2	1,7 W/m^2.K		0.70	74	40(-2;-5)	71.0
TGU	6-12-4-12-44.2 (XTREME 61/29 face 2 + ECLAZ face 5)	COOL-LITE® XTREME 61/29 + ECLAZ	42,8 mm	46 kg/m^2	0,7 W/m^2.K		0.27	56	40(-2;-5)	73.8
TGU	6-12-4-12-44.2 (XTREME 50/22 II face 2 + ECLAZ face 5)*	COOL-LITE® XTREME 50/22 II + ECLAZ	42,8 mm	46 kg/m^2	0,7 W/m^2.K		0.19	43	40(-2;-5)	73.8

Datasets and emission factors used in the calculations
Glass - Step 2 Design Choices only (A1 - A3 stages)

Additional assumptions for Step 2 Design Choices

Design Assumptions

Rails: Horizontal spacing for GRC cladding was taken to be 1000 mm.

Blinds: A motorised blind was assumed and motors were included in the calculation.

Stiffeners. The following assumptions were made for the stiffener design:

- Aluminium “L” shape dimension was 100x100x6 mm
- The horizontal spacing was assumed to be 1000 mm
- The vertical spacing was assumed to be 1500 mm
- Stiffeners were assumed to be required required if the opaque panel width was larger than 1000 mm

Fins. The following assumptions were made for the fin design:

- The horizontal and vertical spacing was assumed to be 600 mm
- The fin depth was assumed to be 400 mm

Structural Checking

The following structural checks were undertaken.

Second moment of area (minor axes) for the following elements:

- Split transom (Top and Bottom)
- Intermediate transom

Second moment of area (major axes) for the following elements:

- Split mullion
- Split transom (Top and Bottom)
- Intermediate mullion
- Intermediate transom

U-value check

The following U-values were used:

Glass:

- DGU: 1.0 W/m²K
- TGU: 0.70 W/m²K

Opaque spandrel

- 150 mm of mineral wool aluminium sandwich panel
- 180 mm of mineral wool aluminium sandwich panel

Frame: Dependent on the frame dimensions.

PSI-value

For the opaque panel, 0.2 W/mK has been considered in accordance with BS EN ISO 12631:2017 Table D.5 (page 51)

For the IGUs, a Swisspacer has been considered

- For the DGU 0.04 W/mK
- For the TGU 0.037 W/mK

CHI-value: For the fin brackets a value of 0.18 W/K has been considered (from our database)

Additional assumptions for Step 2 Design Choices

Variable operational parameters

A number of variable operational parameters for the study were derived from design decisions made for the structure and calculations undertaken as a part of the embodied carbon modelling process. The variable operational parameters considered were:

Building use: commercial; residential

- For commercial use, WWRs of 50%, 60%, 70% and 80% were modelled.
- For residential use, WWRs of 30%, 40%, 50% and 60% were modelled.

Location: Frankfurt; London

Façade orientation: North; South; West

U-value: dependent on panel build-up

Visible light transmission (VLT): dependent on shading / glass build-up

Solar shading (g-value): None; coated glass (3 types); internal venetian blinds; external fins.

Glass build-up development

Glass build-ups were selected and data provided by Saint-Gobain Glass.

Build-ups were developed through application of the French standard NF DTU39 P4 (July 2012). This process involved three steps:

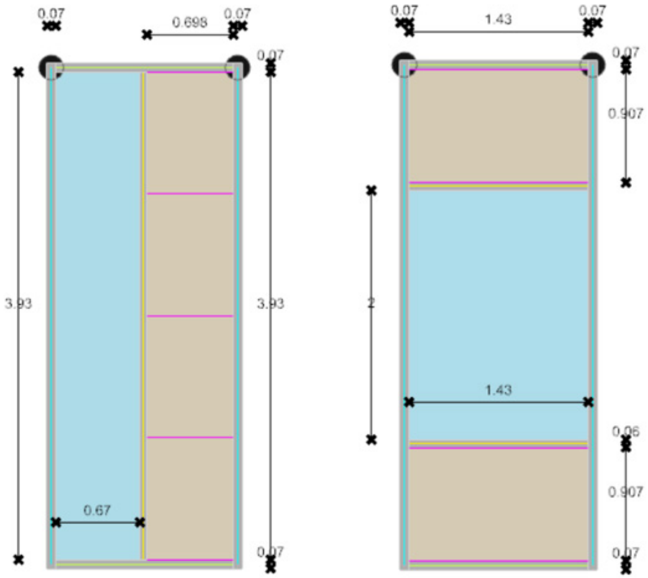
- Determination of minimum thickness, and calculation of e1 (required to determine glazing resistance), based upon the glazing size and a wind-load pressure P1 of 1800 Pa (corresponding to an ELU wind-load).
- Calculation of the equivalent thickness for the relevant e1 and P1 for both the DGU and the TGU.
- Values selected were for the glazing unit with an e1 value closest too and above the calculated value.

Study parameters for Step 2 Design Choices

Panel orientation

Two panel orientations were considered in the study:

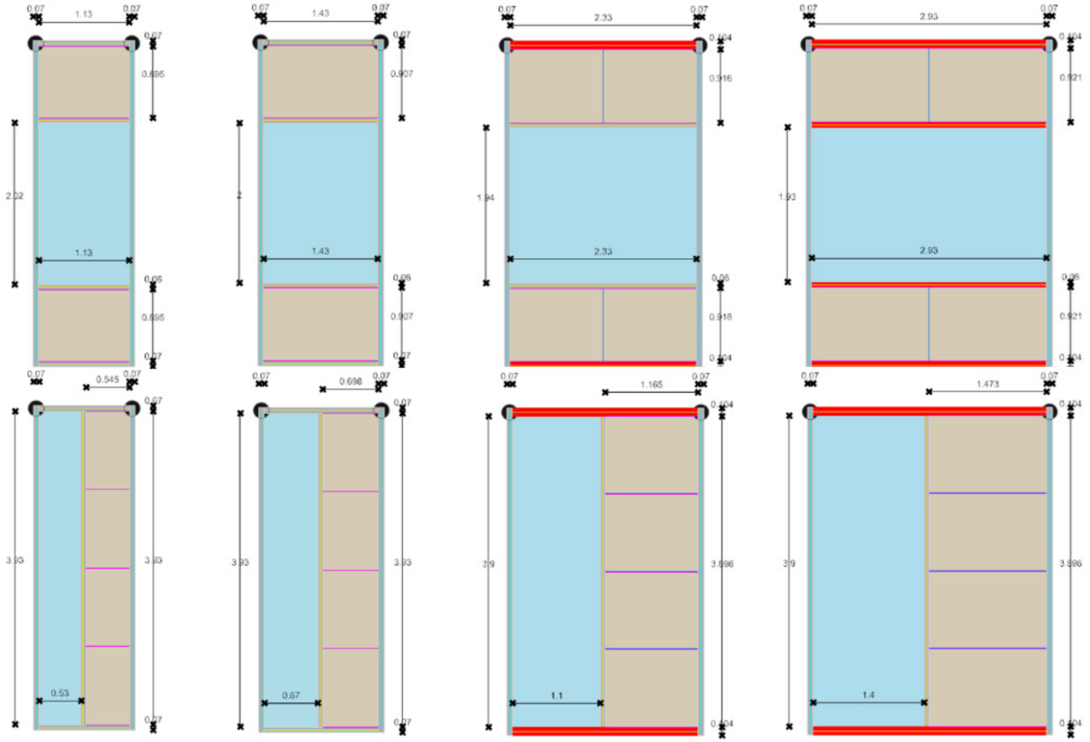
- Vertical: both the glazing panel and the opaque panel span the full height of the module. Transoms are required at multiple locations behind the opaque panel.
- Horizontal: both the glazing panel and the opaque panel(s) span the full width of the bay. Transoms are required at the interface between the glazed and the opaque panel.



Vertical orientation (left); horizontal orientation (right)
Bay size: 1.5m, GRC spandrel, aluminium frame

Bay size

- Four bay sizes were considered in the study. For each bay size, a vertical and a horizontal configuration was defined.
- As bay size increases, strength requirements and thus dimensions for mullions and transoms vary.



Variation in bay size
WWR: 50%; GRC spandrel, Aluminium frame

Study parameters for Step 2 Design Choices *cont.*

Operational considerations

The operational performance was estimated for a sample room with WxDxH of 4x5x4m.

Key outputs of the operational performance model

The operational performance was estimated in terms of:

- Thermal transmittance (U-value) in W/m².K
- Percentage of floor area in good daylight (DF) in % per sqm of floor area
- Heating demand (HD) in kWh per sqm of floor area
- Cooling demand (CD) in kWh per sqm of floor area
- Electricity demand (ED) in kWh per sqm of floor area
- Operational carbon emissions (OCE) in kgCO₂e per sqm of façade
- Embodied carbon emissions (ECE) in kgCO₂e per sqm of façade

Fixed assumptions are shown on the right.

	Unit	Commercial	Residential
Room width	m	4	4
Room depth	m	5	5
Floor to ceiling height	m	4	4
Floor area	m^2	20	20
Façade area	m^2	16	16
Volume	m^3	80	80
Temperature set points	℃	21-25	21-25
Occupancy density	m^2/person	8	20
Occupancy profile	-	Typical ASHRAE for office	Typical ASHRAE for resid.
Small power loads	W/m^2	25	20
Lighting loads	W/m^2	8	2
Ventilation rate	ACH	1.35	1
Infiltration	$m^3/(h.m^2fac)$ @50Pa	5	5
Cooling system efficiency	-	3.6	3.6
Heating system efficiency	-	2.1	2.1
Thermal bridging correction factor	-	1.1	1.1
Heat recovery efficiency	-	0.85	0.85
Carbon intensity factor for electricity	$kgCO_2e/kWh$	0.233	0.233

Study parameters for Step 2 Design Choices *cont.*

Materiality

A number of different material combinations are modelled for each module configuration:

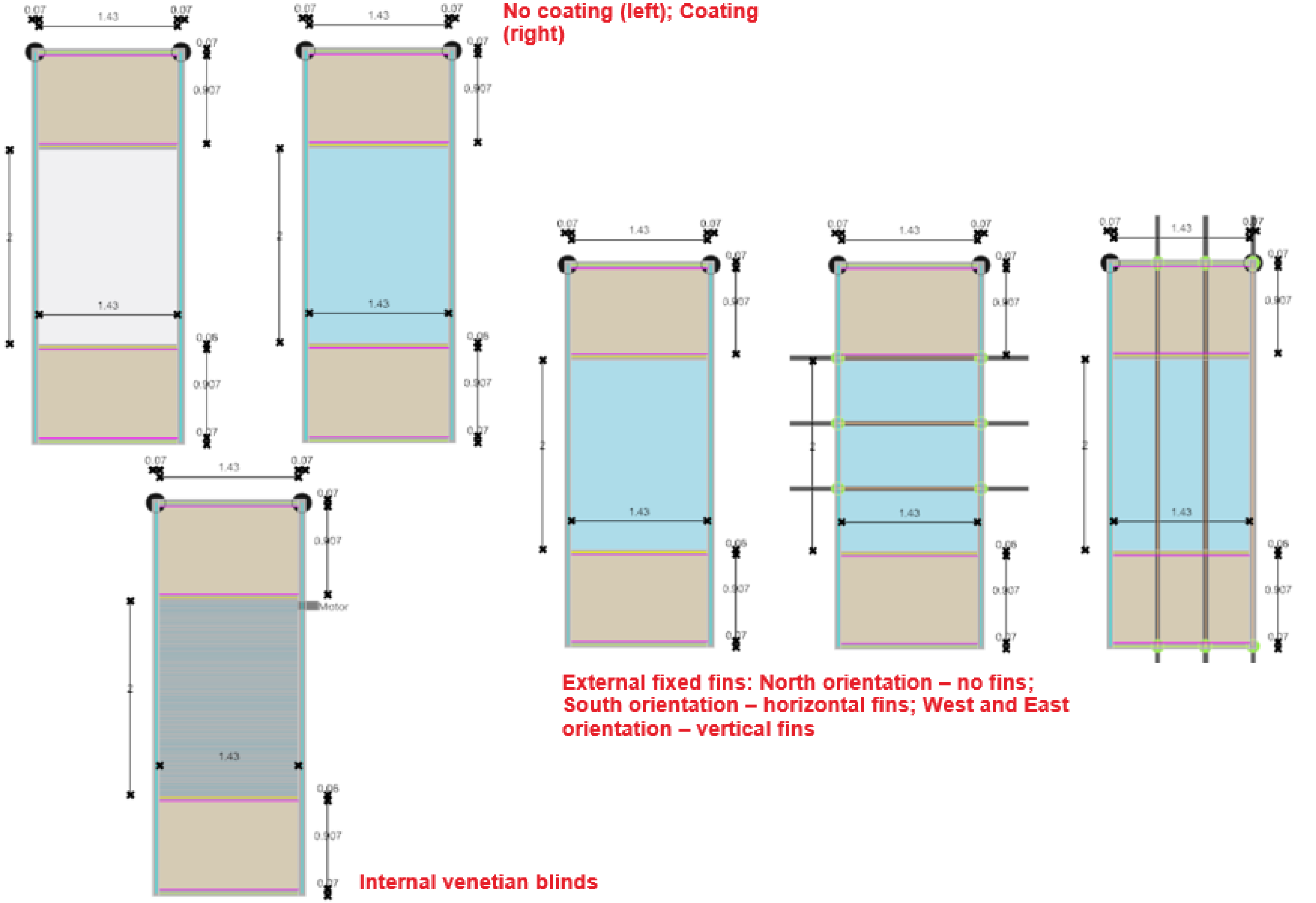
- Frame material: aluminium or timber framing.
- Spandrel material: aluminium or glass reinforced concrete opaque panel.
- Glazing configuration: double or triple glazed unit.

Solar Shading

Four types of solar control were considered:

- No coating (considered only to develop a baseline for comparison of operational carbon)
- Three types of solar control coating: COOL-LITE® XTREME 70/33; COOL-LITE® XTREME 61/29; COOL-LITE® XTREME 50/22
- Internal venetian blinds
- External fixed fins (North orientation – no fins; South orientation – horizontal fins; West and East orientation – vertical fins)

The embodied carbon associated with the different solar control coatings is assumed to be equivalent. Both internal venetian blind and external fixed fin scenarios also have a solar control coating applied. This is reflective of standard practice, as it is unlikely that non-coated glass would be used. COOL-LITE® XTREME 70/33 has been used.



No coating (left); Coating (right)

Internal venetian blinds

External fixed fins: North orientation – no fins; South orientation – horizontal fins; West and East orientation – vertical fins

Types of solar control
WWR: 50%; Frame: Aluminium; Spandrel: GRC

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