International Journal of Architectural Engineering & Urban Planning, Volume 36, Number 3, 2026
***DOI:* 10.22068/ijaup.986**

Research Paper

A Multi-Scale Architectural Decision Framework for Natural Ventilation in School Classrooms [1]

Farzad Eradati [1], Mansoureh Tahbaz [1*], Azadeh Khaki Ghasr [2], Omid Rahaei [3]

[1] *Department of Building, Faculty of Architecture and Urban Planning, Shahid Beheshti University, Tehran, Iran*

[2] *Department of Architecture, Faculty of Architecture and Urban Planning, Shahid Beheshti University, Tehran, Iran*

[3] *Department of Architectural Technology, Faculty of Architecture Engineering and Urban Planning, Shahid Rajaee Teacher Training University, Tehran, Iran*

Received: February 2026, **Revised:** June 2026, **Accepted:** July 2026, **Publish Online:** July 2026

Abstract
Classrooms are high-occupancy spaces where ventilation performance directly affects students' health, attention, and learning. While natural ventilation (NV) is widely promoted as a low-energy means of improving indoor air quality (IAQ) and reducing dependence on mechanical systems, design guidance is often fragmented across disciplines and reported in forms that are difficult to translate into early architectural decisions. This study addresses that gap by converting dispersed evidence into an architect-readable, multi-scale decision framework for naturally ventilated school classrooms. The research integrates (i) a systematic evidence synthesis of international and Iranian evidence primarily published between 2000 and 2025 and (ii) a rubric-guided case-selection procedure to identify well-documented school precedents for comparative interpretation. The final dataset comprises 117 sources, including peer-reviewed papers, theses/dissertations, standards and regulations, and books. Results are structured across interconnected architectural scales—site and massing, plan and section, façade and openings, and NV-supporting components—showing how early design moves shape airflow paths, controllability, and operational feasibility under variable outdoor conditions. The paper contributes a replicable workflow (evidence synthesis plus rubric-based case screening) and a design-oriented framework that translates ventilation evidence into prioritized architectural decisions and supports robust NV classroom design under real-world constraints such as seasonal variability, outdoor pollution, noise, security, safety, and user operation.

Keywords: *Natural ventilation, School classrooms, Indoor air quality, Architectural design, Airflow control.*

[*] *Corresponding author: m-tahbaz@sbu.ac.ir*

[1] The present article is derived from an ongoing Ph.D. thesis by Farzad Eradati, entitled "Feasibility Study of Applying Natural Ventilation in Elementary School Classrooms by Passive Architectural Strategies (Case Study in Hot-Arid and Cold Climates of Iran)," which is being conducted at the Faculty of Architecture and Urban Planning, Shahid Beheshti University, Tehran, Iran, under the supervision of Dr. Mansoureh Tahbaz and Dr. Azadeh Khaki Ghasr and with the advice of Dr. Omid Rahaei.

INTRODUCTION

School classrooms are high-occupancy spaces in which ventilation conditions directly affect indoor air quality (IAQ), thermal comfort, health, and students' ability to remain attentive. Long occupied hours, fluctuating density, and the sensitivity of school-age users make adequate outdoor-air provision a critical consideration in educational environments. Natural ventilation (NV), driven primarily by wind pressure and thermal buoyancy, is widely recognized as a low-energy strategy for improving IAQ and reducing dependence on mechanical systems when outdoor conditions and building operation permit its effective use (Gil et al., 2017a, 2017b; Kapoor et al., 2021; Toyinbo, 2023).

Reliable NV, however, cannot be achieved merely by providing operable windows. It is an airflow system shaped by coordinated architectural decisions across multiple spatial scales. Site exposure and massing influence pressure differences; plan depth, internal partitions, and sectional organization determine the continuity of airflow paths; and façade permeability, opening geometry, and dedicated ventilation elements affect air entry, distribution, exhaust, and user control (Aflaki et al., 2015; Jia et al., 2021; Khoshnaw et al., 2025). These decisions must also respond to seasonal variability, outdoor pollution, acoustic disturbance, safety, security, and occupant behavior (Diaz-Lopez, Serrano-Jimenez, Lizana, et al., 2022; Diaz-Lopez, Serrano-Jimenez, Verichev, et al., 2022). Accordingly, intermittent window opening may provide temporary airing without ensuring stable, predictable, or controllable ventilation performance.

Research on NV in educational buildings has expanded across building physics, environmental engineering, public health, and climate-responsive architecture (Cuce et al., 2019). International studies have examined airflow mechanisms, opening configurations, classroom environmental performance, ventilation and infection-risk concerns, and the health and cognitive implications of indoor environmental quality (Aguilar-Carrasco et al., 2025; Becker et al., 2007; Cordero et al., 2024; Ferrari et al., 2022; Fisk, 2017; Paridokht et al., 2025). Earlier school-focused design studies also emphasize the architectural role of form, orientation, openings, and spatial organization in establishing ventilation strategies (Alatalo, 2016; Sireesha, 2016; Uzunhasanoglu, 2015). Iranian studies have contributed context-specific evidence on climate-responsive school design, inlet–outlet relationships, façade configuration, classroom geometry, shading, adjustable openings, and operational constraints (Kabir, 2015; Hendoukolaei, 2018; Haji Hosseini, 2020; Khojasteh, 2022). Iranian standards and guidance documents also address outdoor-air provision, CO_2 thresholds, opening requirements, classroom dimensions, daylight–ventilation relationships, pollutant-source separation, safety, and hybrid ventilation strategies (Plan and Budget Organization of Iran, 2021; Ministry of Health, Treatment, and Medical Education, 2022; Institute of Standards and Industrial Research of Iran, 1998, 2001, 2002; Management and Planning Organization of Iran, 2016).

Despite this growing body of knowledge, the available evidence remains fragmented across disciplines and is often reported through heterogeneous indicators, assumptions, and boundary conditions. Many studies focus on isolated variables or individual cases rather than integrated architectural decision structures. Standards provide performance benchmarks, but their application still requires architectural interpretation in relation to spatial configuration, airflow-path continuity, and operational feasibility. Consequently, architects lack a concise and prioritized framework that can translate dispersed evidence into early-stage design decisions.

This study addresses that evidence-to-decision gap by developing a multi-scale architectural decision framework for NV in school classrooms. The research synthesizes international and Iranian evidence primarily published between 2000 and 2025 and organizes the findings across four interconnected scales: site and massing, plan and section, façade and openings, and NV-supporting components. A rubric-guided screening procedure is also used to identify well-documented school precedents for comparative interpretation. The intended contribution is an architect-readable framework and a transparent evidence-to-decision workflow that link airflow mechanisms and performance evidence to prioritized design decisions under real-world constraints.

The study is guided by the following two research questions:

RQ1. What multi-scale architectural decision framework can translate dispersed international and Iranian evidence into actionable NV strategies for school classrooms?

RQ2. How can a transparent rubric-guided procedure be used to identify and compare well-documented school precedents for evidence-based interpretation and transfer of NV design decisions?

MATERIALS AND METHODS

Research Design

This study developed a multi-scale architectural decision framework for natural ventilation (NV) in school classrooms through an integrated evidence-synthesis approach. The method combined a PRISMA-guided review of international and Iranian sources, a design-oriented thematic synthesis, and a rubric-guided comparative analysis of architectural precedents. Iranian M.Sc. theses and national standards were also examined as complementary evidence streams to capture context-specific design concerns and regulatory constraints.

The analysis treated classroom NV as a coordinated airflow system rather than as a matter of window area alone. Evidence was interpreted across four interconnected architectural scales: site and massing, plan and section, façade and openings, and NV-supporting components. Particular attention was given to the traceability of the airflow path: supply, transfer, and exhaust.

Evidence Sources and Search Strategy

International records were identified through Scopus, Web of Science, and Google Scholar. Iranian records were collected from IranDoc/Ganj, selected university repositories, SID, Magiran, Noormags, and Civilica. The review focused on sources published between 2000 and 2025; currently applicable national standards issued outside this period were retained when they defined directly relevant architectural or regulatory constraints. Search terms were organized around three concept groups: natural ventilation, school or classroom environments, and architectural design strategies. Equivalent English and Persian terms were adapted to the indexing structure of each database.

The search identified 1,013 records before de-duplication, including 924 international records and 89 Iranian records. Standards, regulations, books, and institutional guidance documents were retained when they contributed directly to the architectural interpretation of classroom NV.

Screening and Eligibility Assessment

The review followed a PRISMA-guided workflow comprising identification, de-duplication, title-and-abstract screening, full-text eligibility assessment, and final inclusion. The screening process is presented in Figure 1.

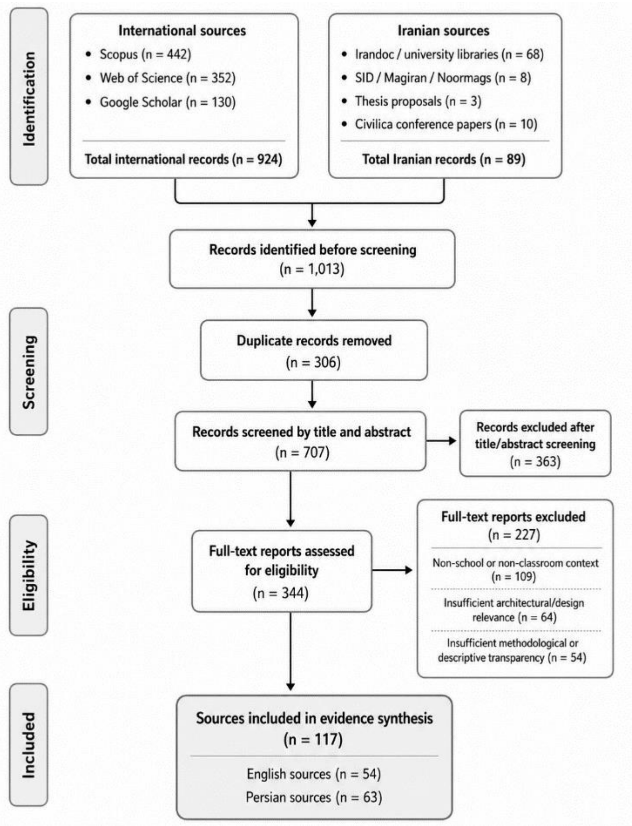


Fig 1. PRISMA Flow Diagram of Screening and Eligibility

Sources were retained when they addressed naturally ventilated or mixed-mode school environments and provided design-relevant evidence, such as orientation, plan depth, sectional configuration, façade permeability, opening geometry, airflow paths, operational assumptions, or NV-supporting components. Sources were excluded when they focused on non-educational settings without transferable implications, addressed mechanical systems without architectural relevance, or lacked sufficient methodological or descriptive transparency.

Following screening and eligibility assessment, 117 sources were retained for synthesis, comprising 54 English-language sources and 63 Persian-language sources.

Data Extraction and Thematic Synthesis

A structured extraction protocol recorded climatic context, school typology, ventilation mode, driving force, airflow-distribution principle, architectural variables, operational assumptions, analytical method, performance indicators, and reported implications. Evidence was synthesized through a design-oriented thematic analysis linking each finding to supply–transfer–exhaust logic and to the relevant stage of architectural decision-making.

Rubric-Guided Precedent Selection

An initial pool of 56 school precedents was compiled from the reviewed literature. Each case was evaluated using five criteria: clarity of the ventilation principle, legibility of the airflow path, availability of quantitative or validated evidence, traceability of operational assumptions, and transferability to early-stage design decisions. Each criterion was scored from 0 to 2, where 0 indicated absent or unclear evidence, 1 indicated partial evidence, and 2 indicated clear and design-transferable evidence. The rubric is presented in Table 1.

The cases were ranked by total score, and seven precedents with the strongest combination of architectural legibility, evidence quality, and transferability were retained for comparative analysis. Their scores and principal sources are summarized in Table 2.

Table 1. Rubric Criteria and Scoring (ΣC1–C5) Used for Screening and Prioritizing Case-study Candidates

Criterion	Score 0	Score 1	Score 2
C1. Driving force & principle clarity	Not stated / unclear	Partially stated	Explicit (wind/stack/hybrid + principle)
C2. Architectural traceability	No usable drawings/air-path	Some drawings, limited traceability	Clear plans/sections/air-path diagrams
C3. Quantitative/validated evidence	None	Indirect/limited	Measured or simulation-validated
C4. Operation/control traceability	Not reported	Partial qualitative description	Clear operational/control logic
C5. Transferability	Low	Medium	High; explicit design implications

Table 2. Final School Cases Retained for In-depth Comparative Analysis (Rubric-Selected Precedents): Code, Case (School/Project), Main Evidence in Source, Score (ΣC1–C5), and Sources

Code	Case (School/Project)	Main evidence in source	Score (ΣC1–C5)	Source(s)
CS1	Evangelical Comprehensive School	Case-study set (plans/sections + NV narrative)	9	Kleiven (2003)
CS2	Waldorf School	Case-study set (plans/sections + NV narrative)	8	Kleiven (2003)
CS3	Jaer School	Case-study set + operational/quantitative evidence used for strengthening	8	Kleiven (2003)
CS4	Tredal School	Case-study set (plans/sections + NV narrative)	7	Kleiven (2003)
CS5	Tånga School	Case-study set (plans/sections + NV narrative)	9	Awbi (2008)
CS6	Mediå School	Diagrams/sections showing supply/extract paths	8	Kleiven (2003)
CS7	Charles de Gaulle High School	Case-study set (plans/sections + NV narrative)	8	Passe & Battaglia (2015)

Iranian M.Sc. Thesis Analysis

Within the retained evidence set, 40 Iranian M.Sc. theses were analyzed as a national evidence stream. They were classified by research orientation, thematic focus, and analytical method to identify recurring design concerns, dominant research patterns, and gaps in translating performance findings into explicit architectural rules.

RESULTS

The evidence synthesis shows that reliable natural ventilation (NV) in school classrooms cannot be reduced to operable windows or isolated components. It emerges from coordinated decisions across design scales, airflow mechanisms, and operational conditions (Baeumle, 2021; Baeumle & Hunt, 2018). The results are organized around two complementary perspectives: NV as a multi-scale design process, and NV as a system of architectural elements and airflow mechanisms. Figure 2 summarizes these perspectives and frames the following subsections.

The central principle linking the findings is a traceable supply–transfer–exhaust pathway: outdoor air should enter through a viable inlet, pass through the occupied zone, and reach an effective outlet without excessive resistance, short-circuiting, or unintended bypass (Etheridge, 2012; Awbi, 2008; Kleiven, 2003). Table 3 summarizes the operational vocabulary used to describe this pathway, Table 4 presents key geometry and depth rules, and Table 5 consolidates Iranian standards as architectural constraints (CIBSE, 2005; Institute of Standards and Industrial Research of Iran, 1998, 2001, 2002; Management and Planning Organization of Iran, 2016; Ministry of Health, Treatment, and Medical Education, 2022; Plan and Budget Organization of Iran, 2021).

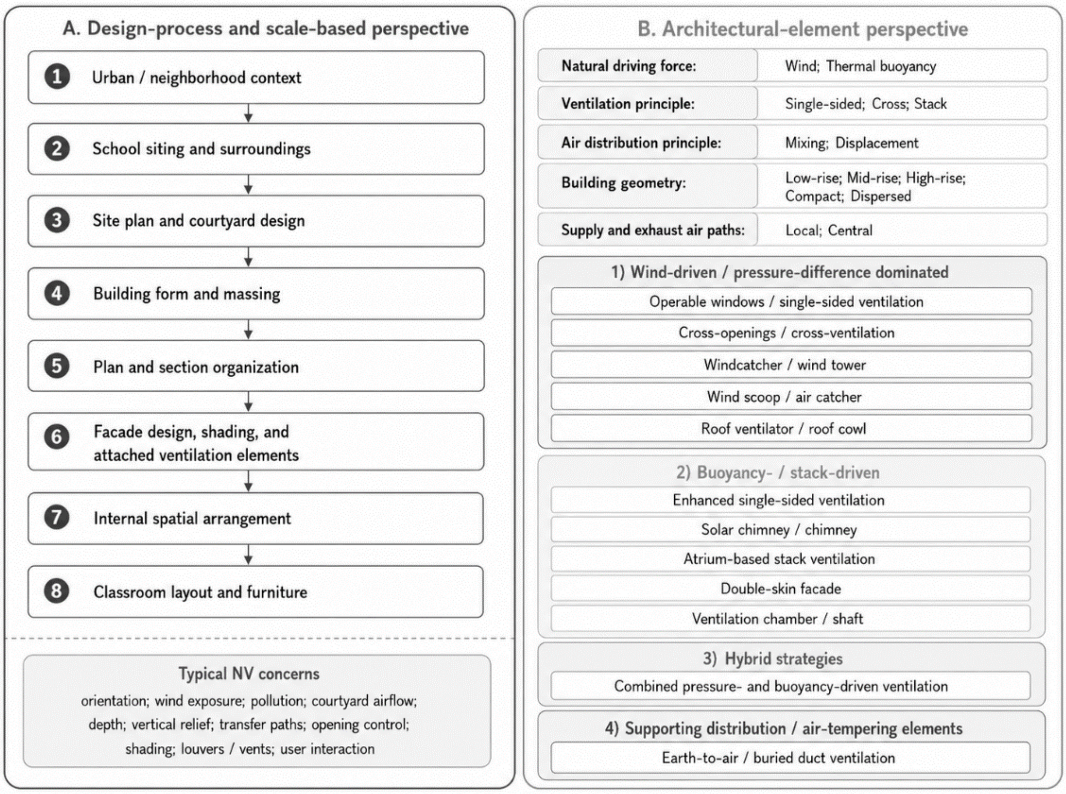
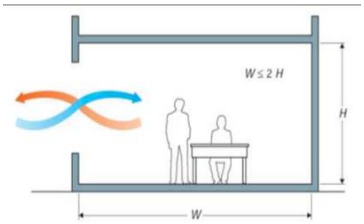
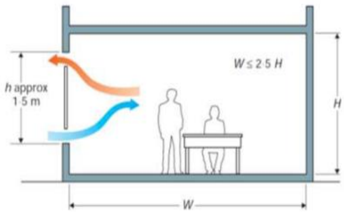
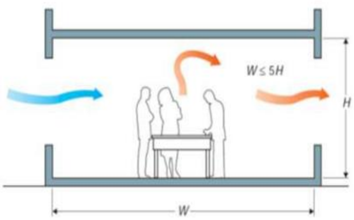


Fig 2. Two Complementary Architectural Perspectives on Natural Ventilation in School Design: (A) Design-process and Scale-based Perspective, and (B) Architectural-element Perspective

Table 3. Operational Dimensions and Defining Variables Used to Specify Natural Ventilation (NV) Concepts in School Classrooms (Adapted from Awbi, 2008; Kleiven, 2003)

Operational dimension	Defining variable(s)
Natural driving force	Wind; Thermal buoyancy
Ventilation principle	Single-sided; Cross; Stack
Air distribution principle	Mixing; Displacement
Characteristic ventilation elements	Ventilation openings in the facade (windows); Wind scoop; Windcatcher; Wind tower; Chimney / Solar chimney; Double facade; Atrium; Ventilation chamber; Embedded duct
Building geometry	Low-rise; Mid-rise; High-rise; Compact; Dispersed
Supply and exhaust air paths	Local; Central

Table 4. Natural Ventilation (NV) Principles in Buildings and Rule-of-Thumb Depth/Geometry Constraints for Early Design (Adapted from CIBSE, 2005, pp. 15–16)

Principle / NV strategy		Description (design logic)	Rule-of-thumb / key notes
Single-sided ventilation (one facade opening)		Primary drivers are typically buoyancy in colder periods and wind-induced exchange in warmer periods. Compared with other modes, air-change rates are usually lower and fresh air penetrates a limited depth.	Effective depth for meaningful ventilation is typically ≈ 2H (H = floor-to-ceiling height).
Enhanced single-sided (two vertically separated openings on the same facade; stack-assisted)		Ventilation rate can increase due to a stronger stack effect and larger vertical separation between openings; fresh-air penetration improves when a clear low-inlet / high-relief route exists.	Effective depth may extend to ≈ 2.5H, provided the transfer path between low-level supply and high-level relief is not obstructed.
Cross-ventilation (through-flow between opposite openings)		Main driver is pressure difference between inlet and outlet openings. Performance can be strong under favorable wind exposure but is sensitive to wind direction changes and internal resistance.	Maximum practical distance between inlet and outlet façades is commonly ≈ 5H. For deeper plans, use narrower blocks / linear forms or courtyard-assisted layouts.

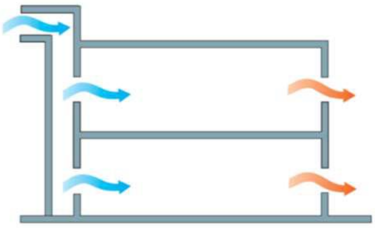
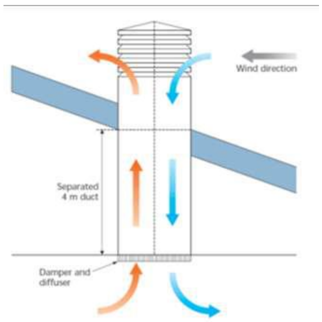
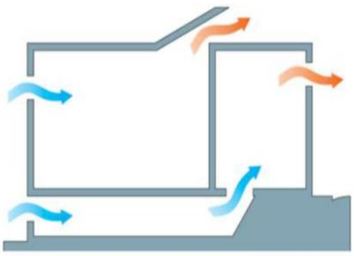
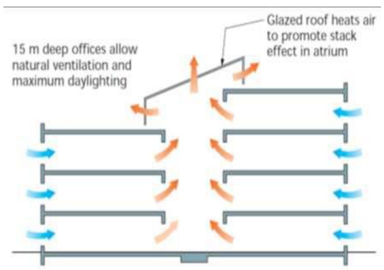
Principle / NV strategy		Description (design logic)	Rule-of-thumb / key notes
Windcatcher (wind tower / wind-driven intake)		A windcatcher captures higher-level winds (higher dynamic pressure), supplying additional driving pressure to move air through the building toward leeward exhaust.	Best when prevailing wind direction is reasonably stable. For variable winds, consider multi-directional intakes and control measures to reduce short-circuiting.
Roof ventilator (modern roof-mounted windcatcher / roof cowl)		Uses pressure differences around the roof to drive supply and exhaust via a roof unit; flow can be moderated by dampers; air distribution can be improved with diffuser details.	Useful for improving roof-level driving forces; requires attention to control and distribution to avoid drafts/short-circuiting.
Earth-to-air / buried duct ventilation		Brings outdoor air via buried ducts to deeper interior zones (e.g., second row of classrooms) and can enable one-sided supply when one façade cannot be opened (pollution/noise constraints).	Because natural-driving pressures are small, duct design must minimize pressure losses (keep paths smooth/short, avoid excessive bends, size appropriately).
Atrium-based stack ventilation (stack/solar-assisted via atrium)		Places openings at both low and high levels; buoyancy becomes the dominant driver, potentially enabling higher and steadier exhaust and greater penetration when air is transferred across/through the atrium.	Can ventilate greater plan depths when cross-transfer through the atrium is well defined and high-level relief is effective.

Table 5. Iranian Standards and Guidance Consolidated as Architectural Constraints for Classroom Natural Ventilation

Design / operational issue	Benchmark or requirement	Source(s)	Architectural implication for NV design
Outdoor-air provision	Green-school guidance reports approximately 7.1 L/s per person and 3.5 L/s per m². A stricter school ventilation baseline is approximately 10 L/s per student/teacher, or about 6 ACH.	Plan and Budget Organization of Iran (2021); Ministry of Health, Treatment, and Medical Education (2022)	Treat outdoor-air provision as a design target that must be supported by effective operable area and a continuous inlet-transfer-exhaust path.
CO_2 threshold & monitoring	An acceptable CO_2 range of about 350-1000 ppm is reported, with indoor CO_2 recommended below 1000 ppm. For natural/hybrid ventilation, average daily CO_2 below 1000 ppm and a maximum of 2000 ppm for up to 20 minutes are stated. Exceeding 1000 ppm indicates the need to increase ventilation; sensor installation is noted for naturally ventilated spaces.	Plan and Budget Organization of Iran (2021)	Provide staged and monitorable operation: accessible openings, high-level relief, sensor feedback, and user protocols for increasing ventilation when CO_2 rises.
Supply-air quality & pollutant separation	Outdoor-air inlets should be separated from pollutant sources: examples include about 5 m from parking entries, 5.7 m from contaminated discharges, and 8 m from waste storage. Operable windows used for NV should be at least 10 m from pollution sources. At the site-selection scale, distance from major pollutant sources should not be less than 500 m.	Plan and Budget Organization of Iran (2021); Institute of Standards and Industrial Research of Iran (2001)	Select inlet façades and intake heights by air quality as well as wind exposure. The most wind-exposed façade is not always the best source of outdoor air.
Opening geometry & operable area	Operable windows with an opening angle of at least 45 degrees and operable window area of about 10-20% of floor area are suggested to achieve 10 L/s per person. For classrooms with more than 20 occupants, glazing area/floor area = 1:5 and ventilation opening area/floor area = 1:12 are reported. A minimum operable window area of 5% of floor area is also specified, together with a high-level exhaust/relief path.	Ministry of Health, Treatment, and Medical Education (2022); Plan and Budget Organization of Iran (2021)	Distinguish total glazing from the effective operable portion. Coordinate opening angle, height, inlet-outlet position, and high-level relief rather than relying on window size alone.

Design / operational issue	Benchmark or requirement	Source(s)	Architectural implication for NV design
Daylight–ventilation coordination	Window-to-classroom area is recommended in the range of 1:8 to 1:5 depending on climate. Other daylight criteria include window area around 1:5 of classroom area, not less than 1:6, and classroom façade daylight-opening area at least 1:3 of the classroom façade area.	Institute of Standards and Industrial Research of Iran (2001, 2002); Management and Planning Organization of Iran (2016)	Design façade area, operable area, shading, and solar control together so that daylight requirements do not conflict with usable ventilation openings.
Window safety & operability	Minimum window-opening dimensions of 50 × 60 cm and minimum operable opening area of 0.53 m² are stated, together with access and safety requirements for window hardware.	Institute of Standards and Industrial Research of Iran (1998)	Ensure that windows satisfying nominal area requirements are actually reachable, safe, and usable during occupied hours.
Geometry & cross-ventilation feasibility	Cross-ventilation through opposing operable openings is required for plan depths of about 7-15 m. Openings on both sides are considered necessary when classroom width exceeds 7.20 m. Maximum classroom dimensions are reported as about 8 m length and 7 m width.	Plan and Budget Organization of Iran (2021); Management and Planning Organization of Iran (2016); Institute of Standards and Industrial Research of Iran (2001)	Control depth and width early. Avoid deep or obstructed classrooms where later opening enlargement cannot prevent stagnant zones.
Hybrid strategies & operation schedule	Hybrid/combined ventilation is recommended, and windcatchers and chimneys are proposed for hot-arid and hot-humid climates. Operational guidance suggests opening windows 30 minutes before and after occupancy and for 10 minutes every hour.	Plan and Budget Organization of Iran (2021); Ministry of Health, Treatment, and Medical Education (2022)	Provide accessible hardware, staged opening modes, seasonal control logic, and maintenance access for airflow-enhancing components.

Note. NV = natural ventilation; IAQ = indoor air quality; CO_2 = carbon dioxide; ACH = air changes per hour. The table synthesizes the standards-related evidence discussed in the reviewed manuscript and translates it into architectural design implications.

Conceptual Framing and Operational Vocabulary

The reviewed evidence was translated into six operational dimensions: driving force, ventilation principle, airflow-distribution principle, ventilation elements, building geometry, and supply-exhaust air paths (Awbi, 2008; Kleiven, 2003). This vocabulary shifts the discussion from isolated performance indicators, such as air-change rate or CO_2 concentration, toward variables that architects can control: form, depth, section, opening location, facade elements, and airflow paths. This translation process is illustrated in Figure 3, which shows how performance-oriented evidence is reframed through the six operational dimensions into architect-controllable design variables.

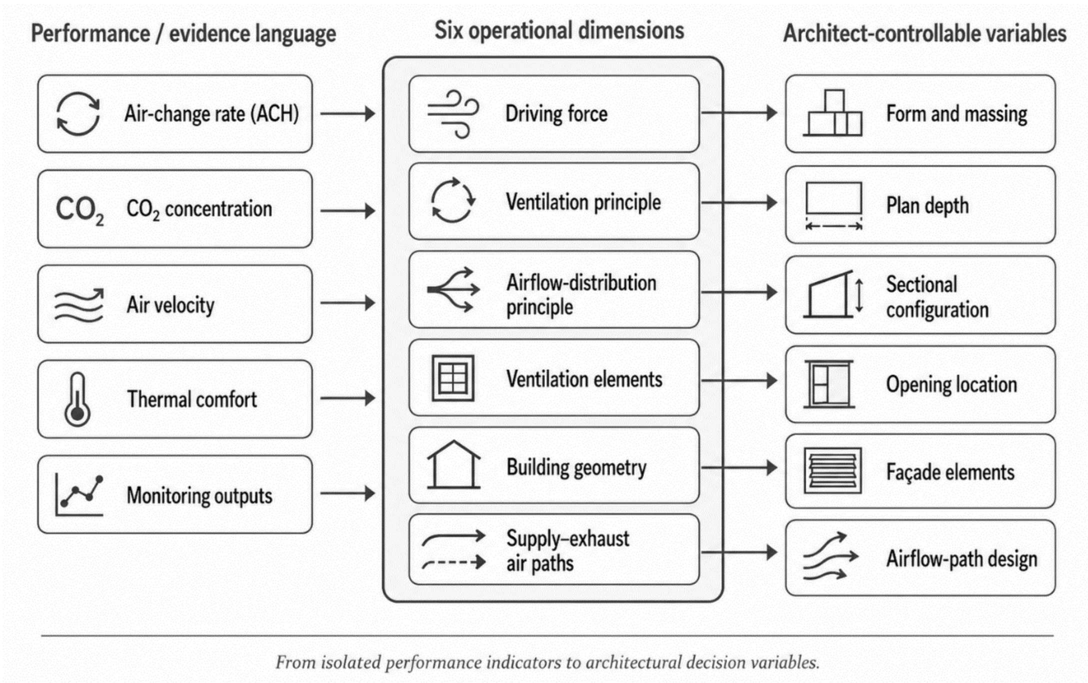


Fig 3. Translation of Reviewed Ventilation Evidence into Six Operational Dimensions and Architect-controllable Design Variables

Natural airflow may be wind-driven, buoyancy-driven, or hybrid (Bayoumi, 2021; Indarti et al., 2023). Depending on geometry and context, classrooms may rely on single-sided ventilation, enhanced single-sided ventilation, cross-ventilation, stack ventilation, displacement-oriented airflow, or combined strategies. However, ventilation quantity and airflow distribution are not equivalent. Acceptable average values for ACH, CO_2, or air velocity may still conceal stagnant seating zones, draughts, warm-air accumulation, or short-circuiting (Miao et al., 2025; Pinto et al., 2014; Hsu et al., 2024). Reliable NV therefore requires the alignment of performance targets, air-path-forming architecture, and implementable operation (Bienvenido-Huertas et al., 2023; Duarte et al., 2024; Heeboll et al., 2018).

Scale-Based Design Findings across the School Design Process

The first perspective in Figure 2 shows that NV should be treated as a front-loaded architectural decision. Its feasibility is largely established before details are designed, when urban exposure, school siting, building orientation, massing, plan depth, circulation layout, and section are defined (Baeumle, 2021; Baeumle & Hunt, 2018; Hiyama & Glicksman, 2015; Wang & Malkawi, 2019; Yuan, 2018).

At the urban, neighborhood, and site-plan scales, wind availability must be evaluated together with surrounding obstructions, pollution, noise, vegetation, courtyard geometry, and adjacent land uses. In polluted or noisy contexts, the most wind-exposed facade may not be the most appropriate inlet location (Tikul et al., 2023; Yin et al., 2024). Courtyards and semi-open spaces can support staged airflow transfer, but excessive enclosure may reduce air movement; one study identifies approximately 60% courtyard openness as a balance between air speed, air age, and usability (Li et al., 2025).

At the building, plan, and section scales, orientation, compactness, wing arrangement, floor level, classroom depth, corridor type, ceiling height, and high-level relief determine whether air can pass through the occupied zone. Upper floors and windward wings may ventilate better than lower or sheltered zones, and external corridors can improve airflow compared with internal corridors under tested conditions (Idowu et al., 2022; Yang et al., 2019). As preliminary geometry gates, single-sided ventilation is typically limited to about 2H, enhanced single-sided ventilation to about 2.5H, and cross-ventilation to about 5H under favorable exposure, where H is floor-to-ceiling height (CIBSE, 2005). These early-stage geometry rules are summarized in Table 4.

Facade design and internal arrangement complete the airflow path. Shading devices, louvers, trickle vents, ventilating panels, opening height, inlet–outlet position, and user access influence air entry, airflow direction, and user control over the ventilation pathway (Le et al., 2023; Farokhyan et al., 2020). Larger openings do not automatically improve performance; effective ventilation depends on through-flow, vertical separation, solar control, acoustic limits, and realistic operation (Aflaki et al., 2015; Chiang et al., 2013; Kouhirostami, 2018; Olufowobi & Adenuga, 2012; Ragab et al., 2025). At classroom scale, partitions, doors, transoms, furniture, and occupant distribution affect the breathing zone; for example, adding a 15 cm under-door gap with open windows increased ventilation from about 2 ACH to 8 ACH in one classroom study (Hsu et al., 2024).

Element-Based Findings: Wind-Driven, Stack-Driven, and Hybrid Strategies

The second perspective in Figure 2 interprets NV through architectural elements and airflow mechanisms. Wind-driven or pressure-difference-dominated strategies include operable windows, cross-openings, windcatchers, wind towers, wind scoops, roof ventilators, and ventilating facades. These elements are effective only when they connect to a clear transfer and relief path. Windcatchers and wind towers can capture higher-level winds where facade openings are insufficient, but their performance depends on geometry, dampers, controllable windows, seasonal operation, and prevailing wind stability (Aflaki et al., 2015; Jomehzadeh et al., 2017; Jones & Kirby, 2010, 2012; Kolokotroni et al., 2002; Mavrogianni & Mumovic, 2010; Nejat et al., 2025; Salavatian & Babazadeh, 2025).

Buoyancy- or stack-driven strategies include enhanced single-sided ventilation, solar chimneys, atria, ventilation shafts, roof monitors, double-skin facades, and ventilation chambers. These rely on vertical separation, temperature differences, and high-level relief. Solar chimneys can strengthen extraction during weak-wind periods, but mean velocity or ACH gains do not guarantee occupied-zone improvement unless inlet height and distribution geometry are tuned (Khedari et al., 2000; Suhendri et al., 2018; Tan & Wong, 2012; Wang et al., 2024). Atria and shafts can support deeper plans when cross-transfer and relief paths are legible, while double-skin facades require careful seasonal control and maintenance (Bugenings et al., 2022; Mohamed et al., 2021; O'Connor et al., 2014).

Hybrid strategies combine wind-driven supply with buoyancy-assisted exhaust. Supporting distribution and air-tempering elements, such as earth-to-air or buried duct systems, can serve deeper interiors or classrooms where one façade cannot be opened because of pollution, noise, or security. However, ducts must be short, smooth, and carefully sized because natural driving pressures are limited. The Mediå School case illustrates an integrated strategy using supply towers, underground ducts, plenums, central exhaust towers, sensors, and building-management control (Kleiven, 2003).

Iranian standards reinforce the same logic: outdoor-air provision, CO_2 thresholds, pollutant separation, opening geometry, daylight-ventilation coordination, window safety, classroom dimensions, and hybrid operation schedules all imply that NV should be designed as a controllable and monitorable architectural system rather than as a nominal window-area requirement. These constraints are summarized in Table 5.

Findings from the Iranian M.Sc. Thesis Stream

The analysis of 40 Iranian M.Sc. theses provides a context-specific view of NV in educational buildings. The studies reflect climatic diversity, urban constraints, regulatory requirements, and operational challenges in Iran, while also revealing an evidence-to-decision gap: many evaluate performance in detail, but fewer convert findings into early-stage architectural rules (Kabir, 2015; Hendoukolaei, 2018; Farahani, 2019; Haji Hosseini, 2020; Akhyani, 2022).

The theses were grouped into performance-oriented (Zomorodian, 2012; Amini, 2023), design-oriented (Hosseini Sang No, 2018; Shirazi, 2019; Mahmoudi, 2020; Pourakbarian Gashti, 2022), detail/envelope-oriented (Lotfi Gharaee, 2018; Ahmadi nia tabesh, 2019; Nasr Abadi, 2021), context-oriented (Zahedi, 2019; Aram, 2022; Bagheri Fazel, 2023), health-oriented (Eradati, 2021; Khojasteh, 2022; Khosravi Zad, 2022; Malekpour, 2023; Majidpour, 2023), and multi-variable streams (Khosravi, 2022; Alizade, 2024).

Figures 4–8 summarize their thematic coverage, research streams, spatial distribution, methods, software tools, and variable-method-outcome patterns. The corpus covers 26 Iranian cities and is strongly simulation-led, with field monitoring and post-occupancy evaluation appearing less frequently. Recurrent variables include opening geometry, airflow paths, windcatchers, solar chimneys, atria, shading, courtyards, opening schedules, occupancy patterns, and health-risk scenarios (Ahmadi, 2021; Beiragh Shamshir, 2022; Rahaee et al., 2024; Rahaei & Azemati, 2020; Rahaei et al., 2024). Overall, the thesis stream confirms that opening size alone is insufficient unless airflow paths and realistic operation are addressed concurrently.

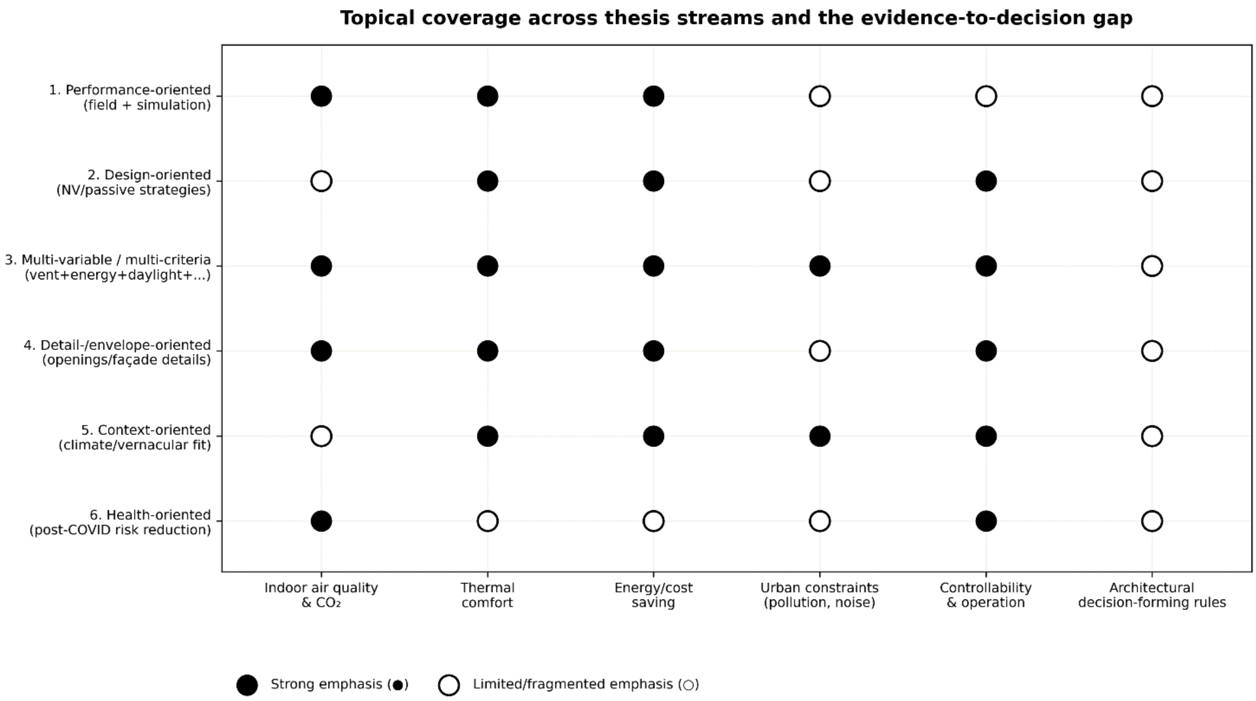


Fig 4. Thesis-stream Mapping of Topical Coverage and the Evidence-to-decision Gap

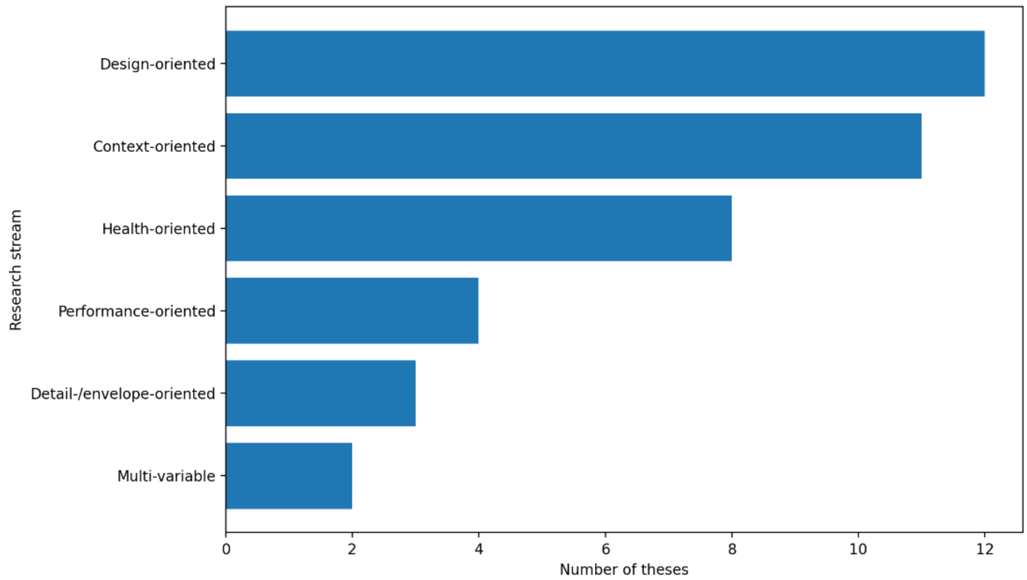


Fig 5. Distribution of Iranian M.Sc. Theses by Research Stream

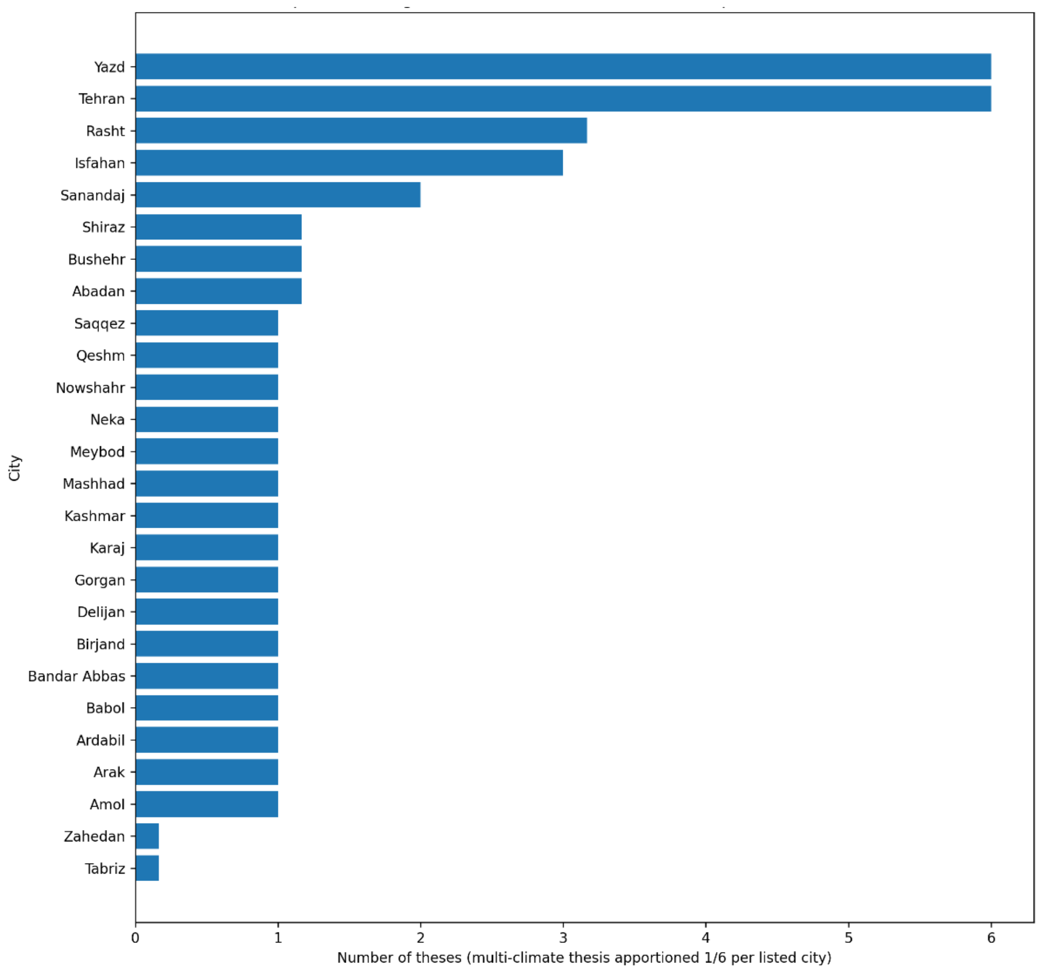


Fig 6. Spatial Coverage of Iranian M.Sc. Theses

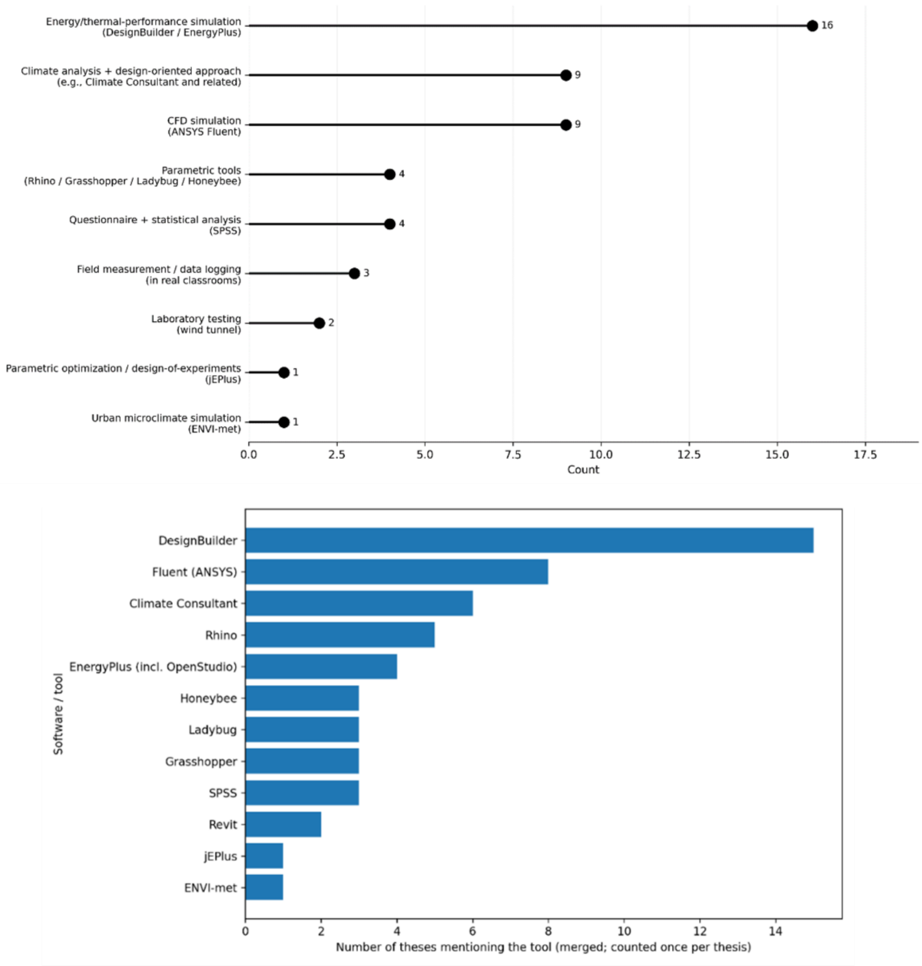


Fig 7. Methodological Distribution (up) and Software/tool Frequency (Down) in Iranian M.Sc. Theses

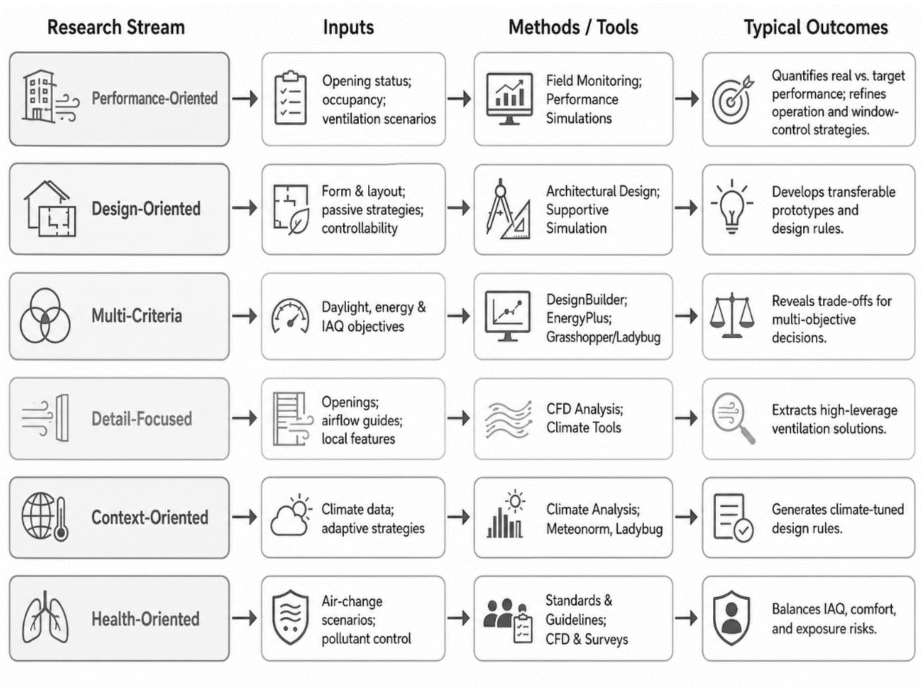


Fig 8. Dominant Research Streams and Recurrent Variable–method–outcome Patterns

Architectural Patterns from the Case-Study Review

The seven rubric-selected precedents show how NV principles become legible architectural configurations. Their scores and evidence sources are summarized in Table 2, and recurring plan and section patterns are synthesized in Figure 9 (Awbi, 2008; Kleiven, 2003; Passe & Battaglia, 2015).

Four plan patterns recur: central halls or internal streets that act as climatic buffers and transfer zones; linear blocks with short cross-flow routes; courtyard-centered layouts that moderate pressure and support staged transfer; and distributed low-level supply networks, including ducts or plenums, for deeper plans where facade supply alone is insufficient (CIBSE, 2005; Kleiven, 2003; Li et al., 2025; Passe & Battaglia, 2015). Four section patterns also recur: central vertical exhaust axes, roof-level stacks or monitors, low-level supply with high-level relief, and courtyard-solar-chimney combinations. Across these precedents, the transferable lesson is consistent: the supply–transfer–exhaust pathway must be legible in both plan and section, supported by intermediate spaces where necessary, and linked to operation, maintenance, and seasonal control.

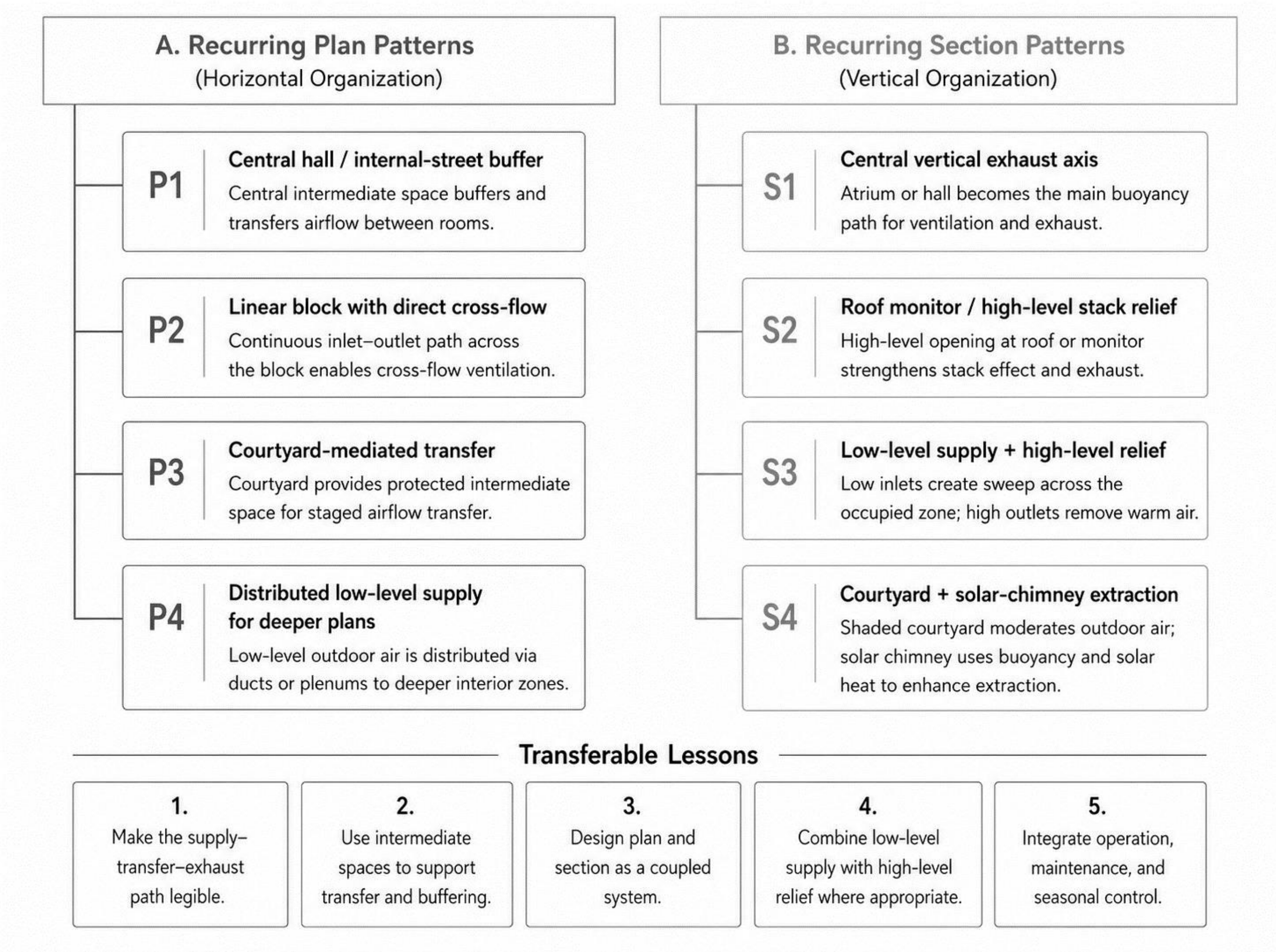


Fig 9. Recurring Plan and Section Patterns Derived from Rubric-selected School Precedents, with Transferable Lessons for Classroom Natural-Ventilation Design

Consolidated Decision Framework

The consolidated framework in Figure 10 brings together the scale-based design process and the architectural-element perspective. It links contextual inputs, design sequence, architectural scales, operational control, and evaluation criteria around one invariant: maintaining a traceable supply–transfer–exhaust pathway through the occupied zone.

Across international evidence, Iranian sources, theses, standards, and precedents, classroom NV performance is not reducible to larger openings or generic passive-design prescriptions. It results from the interaction of site and form, plan and section, facade design, opening controllability, supporting components, and realistic operation under constraints such as climate, season, pollution, acoustics, safety, security, and user behavior (Aflaki et al., 2015; CIBSE, 2005; Hsu et al., 2024; Tikul et al., 2023; Yin et al., 2024). The framework's decision-ready contribution is that it clarifies where NV should be considered, which elements can support it, and under what contextual and operational conditions those elements can function reliably.

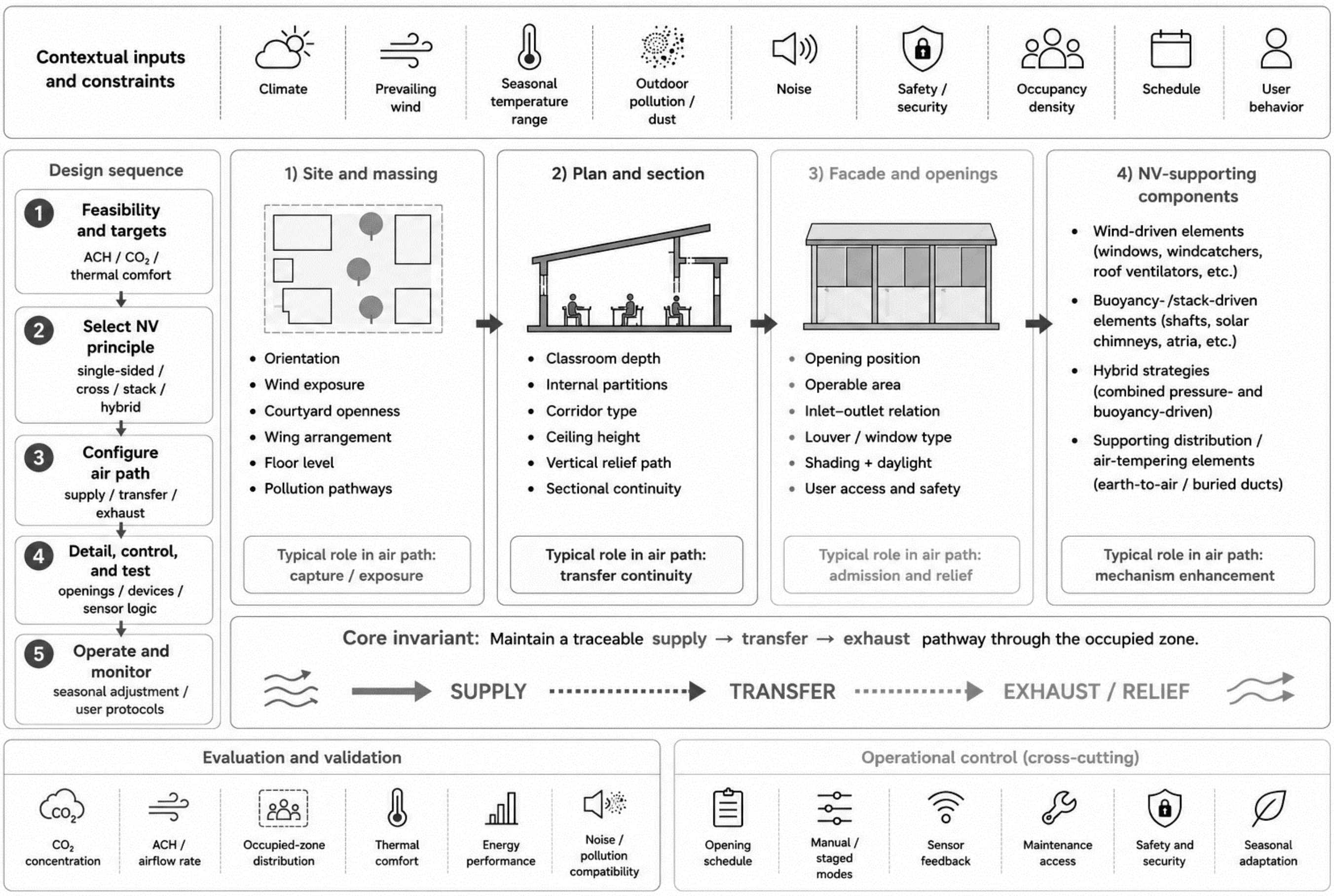


Fig 10. Multi-scale Architectural Decision Framework for Classroom Natural Ventilation

DISCUSSION

From Performance Evidence to Architectural Decisions

The principal contribution of this study is the translation of dispersed natural-ventilation (NV) evidence into a multi-scale architectural decision framework for school classrooms. Although the reviewed literature contains numerous performance indicators, simulation results, standards, and documented precedents, findings are often reported as isolated values without clarifying which architectural decisions produced the reported outcomes. This limits their usefulness for architects during concept and schematic design, when decisions about site, massing, plan depth, section, façade composition, and classroom layout are still open.

The results show that reliable classroom NV is rarely achieved by increasing opening area alone. Its effectiveness depends on the alignment of site exposure, building form, classroom depth, plan organization, sectional configuration, façade operability, supporting components, and realistic operation (Awbi, 2008; CIBSE, 2005; Kleiven, 2003). This reinforces the need to introduce NV before massing, circulation patterns, plan depth, and façade composition have been fixed. Later refinement through windows, louvers, shafts, or chimneys can improve performance, but it cannot fully compensate for unsuitable geometry or an unclear airflow pathway.

The framework shifts attention from component selection to decision sequencing. Site and massing determine exposure to wind, surrounding obstructions, pollutant sources, and noise. Plan and section establish the horizontal and vertical continuity of the airflow route. Façade openings, shading devices, vents, and louvers regulate admission, distribution, relief, daylight interaction, and user control. NV-supporting components strengthen performance under specific climatic or operational conditions. Monitoring and user control sustain the intended strategy after occupancy.

The evidence-to-decision translation process is summarized conceptually in Figure 2 and operationalized in the consolidated framework presented in Figure 10 Rather than treating air-change rate, CO_2 concentration, thermal comfort, air velocity, standards, precedents, and thesis findings as isolated inputs, the framework interprets them through five lenses: driving force, ventilation principle, airflow pathway, operating assumptions, and contextual constraints. These lenses convert dispersed evidence into actionable architectural decisions at the scales of site, plan, section, façade, supporting components, and operation.

Airflow-Path Traceability and Contextual Constraints

A recurring limitation in both international and Iranian studies is the use of aggregate performance indicators without sufficient explanation of airflow behavior in the occupied zone. A classroom may achieve an acceptable average air-change rate while still containing stagnant regions around seating areas. Similarly, high-level outlets may increase extraction while allowing fresh air to bypass the breathing zone. Short-circuiting, draughts, warm-air accumulation, and sensitivity to wind-direction shifts may remain hidden when performance is reported only through global values (Awbi, 2008; Hsu et al., 2024).

The case-study review shows that evidence becomes more transferable when the airflow pathway is explicit: where outdoor air enters, how it engages the occupied zone, how it reaches intermediate spaces or transfer routes, and where it is exhausted. This traceability allows architects to identify which spatial move produced which airflow effect and under what climatic, geometric, and operational assumptions. Therefore, the key design question is not only whether a classroom has operable windows or passive components, but whether the supply–transfer–exhaust sequence is legible in plan, section, façade, and operation.

Iranian standards reinforce the same design logic. Outdoor-air rates, CO_2 thresholds, opening-area requirements, classroom dimensions, daylight criteria, safety provisions, and pollution-source separation should not be treated independently. Together, they define the physical and operational conditions under which NV remains feasible (Institute of Standards and Industrial Research of Iran, 1998, 2001, 2002; Management and Planning Organization of Iran, 2016; Ministry of Health, Treatment, and Medical Education, 2022; Plan and Budget Organization of Iran, 2021). Table 5 makes this relationship explicit by translating standards-based benchmarks into architectural constraints.

CO_2 thresholds are particularly useful because they connect design with operation. Maintaining indoor CO_2 below the recommended threshold requires not only adequate opening provision, but also accessible controls, staged opening modes, high-level relief, and, where possible, sensor feedback. In this sense, CO_2 monitoring should not be understood as a purely technical add-on; it is part of the operational logic that determines whether a naturally ventilated classroom can perform reliably during occupancy.

The Iranian thesis stream reveals an additional limitation. The evidence is strongly simulation-led, while field monitoring and post-occupancy validation remain comparatively limited. Simulation is valuable for comparing alternatives and testing design variables, but actual performance may differ when windows are partially opened, noise restricts operation, maintenance is inconsistent, security concerns limit opening use, or pollution episodes reduce outdoor-air admission. This confirms the need to connect simulated performance with real operating conditions and user behavior.

Decision-Ready Architectural Rules

The evidence synthesis and case-study interpretation support a set of decision-ready architectural rules for classroom NV. These rules, derived from the consolidated framework in Figure 10 and the standards-based constraints in Table 5, distinguish essential conditions from recommended practices and common failure modes. Their purpose is not to prescribe a universal technical solution, but to clarify the architectural logic that should remain intact when strategies are adapted to different climates, school types, and operational constraints.

The essential conditions are the creation of a legible supply–transfer–exhaust pathway, the use of section as a ventilation engine, engagement of the occupied breathing zone, staged controllability, and integration of operation and maintenance. Without these conditions, NV may exist as a formal design intention but fail as an occupied classroom system.

The recommended practices include designing plan and section as a coupled system, using intermediate spaces as pressure moderators, differentiating supply, transfer, and relief openings, applying passive components strategically during weak-wind or high-temperature periods, coordinating ventilation with daylight and acoustics, and using CO_2 monitoring as an operational trigger. These practices help prevent natural ventilation from becoming dependent on accidental window use or favorable weather alone.

The failure modes to avoid include equating NV with larger windows, using deep plans without relief or assistance, placing inlet and outlet openings at the same level without clear pressure logic, relying on unstructured user behavior, and leaving conflicts with daylight, noise, pollution, safety, or security unresolved. Across all three categories, the central requirement is consistent: ventilation performance should emerge from a legible airflow pathway, coordinated plan-and-section design, and implementable control rather than from isolated component optimization.

This interpretation is also important for retrofitting existing classrooms. In retrofit contexts, the most effective intervention may not be simply enlarging windows. More targeted measures may include adding high-level relief, improving transfer paths through doors or transoms, introducing controllable vents or louvers, using shading devices that also guide airflow, separating supply and exhaust functions, or adding stack-assisted components where direct cross-ventilation is not feasible. However, such measures should be assessed against safety, accessibility, maintenance, seasonal comfort, and actual user behavior.

Limitations and Future Research

The retained sources differ in climatic context, school typology, occupancy assumptions, analytical methods, and performance indicators. This heterogeneity prevents universal numerical prescriptions. The proposed framework should therefore be understood as a structured decision aid rather than as a fixed design formula. It helps architects identify relevant decisions, relationships, and constraints, but project-specific validation remains necessary.

The precedent set is intentionally small and documentation-driven. Its purpose is mechanism interpretation rather than statistical generalization. Cases were selected because they made the driving force, airflow path, operational logic, and architectural transferability sufficiently legible. This strengthens interpretive value but limits the possibility of broader statistical comparison.

The Iranian thesis stream also varies in methodological depth, and field-based studies remain limited. Future studies should therefore prioritize field validation across climates and seasons, integration of CO_2 monitoring with practical opening and control strategies, and multi-objective analysis addressing NV, daylight, thermal comfort, acoustics, safety, and outdoor-air quality simultaneously (López-Chao et al., 2020). Simulation should be paired more frequently with field measurement and post-occupancy evaluation. Research should also report airflow-path logic and operational assumptions more explicitly so that performance findings can be translated into architectural rules.

Overall, reliable classroom NV depends on the alignment of three elements: performance targets, air-path-forming architecture, and implementable operation.

CONCLUSIONS

This study developed a multi-scale architectural decision framework for natural ventilation (NV) in school classrooms by synthesizing international evidence, Iranian sources, standards and guidance documents, M.Sc. theses, and rubric-selected school precedents. The findings show that successful classroom NV is not achieved simply by providing operable windows or increasing opening area. It depends on whether the airflow path is architecturally formed, spatially legible, and operationally controllable.

The main contribution of the paper is the translation of dispersed ventilation evidence into an architect-readable decision structure. The proposed framework shows that NV should be considered through two complementary perspectives: first, as a multi-scale design process extending from urban and neighborhood conditions to classroom layout and furniture; and second, as a system of architectural elements and airflow mechanisms, including wind-driven, buoyancy-driven, and hybrid strategies. Across both perspectives, the central requirement is the continuity of a supply–transfer–exhaust pathway through the occupied zone.

The study concludes that reliable classroom NV requires the alignment of three elements: performance targets, air-path-forming architecture, and implementable operation. Performance targets define what the indoor environment should achieve; architecture makes the airflow pathway physically possible through site, massing, plan, section, façade, openings, intermediate spaces, and supporting components; and operation determines whether the intended strategy can function safely and consistently under real conditions of climate, pollution, noise, safety, security, maintenance, and user behavior.

The decision-ready implications can be summarized as follows. Designers must make the airflow route legible in plan and section, provide effective inlets, transfer paths, and high-level relief, and integrate operation and maintenance from the beginning of design. They should design plan and section as a coupled system, differentiate supply, transfer, and exhaust functions, use intermediate spaces and passive components strategically, and coordinate ventilation with daylight, acoustics, thermal comfort, and outdoor-air quality. They should not reduce NV to larger windows, rely on accidental user behavior, use deep plans without relief or assistance, or leave conflicts with noise, pollution, safety, and security unresolved.

The framework is intended as a design aid rather than a universal performance formula. Because the reviewed evidence varies in climate, school type, method, and operational assumptions, project-specific testing, simulation, field monitoring, and post-occupancy evaluation remain necessary. The Iranian thesis stream also indicates a geographically diverse but predominantly simulation-led evidence base, with limited field monitoring and post-occupancy validation; this reinforces the need to test the proposed decision rules under real operating conditions. Future research should validate the proposed decision rules across different climates and school types and should more explicitly connect CO_2-based monitoring, façade operability, user protocols, and multi-objective design performance. In this way, classroom NV research can move from isolated performance optimization toward integrated architectural decision-making.

ACKNOWLEDGMENTS

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

REFERENCES

Aflaki, A., Mahyuddin, N., Al-Cheikh Mahmoud, Z., & Baharum, M. R. (2015). A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy and Buildings*, *101*, 153–162. https://doi.org/10.1016/j.enbuild.2015.04.033

Ahmadi, B. (2021). *Designing a 12-grade elementary school for girls in Yazd with an energy saving approach through natural ventilation* (Master's thesis, Yazd University, Yazd). [in Persian]

Ahmadi Nia Tabesh, N. (2019). *Optimal form design for elementary girl's school with using effective natural ventilation located in Bushehr, Iran* (Master's thesis, Tehran East Branch, Islamic Azad University, Tehran). [in Persian]

Aguilar-Carrasco, M., López-Lovillo, R., Suárez, R., & León-Rodríguez, A. (2025). Ventilation Strategies to Ensure Thermal Comfort for Users in School Buildings: A Critical Review. *Applied Sciences-Basel*, *15*(10). (WOS:001495846900001). https://doi.org/10.3390/app15105449

Akhyani, M. (2022). *Designing a 12-class school with the approach of reducing the dispersion of pollutants around and inside the classrooms* *(case study: Tehran)* (Master's thesis, Department of Architecture, Iran University of Science and Technology, Tehran). [in Persian]

Alatalo. (2016). Enhancing the building performance of low-cost schools in Pakistan - A study of natural ventilation, thermal comfort and moisture safety (A study of natural ventilation, thermal comfort and moisture safety). Master's thesis in Structural Engineering and Building Technology. Chalmers University of technology. Gothenburg, Sweden. BOMX02-16-18.

Alizade, S. (2024). *Optimization of daylight and natural ventilation in a school in Sanandaj to improve the sustainability of the building* (Master's thesis, Department of Architecture and Energy, University of Kurdistan, Sanandaj). [in Persian]

Amini, H. (2023). *Presenting a theory for the educational space of exceptional children in the direction of natural ventilation using suitable windows to promote mental comfort in Sanandaj* (Master's thesis, Pars University of Art and Architecture, Tehran). [in Persian]

Aram, B. S. (2022). *Designing a 6-grade primary school with the benefit of passive energy in Khorramabad village of Mashhad* (Master's thesis, Yazd University, Yazd). [in Persian]

Awbi, H. B. (2008). *Ventilation Systems: Design and Performance*.

Baeumle, R. (2021). *Natural Ventilation of Buildings: From Fluid Mechanics to Architectural Design Guidance*.

Baeumle, R., & Hunt, G. (2018). Capturing the needs of architects: A survey of their current information requirements of natural ventilation design. *International Journal of Ventilation*, *17*(2), 120–147. (WOS:000438785300004). https://doi.org/10.1080/14733315.2017.1351737

Bagheri Fazel, A. (2023). *Designing a twelve-class elementary school in Qeshm city, with the approach of reducing the spread of infectious diseases in open and semi open spaces.* (Master's thesis, Department of Architecture, Iran University of Science and Technology, Tehran). [in Persian]

Bayoumi, M. (2021). Improving Indoor Air Quality in Classrooms via Wind-Induced Natural Ventilation. *Modelling and Simulation in Engineering*, *2021*, 1–14. https://doi.org/10.1155/2021/6668031

Becker, R., Goldberger, I., & Paciuk, M. (2007). Improving energy performance of school buildings while ensuring indoor air quality ventilation. *Building and Environment*, *42*(9), 3261–3276. https://doi.org/10.1016/j.buildenv.2006.08.016

Beiragh Shamshir, M. (2022). *Design of 12-Grade School with an Approach of Reducing the Energy Consumption in Yazd (Simultaneous Use of Windcatcher and Atrium).* (Master's thesis, Department of Architectural Engineering, Faculty of Architecture and Urban Planning, Shahrood University of Technology, Shahrood, Iran). [in Persian]

Bienvenido-Huertas, D., de la Hoz-Torres, M., Aguilar, A., Tejedor, B., & Sánchez-García, D. (2023). Holistic overview of natural ventilation and mixed mode in built environment of warm climate zones and hot seasons. *Building and Environment*, *245*. (WOS:001094487200001). https://doi.org/10.1016/j.buildenv.2023.110942

Bugenings, L., Schaffer, M., Larsen, O., & Zhang, C. (2022). A novel solution for school renovations: Combining diffuse ceiling ventilation with double skin facade. *Journal of Building Engineering*, *49*. (WOS:000776398200002). https://doi.org/10.1016/j.jobe.2022.104026

Chiang, W., Hsu, H., & Huang, J. (2013). Facade Design Effect on Cross-Ventilation in Taiwanese School Buildings. *Journal of Green*

Building, *8*(2), 90–111. (WOS:000322718100007). https://doi.org/10.3992/jgb.8.2.90

CIBSE. (2005). *Natural ventilation in non-domestic buildings*.

Cordero, A. S., Melgar, S. G., & Marquez, J. M. A. (2024). Validation of Dynamic Natural Ventilation Protocols for Optimal Indoor Air Quality and Thermal Adaptive Comfort during the Winter Season in Subtropical-Climate School Buildings. *Applied Sciences-Basel*, *14*(11), 4651. https://doi.org/10.3390/app14114651

Cuce, E., Sher, F., Sadiq, H., Cuce, P. M., Guclu, T., & Besir, A. B. (2019). Sustainable ventilation strategies in buildings: CFD research. *Sustainable Energy Technologies and Assessments*, *36*, 100540. https://doi.org/10.1016/j.seta.2019.100540

Diaz-Lopez, C., Serrano-Jimenez, A., Lizana, J., Lopez-Garcia, E., Molina-Huelva, M., & Barrios-Padura, A. (2022). Passive action strategies in schools: A scientific mapping towards eco-efficiency in educational buildings. *Journal of Building Engineering*, *45*, 103598. https://doi.org/10.1016/j.jobe.2021.103598

Diaz-Lopez, C., Serrano-Jimenez, A., Verichev, K., & Barrios-Padura, A. (2022). Passive cooling strategies to optimise sustainability and environmental ergonomics in Mediterranean schools based on a critical review. *Building and Environment*, *221*. (WOS:000823045400003). https://doi.org/10.1016/j.buildenv.2022.109297

Duarte, R., Rodrigues, A., Pimentel, F., & Gomes, M. (2024). The Effect of Occupancy and Environmental Physical Variables on Classrooms' Natural Ventilation: A Path Modeling Approach. *Applied Sciences-Basel*, *14*(24). (WOS:001384102200001). https://doi.org/10.3390/app142411705

Eradati, F. (2021). *Optimization of Natural Ventilation through Single-sided Windows in order to Prevent the Spread of Pathogens in Educational Spaces in Tehran* (Master's thesis, University of Tehran, Tehran). [in Persian]

Etheridge. (2012). *Natural Ventilation of Buildings Theory, Measurement and Design*.

Farahani, A. (2019). *Evaluation of Thermal Comfort and Indoor Air Quality in Educational Spaces with Natural Ventilation (Case Study: Highschools in Arak)* (Master's thesis, Department of Architecture and Urban Planning, Shahid Beheshti University, Tehran). [in Persian]

Farokhyan, F., Vasigh, B. and Didehban, M. (2020). Determination the Morphological Pattern of Educational Building Facades to Control the Dust Haze. *Journal of Natural Environmental Hazards*, *9*(26), 185-202. https://doi.org/10.22111/jneh.2020.32951.1610

Ferrari, S., Blázquez, T., Cardelli, R., Puglisi, G., Suárez, R., & Mazzarella, L. (2022). Ventilation strategies to reduce airborne transmission of viruses in classrooms: A systematic review of scientific literature. *Building and Environment*, *222*, 109366. https://doi.org/10.1016/j.buildenv.2022.109366

Fisk, W. J. (2017). The ventilation problem in schools: Literature review. *Indoor Air*, *27*(6), 1039–1051. https://doi.org/10.1111/ina.12403

Gil-Baez, M., Barrios-Padura, Á., Molina-Huelva, M., & Chacartegui, R. (2017a). Natural ventilation systems in 21st-century for near zero energy school buildings. *Energy*, *137*, 1186–1200. https://doi.org/10.1016/j.energy.2017.05.188

Gil-Baez, M., Barrios-Padura, A., Molina-Huelva, M., & Chacartegui, R. (2017b). Natural ventilation systems to enhance sustainability in buildings: A review towards zero energy buildings in schools. In B. Kazmierczak, M. Kutylowska, K. Piekarska,

H. Jouhara, & J. Danielewicz (Eds.), *University of Sevilla* (Vol. 22). (WOS:000417352100053). https://doi.org/10.1051/e3sconf/20172200053

Haji Hosseini, F. (2020). *Vernacular model in interior design of schools in hot and humid* (Master's thesis, Faculty of Architecture and Urban Planning, Art University of Tehran, Tehran). [in Persian]

Heeboll, A., Wargocki, P., & Toftum, J. (2018). Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits Ashrae Rp1624. *Science and Technology for The Built Environment*, *24*(6), 626–637. (WOS:000436865600008). https://doi.org/10.1080/23744731.2018.1432938

Hendoukolaei, S. (2018). *Enhancing the Quality of Natural Ventilation in Schools Classes of Amol, According to the Openings) Case study: Amol ,City schools)* (Master's thesis, Shahid Rajaee Teacher Training University, Tehran). [in Persian]

Hiyama, K., & Glicksman, L. (2015). Preliminary design method for naturally ventilated buildings using target air change rate and natural ventilation potential maps in the United States. *Energy*, *89*, 655–666. https://doi.org/10.1016/j.energy.2015.06.026

Hosseini Sang No, S. M. (2018). *Enregy Consumption Optimizing in Educational Facilities, School Desining in Noshahr City* (Master's thesis, Department of Engineering, Allameh Mohaddes Noori University, Noor). [in Persian]

Hsu, H., Chang, C., Chen, C., & Pan, C. (2024). Natural Ventilation: Optimizing Window Opening Size for CO2 Concentration Control and Thermal Comfort on Nonwindward Facades. *Indoor Air*, *2024*. (WOS:001336593200001). https://doi.org/10.1155/2024/1435400

Idowu, O. M., Marafa, U. G., Mohammed, S. A., & Ayoosu, M. I. (2022). Variation of Natural Ventilation with Floor Level and Orientation of Classrooms. *International Journal of Education, Psychology and Counseling*, *7*(45), 166–174. https://doi.org/10.35631/IJEPC.745013

Indarti, F., Indrawan, I., Rizqiyah, F., Krisdianto, J., Nuffida, N. E., & Defiana, I. (2023). The Predicted Performance of Natural Ventilation Strategies in Islamic Boarding School Design in Magelang. *Pawon: Jurnal Arsitektur*, *7*(2), 301–314. https://doi.org/10.36040/pawon.v7i2.7018

Institute of Standards and Industrial Research of Iran. (1998). *ISIRI NUMBER 5018 (Educational buildings windows)*. [in Persian]

Institute of Standards and Industrial Research of Iran. (2001). *Isiri Number 2086 (School hygiene)* (1st ed.). [in Persian]

Institute of Standards and Industrial Research of Iran. (2002). *ISIRI NUMBER 7331 (Primary school classroom - Specifications)* (1st ed.). [in Persian]

Jia, L., Han, J., Chen, X., Li, Q., Lee, C., & Fung, Y. (2021). Interaction between Thermal Comfort, Indoor Air Quality and Ventilation Energy Consumption of Educational Buildings: A Comprehensive Review. *Buildings*, *11*(12). (WOS:000736171100001). https://doi.org/10.3390/buildings11120591

Jomehzadeh, F., Nejat, P., Calautit, J. K., Yusof, M. B. M., Zaki, S. A., Hughes, B. R., & Yazid, M. N. A. W. M. (2017). A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment. *Renewable and Sustainable Energy Reviews*, *70*, 736–756. https://doi.org/10.1016/j.rser.2016.11.254

Jones, B. M., & Kirby, R. (2010). The performance of natural ventilation windcatchers in schools—A comparison between prediction and measurement. *International Journal of Ventilation*, *9*(3), 273–286. Scopus. https://doi.org/10.1080/14733315.2010.11683886

Jones, B. M., & Kirby, R. (2012). Indoor air quality in U.K. school classrooms ventilated by natural ventilation windcatchers. *International Journal of Ventilation*, *10*(4), 323–338. Scopus. https://doi.org/10.1080/14733315.2012.11683959

Kabir, E. (2015). *Designing a school building based on natural ventilation approaches in Gorgan city* (Master's thesis, Department of Art and Architecture, Islamic Azad University, Gorgan Branch, Gorgan). [in Persian]

Kapoor, N. R., Kumar, A., Meena, C. S., Kumar, A., Alam, T., Balam, N. B., & Ghosh, A. (2021). A Systematic Review on Indoor Environmental Quality in Naturally Ventilated School Classrooms: A Way Forward. *Advances in Civil Engineering*, *2021*(1), 8851685. https://doi.org/10.1155/2021/8851685

Khedari, J., Boonsri, B., & Hirunlabh, J. (2000). *Ventilation impact of a solar chimney on indoor temperature fluctuation and air change in a school building.*

Khojasteh, S. (2022). *Study of the effect of ventilation and architectural components in order to reduce the spread of diseases and maintain the thermal comfort of users of educational spaces in Tehran* (Master's thesis, University of Tehran, Tehran). [in Persian]

Khoshnaw, D., Mustafa, F., Katona, T., & Baranyai, B. (2025). Indoor environmental quality and achieving performance goals for classroom enhancement: A systematic literature review and bibliometric analysis. *Results in Engineering*, *27*. (WOS:001540248600001). https://doi.org/10.1016/j.rineng.2025.106082

Khosravi, M. (2022). *Investigation, analysis, and design of a green school based on the passive solar systems in Tehran city* (Master's thesis, Faculty of Arts and Architecture, University of Kurdistan, Sanandaj). [in Persian]

Khosravi Zad, C. (2022). *Designing a sustainable educational complex in Tehran with the approach of improving air quality and resilience against coronas and future pandemics* (Master's thesis, Department of Architecture, Iran University of Science and Technology, Tehran). [in Persian]

Kleiven, T. (2003). *Natural Ventilation in Buildings (Architectural concepts, consequences and possibilities)*. Thesis submitted in partial fulfilment of the requirements for the degree of Doktor Ingeniør. Department of Architectural Design, History and Technology. Faculty of Architecture and Fine Art. Norwegian University of Science and Technology.

Kolokotroni, M., Ge, Y. T., & Katsoulas, D. (2002). Monitoring and Modelling Indoor Air Quality and Ventilation in Classrooms within a Purpose-Designed Naturally Ventilated School. *Indoor and Built Environment*, *11*(6), 316–326. https://doi.org/10.1177/1420326X0201100603

Kouhirostami. (2018). Natural Ventilation Through Windows in a Classroom (CFD Analysis Cross Ventilation of Asymmetric Openings: Impact of Wind Direction and Louvers Design). A Thesis In Digital Design and Fabrication. Submitted to the Graduate Faculty of Texas Tech University in Partial Fulfillment of the Requirements for the Degree of Master of Science.

Le, T. H. V., Gillott, M., & Rodrigues, L. (2023). Parametric Study of Design Parameters and Thermal Comfort in Primary Schools in Ho Chi Minh City, Vietnam. In Grabovy P.G. & Thuong L.V. (Eds.), *AIP Conf. Proc.* (Vol.

2560). American Institute of Physics Inc. Scopus. https://doi.org/10.1063/5.0125338

Li, M., Li, Y., Zhang, B., & Tao, L. (2025). Investigation on the ventilation impact of enclosed-type teaching buildings under different aperture ratios and wind directions. *Journal Of Asian Architecture and Building Engineering*. (WOS:001417955500001). https://doi.org/10.1080/13467581.2025.2455018

López-Chao, V., Amado Lorenzo, A., Saorín, J. L., De La Torre-Cantero, J., & Melián-Díaz, D. (2020). Classroom Indoor Environment Assessment through Architectural Analysis for the Design of Efficient Schools. *Sustainability*, *12*(5), 2020. https://doi.org/10.3390/su12052020

Lotfi Gharaee, A. (2018). *Designing and locating building's external wall openings by optimizing effective factors or using natural ventilation (A Case study: Designing a primary school in Kashmar city)* (Master's thesis, Khavaran Higher Education Institute, Mashhad). [in Persian]

Mahmoudi, S. (2020). *Design of a Low-energy Educational Building in Khansar village with Thermal Behavior Approach* (Master's thesis, Department of Energy, Pars University of Art and Architecture, Tehran). [in Persian]

Majidpour, H. (2023). *The effect of natural ventilation on indoor respiratory viruses exposure: A case study of a high school in Saqqez* (Master's thesis, Department of Architecture and Urban Planning, Imam Khomeini International University, Qazvin). [in Persian]

Malekpour, S. (2023). *Evaluation of Indoor Air Quality in Educational Spaces with regard to the Spread of the COVID-19 while maintaining Thermal Comfort in Cold Climates (Case Study: Middle school in Ardabil)* (Master's thesis, Department of Architecture and Urban Planning, Shahid Beheshti University, Tehran). [in Persian]

Management and Planning Organization of Iran. (2016). *Regulations for Design of Educational Buildings (Planning for Uniform Architectural Design of Primary and Elementary Schools)* (Regulation No. 697). [in Persian]

Mavrogianni, A., & Mumovic, D. (2010). On the Use of Windcatchers in Schools: Climate Change, Occupancy Patterns, and Adaptation Strategies. *Indoor and Built Environment*, *19*(3), 340–354. (WOS:000278481300004). https://doi.org/10.1177/1420326X09341507

Miao, S., Gangolells, M., & Tejedor, B. (2025). Validating single-sided natural ventilation models for educational buildings. *Building and Environment*, *282*. (WOS:001530651000001). https://doi.org/10.1016/j.buildenv.2025.113329

Ministry of Health, Treatment, and Medical Education. (2022). *Ventilation guidelines for schools (with emphasis on COVID-19 conditions)*. [in Persian]

Mohamed, S., Al-Khatri, H., Calautit, J., Omer, S., & Riffat, S. (2021). The impact of a passive wall combining natural ventilation and evaporative cooling on schools' thermal conditions in a hot climate. *Journal of Building Engineering*, *44*, 102624. https://doi.org/10.1016/j.jobe.2021.102624

Nasr Abadi, M. (2021). *An investigation of the effect of natural ventilation in educational buildings by using a windbreak (Complete modeling with Energy Plus)* (Master's thesis, Mechanical Engineering Department, Pirouzan Higher Education Institute, Ferdows). [in Persian]

Nejat, P., Fekri, Y., Pourghasemian, M., Alsaad, H., & Voelker, C. (2025). Passive cooling assessment of natural ventilation by windcatchers for enhancing thermal comfort and indoor air quality in European schools.

Building and Environment, *276*. (WOS:001450262300001). https://doi.org/10.1016/j.buildenv.2025.112848

O'Connor, D., Calautit, J., & Hughes, B. (2014). A study of passive ventilation integrated with heat recovery. *Energy and Buildings*, *82*, 799–811. (WOS:000343781400077). https://doi.org/10.1016/j.enbuild.2014.05.050

Olufowobi & Adenuga. (2012). *Towards the Specification of Windows Sizes for Natural Ventilation in Classrooms in a Warn Climate, Nigeria*.

Paridokht, F., Tabrizi, A., Khorshidi Behzadi, Y., & Farhang Dehghan, S. (2025). Investigating Thermal Comfort and Ventilation in Schools: A Systematic Review. Journal of Health and Safety at Work, 15(3), 687–723. http://jhsw.tums.ac.ir/article-1-7213-fa.html. [in Persian]

Passe, U., & Battaglia, F. (2015). *Designing Spaces for Natural Ventilation: An Architect's Guide* (0 ed.). Routledge. https://doi.org/10.4324/9780203583470

Pinto, M., Almeida, R., Pinho, P., & de Lemos, T. (2014). *Experimental Assessment of Iaq Improvement in Naturally Ventilated Educational Buildings*.

Plan and Budget Organization of Iran. (2021). School Green Management Reference Guide (Regulation No. 847). [in Persian]

Pourakbarian Gashti, M. (2022). *Design of a conservatory in Rasht with the approach of improving natural ventilation in cassrooms* (Master's thesis, Department of Architecture and Urban Planning, Shahid Rajaee Teacher Training University, Tehran). [in Persian]

Ragab, A., Hassieb, M., & Mohamed, A. (2025). Exploring the impact of window design and ventilation strategies on air quality and thermal comfort in arid educational buildings. *Scientific Reports*, *15*(1). (WOS:001503071800022). https://doi.org/10.1038/s41598-025-01362-y

Rahaee, O., Salehi, S. S. and Shirdel, A. (2024). Improving the quality of natural ventilation in Masjedsoleiman's Schools' classrooms based on the openings' position and the outdoor shading blades with CFD Method. *Journal of Sustainable Architecture and Urban Design*, *12*(1), 129-150. https://doi:10.22061/jsaud.2024.10110.2179. [in Persian]

Rahaei, O, & Azemati, H. R. (2020). Improving the Quality of Natural Ventilation in Classrooms of Mazandaran Province Based on the Position of the Openings Using CFD Method. Iranian Architecture and Urbanism, 11(19), 57-71. SID. https://sid.ir/paper/386912/en. [in Persian]

Rahaei, O., Omidi, M. and Dehdashti, S. (2024). Numerical investigation of indoor airflow behavior in Bushehr's Sa'adat School based on the Openings and corridors situation using CFD Method. *Soffeh*, *34*(3), 39-54. http://doi:10.48308/sofeh.2024.104797. [in Persian]

Salavatian,S. M. and Babazadeh,A. M. (2025). Application of the new generation wind catchers to control natural ventilation and CO2 level in educational spaces of moderate and humid climate in Iran. *Journal of Renewable and New Energy*, *12*(1), 148-156. https://doi:10.22034/jrenew.2025.201463. [in Persian]

Shirazi, A. (2019). *Designing a low Energy Senior high School for boys with the approach of natural ventilation in city of Karaj* (Master's thesis, Department of Architecture, Pars University of Art and Architecture, Tehran). [in Persian]

Sireesha, N. L. (2016). Architect's Role in Designing of Schools—Ventilation Strategies Adopted. *Paripex - Indian Journal of Research*, *5*(12).

Suhendri, Koerniawan, M., & Alprianti, R. (2018). Solar Chimney as a Natural Ventilation Strategy for Elementary School in Urban Area. In Y. Indartono, P. Prawisudha, P. Sambegoro, & A. Irhamna (Eds.), *Institute Technology of Bandung* (Vol. 1984). (WOS:000447900000043). https://doi.org/10.1063/1.5046628

Tan, A. Y. K., & Wong, N. H. (2012). Natural ventilation performance of classroom with solar chimney system. *Energy and Buildings*, *53*, 19–27. https://doi.org/10.1016/j.enbuild.2012.06.010

Tikul, N., Hokpunna, A., & Chawana, P. (2023). The effect of horizontal elements and building orientation on PM2.5 concentration in classrooms. *Frontiers of Architectural Research*, *12*(4), 775–787. (WOS:001034624100001). https://doi.org/10.1016/j.foar.2023.05.007

Toyinbo, O. (2023). Indoor Environmental Quality, Pupils' Health, and Academic Performance-A Literature Review. *Buildings*, *13*(9). (WOS:001073295600001). https://doi.org/10.3390/buildings13092172

Uzunhasanoglu, T. (2015). *Design Strategies for Natural Ventilation in Secondary Schools In Istanbul*.

Wang, B., & Malkawi, A. (2019). Design-based natural ventilation evaluation in early stage for high performance buildings. *Sustainable Cities and Society*, *45*, 25–37. https://doi.org/10.1016/j.scs.2018.11.024

Wang, Y., Phipps, R., Boulic, M., Plagmann, M., Cunningham, C., & Guyot, G. (2024). Retrofitting solar air heaters in New Zealand schools—A randomized crossover intervention study. *Building and Environment*, *258*. (WOS:001240943800001). https://doi.org/10.1016/j.buildenv.2024.111552

Yang, L., Liu, X., Qian, F., & Du, S. (2019). Ventilation effect on different position of classrooms in "line" type teaching building. *Journal of Cleaner Production*, *209*, 886–902. https://doi.org/10.1016/j.jclepro.2018.10.228

Yin, X., Muhieldeen, M., Razman, R., Ee, J., & Chiong, M. (2024). The potential effects of window configuration and interior layout on natural ventilation buildings: A comprehensive review. *Cleaner Engineering and Technology*, *23*. (WOS:001346797300001). https://doi.org/10.1016/j.clet.2024.100830

Yuan, C. (2018). Natural Ventilation Modeling and Analysis for Climate-Sensitive Architecture Design. In C. Yuan, *Urban Wind Environment* (pp. 101–114). Springer Singapore. https://doi.org/10.1007/978-981-10-5451-8_6

Zahedi, T. (2019). *Design of Fine Arts Conservatory for Girls with Approach to Architecture compatible to climate of Hormozgan province* (Master's thesis, Department of Engineering, Islamic Azad University, Bandar Abbas Branch, Bandar Abbas). [in Persian]

Zomorodian, Z. S. (2012). *Assessment of Architecture Strategies to Reduce Energy Consumption in Shiraz Elemntary Schools* (Master's thesis, Faculty of Art and Architecture, Shiraz University, Shiraz). [in Persian]

AUTHOR (S) BIOSKETCHES

F. Eradati., *Department of Building, Faculty of Architecture and Urban Planning, Shahid Beheshti University, Tehran, Iran*

Email: f_eradati@sbu.ac.ir

M. Tahbaz., *Department of Building, Faculty of Architecture and Urban Planning, Shahid Beheshti University, Tehran, Iran*

Email: m-tahbaz@sbu.ac.ir

A. Khaki Ghasr., *Department of Architecture, Faculty of Architecture and Urban Planning, Shahid Beheshti University, Tehran, Iran*

Email: a_khakighasr@sbu.ac.ir

O. Rahaei., *Department of Architectural Technology, Faculty of Architecture Engineering and Urban Planning, Shahid Rajaee Teacher Training University, Tehran, Iran*

Email: o.rahaei@sru.ac.ir

HOW TO CITE THIS ARTICLE

Eradati, F., Tahbaz, M., Khaki Ghasr, A., Rahaei, O. (2026). A Multi-Scale Architectural Decision Framework for Natural Ventilation in School Classrooms. *Int. J. Architect. Eng. Urban Plan,* 36(3): 1-29, https://dx.doi.org/10.22068/ijaup.986

URL: http://ijaup.iust.ac.ir