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Integrated Design of Building Facades: Comparing BIM vs. Traditional Techniques

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Abstract

Today’s building envelope is a complex system in which design goals must be balanced against structural requirements and manufacturing accuracy. Although the AEC industry increasingly requires Building Information Modelling (BIM), façade engineering still has a significant technological gap. This thesis examines the challenges of integrating different digital tools, particularly the gap between BIM’s large-scale coordination and the fine tolerances required for actual construction.

From a Façade Consultant’s perspective, this research finds that reliance on BIM alone is insufficient to address the complexities of building envelopes. BIM is strong at managing overall shapes and connections, but it often cannot handle the fine details required for manufacturing, such as glazing tolerances, gasket compression, and bracket adjustments, without making the model too complex. As a result, the industry still relies on 2D CAD as the primary reference for designing and documenting parts.

For its case study, this research uses a three-story commercial building in Milan, Italy, to examine how digital tools function in practice. The study compares traditional 2D CAD methods with an integrated BIM workflow. It closely examines the “Consultant’s Dilemma”: how to connect the rough concrete main structure, with centimetre tolerances, to the precise aluminium secondary structure, with millimetre tolerances.

The results show that BIM is necessary for identifying major clashes and managing quantities, but it cannot yet fully replace 2D CAD for preparing shop drawings for fabrication. The thesis recommends that Façade Consultants use a Hybrid Integrated Methodology. This means using BIM for 3D coordination and data management, while keeping 2D CAD for detailed construction drawings. The evidence indicates that combining these tools, rather than relying on a single one, is key to reducing project risks, ensuring watertightness, and connecting the modern supply chain.

Keywords: Façade Engineering, Building Information Modelling (BIM), Milan, Constructability, 2D CAD, Hybrid Workflow, Interoperability, Shop Drawings.

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Figure 45: Standard Horizontal Corner Connection Detail developed with Revit: Author

1. Introduction

1.1. Context: The Evolution of the Building Envelope

The building façade has historically been conceived as a static barrier, a simple separation between the interior and exterior environments. However, over the last two decades, the building's "skin" has evolved into a complex, multifunctional machine. Modern envelopes are required to perform several roles simultaneously: they must provide structural stability, regulate thermal transmission, manage acoustic insulation, and contribute to the building's energy generation, all while satisfying increasingly ambitious aesthetic requirements.

This increase in functional complexity has been paralleled by a digital transformation in the Architecture, Engineering, and Construction (AEC) industry, often referred to as "Construction 4.0." The transition from hand drafting to Computer-Aided Design (CAD) and, more recently, to Building Information Modelling (BIM) has the potential to revolutionise how buildings are designed and delivered. Yet, while the structural and Architectural disciplines have largely integrated into the BIM environment, Façade Engineering is still a discipline caught between two realms.

On one side, the architectural design is managed in 3D BIM environments (e.g., Revit, ArchiCAD) to coordinate global geometry. On the other side, the manufacturing and fabrication of façade components, specifically Stick Curtain Wall systems, which require sub-millimetre precision for joints and bracketry, remains firmly established in 2D CAD and mechanical solid modelling (MCAD). This thesis explores the friction at this interface, analysing how the Façade Consultant can bridge the gap between "digital coordination" and "physical constructability.

1.2. Problem Statement: The "Interoperability Gap"

Although the theoretical benefits of BIM are significant, its actual implementation in the engineering of Stick Systems (Post-and-Beam) is hindered by a significant "Interoperability Gap."

The Scale Disconnect: Architectural BIM models typically operate at a "Macro-scale" (LOD 300), defining general forms and grids. However, a Stick System requires "Micro-scale" precision (LOD

400), requiring the exact positioning of spigots, pressure plates, and thermal breaks. Attempting to model these microscopic details in a standard BIM environment often leads to "model overload," rendering files unmanageable.

1. **The Construction vs. Manufacturing Conflict:** The façade consultant must mediate between the primary structure (reinforced concrete), which is built to centimetre-level tolerances (25mm), and the aluminium mullions, which are manufactured to millimetre-level tolerances (1mm). In a Stick System, where assembly occurs on-site, this conflict is critical. Standard BIM workflows often assume a "perfect" theoretical structure, not considering the site deviations that dictate the design of the adjustable anchor brackets.
2. **The Persistence of 2D CAD:** Because of these limitations, the industry relies on a fragmented workflow. While the *coordination* happens in 3D, the *legal construction documentation* (Shop Drawings) is almost exclusively produced in 2D CAD. This double workflow creates a possibility of data loss and synchronisation errors.

1.3. Research Questions

This research intends to address the following critical questions regarding the function of digital tools in façade delivery:

- **RQ1:** To what extent can BIM effectively replace traditional 2D CAD workflows for the detailed design and fabrication of **Stick System** curtain walls?
- **RQ2:** How can the "Consultant's Dilemma", the management of tolerances between the rough concrete structure and the precise aluminium grid, be resolved using digital tools?
- **RQ3:** What is the optimal 'Integrated Methodology' that utilizes BIM for coordination and CAD for constructability to improve work process efficiency and minimise errors without redundant work?

1.4. Aims and Objectives

The primary aim of this thesis is to define a "Hybrid Integrated Workflow" for Façade Engineering that optimises the transition from architectural design to fabrication.

To achieve this, the following specific objectives have been established:

1. **To analyse** the current state of the art in digital façade design, identifying the shortcomings of current BIM software regarding file size and geometrical complexity for stick systems.
2. **To compare** traditional CAD-based workflows against BIM-based workflows using a practical case study.
3. **To evaluate** the effectiveness of automated clash detection in identifying interface conflicts (e.g., slab edge deviations vs. mullion anchors) prior to site installation.
4. **To propose** a guideline for Façade Consultants on how to manage the "Level of Development" (LOD) to balance model performance with fabrication necessity.

1.5. Methodology and Case Study

This research adopts a comparative methodology, analysing qualitative and quantitative data derived from a specific pilot project.

- **The Case Study:** The research concentrates on a three-story commercial building located in Milan, Italy.
- **System Typology:** The project features a Stick System Curtain Wall (Mullion-Transom). This typology was selected because, unlike unitised systems, which are pre-assembled, Stick Systems require extensive on-site assembly and bracket adjustment, making the coordination between the digital model and the physical concrete structure particularly critical.
- **Simulation Strategy:** The project documentation was processed using two distinct workflows:
    - **Workflow A (Traditional):** Reliance on 2D AutoCAD for detailing and manual coordination overlay.
    - **Workflow B (Integrated BIM):** Utilisation of Autodesk Revit for 3D modelling of the mullion grid and Autodesk Navisworks for clash detection against the concrete frame.

2. Theoretical Fundamentals of the Building Envelope

The building envelope serves as the primary physical boundary between the controlled interior environment and the unconditioned exterior. In modern engineering, it is no longer sufficient to view the envelope merely as a barrier; it must be understood as a complex, active system designed to regulate physical interactions. A conceptual framework for façade design must therefore integrate multiple domains of building physics, specifically, thermodynamics, aerodynamics, and structural mechanics, to guarantee the structure's safety, comfort, and durability. This chapter analyses the basic principles governing these interactions and establishes the baseline requirements for any high-performance façade system.

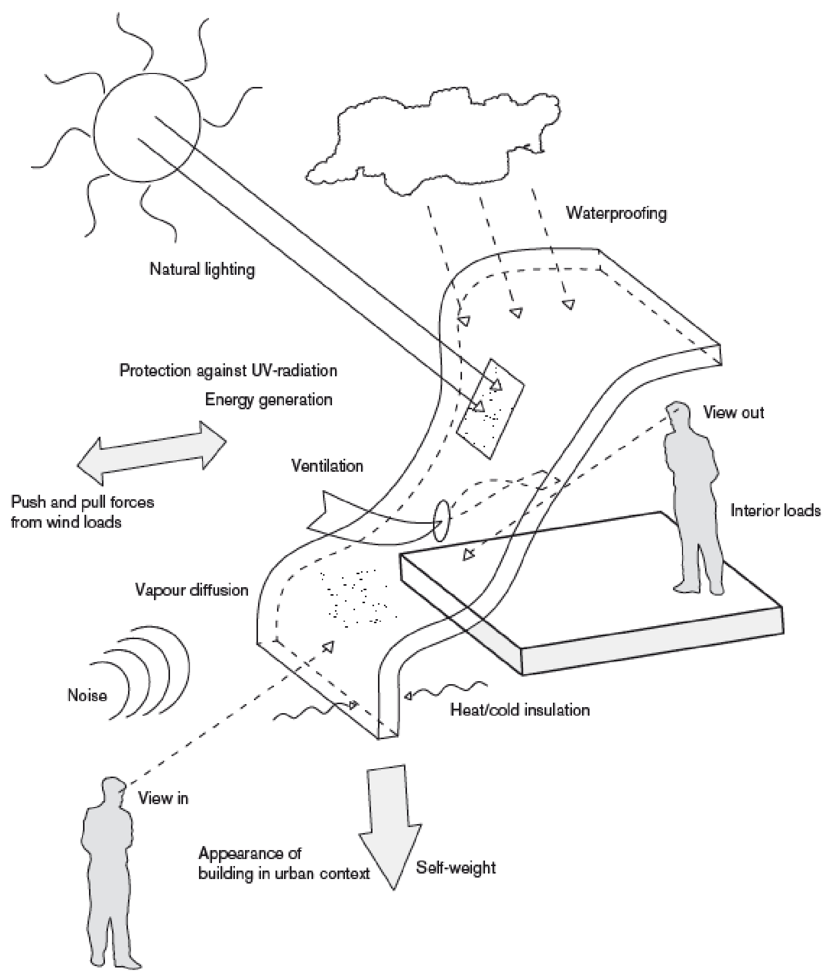


Figure 1: Fundamentals of the Building Envelope: (Ulrich Knaack et al., 2007)

2.1. The Paradigm Shift: From Barrier to Environmental Interface

The conceptual role of the façade has undergone a radical transformation over the last century, evolving from a passive load-bearing element into a dynamic "environmental interface." This change was driven by technological advancements that significantly modified how buildings are constructed and how they interact with their surroundings.

2.1.1. Historical Evolution and the Separation of Skin and Structure

For millennia, architecture was defined by the logic of the monolithic wall. In traditional heavy construction, the exterior wall performed all necessary functions simultaneously: it supported the load of the floors and roof, provided thermal mass, and served as the weather shield. (Ulrich Knaack & Marcel Bilow, 2007) Note that this interdependence imposed a rigid design limitation, thereby increasing the size of openings for light and compromising the building's structural stability. The key moment in this evolution was the development of the structural frame (steel and reinforced concrete) in the late 19th century. By transferring loads to a structural grid of columns, the exterior wall was relieved of its structural duties. This "separation of skin and structure" allowed the façade to become a lightweight curtain, suspended from the floor slabs, thereby granting architects unprecedented freedom in material selection and transparency.

2.1.2. The Concept of the "Polyvalent Wall" and Functional Decoupling

The structural liberation of the façade led to the development of what (Herzog, Thomas and Krippner, Roland and Lang, 2012) term the "Polyvalent Wall." Unlike the homogeneous cross-section of traditional masonry, in which a single material must perform all functions, the modern envelope relies on "functional decoupling." In this approach, specific physical requirements are assigned to specialised, independent layers. A typical modern assembly segregates functions into distinct zones: a durable outer skin to deflect rain, a ventilated cavity to manage moisture, a high-performance insulation layer to control heat transfer, and an inner seal to ensure airtightness. This stratification enables the optimisation of each component, selecting a material solely for its thermal resistance, without requiring it to carry load, transforming the façade from a static barrier into a precise, tunable filter.

2.1.3. Functional Layering and Component Hierarchy

To manage the increasing complexity of modern building envelopes, (Ulrich Knaack & Marcel Bilow, 2007) create a clear functional hierarchy. This classification is not simply theoretical; it functions as the foundational logic for structural engineering and the organisation of Building Information Models (BIM). By dividing the construction into distinct zones, Primary, Secondary, and Infill, engineers can manage the critical interfaces where tolerances, movements, and load transfers occur.

2.1.4. Primary Structure: Global Building Movements and Deflections

The Primary Structure refers to the main load-bearing skeleton of the building, typically composed of reinforced concrete slabs, columns, and shear walls, or a structural steel frame. Its main function is to ensure the global stability of the building, transferring massive dead and live loads to the foundations. From a façade engineering perspective, the primary structure is defined by its movements.

(Ulrich Knaack & Marcel Bilow, 2007) emphasise that the main frame is subject to built-in deformations, including elastic deflection under live loads, long-term creep (in concrete), and sway due to wind or seismic activity. A fundamental rule of façade design is that the envelope must be isolated from these movements; it must accommodate the primary structure's deflections without becoming a load-bearing element itself, which would risk buckling or glass failure.

2.1.5. Secondary Structure: The Façade Structural Grid

The Secondary Structure constitutes the independent load-bearing framework of the façade, acting as the intermediary between the exterior skin and the building skeleton. In curtain wall applications, this is most commonly realised as a grid of vertical profiles (mullions) and horizontal profiles (transoms).

According to (Herzog, Thomas and Krippner, Roland and Lang, 2012), the secondary structure has two mechanical functions: it must support the dead weight of the infill elements and resist local wind pressure, transferring these forces back to the primary structure through distinct anchor points (brackets). This layer is critical for tolerance management; the connection between the rough, imprecise primary structure (frequently measured in centimetres) and the precise secondary structure (measured in millimetres) is achieved through adjustable bracketry that neutralises construction deviations.

2.1.6. Infill and Weatherproofing: Glazing, Cladding, Membranes, and Gaskets

The Infill Elements represent the outermost physical barrier, the "skin", strictly speaking. These components, including glazing units, opaque panels, sheet-metal cladding, and ventilation louvres, are supported entirely by the secondary structure. While they do not contribute to the building's global stability, they are the primary line of defence against environmental stresses.

(Ulrich Knaack & Marcel Bilow, 2007) Note that this layer is also the most complex with respect to material contacts; it typically comprises a system of EPDM gaskets, sealants, and foils designed to maintain airtightness and watertightness while allowing the infill materials (e.g., glass or aluminium) to expand and contract thermally without inducing stress on the frame.

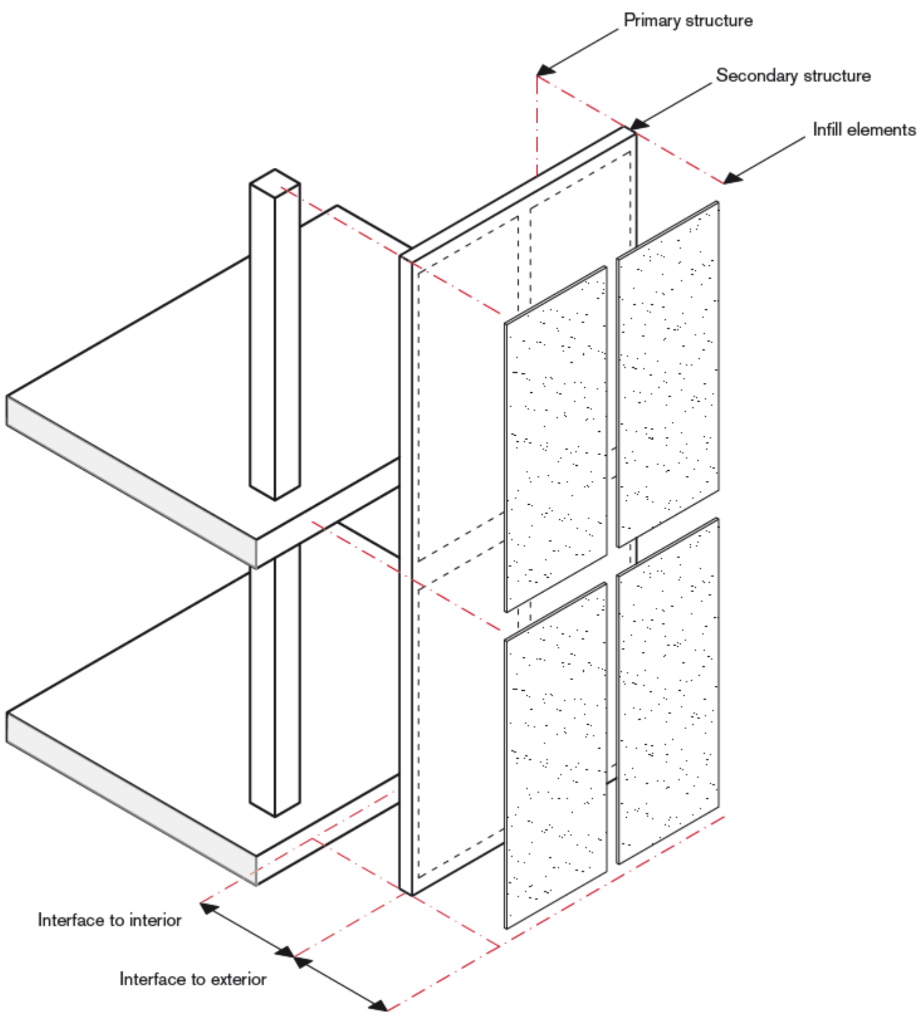


Figure 2: Structural Hierarchy in Facade: (Ulrich Knaack et al., 2007)

2.1.7. Façade Bearing Structures and Load Transfer

The structural design of the building envelope is distinct from the primary building frame. While the main skeleton (columns and slabs) is designed to resist gravity and seismic loads, the façade structure serves as a secondary system responsible for local load transfer and the management of differential movement. According to (Schlaich & Bergermann,2003), the main challenge in façade engineering is to create a stable, load-bearing skin that is sufficiently flexible to accommodate inevitable deformations of the primary structure without inducing stresses in the fragile infill components (such as glass).

2.1.8. Classification of Loads

To guarantee structural integrity, the façade support system must be designed to resist specific actions defined by international standards, such as (EN 1991-1-1:2002: Eurocode 1: Actions on Structures - Part 1-1: General Actions - Densities, Self-Weight, Imposed Loads for Buildings, 2002). Classify these loads into three primary categories:

- **Dead Loads (G):** The self-weight of the façade components, including the glazing units, aluminium profiles, and insulation. In modern multi-layered façades, this permanent load can be significant, often requiring specific verification of the mullion's buckling resistance.
- **Wind Loads (Qw):** These are dynamic, variable actions acting perpendicular to the façade surface. (Patterson, 2011) emphasises that wind induces both positive pressure ("push") and negative suction ("pull"), particularly at building corners where vorticity creates localised high-pressure zones. The support structure must therefore be designed for bidirectional bending.
- **Environmental and Constraint Loads:** These include thermal expansion and contraction caused by temperature fluctuations (ΔT), as well as potential ice or snow loads on inclined surfaces. If the façade is restrained from moving, these environmental factors generate "constraint forces" capable of shearing bolts or cracking glass (Ulrich Knaack et al., 2007).

2.2. Load Transfer Mechanisms: From Infill to Structure

The transfer of forces follows a hierarchical path: from the infill element to the secondary framing, and finally to the primary structure.

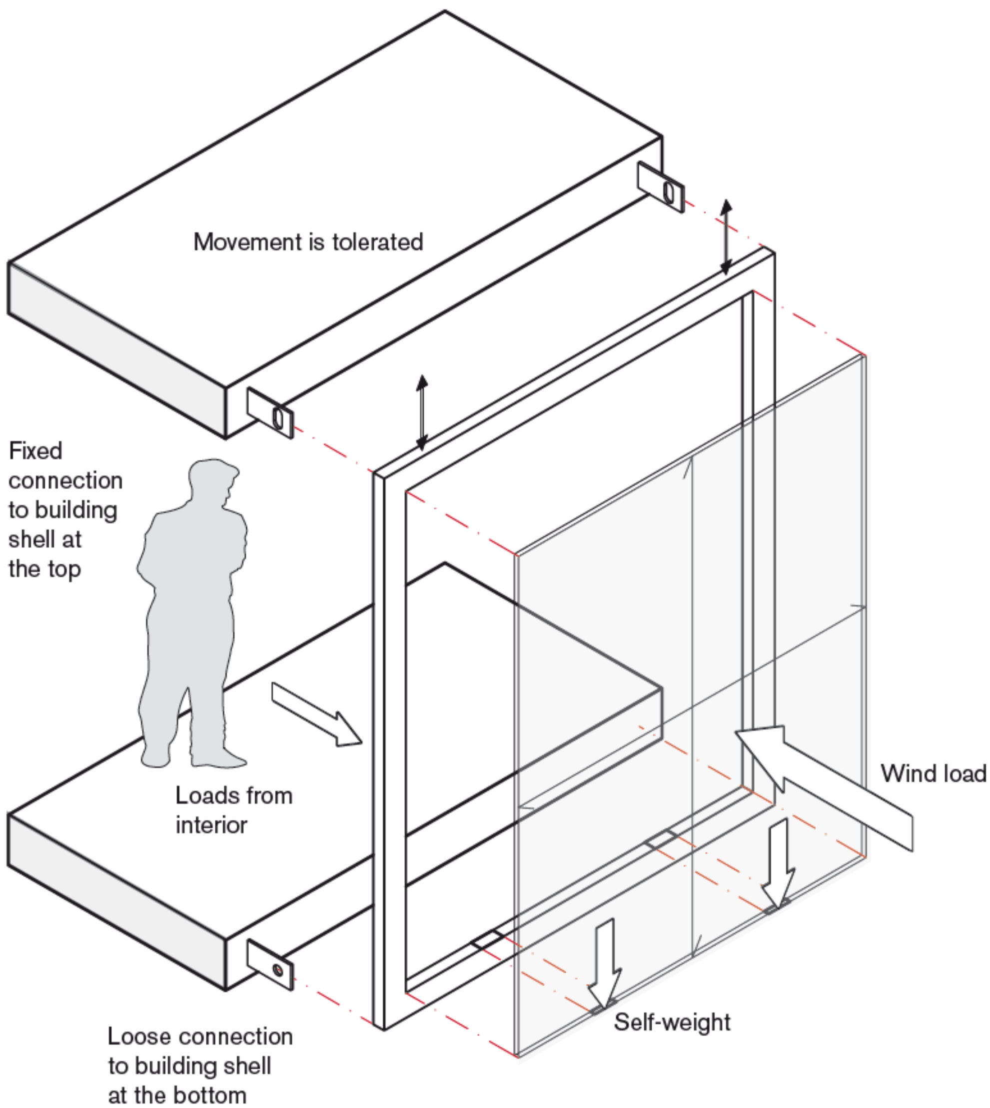


Figure 3: Load Transfer Mechanism: (Ulrich Knaack et al., 2007)

The Role of Setting Blocks

In glazed systems, the load transfer begins at the interface between the glass and the aluminium frame. Wurm (2007) notes that glass cannot withstand localised stress concentrations; therefore, the dead load of the pane must be distributed via setting blocks (typically neoprene or EPDM).

- **Positioning:** Standard glazing guidelines (such as the GANA Glazing Manual) dictate that setting blocks should be located at the quarter points (L/4) or typically at 100–150 mm from the corners to minimise deflection in the horizontal transom.
- **Function:** These blocks transmit the gravity load of the glass into the transom, which then transfers it to the vertical mullions via mechanical shear connections (cleats or screws).

2.2.1. Connection Strategies: Fixed and Loose Bearings

The critical interface in façade engineering is the bracket connection to the main building slab. Because the primary structure deflects under live loads and the façade expands under thermal loads, a rigid connection would result in structural failure. (Ulrich Knaack et al., 2007) and (Herzog, Thomas and Krippner, Roland and Lang, 2012) Describe the standard solution as a system of Fixed and Sliding (Loose) Bearings:

- **Fixed Bearing (Dead Load Support):** This anchor point is typically located at the top of the mullion and restrains the façade in all three axes (X, Y, Z). It carries the dead weight of the panel and transfers it to the floor slab.
- **Sliding/Loose Bearing (Wind Load Support):** This connection, typically located at the bottom of the mullion or at the expansion joint, restrains the façade perpendicular to the plane (resisting wind load) but allows for vertical movement (Z-axis).

This configuration creates a statically determinate (isostatic) system. It ensures that, when the floor slab deflects, or the aluminium mullion expands in summer heat, the façade can "breathe" without transferring load to the glass, thereby preventing breakage.

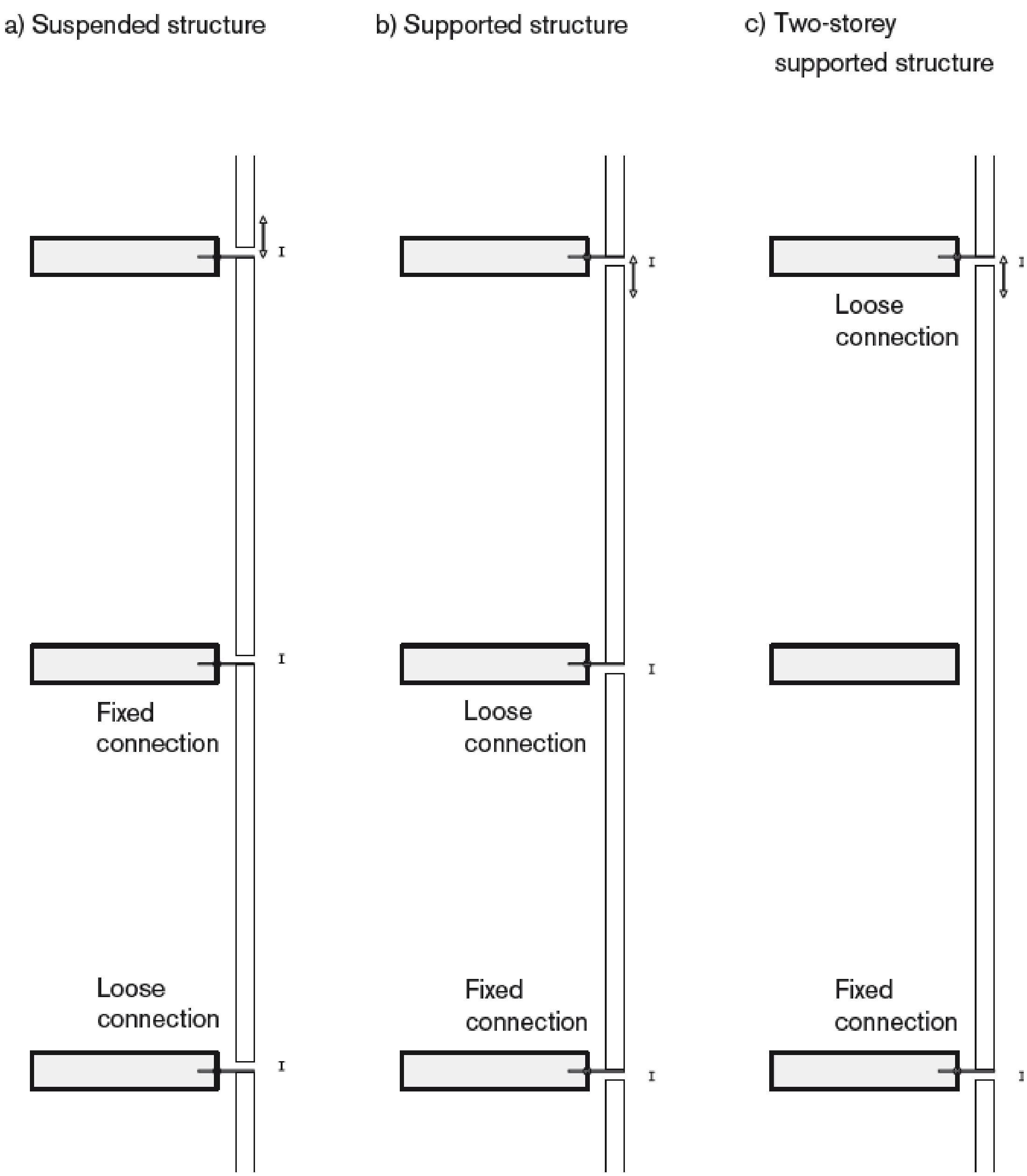


Figure 4: Connection Strategies: (Ulrich Knaack et al., 2007)

2.3. Grid Rationalisation and Structural Positioning

The integration of the façade into the building requires a rigorous geometric strategy. According to (Ulrich Knaack et al., 2007) the efficiency of the building process is heavily dependent on the definition of a "Modular Unit." This unit helps structure and organise the building volume, enabling the standardisation of spans, thereby saving time and effort during construction.

2.3.1. The Modular Strategy: Primary vs. Secondary Grids

Façade engineering distinguishes between two fundamental coordinating grids:

- **The Primary Grid:** This is based on the main load-bearing structure (columns and shear walls).
- **The Secondary Grid:** This dictates the rhythm of the façade elements (mullions).

For optimum efficiency, these grids are typically aligned. For example, modern office buildings frequently utilise a standard planning grid of 1.35 m, which facilitates efficient office furnishing. This dimension is modularly related to the primary structure; underground parking grids are often set at 5.40 m or 8.10 m (multiples of 1.35 m) to accommodate vehicle spaces between columns. This recurrence of geometrical relations facilitates the alignment of joints and details between the shell and the envelope.

2.3.2. Geometric Alignment Types

The relationship between the primary and secondary grids can be categorised into three typologies:

1. **Centreline Grid:** The base grid aligns with the centreline of the building components. This is useful when specific component sizes are not yet defined.
2. **Modular Grid:** An extrapolation of the primary structure where the façade aligns strictly with the structural grid, though this may create zones of varied widths.
3. **Offset Grid:** The façade grid is shifted relative to the secondary grid. While this can serve as a planned design element, it requires careful consideration of wall joints and intermediate members for adjustment.

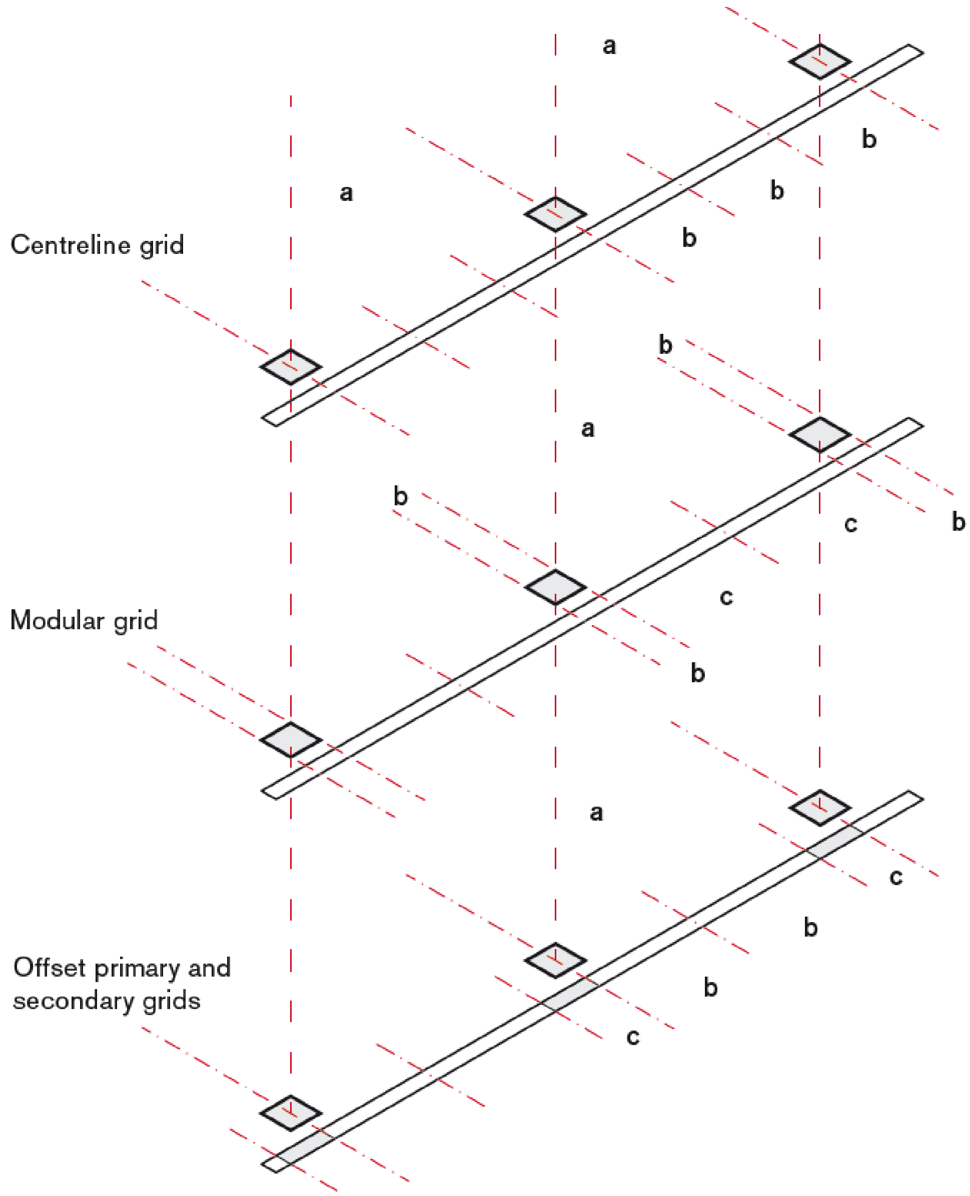


Figure 5: Geometric Alignment Types: (Ulrich Knaack et al., 2007)

2.3.3. Interface Positioning: In-Front, Flush, and Behind

Determining the façade's position relative to the load-bearing structure is a primary design consideration that affects thermal performance and fire safety.

- **Position A: Façade in Front of Structure (Curtain Wall)** The secondary structure runs continuously in front of the floor slabs. This creates a uniform external appearance. However, specialised consideration must be given to the gap between the façade and the slab edge to prevent flashover (vertical fire spread) and to ensure acoustic separation.
- **Position B: Façade Flush with Structure (Infill)** The façade is positioned between the floor slabs. In this scenario, the outer face of the ceiling slab is exposed to the exterior and must be insulated to meet thermal requirements. The column position typically creates an enclosed corner detail.
- **Position C: Façade Behind Structure** The envelope sits behind the primary frame (e.g., an exoskeleton). Here, the floor slab penetrates the building's insulation line, creating a severe thermal bridge that requires thermal decoupling (structural thermal breaks). The columns stand unattached in the outer corners.

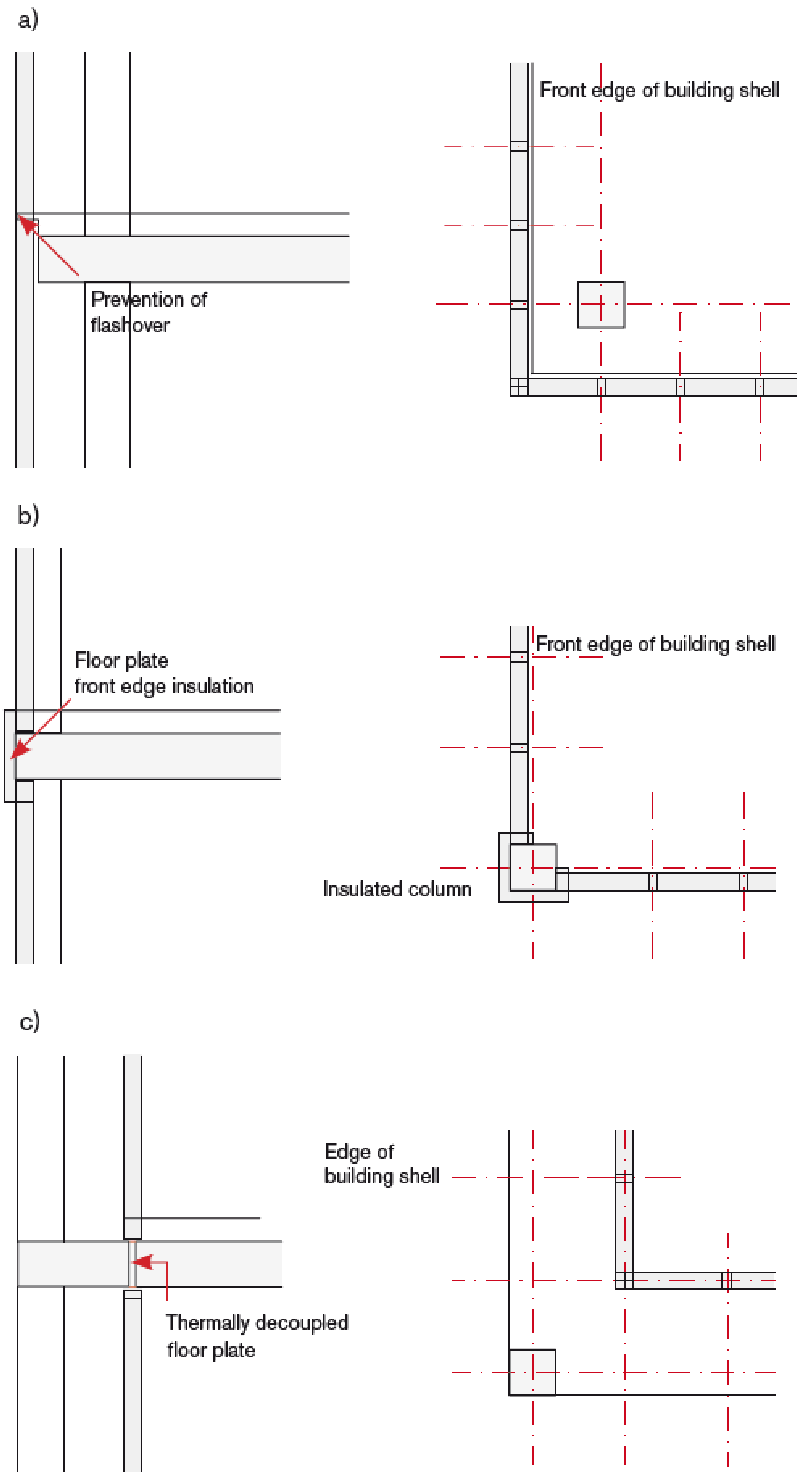


Figure 6: Geometric Alignment Types: (Ulrich Knaack et al., 2007)

3. Taxonomy of Façade Construction Systems

To navigate the complexity of modern building envelopes, it is necessary to establish a clear taxonomy. (Ulrich Knaack & Marcel Bilow, 2007) Classify façade systems not by their aesthetic appearance, but by their physical configuration and the relationship between the exterior cladding and the thermal barrier. The primary distinction lies in the number of shells (single-leaf vs multi-leaf) and in the treatment of the air cavity (warm vs cold).

3.1. Typological Classification

3.1.1. Single-leaf vs. Multi-leaf Systems

A single-leaf façade is a system where a single building component fulfils all physical requirements, such as load-bearing capacity, insulation, and weatherproofing. While this was the standard in traditional masonry architecture, it is rare in modern lightweight construction, except in specific applications such as single-glazed buffer zones or monolithic concrete walls. The dominant modern typology is the multi-leaf façade, where functions are distributed across separate layers. This separation allows the "decoupling" of performance criteria: the outer leaf protects against weather exposure, while the inner layers provide insulation and airtightness. This category is further subdivided based on the presence of a ventilated air gap.

3.1.2. Warm Façades: Sealed and Thermally Broken Systems

The "Warm Façade" (or sealed system) is characterised by the absence of a ventilated cavity between the external skin and the insulation. In this configuration, the insulation is either integrated directly into the profile (as in curtain walls) or applied directly to the backing wall (as in EIFS).

Common examples include standard Stick Systems and Unitised Systems. Because there is no air gap to dissipate heat or moisture, the thermal performance of the assembly relies entirely on its material properties.

Thermal Breaking: In aluminium curtain walls, the critical technology is the thermal break (typically a polyamide bar reinforced with fibreglass). (Ulrich Knaack & Marcel Bilow, 2007) explain that this isolator physically separates the outer aluminium pressure plate (which is cold in winter) from the inner structural mullion (which is warm), preventing conductive heat loss and surface condensation.

Watertightness: Since there is no drainage cavity, the weather seal (gaskets and sealants) must be perfect. Any water that penetrates the outer skin has no means of escape, making construction quality control paramount.

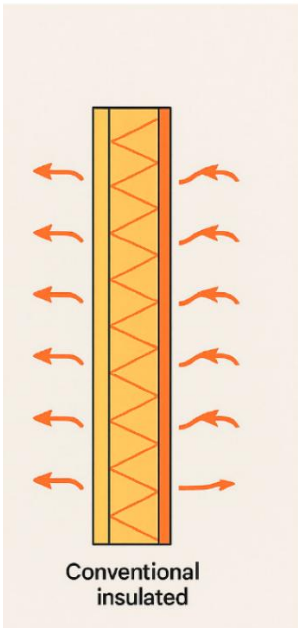


Figure 7: Warm Facade. Source: https://www.mdpi.com/2227-9717/13/7/2275

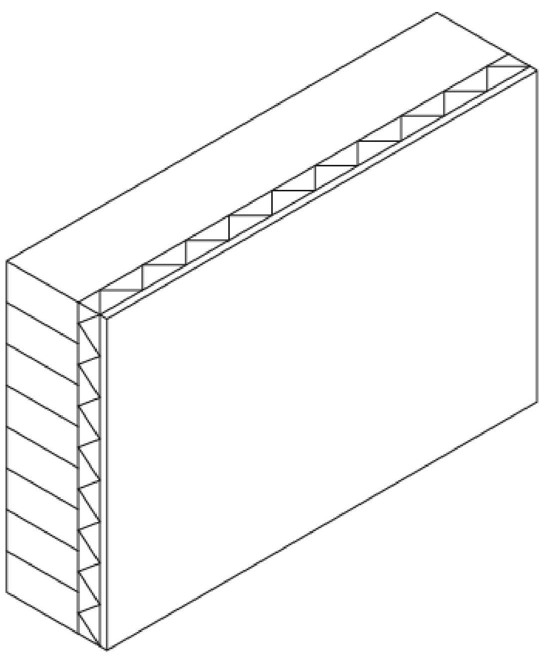


Figure 8: Warm Facade. Source: (Ulrich Knaack et al., 2007)

3.1.3. Cold Façades (Ventilated/Rainscreen): Functional Criteria and the "Chimney Effect"

The "Cold Façade," more commonly known as the Ventilated Façade or Rainscreen, is defined by a physical separation between the external cladding and the thermal insulation layer. This separation creates a continuous air gap that connects to the outside environment at the base and top of the wall.

The Chimney Effect: According to (Souza, 2010) the fundamental principle of this system is the "Chimney Effect" (also known as the stack effect). Due to thermal differences, the air inside the cavity warms up (typically from solar radiation on the cladding) and becomes less dense than the external air, causing it to rise. This creates a continuous upward airflow that provides three critical functional benefits:

- **Heat Removal:** In summer, moving air carries away excess heat absorbed by the cladding, thereby reducing the building's cooling load.
- **Moisture Control:** In winter, the airflow helps drain any rainwater that penetrates the open joints and removes interstitial humidity diffusing from the interior, keeping the insulation dry (Campos, 2010).
- **Thermal Stability:** Placing the insulation on the outer face of the primary wall keeps the structural mass at a constant temperature, thereby eliminating thermal bridges and reducing stress on the concrete.

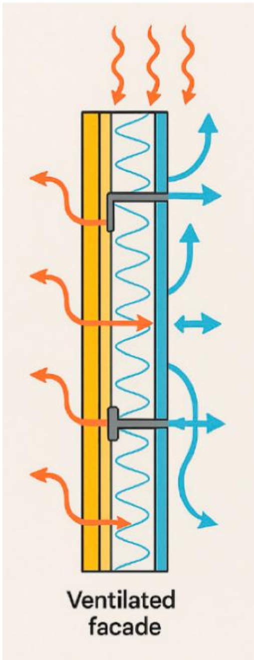


Figure 9: Cold Facade. Source: https://www.mdpi.com/2227-9717/13/7/2275

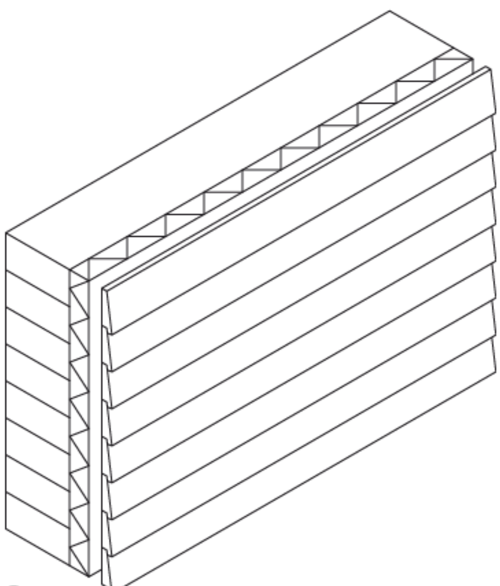


Figure 10: Cold Facade. Source: (Ulrich Knaack et al., 2007)

3.2. Ventilated Façades

The ventilated façade (or rainscreen cladding) is a multilayer envelope system in which the outer protective skin is physically separated from the thermal insulation by an air cavity. This typology has become a dominant solution in contemporary architecture due to its ability to combine high aesthetic versatility with superior performance in building physics. By decoupling the weather barrier from the thermal barrier, the system enhances the longevity of the primary structure while optimising energy efficiency.

According to Campos (20100), the ventilated façade substructure can be divided into the main components:

1. Cladding,

2. Air gap.

3. Supporting substructure.

4. Thermal insulation.

5. Base layer.

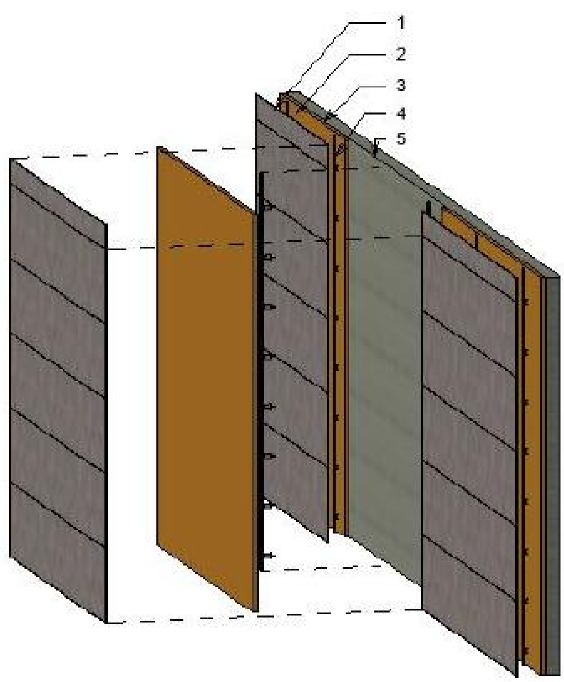


Figure 11: Ventilated facade layers. Source: (Campos, 2010).

3.2.1. Functional Benefits

According to (Souza, 2010)The adoption of ventilated façades is driven by three primary performance advantages: energy efficiency, moisture control, and durability.

Energy Savings: The system contributes to the building's energy balance in both heating and cooling seasons. In summer, the "shielding effect" of the cladding blocks directs solar radiation, while the air cavity dissipates the absorbed heat via natural convection before it reaches the interior. (Campos, 2010). In winter, the continuous insulation layer reduces thermal bridging, preserving the building's thermal inertia.

Moisture Control: The constant airflow within the cavity creates a "sweeping" effect that removes water vapour diffusing from the interior, preventing interstitial condensation. Furthermore, the decoupling of the cladding prevents rain penetration from reaching the insulation, mitigating pathologies such as efflorescence or infiltration.

Durability: Placing the insulation on the outer face protects the primary structure (concrete or masonry) from thermal shock (expansion/contraction cycles), thereby significantly extending its service life.

3.2.2. Structural Layering

A specific sequence of layers defines a ventilated façade. (Herzog, Thomas and Krippner, Roland and Lang, 2012) and (Souza, 2010) Categorise these components from the exterior to the interior as follows:

Cladding Materials: The outer skin defines the aesthetic identity of the building and resists mechanical stresses (wind and impact).

- **Natural Stone:** Panels are typically supported at 3 or 4 points. The design must account for the stone's specific weight and flexural strength.
- **Ceramic:** Manufactured via extrusion (terracotta) or dry pressing (porcelain stoneware), these panels offer high resistance to chemical weathering and frost.
- **Concrete:** Glass Fibre-Reinforced Concrete (GRC) or Fibre-cement panels enable large-format, lightweight, and distinct geometries.

- **Metal:** Aluminium, stainless steel, copper, or zinc sheets are common. These materials require careful detailing to accommodate significant thermal expansion.
- **Composite:** Aluminium Composite Materials (ACM) or High-Pressure Laminates (HPL) provide flatness and colour consistency at reduced weights.

Fixation Systems: The connection between the cladding and the sub-structure is critical for load transfer and aesthetics.

- **Visible Systems:** These utilise exposed mechanical fasteners such as clips, rivets, or screws. While cost-effective and secure, the fasteners interrupt the visual continuity of the façade surface.
- **Concealed Systems:** These provide a clean, uninterrupted surface. Techniques include undercut anchors (Keil anchors) drilled into the back of stone/ceramic panels, structural adhesives (chemical bonding), or hanging hooks that engage with rails on the sub-structure.

Air Gap Layer: The cavity is the system's functional core. Its performance relies on the "Chimney Effect" (Stack Effect). Solar radiation heats the cladding, warming the air in the cavity. This lowers the air density, creating a pressure differential that drives airflow. (Giancola, 2016). To function correctly, the gap must be unobstructed and have clear ventilation openings at the base and top of the wall to ensure continuous air exchange.

Thermal Insulation Layer: To maximise efficiency, the insulation must be continuous and tightly fitted to the backing wall.

- **Mineral Wool (Rock/Glass Wool):** The preferred choice for fire safety (Euro class A1) and breathability (low vapour resistance).
- **Plastic Foams (EPS/PUR/PIR):** have lower thermal conductivity per unit thickness but require fire barriers due to their mappiness.

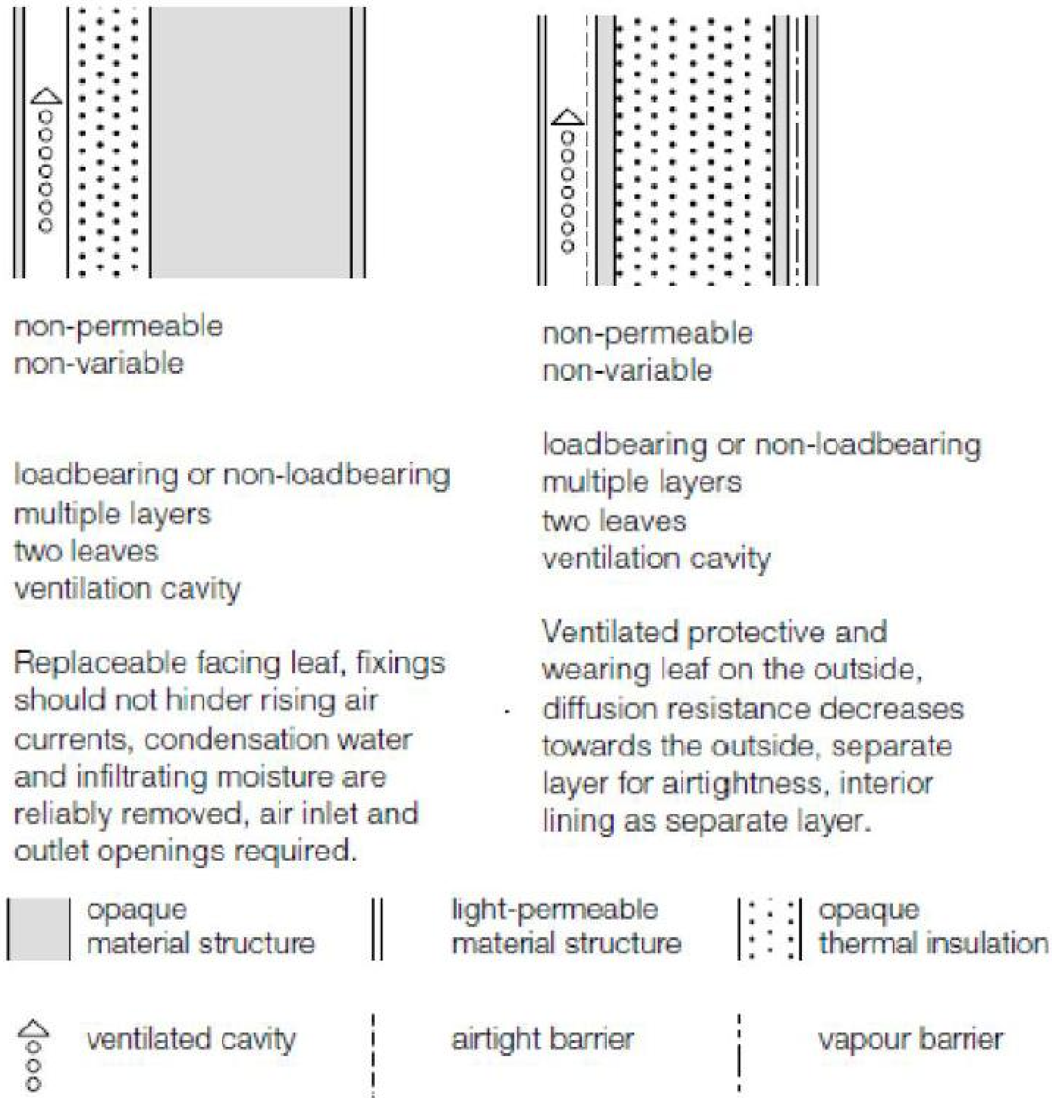


Figure 12: Typical ventilated facade assemblies. Source: Herzog et al. 2004

Supporting Sub-Structure, the sub-structure is the skeleton of the façade, typically composed of aluminium or galvanised steel profiles (vertical 'T' or 'L' shapes). Its primary structural role is to transfer the dead load of the cladding and the horizontal wind loads to the primary building wall. Crucially, the sub-structure brackets provide adjustability (in three axes), allowing installers to correct the inevitable dimensional tolerances of the rough concrete work (often 20 mm) to achieve a perfectly plumb façade surface.

3.3. Stick System Construction (Post-and-Beam)

The Stick System (also referred to as the Post-and-Beam or Mullion-Transom system) is the most widely used construction method for standard curtain walls. As defined by Ulrich Knaack & Marcel Bilow (2007)It is a non-load-bearing lattice structure assembled on-site, piece by piece. unitised systems where large panels arrive pre-assembled, the stick system requires the delivery of individual profiles, glass units, and gaskets, making the installation process highly flexible but dependent on-site conditions and skilled labour.

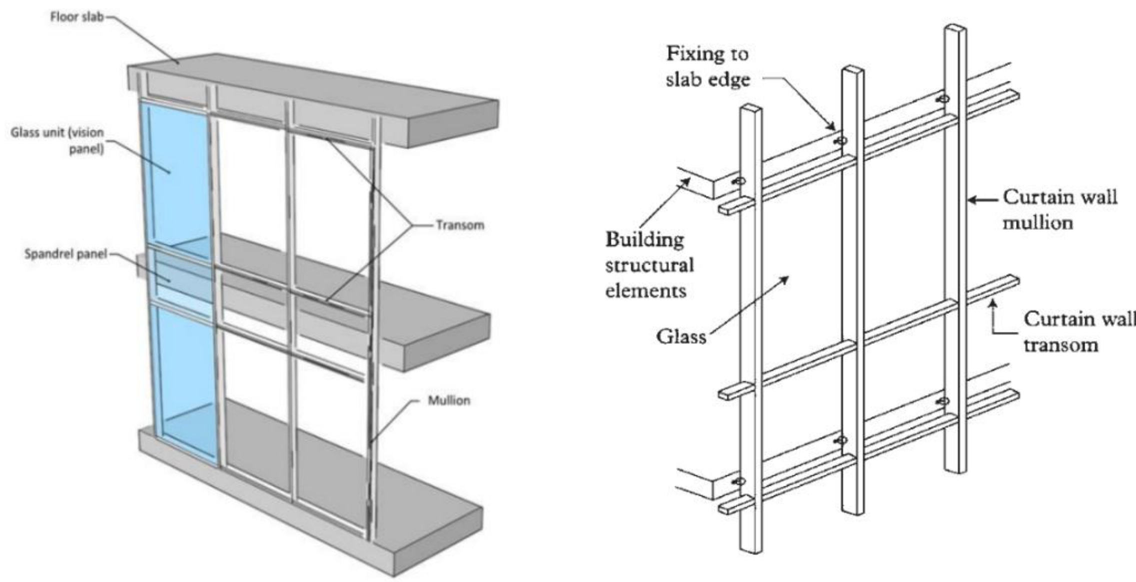


Figure 13: https://qstuts.com/curtain-wall-systems-types-benefits-design-and-trends/

3.3.1. Structural Anatomy: Vertical Mullions vs. Horizontal Transoms

The structural logic of the system relies on a hierarchical grid of aluminium profiles, typically hollow box sections designed to resist buckling and torsion.

Vertical Mullions (Posts): These are the primary load-bearing elements. They span vertically from floor to floor (or across multiple floors) and are responsible for transferring wind loads and the façade's dead weight to the main building structure. Because they carry the highest loads, mullions often have a deeper cross-section than transoms.

Horizontal Transoms (Beams): These profiles run horizontally between the mullions. Their primary function is to support the dead load of the glazing infill and transfer it to the mullions via mechanical connections (T-cleats or screws). According to (Herzog, Thomas and Krippner, Roland and Lang, 2012)The connection joint between the mullion and transom must be carefully detailed to prevent water ingress. Typically, the transom profiles are notched to overlap the mullion, ensuring that any water in the rebate drains into the mullion's vertical drainage channel.

3.3.2. Assembly Logic: On-site Installation Sequence and Bracketry

The installation follows a strict linear sequence, which (Ulrich Knaack & Marcel Bilow, 2007) described as follows:

Anchoring: Steel or aluminium brackets are surveyed and fixed to the edge of the floor slabs.

Skeleton Erection: The vertical mullions are installed first and levelled. Subsequently, the horizontal transoms are bolted between them to form the grid.

Infill Installation: The glazing units (or opaque panels) are lifted into position and placed on setting blocks located on the transoms.

Clamping: The glass is mechanically secured from the outside using a pressure plate (screwed into the thermal break of the mullion), which compresses the inner and outer EPDM gaskets against the glass.

Finishing: A decorative cover cap is snapped onto the pressure plate to conceal the screws and deflect rain.

This methodology allows for high adjustability during construction, making it ideal for buildings with complex geometries or irregular concrete tolerances.

3.3.3. The Expansion Joint: Spigot Connections and Handling Thermal Elongation

A critical physical challenge in stick systems is the thermal behaviour of aluminium. With a high thermal expansion coefficient, aluminium profiles expand and contract significantly in response to temperature fluctuations. If a mullion were fixed rigidly at both ends, these forces would cause the profile to buckle or the glass to shatter.

To resolve this, engineers utilise the Spigot Joint (or sleeve connection). As detailed by (Ulrich Knaack & Marcel Bilow, 2007) Vertical mullions are not continuous; they are cut at specific intervals (usually every floor). A hollow internal sleeve (spigot) connects the two mullion sections, maintaining structural alignment while leaving a physical gap (dilatation joint) of 10–20 mm between the profiles. This gap allows the mullions to expand freely without inducing stress. This movement is managed at the slab interface through the bracketry strategy:

Fixed Bearing: One bracket per mullion (usually at the top) supports the weight and fixes the position.

Sliding Bearing: The other brackets hold the mullion horizontally (against wind) but allow it to slide vertically to accommodate thermal movement.

3.4. Unitised Façade Systems (Element Façades)

The Unitised Façade (or Element Façade) represents the industrialisation of the building envelope. In contrast to the Stick System, in which assembly occurs on site, the unitised system consists of fully pre-assembled, storey-high panels. These "elements" arrive on site complete with glazing, gaskets, opaque spandrels, and even sun shading devices. (Ulrich Knaack & Marcel Bilow, 2007) Identify this shift from construction to manufacturing as a key driver of quality control. Because assembly takes place in a climate-controlled factory environment, sealing quality (airtightness and watertightness) is significantly higher than what is achievable on an exposed construction site.

Off-site Prefabrication, Penalisation Logic, and Transport Constraints: The design logic of a unitised system is governed by the "penalisation" of the architectural surface. The façade grid is subdivided into repeating modules, typically one floor high and one axis wide.

Logistics: While prefabrication accelerates on-site installation (often requiring no scaffolding), it imposes strict geometric constraints. (Ulrich Knaack & Marcel Bilow, 2007) Note that panel dimensions are limited by transport regulations (e.g., standard truck width or shipping container sizes) and crane capacity.

Handling: The panels are lifted by crane or monorail and secured to pre-installed brackets on the floor slabs. This method allows the façade to enclose the building rapidly, "chasing" the concrete frame structure upwards.

The Male-Female Stack Joint Principle: The defining technical feature of the unitised system is the "Stack Joint" (or split mullion). Unlike the stick system, which uses a single mullion profile, the unitised system employs two interlocking profiles: a "male" half attached to one panel and a "female" half attached to the adjacent panel. When panels are installed, they slide together to form a combined structural mullion. This interlocking mechanism relies on a system of complex EPDM gaskets rather than wet sealants. Crucially, this joint accommodates three-dimensional movement: it allows independent expansion of each unit and absorbs differential building movements (seismic or settlement) without transmitting stress to the glass.

3.5. Advanced Typologies: Double-Skin Façades

The Double-Skin Façade (DSF) is an advanced envelope typology designed to maximise transparency while controlling the high energy loads associated with glass buildings. Conceptually, it consists of two distinct glazed skins separated by an air corridor. This intermediate zone acts as a thermal buffer and an acoustic barrier.

Buffer Zones, Extract-Air Façades, and Twin-Face Concepts (Mendonça, 2005) Classify DSFs based on their ventilation strategy and compartmentalisation:

Buffer Systems: These are typically sealed cavities that serve as insulating blankets. They rely on the greenhouse effect to trap solar heat in winter, reducing heating loads. They are often used in renovation projects that add a second glass skin to an existing façade.

Extract-Air Façades: In this active system, the air cavity is connected to the building's HVAC return air. Mechanical fans extract air from the room through the cavity. As air passes over the inner glass, it absorbs solar heat and rejects it before it enters the occupied space. This is highly effective for cooling-dominated climates but requires integration with mechanical systems.

Twin-Face Façades: The most common passive-ventilated type. It features an external skin (usually single-glazed with ventilation openings) and an internal skin (double-glazed). The cavity houses automated shading devices (blinds). Because the blinds are protected from wind, they can be deployed even during storms. The ventilation prevents the cavity from overheating, while the mass-spring-mass layering provides superior acoustic insulation against urban noise.

3.6. Performance Criteria and Regulatory Frameworks

A rigorous performance framework governs the structural and physical design of the building envelope. In the European context, these requirements are defined by harmonised standards (EN) and specific national regulations (such as the Italian UNI norms and NTC decrees). A high-performance façade must verify compliance across four primary domains: hygrothermal physics, structural mechanics, fire safety, and acoustics.

3.6.1. Hygrothermal Physics: Transmission, Bridging, and Condensation

The energy efficiency of the envelope is primarily determined by its thermal transmittance (U-value), which quantifies the rate of heat transfer through opaque and transparent components. However, modern regulations, including (UNI EN ISO 10211:2018)Emphasise that calculating the U-value of the planar surface is insufficient. Engineers must also calculate the linear thermal transmittance (Ψ-value) at critical nodes—such as the slab edge, corner connections, and window interfaces—where "thermal bridges" occur. These bridges are not only sources of heat loss but are critical zones for potential pathology.

(Souza, 2010) highlights that the most insidious risk in façade design is interstitial condensation. This occurs when water vapour diffuses through the wall assembly and encounters a cold surface below its dew point. If this moisture accumulates within the insulation or on metallic brackets, it can lead to corrosion and biological growth. To mitigate this, ventilated façade strategies are often employed, utilising the air cavity to equalise pressure and remove moisture via the stack effect.

3.6.2. Structural Mechanics: Wind Load and Safety Verification

While the façade does not support the building, it must support itself and resist environmental loads.

- **Dead Load Transfer:** The permanent weight of cladding and profiles is transferred to the primary structure via fixed bearings.
- **Wind Load Distribution:** The dominant variable action is wind pressure. According to (EN 1991-1-1: 2002) and the Italian Technical Standards for Construction, wind load is treated as a stochastic variable dependent on site topography, building height, and shape.

The design pressure (P) is derived from the basic wind velocity and exposure coefficients, modified by external (Cpe) and internal (Cpi) pressure coefficients. Structural verification must ensure that the façade meets the Ultimate Limit State (ULS) —preventing collapse or detachment under extreme wind events—and the Serviceability Limit State (SLS), ensuring that deflections under normal conditions do not exceed limits (typically L/200 or L/300) that would damage glazing or seals.

3.6.3. Fire Safety: Vertical Propagation and Spandrel Geometry

In multi-storey buildings, the façade poses a specific risk for vertical fire spread, known as the "leapfrog" effect, in which flames exiting a window on one floor ignite the floor above.

- **Reaction to Fire:** Materials are classified under (EN 13501-1:2018 , with a preference for Euro class A1 or A2 (non-combustible) materials for cladding and insulation in high-rise applications.
- **Geometric Barriers:** In Italy, the Decree (D.M. 25/01/2019, n.d.) (and the guiding Circular n. 5043) prescribes specific geometric constraints to ensure physical separation between openings. This often requires a vertical spandrel (opaque band) of at least 1 meter between floors or the use of horizontal fire-stopping projections to deflect flames away from the façade surface.

3.6.4. Acoustic Analysis: Sound Insulation and Mitigation

As the barrier between the city and the occupant, the façade is the primary defence against noise pollution. Acoustic performance is regulated under (UNI EN ISO 717-1, n.d.) , which defines the weighted standardised level difference. Unlike traditional masonry, which relies on mass to block sound, lightweight façades utilise the "mass-spring-mass" principle. By decoupling the outer cladding from the inner insulation layers, ventilated or double-skin systems can achieve high levels of acoustic attenuation at lower structural weights, provided that air gaps are properly baffled to prevent sound flanking.

4. Professional Practice and Project Delivery

4.1. The Façade Supply Chain and Stakeholder Fragmentation

The delivery of a high-performance building envelope differs fundamentally from the construction of the primary structure. While the building frame is typically cast or erected on-site, the façade is a high-precision industrial product, manufactured off-site and delivered through a complex, tiered supply chain. This process is characterised by high fragmentation, in which design intent, technical data, and legal liability are transferred among multiple distinct entities. Understanding this ecosystem is critical, as the "interoperability gaps" between these stakeholders are often where traditional workflows fail and where BIM offers the most significant potential for integration (Rafael Sacks, Charles Eastman, Ghang Lee, 2018)

4.1.1. The Façade Consultant: Performance Specification and System Intent

In modern, complex projects, the architect rarely possesses the specialised knowledge of physics required to detail the envelope. The Façade Consultant (typically a specialised engineering firm) bridges this gap.

System Intent: The consultant translates the architect's aesthetic concept into a technical reality. They determine the appropriate typology—for example, advising that a twisted tower requires a "Cold bent unitised system" rather than a standard stick system to accommodate the geometry.

Performance Specification: Rather than drawing every screw, the consultant produces a "Performance Specification." As noted by (Patterson, 2011) This is a legal document that defines the *wall's behaviour* rather than its exact construction. It sets the non-negotiable targets: structural resistance (e.g., wind loads of 2.5 kPa), thermal limits (e.g., U = 1.1 W/m²K), and acoustic attenuation targets. This approach provides the supply chain with the flexibility to propose the most efficient technical solution that meets the criteria.

4.1.2. The Specialist Contractor: Management, Logistics, and Procurement

The Specialist Contractor (often referred to as the Façade Contractor) is the entity that is contractually responsible for delivering the façade. In Design & Build (D&B) contracts, the contractor assumes full responsibility for the detailed design and performance of the system.

Risk Management: Their primary role is to manage risk. They must guarantee that the system they build will perform for the specified lifespan (often 25–50 years). This involves conducting advanced structural calculations and thermal simulations to validate the design before materials are ordered.

Procurement Hub: They act as the logistical hub, coordinating the flow of materials from glass manufacturers (often in one country), aluminium extruders (in another), and gasket suppliers, ensuring they all arrive at the fabrication plant in the correct sequence (Ulrich Knaack and Marcel Bilow 2007).

4.1.3. The System Supplier: Profile Extrusion and Standard Testing

The System Supplier (e.g., Schüco, Reynaers, Wicona, Kawneer) functions as the technology provider and Intellectual Property (IP) holder. They typically do not fabricate windows; they develop and sell the "System."

The "System Pass" (Cascading ITT): The supplier's crucial value is the Initial Type Testing (ITT). They test their standard profiles in certified laboratories for air permeability, water tightness, and wind resistance in accordance with European Norms. (EN 13830:2015+A1:2020: Curtain Walling - Product Standard, 2020). This allows the fabricator to use a "proven" solution without incurring the cost of expensive testing on every project, provided they adhere strictly to the supplier's fabrication manual.

Profile Extrusion: They manage the extrusion of aluminium profiles (mullions and transoms) and the production of specific accessories (polyamide thermal breaks and proprietary brackets) that define the system's thermal and mechanical performance.

4.1.4. The Fabricator: Machining, Assembly, and Shop Drawings

The Fabricator is the manufacturing arm of the supply chain, responsible for transforming raw components into finished building elements. This role may be performed either by the Specialist Contractor's internal factory or by a local metalworking firm.

Shop Drawings: The fabricator translates the architectural drawings into Shop Drawings. These are 1:1-scale instructional documents used in manufacturing. (Rafael Sacks, Charles Eastman, Ghang Lee, 2018) highlights that shop drawings are the definitive "source of truth" for

Production: they detail every tolerance, joint dimension, and screw location. If a detail is not in the shop drawing, it will not be built.

Machining and Assembly: The physical workflow involves distinct stages:

- **CNC Machining:** Aluminium bars (delivered in 6m lengths) are cut, drilled, and notched using Computer Numerical Control (CNC) centres.
- **Assembly:** The machined profiles are crimped or screwed together to form frames.

Glazing (Bonding): In unitised systems, the glass is bonded to the frame using structural silicone in a dust-free environment. This "off-site" bonding ensures a seal quality that is impossible to achieve on a windy construction site.

4.2. Conventional Documentation Workflows (2D CAD)

Despite the construction industry's rapid shift toward digitisation, 2D Computer-Aided Design (CAD) remains the entrenched standard for the detailed engineering and manufacturing of façade systems. While architectural teams may initiate projects using sophisticated 3D tools, the transition to the fabrication stage typically triggers a "regression" to 2D vector-based drafting.

The Prevalence of AutoCAD for Manufacturing Details According to (Rafael Sacks, Charles Eastman, Ghang Lee, 2018) The persistence of 2D CAD in the supply chain is driven by the need for microscopic precision that standard architectural BIM tools (such as Revit or ArchiCAD) struggle to manage efficiently. Façade fabrication requires tolerances in the sub-millimetre range to ensure air- and watertightness. A standard 2D CAD environment allows the fabricator to draw "micro-details" such as the specific compression of an EPDM gasket (often compressed 3–5 mm in the final assembly) or the thread pitch of a screw with absolute geometric certainty. Furthermore, the global supply chain is heavily invested in legacy 2D libraries; aluminium extruders and glazing suppliers have decades of certified standard details stored in .dwg format, making the shift to object-oriented modelling a significant logistical and financial hurdle. (Rafael Sacks, Charles Eastman, Ghang Lee, 2018)

Limitations: Static Geometry and Lack of Parametric Intelligence. The reliance on 2D workflows creates what (Holzer, 2016) describes as "information silos." In a conventional workflow, the architect issues a set of drawings which serves as a static snapshot of the design intent. The façade contractor must then manually interpret and redraw this information.

Static Geometry: Unlike BIM objects, 2D lines possess no inherent relationship to one another. If the architect shifts a floor slab by 100mm, the façade drawings do not update automatically. The fabricator must manually locate and modify every affected sheet, a process that is labour-intensive and highly error-prone. (Ghaffarianhoseini et al., 2017).

Lack of Semantic Data: CAD-generated data is purely geometric. It lacks the "I" (Information) of BIM. A line representing a "thermal break" does not convey thermal-conductivity data; it is merely a visual representation. This prevents automated analysis of energy performance or material take-offs, forcing engineers to perform quantity calculations manually in separate spreadsheets.

4.3. The "Hybrid" Integrated Workflow

To overcome the limitations of 2D drafting without losing the necessary fabrication precision, leading façade practitioners have adopted a "Hybrid" or "Inter-scalar" workflow. This approach acknowledges that no single software platform can currently handle the entire scope of façade engineering, from the macroscopic building massing to the microscopic screw threads.

Coordination via BIM (Macro-scale) vs. Fabrication via MCAD (Micro-scale): This workflow relies on a strategic division of labour between two distinct types of modelling environments:

- **Macro-scale (BIM):** The façade's global geometry is managed in a BIM environment (e.g., Revit, ArchiCAD). As noted by (Succar, 2009) This model's primary function is "spatial coordination." It defines the primary grid, the exterior visual surface, and the critical interfaces with the main structure (LOD 300). Its goal is to detect "hard clashes" such as a ventilation duct hitting a transom before construction begins.
- **Micro-scale (MCAD):** For production, the geometry is transferred to a Mechanical CAD (MCAD) system (e.g., Autodesk Inventor, Dassault CATIA, or SolidWorks). (Holzer, 2016) explains that MCAD tools operate on a different mathematical kernel than architectural BIM, allowing for "solid modelling" at a scale of 1:1. In this environment, the contractor models the façade at LOD 400 (Fabrication Ready), including machining operations (drills, notches) and creating a precise Bill of Materials (BOM) for procurement.

The Role of Shop Drawings in Bridging the Gap. In this hybrid workflow, the "Shop Drawing" transitions from manual creation to automated extraction. Instead of drawing lines, the fabricator generates 2D views directly from the high-fidelity MCAD model. (Rafael Sacks, Charles Eastman, Ghang Lee, 2018) highlight that this ensures "single-source truth": if the 3D manufacturing model is modified, the 2D shop drawings update instantly. This workflow effectively bridges the design-to-production gap, ensuring that components installed on-site align with the coordinated architectural intent, thereby significantly reducing rework and material waste.

5. BIM

5.1. BIM Definition

Building Information Modelling (BIM) is commonly defined as a digital representation of the physical and functional characteristics of a built object, providing a reliable basis for decision-making throughout the building lifecycle. (International Organization for Standardization, 2016). The Royal Institute of British Architects (Architects, 2012) emphasises that BIM should be understood not only as *"Building Information Modelling"* but also as *"Building Information Modelling and Management,"* since it enables both the creation of digital models and the structured management of information within them. Similarly, the (UK Government BIM Task Group, 2011) describes BIM as a digital methodology for developing 3D models enriched with project data, which enhances collaboration in the design stage, improves integration of complex components during construction, and provides real-time asset information in the operational phase (UK Government BIM Task Group, 2011). (Rafael Sacks, Charles Eastman, Ghang Lee, 2018) further highlight BIM's distinction from CAD by framing it as a parametric, object-oriented process in which building elements are modelled with embedded data, including materials, performance, and lifecycle attributes. This data-rich approach is particularly relevant for façade projects, where multidisciplinary coordination and performance considerations are essential.

5.2. BIM and Industry 4.0

The construction sector is undergoing a profound transformation aligned with the principles of Industry 4.0, characterised by digitalisation, automation, and integration across the entire value chain. According to the Italian BIM Association (Asso BIM, 2018)Building Information Modelling (BIM) is a cornerstone of this transformation, enabling a digital shift across all phases of the building lifecycle, from conceptual design through execution to long-term management. BIM is therefore not only an innovative modelling tool but a methodology that redefines how projects are designed, coordinated, and delivered.

(Deloitte, 2018) highlights that digitalisation and technology are the two dominant themes for the future of the European construction industry. Nearly all major construction companies surveyed expressed their intention to lead in "digital construction," with strategies focused on robotisation, drones, 3D printing, and BIM adoption. Many firms reported pilot projects where

BIM technologies were applied to reduce costs, improve productivity, and optimise workflows. This illustrates the growing recognition of BIM as a decisive factor in competitiveness, particularly for complex building elements such as façades, where parametric modelling and coordination are critical.

The (World Economic Forum, 2016) report, Shaping the Future of Construction, reinforces this perspective, identifying integrated BIM methodology as one of the technologies with the greatest potential impact on the sector. By absorbing best practices from advanced engineering domains, BIM supports digital workflows, process automation, and skill transformation, which are essential in bringing construction closer to manufacturing standards.

The European BIM Task Group (EU BIM Task Group, 2017) further underscores that BIM is central to the digital transition in construction. The group highlights BIM's role in improving collaboration, reducing errors, cutting costs, and lowering the carbon footprint of construction projects. These benefits are echoed in the UK Government's *Level 3 BIM Strategic Plan*, which identifies BIM as a pathway to:

- Delivering better public services with lower capital investment.
- Improving facility and infrastructure performance through preventive interventions.
- Reducing costs and environmental impact via integrated supply chains and more efficient project delivery.

For façade design, this alignment with Industry 4.0 is particularly relevant. Façades often involve complex geometries, multidisciplinary inputs, and high-performance requirements. BIM's ability to integrate parametric design, performance analysis, and automated fabrication makes it a natural enabler of Industry 4.0 practices in the construction sector.

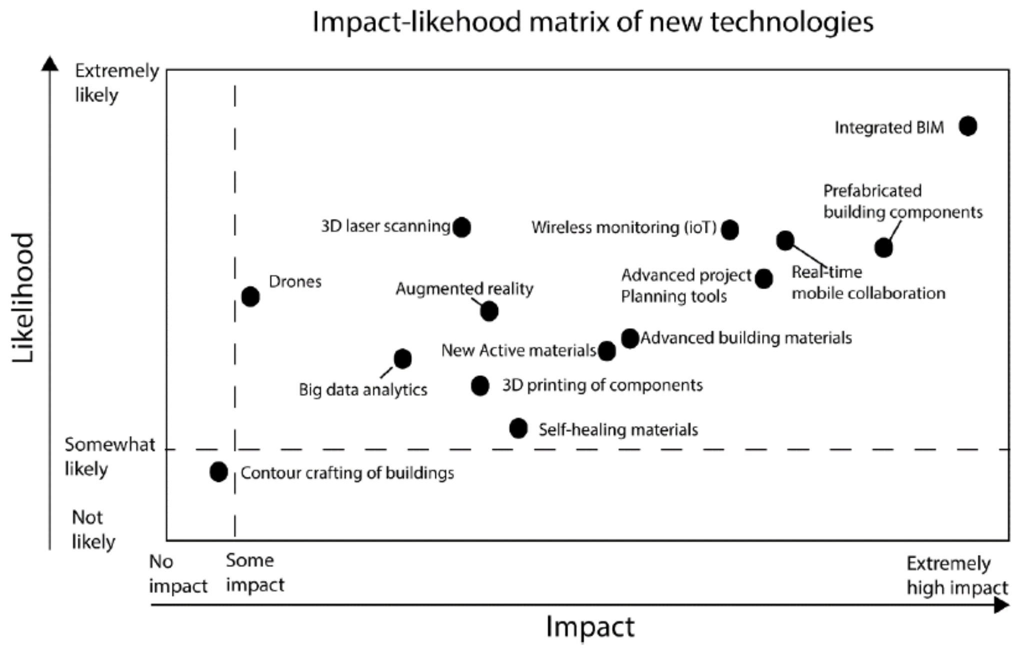


Figure 14: Impact of new technologies on the construction sector. Source: World Economic Forum – Shaping the future of the construction

5.3. BIM Overview in Europe

The adoption of Building Information Modelling across Europe has accelerated in recent years, largely driven by public policy and procurement requirements. According to the *EU BIM Handbook* (EU BIM Task Group, 2017) Many European countries have recognised BIM as a strategic enabler for innovation, transparency, and efficiency in the construction sector. Governments and professional bodies are increasingly mandating BIM for public works, creating a ripple effect across the private sector and supply chains.

(Deloitte, 2018) provides a country-by-country analysis of BIM uptake. The report highlights the diversity of adoption patterns:

Belgium: growth in digital technologies, including BIM, robotisation, and 3D printing.

Czech Republic: the market is beginning to adopt BIM as part of a broader trend towards digital construction.

Denmark: BIM and digital construction are maturing rapidly, especially among larger firms.

Finland: BIM is widely applied in construction projects, supported by strong government backing.

Ireland: rapid increase in BIM activity influenced by UK and Scottish legislation.

Italy: the *(Legislative Decree 19 April 2017, n. 56 (Procurement Code), 2017)* made BIM mandatory for public projects above €100 million, significantly accelerating national adoption.

Norway: major companies report higher quality outcomes and lower costs from BIM-enabled projects.

Portugal: client demand is driving the adoption of BIM in medium- and large-scale projects.

United Kingdom: BIM is a key trend in digital construction, improving efficiency, productivity, and profit margins.

(EU BIM Task Group, 2017) emphasises that this varied adoption is part of a broader movement towards a digitally enabled construction market. By harmonising strategies across Europe, BIM is expected to reduce fragmentation, foster cross-border collaboration, and enhance competitiveness globally.

For façade design, these developments mean that BIM is increasingly required rather than optional, particularly in public projects where façade complexity and performance must be demonstrated at early design stages. The push from European legislation and industry standards is therefore a key driver for integrating BIM into façade workflows, replacing traditional CAD-based approaches.

5.4. BIM Levels

The concept of BIM maturity levels describes the progressive stages through which construction projects move from traditional, non-digital approaches to fully integrated digital collaboration. Both the UK and Italy have developed frameworks to classify these stages, providing a reference for assessing the practical adoption of BIM.

5.4.1. RIBA Levels of Maturity

The Royal Institute of British Architects (RIBA) employs the BIM Maturity Diagram created by (Bew, Mark; Richards, 2008) to illustrate how collaboration and information exchange evolve across four maturity levels (Architects, 2012).

Level 0: limited to 2D CAD, producing drawings without embedded data. The NDS National Report (2017) notes that most of the British industry has surpassed this stage.

Level 1: use of 3D models for conceptual visualisation, but without collaboration between stakeholders.

Level 2: the first collaborative stage, where all team members produce 3D models enriched with non-graphical data. Interoperability is ensured through neutral formats such as IFC and COBie, enabling exchange across different platforms. This is currently the minimum BIM requirement for UK public projects.

Level 3: still under development, aimed at achieving a single online collaborative model integrating 3D geometry with time, cost, and lifecycle information (BSI, 2014).

This framework highlights the transition from isolated CAD workflows (Levels 0–1) to collaborative BIM (Levels 2–3), a crucial shift for façade projects, where cross-disciplinary coordination is essential.

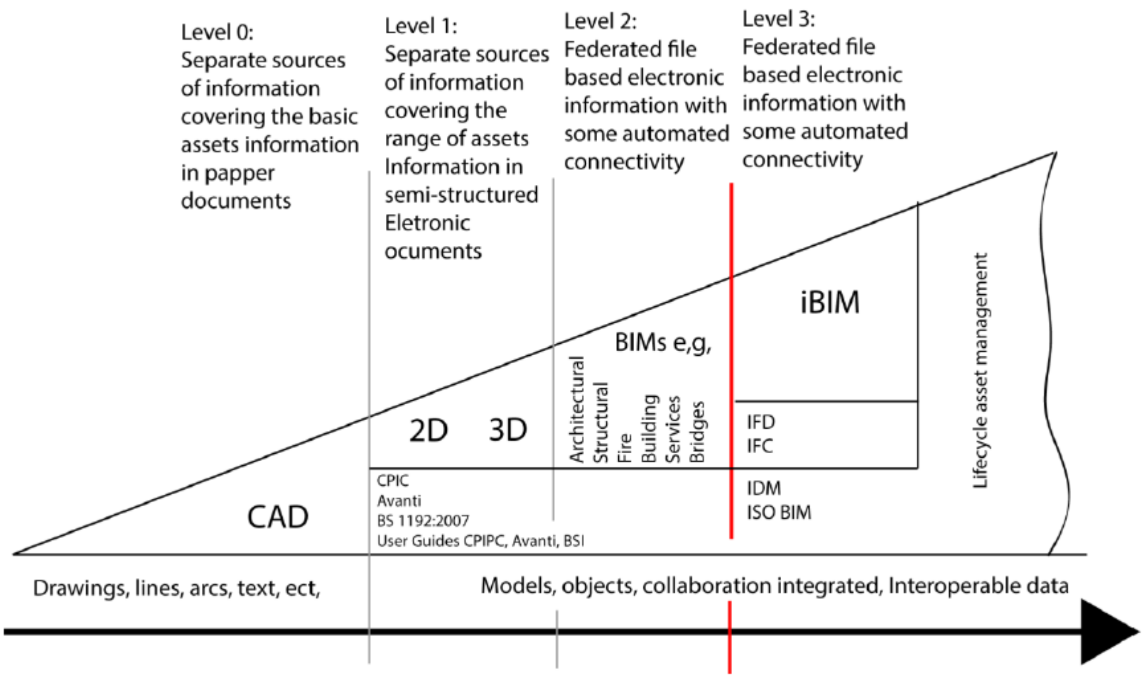


Figure 15: British BIM Levels of maturity. Source: BS 1192-4:2014

5.4.2. UNI 11337 Levels of Maturity

The Italian standard (UNI 11337-1, 2017) defines digital maturity levels that reflect information exchange among project stakeholders (UNI, 2017). Unlike the RIBA framework, which emphasises collaboration levels, UNI focuses on the contractual and information flow aspects of BIM.

Level 0 – Not Digital: information exchanged through non-digital documents, mainly paper-based.

Level 1 – Base: transfer of both digital and non-digital documents; represents a basic digital project environment.

Level 2 – Elementary: use of graphic information models and digital sheets, with metric calculations extractable from the digital model.

Level 3 – Advanced: improved interoperability between graphic models and digital data through specialised processes; direct linkage between models and data sheets.

Level 4 – Optimal: all disciplines exchange fully digital information models, with drawings derived directly from these models, ensuring full lifecycle integration.

The UNI (UNI 11337-1, 2017) The framework demonstrates a progression from paper-based communication to fully digital workflows, aligned with European directives on public procurement. For façade projects, achieving UNI Levels 3–4 enables the seamless integration of structural, thermal, and fabrication data into a single collaborative workflow, reducing the inefficiencies typical of CAD-based methods.

LOD A	LOD B	LOD C	LOD D	LOD E	LOD F	LOD G
						
Geometry Architectonic elements represented by a 2D symbol	**Geometry** Geometrical 3D representation through solid with approximated shape and thickness.	**Geometry** Vertical architectonical element represented with correct dimensions, shape and position	**Geometry** Vertical architectonical element represented with correct dimensions, shape and position, integrated with the interface with another systems	**Geometry** Vertical element represented with correct dimensions, shape and position. Each physical element and component and accessories of the facade are represented. All materials, finishes and specific data of commercial products are present in the model	**Geometry** As LOD D (with updates from the construction site if needed)	**Geometry** As LOD F
Object 2D Graphics	**Object** 3D solid and axis lines	**Object** Combined 3D solid and axis lines	**Object** Combined 3D solid	**Object** Combined 3D solid	**Object** Combined 3D solid	**Object** Combined 3D solid
Characteristics placement of the symbols	**Characteristics** Simply general geometry	**Characteristics** Proprieties of the facade panel: -Type of facade -Materials definition -Dimensions -Presence of openable elements	**Characteristics** Proprieties of the facade panel: -All characteristics of LOD C -Fixing system and other interface components	**Characteristics** Proprieties of the facade system: -All characteristics of LOD D -Finishes -Type of glass -Type of openable components -Accessories -Presence of certifications	**Characteristics** Proprieties of the facade system: - All characteristics of LOD E - Maintenance plan	**Characteristics** Proprieties of the facade system: - All characteristics of LOD F - Data regarding the maintenance and substitution of components - maintenance object - Type of intervention

Figure 16: LOD definitions for a façade system, presented at the annex C.9 of the UNI 1337-4:

5.5. BIM Dimensions

Beyond geometric modelling, BIM introduces multiple "dimensions" of information that expand its utility throughout the project lifecycle. These dimensions progressively link the 3D model with additional layers of data, enabling better coordination, planning, and performance analysis (Rafael Sacks, Charles Eastman, Ghang Lee, 2018).

3D – Geometry: the foundation of BIM, representing the physical form of the building. In façade projects, 3D models capture curtain walls, ventilated façades, and other envelope systems with parametric accuracy.

4D – Time: integrates scheduling with the 3D model, allowing simulation of the construction sequence. For façades, 4D modelling supports planning of panel installation, scaffolding, and sequencing of cladding systems.

5D – Cost: links model components with cost information. Façade elements such as profiles, anchors, and glazing units can be directly associated with budget estimates, reducing cost overruns.

6D – Sustainability: Performance includes environmental and energy data, enabling life-cycle analysis. This allows façade performance—thermal insulation, solar control, and acoustic behaviour—to be evaluated early in the design process.

7D – Facility Management: extends BIM into the operational phase by linking models to maintenance schedules, performance monitoring, and asset management. For example, façade components can be tagged with warranties, inspection intervals, and repair histories.

The introduction of these dimensions transforms BIM from a design tool into a lifecycle management platform, distinguishing it from CAD, which remains limited to 2D/3D geometry. In façade design, a multidimensional approach ensures that geometry, time, cost, sustainability, and maintenance considerations are integrated within a single digital workflow, thereby enhancing both accuracy and collaboration.

5.6. LOD – Level of Development

The Level of Development (LOD) defines the degree of detail, reliability, and stability of information associated with digital building objects. It ensures a shared understanding among stakeholders of how much information can be relied upon across different project phases. The concept is critical in façade design, where model accuracy and data requirements increase progressively from conceptual design to fabrication and maintenance.

According to the (BIMForum, 2018) and *(Rafael Sacks, Charles Eastman, Ghang Lee, 2018)*, LODs are commonly classified on a numeric scale ranging from LOD 100 to LOD 500:

LOD 100 – Conceptual: symbolic representation of building elements with approximate parameters (e.g., generic façade planes).

LOD 200 – Approximate Geometry: elements modelled with generic systems and indicative attributes (e.g., schematic panel grids).

LOD 300 – Precise Geometry: accurate dimensions, positions, and attributes for coordination across disciplines (e.g., mullions, anchors modelled to size).

LOD 400 – Fabrication: model suitable for manufacturing and assembly, containing product-specific details and tolerances.

LOD 500 – As-Built: verified on-site conditions, including operational and maintenance data.

In parallel, the (UNI 11337-4, 2017) adopts an alphabetic classification (LOD A–G), defining the depth and stability of information for digital objects throughout the lifecycle (UNI, 2017). This framework emphasises both geometry and information management:

LOD A: symbolic 2D representation with indicative characteristics.

LOD B: generic 3D geometry, approximate properties.

LOD C: defined geometry with general properties (e.g., type of façade, material).

LOD D: detailed geometry and specific characteristics, including interfaces with other systems.

LOD E: product-specific details linked to manufacturers, including finishes, certifications, and accessories.

LOD F: as-built conditions with verified geometry, including maintenance and replacement data.

LOD G: updated lifecycle representation, reflecting interventions and the current condition of façade components.

For façade systems, the UNI 11337 standard provides explicit examples:

At LOD C, panels are modelled with dimensions, material definitions, and openable elements.

At LOD D, fixing systems and interface components are included.

At LOD E–G, detailed product specifications, certifications, and maintenance plans are integrated, enabling facility managers to track façade performance over time.

Compared with CAD workflows, where such progression is often informal and nonstandardized, BIM and the LOD framework provide a structured roadmap. This ensures that façade models evolve consistently, supporting design development, fabrication, and lifecycle management with increasing precision.

5.7. Product Classifications

With the growing use of BIM technologies, the classification of building components has become essential to ensure consistency, interoperability, and reliable information exchange across disciplines. As (T. Lima et al., 2022) emphasises that product classification systems enable construction components to be organised by class or intended use, thereby grouping them in a coherent, structured way. This is particularly critical in façade design, where a wide variety of materials and components, such as mullions, anchors, insulation, and cladding panels, must be integrated into coordinated models.

The main international product classification systems include:

OmniClass: a comprehensive classification system for the construction industry, used to organise library materials, product literature, and project information. It is especially suited for electronic databases and BIM libraries, where façade components can be stored, indexed, and reused systematically (OmniClass Secretariat; Construction Specifications Institute (CSI), 2020b).

MasterFormat: developed by the Construction Specifications Institute (CSI), it classifies information by work results and construction practices, supporting project manuals, cost data, and drawing specifications. For façades, MasterFormat provides categories for exterior enclosures, curtain walls, and cladding trades, helping reduce costly errors or missing data during design and procurement (OmniClass Secretariat; Construction Specifications Institute (CSI), 2020a)

Uniformat: organises information by functional building elements (systems and assemblies) rather than by trades or materials. This approach is particularly useful for early design and cost estimation of façade systems, where entire assemblies (e.g., exterior enclosure) can be analysed without focusing on individual products (OmniClass Secretariat; Construction Specifications Institute (CSI), 2020a)

Uniclass: the UK's unified classification system, covering all scales from infrastructure to products. It allows façade systems and components to be structured to a recognised national standard, improving consistency in BIM-based workflows (NBS, 2020)

By embedding these classification systems within BIM, façade elements are not only geometrically modelled but also enriched with standardised identifiers, enabling linkage to specifications, costs, maintenance data, and performance information. This structured approach contrasts with CAD-based workflows, in which classification is typically handled via annotations or external documents, often leading to inconsistency and fragmentation.

5.8. Industry Foundation Classes (IFC) Format

The Italian standard (UNI 11337-1, 2017) distinguishes between proprietary and open formats for exchanging project information. Proprietary formats are based on non-public syntax controlled by specific software providers, which can limit accessibility and interoperability. In contrast, open formats are based on public-domain syntax and are freely accessible to all stakeholders. The most widely adopted open standard in the construction industry is the Industry Foundation Classes (IFC), developed and maintained by (buildingSMART International, 2020).

According to (buildingSMART International, 2020)IFC provides a neutral, standardised data schema for representing buildings and infrastructure. It enables the transfer of both geometric and non-geometric data across different software applications used in design, construction, and facility management (buildingSMART International, 2020). Autodesk and other BIM providers emphasise the importance of IFC in supporting open BIM workflows, in which multiple stakeholders often rely on different authoring tools. For example, in façade projects, architects may work in Revit, engineers in Tekla, and façade contractors in Rhino/Grasshopper. IFC allows these models to be integrated, ensuring consistency without requiring all parties to use the same software.

IFC's role in façade design is critical, as such projects typically involve multidisciplinary coordination and complex geometries. IFC ensures that critical data—such as material properties, performance attributes, fixing details, and lifecycle information—is transferred accurately between platforms. This interoperability reduces the risk of errors, minimises rework, and facilitates smoother transitions between design, fabrication, and operation phases.

BuildingSMART, originally founded as the International Alliance for Interoperability (IAI), has been the leading body in promoting IFC since its inception. Its mission is to support integrated project delivery across the AEC/FM industries, helping organisations move from fragmented, CAD-based workflows to collaborative BIM environments.

Thus, IFC serves as the backbone of open BIM practices, allowing façade systems to be modelled, shared, and maintained consistently across the building lifecycle. Compared with CAD, where file exchanges are typically locked in proprietary formats, IFC provides a transparent, future-proof mechanism for digital collaboration in construction.

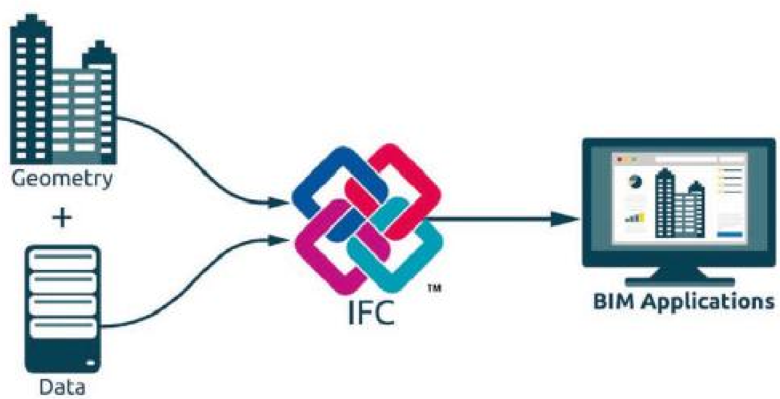


Figure 17: IFC workflow. Source: www.bimcommunity.com

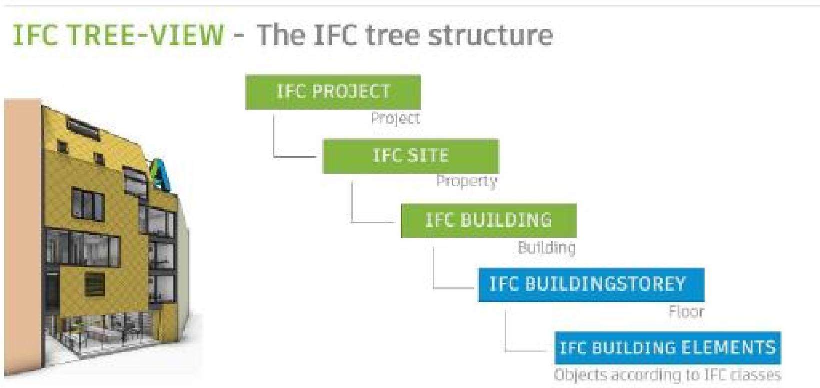


Figure 18: IFC structure. Source: Autodesk Revit IFC manual 02 – 2018

5.9. BIM Parametric Modelling

Parametric modelling is one of the most transformative features of BIM, replacing fixed geometric representations with rule-based, intelligent objects. (Rafael Sacks, Charles Eastman, Ghang Lee, 2018) define object-based parametric design as a system in which geometry and properties are governed by parameters and rules, allowing dynamic updates when contextual or user-defined changes occur.

Typical parameters include distances, angles, materials, and logical constraints (e.g., *if-then* rules, "parallel to," or "attached to"). These parameters enable models to respond intelligently to modifications without requiring the redrawing of individual components. For façade systems, this means that the dimensions of curtain wall panels or the spacing of mullions can be automatically adjusted when gridlines are altered, ensuring consistency across the model.

Parametric assemblies further extend this capability by nesting objects within hierarchical systems. In façade design, brackets, anchors, mullions, and cladding panels can be grouped into assemblies, allowing the model to generate quantities, material take-offs, and performance properties directly from the parametric logic. This approach not only improves design accuracy but also facilitates automation in fabrication and installation.

Thus, parametric BIM modelling provides a powerful methodology for streamlining façade workflows, reducing repetitive manual modelling, and enhancing cross-disciplinary coordination compared with CAD-based practices.

5.10. BIM Libraries

A BIM model is composed of Building Element Models (BEMs), which represent construction products such as windows, doors, furniture, or façade panels (Rafael Sacks, Charles Eastman, Ghang Lee, 2018). BIM libraries store these elements and their associated properties, making them reusable across multiple projects and ensuring that consistent information is applied throughout the design process.

The development of libraries introduces both opportunities and challenges for the AEC industry. On one hand, libraries allow designers to specify elements with defined dimensions, materials, and performance attributes early in the project, reducing the need to re-enter data in later stages. On the other hand, managing and standardising these libraries requires careful curation to ensure reliability, particularly when they are shared across organisations.

Currently, BIM libraries are provided through both public and private platforms. Public portals typically allow free download and, in some cases, upload of objects, thereby promoting community-driven collaboration. In contrast, private portals restrict access to subscribed firms, ensuring control over proprietary designs while supporting secure collaboration.

For façade projects, BIM libraries are particularly valuable as they contain manufacturers' digital products (e.g., profiles, brackets, fasteners, glazing systems). These ready-to-use objects not only accelerate modelling but also embed technical specifications, CE marking, and sustainability data, enabling designers to integrate compliance and performance considerations directly into the model.

5.10.1. BIMRel Platform

The BIMRel platform is an Italian initiative developed in collaboration among the Lombardy Region, the Politecnico di Milano, and private companies. Its primary aim is to create an open-source digital repository of construction products, with a particular emphasis on promoting Lombardy's industry at the international level (BIMRel, 2018)

The platform allows users to upload and access BIM objects enriched with detailed metadata. Uploaded objects can be classified according to European regulations, covering product family, category, type, material, standard, and CE mark. This classification ensures that façade components, such as profiles, anchors, and cladding elements, can be searched for and filtered using standardised criteria.

Key features of the BIMRel platform include:

- **Advanced Search Tools:** Users can filter products by family, category, type, material, or regulatory compliance to precisely identify façade components.
- **Data Enrichment:** In addition to BIM objects, manufacturers can upload technical datasheets, declarations of performance (DoP), sustainability information (EN 15804 parameters and life-cycle data), and packaging details.
- **Interoperability:** BIMRel supports downloading IFC and XML files, enabling the integration of objects with most BIM authoring tools. This ensures that digital façade components can be exchanged seamlessly across software platforms.
- **Anonymised Models:** For public procurement, the platform enables the creation of anonymous digital models that contain all technical data but exclude the manufacturer's identity, thereby supporting fair tendering practices.

For façade design, BIMRel provides a robust resource for sourcing standardised, compliant, and performance-rich digital components, enabling more efficient collaboration between architects, engineers, and manufacturers. Moreover, its alignment with open BIM principles ensures interoperability, making it a valuable tool in bridging the gap between digital design and real-world construction.

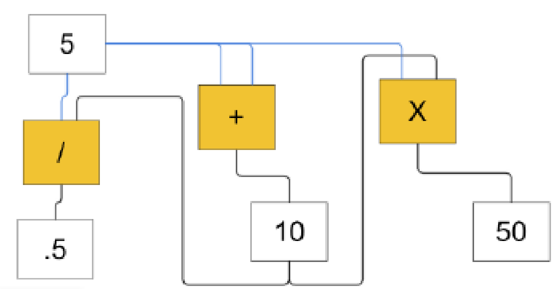
5.11. Visual Programming

Visual programming has emerged as a powerful complement to BIM workflows, enabling designers to embed computational logic into their projects without conventional programming skills. (Kirschner, 2015) defines visual programming as a programming language based on tangible objects, typically represented as blocks with input and output ports, which are connected to form algorithms. Unlike traditional textual programming, in which commands must be written in code, visual programming relies on graphical interfaces that enable users to manipulate functions by linking predefined components.

(Cezar, 2017) emphasises that this method allows designers to construct algorithms graphically, reducing the complexity of learning syntax-heavy languages. Through node-based environments such as Dynamo or Grasshopper, users can implement programming concepts in their projects by connecting elements, thereby making computational design more accessible to architects and engineers.

(Mengana, S.; Mousiadis, 2016) Furthermore, visual programming lowers the barrier to entry for non-programmers, as the graphical manipulation of functions makes algorithms easier to understand and apply. This is particularly valuable in the AEC industry, where many professionals come from non-computational backgrounds but still require tools to automate repetitive tasks, optimise designs, and integrate performance analysis.

In façade design, visual programming enables tasks such as the parametric distribution of mullions and panels, the optimisation of cutting patterns, and the integration of performance indicators (e.g., daylight or energy performance). These capabilities extend BIM's potential beyond static modelling, making it a platform for automation, optimisation, and multidisciplinary integration.




```
number1 = 5

number3 = sum(number1,number1)

number4 = divide(number1,number3)

number5 = multiply(number1,number3)
```

Figure 19: Visual and textual programming. Source: Kirschner (2015)

5.11.1. Visual Programming Components

Visual programming environments are typically composed of three fundamental components:

Nodes: The basic blocks representing functions or objects. In Dynamo, for example, nodes can generate geometry, perform calculations, or manipulate data (Kirschner, 2015)

Ports: Input and output connections on each node, allowing information to flow into and out of operations. Ports define how data is processed within the algorithm (Dynamo BIM; Autodesk, 2018).

Wires: The connectors that establish relationships between nodes. Wires transfer information, creating the logic flow of the algorithm (Kirschner, 2015).

These components are typically organised into libraries, which serve as collections of available functions. Libraries may also include custom or imported components, allowing users to extend the functionality of visual programming environments and tailor them to project-specific needs. In façade projects, this structure enables the creation of reusable scripts to distribute fixings, generate geometry, or calculate material quantities.

5.11.2. Dynamo

Dynamo is a widely used visual programming tool, available as a free standalone application or as a plug-in for Autodesk Revit. According to (Mengana, S.; Mousiadis, 2016)Dynamo enables the creation of custom algorithms that process data and automate design tasks directly within a BIM environment. The software relies on Python nodes, providing both a graphical and a textual programming interface for advanced users.

(Cezar, 2017) highlights Dynamo's value in automating repetitive tasks, such as numbering elements, generating schedules, or distributing façade components. In conventional design processes, these tasks are time-consuming and error-prone, whereas Dynamo scripts can execute them automatically with consistent accuracy.

An additional advantage of Dynamo is its ability to interact with external data sources, particularly Excel spreadsheets. As (Pires, 2017) This connection enables designers to create real-time material quantity sheets, performance indicators, and project databases that update dynamically with model changes. For façade design, this capability is particularly relevant for directly linking bill of quantities, thermal properties, and supplier data to the BIM model.

By integrating Dynamo into BIM workflows, designers can combine parametric design, automation, and data management, making façade modelling more efficient, flexible, and aligned with multidisciplinary coordination requirements.

6. Technological Barriers in Digital Façade Engineering

While BIM offers a theoretical framework for seamless integration, the practical application of digital tools in façade engineering is hindered by significant technological barriers. These challenges stem primarily from the physical realities of construction, specifically the disparity between the "perfect" digital model and the imperfect physical site, and the complexity of translating architectural geometry into manufacturable components.

6.1. Dimensional Tolerances and Geometric Fidelity

One of the most persistent issues in digital workflows is managing geometric fidelity. A BIM model is mathematically precise; coordinates are defined to eight decimal places. However, the physical building is subject to material behaviour, gravity, and human error. This disconnect creates a "reality gap" that must be actively managed.

6.1.1. The Scale Gap: Conflict between Construction Tolerances (cm) and Manufacturing Tolerances (mm)

The fundamental conflict in façade engineering lies in the interface between two distinct construction cultures: the "wet" trades (concrete and site work) and the "dry" trades (prefabricated manufacturing).

The Scale of Error: As noted by (Ulrich Knaack & Marcel Bilow, 2007) The primary structure (concrete slabs and columns) is typically built to Construction Tolerances, which allow deviations of up to 25 mm (e.g., under DIN 18202 or ISO 1803). Conversely, the façade components are produced in a machine-controlled environment to Manufacturing Tolerances, where deviations are measured in millimetres or tenths of a millimetre (e.g.,0.5mm for aluminium extrusions).

The BIM Conflict: In a standard BIM workflow, the façade is often modelled attached to a "theoretical" structural model that assumes perfect verticality and slab edge alignment. When prefabricated high-precision panels arrive on site, they often clash with bulging concrete or fail to span gaps caused by a receding slab. To mitigate this, the "hybrid" workflow increasingly relies on 3D Laser Scanning (LiDAR) of the as-built structure. The resulting Point Cloud is superimposed over the BIM model, allowing engineers to adjust the bracket lengths in the digital model before the panels are fabricated.

6.1.2. Geometric Rationalisation: Simplification of Complex Curves for Fabrication

Contemporary architecture frequently features freeform, double-curved surfaces (NURBS) that are aesthetically compelling but economically prohibitive to manufacture directly. (Pottmann et al., 2015) define "Geometric Rationalisation" as the mathematical process of approximating a smooth, complex surface with a set of discrete, manufacturable panels.

Planarization: The primary objective is usually "Planarization." While standard float glass can be bent (cylindrical or spherical), it is substantially cheaper to produce flat panes. The challenge for the façade engineer is to discretise the curved design into flat quadrilaterals (quads) or triangles without deviating visibly from the architect's intent.

Panel Optimisation: A second layer of rationalisation involves reducing the number of *unique* panel shapes. A freeform surface might theoretically require 5,000 distinct glass shapes, necessitating 5,000 distinct CNC programs and logistical tracking. Through algorithmic optimisation (using tools like Dynamo or Grasshopper), engineers attempt to "cluster" these shapes, tweaking the geometry slightly so that 5,000 unique panels can be reduced to 50 repeatable mould types, significantly lowering the project cost.

6.2. Interoperability and Data Exchange

Interoperability, the ability of different software systems to exchange information without loss or distortion, remains the "Achilles' heel" of digital construction. In façade engineering, this challenge is magnified because the discipline sits at the intersection of two fundamentally different software environments: Architectural BIM and Mechanical CAD.

6.2.1. AEC vs. MCAD: Disconnection between Architectural BIM and Mechanical CAD

The primary technological fracture in the façade workflow is the separation between the Architecture, Engineering, and Construction (AEC) domain and the Manufacturing (MCAD) domain.

Architectural BIM (AEC): Tools like Autodesk Revit, Graphisoft ArchiCAD, and Bentley AECOsim are designed for "Macro-scale" coordination. They are optimised to handle large datasets (entire buildings) at relatively low geometric resolution. They use parametric "families" or objects defined by simplified rules (e.g., a window is a hole in a wall with a frame).

Mechanical CAD (MCAD): Tools like SolidWorks, Autodesk Inventor, and CATIA are designed for "Micro-scale" fabrication. They use "boundary representation" (B-rep) solid modelling engines (such as Parasolid or ACIS) that can define complex curves and mechanical assemblies to sub-millimetre precision.

The Disconnection: As (Holzer, 2016) explains, these two categories of software rely on different mathematical kernels. Consequently, a "native" Revit file cannot be opened in SolidWorks with all its parametric intelligence intact. When data is migrated from AEC to MCAD, it is often "dumbed down" to static geometry (e.g., SAT or STEP files), breaking the parametric link. This means that if the architect changes the building grid in Revit, the fabricator in SolidWorks does not receive an automatic update, necessitating manual reconstruction and increasing the risk of version conflicts.

6.2.2. IFC Limitations: Data Loss during Open Standard Exchange

To bridge this gap without relying on proprietary file formats, the industry utilises the Industry Foundation Classes (IFC) schema, an open standard developed by (buildingSMART International, 2020). Theoretically, IFC allows data to flow neutrally between any BIM platform. However, in practice, the exchange is often imperfect.

(Silva & Amorim, 2011) document that "data loss" and "geometric distortion" are frequent occurrences during IFC export and import processes.

Geometric Simplification: Complex façade geometries, such as NURBS surfaces or detailed extrusion profiles, are often tessellated (broken into triangles) during IFC conversion. This renders the model useless for CNC manufacturing, which requires smooth mathematical curves.

Semantic Loss: While geometry may transfer, the associated data (metadata) often disappears or is mapped incorrectly. For instance, a "Fire Rating" parameter attached to a panel in the architectural model may not appear in the structural engineer's software if the specific IFC property set is not configured correctly.

"Frozen" Data: Crucially, an IFC file is typically a static snapshot. It is "reference data" rather than "editable data." Once a model is exported to IFC, it loses its parametric history; a window is no longer a parametric object with an adjustable width, but a static geometry block. This limits downstream stakeholders' ability to modify the design without rebuilding it.

6.3. Information Management and Model Complexity

As BIM adoption matures, the industry faces a paradox: the desire for more detailed models conflicts with the computational limits of current hardware. Façade systems, being arguably the most geometrically complex and component-heavy parts of a building, are often the primary cause of model performance issues.

6.3.1. Model Overload: The Computational Impact of Modelling Gaskets and Screws

A common pitfall in digital façade engineering is "over-modelling." The Journal of Facade Design and Engineering (Boeke et al., 2019) highlights that while it is technically possible to model every single screw, washer, and EPDM gasket in a BIM environment, doing so creates massive, unmanageable files.

The Polygon Count Problem: In a high-rise tower, a curtain wall might contain 5,000 panels. If each panel contains 200 detailed screws (with threads modelled), the total polygon count explodes into the billions. This "Model Overload" makes the file sluggish or impossible to open (crashing), effectively paralysing the collaborative process.

LOD Management: The solution lies in strict Level of Development (LOD) management. A screw should be modelled geometrically only if it serves a specific purpose (e.g., for clash detection in a tight node). For general coordination, it is far more efficient to represent the screw as a simple line or point, or as purely alphanumeric data attached to the assembly, rather than as complex 3D geometry.

6.3.2. External Data Repositories: Strategies for "Light BIM"

To combat model bloat, the industry is shifting toward "Light BIM" strategies. In this workflow, the 3D model remains geometrically simple (a "placeholder"), while the bulk of the data is stored in external cloud databases.

Linked Data: Instead of embedding a 5MB PDF datasheet and a complex thermal simulation result directly into a Revit family, the object contains a URL or a unique ID (GUID) that links to an external repository.

The "Single Source of Truth" approach ensures that, when a manufacturer updates a product's fire certification, the change is made once in the central database, and all linked models reference the new data automatically without requiring re-downloading of large files. This method keeps the BIM model agile and responsive while maintaining a deep reservoir of information available on demand.

6.4. Skills Gap and Cultural Resistance

The final barrier to full digital integration is human rather than technological. The shift from drawing lines (CAD) to managing databases (BIM) requires a fundamental re-skilling of the workforce.

Shortage of Interdisciplinary Professionals Façade engineering in the BIM era requires a hybrid skill set. Professionals must understand structural physics (to design the wall), manufacturing constraints (to build it), and computational logic (to model it). Currently, there is a significant shortage of "Computational Façade Engineers" who can bridge the gap between architectural vision and fabrication code. Architects often lack manufacturing knowledge, while fabricators often lack BIM expertise, resulting in communication breakdowns that require rebuilding models from scratch at each stage.

Intellectual Property (IP) Concerns in Sharing Fabrication-Level Models. A significant cultural barrier is the protection of Intellectual Property. In a fully integrated "Level 3 BIM" workflow, all stakeholders would work on a single shared model. However, Specialist Contractors are often reluctant to share their native, high-fidelity fabrication models (LOD 400) with the wider project team(Deutsch, 2011).

The "Black Box" Approach: Fabricators invest heavily in developing proprietary profiles and connection details. They fear that sharing the source 3D files allows competitors or clients to "reverse engineer" their systems or use their detailed work to tender the project to a cheaper rival. Consequently, they often share only "dumb" geometric shells (like IFC wrappers) that show the outer dimensions but hide the internal mechanical intelligence, hindering true collaborative integration (Holzer, 2016).

7. Case Study

7.1. Project Overview and Context

The selected case study, herein referred to as "Project L," involves the major renovation of a commercial complex located in the Porta Romana district of Milan. The project encompasses three existing buildings interconnected by a unified façade strategy. The primary intervention is to strip the existing envelope and replace it with a high-performance **Stick Curtain Wall System**.

From a consultancy perspective, this project is significant because it represents a "Brownfield" intervention. The new high-precision façade must be anchored to an existing reinforced concrete structure from the late 20th century, presenting significant challenges regarding geometric tolerances and structural alignment.

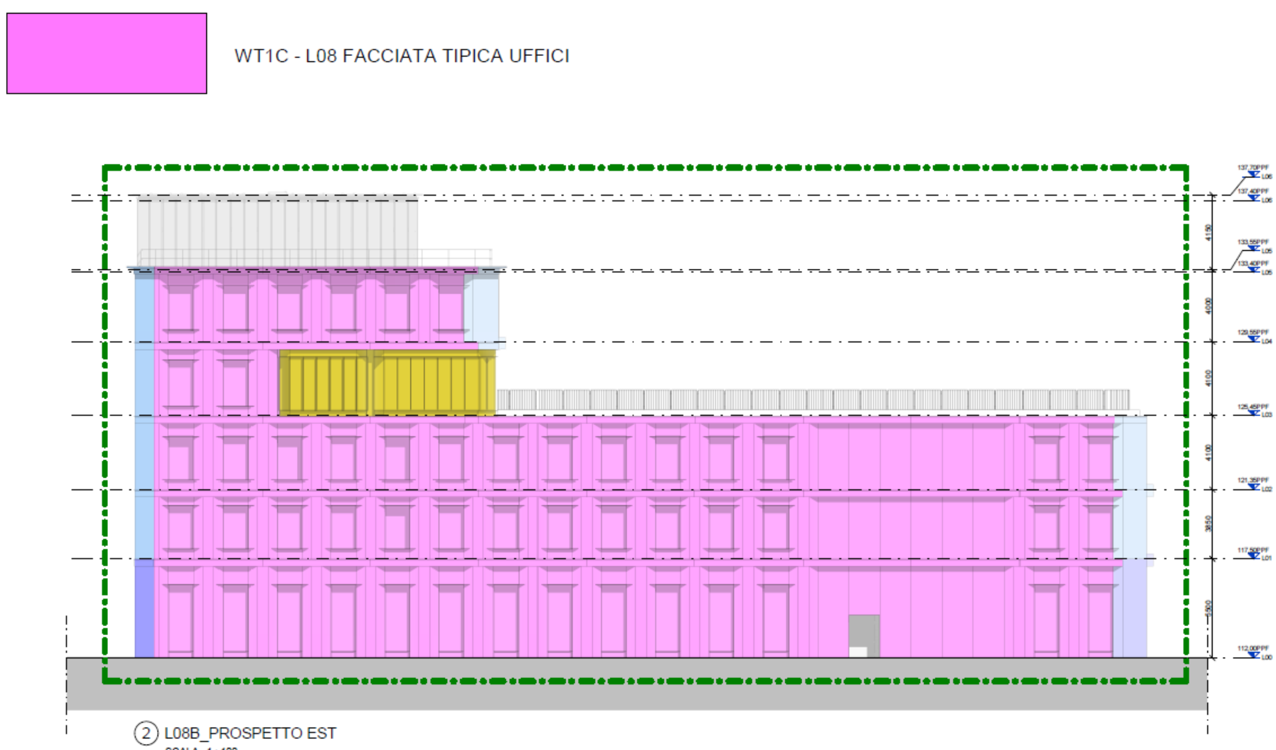


Figure 20: East Elevation Showing different façade modules. Source: Author

7.2. System Description: Mullion-Transom Stick System

For the primary envelope of the office levels, the project employs a **Mullion-Transom Stick System** (Curtain Wall). This typology was selected for its flexibility in accommodating the irregular structural tolerances of the existing concrete frame and its ability to achieve high-performance thermal and acoustic ratings within a slim profile depth.

System Concept

The system acts as a non-load-bearing, thermally broken grid of vertical and horizontal aluminium profiles. It is a "top-hung" system, meaning the vertical mullions are suspended from the floor slab above, allowing gravity to align the profiles naturally. The connection to the primary structure is achieved via adjustable steel brackets that manage dead loads and wind loads while accommodating differential movements between the façade and the building frame.

Key Components Breakdown

1. **Vertical Mullions (Primary Profile):**
    - **Function:** The main structural backbone of the façade, spanning floor-to-floor (typically 3.5m to 4.0m).
    - **Geometry:** Hollow aluminium box sections with a visible face width of **50 mm**. The depth varies (typically 150-200mm) based on the static calculations required to resist wind loads at different heights.
    - **Feature:** The mullions are not continuous; they are interrupted at every floor level by a "spigot joint" (expansion sleeve) to allow for thermal expansion and contraction without inducing stress.

2. **Horizontal Transoms (Secondary Profile):**
    - **Function:** Spanning horizontally between mullions to support the dead weight of the glass and opaque panels.
    - **Connection:** Transoms are connected to the mullions using mechanical T-cleats or shear blocks. The profile is notched to overlap the mullion gasket, ensuring that any water in the rebate drains into the mullion's vertical drainage channel (the "overlapping drainage" principle).
3. **Glazing Infill (IGU):**
    - **Specification:** Double Insulating Glass Units (DGU) comprising a laminated inner pane (safety) and a toughened outer pane (thermal resistance).
    - **Performance:** The glass features a high-selectivity magnetron coating to maximise natural light while limiting solar heat gain.
    - **Fixing:** The glass is mechanically secured by an external aluminium pressure plate, which compresses EPDM gaskets against the glass, creating a watertight seal.
4. **Opaque Spandrel Zones:**
    - **Function:** To conceal the floor slabs and ceiling plenums (MEP zone).
    - **Composition:** A "shadow box" or back-painted glass panel backed by mineral wool insulation. An internal aluminium back-pan provides the vapour barrier and finish.
5. **Anchoring Brackets:**
    - Function: The critical interface between the aluminium grid and the rough concrete slab.
    - **Adjustability:** The brackets are designed with 3-way adjustment slots (x, y, z). This allows the installation team to align the façade perfectly plumb, even if the existing concrete slab edge deviates by ± 30mm.

7.3. From Standard to Specific: The WT1C Typology

The development of a façade project typically commences with the selection of a proprietary "Standard System" provided by System Suppliers (e.g., Schüco, Reynaers). These off-the-shelf solutions serve as the initial Basis of Design, defining the fundamental physics—air tightness, water tightness, and profile width.

However, a catalog system assumes an ideal building geometry. The Consultant's role is to adapt this standard product to survive the reality of the construction site. For Project L, we developed the **"WT1C" System** (Wall Type 1 - Curtain Wall). This is the governing typology for the project, engineered as a "master detail" that covers approximately 90% of the building perimeter.

The Adaptation Workflow

The challenge in renovation projects is that the existing concrete structure is rarely straight. The transition from the "Typical Design" to the final "Construction Issue" follows a specific four-step cycle to manage these imperfections:

1. **Developing the Master Typology:** The WT1C detail is designed to be universal. It establishes the visual intent (glass plane, cap width) and the performance line. At this stage, the detail assumes the concrete slab is exactly where the CAD drawing indicates.
2. **The Reality Check (Site Survey):** Before fabrication begins, a 3D laser scan of the primary structure is conducted. This reveals the "Civil Tolerances"—areas where the existing slab edge bulges out or recedes compared to the theoretical grid.
3. **Identifying Deviations:** By overlaying the survey onto the design grid, we identify zones where the standard WT1C detail physically won't fit. This might be because the slab is too close to the glass (leaving no room for the bracket) or too far away (exceeding the bracket's reach).
4. **Engineering the "Invisible" Fix:** The goal is to keep the exterior appearance identical to the standard WT1C typology, regardless of the structural conditions behind the glass. To achieve this, we modify the hidden components:
   - **Bracket Adjustment:** We utilize anchors with elongated slots or serrated washers. This allows us to slide the mullion in and out (x-axis) or left and right (y-axis) to absorb the slab error without moving the glass line.

- **Shim Stacking:** In areas where the floor level varies, we adjust the thickness of the horseshoe shims under the bracket to ensure the mullion stays plumb.
- **Profile Extension:** If the slab edge is too far back, we increase the "hidden length" of the mullion spigot or transom depth to ensure structural bite is maintained.

This methodology ensures that while the internal engineering changes to match the structure, the external architecture remains uniform.

8. Simulation of Workflows

To test the "Hybrid" methodology proposed in this thesis, a typical bay of the Project L façade (4.5m wide × 3.5m high) was developed using two distinct workflows to compare their efficacy.

8.1. Workflow A: BIM (Revit)

Below typical module and details developed using Revit.

WT1C typical details:

Key to Reading the Technical Drawings To ensure clarity across the construction documentation and to distinguish between the various functional layers of the envelope, a standardized graphical protocol was established. The details should be interpreted according to the following material legend:

G - Glass

- G.1 Double Glazing Unit (DGU): Performance, coatings, and treatments as per technical specifications.
- G.2 Single laminated glass: Performance, coatings, and treatments as per technical specifications.
- G.3 Single tempered glass.

A - Aluminium

- A.1 Extruded aluminium profiles: Finish as per technical specifications.
- A.2 Aluminium sheet/plate: Finish as per technical specifications.
- A.3 Aluminium brackets and fixing accessories.
- A.4 Removable aluminium cover/cap: Finish as per technical specifications.
- A.5 Aluminium honeycomb panel: Finish as per technical specifications.

S - Steel

- S.1 Galvanised steel sheet.
- S.2 Painted steel profiles: Finish as per technical specifications.
- S.3 Galvanised steel brackets and fixing accessories.
- S.4 Galvanised steel profile.
- S.5 Galvanised steel brackets protected with water-based intumescent paint: As per civil works technical specifications.

C - Cladding & Concrete

- C.1 Prefabricated concrete panel: Finish as per technical specifications.
- C.2 Expanded metal mesh cladding.
- C.3 Fibre cement cladding.

I / D / F - Insulation, Sealants & Fixings

1. I.1 Mineral wool insulation.
2. D.1 Silicone or EPDM gasket.
3. D.2 Structural silicone.
4. D.3 Silicone sealant.
5. D.4 Backer rod (joint filler).
6. F.1 Halfen-type anchor channel.

MV - Miscellaneous Materials

- MV.1 Reinforced polyamide thermal break strips (or similar).
- MV.2 Extruded PVC profiles.
- MV.3 Gypsum board / Plasterboard.
- MV.4 Waterproof membrane / Flashing.
- MV.5 Calcium silicate board (for fire resistance).
- MV.6 Expanded plastic material / Plastic foam

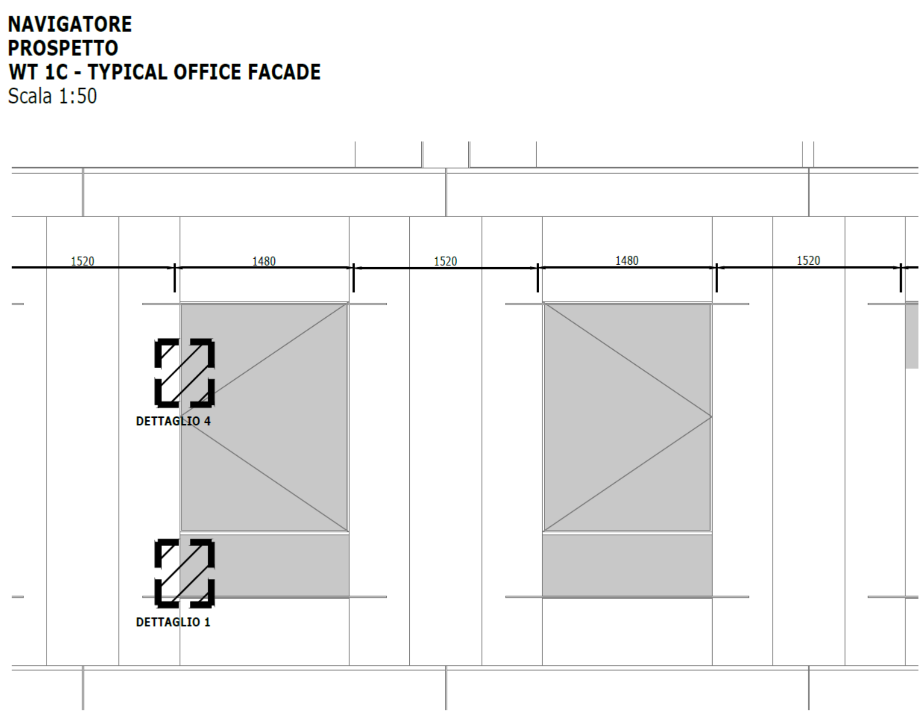


Figure 21: East Elevation WT-1C Typical façade module- Key Elevation. Source: Author

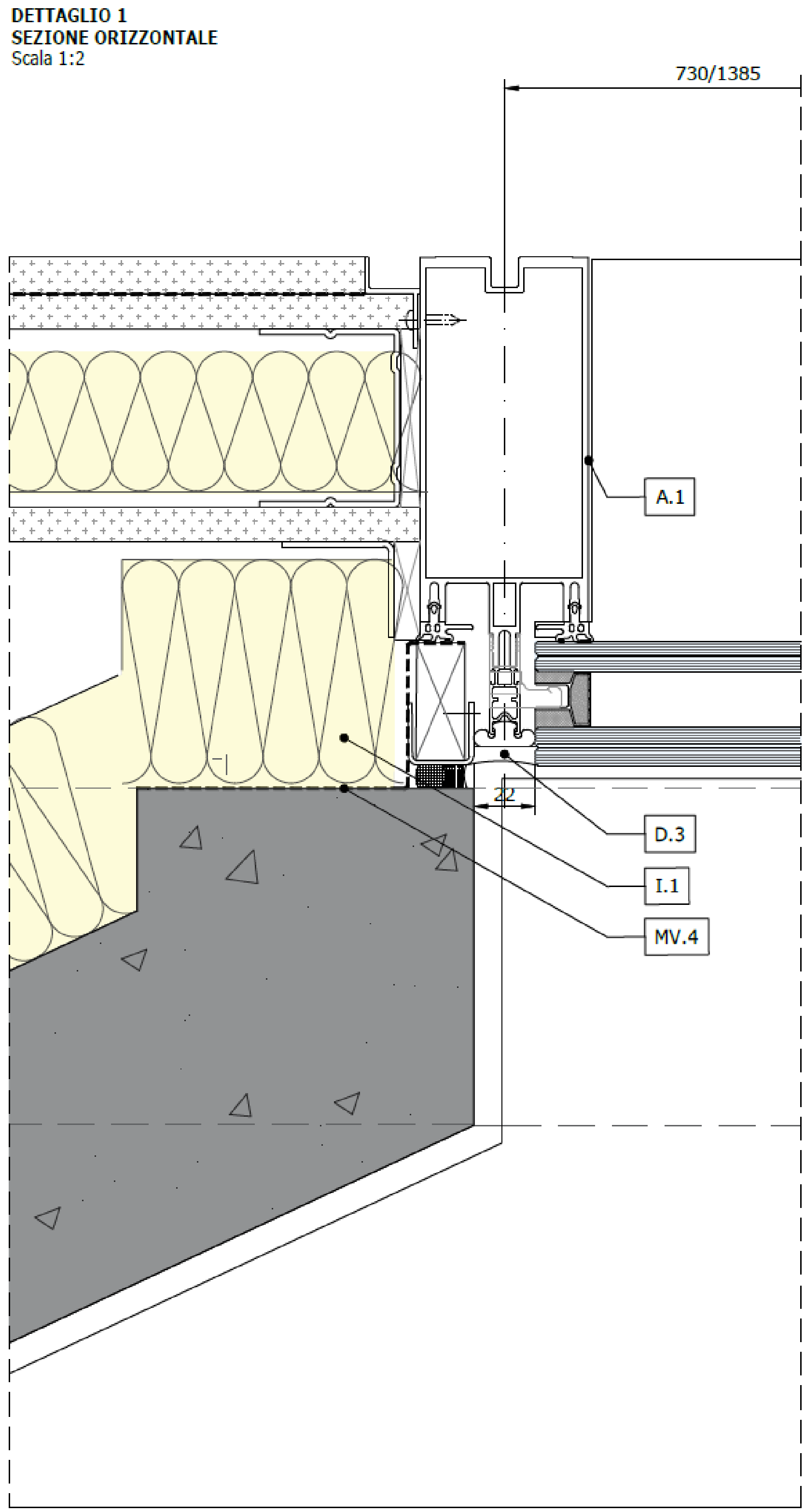


Figure 22: East Elevation WT-1C façade module typical plan Detail 1. Source: Author

DETTAGLIO 4
SEZIONE ORIZZONTALE
Scala 1:2

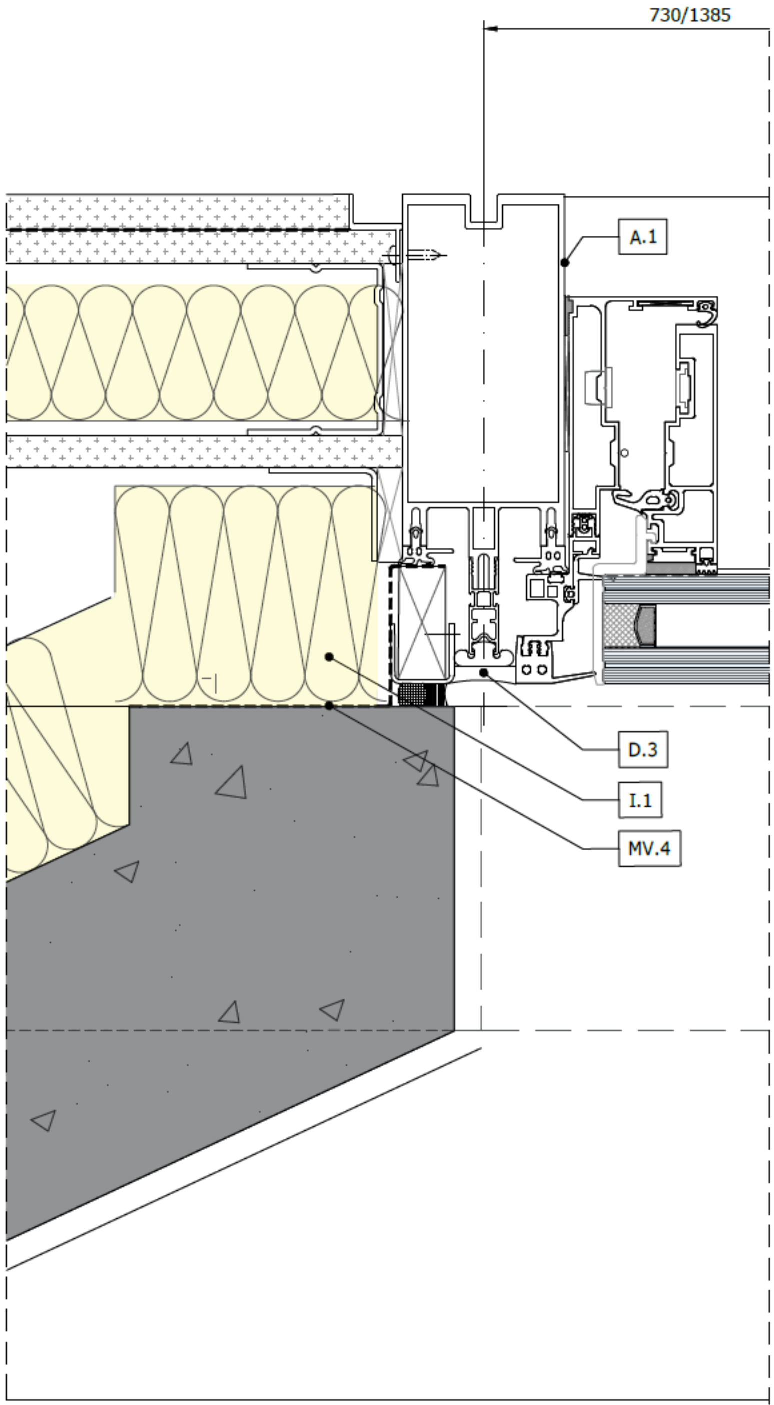


Figure 23: East Elevation WT-1C façade module typical plan Detail 2. Source: Author

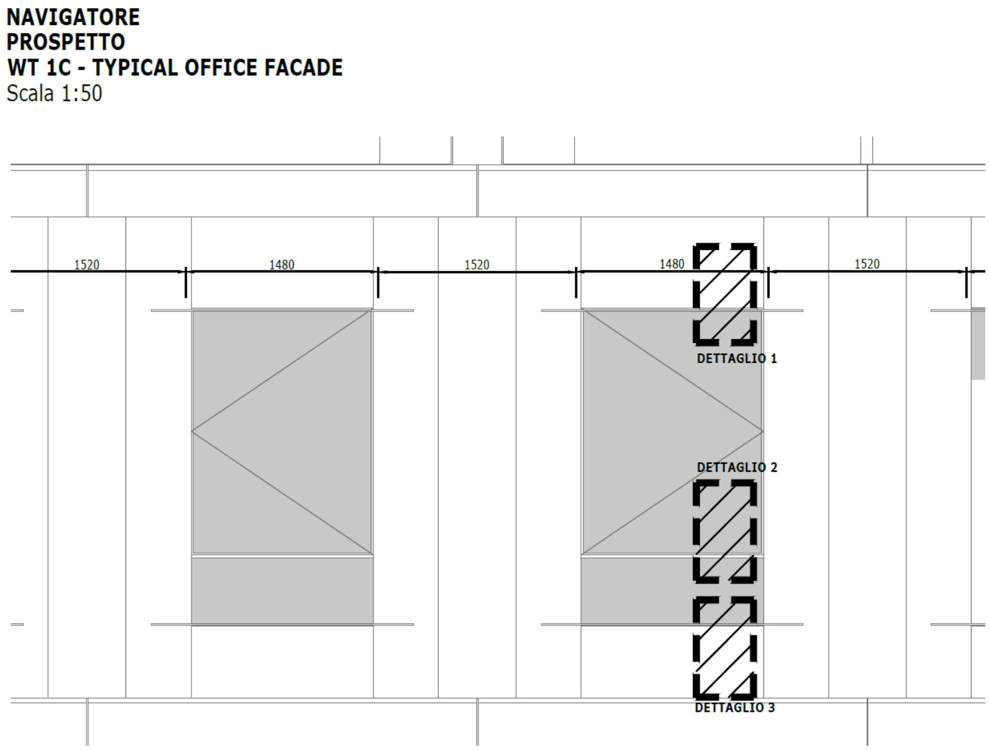


Figure 24: East Elevation WT-1C façade module Key. Source: Author

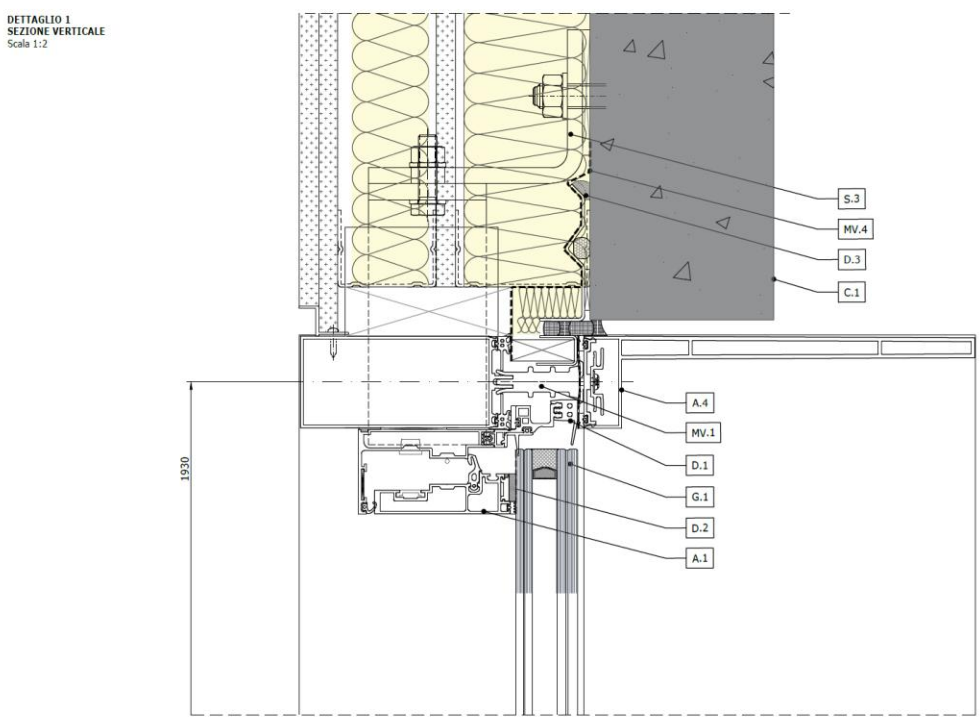


Figure 25: East Elevation WT-1C façade module typical Section Detail 1. Source: Author

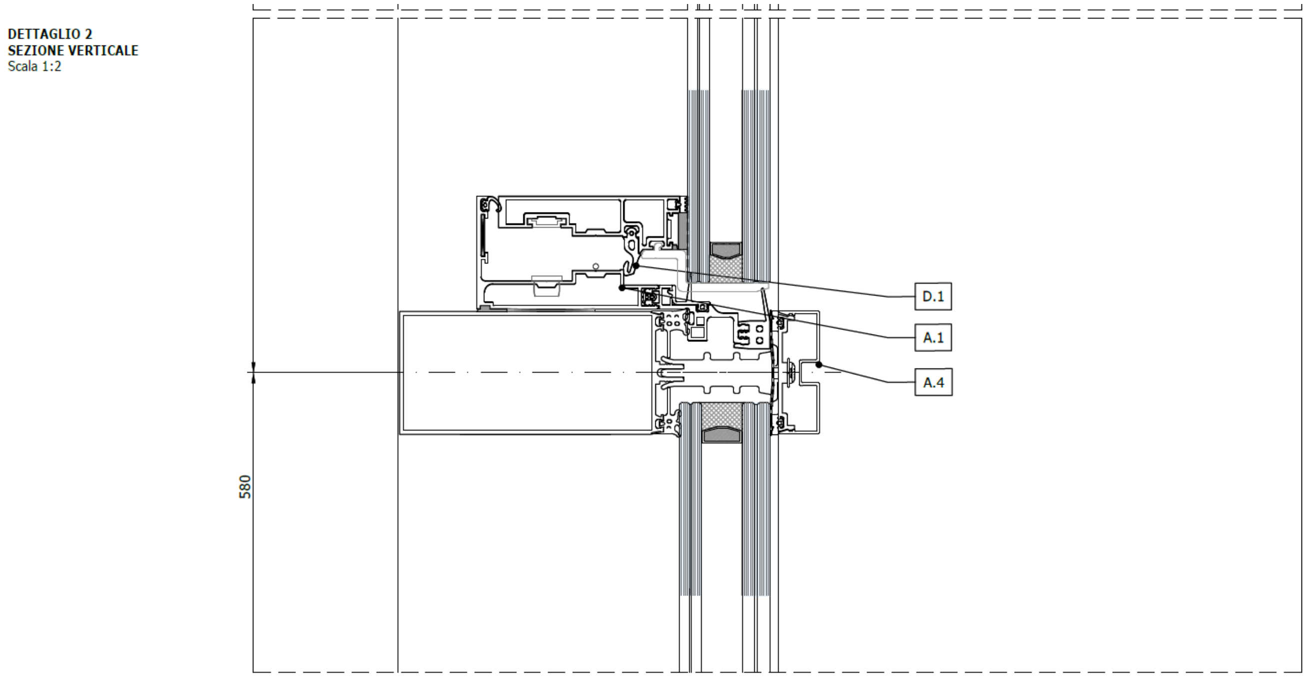


Figure 26: East Elevation WT-1C façade module typical Section Detail 2. Source: Author

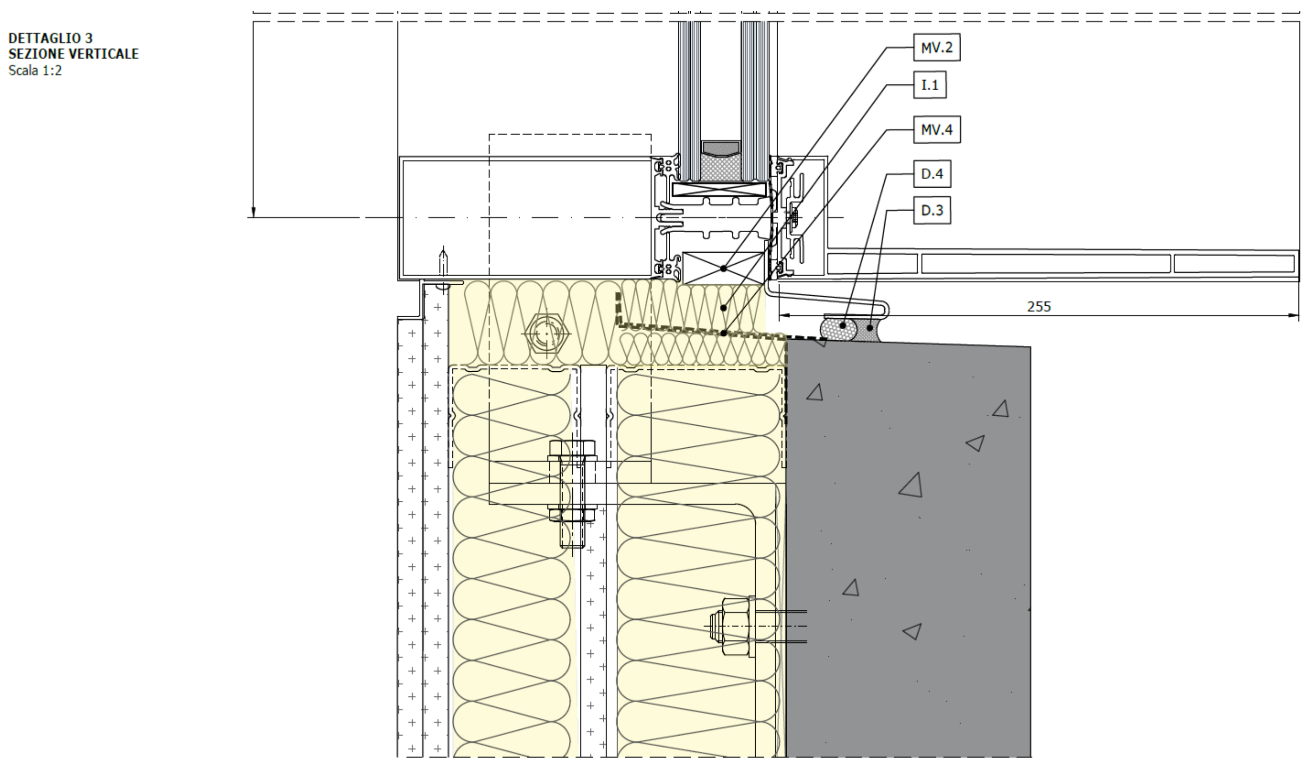


Figure 27: East Elevation WT-1C façade module typical Section Detail 3. Source: Author

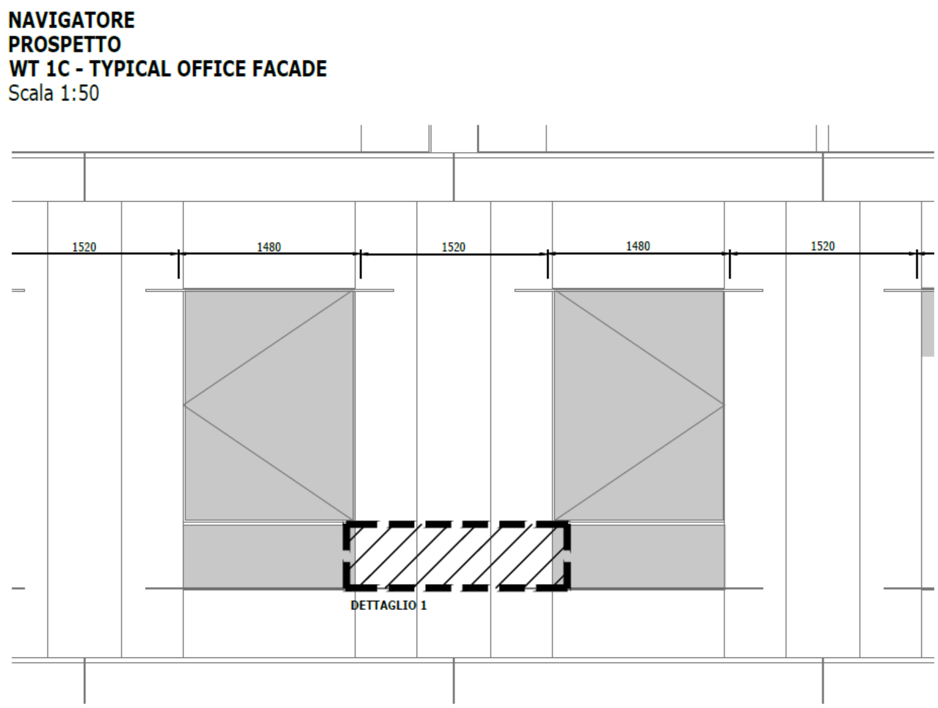


Figure 28: East Elevation WT-1C façade module Key. Source: Author

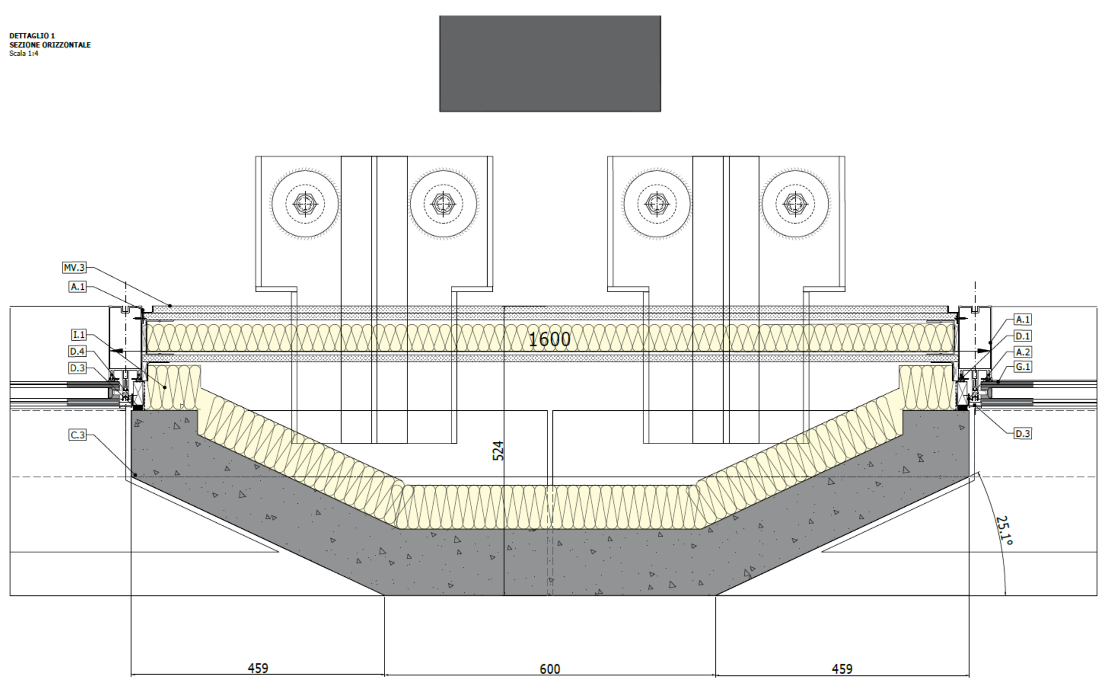


Figure 29: East Elevation WT-1C façade module typical- Prefab- Plan Detail 1. Source: Autho

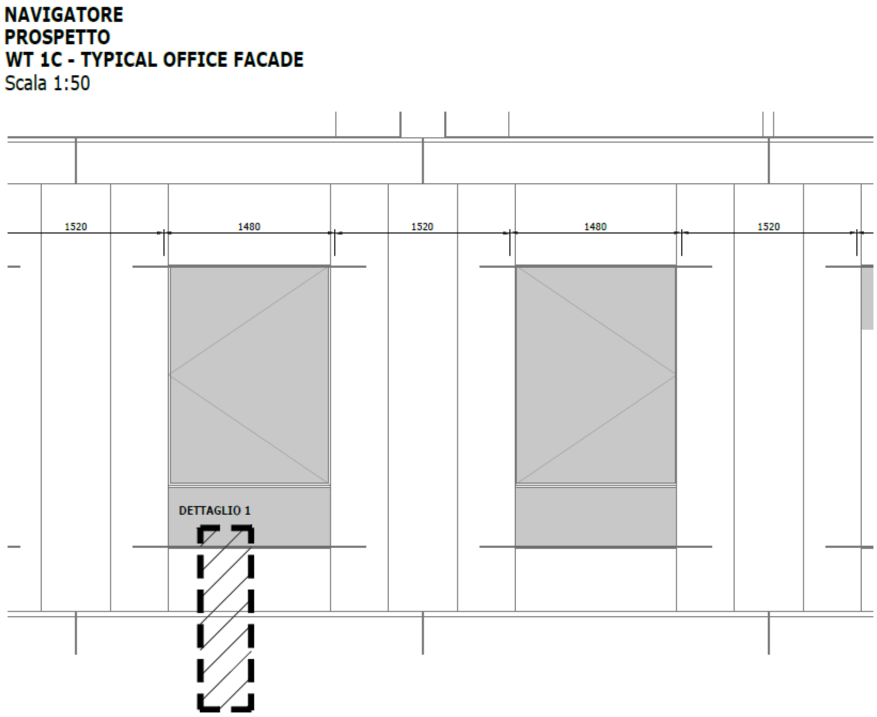


Figure 30: East Elevation WT-1C façade module Key. Source: Author

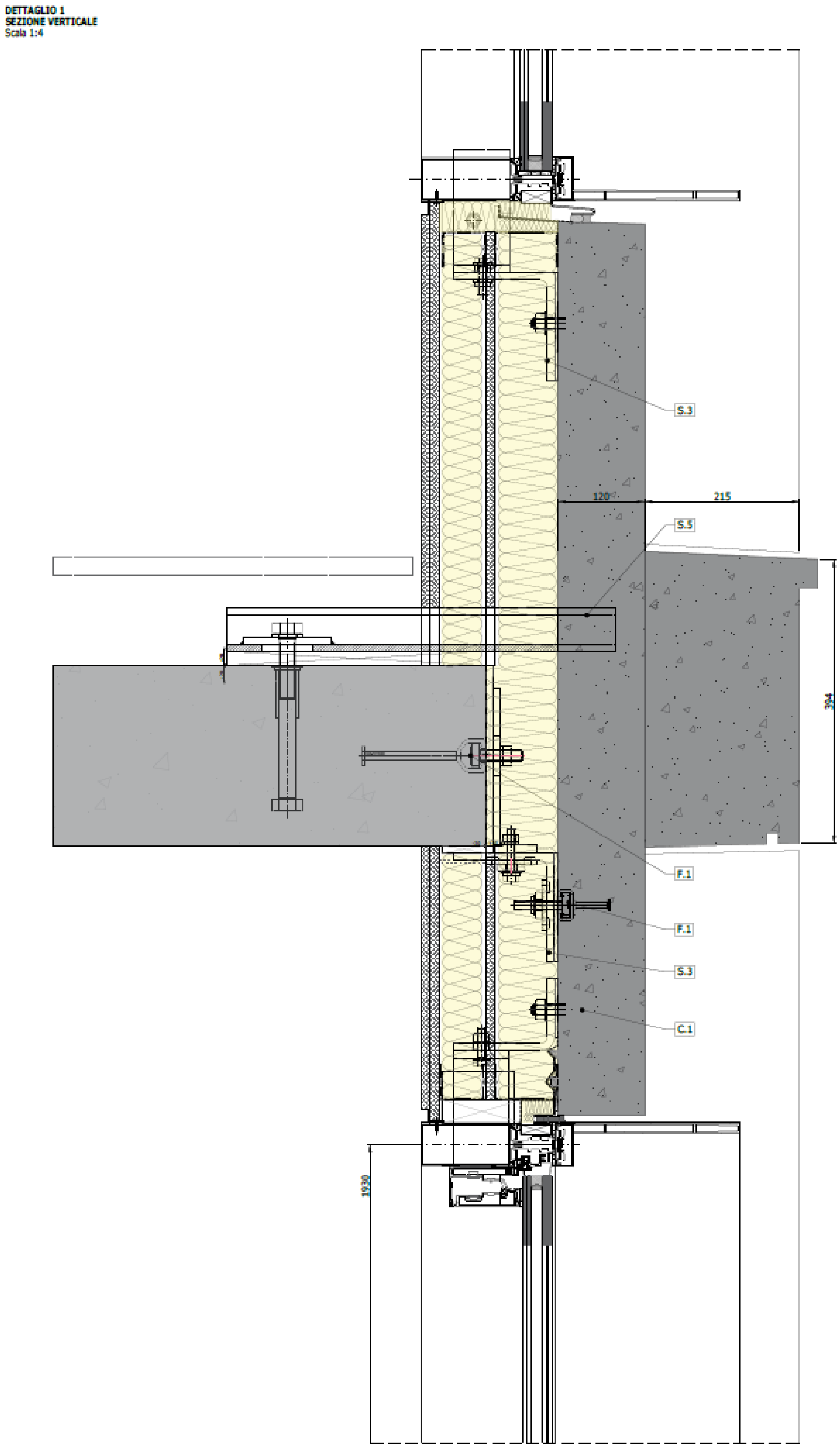


Figure 31: East Elevation WT-1C façade module typical- Prefeb- section Detail 1. Source: Author

8.2. Workflow A: Traditional 2D Documentation (AutoCAD)

Below module and detail have been developed by using AutoCAD traditional workflow

Estrusi in alluminio - Sistema Wicona WICTEC 60NG
finitura anodizzata naturale arg. (Qualanod Classe AA20):
AL.W1 - Montante rif. NP55 rif. 3332884;
AL.W2 - Traverso rif. 3030233;
AL.W3 - Copertina rif. COP2-3332917;
AL.W4 - Copertina rif. COP1-3332916;
AL.W5 - Copertina rif. 3030253;
AL.W6 - Copertina rif. 3030254.
AL.W7 - Copertina rif. 3030251;
AL.W12 -Copertina rif. COP3;
AL.W16 -Profilo estetico cieco rif. NP56;
AL.W20 -Copertina rif. COP20-3332893;
AL.W21 -Copertina rif. COP21;
AL.W22 -Copertina rif. COP5;
AL.W23 -Copertina rif. COP6;
AL.W24 -Montante rif. NP65-3332886;
AL.W25 -Montante rif. NP51-3332885;
AL.W26 -Traverso rif. 3030230;
AL.W28 -Profilo Spandrel;
AL.W29 -Copertina rif. 3331006;
AL.W31 -Copertina COP15 25mm rif. 3332919;
AL.W32 -Copertina COP22 rif. 3332894;
AL.W33 -Copertina COP23 rif. 3332895;
AL.W34 - Supporto per vetro 34mm 550N rif. 4080285
AL.W37 - Appoggio vetro su rif. 4080285
AL.W39 - Copertina rif 3332920

Estrusi in alluminio - Sistema Wicona WICTEC 60NG
- finitura anodizzata nero (Qualanod Classe AA20):
AL.W27 - Copertina rif. COP15;
- finitura grezza:
AL.W10 - Supporto per vetro rif. 4080522;
AL.W11 - Pressore rif. 3030265;

Estrusi in alluminio - Sistema Wicona WICTEC 60NG
- finitura grezza:
AL.W14 - Supporto per vetro rif. 4080533;
AL.W15 - Traverso rif. 3030243;
AL.W30 - Staffa di fissaggio pinne rif. 3300376;
AL.W35 - Profilo di rinforzo rif. 3030273;

Estrusi in alluminio - Sistema Wicona WICLINE 90 SG
finitura anodizzata naturale arg. (Qualanod Classe AA20):
AL.W8 - Traverso rif. 3030095;
AL.W9 - Traverso rif. 3030096;
AL.W36 -Piastra Incollaggio SSG rif. 3091000;
AL.W38 -Vulcanizz.Telaio 4010418 Sil. rif. W4020560

Guarnizioni in EPDM - Sistema Wicona WICTEC 60NG
finitura nera:
GE.W1 - Guarnizioni rif. 0190280;
GE.W2 - Guarnizioni rif. 0190281;
GE.W3 - Guarnizioni rif. 401007;
GE.W4 - Guarnizioni rif. 4910026;
GE.W13 - Guarnizioni rif. 4010349;
GE.W15 - Guarnizioni rif. 4910028;

- Sistema Wicona WICTEC 90 NG
finitura nera:
GE.W5 - Guarnizioni rif. 4010437;
GE.W6 - Guarnizioni rif. 4010414;
GE.W7 - Guarnizioni rif. 4010417;
GE.W8 - Guarnizioni rif. 4010418;
GE.W9 - Guarnizioni rif. 4010045;
GE.W10 - Guarnizione rif. 0190286;
GE.W11 - Guarnizione rif. 190288;
GE.W12 - Guarnizione rif. 4010071;

Guarnizioni in TPE - Sistema Wicona WICTEC 60NG
finitura nera:
GT.W1 - Guarnizioni rif. 4010351;

Guarnizioni in silicone
finitura nera
Sistema Wicona WICTEC 60NG:
GS.W1 - Guarnizioni rif. 4020558
Sistema Wicona WICLINE 90 SG
GS.W2 - Guarnizioni perim est rif. 4010413;

Viteria di sistema: Sistema Wicona WICTEC 60:
VS.P1 - Vite autofilettante fissaggio pressore rif. 4070060

Profili a taglio termico in ABS:
Sistema Wicona WICTEC 60NG:
TT.W1 - Profilo rif. 0196063;
TT.W2 - Profilo estensore rif. 4030228;
TT.W3 - Profilo estensore rif. 4030144;
TT.W4 - Profilo rif. 196064;

Estrusi in alluminio - finitura grezza:
AL.F1 - canotto di fissaggio;
AL.F2 - Staffa di fissaggio;
AL.F3 - Profilo "L" 30x20x2 DOMAL rif. XL30202;
AL.F4 - Staffa in acciaio carbonio zincata a caldo supporto peso;
AL.F5 - Staffa in acciaio carbonio zincata a caldo supporto vento;
AL.F6 - Profilo in alluminio, "L" 50x30x3
AL.H1 - Gancio HILTI MFT- HP;
AL.H2 - Binario HILTI MFT- HP;

Lamiere in alluminio - finitura anodizzata naturale arg.:
AL.L1 - spessore 30/10 mm;
AL.L2 - spessore 15/10 mm;
AL.L3 - spessore 20/10 mm;

Lamiere in alluminio - finitura grezza:
AL.G1 - spessore 15/10 mm;

Pannello in lamiera stirata - ITALMESH
in alluminio finitura anodizzata naturale arg.:
AL.ST1- angolare 50x30x3 spessore 15/10 mm + Lamiera stirata;

Tubolari in alluminio - finitura grezza:
AL.G2 - spessore 15/10 mm;

Pannelli ISOLANTI
RW.P1 - spessore 60 mm; ROCKWOOL;
RW.P2 - spessore 100 mm ROCKWOOL;
RW.P3 - pannello lana minerale - Isover_Arena 34
RW.P4 - pannello coibentato LATTONEDIL - Isopar HP
RW.S1 - spessore 25 mm ALUCORE;
RW.S2 - spessore 40 mm; LATTONEDIL;

Separatore Temico
ST.T1 - ONGROFOAM ULTRA 926 white

Impermeabilizzanti in EPDM:
IM.E1 - TRESTARD 420 black FR

Impermeabilizzanti in silicone:
SIL.1 - Silicone neutro WURTH A8 PRO;
SIL.2 - Silicone sigillante MS SPECIAL N - nero;
SIL.3 - Silicone strutturale TORGGLER-Low-Modulus;

Tamponamenti ciechi
PA.C1 - Pannello sandwich commerciale tipo Marcegaglia lamiera esterna liscia, finitura anodizzato naturale sp. 50mm
PA.C2 - Pannello di finitura tipo Honeycomb finitura anodizzato naturale sp. 15 mm;
PA.C3 - Pannello sandwich commerciale tipo Marcegaglia lamiera esterna liscia finitura anodizzato naturale sp. 42mm

Profili in acciaio:
AC.P1 - UPN 160;
AC.P2 - "L" ad ali diseguali 80x120 mm;

Accessori facciata:
BKR.1 - Fondogiunto in filtene;

Profili di ancoraggio in acciaio:
FIX.1 - Cast in channel rif. GP 40/223 (L=250mm) - zincatura a caldo;
FIX.7 - Cast in channel rif. HAC-V 40 (L=300mm)
Vite in acciaio - sistema GL Locatelli:
FIX.2 - Vite V40/22 testa ad ancora rif. D4Z1270-88 - zincatura a caldo;
FIX.8 - Vite HBC-C-N M12x60 8.8F

Profili canalina:
PC.UW - Profili canalina Urano Wall

Accessori in acciaio - sistema GL Locatelli:
FIX.3 - Piastra zigrinata rif. 13/04 - galvanizzata a caldo;
FIX.4 - Contropiastra zigrinata rif. PY2 - galvanizzata a caldo;
FIX.5 - Rondella elastica UNI 1751 rif. AGZ16 - zincata;

Fissaggi chimici:
FIX.6 - Barra filettata Hilit HAS-U 8.8 M12 con resina HIT-RE 500V4;

Lamiere in acciaio - zincate a caldo DX51D +Z100:
AC.Z1 - Lamiera spessore 20/10 mm;
AC.Z2 - Lamiera spessore 15/10 mm;

Fissaggi in acciaio - S275
- verniciati a polvere (Qualisteelcoat):
ST.S1 - Staffa PI GRECO;
ST.S2 - Piatto di regolazione spessore 10mm, grado S235JR;
ST.S3 - Staffa di fissaggio lesena verticale 250x150 SP. 10 mm acciaio Inox Aisi 316 saldata;
ST.S4 - Staffa a canotto inferiore acciaio S275 - galvanizzata a caldo;
ST.S5 - Staffa in acciaio a L 260x150 sp. 10 mm - galvanizzato a caldo;
ST.S6 - staffa in acciaio superiore a canotto in acciaio S275 - galvanizzato a caldo;
ST.S7 - rinforzo montanti a canottto realizzato con due lamiere in acciaio S275 sp. 4 mm - galvanizzate a caldo;
ST.S8 - Tubo quadro 80x80 mm;
ST.S9 - Staffa in acciaio a "L" 90x90x120 sp. 4 mm - galvanizzato a caldo;

Viterie in acciaio
- Inox A2:
VM.S1 - Vite autoforante T.C. con intaglio a croce WURTH Zebra Pias;
VM.S2 - Vite T.E. con filettatura metrica ISO WURTH UNI EN 15048;
VM.S3 - Rondella elastica WURTH UNI EN 1751;
VM.S7 - Vite TPS con filettatura metrica;
VM.S8 - Vite TCEI con filettatura metrica;
VM.S9 - Rondella piana;
VM. S10 - Tubolare inox;
- zincatura a caldo:
VM.S4 - Vite T.E. con filettatura metrica ISO WURTH UNI EN 15048;
VM.S5 - Dado con filettatura metrica ISO WURTH UNI EN 898:2021;
VM.S6 - Vite per calcestruzzo,WURTH W-BS/S in acciaio zincato con testa esagonale flangiata
VM.S11 - Tassello W-FAZ/S in acciaio zincato

Porta Girevole: GEZE - Revo.PRIME

Vetreria:
GL.1A - Vetrocamera (EL. FISSI)
-Lastra esterna: vetro extra-chiaro (low-iron) stratificato, AGC Stratophone 66.4 (6 mm Planibel Clearvision + 1.52mm Acoustic PVB clear + 6 mm Stopray Vision 70/35T on Clearvision pos.2).
Lastre in vetro indurite termicamente (HS)
-Intercapedine: 20mm gas argon (90%) e canalino "warm edge"
-Lastra interna: vetro extra-chiaro (low-iron) stratificato, AGC Stratophone 55.2 (5 mm Planibel Clearvision + 0.76mm Acoustic PVB clear + 5 mm Planibel Clearvision).
Lastre in vetro ricotto (AN);

GL.1B - Vetrocamera (EL. APRIBILI)
-Lastra esterna: vetro extra-chiaro (low-iron) stratificato, AGC Stratophone 66.4 (6 mm Planibel Clearvision + 1.52 mm Acoustic PVB clear + 6 mm Stopray Vision 70/35T on Clearvision pos.2).
Lastre in vetro indurite termicamente (HS)
-Intercapedine: 16 mm gas argon (90%) e canalino "warm edge"
-Lastra interna: vetro extra-chiaro (low-iron) stratificato, AGC Stratophone 55.2 (5 mm Planibel Clearvision + 0.76 mm Acoustic PVB clear + 5 mm Planibel Clearvision).
Lastre in vetro ricotto (AN);

GL.1C - Vetrocamera (EL. APRIBILI)
-6 mm Stopray Vision 70/35T on clearvision;

GL.2A - Vetrocamera (EL. APRIBILI)
-Lastra esterna: vetro extra-chiaro (low-iron) stratificato, AGC Stratophone 46.4 (4 mm Planibel Clearvision + 1.52 mm Acoustic PVB clear + 6 mm Stopray Vision 70/35T on Clearvision pos.2). Lastre in vetro indurite termicamente (HS).
-Intercapedine: 16 mm gas argon (90%) e canalino "warm edge"
-Lastra interna: vetro extra-chiaro (low-iron) temprato, AGC Planibel Clearvision 6 mm.
Lastra in vetro temprata + Heat Soaked (HST);

GL.3A - Vetrocamera (EL. FISSI)
-Lastra esterna: vetro extra-chiaro (low-iron) stratificato, AGC Stratophone 88.4 (8 mm Planibel Clearvision + 1.52 mm Acoustic PVB clear + 8 mm Stopray Vision 70/35T on Clearvision pos.2).
Lastre in vetro indurite termicamente (HS)
-Intercapedine: 20mm gas argon (90%) e canalino "warm edge"
-Lastra interna: vetro extra-chiaro (low-iron) stratificato, AGC Stratophone 66.2 (6 mm Planibel Clearvision + 0.76 mm Acoustic PVB clear + 6 mm Planibel Clearvision).
Lastre in vetro ricotto (AN);

GL.4A - Vetrocamera (EL. FISSI)
Vetro stratificato, AGC Stratobel 88.4 (8 mm Planibel Clearvision + 1.52 mm PVB Clear + 8 mm Planibel Clearvision). Lastra di vetro indurita termicamente (HS);

GL.4B - Lamelle
Vetro AGC Stratobel 1212,4 (12 mm Planibel Clearvision + 1.52 mm PVB Clear + 12 mm Planibel Clearvision).
Lastra di vetro indurita termicamente (HS);

GL.5A - Vetrocamera (EL. FISSI)
-Lastra esterna: vetro extra-chiaro (low-iron) stratificato, AGC Stratophone 66.4 (6 mm Planibel Clearvision + 1.52 mm Acoustic PVB clear + 6 mm Stopray Vision 70/35T on Clearvision pos.2).
Lastre in vetro indurite termicamente (HS)
-Intercapedine: 16 mm gas argon (90%) e canalino "warm edge"
-Lastra interna: vetro extra-chiaro (low-iron) stratificato, AGC Stratophone 66.2 (6 mm Planibel Clearvision + 0.76 mm Acoustic PVB clear + 6 mm Planibel Clearvision).
Lastra di vetro indurita termicamente (HS).

Figure 32: Material List. Source: Author

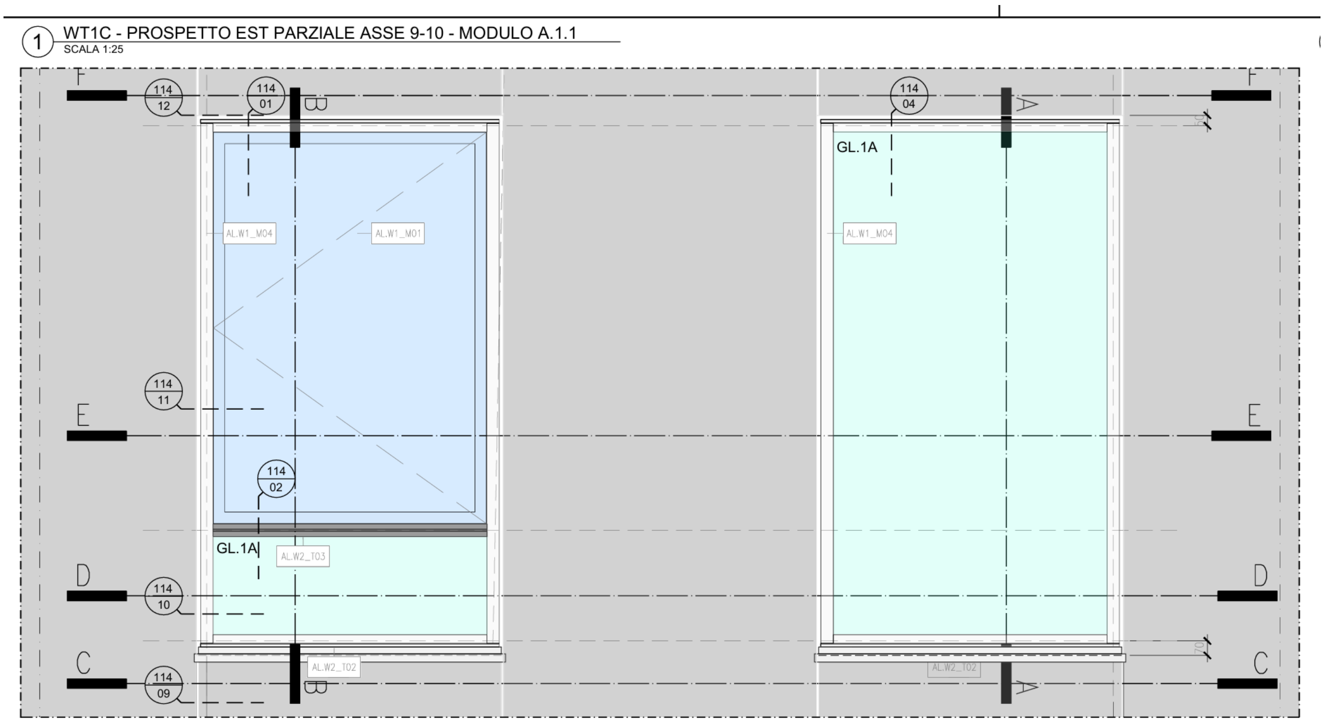


Figure 33: Typical Elevation. Source: Author

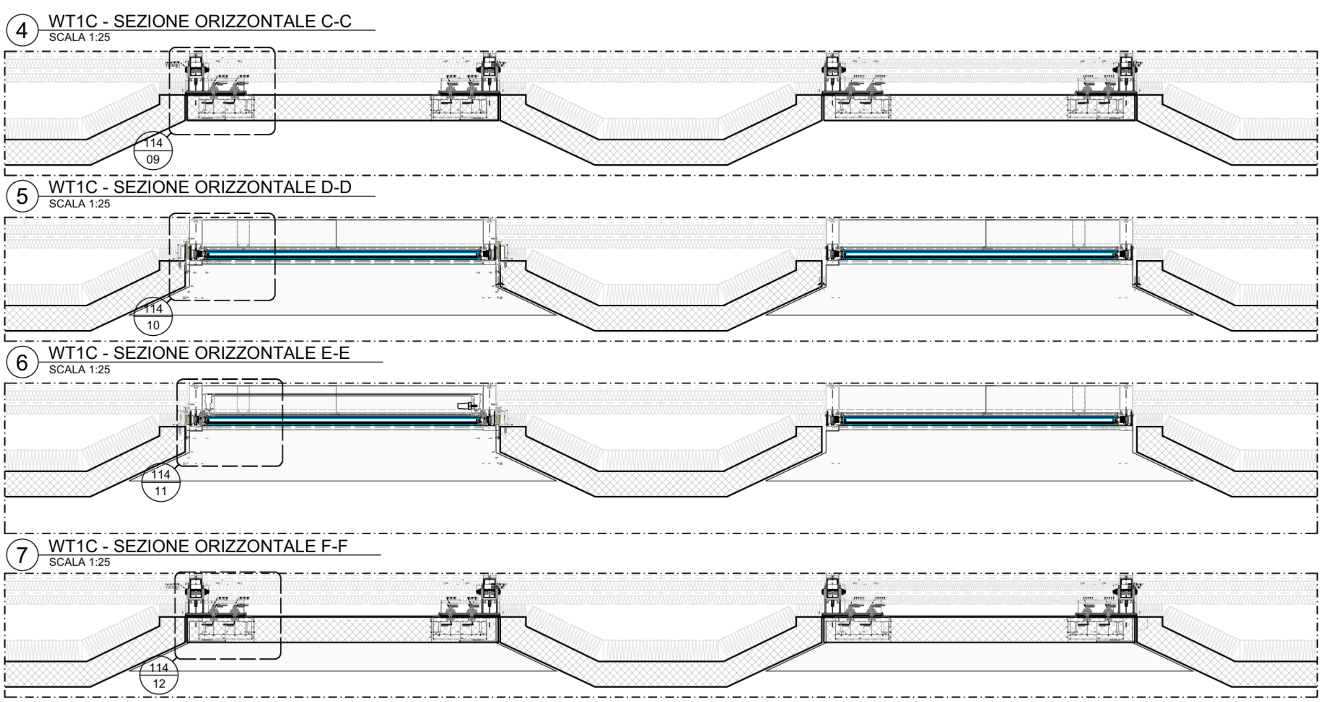


Figure 34: Detail Horizontal sectional plans : Author

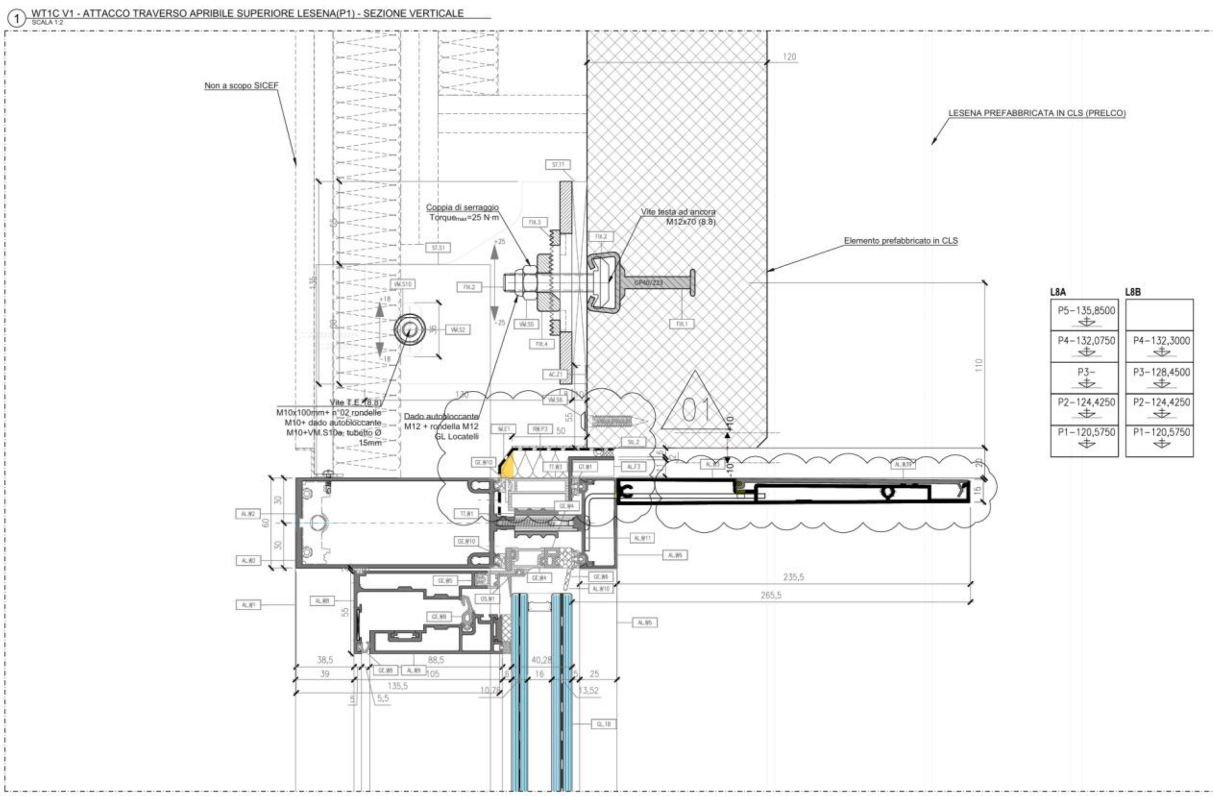


Figure 35: Vertical Detail 114-01: Author

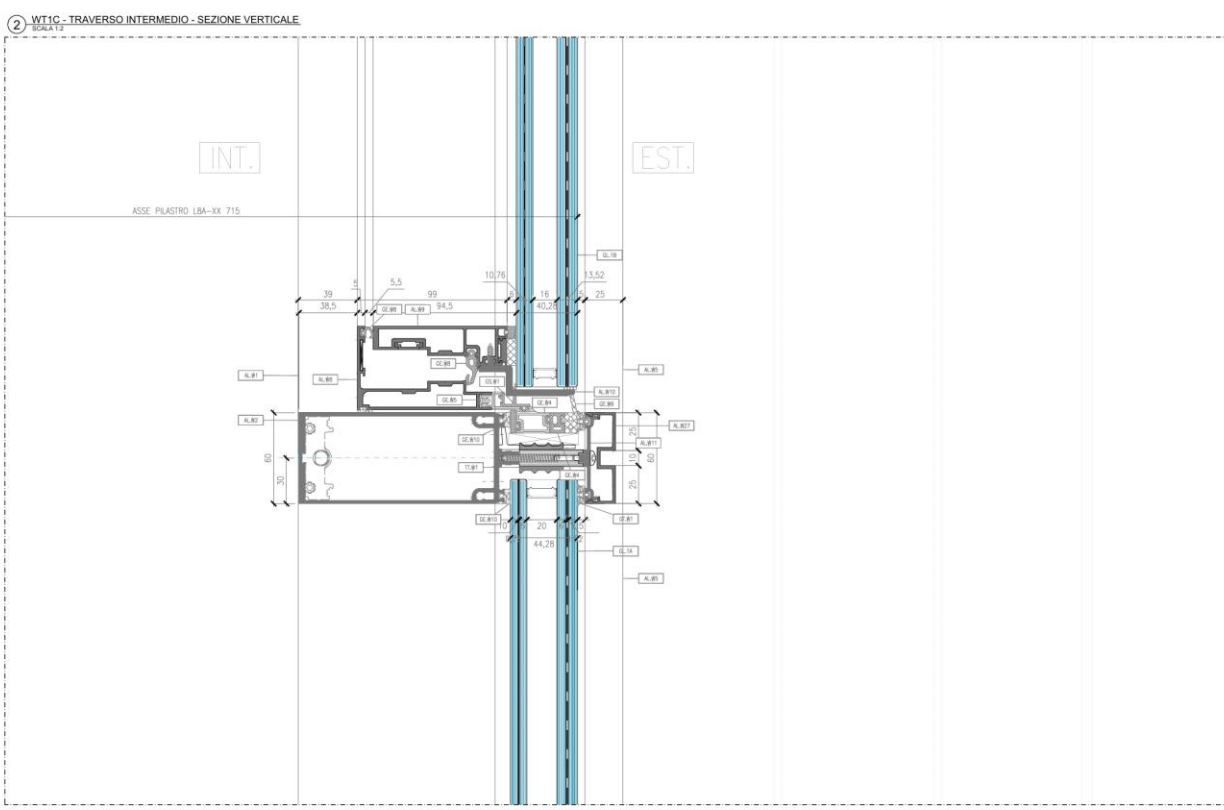


Figure 36: Vertical Detail 114-02: Author

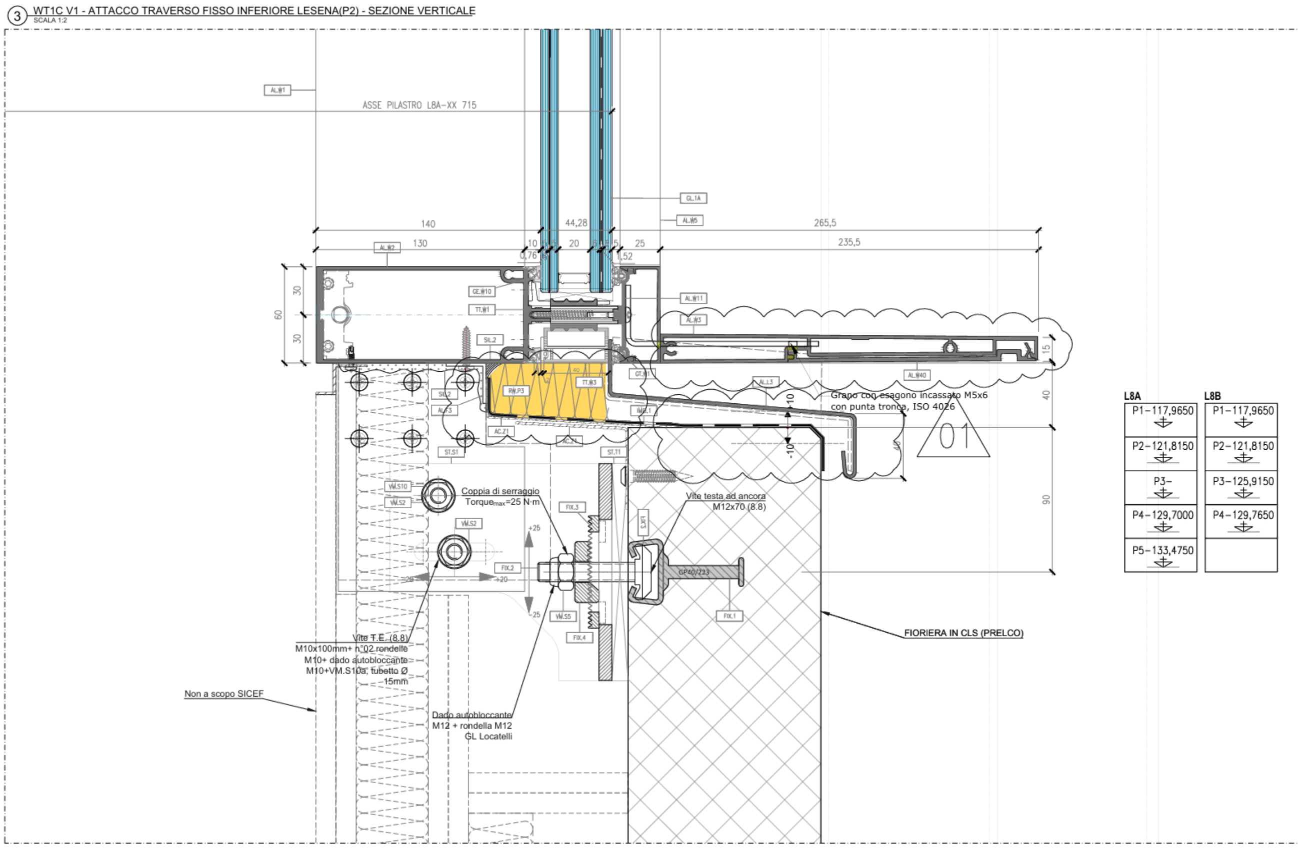


Figure 37: Vertical Detail 114-03: Author

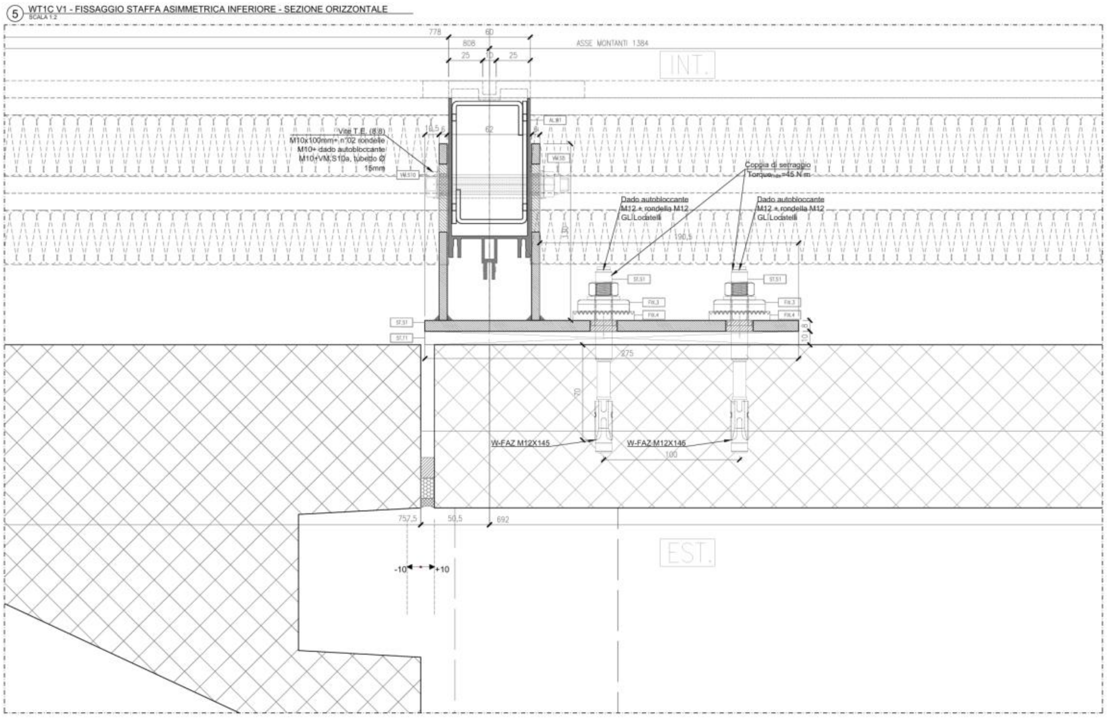


Figure 38: Vertical Detail 114-09: Author

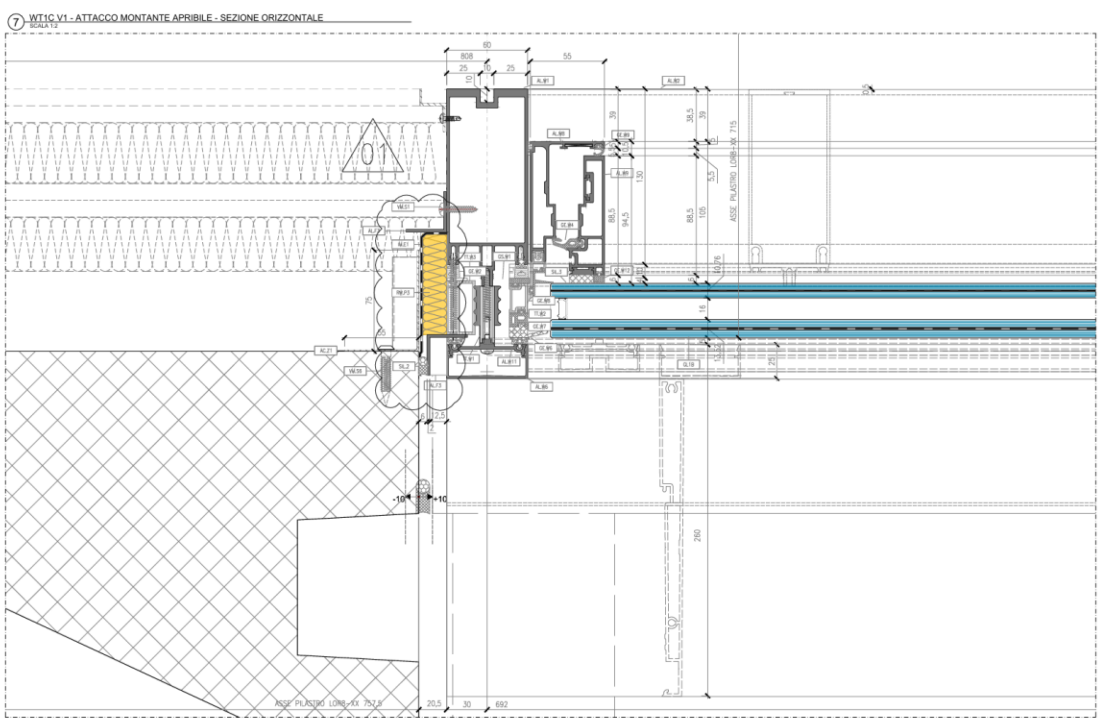


Figure 39: Vertical Detail 114-10: Author

8.3. Critical Node Analysis (Comparative Details)

8.3.1. Node 1: The Standard Top Bracket Connection

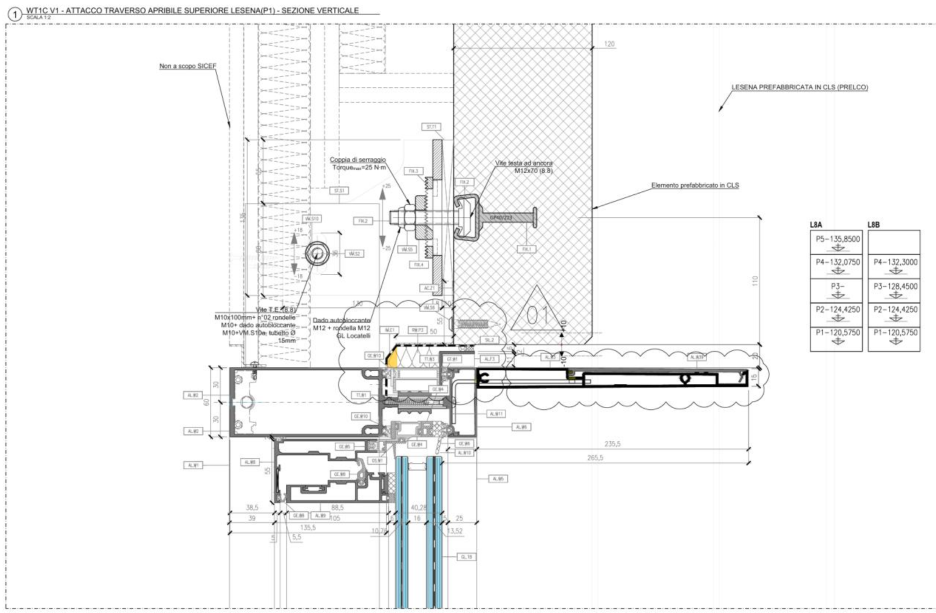


Figure 40: Standard Top Bracket Connection Detail developed with AutoCAD: Author

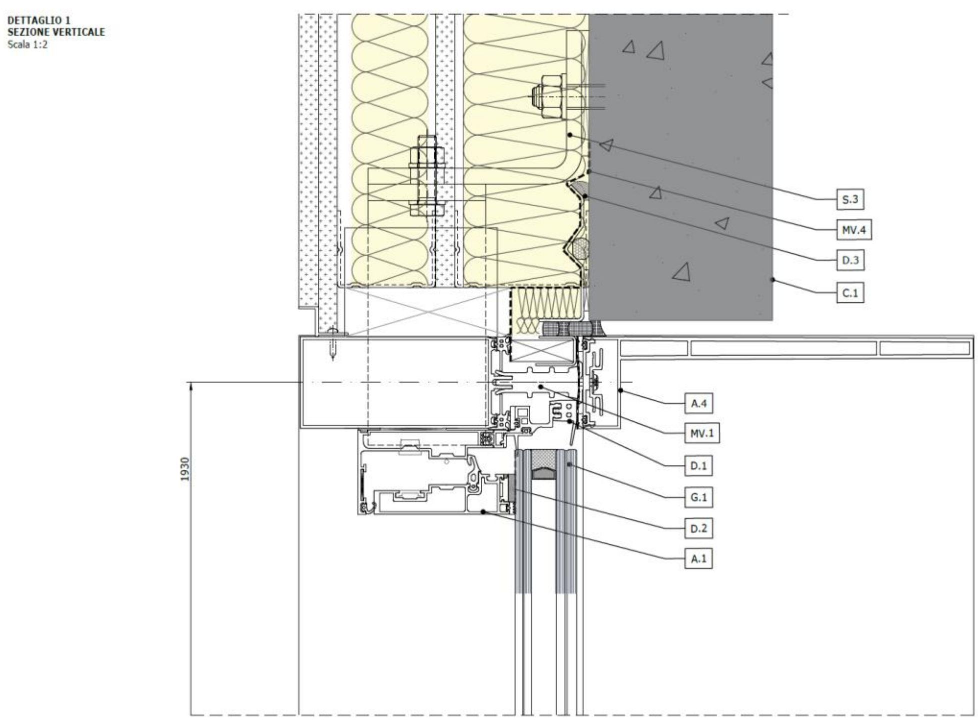


Figure 41: Standard Top Bracket Connection Detail developed with Revit: Author

Figure 40 (AutoCAD): The 2D detail is characterised by high graphical density. The waterproofing membranes (EPDM) are drawn as complex, continuous polylines that fold specifically around the bracket head. The thermal break shim is clearly hatched to distinguish it from the steel. The "Fixed Point" bolt configuration is explicitly drawn with a defined nut-and-washer stack.

Figure 41 (Revit): The 3D view presents the bracket as a simplified volumetric solid. While the overall space claim is accurate, the intricate "soft" layers (membranes, tape, sealants) are omitted or simplified to flat planes. The bolt is represented as a generic cylinder without a thread definition.

Technical Comparison

1. **Waterproofing Strategy**

The critical failure point in this node is water ingress at the slab edge. The AutoCAD detail serves as a step-by-step guide for the installer, showing how to overlap the EPDM foil onto the concrete. The Revit model, by omitting these laps to save file size, fails to communicate the watertightness continuity.

2. **Structural Coordination**

The AutoCAD detail assumes the concrete slab is a limitless solid. In contrast, the Revit model utilised "Transparency Views" to reveal the slab's internal steel reinforcement. This highlighted a potential clash: the anchor bolt locations in the standard bracket could interfere with the bottom layer of slab rebar. Revit enabled the simulation of moving the bracket 20mm laterally to verify a clear anchor path.

3. **Thermal Bridge Visibility**

In AutoCAD, the PVC thermal isolator is highlighted with a specific hatch pattern, making it a mandatory visual check. In Revit, the isolator is a small 5mm object that can be easily invisible in a large model, increasing the risk that it will be accidentally deleted or overlooked during material takeoff.

8.3.2. Node 2: The Standard Bottom Bracket Connection

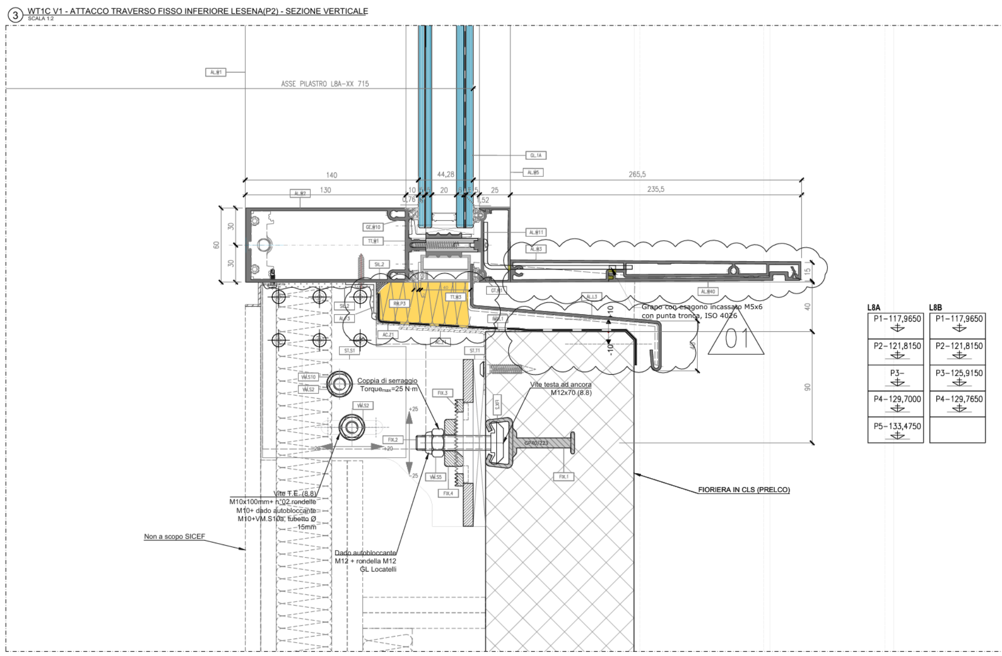


Figure 42: Standard Bottom Bracket Connection Detail developed with AutoCAD: Author

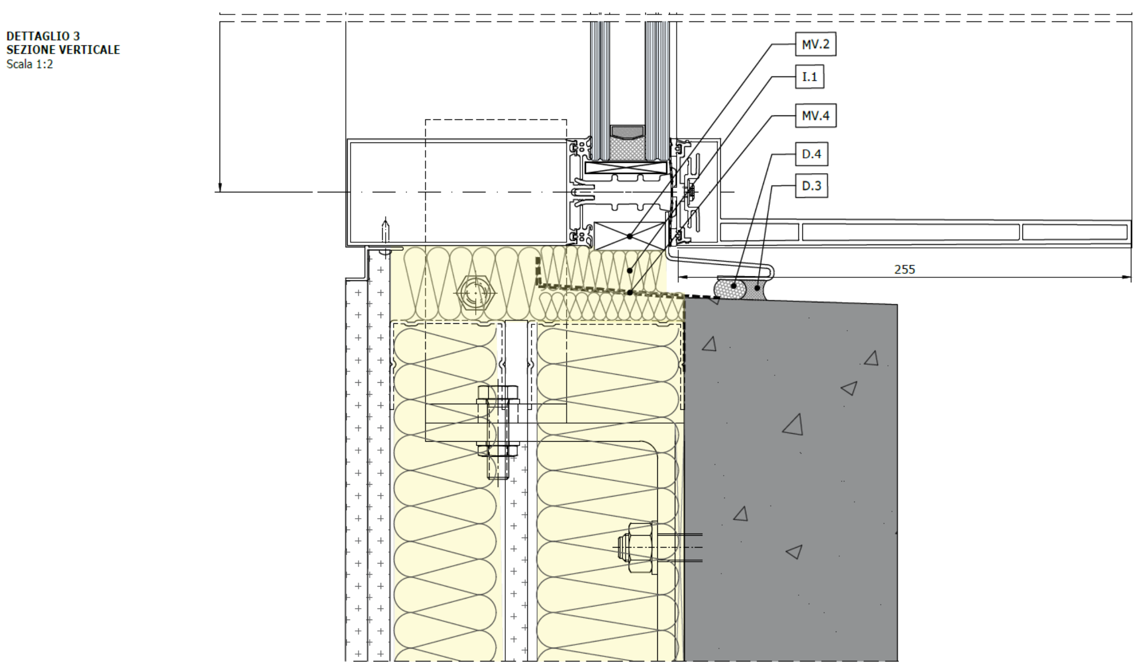


Figure 43: Standard Bottom Bracket Connection Detail developed with Revit: Author

Figure 42 (AutoCAD): The detail focuses on the interface with the internal floor finish. It explicitly draws the "Raised Floor" pedestal and the precise alignment of the aluminium sill profile to ensure the floor tile sits flush. The expansion slot in the bracket is annotated with a dimension showing the required clearance.

Figure 43 (Revit): The detail effectively illustrates the relationship between the façade and the MEP systems. The 3D view visualises the "Fan Coil Unit" (FCU) box located in the floor void and checks whether the bracket obstructs the air supply grille.

Technical Comparison

1. **Movement Dynamics**

The concept of a "Sliding Joint" is dynamic. In AutoCAD, the movement is represented by a static arrow and a text note ("Allow +/- 15mm"). In Revit, the parametric family allows the engineer to physically slide the mullion up and down to verify whether the spigot disengages or the transom contacts the floor finish at maximum deflection. This "Motion Study" provides a higher level of safety assurance.

2. **Floor Interface Precision**

The junction between the aluminium sill and the raised floor tile requires millimetre-perfect tolerance to avoid a trip hazard. AutoCAD allows the architect to draw the specific silicone pointing and the stainless steel edge trim profile. Revit typically models the floor as a generic slab, lacking the finesse to define the specific edge trim condition needed for the "Progetto Esecutivo."

3. **Spandrel Insulation Continuity:**

The AutoCAD detail clearly traces the continuous line of the vapour barrier from the spandrel back-pan to the floor slab. This continuity is difficult to trace in Revit, where the insulation is often modelled as separate, disjointed blocks (Facade Family vs Floor Family).

8.3.3. Node 3: The Standard Horizontal Corner Connection

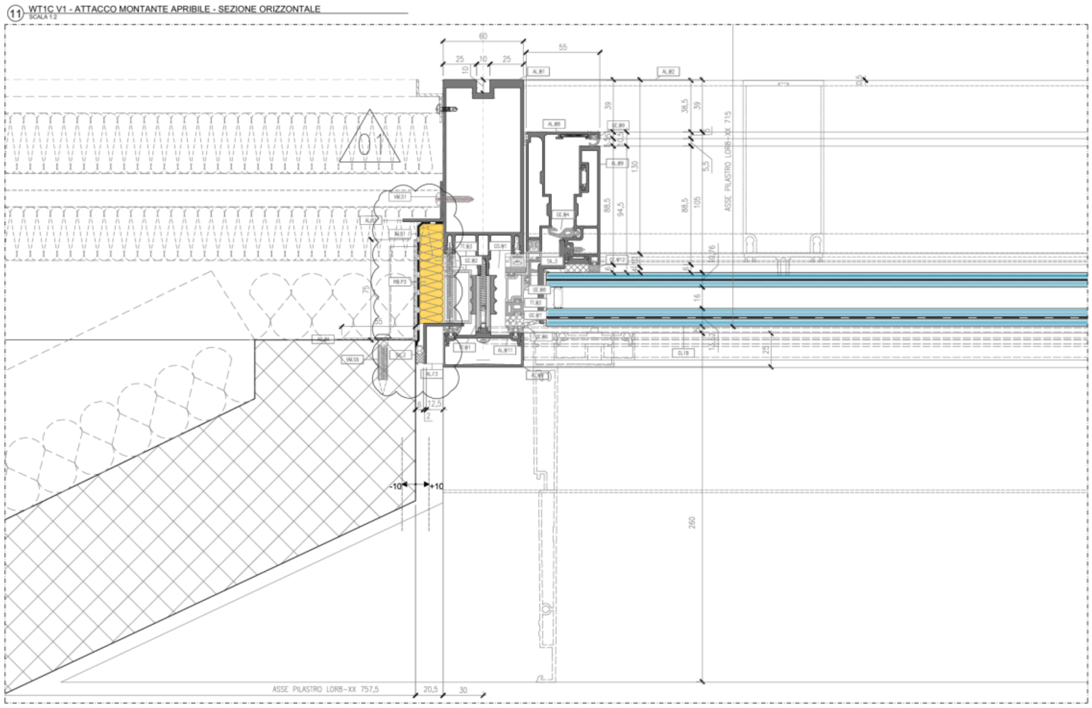


Figure 44: Standard Horizontal Corner Connection Detail developed with AutoCAD: Author

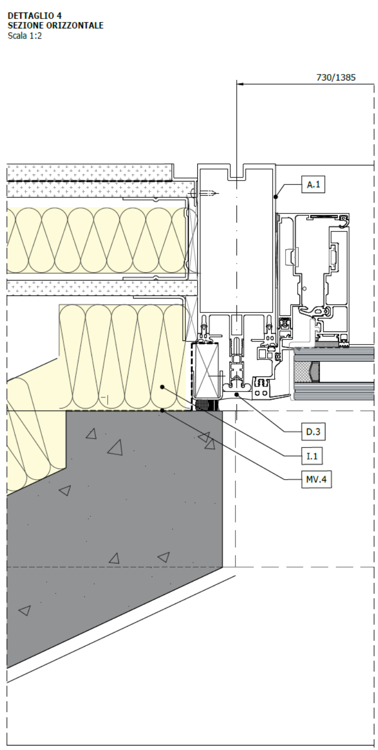


Figure 45: Standard Horizontal Corner Connection Detail developed with Revit: Author

Figure 44 (AutoCAD): The 2D Plan view shows the precise mitre joint of the cover caps and the large volume of silicone sealant required to weather-seal the gap between the two mullions. It clearly defines the "mating" of the two aluminium profiles.

Figure 45 (Revit): The 3D view ("Exploded Axonometric") shows the components pulled apart: the inner mullion, the pressure plate, and the outer cap. This view clarifies the mechanical assembly order.

Technical Comparison

1. **Installation Sequence (Winner: Revit):**

A major site challenge with corners is "Screw Access." Can the installer physically fit their drill between the two mullions to tighten the pressure plate? The 2D CAD plan does not show the drill tool. The 3D Revit model supports a "Constructability Check" by modelling the drill tool in the space to demonstrate that installation is physically possible.

2. **Sealant Volume Calculation (Winner: AutoCAD):**

Corner joints rely heavily on structural silicone to close the gap. AutoCAD allows the quantity surveyor to measure the exact cross-sectional area of the sealant joint ($Area \times Length$) to order the correct number of silicone cartridges. Revit models this gap as empty space, making accurate material estimation for "wet" sealants impossible.

3. **Mitre Complexity:**

The aesthetic success of a corner depends on the mitre cut of the cover cap. AutoCAD allows for the precise drafting of the "sharp" vs. "blunt" corner connection. Revit often displays a default join that looks clean but creates an impossible manufacturing condition (e.g., overlapping solids) that the fabricator would reject.

9. Conclusion

9.1. Research Summary

This thesis investigated the "Interoperability Gap" in modern façade engineering, focusing on the friction between macro-scale spatial coordination enabled by Building Information Modeling (BIM) and the micro-scale accuracy required for manufacturing and site installation. A detailed comparative study of a complex commercial renovation in Milan ("Project L") evaluated the efficacy of two distinct digital environments: a traditional 2D CAD-based approach (AutoCAD) and an integrated 3D BIM-based approach (Revit).

The research focused on a high-performance Stick Curtain Wall System (WT1C typology) and aimed to determine how the Façade Consultant can successfully bridge the gap between the rough tolerances of the primary civil structure and the exacting tolerances of the aluminum envelope. The results show that, although the Architecture, Engineering, and Construction (AEC) industry is advancing toward a "BIM-only" delivery standard, current software paradigms are not yet sufficient to fully replace 2D CAD for generating fabrication-ready "Progetto Esecutivo" details.

9.2. Synthesis of Findings: The "Hybrid" Reality

The comparative study of the critical architectural nodes (Top Bracket, Bottom Bracket, and Corner Assembly) produced three distinct technical findings regarding the application of digital tools to Stick Systems:

1. **Geometric Validation (The Domain of BIM):** The research demonstrated that BIM is highly effective for volumetric "Space Claiming" and structural coordination. In the Milan case study, the 3D model identified critical "hard clashes," such as anchor bolts intersecting with concrete reinforcement and brackets conflicting with structural columns, which were not apparent in standard 2D sections. Additionally, the parametric environment enabled

dynamic "Kinematic Checks" to visually verify that adjustable brackets provided sufficient slot length to accommodate measured site deviations.

2. **Material Definition (The Domain of CAD):** Conversely, the research found that BIM faces major challenges with "Materiality" at the micro-scale. Complex, non-rigid layers essential for building physics and weather-tightness, such as thin EPDM membranes, foil lap joints, and sealant beads, could not be precisely modeled in Revit without causing severe "Model Overload" and computational lag. 2D CAD remained the only effective and computationally efficient tool capable of producing the explicit, step-by-step "Instruction Manual" required by the site installation team to ensure a watertight envelope.
3. **The "Consultant's Dilemma":** The study indicates that utilizing a single software workflow brings considerable project risk. Exclusive reliance on BIM increases the risk of Watertightness Failure due to undefined or simplified sealing layers, while exclusive reliance on 2D CAD increases the risk of Constructability Failure due to undetected, multi-dimensional structural clashes.

9.3. Answers to Research Questions

Based on the empirical evidence gathered, the research questions established at the outset are addressed as follows:

RQ1: To what extent can BIM effectively replace traditional 2D CAD workflows for the detailed design and fabrication of Stick System curtain walls?

A: At the current technological level (LOD 350-400), standard architectural BIM cannot replace 2D CAD effectively in the final execution phase. The geometric rigidity and computing requirements required to achieve manufacturing-level fidelity render the model unmanageable. While BIM automates Bill of Quantities (BoQ) and grid layout, CAD remains the essential "Source of Truth" for defining complex waterproofing logic and legal construction documentation.

RQ2: How can the "Consultant's Dilemma", the management of tolerances between the rough concrete structure and the precise aluminum grid, be resolved using digital tools?

A: Solving this dilemma requires a coordinated 3D-to-2D translation. The 3D environment is used to map "Civil Deviations" (Survey Point Cloud versus Theoretical Grid) to define the bracket's spatial position and adjustment capacity. Subsequently, the 2D detail defines the specific connection typology, thermal-break continuity, and sealing strategy required to address the identified geometric gap.

RQ3: What is the optimal "Integrated Methodology" that leverages the strengths of both platforms?

A: The optimal methodology is a Hybrid Workflow. This approach methodically utilizes BIM for worldwide coordination, clash detection, and parametric scheduling, while retaining 2D CAD for generating 1:5-scale construction sections. The effectiveness of this workflow depends on data linkage, with 3D BIM elements containing embedded metadata that directly reference the detailed 2D CAD sheets.

9.4. Guidelines for Professional Practice

Informed by the study's comparative findings regarding the limitations and strengths of both BIM and 2D CAD workflows, the following targeted guidelines are recommended for Façade Consultants to optimize project delivery in the current transitional market:

1. **Establish a strict "LOD Split":** Avoid over-modeling by implementing a clear BIM Execution Plan (BEP) protocol that limits the 3D model to the "Profile Outer Boundary" (LOD 300) to maintain file performance, while 2D details are used for internal components, gaskets, and screws (LOD 400).
2. **"Clash First, Draw Second" Protocol:** Do not begin detailed 2D drafting of a defined structural interface until a basic 3D massing check has been performed against the primary

structure model. This method prevents the costly drafting of bespoke details that are geometrically impossible to install on site.

3. **Treat tolerance as a primary design element:** In renovation or "Brownfield" projects, the adjustable anchor bracket should be considered a critical design driver rather than an accessory. It must be modeled dynamically in 3D to demonstrate spatial viability before mass procurement.

9.5. Limitations and Future Research

It is important to acknowledge that this study's focus on the Stick System (Mullion-Transom) typology constitutes a significant limitation, as the findings concerning workflow efficacy may not be directly transferable to other façade systems. In particular, Unitized Curtain Wall Systems, which rely on factory-controlled off-site prefabrication, present distinct challenges and opportunities for digital workflow integration. The use of advanced Mechanical CAD (MCAD) software (e.g., Autodesk Inventor, SolidWorks, or Dassault Systèmes CATIA) in unitized systems enables higher geometric fidelity and enhanced control over micro-scale assemblies, often surpassing the capabilities of conventional architectural BIM platforms. This fundamental difference suggests that the operational constraints, data exchange requirements, and the efficacy of digital tools identified in the context of Stick Systems may limit the generalizability of the present study's conclusions. Therefore, further research is required to critically evaluate whether similar interoperability gaps exist in the digital delivery of unitized façades and to what extent these alternative workflows can inform best practices across varying façade system typologies.

Future research should specifically explore the development of integrated workflows for embedding native MCAD assemblies, including parametric curtain wall nodes and custom bracket components, directly within existing architectural BIM platforms such as Autodesk Revit. Comparative studies examining interoperability solutions, including IFC-based data exchange and native plugin development, would provide valuable insight. In addition, rigorous investigation is needed into the automation of 2D waterproofing detail generation using Visual Programming languages and Generative Design frameworks (for example, implementing Dynamo scripts to extract tolerance data from point cloud analysis or deploying Grasshopper definitions to translate 3D deviations into annotated construction-ready details). Experimental pilot projects linking automated 3D-to-2D translation outcomes with actual site installation quality would deliver measurable evidence regarding the viability of such tools to fully support and potentially close the identified interoperability gap.

9.6. Concluding Remarks

The digitalization of the Architecture, Engineering, and Construction industry involves the intelligent and calculated integration of traditional methodologies rather than their complete replacement. For the Façade Consultant, the ultimate value delivered to the client is not the creation of a "perfect digital model," but the execution of a "perfect physical building."

As demonstrated by the Milan case study, the most effective approach to producing a watertight, thermally efficient, and structurally sound building envelope is to fully utilize the volumetric coordination capabilities of Building Information Modeling while retaining the communicative clarity and accuracy of 2D technical drawings. The immediate future of façade engineering lies in the synchronized, carefully managed coexistence of 2D and 3D methodologies.

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