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Performance-driven choice of steel vs aluminum curtain walls: a scenario-based comparison

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ABSTRACT

Curtain wall systems play a key role in the aesthetic of modern buildings, serving as a bridge between architectural look and engineering requirements. This study presents a comparative engineering evaluation of steel and aluminum curtain wall systems using a novel Performance Index (PI) framework. The study integrates qualitative SWOT analysis and parametric analysis to support context-specific material selection for projects with seismic, fire-rated, or sustainability priorities. The PI model quantifies compromise across key criteria such as strength, fire resistance, environmental impact, aesthetics, and cost. Results show that steel excels in structurally demanding and fire-critical applications, while aluminum offers superior corrosion resistance, aesthetic flexibility, and environmental advantages. The extended PI model further demonstrates that aluminum becomes competitive in visually expressive and sustainability-driven designs. Ultimately, this framework empowers engineers and architects to make smarter, context-sensitive decisions when selecting curtain wall materials, balancing safety, sustainability, and design intent.

1 Introduction

1.1 Background

In an era where buildings must balance efficiency, resilience, and visual impact, curtain wall systems have emerged as a defining feature of 21st-century architecture. Cities like Singapore, Dubai, and New York are increasingly relying on advanced façade systems to meet ambitious energy and performance goals. As buildings evolve to meet higher expectations in energy performance and visual expression, the choice of façade materials becomes increasingly complex and consequential.

Curtain wall systems are a defining feature of modern architecture, combining structural efficiency with aesthetic versatility. Steel and aluminum are among the most widely used materials for curtain wall framing, each offering distinct advantages across mechanical, economic, and environmental dimensions. Aluminum's lightness and natural corrosion resistance make it a favorite among designers aiming for sleek, low-maintenance exteriors.

According to a recent market analysis by Global Market Insights (2024), the aluminum curtain wall market was valued at approximately USD 43.6 billion in 2023 and is projected to grow at a compound annual growth rate (CAGR) of over 7.1% from 2024 to 2032. This growth is driven by rapid urbanization, increasing demand for energy-efficient

buildings, and advancements in façade technologies. Particularly in the Asia-Pacific region, countries such as China and India are experiencing significant construction activity, contributing to a regional market value that exceeded USD 19 billion in 2023, with projections reaching USD 35.8 billion by 2032. Key trends include the adoption of unitized systems for faster installation and the integration of innovative building technologies into curtain wall systems for enhanced performance and monitoring [1].

In addition to conventional carbon steel systems, stainless steel curtain wall systems are gaining increasing attention in high-performance façade applications due to their enhanced durability, corrosion resistance, and aesthetic appeal. According to the curtain wall market [2], [3], the market is experiencing steady growth, driven by demand for long-life, low-maintenance façade solutions in coastal, industrial, and high-humidity environments.

Curtain wall systems are non-structural cladding systems used in building envelopes to resist air and water infiltration, sway induced by wind and seismic forces, and support their self-weight. Traditionally, Aluminum has dominated this market due to its lightweight and corrosion-resistant nature, as shown in Table 1. However, with increasing demand for seismic resilience, steel is gaining traction, especially in designs requiring high deformability and load-bearing capacity under significant forces [4].

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Table 1. Comparative overview: steel vs. aluminum [5]

Property	Steel	Aluminum
Strength	High strength; ideal for seismic loads	Moderate strength; requires larger profiles
Weight	Heavier	Lightweight
Corrosion Resistance	Requires coating; prone to rust	Naturally corrosion-resistant
Fabrication	More difficult to fabricate	Easy to extrude and shape
Aesthetics/Finishing	Limited finish options	Superior finishing and color options
Cost	Higher initial cost	Lower initial cost
Maintenance	Requires regular inspection/coating	Low maintenance

Although curtain wall systems are classified as non-structural cladding, their material behavior, anchorage design, and integration with structural systems significantly influence the building's overall seismic response. In particular, steel curtain wall frames, due to their high strength and ductility, are better suited to accommodate inter-story drift, seismic-induced deformation, and dynamic demands without compromising façade integrity. Furthermore, in hybrid or performance-based designs, steel frames can be mechanically connected to structural bracing elements or backup frames, thereby enabling enhanced load transfer and minimizing the risk of detachment or glazing failure during seismic events. While the curtain wall itself does not carry gravity or lateral structural loads, its ability to remain intact and deform compatibly with the primary structure is essential for life safety, post-earthquake reparability, and façade performance continuity.

In addition to conventional carbon steel systems, stainless steel curtain walls are gaining traction in high-performance applications due to superior durability and aesthetics. However, stainless steel comes with higher costs and is not the focus of this study. The current work focuses on carbon steel and aluminum, which are the dominant framing materials.

1.2 Literature review

While market trends are clear, selecting the right curtain wall material involves a complex interplay of structural, environmental, aesthetic, and economic factors. Several researchers have introduced multi-criteria models to guide material selection, particularly in the context of building envelopes. New trends include using brushed and mirror-like finishes for high-quality buildings and combining glass technology with stainless steel frames for a smooth look. While stainless steel systems typically necessitate higher material and fabrication costs, their lifecycle performance, fire resistance, and minimal maintenance requirements make them a strategic choice for landmark buildings and infrastructure projects aiming for long-term value and sustainability [6]. The global stainless steel curtain wall market is projected to grow steadily from approximately USD 1.5 billion in 2024 to USD 2.5 billion by 2033, representing a compound annual growth rate (CAGR) of 6.5%. This upward trend reflects increasing demand across multiple regions, particularly in North America, Europe, and Asia-Pacific, driven by urban development, architectural innovation, and the need for durable, low-maintenance façade systems. While market trends are clear, choosing the right material still requires careful understanding of performance trade-offs, which this study sets out to explore [6].

Despite widespread use, there exists a need for a comprehensive, quantitative comparison between these materials that goes beyond qualitative trade-offs. This study introduces a performance index-based framework. It applies

scenario-specific evaluations to assess how Aluminum and steel perform across key criteria such as strength-to-weight ratio, lifecycle carbon emissions, fire resistance, and cost efficiency. By integrating SWOT analysis [7], [8], normalized performance scoring, and visual data modeling, the paper aims to explore how to guide engineers, architects, and developers in selecting the most appropriate framing material based on performance priorities and environmental context.

Recent advances in materials engineering have emphasized the need for multi-criteria frameworks to support material selection in building envelopes, particularly where structural, environmental, and aesthetic factors intersect. Ashby's foundational work on performance indices (e.g., σ/ρ) provided a basis for comparing materials based on mechanical efficiency alone [9], [10]. Building upon this, researchers such as Jahan et al. [11], [12], [13] and Papadopoulos and Giama [14] have employed multi-criteria decision-making (MCDM) methods like TOPSIS and environmental scoring models to incorporate factors such as cost, recyclability, and life-cycle impact into material selection. However, these methods often involve complex weighting schemes or black-box optimization, limiting their accessibility for architects and façade engineers. More recent studies, such as [15], [16], and [17], have introduced optimization techniques that consider aesthetics and energy performance. Several researchers, such as those in [18], [19], [20], [4], [21] have highlighted the need for quantitative evaluation in selecting fire and seismic-resistant materials for curtain wall systems. Despite these contributions, there remains a gap in the literature for a transparent, scenario-adaptive, and visually interpretable model tailored to façade engineering.

1.3 Research objectives and contribution

This study addresses that gap by introducing a dual Performance Index (PI and PI_{ext}) framework that normalizes key parameters including strength, fire resistance, environmental impact, cost, and aesthetic flexibility, into a unified, unitless scoring system suitable for early-stage design decision-making.

The research aims to:

- Provide a clear, quantitative comparison of steel and aluminum curtain wall systems.
- Offer a scenario-based analysis to understand how performance priorities affect material choice.
- Combine qualitative SWOT analysis with a normalized PI framework to bridge design and engineering priorities.
- Present a visually interpretable tool (e.g., radar chart) for professionals in architectural and engineering design.

The study also highlights practical trade-offs using market data, literature benchmarks, and manufacturer specifications, offering a holistic approach to façade material selection.

2 Methodology

The research employs a quantitative and qualitative approach to compare steel and aluminum curtain wall systems. The methodology consists of a SWOT analysis and the PI index approach. To complement the quantitative findings, a SWOT analysis identifies each material's strengths, weaknesses, opportunities, and threats. A radar chart is generated to visually present comparative data across ten normalized performance factors.

A custom Performance Index (PI) is formulated using Equation (1).

$$PI = \frac{(\sigma \times \phi \times \varepsilon)}{(\rho \times \kappa)} \quad (1)$$

In addition, Equation (2) is used for Extended PI (PI_{ext}) with Aesthetic Consideration

$$PI_{\text{ext}} = \frac{(\sigma \times \phi \times \varepsilon \times \alpha)}{(\rho \times \kappa)} \quad (2)$$

Where:

σ	Structural strength	MPa (megapascal) = N/mm ²
ϕ	Fire resistance	Hours (h)
ε	Environmental factor	Dimensionless (0–1 scale)
ρ	Density	kg/m ³
κ	Cost factor	Dimensionless (1–3 scale)
α	Aesthetic Consideration	

These formulas reflect the trade-offs between performance benefits and material limitations, allowing comparative scoring under different project contexts. This extended formulations enables the PI to reflect both engineering and architectural priorities, particularly for projects where visual appeal and surface customization are essential.

The formulations of PI and PI_{ext} used in this study are adapted from established materials selection principles (e.g., Ashby's indices [9], [10]), which compare performance via mechanical or cost-related ratios. However, this study contributes a customized, scenario-adaptive framework in which multiple parameters including fire resistance, environmental factor, and aesthetic flexibility are integrated into a single scoring system. While the mathematical structure of the index is not new per se, its application to curtain wall materials, the selection and normalization of parameters, and its use in parametric case modeling are novel contributions. Therefore, rather than proposing a new theoretical model, we present a performance evaluation framework that enables structured, data-driven comparison in façade design. The term "model" is used throughout the paper in this applied sense.

The parameter α in the PI_{ext} formulation represents aesthetic and finishing flexibility, which is a relevant consideration in architectural façade design. Since aesthetics are inherently subjective, the α score was assigned through a qualitative assessment based on three key criteria:

- (1) Range of available finishes and colors,
- (2) Ease of achieving custom surface treatments, and
- (3) Suitability for integration with modern architectural styles (e.g., minimalism, transparency, industrial).

On a normalized scale of 0 to 10, aluminum was assigned a score of 9, due to its superior ability to accommodate anodizing, powder coating, polishing, and color matching with minimal fabrication effort. Carbon steel received a score

of 6, reflecting moderate aesthetic flexibility, typically requiring additional coatings or claddings to achieve desired finishes. Stainless steel scored 8, offering high-end visual finishes (e.g., brushed, mirror, etched), especially in prestige projects, but at a higher cost and lower availability in varied colors.

These scores are aligned with industry practice and façade material guidelines (e.g., CWCT and ASTM finish classifications), and provide a consistent basis for comparing materials in design-sensitive applications.

Aesthetic flexibility (α) was assessed based on finish variety, surface treatment compatibility, and architectural integration potential, in alignment with surface finish classifications and appearance standards defined in ASTM A480 [22], ASTM B209 [23], and CWCT [24]. These standards provide industry benchmarks for architectural-grade surface treatments, color consistency, and visual performance.

When projects demand maximum strength and safety, like high-rises or fire-sensitive zones, steel remains the engineer's material of choice. A scenario-specific, performance-index approach enables smarter, data-driven decisions in curtain wall material selection. This integrated methodology supports a balanced, scenario-sensitive material selection framework for architects, façade engineers, and developers. While the PI model offers a numerical value for comparing materials, real-world decisions also depend on qualitative factors. To address this, a SWOT analysis was conducted to assess each material's broader strategic implications.

For comparative clarity and consistency, all input parameters used in the PI and PI_{ext} models have been scaled using consistent units across both materials. While full normalization (i.e., converting all parameters to a unitless 0–1 range) was explored during model development, the final analysis retains dimensional values to preserve interpretability and traceability to real-world material properties. Nevertheless, the PI model structure allows for straightforward normalization if required for future comparative studies or integration into multi-criteria decision-making tools.

The selection of parameters for the Performance Index (PI) and its extended form (PI_{ext}) was based on their critical relevance to structural performance, fire safety, environmental impact, cost efficiency, and aesthetic adaptability, all of which are key priorities in early-stage curtain wall system design. These parameters were chosen due to their direct influence on material selection in fire-rated, seismic, and design-sensitive applications, where trade-offs between safety, sustainability, and visual intent are most pronounced. While thermal insulation and acoustic transmission are also important performance aspects of façade systems, they were not included in this version of the PI model due to the lack of standardized, comparable data across different curtain wall frame materials in the public domain. Additionally, thermal and acoustic performance in curtain walls is significantly influenced by the glazing system, spandrel design, and insulation configuration, which vary widely between systems and manufacturers, making normalization difficult.

Similar approaches using performance indices have been adopted in materials selection research, notably in the works of Ashby [9], [10], Jahan et al. [11], [12], [13], and Papadopoulos and Giama [8], where mechanical, cost, and sustainability factors dominate the assessment framework. While these studies primarily focus on structural or component-level materials, the current paper extends such

methods into façade engineering by integrating scenario-based parameters, including aesthetics, which are typically underrepresented in quantitative models.

The proposed PI framework is modular and can be extended to include thermal transmittance (U-value) and sound transmission class (STC/Rw) in future iterations, provided that consistent datasets are available. A modified version of the PI formula could incorporate these additional parameters either through multiplicative factors or as additive penalty/reward terms, depending on the intended application context. This remains a promising direction for future research, especially for projects where energy efficiency and occupant comfort are prioritized alongside structural and visual performance.

To provide context for the cost factor included in the PI_{ext} , indicative façade system costs were compiled based on industry reports and manufacturer data. While actual costs vary depending on region, finish, fire rating, and system complexity, Table 2 shows approximate ranges reflect base-level procurement and installation prices per square meter [25].

Aluminum systems remain the most cost-effective in most commercial applications due to their lightweight, ease of extrusion, and widespread availability. Steel systems, while heavier and more fabrication-intensive, are increasingly used in seismic and fire-rated applications due to their superior strength. Stainless steel is typically reserved for high-end or coastal projects where corrosion resistance and architectural finishes justify the higher cost. These values were used as the basis for normalized cost scoring in the PI_{ext} model.

3 SWOT analysis

While numbers tell part of the story, real-world decisions depend on more than just data. To bridge this gap, a qualitative SWOT analysis complements the quantitative model.

To complement the quantitative evaluation of material performance, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis is conducted for both steel and aluminum curtain wall systems. This qualitative framework helps identify context-specific advantages and limitations that influence material selection in real-world architectural and engineering scenarios. The comparative strengths, weaknesses, opportunities, and threats of steel curtain wall systems are summarized in Figure 1, providing insight into their performance advantages in structural and fire-critical applications. Similarly, Figure 2 outlines the SWOT analysis for aluminum curtain wall systems, highlighting their benefits in lightweight construction, corrosion resistance, and aesthetic flexibility [8].

3.1 Steel curtain wall systems

Steel curtain wall systems exhibit excellent mechanical performance and are well-suited for applications where structural strength, fire resistance, and seismic resilience are critical. However, they also present challenges related to fabrication complexity and susceptibility to corrosion. The SWOT analysis in this section outlines the internal capabilities and external factors affecting the use of steel in façade systems (see Figure 1).

Table 2. Approximate cost ranges per square meter for curtain walls [26], [27]

Material	Indicative Cost Range (USD/m ²)	Primary Use Cases
Aluminum	150–220	Commercial façades, unitized systems
Carbon steel	200–280	Fire-rated, seismic zones, braced backup systems
Stainless steel	300–450	Landmark buildings, coastal zones, high-end design

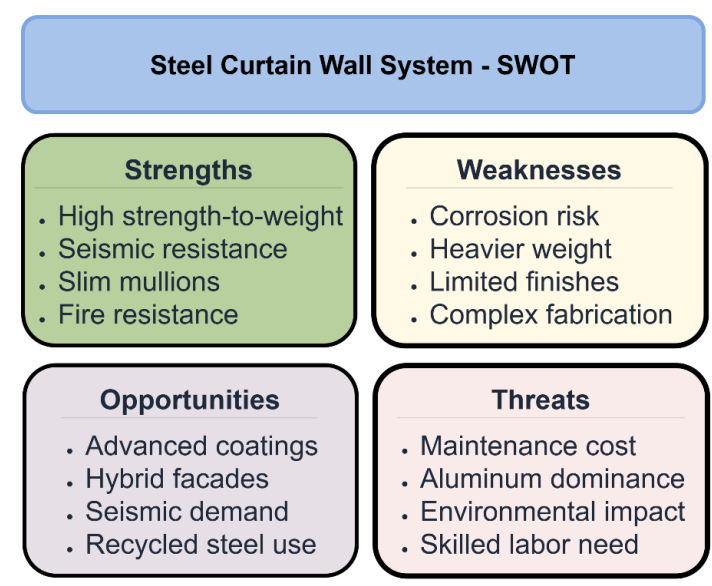


Figure 1. SWOT analysis for steel curtain wall systems

3.2 Aluminum curtain wall systems

Aluminum curtain wall systems offer significant benefits in terms of weight reduction, corrosion resistance, and fabrication ease, making them a popular choice in modern façade design. Nonetheless, their lower strength and fire resistance compared to steel limit their application in specific high-performance scenarios. The following SWOT analysis captures the key strategic considerations associated with aluminum systems (see Figure 2).

Beyond material properties, the performance of curtain wall systems also depends heavily on the capabilities of manufacturers. The following section provides insights into how leading companies implement steel and aluminum technologies in practice

4 Manufacturer comparison

While SWOT analysis helps clarify material-level advantages, real-world applications also depend on the capabilities of manufacturers. The following section investigates how leading industry players implement steel and aluminum systems to meet diverse project demands. The construction sector has emerged as a primary driver for aluminum demand, with the global construction industry projected to reach approximately USD 8.2 trillion in revenue by the end of 2022. This growth is particularly pronounced in the Asia-Pacific region, where rapid urbanization and infrastructure development have created substantial opportunities for aluminum applications. This versatility is reflected in its widespread use across various construction applications, including windows, curtain walls, roofing and cladding, solar shading, solar panels, railings, and other temporary structures. It is the second most widely used metal in the building and construction industry. Source: <https://www.mordorintelligence.com/industry-reports/aluminum-market> [28], [29], [30], [31], [32].

The Technical Glass Products (TGP) [33] steel curtain wall system offers a high-performance, modular framing solution engineered for structural and aesthetic versatility. The system utilizes 60 mm-wide steel profiles, which are pre-galvanized and finished with a durable powder coat, with optional availability in 304 stainless steels featuring a brushed finish for enhanced corrosion resistance and visual

appeal. Glass units are assembled using extruded aluminum cassettes that are applied in the factory and later field-installed into the steel framing. The system incorporates continuously extruded silicone gaskets, structural silicone, and foam tape for weather sealing and structural bonding. The bond line dimensions are determined by wind load and panel size, using a standardized formula to ensure performance integrity. Aluminum or stainless-steel toggles, spaced at 9–12 inches, secure the units depending on wind load requirements. The system can support individual vertical modules up to 1800 mm in height, arranged in unlimited stacked arrays. These construction details and modular capabilities are illustrated in Figure 3, which presents a typical vertical section through the system.

The Wrightstyle steel curtain wall system E30–E120 [34] is designed to offer robust fire-rated performance across a range of classifications and structural configurations. The system supports fire resistance ratings of E30, E60, E90, and E120, each capable of spanning up to 4.0 meters in height by 2.0 meters in width. It accommodates a wide range of glazing thicknesses, from 5 mm to 29 mm, allowing flexibility in selection based on thermal, acoustic, or safety performance requirements. The framing system is available at 50 mm or 60 mm depths, providing structural adaptability and aesthetic consistency.

The Wrightstyle steel curtain wall system utilize mechanical fasteners, such as toggles, brackets, and anchors to secure glazing units within steel or aluminum frames. In fire-rated systems, the entire assembly, including the framing material, fasteners, gaskets, and glazing, must be tested as a complete unit in accordance with standards such as EN 1364-3 or ASTM E119 [35]. The presence of mechanical fasteners does not inherently reduce fire resistance; however, their material composition, spacing, and thermal behavior must be carefully engineered to maintain fire compartmentation and structural stability during exposure. Often thermal breaks are used in combination with fasteners to prevent early failure due to heat transfer. Manufacturers typically certify these systems based on full-scale fire testing, ensuring that the fasteners support the structural integrity of the façade under rated fire durations (e.g., E60, E90, E120). Therefore, the impact of mechanical fasteners on fire performance is accounted for in system-level certification, rather than being assessed in isolation.

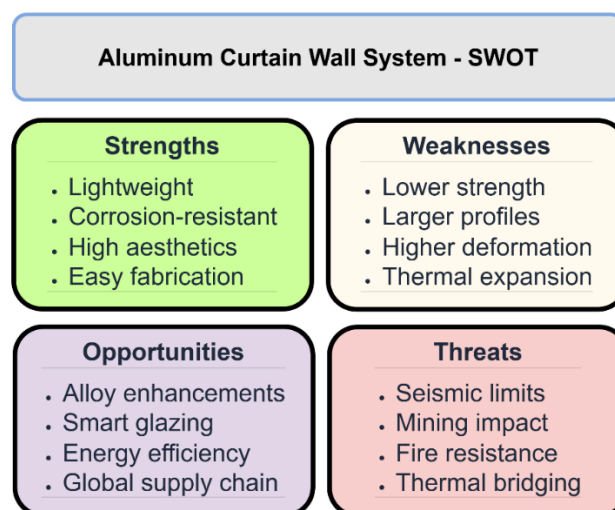


Figure 2. SWOT analysis for aluminum curtain wall systems

Notably, the frames are engineered to be mechanically joined, enabling the creation of unlimited curtain wall runs without compromising integrity or fire performance. These specifications are visually detailed in Figure 4, which illustrates the system's dimensional and modular capabilities.

To further understand the practical implications of choosing between steel and aluminum curtain wall systems, it is essential to examine the offerings of key industry

manufacturers. These companies supply materials and also develop their framing systems, thermal features, and installation methods that shape the performance and feasibility of curtain wall designs. By analyzing the strengths and weaknesses of major players in the market, ranging from European precision-engineered systems to large-scale mass-production facilities, façade engineers can make more informed decisions based on reliability, innovation, regional availability, and project-specific requirements.

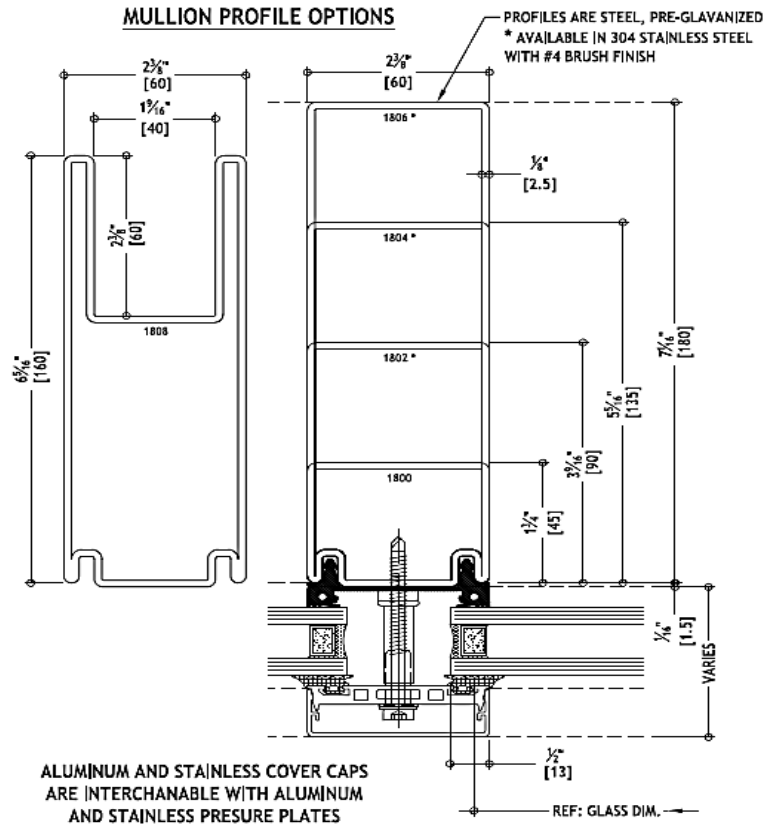


Figure 3. Technical Glass Products (TGP) America [33] system, steel-built 60 mm profiles in various depths

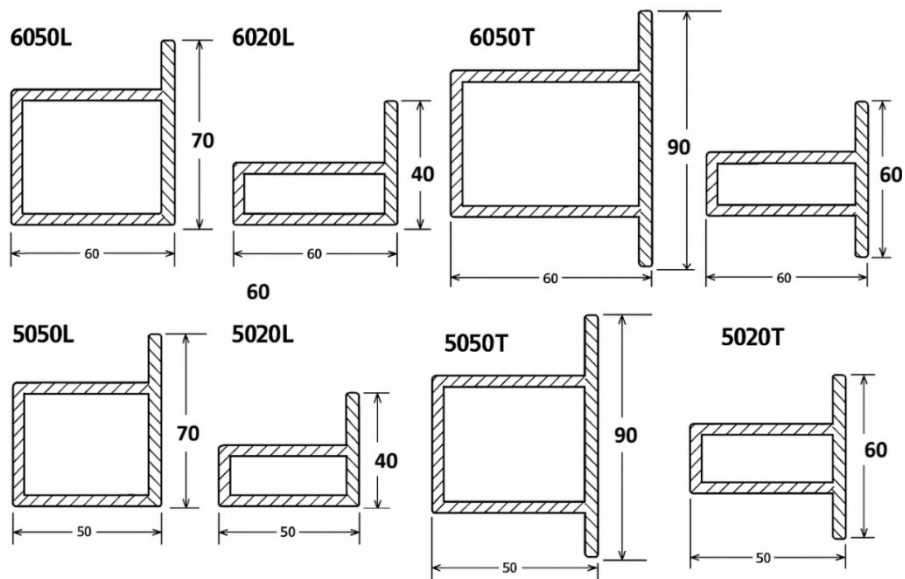


Figure 4. Wrightstyle steel curtain wall system United Kingdom 50/60 series of glazing systems

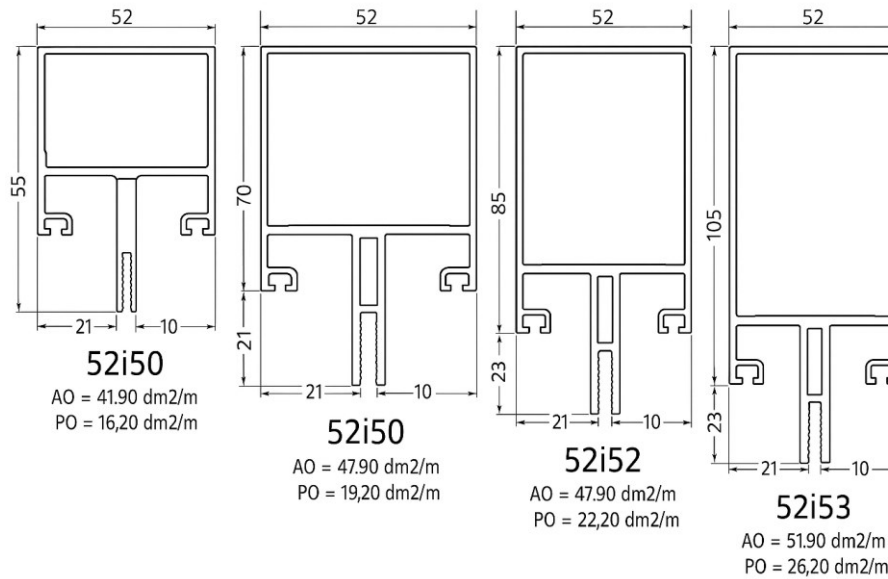


Figure 5. A few profiles of the RC/Sapa aluminum curtain wall system from the Elegance 52 series

The RC/Sapa aluminum curtain wall system, represented here by the Elegance 52 series, is a modular façade solution designed for performance, flexibility, and aesthetic integration. The system is based on a 52 mm profile depth, with a wide variety of mullion and transom profiles, such as 52i50, 52i52, 52i53, and 52i54 to accommodate different structural and architectural requirements (refer to **Figure 5**). Mullion depths range from 55 mm to 125 mm, allowing for efficient load distribution and design adaptability. The profiles are engineered for thermal insulation, incorporating internal chambers and pressure equalization zones to optimize energy efficiency. The system supports multiple glazing options and integrates seamlessly with accessories like pressure plates, cover caps, and mechanical fixings. This configuration is especially suited for stick-built installation, offering ease of on-site assembly while maintaining factory-controlled precision.

Aluminum and steel curtain wall systems differ significantly in terms of material behavior, fabrication methods, and performance applications. Aluminum systems, such as those developed by manufacturers like Sapa, are typically formed through precision extrusion, allowing for

consistent geometry, integrated thermal breaks, and modular detailing. These systems are lightweight, corrosion-resistant, and ideal for fast-track construction. Glass panels are generally fixed using pressure plates, snap-on caps, or toggled methods. These profiles are engineered to enhance thermal performance and ease of installation, especially in stick-built or unitized configurations (refer to Table 3 for comparisons of different systems of curtain walls).

By contrast, steel systems, like those from Wrightstyle or TGP, are favored for their high structural capacity, enabling longer spans, minimal framing, and superior performance under fire, blast, or impact loading conditions. Steel profiles are usually rolled, welded, or mechanically assembled and allow for the integration of fire-rated or large-format glazing. While heavier and more labor-intensive to install, steel curtain walls provide unmatched strength and are often specified in projects requiring increased safety, durability, or minimal visual obstruction.

The choice between aluminum and steel curtain walling typically depends on project-specific performance requirements, including thermal insulation, fire resistance, structural demands, and architectural expression.

Table 3. Curtain wall system manufacturers – steel vs. aluminum

Manufacturer	Material	Key Systems	Strengths	Weaknesses	Installation Method
Schüco [36]	Aluminum	FW 50+, FW 60+, Unitized Façade Systems	High-precision German engineering, Extensive thermal break technologies, Excellent aesthetic and design options	Primarily aluminum-based, Limited steel offerings, Higher cost	Stick system, Unitized
Reynaers Aluminium [37]	Aluminum	CW 50, CW 60, Concept Wall 86	A broad range of solutions, Integrated solar shading and HVAC options, Strong global presence	Aluminum only, less suitable for high seismic zones unless reinforced	Stick & Unitized

WICONA (- Hydro Group) [38]	Aluminum	WICTEC 50, WICTEC 60	Sustainable materials (recycled Aluminum), Integrated façade automation, High acoustic performance	Focused on Aluminum, Lower structural capacity	Stick, Unitized
Sapa (Hydro) [39]	Aluminum	Elegance 52, Sapa 4150, Sapa 5050	Strong thermal insulation, Modular system design, High recyclability, and sustainable production	Limited structural capacity compared to steel, Design flexibility lower than premium brands	Stick, Unitized
Forster Profile Systems [40]	Steel, Stainless Steel	Unico, Thermfix Vario	Fire-resistant curtain walls, High load-bearing capacity, Good thermal performance with thermal breaks	Higher cost requires more coordination in detailing	Stick system
TGP (Technical Glass Products) [41]	Steel	SteelBuilt Curtainwall Infinity™	High fire-rated performance, Clean frameless aesthetic with toggled glass, Compatible with large glass panels	Limited thermal break options require precise shop/factory prefabrication.	Stick system with toggled glass cassettes
Wrightstyle [42]	Steel	SR60, SR48, ISOFire systems	Tested to E30–E120 fire ratings, Mechanically joined frames for unlimited runs, Compatible with wide glazing range (5–29 mm)	Heavier than Aluminum, Requires fire-rated glazing certification	Stick system
Yuanda China [43]	Aluminum, Hybrid	Custom Unitized Systems	Mass production capability, Cost-effective, Rapid fabrication for large projects	Quality inconsistencies reported, Less design flexibility	Unitized
Permasteelisa Group [44]	Aluminum, Steel (Hybrid Custom)	Custom-engineered façades	Global leader in iconic façade projects, Advanced engineering, and bespoke systems, Hybrid steel-aluminum systems	Expensive, Long times for custom projects	Unitized, Custom Modular

- **Stick System:** Components are assembled piece-by-piece on site. Offers flexibility but has a slower installation.

- **Unitized System:** Prefabricated panels are manufactured in a factory and installed on site. Faster and more precise, but requires upfront planning.

5 Quantitative comparison

In addition to qualitative assessments, quantitative data offers a more objective basis for comparing steel and aluminum curtain wall systems. Metrics such as material strength, weight, thermal conductivity, fire resistance, and environmental impact can significantly influence the choice of curtain wall material depending on project requirements. Table 4 summarizes key performance for steel and aluminum systems.

Table 4. Key performance and market statistics for steel and aluminum systems [45], [46], [47]

Metric	Steel Systems	Aluminum Systems	Remarks
Global Market Share (2023)	12%	82%	Aluminum dominates due to ease of use
Material Strength (MPa)	250–400	70–150	Steel offers superior load capacity
Density (kg/m ³)	7850	2700	Aluminum is much lighter
Thermal Conductivity (W/m·K)	~50	~205	Aluminum requires thermal breaks
Fire Resistance (Hours)	Up to 4	0.5–1	Steel excels in fire performance
Seismic Deformability	High	Low	Steel is better suited for seismic zones
Corrosion Resistance	Low (requires coating)	High (natural oxide layer)	Aluminum is low-maintenance
Lifecycle Cost (30 years)	Higher	Medium	Steel may need more upkeep
CO ₂ Emissions (kg CO ₂ /kg)	~2.0	~11.5	Recycled Aluminum can reduce impact

These statistics can be visualized through diagrams such as bar charts, radar charts, and pie charts to highlight performance differences. For example, a radar chart could compare key physical and environmental metrics, offering a holistic view of each system's strengths and weaknesses. A lifecycle cost line graph may also help illustrate long-term economic impacts.

As shown in Figure 6, the radar chart illustrates that steel excels in structural strength, fire resistance, and seismic performance, while Aluminum outperforms in weight and corrosion resistance. Seven key performance parameters were selected to produce the radar chart. Quantitative data was sourced from engineering literature, manufacturer

datasheets, and environmental assessments. Inverted metrics such as weight and environmental impact were scaled accordingly to maintain a consistent interpretation. All values were normalized to a 0–10 scale, where 10 is best for performance (e.g., highest strength, lowest weight, etc.) [48], [49], [50], [51].

Inverse parameters such as weight and thermal conductivity were scored such that lower values correspond to higher scores, ensuring consistent interpretation. The radar chart offers a visual synthesis of performance trade-offs, which is particularly useful in early-stage material selection.

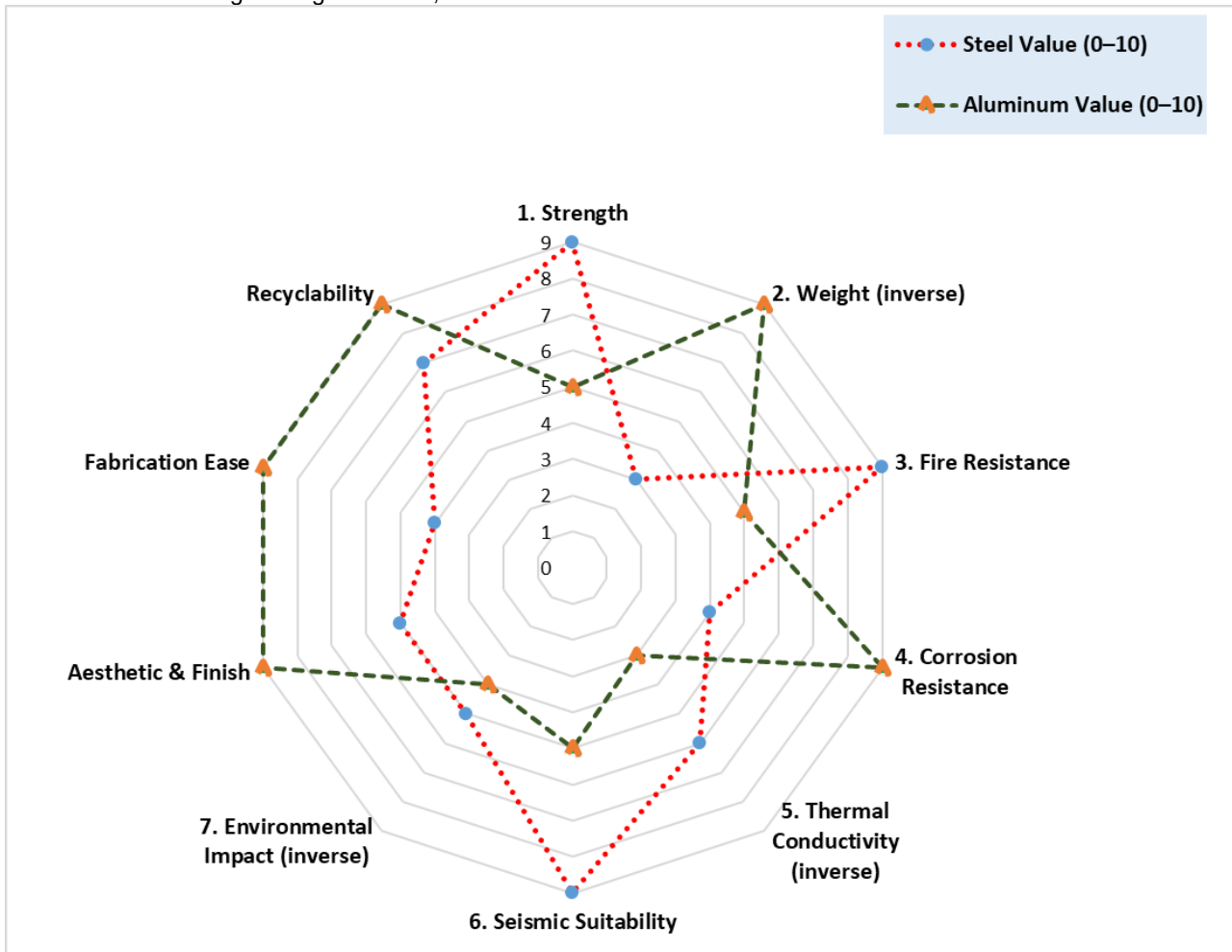


Figure 6. Radar chart comparing normalized performance attributes of steel and aluminum curtain wall systems. Scores are scaled from 0 to 10, where 10 represents the best performance (e.g., highest strength or lowest weight)

The performance parameters used in the radar chart (Figure 7) were derived from engineering handbooks [52], [53] and industry standards [54], [55], [56]. Environmental and market data were sourced from the [46], [57] and market research reports [58], [28].

Performance index calculation

The Performance Index (PI) framework was developed to provide a quantitative basis for comparing curtain wall framing materials in terms of both structural performance and lifecycle sustainability. Initially, five key parameters were selected based on their critical influence in façade

engineering: Structural Strength (σ), Fire Resistance (φ), Environmental Impact (ϵ), Material Density (ρ), and Cost Factor (κ). These parameters were integrated into **Equation (1)**. Using representative values derived from engineering literature and manufacturer data, the following inputs were applied:

- **Steel:** Strength = 300 MPa, Fire Resistance = 3.5 hours, Environmental Factor = 0.8, Density = 7850 kg/m³, Cost Factor = 3

- **Aluminum:** Strength = 110 MPa, Fire Resistance = 0.75 hours, Environmental Factor = 0.2, Density = 2700 kg/m³, Cost Factor = 1

The numerical inputs for each parameter in the PI and PI_{ext} were selected based on published engineering standards, environmental data, and market reports. Strength values (σ) reflect typical grades used in curtain wall framing (e.g., ASTM A36 for steel and AA6061-T6 for aluminum). Fire resistance (φ) is derived from EN 1364-3 and ASTM E119 test data, where steel systems achieve E90–E120 ratings, while aluminum systems typically achieve E30–E60. Environmental scores (ϵ) are based on embodied carbon benchmarks from EPDs and recent LCA studies [59], [60]. Density values are standard as per ASM Handbook [61]. Cost factors (κ) are normalized based on typical procurement and installation costs [26], [27].

The resulting original PI values are 0.0428 for steel and 0.0041 for aluminium. Figure 7 visualizes these results, clearly illustrating that steel systems dominate the original performance index, accounting for approximately 91% of the total PI score. This reinforces steel's suitability for structurally demanding, fire-rated, and seismic applications.

To reflect the increasing importance of architectural expression and visual quality in façade design, an additional parameter was introduced: Aesthetic and Finishing Score (α). This results in an extended formulation given by Equation (2). In this model, an aesthetic score (α) was

assigned based on material flexibility and surface finish. In this model, we consider the aesthetic score to be equal to 0.5 for steel and 0.9 for aluminium. Applying these values, the PI_{ext} results in 0.0001376 for steel versus 0.0001667 for aluminium. These values are shown in Figure 8, where aluminium overtakes steel, contributing approximately 55% of the total PI_{ext} . This shift highlights aluminum's strength in aesthetic-driven or design-sensitive projects, where factors such as anodizing, powder-coating options, and lightweight installation are prioritized alongside performance.

These results suggest a clear trend, for example, steel continues to dominate in scenarios where safety and structural integrity are paramount. At the same time, aluminum is considered suitable and recommended in projects where design versatility and sustainable appeal are prioritized. The significant difference between the original PI and PI_{ext} outcomes underscores the importance of a multi-criteria, context-sensitive approach to material selection. This dual-model framework offers architects and engineers a practical tool for aligning material choice with project-specific performance goals, whether structural, environmental, or aesthetic.

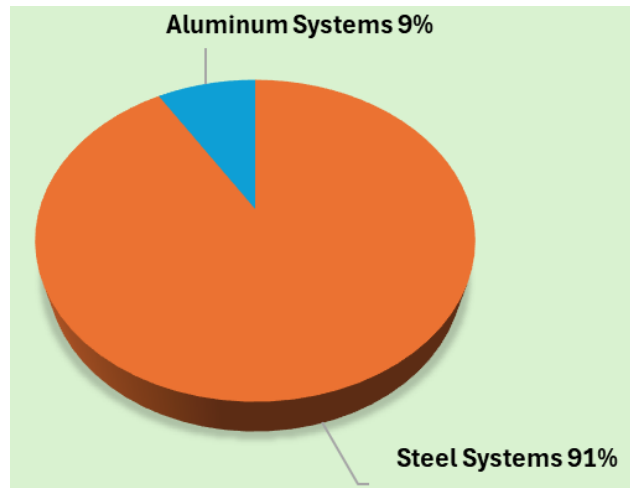


Figure 7. Performance Index (PI) comparison between steel and aluminum curtain wall systems

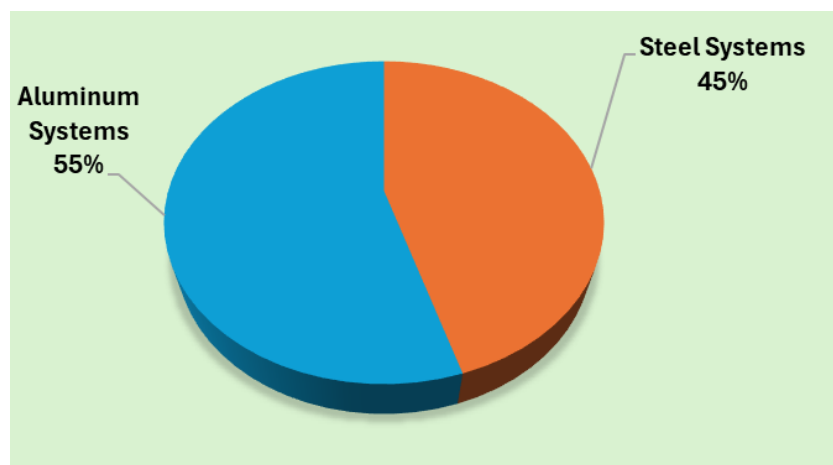


Figure 8. Performance Index (PI) comparison between steel and aluminum curtain wall systems with aesthetic considerations

Table 5. Criteria for assigning parameter values

Parameter	Selection Criteria	Steel (Value)	Aluminum (Value)
σ	Average yield/tensile strength from structural codes or datasheets (e.g., EN 1993, ASTM A36, AA6061-T6) [62], [63], [64], [65], [66]	300 MPa (typical structural steel)	110 MPa (standard alloy)
ϕ	Fire test data from EN 1364 / ASTM E119 for frame assemblies [35], [67]	3.5 hrs (steel frame capacity)	0.75 hrs (non-rated Aluminum)
ϵ	Life Cycle Assessment (LCA) data, embodied CO ₂ (e.g., GWP from EPDs) [59],	0.8 (lower CO ₂ footprint)	0.2 (higher unless recycled)
α	Qualitative scoring based on finish variety (e.g., anodizing, powder coating, shapes)	0.5 (limited finishes)	0.9 (high aesthetic flexibility)
ρ	Handbook values / material databases (e.g., CES EduPack, ASM Handbook) [61]	7850 kg/m ³	2700 kg/m ³
κ	Market cost normalized (1 = low, 3 = high), based on cost/m ² or kg (regionally adjusted)	3 (higher + fabrication)	1 (lower + modularity)

The environmental factor (ϵ) values are scaled inversely to embodied CO₂ emissions [60]. A value of 0.8 was assigned to steel (2.3 kgCO₂/kg), and 0.2 to aluminum, assuming partial recycled content. For virgin aluminum (≈ 16.5 kgCO₂/kg), a lower ϵ value (≈ 0.1) may be more appropriate.

As shown in Table 5, parameter values for steel and aluminum are derived from a combination of engineering standards (e.g., EN 1993, ASTM A36), environmental product declarations (EPDs), and manufacturer datasheets.

- Strength (σ) and density (ρ) values reflect typical structural grades used in curtain wall systems.
- Fire resistance (ϕ) values are based on available fire ratings for steel and aluminum frames.
- Environmental factors (ϵ) were scaled between 0 and 1 based on embodied carbon metrics.
- Aesthetic scores (α) were assigned according to finish variety and design flexibility.
- A normalized cost factor (κ) was used to reflect relative material and fabrication costs.

6 Parametric analysis

To complement the parametric analysis, a study was conducted to evaluate how variations in fire resistance, environmental performance, aesthetics, and cost affect the performance of steel and aluminum curtain wall systems.

In this analysis, the material strength (σ) was held constant at 300 MPa for steel and 110 MPa for aluminum. This allowed other design variables to be varied realistically without altering the structural capacity of the material. The performance indices were calculated using Equations (1) and 2. Six design scenarios, as shown in Table 6, were defined based on real-world façade design priorities.

It was observed that choosing steel material (blue lines in Figure 9) performs better in fire- and performance-critical scenarios (Cases 1, 2 and 3). On the other hand, aluminum becomes competitive in budget-friendly and eco-friendly cases (Case 5) due to its lower cost and better environmental factor. Interestingly, even in aesthetic-priority designs (Case 4), where aluminum typically excels due to its visual flexibility, the PI_{ext} for steel remains higher, suggesting that structural and fire resistance factors still play a dominant role. Both materials perform poorly in the worst-case scenario (Case 6), though steel retains a structural advantage.

Table 6. Parametric Case Definitions

Case	Description	Fire (ϕ)		Environmental (ϵ)		Aesthetic (α)		Cost (κ)	
		Steel	Aluminium	Steel	Aluminium	Steel	Aluminium	Steel	Aluminium
1	Base Case	3.5	0.75	0.8	0.2	0.5	0.9	3	1
2	High Fire Rating	5.0	1.2	0.6	0.1	0.5	0.9	3	1
3	Budget-Constrained	3.0	0.6	0.7	0.3	0.4	0.8	2	0.6
4	Aesthetic Priority	3.0	0.6	0.6	0.2	0.8	1.0	3.5	1.2
5	Eco-Focused	3.5	0.75	0.95	0.8	0.5	0.9	3	1
6	Worst Case	2.0	0.4	0.3	0.1	0.3	0.6	4	1.4

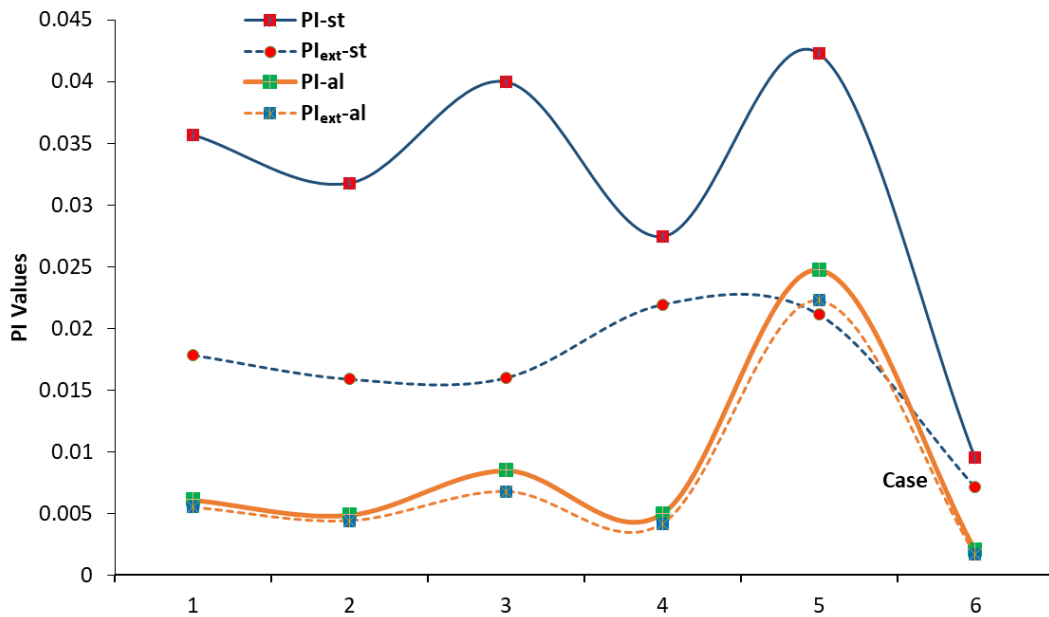


Figure 9. PI and PI_{ext} Comparison Across Parametric Cases

7 Limitations

While the proposed Performance Index (PI) framework offers a practical tool for comparing curtain wall materials, it is subject to certain limitations. The model is based on representative material properties and normalized cost factors, which may not reflect regional variations or project-specific conditions. Thermal bridging effects, long-term maintenance costs, and detailed lifecycle energy performance are not explicitly modeled. Additionally, the aesthetic score is inherently subjective and may vary depending on architectural preferences. Finally, although the model is designed with adaptability in mind, its full potential could be realized through integration with digital tools like BIM or dynamic costing platforms, areas that offer promising directions for future development.

8 Conclusion

This study presents a practical, scenario-driven approach to one of the most common and often overlooked challenges in façade design: choosing the right material for the right purpose. By combining a normalized Performance Index (PI) model with parametric analysis and qualitative SWOT evaluation, the paper provides a holistic method for data-driven material selection. The results confirm that steel remains the preferred material where high structural capacity, fire resistance, and seismic resilience are critical, particularly in high-rise, infrastructure, and fire-rated projects. In contrast, aluminum demonstrates clear advantages in aesthetic flexibility, corrosion resistance, ease of fabrication, and lower environmental impact, making it ideal for visually driven and low-rise or modular applications.

Significantly, the introduction of an extended PI framework (PI_{ext}), which incorporates aesthetic performance, shifts the material preference in some instances, highlighting aluminum's strength in design-sensitive architecture. The parametric analysis further illustrates how varying project

priorities (e.g., cost, sustainability, fire rating) can influence optimal material choice.

Overall, the dual-PI framework helps bridge the gap between engineering performance and design intent. It offers a practical decision-support tool for architects, façade engineers, and developers who must navigate complex trade-offs in curtain wall system selection.

Future research may extend this model by integrating thermal simulation, embodied carbon tracking, and BIM-based lifecycle forecasting for enhanced project integration using the experience of architects, engineers, and designers through a survey. This dual-PI framework is more than just a calculation, as it helps balance performance with design, and cost with creativity. This framework can support early-stage decisions in architectural competitions, urban planning, and performance-based façade design.

Author contributions

Muhammad Tayyab Naqash (First Author)

Conceptualization: Developed the Performance Index framework and scenario-based methodology.

Data Curation: Collected and processed data from literature, industry reports, and manufacturer datasheets.

Formal Analysis: Conducted PI calculations, parametric studies, and performance comparisons.

Investigation: Analyzed material properties, market trends, and performance trade-offs.

Methodology: Designed the dual PI model and integrated SWOT analysis.

Project Administration: Managed research planning and coordination.

Resources: Compiled references, technical standards, and environmental data.

Software: Used tools for modeling, visualization (e.g., radar charts), and document formatting.

Validation: Verified calculation accuracy and logical consistency.

Visualization: Created figures, tables, and charts for clear data presentation.

Writing – Original Draft: Wrote the full manuscript.

Writing – Review & Editing: Revised and refined the final version.

Ehsan Noroozinejad Farsangi (Second Author)

Supervision: Provided academic guidance and reviewed research direction.

Conceptualization: Contributed to framing the research scope and objectives.

Validation: Reviewed findings and contributed to interpretation.

Writing – Review & Editing: Edited the manuscript for clarity and academic quality.

Declaration

Competing interests

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Availability of data and materials

All data and materials used in this study are included within the manuscript.

Use of AI tools

Artificial intelligence tools (e.g., Grammarly and ChatGPT) were used to assist with grammar correction, language refinement, and clarity enhancement. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Nomenclature

Symbol	Parameter	Unit / Scale	Description
PI	Performance Index	—	Composite performance score (Equation 1)
PI _{ext}	Extended Performance Index	—	Modified index including aesthetic/finishing quality (Equation 2)
σ	Structural Strength	MPa	Tensile or yield strength of the material
φ	Fire Resistance	Hours	The duration the system withstands fire before failure
ε	Environmental Factor	0–1 (normalized)	Embodied carbon, recyclability, and lifecycle environmental impact
α	Aesthetic/Finishing Score	0–1 (normalized)	Visual flexibility, surface finish quality, and design adaptability
ρ	Density	kg/m ³	Mass per unit volume of the material
κ	Cost Factor	1–3 (normalized)	Relative material and fabrication cost (1 = low, 3 = high)
SWOT	Strengths, Weaknesses, Opportunities, and Threats	—	A strategic matrix is used to assess material suitability in different scenarios qualitatively.

References

[1] Global Market Insights., “Aluminum Curtain Wall Market Size | Forecast Report 2032.” Aluminum Curtain Wall Market Size | Forecast Report 2032., 2024.

[2] “The curtain wall market size is expected to reach USD 151.4 billion in 2030.” Accessed: Jun. 28, 2025. [Online]. Available: <https://www.betterglass.com/article/the-global-curtain-wall-market-size-is-expected-to-reach-usd-151-4-billion-in-2030.html>

[3] “Curtain Wall Market Size & Share Analysis, Growth Forecast 2029.” Accessed: Jun. 28, 2025. [Online]. Available: <https://www.arizton.com/market-reports/curtain-wall-market>

[4] A. Pisapia, E. Natri, V. Piluso, A. Formisano, and F. Massimo Mazzolani, “Experimental campaign on structural aluminium alloys under monotonic and cyclic loading,” *Eng. Struct.*, 2023, doi: 10.1016/j.engstruct.2023.115836.

[5] A. Chapman, “STEEL VS AL: Steel still trumps aluminium for cost-efficient, sustainable carmaking.,” *Met. Bull. Dly.*, 2014.

[6] “Stainless Steel Curtain Wall Market Size, Evaluation, Expansion & Forecast 2033.” Accessed: May 17, 2025. [Online]. Available: <https://www.verifiedmarketreports.com/product/stainless-steel-curtain-wall-market/>

[7] M. A. Benzaghta, A. Elwalda, M. Mousa, I. Erkan, and M. Rahman, “SWOT analysis applications: An integrative literature review,” *J. Glob. Bus. Insights*, 2021, doi: 10.5038/2640-6489.6.1.1148.

[8] A. B. M. S. Ayed Eid Alluqmani and Muhammad Tayyab Naqash, .nIslam, “Seismic performance evaluation and SWOT analysis of retrofitted reinforced concrete building,” vol. X, pp. 1–27.

[9] M. F. Ashby and D. Cebon, “Materials selection in mechanical design,” in *Journal De Physique*, 1993. doi: 10.1051/jp4:1993701.

[10] M. F. Ashby, Y. Bréchet, and D. Cebon, “Selection strategies for materials and processes,” *Adv. Eng. Mater.*, 2002, doi: 10.1002/1527-2648(20020605)4:6<327::AID-ADEM327>3.0.CO;2-N.

[11] A. Jahan, F. Mustapha, M. Y. Ismail, S. M. Sapuan, and M. Bahraminasab, “A comprehensive VIKOR method for material selection,” *Mater. Des.*, 2011, doi: 10.1016/j.matdes.2010.10.015.

- [12] M. Bahraminasab and A. Jahan, "Material selection for femoral component of total knee replacement using comprehensive VIKOR," *Mater. Des.*, 2011, doi: 10.1016/j.matdes.2011.03.046.
- [13] A. Jahan, M. Y. Ismail, S. M. Sapuan, and F. Mustapha, "Material screening and choosing methods - A review," *Mater. Des.*, 2010, doi: 10.1016/j.matdes.2009.08.013.
- [14] A. M. Papadopoulos and E. Giama, "Environmental performance evaluation of thermal insulation materials and its impact on the building," *Build. Environ.*, 2007, doi: 10.1016/j.buildenv.2006.04.012.
- [15] M. Manni and A. Nicolini, "Multi-Objective Optimization Models to Design a Responsive Built Environment: A Synthetic Review," *Energies*. 2022. doi: 10.3390/en15020486.
- [16] G. Chiandussi, M. Codegone, S. Ferrero, and F. E. Varesio, "Comparison of multi-objective optimization methodologies for engineering applications," *Comput. Math. with Appl.*, 2012, doi: 10.1016/j.camwa.2011.11.057.
- [17] Y. Cui, Z. Geng, Q. Zhu, and Y. Han, "Review: Multi-objective optimization methods and application in energy saving," *Energy*. 2017. doi: 10.1016/j.energy.2017.02.174.
- [18] S. Sassi *et al.*, "Fire safety engineering applied to high-rise building facades," in *MATEC Web of Conferences*, 2016. doi: 10.1051/mateconf/20164604002.
- [19] S. Dzidic, A. Ademovic, and A. El Sayed, "Fire Resistance of Steel Girders," in *Lecture Notes in Networks and Systems*, 2023. doi: 10.1007/978-3-031-34721-4_29.
- [20] S. Labò *et al.*, "Diagrid solutions for a sustainable seismic , energy , and architectural upgrade of European RC buildings," *Proc. XII Int. Conf. Struct. Repair Rehabil.*, 2016.
- [21] E. Georgantzia and M. M. Kashani, "Monotonic and cyclic behaviour of 6082-T6 aluminium alloy," *ce/papers*, 2023, doi: 10.1002/cepa.2315.
- [22] ASTM, "ASTM A480/A480M Standard Specification for General Requirements for Flat-Rolled Stainless and Heat-Resisting Steel Plate, Sheet, and Strip," *ASTM B. Stand.*, 2015.
- [23] Astm Norma B 209-07, "Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate (metric)," *Standards*, 2007.
- [24] "FACETS | CWCT." Accessed: Jun. 28, 2025. [Online]. Available: <https://www.cwct.co.uk/pages/facets#!articles/1222-9023-0306-fit-and-appearance>
- [25] A. Leśniak and M. Górka, "Structural analysis of factors influencing the costs of facade system implementation," *Appl. Sci.*, 2020, doi: 10.3390/app10176021.
- [26] "Curtain Wall System Cost and Comparison with Other Wall Systems - United Facade." Accessed: Jun. 28, 2025. [Online]. Available: <https://unitedfacade.com/curtain-wall-system-cost-and-comparison-with-other-wall-systems/>
- [27] Y. Han, "Research on Cost Control of External Curtain Wall Engineering of Small and Medium-sized Station House," *建筑结构*, 2022, doi: 10.26789/jzjg.v7i6.1571.
- [28] "Aluminum Market Report | Industry Analysis, Size & Trends Overview." Accessed: May 13, 2025. [Online]. Available: <https://www.mordorintelligence.com/industry-reports/aluminum-market>
- [29] N. M. Tayyab, A. Formisano, and D. M. Gianfranco, "Design and performance testing of a skylight in Qatar," in *Key Engineering Materials*, 2016. doi: 10.4028/www.scientific.net/KEM.710.262.
- [30] M. T. Naqash, A. Formisano, and E. Noroozinejad Farsangi, "Using a Full-Scale Mock-Up of Skylight to Evaluate Its Performance Following Standards Criteria," *Arab. J. Sci. Eng.*, vol. 47, no. 10, pp. 13407–13420, 2022, doi: 10.1007/s13369-022-06817-2.
- [31] M. T. Naqash, S. Khoso, and E. Noroozinejad Farsangi, "Wind-Induced Structural Response of Skylights: A Eurocode-Based Assessment," *Pract. Period. Struct. Des. Constr.*, 2024, doi: 10.1061/ppscfx.sceng-1381.
- [32] A. Formisano and M. T. Naqash, "Numerical Studies on Innovative Prestressed Aluminium Alloy Profiles for Curtain Wall Systems," *Lect. Notes Civ. Eng.*, vol. 520 LNCE, pp. 863–871, 2024, doi: 10.1007/978-3-031-62888-7_75.
- [33] "SteelBuilt Curtainwall Systems | Superior to Aluminum Curtain Walls." Accessed: Jun. 27, 2025. [Online]. Available: <https://www.tgpamerica.com/products/framing/steelbuilt-curtainwall/>
- [34] "Curtain Wall & Roof Glazing Systems - Wrightstyle." Accessed: Jun. 27, 2025. [Online]. Available: <https://www.wrightstyle.co.uk/curtain-wall-system/>
- [35] ASTM, *ASTM E119 - Standard test methods for fire test of building construction and materials*. 2000.
- [36] "Facades." Accessed: May 18, 2025. [Online]. Available: <https://www.schueco.com/de-en/architects/products/facades>
- [37] "Façades | Reynaers." Accessed: May 18, 2025. [Online]. Available: <https://www.reynaers.com/products/facades>
- [38] "WICONA - Aluminium Building Solutions." Accessed: May 18, 2025. [Online]. Available: <https://www.wicona.com/en/int/>
- [39] "SAPA By Hydro: High-end design and innovative aluminium solutions." Accessed: May 18, 2025. [Online]. Available: <https://www.sapabuildingsystem.com/>
- [40] "Forster Profile Systems Ltd: Forster Profilsysteme AG, Romanshorn." Accessed: May 18, 2025. [Online]. Available: <https://www.forster-profile.ch/gb-en/forster-profile-systems-ltd.html>
- [41] "Technical Glass Products Home | Fabricating Fused Quartz since 1990." Accessed: May 18, 2025. [Online]. Available: https://technicalglass.com/?srsltid=AfmBOoprXbBfQ5Gykt-7qki_D55nkpngTPjFtO4rA3a7svtPUgoBrTXf
- [42] "Wrightstyle Steel Glazing Systems." Accessed: May 18, 2025. [Online]. Available: <https://www.wrightstyle.co.uk/>
- [43] "Yuanda China - Shenyang Yuanda Enterprise Group." Accessed: May 18, 2025. [Online]. Available: <https://www.cnydgroup.com/index.php/en/yuanda-industry-2/buliding/cnydchina.html>
- [44] "Permasteelisa Group: Architectural Envelopes." Accessed: May 18, 2025. [Online]. Available: <https://www.permasteelisagroup.com/>
- [45] "Aluminum Systems Market Share & Trends [2033]." Accessed: Jun. 27, 2025. [Online]. Available: <https://www.marketreportsworld.com/market-reports/aluminum-systems-market-14716442>

- [46] Worldsteel Association, "World Steel in Figures 2018-2022," p. 17, 2023, [Online]. Available: <https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2023/#direct-reduced-iron-production-%3Cbr%3E-2018-to-2022>
- [47] "Steel industry - Statistics & Facts | Statista." Accessed: Jun. 27, 2025. [Online]. Available: <https://www.statista.com/topics/1149/steel-industry/>
- [48] I. Mazínová and P. Florian, "Materials selection in mechanical design," in *Lecture Notes in Mechanical Engineering*, 2014. doi: 10.1007/978-3-319-05203-8_21.
- [49] M. Ashby, *Materials selection in mechanical design: Fourth edition*. 2010.
- [50] D. Cebon and M. F. Ashby, "MATERIALS SELECTION FOR MECHANICAL DESIGN," in *ASTM Special Technical Publication*, 1992. doi: 10.1520/STP23757S.
- [51] *Modeling and Simulation for Material Selection and Mechanical Design*. 2003. doi: 10.1201/9780203913451.
- [52] C. R. Clayton, "Materials science and engineering: An introduction," *Mater. Sci. Eng.*, 1987, doi: 10.1016/0025-5416(87)90343-0.
- [53] W. D. Callister Jr, "Materials Science and Engineering - An Introduction (5th ed.)," *Anti-Corrosion Methods Mater.*, 2000, doi: 10.1108/acmm.2000.12847aae.001.
- [54] British Standards Institution, "Fire tests on building materials and structures — BS 476-22: 1987," *Br. Stand. Inst.*, 1987.
- [55] ASTM, "Standard Test Method for Fire-Resistive Joint Systems," 2015.
- [56] BS 476, "Fire tests on building materials and structures - Method for determination of the fire resistance of elements of construction, BS 476-20: 2009," 2008.
- [57] "European Aluminium Industry Focus 2022." Accessed: May 13, 2025. [Online]. Available: https://www.alcircle.com/emagazine/european-aluminium-industry-focus-2022-1012?srsId=AfmBOorHntNy1KIKFhLDqmTsA5v9JN9I_FRXP7MYqkhp4QXU5aiQEUi
- [58] Statista, "Statista - The Statistics Portal for Market Data, Market Research and Market Studies," *Statista*. 2023.
- [59] A. Shen and J. Zhang, "Technologies for CO2 emission reduction and low-carbon development in primary aluminum industry in China: A review," *Renewable and Sustainable Energy Reviews*. 2024. doi: 10.1016/j.rser.2023.113965.
- [60] J. Kang and J. A. Gapay, "Factors Affecting Carbon Dioxide Emissions Embodied in Trade," *SSRN Electron. J.*, 2023, doi: 10.2139/ssrn.4618106.
- [61] Asm, "ASM Handbook," *Mater. Charact.*, 1986.
- [62] EN 1993-1-8, *Eurocode 3: Design of steel structures - Part 1-8: Design of joints*. 2005.
- [63] F. Breinlinger *et al.*, "Eurocode 1 - Actions on structures," *Bauingenieur*, 2011, doi: 10.1007/978-3-642-41714-6_51754.
- [64] ASTM, "ASTM D6481-99 (2004) - Standard Test Method for Determination of Phosphorus, Sulfur, Calcium, and Zinc in Lubrication Oils by Energy Dispersive X-ray Fluorescence," *ASTM Int.*, 2010.
- [65] C. Bernuzzi and B. Cordova, *Structural Steel Design to Eurocode 3 and AISC Specifications*. 2016. doi: 10.1002/9781118631201.
- [66] European-Union, "Eurocode 9: Design of aluminium structures - Part 1-1: General structural rules," *Eur. Comm. Stand.*, 2007.
- [67] A. Law and L. Bisby, "The rise and rise of fire resistance," *Fire Saf. J.*, 2020, doi: 10.1016/j.firesaf.2020.103188.