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Article

From Openable to Operable: A Comparative Policy Analysis of Window Standards and Occupant Agency

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Abstract

Operable windows are critical for indoor environmental quality (IEQ) and occupant agency, yet their usability is increasingly compromised by the conflict between regulatory compliance and building performance. This study investigates the gap between geometrically compliant provisions and genuinely operable windows. By conducting a comparative policy analysis of mandatory codes (Level 1), green rating systems (Level 2), and regenerative frameworks (Level 3), this research identifies a critical discrepancy termed the Geometric Trap. Results reveal that in the US, South Korea, Japan, and the UK, mechanical ventilation legally substitutes for natural access. While the US, South Korea, and Japan employ explicit 'OR' waivers, the UK enforces substitution through conditional constraints like noise. Consequently, windows are rendered sealed despite geometric compliance, unlike in Germany where operability remains mandatory. Furthermore, while evolving green rating systems (Level 2) prioritize resilience, they still treat operability as an optional trade-off. In contrast, regenerative frameworks (Level 3) mandate it as a non-negotiable prerequisite for occupant health. Finally, the study argues for a regulatory shift toward the Effective Opening Area framework to resolve this discrepancy. By redefining operability through the lens of accessibility and agency, this research contributes to a paradigm shift from static geometric compliance to dynamic, occupant-centric performance.

Keywords: operable window; natural ventilation; building codes; green building rating systems; occupant control; indoor environmental quality (IEQ); regenerative design

1. Introduction

1.1. Background

For centuries, the window served as the vital respiratory organ of a building, acting as a permeable membrane that negotiates the relationship between the interior and the exterior. It was the primary instrument for light, fresh air, and connection to the natural world. However, as contemporary architectural discourse observes, the modernization of building skins has fundamentally decoupled these functions. With the advent of centralized HVAC systems and high-performance curtain walls, the window has been transformed from an operable device into a sealed surface. As Rem Koolhaas observed in *Elements of Architecture* (2014), the window has effectively assumed a dual role within the modern building system—acting, in his terms, as both a "victim and accomplice" to the mechanization of comfort [1]. Through this lens, the window is increasingly reduced to a mere "transparent enclosure", severing its historical function as a permeable threshold for environmental connection.

This architectural evolution was driven by a pursuit of the "perfect seal" to maximize energy efficiency and thermal consistency. As early as 1930, Le Corbusier, the pioneer of modernism, envisioned a "neutralizing wall," or *mur neutralisant*, that would hermetically seal the interior. He proposed replacing unpredictable natural breezes with mechanically controlled "exact respiration," known as *respiration exacte* [2].

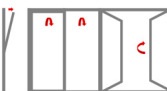
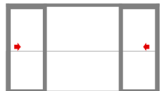
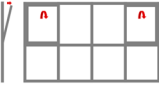
This Modernist ideal of environmental control effectively institutionalized the separation of the occupant from the exterior. As Kiel Moe [3] argues in *Insulating Modernism*, this paradigm shifts architecture toward “isolated thermodynamics,” where the building envelope is designed to resist rather than interact with the environment. This reliance on insulation and mechanical sealing has created a “metabolic rift,” structurally preventing the passive exchanges that operable windows were originally designed to facilitate.

Following this modernist ideal, contemporary buildings have increasingly adopted airtight envelopes. Reyner Banham later critiqued this trend in 1969, arguing that it prioritized mechanical dominance over environmental interaction [4].

This creates what critics describe as a paradoxical “comfort in closure,” a term coined by Norihito Nakatani [1] in the aftermath of the Tokyo subway sarin incident, where the sealed interior is perceived as a sanctuary from the unpredictable exterior. While this “comfort in closure” promises a controlled indoor environment, it simultaneously strips occupants of their agency, specifically the ability to control their immediate surroundings. Research consistently shows that the ability to open a window significantly increases occupant tolerance for wider temperature ranges and improves psychological well-being [5].

As illustrated in Table 1, the gap between geometric and effective areas is physically inherent in modern window typologies. While sliding windows offer moderate openness (~50%), high-rise typologies such as project-out windows or glass-railing systems are structurally restricted to less than 10% efficiency due to safety limiters and barrier codes, creating a foundational Geometric Trap before policy even intervenes.

Table 1. Classification of Window Typologies based on Geometric Efficiency.

Typology						
	(a)	(b)	(c)	(d)	(e)	(f)
	Turn & Tilt	Sliding	Split-Sash	Glass Railing	Project-out	Fixed
Geometric Efficiency (Estimated)	≈ 100%(Turn)/<5%(Tilt)	≈ 50%	≈ 25%	≈ 20%	<10%	0%
Mechanism	European (Dual-Mode)	Standard (Sliding)	Split-Sash (View Type)	Glass rail (Panoramic)	High-Rise (Office Tower)	Sealed (Mechanical)
Control	Full	High	Restricted	Obstructed	Minimal	None

Note: Efficiency percentages are approximate values based on standard discharge coefficients found in ASHRAE Fundamentals and CIBSE Guide A. Values for project-out windows assume the application of safety limiters (e.g., 100mm restriction) commonly required in high-rise buildings.

Crucially, this marginalization of the operable window is not merely a stylistic trend but a phenomenon codified and reinforced by regulatory frameworks. Across the globe, building codes ostensibly mandate openable windows for safety or theoretical ventilation compliance. Yet, a closer examination reveals a critical Mechanical Exception where regulations often permit the requirement for natural ventilation to be waived if a mechanical system is present. This regulatory Substitution Logic has normalized the sealed building typology, creating a condition where windows are legally openable to satisfy geometric criteria for egress but functionally inoperable for daily environmental control.

Furthermore, a historical perspective suggests a disturbing regression in standards. While early 20th-century codes prioritized ample natural ventilation for public health, modern regulations have progressively reduced these requirements in favor of mechanical solutions. For instance, the 1964 Uniform Building Code (UBC) in the US required ventilation openings equivalent to approximately 6.25% of the floor area [6], whereas contemporary codes often mandate significantly lower ratios, such as the 4% requirement in the International Building Code (IBC) [7]. Despite the growing risks of

indoor pollutants and airborne pathogens, recently underscored by the global pandemic, the regulatory mandate for natural ventilation capacity has stagnated or regressed. This trend creates a widening gap between legal compliance and actual occupant health.

This inquiry is particularly urgent given that the current period marks a global pivot point in building standards. Leading international frameworks, such as LEED and BREEAM, are fundamentally shifting their focus from static energy efficiency to resilience and carbon neutrality. Unlike the rigid prescriptions of mandatory codes, these evolving standards increasingly recognize the operable window as a critical instrument for climate adaptation and passive survivability. However, mandatory building codes have remained largely stagnant, prioritizing mechanical control over natural contingency. This widening divergence, specifically between the static legal minimums and the resilience-driven voluntary standards, demands a rigorous comparative analysis to identify the regulatory gaps hindering true occupant agency.

1.2. A Literature Review

Prior research underscores that the value of operable windows extends far beyond simple air exchange, functioning as a critical leverage point for energy efficiency, indoor environmental quality (IEQ), and occupant psychology.

1.2.1. Environmental Performance and Energy Efficiency

Contrary to the perception that window opening compromises energy efficiency, literature on mixed-mode buildings demonstrates significant potential for energy reduction. Studies on hybrid ventilation strategies [8] indicate that operable windows allow for passive cooling, significantly reducing the reliance on mechanical air conditioning during intermediate seasons. This aligns with the fundamental benefit that utilizing natural wind pressure costs nothing compared to the energy-intensive cooling of entire spaces. Furthermore, natural ventilation serves as an effective strategy for hygiene, preventing stagnant air and mold growth in moisture-prone areas like kitchens and bathrooms [9].

1.2.2. Adaptive Comfort and Occupant Agency

Beyond physical parameters, operable windows are fundamental to adaptive thermal comfort [5]. However, the theoretical benefits of comfort are often constrained by reality. Ackerly and Brager [10] highlighted a critical disconnect between design intent and occupant behavior, revealing that even in buildings designed for natural ventilation, occupants often refrain from using windows due to lack of agency or poor signaling systems. This complexity is further supported by Haldi and Robinson [11], who showed that window usage is governed by stochastic interactions between occupancy patterns and outdoor conditions rather than simple temperature thresholds. Crucially, advanced control models have been shown to improve indoor air quality and thermal comfort by more than 90% when these behavioral patterns are integrated [12]. This suggests that when occupants are given true agency (operability), both satisfaction and building performance improve significantly.

1.2.3. The Drivers of Marginalization: Cost, Aesthetics, and Control

Despite the clear environmental and psychological benefits, the operable window faces increasing marginalization in practice due to a convergence of economic, aesthetic, and managerial pressures.

First, from a construction management perspective, operable units represent a significant cost premium. The complexity of hardware, such as hinges, locks, and gaskets, makes them a prime target for Value Engineering (VE). While a vanguard of architects, notably Pritzker laureates Glenn Murcutt [13] and Lacaton & Vassal [14], advocates for buildings as permeable instruments to reintegrate natural ventilation, these efforts are frequently compromised or eliminated during budget cuts and replaced by cheaper fixed glazing. However, this economic logic is often short-sighted. In contrast to

the US market, data from Stuttgart, Germany, reveals that office buildings with operable windows command up to a 30% premium in rental rates [1], proving that occupant control holds tangible market value beyond initial construction costs.

Second, the prevailing architectural desire for seamless transparency favors large fixed panes that eliminate the visual interruption of thick frames and insect screens. This tendency is exemplified by the works of SANAA, where the pursuit of aesthetic purity often overrides function. As noted by Koolhaas [1], elements like operable vents are frequently eliminated to achieve a "nonexistent enclosure," resulting in fixed facades where occupants are visually connected but physically isolated from the exterior. Finally, for facility managers and engineers, the operable window introduces a variable of unpredictability [15]. Open windows can disrupt the pressure balance of sophisticated HVAC systems and introduce safety liabilities [16]. Consequently, despite the best intentions of sustainable design, the sealed box creates a structural lock-in that prioritizes predictable building operation over occupant agency.

1.2.4. Research Gap: From Behavioral Analysis to Policy Critique

While existing literature has extensively validated the benefits of natural ventilation, it has predominantly focused on quantitative performance metrics, utilizing CFD simulations or energy modeling to predict airflow rates and thermal reduction [17,18]. These studies typically rely on the assumption that if a window is physically present, it will be utilized effectively.

However, a critical gap remains in the institutional dimension. There is a distinct scarcity of research that scrutinizes the legal frameworks governing these architectural elements. Moreover, most policy-related studies analyze building codes solely through the lens of energy efficiency, rarely addressing the structural conflict between mechanical compliance and occupant agency.

Consequently, a direct comparative analysis of how different nations legally define and restrict window operability, specifically regarding the Mechanical Exception, remains underexplored. This study fills this gap by shifting the analytical lens from theoretical simulation to regulatory critique, exposing the legal mechanisms that render scientifically proven benefits unattainable in practice.

1.3. Research Scope and Objectives

While this study examines global trends, specific attention is paid to South Korea as a critical case study. As a high-density, high-tech urban environment, Seoul exemplifies the Geometric Trap where advanced glazing technologies and strict safety codes have inadvertently created hermetically sealed living spaces.

To address this issue, this study aims to interrogate the structural gap between the potential for natural ventilation encoded in international standards and the actual operability available to users. By contrasting mandatory regulations with advanced wellness frameworks, this paper exposes how mere geometric compliance masks the lack of true performance.

Ultimately, we argue for a shift from static area-based criteria to a performance-based framework, Effective Operability, to restore the window's role as a functional instrument of occupant health.

2. Materials and Methods

2.1. Research Framework: Comparative Policy Analysis

This study employs a Comparative Policy Analysis approach to evaluate the standards governing window operability across distinct regulatory and cultural contexts. The analysis is structured around a three-tiered conceptual hierarchy (Figure 1), which categorizes standards based on their primary objective regarding occupant agency.

- **Level 1:** Mandatory building codes that prioritize safety and minimum hygiene, often treating windows as static egress elements.

- **Level 2:** Voluntary green rating systems that focus on energy optimization and comfort, treating operability as a conditional variable.
- **Level 3:** Regenerative frameworks that frame natural ventilation as a fundamental occupant right and Passive Survivability strategy.

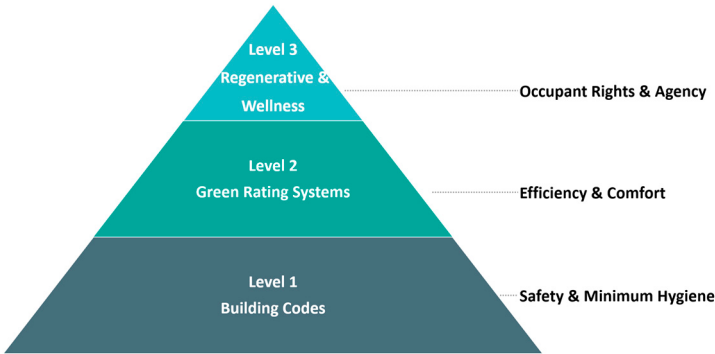


Figure 1. The Conceptual Hierarchy of Window Standards.

2.2. Conceptual Definition: From Geometric to Effective Operability

Existing studies often use "openable area" and "effective area" interchangeably. However, in the context of occupant agency, these two represent fundamentally different realities. To address the Geometric Trap, this study distinguishes between the static potential of a window and its dynamic usability:

- **Geometric Opening Area (A_{geo}):** The maximum physical opening area of a window (Width × Height), typically used for code compliance. It represents a theoretical capacity assuming no obstruction.
- **Effective Opening Area (A_{eff}):** The actual usable area available to the occupant, accounting for physical constraints (e.g., safety limiters, barriers) and environmental factors (e.g., noise, pollution). It represents realized agency.

This distinction is not merely theoretical but physically constrained. For instance, standard discharge coefficients (ASHRAE, CIBSE) indicate that safety-limited project windows often provide only a fraction (<10%) of their geometric potential (see Table 1).

Consequently, regulatory reliance on geometric openability often fails to guarantee effective operability. While the former satisfies the legal requirement, only the latter ensures the Effective Perimeter Zone, the depth (typically 6–8 meters [19]) where natural ventilation meaningfully impacts occupant comfort. Therefore, this study adopts Effective Operability as the primary criterion for evaluating whether a regulatory framework supports or inhibits occupant agency.

2.3. Analysis Framework

To evaluate the structural gap between compliance and agency, this study employs a tripartite analysis framework that categorizes standards into three hierarchical levels of operability:

1. **Level 1 (Mandatory Codes):** The baseline legal requirements focusing on safety and minimum hygiene (e.g., IBC, Building Act of Korea). The primary analysis focuses on whether these codes prioritize Geometric Compliance or Occupant Agency.
2. **Level 2 (Green Rating Systems):** Voluntary high-performance standards (e.g., LEED, BREEAM) that typically emphasize energy efficiency. The analysis examines whether user control credits are genuinely granted or traded off for energy performance.
3. **Level 3 (Regenerative Frameworks):** Human-centric standards (e.g., WELL, LBC) that view operability as a prerequisite for health and biophilia, advancing toward Regenerative Operability.

Coding Criteria for the Mechanical Exception: To ensure rigorous classification, this study applied a specific syntactic rule to identify the Mechanical Exception. A regulatory clause was coded as a Trap (Exception) if it contained an explicit "OR" condition, stating that natural ventilation requirements are waived, reduced, or deemed unnecessary when a mechanical ventilation system is installed. Conversely, regulations were classified as "Decoupled" only if they mandated window operability as an independent requirement (AND condition), regardless of the presence or capacity of the HVAC system.

The specific application of this framework and the resulting divergence in national models are visualized in Figure 2 (see Section 3.1).

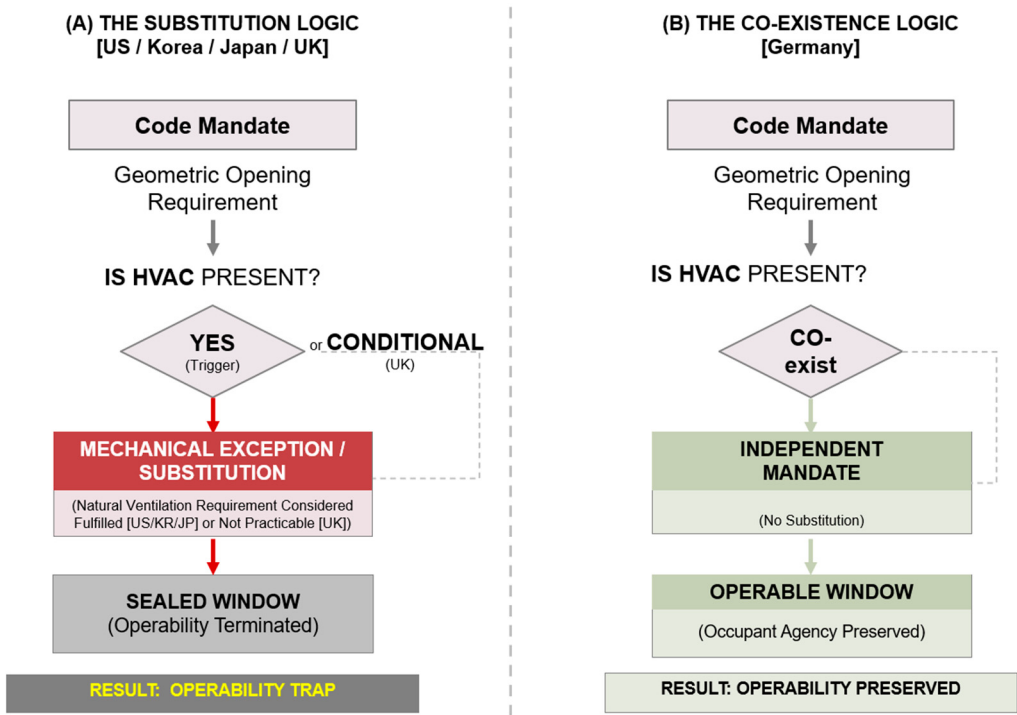


Figure 2. Conceptual framework of regulatory logics: The Substitution Model (Geometric Trap) vs. The Decoupled Model (Occupant Agency). The diagram illustrates how the presence of mechanical ventilation systems alters the regulatory evaluation pathway. In the Substitution Model (Left), the installation of HVAC systems triggers the omission of natural ventilation provisions through either explicit waivers (US, South Korea, Japan) or conditional constraints (UK). In contrast, the Decoupled Model (Right) maintains operability as an independent mandate, ensuring the co-existence of mechanical efficiency and occupant agency regardless of mechanical sufficiency.

2.4. Data Collection

This study strategically selected data sources from nations that possess Global Reference Standards with established international influence. The United States (LEED), the United Kingdom (BREEAM), and Japan (CASBEE) were chosen as the originators of dominant global rating systems and representative standards for high-density Asian contexts, respectively. Additionally, Germany (DGNB) is included to reflect the recent global attention on performance-based resilience and passive design principles. These four regulatory archetypes provide a comprehensive comparative framework for analyzing South Korea (G-SEED), which is the primary focus of this study, allowing for a critical evaluation of how these global sustainability principles are adapted within the specific regulatory and urban context of the researcher’s country.

2.5. Dataset of Standards

This study analyzes the most recent versions of regulatory documents and certification standards active as of 2024–2025, a period marking a significant paradigm shift in global frameworks toward decarbonization.

- **Mandatory Codes (Level 1)**
 - **US:** International Building Code (IBC, 2024) [6]
 - **UK:** UK Building Regulations: Part F (Ventilation) & Part O (Overheating) (2021) [20,21]
 - **Germany:** Model Building Code (MBO, 2019) [22] and Technical Rules for Workplaces (ASR A3.6, 2022) [23].
 - **Japan:** Building Standards Act (2024) [24]
 - **South Korea:** Building Act (2024) [25]
- **Green Rating Systems (Level 2):**
 - **LEED** (US/Global): LEED v5 (2025) [26]
 - **BREEAM** (UK/Global): BREEAM V7 (2025) [27]
 - **DGNB** (Germany): DGNB System Version 2023 (2023) [28]
 - **CASBEE** (Japan): CASBEE for Building Design (2024) [29]
 - **G-SEED** (South Korea): G-SEED Revision Proposal (2025) [30]. While the 2016 version is currently enforced, this study analyzes the 2025 revision proposal to reflect the Korean strategic shift toward carbon neutrality and ESG alignment.
- **Regenerative Frameworks (Level 3):**
 - **Living Building Challenge** (US/Global): LBC 4.1 (2024) [31]
 - **WELL** (US/Global): WELL v2 (2025) [32]

These documents were reviewed to extract quantitative criteria regarding minimum opening areas, distance limitations, and mechanical substitution clauses.

3. Results

3.1. Level 1 Analysis: The Geometric Trap in Mandatory Codes

For a consistent comparative analysis, this study primarily focuses on the regulations for habitable rooms, where occupant agency and natural ventilation are most critical. Figure 2 summarizes the two regulatory logics identified through the Level 1 analysis, distinguishing substitution-based compliance from structurally decoupled mandates. This section examines how the opposing logics of substitution and coexistence manifest in the national building codes of the US, the UK, Germany, Japan, and South Korea.

3.1.1. The Mechanism of Erasure: US, Japan, and South Korea

This cluster represents the clearest manifestation of the Geometric Trap. While the IBC (USA), Building Standards Act (Japan), and Building Act (South Korea) all prescribe a mandatory geometric opening area ranging from 4% to 5% of the floor area, they simultaneously nullify this requirement through the Mechanical Exception.

- **The Substitution Logic:** Specifically, the US IBC §1202.1 establishes an explicit 'OR' condition (Natural OR Mechanical), whereas South Korea’s Rules on Equipment Standards Article 11 and Japan’s Enforcement Decree Article 20-2 employ a conditional waiver where natural ventilation standards are exempted if a mechanical system is installed. Despite this structural difference, both mechanisms effectively prioritize system control over occupant accessibility.
- **The Consequence:** In high-rise offices or mixed-use complexes, windows become legally redundant features solely for daylight or emergency egress (geometric compliance), while their effective operability is sealed off to maintain air-tightness for HVAC efficiency.

3.1.2. Functional Reduction: UK

The UK framework (Approved Document F & O) presents a conditional variation of the trap. Unlike the prescriptive geometric mandates of the US (4%) or Korea (5%), UK regulations primarily rely on a performance-based standard for purge ventilation (typically 4 air changes per hour (ACH)). While Approved Document F advises a minimum window area of 1/20 (5%) of the floor area to meet this performance in dwellings, this is guidance rather than a strict legal mandate for all building types.

- **Conditional Alternative:** Consequently, UK regulations effectively allow mechanical systems to substitute for natural openings when external constraints make opening windows "not practicable." Specifically, Approved Document O (Overheating) stipulates that if external noise or pollution levels are high, windows must be assumed "closed" during overheating assessments. This forces the adoption of mechanical cooling or mechanical ventilation as a primary strategy, rendering the operable window a theoretical feature rather than a usable one.
- **Hygiene vs. Purge:** In this context, window opening is often categorized merely as Purge Ventilation (a rapid, intermittent action to remove smoke or pollutants) rather than a tool for daily adaptive comfort. This limits occupant agency to emergency or specific purge scenarios, unlike the continuous control guaranteed in the German model.

3.1.3. The Regulatory Outlier: Germany

Germany presents a distinct regulatory model that structurally resists the Geometric Trap.

- **Structural Guarantee:** The MBO §47(2) mandates a significantly larger physical opening area of 1/8 (12.5%) for habitable rooms (Aufenthaltsräume), setting a higher geometric baseline than other jurisdictions.
- **Systemic Decoupling:** Crucially, the technical rule ASR A3.6 establishes a decoupled compliance structure. Unlike the US, Japan, or Korean models where mechanical systems legally substitute natural ventilation requirements, German regulations mandate operable windows independently of HVAC installation. Specifically, while ASR A3.6 restricts window usage in cases of high noise or pollution (requiring supplementary mechanical ventilation), standard building codes (MBO §47) still mandate the provision of operable windows for emergency egress and occupant agency. Thus, no architectural waiver exists. This ensures that natural access remains a fixed architectural requirement rather than a tradable variable.
- **Historical Divergence:** This regulatory difference reflects a distinct historical trajectory. While the US approach evolved from an energy-centric paradigm following the 1970s energy crisis [33], German regulations (ASR) originated from an occupational health perspective aimed at combating Sick Building Syndrome in the 1980s [34]. Consequently, window operability is codified not as an optional energy strategy, but as a standard occupational health requirement (see Table 2).

Table 2. Comparative Analysis of Level 1 Mandatory Codes.

Country	Code / Standard	Min. Opening Area	Mechanical Exception ¹	Primary Logic	Impact on Operability	
US	IBC (2024)	4% (1/25)	Yes (Waived)	System Control	Sealed	Box:
					Natural ventilation is legally replaced by HVAC, rendering windows functionally fixed.	is replaced by HVAC,

UK	Approved Document F (2021)	Performance-based (Min. 4 ACH for Purge)	Conditional (Noise/Overheating)	Conditional Substitution (Hygiene & Purge)	Intermittent Use: Windows are framed as 'Purge' devices for rapid ventilation, often substituted by mechanical extraction in noisy areas.
Germany	MBO / ASR A3.6 (2024/2018)	12.5% (1/8)	Not Applicable (Mandatory)	Decoupled	Dual Compliance: Natural ventilation remains mandatory regardless of mechanical systems. HVAC is treated as an additive system, not a substitute.
Japan	Building Standards Act (JP, 2024)	5% (1/20)	Yes (Waived)	Emergency Ingress (Fire)	Firefighter Focus: Windows are for Emergency Entry (Red Triangle ▽), often blocked by rails or limiters (<150mm).
South Korea	Building Act (KR, 2024)	5% (1/20)	Yes (Waived)	Minimum Habitability	The Geometric Trap: High A_{geo} exists on paper, but ERV systems allow total sealing, ignoring actual usability (A_{eff}).

¹ Mechanical Exception: Defines whether the mandatory requirement for natural ventilation openings can be legally removed or ignored if a mechanical ventilation system is installed.

3.2. Level 2 Analysis: The Evolution to Functional Operability

Green building rating systems are actively evolving to bridge the gap left by mandatory codes. The analysis of the most recent standards reveals a unified global paradigm shift: moving from static area-based compliance to control-based performance, as summarized in Table 3.

Table 3. Comparative Analysis of Level 2 Green Rating Systems

System (Region, Year)	Target Credit / Category	Performance Criteria	Operability Status	Limitation
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LEED v5 (US/Global, 2025)	EQ: Resilient Spaces (Option 4)	Emergency Survival (Shift from v4 Control)	Optional Option	Emergency Framing: Redefines windows as disaster relief tools rather than daily rights; often conflicts with fixed Quality Views.
BREEAM v7 (UK/Global, 2025)	Hea 04: Thermal Comfort (Adaptation to Climate Change)	Climate Adaptation (Overheating Prevention)	Critical Option.	Tradable Resilience: Shifts focus from potential (v6) to adaptability (v7) against future warming, but remains tradable for mechanical stability.
DGNB System (Germany, 2023)	SOC 1.4: Thermal Comfort (User Influence)	Spatial Depth (Distance to Window)	High Priority	Mechanical Substitution: Penalizes deep plans (>7m) to ensure user access, but operable windows can be substituted by high-end HVAC.
CASBEE (Japan, 2024)	Q1: Indoor Env. (4.2.2 Nat. Ventilation)	Aggressive Ratio (Target: 1/10)	Optional Score	Instrumentalization: Uses maximum openness (10%) as a tool for Carbon Neutrality (ZEB), subordinating user agency to energy performance.
G-SEED (South Korea, 2025 Proposal)	2: Living Space and Health (2.4: Arrangement)	Window Arrangement	Optional Score	Incomplete Transition : Moves from simple area ratio (>5%) (v2016) to effective arrangement, but the 2025 standard remains a proposal.

3.2.1. LEED v5 (US/Global): From Comfort to Resilience

The evolution from LEED v4 (2013) [35] to the newly drafted v5 (2025) illustrates a critical shift in how natural ventilation is framed: from a tool for daily comfort to a strategy for emergency survival.

- **Continuity of the Equivalency Trap:** Both v4 and v5 versions fundamentally maintain the Thermal Comfort credit structure, where operable windows are legally equivalent to mechanical thermostats. By allowing digital controls to substitute for physical openings, the system continues to treat natural ventilation as an optional amenity for sensory satisfaction rather than a fundamental architectural right.
- **Shift to Resilience:** However, v5 introduces a significant paradigm shift in the Resilient Spaces credit (EQc4). Unlike v4, which focused primarily on everyday air quality, v5 specifically rewards designs where operable windows provide access to outdoor air during heat waves or localized power outages. This reframes the window as a disaster relief tool.
- **The Visual-Aerodynamic Conflict:** Furthermore, the separate Quality Views credit often incentivizes large fixed glazing to maximize visual connectivity. This creates a structural conflict where the right to view (fixed glass) often suppresses the right to air (operable frames), separating the visual experience from the aerodynamic connection.
- **Limitation:** Ultimately, despite acknowledging the survival value of windows, the systemic limitation persists. Since resilience is merely one option within a broader menu, designers can achieve top-tier certification through alternative passive thermal measures, leaving the sealed box typology legally intact for non-emergency operations.

3.2.2. BREEAM (UK/Global): From Potential to Adaptation

The transition from BREEAM V6 (2022) [36] to the recently launched V7 (2025) marks a strategic pivot from checking ventilation potential to demanding climate adaptability.

- **The Potential Standard:** Under the previous Version 6, Criterion Hea 02 (Indoor Air Quality) focused on the potential for natural ventilation. It rewarded designs that simply provided the capability to open windows for fresh air intake, framing operability primarily as an indoor air quality strategy. The metric was static checking if the hardware existed.
- **The Adaptation Imperative:** Version 7 drastically escalates this requirement under Criterion Hea 04 (Thermal Comfort) and the new Resilience category. It mandates a rigorous thermal modeling analysis against future climate scenarios (e.g., 2050s and 2080s weather files). Here, natural ventilation is no longer just for fresh air; it is evaluated as a critical passive strategy to prevent summer overheating without reliance on energy-intensive cooling.
- **Significance:** This shifts the evaluation from "Can the window open?" to "Can the window save the building from overheating?" It redefines the operable window as a primary instrument for climate adaptation.
- **Limitation:** However, despite this rigorous modeling, the optional trap persists. While passive strategies are heavily encouraged to meet Net Zero targets, projects can still achieve compliance through high-efficiency active cooling systems if the passive analysis deems the site too noisy or polluted, effectively trading off the Right to Open for mechanical thermal stability.

3.2.3. DGNB (Germany): The Aggressive Geometric Strategy

While other systems focus on the physical properties of the window itself, the German DGNB System (Version 2023) shifts the analytical focus to the relationship between the user and the façade.

- **Metric of Proximity (Distance to Agency):** Under Criterion SOC 1.4 (Thermal Comfort), DGNB assesses not just the existence of openings, but the User Influence on Thermal Comfort. Crucially, this credit penalizes deep plan typologies. It evaluates the proportion of the usable area situated within a specific distance (typically 6–7 m) from an operable window.
- **Anti-Deep Plan Logic:** This approach redefines operability from a hardware metric to a spatial metric. Even if a building has a high geometric opening ratio, it scores poorly if the floor plate is too deep, effectively rendering the window inaccessible to occupants in the core zone. This enforces a thinner building massing that inherently supports cross-ventilation.
- **Limitation:** However, the fundamental flaw of Level 2 persists. The user influence credit is weighed against mechanical thermal comfort capabilities. A highly efficient, fully sealed building with advanced climate control (Category I) can still achieve a Platinum rating without providing direct user access to windows, turning this spatial right into a tradable commodity.

3.2.4. CASBEE (Japan): The Efficiency-Centric Strategy

The newly released CASBEE-Building 2024 Edition maintains its rigorous quantitative approach established in its predecessor (2014 Edition) [37], pushing the boundaries of geometric openness under the strengthened banner of Carbon Neutrality.

- **Aggressive Geometric Benchmarks:** Unlike other systems that accept minimal compliance, CASBEE has consistently upheld a steep tiered benchmark for the Effective Opening Area (Q1. Indoor Environment, 4.2.2 Natural Ventilation). While the baseline for offices starts at 1/20 (5%), achieving the top-tier Level 5 requires an effective opening area of 1/10 (10%). For schools, the baseline is even stricter at 1/15 (6.7%), reflecting higher ventilation demands.
- **Significance (10% Rule):** This maintained 10% requirement is double the standard international code (typically 1/20), forcing architects to design building envelopes that are physically twice as porous as conventional buildings. It cements CASBEE's position as the advocate for maximum permeability.
- **Evolution (2024 Update):** The 2024 edition explicitly reframes this openness not just as an amenity, but as a critical passive cooling instrument to achieve Net Zero Energy (ZEB) targets. By integrating these geometric metrics with the Natural Energy Utilization credit (LR1), it

instrumentalizes the window as a primary device for cooling load reduction, making the Right to Open subservient to the duty to decarbonize.

3.2.5. G-SEED (South Korea): From Quantity to Arrangement

The evolution of G-SEED illustrates a strategic pivot from Geometric Compliance to Functional Operability.

- **The Limitation (2016 Version)** [38]: Under the current Criterion 3.2.1 (Introduction of Natural Ventilation), evaluations are limited to a simple geometric ratio that rewards designs where the opening area exceeds tiered benchmarks (2, 3, 4, or 5%) of the floor area, regardless of actual airflow effectiveness. This metric often allows for ineffective single-sided ventilation designs that satisfy the code numerically but fail to provide thermal comfort.
- **The Evolution (2025 Revision Proposal)**: Addressing this deficiency, the 2025 Revision restructures the framework under Category 2 (Living Space and Health), introducing Criterion 2.4 (Natural Ventilation through Window Arrangement). This new credit shifts the focus to the effectiveness of airflow paths, explicitly incentivizing cross-ventilation and the strategic placement of windows to ensure effective airflow, although detailed technical specifications have not yet been disclosed.
- **Significance**: This marks a transition from checking hardware existence to verifying architectural performance. However, a critical limitation remains: like other Level 2 systems, this architectural credit remains optional, liable to be discarded in favor of mechanical scores if not prioritized by the client.

3.2.6. The Remaining Limitation: Optional Agency

Despite these advancements, a critical structural flaw remains. In most Level 2 systems (with the qualitative exception of DGNB), operability credits remain optional.

- **The Scoring Trade-off**: Under the current points-based frameworks, a building can achieve a Platinum or Outstanding rating by maximizing energy points (HVAC efficiency, renewables) while completely ignoring occupant control credits.
- **Persistence of the Sealed Box**: This Substitution Logic allows the proliferation of green sealed boxes, buildings that are environmentally efficient on paper but deny occupants the agency to regulate their own environment. This critical discrepancy underscores the necessity for a paradigm shift to Level 3, where agency becomes mandatory.

3.3. Level 3 Analysis: The Return of Mandatory Agency

The most radical departure from the status quo is observed in Level 3 regenerative frameworks. The Living Building Challenge (LBC) and WELL Standard redefine the operable window not as a ventilation backup, but as a fundamental human right and a prerequisite for biological health(Table 4).

Table 4. Comparative Analysis of Level 3 Regenerative Frameworks.

System (Region, Year)	Target Mandate	Performance Criteria	Agency Status	Key Philosophy
LBC 4.1 (US/Global, 2024)	Imp 09: Healthy Interior / Imp 19: Biophilia	100% Coverage (Zero Exception)	Mandatory	Biological Necessity: No window = No certification.
WELL v2 (US/Global, 2025)	A07: Operable Windows	75% Coverage + Thermal Control	Precondition (High Priority)	Health & Productivity: Agency is key to mental/physical well-being.

3.3.1. LBC 4.1 : The Zero-Exception Agency

The Living Building Challenge 4.1 maintains the strictest mandate in the industry, positioning the operable window as a non-negotiable biological necessity.

- **Imperative 09 (Healthy Interior Environment):** Unlike Level 2 systems that allow trade-offs, LBC 4.1 Imperative 09 explicitly requires that every regularly occupied space must have operable windows to provide access to fresh air.
- **Zero-Exception Policy:** This effectively imposes a 100% coverage requirement, eliminating the Sealed Box typology entirely. If a design creates a zone where occupants cannot open a window (excluding specific medical/industrial exceptions), the project fails the Core certification, regardless of its energy efficiency.
- **Biophilic Integration (Imperative 19):** Furthermore, this agency is reinforced by Imperative 19 (Beauty + Biophilia), which frames the connection to the outdoors not merely as a ventilation strategy, but as a psychological lifeline essential for human delight and connection to place.

3.3.2. WELL v2 : The Health-Centric Agency

While LEED v5 focuses on resilience, WELL v2 focuses on daily health and cognitive performance, enforcing agency through rigorous coverage and verification.

- **Feature A07 (Operable Windows):** WELL v2 mandates high accessibility, requiring that at least 75% of regularly occupied spaces have operable windows (Part 1). While not 100% like LBC, it sets a high baseline that prevents the core-heavy deep plans common in conventional offices.
- **Feature T08(Enhanced Control):** Crucially, WELL links operability to Thermal Comfort (Feature T08 Enhanced Operable Windows). It does not treat the window merely as an air intake, but as a tool for individual thermal control, acknowledging that personal agency over temperature is directly linked to occupant productivity and mental well-being.
- **Monitoring Integration:** Uniquely, WELL v2 emphasizes the integration of real-time air quality monitoring (Feature A01), encouraging a mixed-mode approach where occupants are actively informed when to open windows, bridging the gap between human agency and building intelligence.

4. Discussion

4.1. The Geometric Trap: How Codes Fail Occupant Agency

The most significant finding from the comparative analysis is the systemic misalignment between regulatory intent and architectural reality, which this study terms the Geometric Trap. Mandatory codes (Level 1), particularly the IBC and its global derivatives including Korean standards, rely on a binary definition of Openability based solely on geometric dimensions. As long as a window meets the 4% or 5.7 ft² (0.53 m²) requirement, it is deemed compliant.

However, the widespread adoption of the Mechanical Exception (IBC §1202) has fundamentally eroded the window's function. By allowing mechanical systems to legally substitute for natural ventilation, codes have transformed the operable window from a daily environmental control device into a dormant emergency hatch. In high-rise residential contexts in South Korea and the US, this has normalized Fixed or Restricted windows that technically meet safety codes but are functionally useless for cooling or air quality management. This contrasts with the German model (MBOB), which codifies natural ventilation as a non-negotiable environmental standard. The German refusal to waive window requirements highlights a regulatory divergence: while the US model allows for System Substitution (replacing windows with HVAC), the German model enforces Structural Redundancy, requiring both mechanical sufficiency and natural access to function independently.

4.2. *The 2025 Pivot: From Paradox to Passive Survivability*

Historically, green building certifications (Level 2) have inadvertently deepened this crisis through the Energy and Acoustic Paradox. Under previous versions of LEED (v4) and standards like BREEAM V6 or CASBEE, opening a window was often penalized for disrupting the thermal envelope or allowing noise ingress, creating a disincentive for operability in urban zones.

However, the release of LEED v5 and BREEAM V7 in 2025 marks a critical turning point, the Resilience Pivot. The introduction of the Passive Survivability credit acknowledges that in an era of climate destabilization, a sealed building dependent entirely on the grid is not efficient, but dangerous. This shift redefines the operable window: it is no longer a liability for energy loss, but a vital asset for resilience. This aligns with the Whole Life Carbon approach, suggesting that the future of high-performance architecture lies not in hermetically sealing the occupants, but in providing them with robust, low-tech adaptive options during critical discrepancy.

4.3. *The Evolution of Occupant Control*

While the Resilience Pivot is promising, its application in East Asia (South Korea, Japan) faces unique challenges often overlooked by Western-centric standards. In high-density megacities like Seoul and Tokyo, the Right to Open (Level 3) conflicts directly with the Right to Clean Air due to urbanization factors. Environmental factors such as external noise and Particulate Matter (PM2.5) frequently render natural ventilation unviable. Consequently, the actual usability of the window drops to zero, even when the geometric openability requirements are fully met. Furthermore, fire safety regulations often prioritize firefighter ingress over occupant ventilation, resulting in obstructed sashes. Therefore, blindly adopting Western Right to Open standards without addressing these local constraints is ineffective.

4.4. *Toward a Performance-Based Understanding of Operability*

The preceding analysis demonstrates that the structural limitation surrounding operable windows does not stem from the absence of minimum opening requirements, but from the logic by which operability is defined. Across multiple jurisdictions, compliance is evaluated through static geometric thresholds, while the actual capacity of occupants to use windows in daily life remains unexamined.

This gap reveals a fundamental limitation of area-based criteria. A window that satisfies geometric requirements may nevertheless be inaccessible due to spatial depth, restricted hardware, environmental exposure, or mechanical substitution. In such cases, formal compliance masks the collapse of functional operability.

From this perspective, operability should be understood not as a fixed property of the window itself, but as a relational condition shaped by proximity, accessibility, and environmental context. This reframing aligns with emerging regenerative standards, which increasingly prioritize occupant agency and Passive Survivability over nominal compliance.

Rather than prescribing a fixed metric for calculation, the Effective Opening Area framework functions as a diagnostic lens to evaluate whether regulatory and spatial conditions allow occupants to meaningfully access natural ventilation. This shift redefines compliance not as a geometric capacity, but as the preservation of occupant agency against mechanical substitution.

5. Conclusions

This study investigated the structural gap between regulatory compliance and the actual operability of windows, identifying a phenomenon termed the Geometric Trap. Through a comparative analysis of mandatory codes (Level 1), green rating systems (Level 2), and regenerative frameworks (Level 3), the research revealed that current regulations in the US, the UK, Japan, and South Korea systematically nullify the function of operable windows through mechanical substitution. While these codes mandate a specific geometric opening area, they legally allow

mechanical ventilation systems to override natural access, rendering the window a static, sealed building component.

In contrast, the German model demonstrates a structural co-existence, proving that mechanical sufficiency does not require the legal exclusion of natural access. This finding challenges the prevailing industry assumption that sealing buildings is inevitable for climate control. Instead, it suggests that the Mechanical Exception found in other jurisdictions is not a technical necessity, but a regulatory choice that can be reversed.

Furthermore, while early green rating systems (Level 2) have historically focused on energy efficiency, often deepening the reliance on sealed environments, emerging regenerative frameworks (Level 3) are beginning to re-establish the connection between operability and occupant health. However, without a fundamental shift in mandatory legal baselines (Level 1), these voluntary standards remain limited in their widespread impact.

Therefore, this study argues for a paradigm shift from static area-based criteria to the Effective Opening Area framework. This approach moves beyond simple geometric compliance to evaluate the actual accessibility and usability of the window in the context of mechanical systems and environmental constraints. By restoring the window’s role as a functional instrument rather than a theoretical requirement, future building codes can resolve the conflict between energy performance and human needs, ensuring that occupant agency remains central to the design of the built environment.

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Abbreviations

The following abbreviations are used in this manuscript:

A_{eff}	Effective Opening Area
A_{geo}	Geometric Opening Area
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
DGNB	German Sustainable Building Council
G-SEED	Green Standard for Energy and Environmental Design
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IBC	International Building Code
IEQ	Indoor Environmental Quality
LEED	Leadership in Energy and Environmental Design
UBC	Uniform Building Code

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