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User-Centered Adaptive Approaches and Passive Ventilation Strategies in Enclosed Workspaces

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ABSTRACT
The global pandemic has made it imperative to reconsider the built environment so that it can adapt to future crises and climate change. Offices, where people spend the most time after their homes, are among the enclosed environments with the highest infection risk because of occupant density. Inadequate ventilation, common in open-plan workspaces and multi-storey plazas, causes sick building syndrome and pushes organizations toward temporary measures such as remote work. Instead of short-term solutions such as abandoning space or wearing masks, however, permanent and sustainable improvements to climate control systems are required. This study examines the relationship between passive climate control methods and occupants' adaptive behaviors, such as window use and clothing changes, to improve thermal comfort and indoor air quality in office buildings. A structured narrative literature review was conducted: international and national databases (including Web of Science, Scopus, Google Scholar, ScienceDirect, the Avery Index to Architectural Periodicals and DergiPark) were searched between 2023 and 2026, and 115 sources published between 1970 and 2026 in English and Turkish (peer-reviewed articles, books, standards and health guidance documents) were selected against predefined inclusion and exclusion criteria and synthesized thematically along three axes: passive climate control strategies, adaptive occupant behaviors and envelope–window design. The review discusses how occupants' dynamic responses affect comfort and energy performance. The results indicate that existing offices should be improved in line with health norms and new projects designed accordingly. Reducing dependence on mechanical ventilation and providing fresh air through passive and hybrid systems protects health and supports employee motivation and productivity.
Keywords: Office Buildings, Indoor Air Quality, Thermal Comfort, Natural Ventilation, Passive Climate Control, Adaptive Occupant Behaviors.

1. INTRODUCTION
Climate change is today regarded as both one of the most important causes and one of the most important victims of the built environment. According to data from the Intergovernmental Panel on Climate Change (IPCC), global surface temperature increased by approximately 1.1 °C in 2011–2020 compared with 1850–1900 (IPCC, 2023). The buildings and construction sector, in turn, was responsible for approximately 37% of global energy- and process-related carbon dioxide (CO_2) emissions in 2021 (United Nations Environment Programme, 2022). It is known that a significant share of building energy consumption stems from heating, cooling and ventilation systems (Pérez-Lombard et al., 2008). In the face of increasing heat waves and rising cooling loads, the sustainability of a building stock that depends on mechanical climate control is increasingly being questioned (Santamouris, 2016).

In addition to the climate crisis, the coronavirus disease 2019 (COVID-19) pandemic has shown how decisive indoor air quality is for public health (Çolak Demirel & Ayçam, 2026). It is reported that individuals spend approximately 87% of their time indoors (Klepeis et al., 2001). Within this time, the building type in which the most time is spent after residential spaces is the office; owing to their occupant density, offices were among the enclosed spaces where the disease spread the most during the pandemic (Çolak & Ayçam, 2022). The recognition of the airborne transmission potential of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has shown that inadequately ventilated indoor spaces increase the risk of transmission (Morawska & Cao, 2020). Accordingly, increasing ventilation rates, strengthening fresh air supply and rethinking the building envelope in this direction are recommended to reduce the risk of infection indoors (Morawska et al., 2020). Studies conducted in Türkiye likewise emphasize that organizations such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) point to the need to examine in detail climate control parameters such as high-efficiency particulate air (HEPA) filters, 100% outdoor air use, air change rates and distribution systems (Onat & Kabil, 2020). Studies examining the implications of the pandemic for the built environment demonstrate the necessity of spatial and climatic arrangements that prioritize user health (Güvlü & Yılmaz, 2021; Megahed & Ghoneim, 2021). Indeed, Standard 241, published by ASHRAE (2023a), has made ventilation and air cleaning requirements for the control of infectious aerosols part of the building design and operation process.

Fixed-pane curtain wall systems, which are widely preferred in contemporary office buildings and high-rise plazas, largely restrict the intake of fresh air into the interior by natural means. In open-plan workspaces where ventilation and climate control rely solely on central mechanical systems and the recirculation of air, the likelihood of the phenomenon known as "sick building syndrome" increases; this creates a favorable environment for the spread of microorganisms such as viruses, bacteria and fungi (Çolak & Ayçam, 2022; Joshi, 2008). Studies on office buildings in Türkiye also report that rapid and unplanned development has led to insufficient natural ventilation, which in turn has resulted in lower indoor air quality and ailments related to sick building syndrome (Demirarslan & Başak, 2018). The literature shows that low ventilation rates and high CO_2 concentrations are associated with occupants' health complaints and perceived air quality in commercial buildings (Seppänen et al., 1999; Seppänen & Fisk, 2004). These conditions led corporate firms to temporary solutions such as mask mandates and remote work during periods of intense pandemic activity (Çolak & Ayçam, 2022). However, abandoning workspaces or relying solely on personal protective measures is not regarded as a sustainable approach; permanent architectural improvements in the building envelope and climate control strategies are needed.

Indoor environmental quality is important not only for health but also for cognitive performance and productivity (Çilli, 2024), and this relationship is supported by various studies. Fisk and Rosenfeld (1997) estimated that better indoor conditions could yield economically significant gains in health and productivity. A comprehensive review examining the relationship between office indoor quality and employee productivity also reveals this link (Al Horr et al., 2016). Satish et al. (2012) showed that even low to moderate CO_2 concentrations can directly affect decision-making performance. In a controlled exposure study conducted by Allen et al. (2016), employees' cognitive function scores were found to rise markedly in office conditions with high ventilation rates and low CO_2 and volatile organic compound (VOC) levels. These findings show that fresh air supply is not merely an infection control measure but also a design parameter that affects concentration, motivation and job performance (Çolak & Ayçam, 2022).

In this context, reducing dependence on mechanical systems and prioritizing passive climate control strategies offer an important opportunity in terms of both energy and user health. It is reported that passive strategies such as natural ventilation, night cooling,

shading and climate-responsive design of the building envelope can reduce the need for mechanical cooling (Santamouris, 2016). With regard to the building envelope in particular, a study combining full-scale measurements and simulations in an office of a university building in İzmir showed that the glazing properties of a double-skin façade largely determine its cooling load in a hot-humid climate; outer glazing with a low solar heat gain coefficient reduced the cooling load by approximately 7–30% (Göksal Özbalta & Yıldız, 2019). It is stated that giving importance to passive climate control in office-type buildings and bringing fresh air into the space through natural ventilation will contribute positively not only to human health but also to users' work performance (Çolak & Ayçam, 2022). Furthermore, it is noted that where natural ventilation alone is insufficient, hybrid systems can offer a solution in terms of both energy efficiency and air quality, and that building morphology, seasonal variability and user behavior are direct determinants of indoor air quality (Çolak Demirel & Ayçam, 2026). Therefore, the success of passive strategies depends not only on architectural solutions but also on the interaction users establish with the space.

Thermal comfort approaches have traditionally been based on Fanger's (1970) static comfort model; however, this model has been criticized for not sufficiently accounting for individual differences and adaptation opportunities (van Hoof, 2008). In contrast, the adaptive comfort approach demonstrates that occupants can adapt to thermal conditions through behaviors such as opening windows, changing clothing and adjusting their activity level (de Dear & Brager, 1998; Nicol & Humphreys, 2002). In their comprehensive review of human thermal comfort, Rupp et al. (2015) draw attention to the wide comfort range that this adaptive approach provides in naturally ventilated buildings. Occupant behaviors in buildings are classified into directly influential adaptive behaviors, such as opening and closing windows, using shading elements and lighting, and operating climate control devices, and accommodation behaviors, such as changing clothing (Hong et al., 2017). Likewise, the provision of indoor air quality and personal comfort is addressed as depending not only on environmental and structural conditions but also on the user's interaction with the space and, consequently, on the behavior of the space (Topak & Pekeriçli, 2021). The adaptive approach has now also been reflected in international standards. The American National Standards Institute (ANSI)/ASHRAE 55 standard defines an outdoor-temperature-dependent adaptive comfort method for naturally conditioned spaces in which occupants can control thermal conditions through operable windows (ASHRAE, 2023b). Similarly, the European Norm (EN) 16798-1 standard specifies design input parameters for indoor air quality, the thermal environment, lighting and acoustics, and provides adaptive temperature limits and comfort categories for buildings without mechanical cooling (European Committee for Standardization [CEN], 2019). In Türkiye, indoor air quality and thermal comfort assessments are carried out within the framework of Turkish Standard (TS) EN 16798-1, the national equivalent of this standard; however, the lack of criteria specialized at the local and national level limits the scope of these assessments (Çolak Demirel & Ayçam, 2026).

The level of control that users perceive over environmental conditions is also regarded as an important factor determining comfort satisfaction (Hellwig, 2015). Brager et al. (2004) stated that operable windows and personal control options have positive effects on occupant comfort and satisfaction. Moreover, it has been shown that widening indoor temperature setpoint ranges can yield significant energy savings (Hoyt et al., 2015). Therefore, transforming human–space interaction from a static structure into a dynamic and participatory process plays a key role in the energy optimization of buildings.

Comprehensive reviews already exist on individual components of this problem, such as ventilation strategies (Chenari et al., 2016), window-opening behavior (Fabi et al., 2012), occupant behavior modeling (Yan et al., 2015), human thermal comfort (Rupp et al., 2015) and window configuration (Yin et al., 2024). However, these bodies of literature are largely addressed separately, and to the authors' knowledge few studies evaluate passive ventilation strategies, adaptive occupant behaviors and envelope–window design together

and translate this joint evidence into design and retrofit principles for post-pandemic office buildings, particularly for the curtain-wall office stock and the Turkish context. The contribution of this study lies in bringing these three bodies of literature into a single framework and in deriving architectural design and operation implications from their interaction.

Within this framework, the aim of this study is to examine the interaction between passive climate control strategies and adaptive occupant behaviors in order to improve indoor air quality and thermal comfort performance in office buildings within a sustainable framework. Carried out in light of climate change projections and the reports of current health authorities, this research addresses the relationship between the energy performance of buildings and user comfort through a structured narrative literature review, and aims to provide a guiding basis for the rehabilitation of existing buildings and for future new office designs. In line with this aim, the study seeks to answer the following research questions (RQs):

- **RQ1:** Which passive climate control strategies contribute to indoor air quality in office buildings, and under which conditions is their effectiveness limited?
- **RQ2:** How do adaptive occupant behaviors interact with passive strategies and building systems, and how do they affect comfort and energy performance?
- **RQ3:** How do envelope and window design parameters, including the adaptation of existing curtain wall façades, affect the effectiveness of natural ventilation?
- **RQ4:** What integrated design and operation principles can be derived for existing and new office buildings from the joint evaluation of these three axes?

The review method is described in Section 2. RQ1, RQ2 and RQ3 are addressed in Sections 3, 4 and 5, respectively, and RQ4 is answered in Section 6 on the basis of the joint evaluation of these sections.

2. METHODOLOGY

This study was designed as a structured narrative (integrative) literature review (Snyder, 2019). A narrative design was preferred to a systematic review with meta-analysis because the research questions span heterogeneous fields (building physics, indoor air quality and public health, thermal comfort, occupant behavior and façade design) and because the evidence base combines experimental, field, simulation and review studies with standards and guidance documents that cannot be pooled statistically. To ensure transparency, the information sources, search strategy, eligibility criteria, selection procedure and synthesis method are reported below.

2.1. Search Strategy and Information Sources

The literature was compiled by the first author between 2023 and 2026, and the search was updated in 2026 before submission in order to include recent standards and studies. Multidisciplinary and publisher databases were used to cover the building physics, health and architectural dimensions of the topic: Web of Science (WoS), Scopus, Google Scholar, ScienceDirect (Elsevier), Taylor & Francis Online, SpringerLink, Wiley Online Library, IEEE Xplore and ASCE Library for the international literature; the Avery Index to Architectural Periodicals for architecture-specific literature; and DergiPark and the National Thesis Center of the Council of Higher Education (YÖK) for Turkish-language articles and theses. ResearchGate was additionally used to access the full texts of identified publications. Searches were run on titles, abstracts and keywords using combinations of three groups of terms joined with Boolean operators: (1) setting terms ("office building*" OR "workplace*" OR "open-plan office*"); (2) ventilation and indoor environmental quality terms ("natural ventilation" OR "passive cooling" OR "hybrid ventilation" OR "mixed-mode" OR "indoor air quality" OR "thermal comfort" OR "airborne transmission"); and (3) occupant and envelope terms ("adaptive comfort" OR "occupant behavio*" OR "window opening" OR "perceived control" OR "window type" OR "façade" OR "double-skin façade" OR "curtain wall"). A representative search string was: ("office building*") AND ("natural ventilation" OR "indoor air quality" OR "thermal comfort") AND ("occupant behavio*" OR

"window opening" OR "adaptive comfort"). Equivalent Turkish terms (e.g., "büro yapıları", "doğal havalandırma", "iç mekân hava kalitesi", "ısıl konfor", "kullanıcı davranışı") were used in the national databases. The database search was complemented by backward and forward citation tracking of key reviews and by a targeted search of the websites of standardization bodies and health authorities (ASHRAE, CEN, WHO and REHVA) to identify current standards and guidance documents.

No lower publication-year limit was applied, so that foundational works on thermal comfort and natural ventilation could be included. The oldest source in the corpus, Fanger (1970), was retained because his static comfort model remains the reference point against which the adaptive comfort approach discussed in this study has been developed and criticized. Only sources written in English or Turkish were considered; Turkish-language sources were included to reflect the national context. The document types considered were peer-reviewed journal articles, peer-reviewed conference papers, scholarly books and handbooks, graduate theses, and standards, reports and guidance documents issued by recognized international bodies.

2.2. Eligibility Criteria and Selection Procedure

Sources were included if they met all of the following criteria:

- addressing at least one of the three thematic axes of the study: passive climate control and ventilation in relation to indoor air quality; adaptive thermal comfort and occupant behavior; or envelope and window design for natural ventilation;
- concerning office or other non-domestic buildings, or reporting mechanisms transferable to office environments (e.g., airflow through openings, airborne transmission, thermostat use);
- belonging to one of the document types listed in Section 2.1; and
- being available in full text in English or Turkish.

Sources were excluded if they dealt exclusively with the design of mechanical heating, ventilation and air-conditioning equipment without reference to indoor air quality, comfort or occupant interaction; focused on industrial, transport or outdoor environments; were non-scholarly materials (news items, commercial brochures, web pages) or abstract-only records; or were superseded editions of standards for which a current edition exists.

Because the study was designed as a narrative rather than a systematic review, the selection was iterative and purposive. Records retrieved from the databases were first screened by title and abstract against the eligibility criteria, and potentially relevant records were then assessed in full text; the reference lists of included studies were also examined to identify further sources. Screening and selection were carried out by the first author. In line with the narrative design, the number of records retrieved and excluded at each stage was not logged; the selection process is therefore described qualitatively, and the final corpus of 115 sources is characterized in detail below. No formal quality-scoring tool was applied, as is usual in narrative reviews; instead, priority was given to peer-reviewed sources, to current editions of standards and guidance documents from recognized bodies and, for quantitative findings, to studies reporting measured or validated data.

The final corpus comprises 115 sources published between 1970 and 2026: 9 (7.8%) before 2000, 28 (24.3%) between 2000 and 2009, 48 (41.7%) between 2010 and 2019, and 30 (26.1%) in 2020 or later. Of these, 107 are in English and 8 in Turkish. The corpus consists of 98 journal articles, four books and handbooks, four standards, six reports and guidance documents, two conference papers and one master's thesis. Three sources are previous studies by the authors; they were used to contextualize the national and pandemic-related background, and the statements they support are, in most cases, cited together with independent sources. The methodological reference cited in this section (Snyder, 2019) is not part of the reviewed corpus.

2.3. Data Extraction and Synthesis

For each included source, the following information was extracted into a structured matrix: bibliographic data; building type and climate or location; study type (experimental, field measurement, simulation or computational fluid dynamics, review, or standard/guidance); the strategy, behavior or design parameter examined; main findings; and stated limitations. The sources were then coded deductively into the three thematic axes defined by the research questions and inductively into sub-themes that emerged during reading (e.g., single-sided versus cross ventilation, adaptation mechanisms, drivers of window use, window opening types and façade retrofit solutions). A source could be assigned to more than one axis; 35 sources are cited in Section 3, 39 in Section 4 and 35 in Section 5, while the remaining sources provide the background in the Introduction.

The evidence was synthesized narratively and thematically. Within each sub-theme, findings were compared in terms of agreement, divergence and dependence on context (climate, building type and study method). The comparative tables in Sections 3–5 are products of this synthesis: they were compiled by the authors from the cited sources and are qualitative summaries rather than results of statistical pooling. Findings attributed to individual studies are cited accordingly, whereas the design and operation implications presented at the end of Sections 3–5 and the conclusions in Section 6 represent the authors' interpretation of the synthesized evidence.

3. PASSIVE CLIMATE CONTROL STRATEGIES AND INDOOR AIR QUALITY

Numerous studies conducted before and after the pandemic have shown that ventilation plays a decisive role in the spread of particles and microorganisms carried by airborne aerosols (Li et al., 2007; C. C. Wang et al., 2021). Accordingly, health-related authorities recommend using 100% fresh air and increasing hourly air change rates to reduce the risk of transmission (ASHRAE, 2023a; REHVA, 2021; World Health Organization [WHO], 2021).

The main principles for reducing transmission risk in workspaces are summarized below:

- Increasing the outdoor air ratio and, where possible, reducing or disabling recirculated air (REHVA, 2021),
- Operating ventilation systems not only during occupied hours but also before and after occupancy (REHVA, 2021),
- Using filtration and air cleaning applications (HEPA filters, ultraviolet germicidal irradiation [UVGI], etc.) as measures that complement ventilation, subject to regular maintenance (Dietz et al., 2020; Onat & Kabil, 2020),
- Considering natural ventilation as an option in spaces where windows can be opened (WHO, 2021),
- Monitoring indoor CO_2 concentrations as an indicator of ventilation adequacy (Peng & Jimenez, 2021).

However, it is noted that the air change rate alone is not a sufficient criterion and must be evaluated together with space volume, occupant density, outdoor air per person and air distribution (Allen & Ibrahim, 2021). Ventilation strategies are therefore treated not merely as a numerical target but as a holistic design problem encompassing the building envelope, mode of operation and occupant behavior (Lipinski et al., 2020).

3.1. The Importance of Natural Ventilation

To improve air quality in a space, mechanical systems must be supported by natural ventilation (Çolak & Ayçam, 2022). Field measurements conducted in hospital settings show that properly designed natural ventilation can achieve markedly higher air change rates than mechanically ventilated negative-pressure rooms (Escombe et al., 2007). Similarly, analyses based on computational fluid dynamics also show that natural ventilation can be effective in reducing the risk of airborne infections (Qian et al., 2010). In office environments, it is reported that increasing the outdoor airflow rate improves

perceived air quality, reduces sick building syndrome symptoms and increases work productivity (Wargocki et al., 2000).

The applicability of natural ventilation, however, depends on certain conditions. Outdoor air pollution, noise, wind and temperature variability, and security requirements can give rise to situations in which natural ventilation alone is not sufficient (Chenari et al., 2016). For this reason, hybrid approaches in which natural and mechanical methods are designed together are said to offer a balanced solution in terms of both air quality and energy performance (Heiselberg, 2002; Çolak Demirel & Ayçam, 2026).

3.2. Classification of Passive Climate Control Strategies

Passive climate control strategies aim to ventilate and cool the space by exploiting natural driving forces arising from wind and temperature differences (Linden, 1999; Allard & Santamouris, 1998). The main strategies that stand out in office buildings are presented comparatively in Table 1.

Table 1. *Passive climate control strategies in office buildings and their contributions to indoor air quality*

Strategy	Operating principle	Contribution to indoor air quality	Main limitations	Source
Single-sided ventilation	Air intake and exhaust through openings on a single façade by means of wind and temperature differences	Fresh air supply in shallow-plan spaces	Air exchange is limited; effectiveness decreases as plan depth increases	Allard & Santamouris (1998); Linden (1999)
Cross ventilation	Airflow between openings on opposite façades driven by wind pressure differences	High airflow rate and rapid dilution	Sensitive to plan depth, partition walls and wind variability	Allard & Santamouris (1998); Linden (1999)
Stack effect (atrium, chimneys)	Rising of air due to the density difference arising from temperature differences	Maintains air movement even when wind is weak; suitable for multi-storey buildings	Depends on the indoor–outdoor temperature difference; effectiveness may decline in summer conditions	Linden (1999)
Night ventilation	Cooling of the building mass with cool night air	Reduces the daytime cooling load and the need for mechanical cooling	Depends on climatic potential and thermal mass; requires security and rain precautions	Kolokotroni & Aronis (1999); Artmann et al. (2007)
Shading and solar control	Blocking solar gains at the façade	Prevents overheating, thereby keeping windows operable and supporting the continuation of natural ventilation	Must be optimized together with daylight and visual comfort	Santamouris & Kolokotsa (2013)
Hybrid (mixed-mode) ventilation	Using natural and mechanical ventilation together or alternately depending on conditions	Securing air quality and energy performance together	Requires a control strategy and involves operational complexity	Heiselberg (2002); Chenari et al. (2016)

3.3. Economic and Health Dimensions

Giving importance to passive climate control in all building types contributes to making buildings healthier while also making it possible to minimize heating and cooling costs

(Ensarioğlu, 2021). The main implications regarding the economic and health dimensions of this approach are as follows:

- **Energy and cost:** Because a significant share of building energy consumption stems from climate control, passive strategies reduce energy demand by lowering the cooling load (Pérez-Lombard et al., 2008; Santamouris, 2016). Widening indoor temperature setpoint ranges can likewise yield significant energy savings (Hoyt et al., 2015; Yang et al., 2014).
- **Health:** The relationship between inadequate ventilation and sick building syndrome complaints points to the need to strengthen fresh air supply in buildings that depend on mechanical systems (Hosseini et al., 2020). It is also stated that chemicals released from building materials affect indoor air quality (Hosseini et al., 2020).
- **Productivity:** It is anticipated that improving indoor environmental quality can yield economically significant gains in health and productivity (Fisk, 2000; Wargocki et al., 2000).
- **Sustainability:** It is stated that the pandemic experience offers an opportunity to reconsider the built environment in a healthier and more sustainable way (Pinheiro & Luís, 2020).

The key characteristics of ventilation approaches are compared qualitatively in Table 2.

Table 2. *Comparison of mechanical, natural and hybrid ventilation approaches*

Criterion	Mechanical ventilation	Natural ventilation	Hybrid ventilation
Controllability of airflow rate	High	Dependent on outdoor conditions	Medium–high
Energy consumption	Requires fan and climate control energy	Low	Medium
Occupant intervention	Limited	High (opening and closing windows)	Medium–high
Sensitivity to outdoor pollution and noise	Can be reduced by filtration	High	Medium
Continuity of fresh air supply	Depends on system operation	Depends on wind and temperature difference	Supplemented according to conditions

Note. The table was synthesized qualitatively from the studies of Chenari et al. (2016), Heiselberg (2002) and Lipinski et al. (2020).

3.4. Standards and Guidance Documents

The main standards and guidance documents on indoor air quality, thermal comfort and the control of infectious aerosols are summarized in Table 3.

Table 3. *Standards and guidelines on indoor air quality and ventilation*

Document	Publisher	Scope	Relevance to this study
ANSI/ASHRAE 62.1-2022	ASHRAE	Ventilation for acceptable indoor air quality	Outdoor air requirements and ventilation design
ANSI/ASHRAE 55-2023	ASHRAE	Thermal environmental conditions for human occupancy	Adaptive comfort method for naturally conditioned spaces
ANSI/ASHRAE 241-2023	ASHRAE	Control of infectious aerosols	Ventilation and air cleaning requirements
EN 16798-1:2019	CEN	Indoor environmental input parameters (air quality, thermal environment, lighting, acoustics)	Comfort categories and adaptive temperature limits

Document	Publisher	Scope	Relevance to this study
Roadmap to improve and ensure good indoor ventilation in the context of COVID-19	WHO	Improving ventilation	General principles for natural and mechanical ventilation
REHVA COVID-19 guidance document	REHVA	Operation of building service systems in workplaces	Outdoor air ratio and system operating hours

3.5. Design Implications for Office Buildings

When the literature is evaluated together, the potential of passive climate control strategies to improve indoor air quality in office buildings is addressed within the framework of the following design and operation principles:

- Designing ventilation systems in new buildings so as to allow a practical switch to 100% outdoor air use in the event of an outbreak (Çolak & Ayçam, 2022),
- Evaluating parameters such as plan depth, space form, wind and façade orientation in terms of natural ventilation potential (Allard & Santamouris, 1998; Çolak & Ayçam, 2022),
- Providing operable components in fixed-pane façades and enabling occupants to control environmental conditions through window use (Brager et al., 2004; Hong et al., 2017),
- Combining night ventilation and shading strategies so as to limit overheating (Artmann et al., 2007; Santamouris & Kolokotsa, 2013),
- Regular maintenance and replacement of filters in mechanical systems and supporting the systems with natural ventilation (Dietz et al., 2020; Onat & Kabil, 2020),
- Monitoring ventilation adequacy through CO_2 measurements, taking into account occupant-generated CO_2 and measurement limitations (Peng & Jimenez, 2021; Persily & de Jonge, 2017),
- Treating outdoor air quality and noise conditions as a criterion that determines when natural ventilation is applied (Chenari et al., 2016).

These findings show that the contribution of passive climate control strategies to indoor air quality depends not only on architectural solutions but also on how occupants interact with these solutions and on how the systems are operated.

4. ADAPTIVE BEHAVIORS OF OFFICE OCCUPANTS AND BUILDING INTERACTION

People have certain comfort expectations regarding the environments in which they live and work; when these expectations are not met, individuals take actions that adapt either the environment to themselves or themselves to the environment (Nicol & Humphreys, 2002). This principle, which forms the basis of the adaptive comfort approach, shows that when thermal discomfort arises, occupants develop responses aimed at restoring comfort (Brager & de Dear, 1998). Accordingly, the building is treated not as a static physical system independent of its occupants but as a sociotechnical system that operates in continuous interaction with them (Hong et al., 2017). The interactions occupants have with buildings are classified in the literature into two main groups: adaptive and non-adaptive behaviors (Hong et al., 2017; Topak & Pekeriçli, 2021).

4.1. Comfort Expectations and Adaptation Mechanisms

Thermal adaptation is examined under three main headings: behavioral, physiological and psychological (Brager & de Dear, 1998). Examples of these mechanisms in the office environment are summarized in Table 4.

Table 4. *Thermal adaptation mechanisms and their examples in the office environment*

Type of adaptation	Description	Examples from the office environment	Source
Behavioral (personal)	The occupant changing their own state	Changing clothing, adjusting activity level or work position, consuming beverages	Brager & de Dear (1998); Schiavon & Lee (2013)
Behavioral (technological)	The occupant operating building elements and systems	Opening and closing windows, using blinds and shading elements, adjusting the thermostat or fan	Brager & de Dear (1998); Haldi & Robinson (2008)
Physiological	The body becoming accustomed to thermal conditions through long-term exposure	Short- and long-term thermal adjustment (acclimatization)	Brager & de Dear (1998)
Psychological	Expectations and perceived control altering the perception of comfort	Accepting a wider temperature range in line with past experience, control opportunities and expectations	Brager & de Dear (1998); Hellwig (2015)

In the ASHRAE 55 standard, the variables that determine thermal comfort are divided into environmental factors (air temperature, mean radiant temperature, air speed, humidity) and personal factors (metabolic rate, clothing insulation) (ASHRAE, 2023b). Because personal factors can be directly changed through the occupant's behavior, adaptive behaviors are regarded as a determining component in the formation of comfort conditions (Schiavon & Lee, 2013).

4.2. Adaptive and Non-Adaptive Behaviors

Occupant behavior is treated as a process that affects building energy use and in which environmental conditions are rearranged by the occupant; this process is modeled with frameworks that jointly define the drivers, needs, actions and related systems of behavior (Hong et al., 2015; Hong et al., 2017). Two groups of behavior are distinguished within this framework:

- **Adaptive behaviors:** Actions aimed directly at providing comfort, such as occupants opening and closing windows, lowering blinds or adjusting the thermostat to tailor the indoor environment to their needs, or changing their clothing to adapt to their surroundings (Gunay et al., 2013; Hong et al., 2017).
- **Non-adaptive behaviors:** Situations that involve no direct comfort-providing action, such as the occupant's presence in the space, expressing discomfort or remaining motionless. These situations indirectly affect the operation of building systems (Hong et al., 2017; Topak & Pekeriçli, 2021).

The effects of occupant behaviors on building systems are shown schematically in Figure 1 (Topak & Pekeriçli, 2021). In the figure, adaptive behaviors are grouped into active effects, which interact directly with building systems, and passive effects, which do not directly operate building systems. Non-adaptive behaviors are treated as a separate group.

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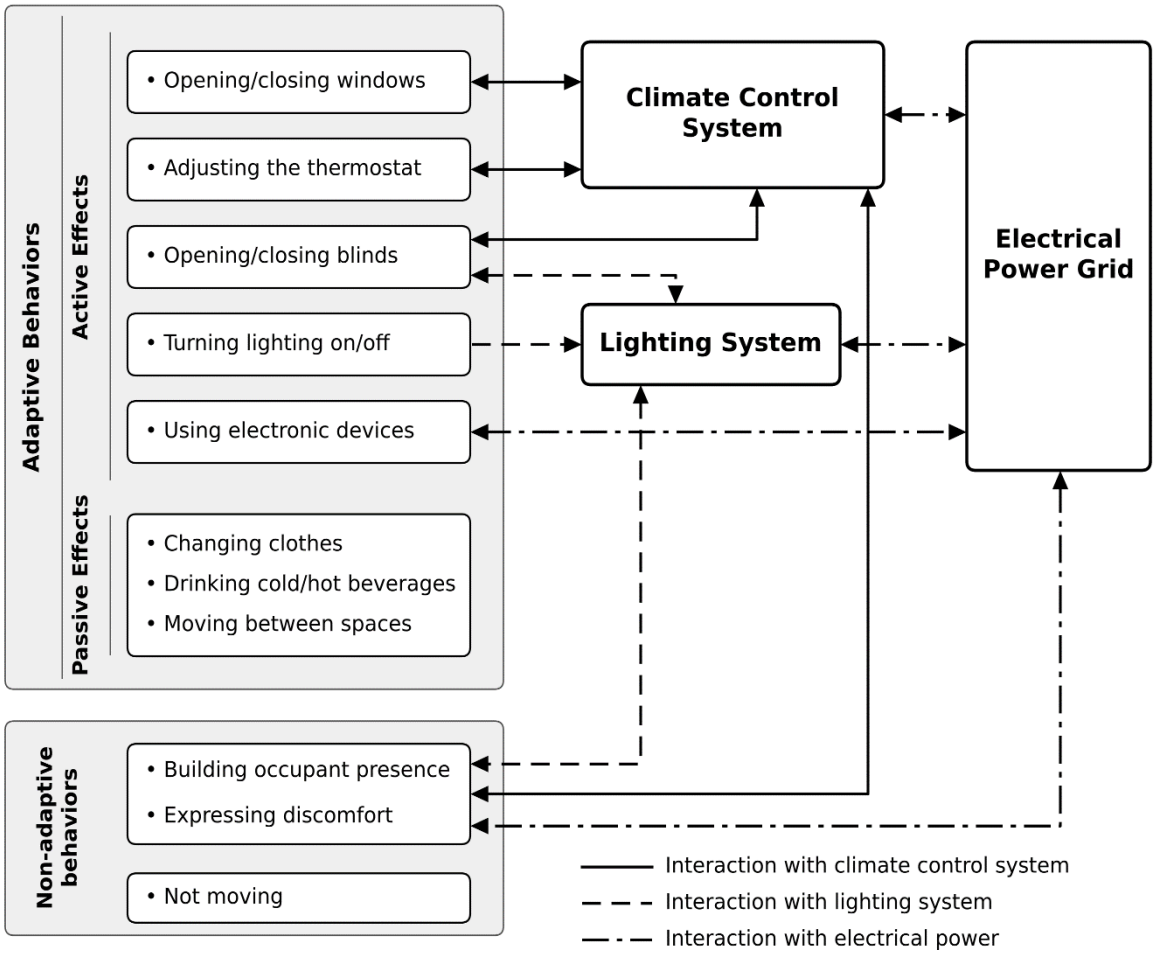


Figure 1. *Behaviors of building occupants and their effects on building systems*

Note. Adapted from Topak and Pekeriçli (2021). The arrows show the two-way interaction of behaviors with building systems and the electrical power grid.

The main aspects of the interactions in the figure are summarized below:

- **Active effects:** Opening and closing windows and adjusting the thermostat interact with the climate control system, while switching the lighting on and off interacts with the lighting system. The use of sunshades affects both the climate control and the lighting system. The use of electronic devices is directly linked to the electrical power grid (Topak & Pekeriçli, 2021).
- **Passive effects:** Changing clothing, consuming cold or hot beverages and moving between spaces are presented as behaviors by which the occupant secures comfort without operating building systems (Topak & Pekeriçli, 2021).
- **Non-adaptive behaviors:** The occupant's presence in the space and expression of discomfort lead to indirect changes in the lighting and climate control systems and, consequently, in electrical energy demand. Remaining motionless, by contrast, involves no direct interaction with building systems (Topak & Pekeriçli, 2021).

The main types of adaptive behaviors, the factors that trigger them and their consequences are presented comparatively in Table 5.

Table 5. *Main adaptive behaviors of office occupants, their drivers and effects*

Behavior	Main drivers	Effect on comfort	Effect on energy	Source
Opening and closing windows	Indoor and outdoor temperature, air quality (CO_2, odor), entering and leaving the space, precipitation and wind	Provides fresh air and cooling; may cause drafts or thermal discomfort under adverse outdoor conditions	May increase heating or cooling loads	Fabi et al. (2012); Haldi & Robinson (2009); Herkel et al. (2008); Rijal et al. (2007)
Using blinds and shading elements	Solar radiation, glare, solar gain, visual comfort	Reduces glare and overheating; may restrict daylight	Changes the cooling load and the need for artificial lighting	Reinhart (2004); Zhang & Barrett (2012); van den Wymelenberg (2012)
Adjusting the thermostat and heating/cooling devices	Perceived thermal discomfort, opportunity for control, gender and individual differences	Allows person-specific comfort conditions to be provided	Directly changes the heating and cooling energy load	Karjalainen (2007); Peffer et al. (2011)
Changing clothing	Outdoor and indoor temperature, dress code	Helps maintain comfort over a wide temperature range	May allow setpoints to be widened	Schiavon & Lee (2013); Hoyt et al. (2015)
Using personal devices (fan, heater, etc.)	Individual thermal preferences, inadequacy of shared climate control conditions	Helps resolve individual differences in comfort	May create additional energy consumption; total energy may decrease through widened setpoints	Zhang et al. (2015); Brager et al. (2015)

The factors affecting occupant behavior are not limited to physical conditions; contextual, psychological and social factors also play a role in shaping behavior (O'Brien & Gunay, 2014; Schweiker et al., 2020). The classification of these factor groups is given in Table 6.

Table 6. *Groups of factors affecting adaptive behavior*

Factor group	Examples	Source
Environmental (indoor)	Air temperature, humidity, CO_2 concentration, glare, noise	Fabi et al. (2012); Haldi & Robinson (2009)
Environmental (outdoor)	Outdoor air temperature, wind, precipitation, solar radiation	Herkel et al. (2008); Fabi et al. (2012)
Contextual (building and space)	Accessibility of windows and controls, whether the space is shared, mode of building operation	O'Brien & Gunay (2014); Ackerly & Brager (2013)
Physiological and individual	Gender, age, activity level, individual thermal preferences	Karjalainen (2007); Schweiker et al. (2020)
Psychological and social	Perceived control, expectations, interaction with other occupants	Hellwig (2015); Boerstra et al. (2013); Day & O'Brien (2017)

4.3. Effects on Energy and Comfort

Occupant behaviors have a significant effect on the heating and cooling energy loads of buildings (Hong et al., 2017; Yan et al., 2015). The main aspects of this effect are as follows:

- **Window use:** A window opened out of a desire for fresh air can weaken the building's overall thermal balance and increase energy consumption, particularly under conditions in which heating or cooling systems operate simultaneously (Rijal et al., 2007; Hong et al., 2017). On the other hand, window-opening behavior also makes it possible to use the potential of natural ventilation and thermal comfort under suitable conditions (Fabi et al., 2012; Haldi & Robinson, 2009).

- **Use of heaters and climate control devices:** Behaviors such as occupants activating heaters or opening windows are decisive for heating and cooling energy loads (Peffer et al., 2011; Yan et al., 2015).
- **Shading and lighting control:** Because the use of blinds changes both solar gain and the need for artificial lighting, it affects energy performance as well as thermal and visual comfort (Reinhart, 2004; Zhang & Barrett, 2012).
- **Non-occupancy energy consumption:** Behaviors such as using equipment and lighting outside working hours can account for a notable share of building energy consumption (Masoso & Grobler, 2010).

However, occupant behavior is not treated solely as a risk factor for building performance; it is also reported that designs that give occupants opportunities for control can increase comfort and satisfaction (Boerstra et al., 2013; Hellwig, 2015). Approaches are therefore being developed to reduce the negative energy effects of occupant behavior. These approaches are summarized in Table 7.

Table 7. *Approaches to reducing energy and comfort problems arising from occupant behavior*

Approach	Description	Expected contribution	Source
Window signalling systems	Visual or audible indicators that guide occupants on opening and closing windows in hybrid buildings	Limiting climate control energy loss while windows are open	Ackerly & Brager (2013)
Widening the setpoint range	Widening temperature setpoint ranges so as to allow occupants to adapt	Energy savings; broader scope for adaptive behavior	Hoyt et al. (2015)
Personal comfort systems	Small-scale heating, cooling and ventilation applications directed at the occupant's immediate surroundings	Meeting individual differences in comfort; allowing general ambient conditions to be relaxed	Zhang et al. (2015); Brager et al. (2015)
Occupant-centric control	Building control strategies based on occupant behavior and preferences	Improving comfort and energy efficiency together	Park & Nagy (2018); Kim et al. (2018)
Informing occupants and providing feedback	Informing occupants about building systems and environmental conditions	Increasing conscious use and satisfaction	Day & O'Brien (2017)

4.4. Limitations of Static Comfort Profiles

Because personal comfort criteria depend on contextual and environmental factors, static comfort profiles cannot go beyond reflecting a general average. Fanger's (1970) Predicted Mean Vote (PMV) model evaluates comfort on the basis of fixed conditions defined for a particular average occupant; however, it is criticized for not sufficiently reflecting individual differences and adaptation opportunities (van Hoof, 2008). It is reported that factors such as gender, activity level and individual preferences create marked differences in thermostat use and comfort perception (Karjalainen, 2007). In response to these limitations, personal comfort models, which predict individuals' thermal preferences from their own behavior, are proposed as a new approach to occupant-centric environmental control (Kim et al., 2018). Frameworks for applying adaptive comfort principles to building design and operation likewise support treating thermal comfort as a dynamic and context-sensitive process (Hellwig et al., 2019).

4.5. Integrated Assessment and Design Implications

The effect of occupant behavior on building performance is cited as one of the main causes of the gap between the energy consumption predicted at the design stage and measured consumption (de Wilde, 2014; Menezes et al., 2012). Representing occupant behavior in building performance simulations with fixed and simplified assumptions can widen this gap

(Hoes et al., 2009; Yan et al., 2015). In this context, the design and operation implications regarding occupant behavior in office buildings are summarized as follows:

- Occupants having accessible and understandable control over windows, blinds and thermal controls (Boerstra et al., 2013; Hellwig, 2015),
- Designing passive climate control strategies together with occupant control; developing operating strategies in which window use does not conflict with mechanical systems (Ackerly & Brager, 2013; Çolak Demirel & Ayçam, 2026),
- Setting comfort setpoints so as to allow adaptation (Hoyt et al., 2015; ASHRAE, 2023b),
- Representing occupant behavior in performance simulations with probabilistic and context-sensitive models (Haldi & Robinson, 2009; Yan et al., 2015),
- Informing occupants about building systems and providing feedback mechanisms (Day & O'Brien, 2017).

Taken together, the reviewed studies indicate that occupant interactions largely determine the actual thermal and energy performance of buildings; passive strategies and adaptive occupant behaviors should therefore be addressed together at the design stage.

5. ENVELOPE AND WINDOW DESIGN INTERACTION FOR NATURAL VENTILATION

The effectiveness of natural ventilation varies depending on design parameters such as the position and size of façade openings and the quality of the frame, in addition to the driving forces arising from wind pressure and temperature difference (Linden, 1999; Etheridge, 2011). Although the window is the most traditional element that brings natural ventilation into the built environment, it is stated that this potential has not been sufficiently exploited, and that window geometry, opening ratio, number of openings, position, type, orientation and the performance of shading systems are among the factors that determine performance (Yin et al., 2024). The position and dimensions of wall openings and the quality of the frame are therefore critical in offices (Aflaki et al., 2015). In Türkiye as well, studies are being conducted on the principles of natural ventilation in removing indoor air pollution (Darçın, 2008).

5.1. Airflow Principles

In a window opening formed in a wall, the temperature difference between the indoor and outdoor environments causes a density difference, which in turn leads to a pressure difference in the vertical direction (Linden, 1999). As a result, polluted and warm air leaves through the upper part of the opening, while cooler, fresh air enters through the lower part (Awbi, 2003; Etheridge, 2011). The components of this flow behavior are summarized below:

- **Upper zone (outflow):** Because the indoor pressure at the upper part of the opening is higher than the outdoor pressure, heated indoor air laden with pollutants is expelled (Etheridge, 2011).
- **Lower zone (inflow):** Because the indoor pressure at the lower part of the opening is lower than the outdoor pressure, cooler and cleaner outdoor air enters the space (Etheridge, 2011).
- **Neutral zone (neutral pressure plane):** No net airflow occurs at this plane, where indoor and outdoor pressures are equal. The position of the plane depends on the height of the openings and the ratio of their areas (Linden, 1999; Etheridge, 2011).

This two-way flow through a single opening constitutes the basic mechanism of single-sided ventilation. With the addition of wind, the flow takes on a more fluctuating character (Larsen & Heiselberg, 2008; Caciolo et al., 2011). In single-sided ventilation the openings are located on only one façade of the building, whereas in cross ventilation they are located on opposite façades (Y. Wang et al., 2021). Although single-sided ventilation can be easily adapted to most office plans, it is frequently not preferred by designers because its capacity to provide comfort conditions is difficult to evaluate (Stabat et al., 2012). The depth of space over which single-sided ventilation is effective is also limited (Allard & Santamouris,

1998; Carrilho da Graça & Linden, 2016). It is reported that the discharge coefficients of window types are generally higher in cross ventilation than in single-sided ventilation (Y. Wang et al., 2021).

The effects of opening parameters on airflow are summarized in Table 8.

Table 8. *Effects of façade opening parameters on natural ventilation*

Parameter	Effect on airflow	Source
Vertical position of the opening	For a large rectangular opening, vertical position is reported to be the most important factor determining the discharge coefficient in single-sided temperature-driven ventilation	Favarolo & Manz (2005); Linden (1999)
Opening area and size	Airflow rate increases as opening area increases; window size is associated with ventilation performance	Sacht & Lukiantchuki (2017); Heiselberg et al. (2001)
Opening angle	There is a positive relationship between the discharge coefficient and the opening angle	Yang et al. (2010); Y. Wang et al. (2021)
Number and distribution of openings	Whether openings are located on one or on opposite façades determines the possibility of single-sided or cross ventilation	Y. Wang et al. (2021); Yin et al. (2024)
Frame type and sash movement	The discharge coefficient varies with both opening area and window type	Heiselberg et al. (2001); Y. Wang et al. (2021)
Orientation and shading	Window orientation and shading systems are counted among the design variables that affect ventilation performance and thermal comfort	Yin et al. (2024)
Interior layout	The geometric and thermal properties of obstacles in the space alter local airflow and comfort conditions	Yin et al. (2024)

5.2. Window Opening Types

A fully opening sash may not be suitable under every condition, because it creates an abrupt and forceful air exchange in the space. The characteristics of the airflow entering the space through an open window vary with window type and opening area (Heiselberg et al., 2001). High air velocities and turbulence, in turn, can cause draft discomfort in occupants (Fanger et al., 1988; Toftum, 2004). For this reason, opening types that can direct the air depending on sash movement, such as horizontal-axis, hopper (tilt-in) or vertical sliding window types, are considered to increase ventilation efficiency (Allard & Santamouris, 1998).

In a study that systematically compared the effect of window opening types on ventilation performance, seven window types, three opening angles and two ventilation modes (wind-driven cross ventilation and temperature-driven single-sided ventilation) were examined in a typical office room using computational fluid dynamics, and the results were validated with a full-scale experiment (Y. Wang et al., 2021). The main findings of the study are as follows:

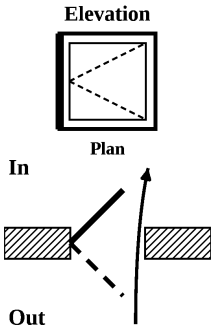
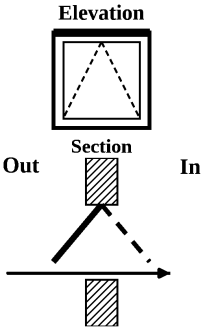
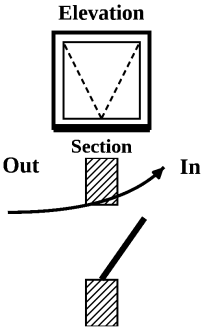
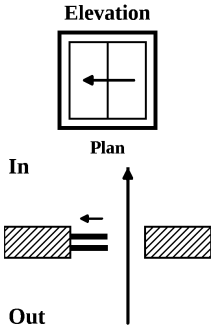
- The discharge coefficient increases as the opening ratio increases; the fully open sliding window reaches the highest values, at 0.68 in cross ventilation and 0.52 in single-sided ventilation (Y. Wang et al., 2021).
- At medium and small openings, the bottom-hung inward-opening window shows the highest discharge coefficient in cross ventilation, and the top-hung inward-opening window in single-sided ventilation (Y. Wang et al., 2021).
- In the integrated indicator that evaluates airflow rate and thermal sensation together, inward- and outward-opening top-hung windows perform better than the other window types in both ventilation modes (Y. Wang et al., 2021).

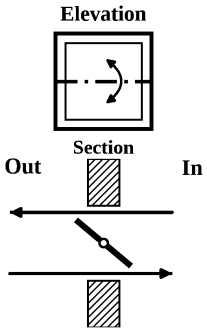
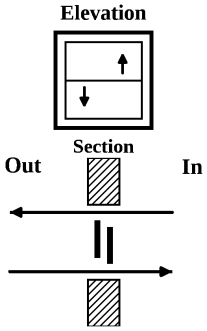
Because these findings were obtained in a specific climate (Tianjin) and for specific room and window dimensions, they should not be directly generalized to different climates and

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geometries (Y. Wang et al., 2021). An evaluation of window design in terms of CO_2 and thermal comfort performance in naturally ventilated offices in the Mediterranean climate likewise shows that regional conditions need to be reflected in design decisions (Abdullah & Alibaba, 2020). The main window opening types are compared in Table 9.

Table 9. *Comparison of window opening types in terms of airflow*

Window type	Schematic image	Sash movement	Effect on airflow	Assessment for offices	Source
Side-hung (casement), opening inward/outward		Sash rotating about a vertical axis	Owing to its asymmetric structure, the discharge coefficient is sensitive to wind direction	Undirected airflow may occur when fully open; the opening angle can be controlled with a limiter	Y. Wang et al. (2021)
Top-hung, opening inward/outward		Sash rotating about a horizontal axis at the top edge	The inward- and outward-opening types are reported to show better integrated performance in both ventilation modes	Considered a suitable option for cross and single-sided ventilation	Y. Wang et al. (2021)
Bottom-hung, opening inward (hopper type)		Sash tilting inward about a horizontal axis at the bottom edge	Has the highest discharge coefficient in cross ventilation at medium and small openings	Because the sash directs incoming air upward, it has the potential to reduce direct draft discomfort	Y. Wang et al. (2021); Allard & Santamouris (1998)
Sliding		Sash sliding within its own plane	Reaches the highest discharge coefficient when fully open	The net opening is generally limited by the sash area; the ability to direct air is restricted	Y. Wang et al. (2021)

Window type	Schematic image	Sash movement	Effect on airflow	Assessment for offices	Source
Horizontal-axis (pivot)		Sash rotating about a horizontal axis	Because it can create openings in the lower and upper zones simultaneously, it allows the stack effect to be exploited	High potential for directing air	Allard & Santamouris (1998); Awbi (2003)
Vertical sliding (hung)		Separate vertical movement of the lower and upper sashes	By opening the lower sash upward and the upper sash downward, openings can be provided in the lower and upper zones at the same time	Allows inlet and outlet openings to be used together	Allard & Santamouris (1998)

Note. The first four rows of the table are based on the findings of Y. Wang et al. (2021), and the last two rows on qualitative assessments in general ventilation handbooks. The naming of window types may differ across sources and countries. The schematic images were prepared by the author. In the elevations, the thick edge indicates the hinge or axis side, and the apex of the dashed triangle indicates the hinge side. In the sections and plans, arrows show the direction of airflow (arrows pointing into the interior indicate incoming air, arrows pointing outward indicate outgoing air), and the dashed gray line represents the outward-opening alternative.

The following points stand out in the selection and implementation of window opening types:

- Designing the opening angle so that it can be controlled with opening limiters (Y. Wang et al., 2021; Yang et al., 2010),
- Selecting sash movement so as to direct airflow away from the occupant and toward the upper zone (Allard & Santamouris, 1998; Fanger et al., 1988),
- Taking into account that outdoor air pollution and noise may restrict the applicability of natural ventilation (Chenari et al., 2016; Tong et al., 2016),
- Considering solutions such as sound-proofed ventilation windows, which can provide noise reduction and ventilation performance together (Du et al., 2020),
- Ensuring that occupants can control thermal and ventilation conditions by opening and closing windows (Brager et al., 2004).

5.3. Adaptation of Existing Façades

Because today's open-plan offices generally have curtain wall façades, the intake of fresh air into the interior by natural means is largely restricted (Çolak & Ayçam, 2022). For this reason, developing natural ventilation modules that can also be adapted to existing curtain wall systems is regarded as a necessity. An example of applications in this direction is the 2012 renovation of the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) office building. In this renovation, prefabricated window modules incorporating air inlet and outlet openings, façade-integrated air ducts and a ventilation unit with moisture and heat recovery were installed, and a long-term monitoring programme including energy, temperature, CO_2 and humidity measurements was carried out (Coydon et al., 2014). Double-skin façades, another approach, are applied in both new and existing buildings,

particularly in temperate climates (Pomponi et al., 2016). The parameters that determine the performance of these façades are addressed in three groups: façade, building and location parameters (Barbosa & Ip, 2014). It is also stated that the classification of double-skin façades is important because it influences the initial approach at the design stage (Poirazis, 2004). The main solutions that can be adapted to existing curtain wall façades are compared in Table 10.

Table 10. *Natural ventilation solutions that can be adapted to existing curtain wall façades*

Solution	Operating principle	Potential contribution	Points to consider	Source
Operable sash modules	Occupant-controlled operable sash or ventilation vane integrated into the façade system	Direct intake of fresh air; control opportunity for the occupant	Water and air tightness, security, noise; control of the opening angle	Karava et al. (2011); Yin et al. (2024)
Prefabricated façade modules with air inlet and outlet	Air inlet and outlet openings integrated into window modules	Controlled fresh air supply; use together with heat recovery systems	Duct layout and system integration; effect of façade-integrated ducts on energy performance	Coydon et al. (2014)
Addition of a double-skin façade	Adding a second skin in front of the existing façade and ventilating the cavity between them	Ventilation through the cavity; potential to improve thermal comfort	Cavity width, ventilation strategy, shading, orientation and climatic conditions	Barbosa & Ip (2014); Gratia & De Herde (2004); Pelletier et al. (2023); Pomponi et al. (2016)
Hybrid (natural and mechanical) ventilation	Bringing in mechanical support where natural ventilation is insufficient	Securing air quality and energy performance together	Control strategy and operational complexity	Heiselberg (2002); Chenari et al. (2016); Çolak Demirel & Ayçam (2026)

The following points need to be addressed together when adapting a natural ventilation module to existing façades:

- Designing the module according to outdoor noise and air pollution conditions (Du et al., 2020; Tong et al., 2016),
- Holistically evaluating the relationship between cavity parameters and ventilation and thermal performance in double-skin façades (Pelletier et al., 2023),
- Carrying out monitoring based on energy, temperature and CO_2 measurements after the retrofit (Coydon et al., 2014),
- Designing modules so that they give occupants an opportunity for control (Brager et al., 2004).

5.4. Integrated Assessment

In summary, the effectiveness of natural ventilation depends on the indoor–outdoor driving forces together with the position, size and frame quality of the opening. The window opening type affects the direction and speed of airflow and thus occupant comfort, while the adaptation of existing curtain wall façades needs to be addressed alongside new designs. Envelope and window design should therefore also encompass occupant control and hybrid operating strategies (Çolak Demirel & Ayçam, 2026; Yin et al., 2024).

6. CONCLUSION AND DISCUSSION

In this study, indoor air quality and thermal comfort in office buildings were addressed through a structured narrative review along three axes: passive climate control strategies, adaptive occupant behaviors, and envelope–window design. In the following, findings reported by individual studies are cited as such, whereas statements without citations represent the authors' synthesis of the reviewed evidence. Overall, the synthesis indicates that a healthy and energy-efficient office environment can be achieved not through a single

system or design decision but through an approach in which the building envelope, the ventilation system and occupant behavior complement one another. The pandemic has made this relationship visible and has shown that ventilation is not merely a comfort parameter but also a public health measure.

With regard to RQ1, the reviewed studies show that properly designed natural ventilation can achieve high air change rates (Escombe et al., 2007) and that increasing the outdoor air supply improves perceived air quality and reduces sick building syndrome symptoms (Wargocki et al., 2000). However, natural ventilation cannot be regarded as sufficient on its own under every condition: outdoor air pollution, noise, wind and temperature variability, and security requirements limit its applicability, particularly in multi-storey offices in dense urban fabric (Chenari et al., 2016). The authors therefore conclude that the priority should be to reduce dependence on mechanical systems through hybrid approaches in which natural and mechanical methods are operated according to conditions, rather than to eliminate mechanical ventilation altogether. Likewise, the goal of 100% outdoor air supply can be met sustainably only through an operating concept in which passive systems predominate and mechanical support is activated when needed.

With regard to RQ2, adaptive occupant behaviors are one of the main factors explaining the gap between predicted and measured building performance (de Wilde, 2014; Yan et al., 2015). Window use plays a two-way role: it allows the potential of natural ventilation and thermal comfort to be used under suitable conditions, but it can cause energy losses when climate control systems operate simultaneously (Rijal et al., 2007; Fabi et al., 2012). In the authors' view, this contradiction is better resolved by guiding occupant control than by restricting it. Perceived control increases comfort satisfaction (Hellwig, 2015), widening temperature setpoint ranges yields energy savings (Hoyt et al., 2015), and window signalling systems help bring window use into harmony with mechanical systems in hybrid buildings (Ackerly & Brager, 2013). These results support replacing narrow, fixed setpoints based on the static comfort model with an adaptive comfort approach that takes outdoor conditions and occupant adaptation into account, particularly in naturally ventilated and hybrid offices.

With regard to RQ3, the reviewed studies indicate that the effectiveness of natural ventilation depends largely on the position, size, opening angle and sash movement of the opening (Favarolo & Manz, 2005; Sacht & Lukiantchuki, 2017; Y. Wang et al., 2021). Window types that can direct air, such as top-hung, hopper and horizontal-axis windows, can offer advantages both in increasing the airflow rate and in reducing draft discomfort. Because comparative assessments of window types have been made for specific climates and geometries, window design should be evaluated separately under different regional conditions. For the fixed-pane curtain wall façades common in contemporary offices, the transformation of existing façades is as important as design principles for new buildings. Operable sash modules, prefabricated façade elements with air inlets and outlets, and double-skin façade additions are feasible options for this transformation, but they require project-specific evaluation in terms of water and air tightness, noise, system integration and climatic conditions.

With regard to RQ4, the joint evaluation of the three axes suggests that health, energy and productivity goals do not have to conflict with one another. Because higher fresh air rates together with low CO_2 and volatile organic compound levels have been associated with better cognitive performance (Allen et al., 2016), investment in indoor environmental quality can be regarded as a design decision that pays back through employee health and productivity. These gains may, however, remain limited unless the energy load brought by increased ventilation rates is balanced with night ventilation, shading, heat recovery and adaptive setpoint strategies. Passive strategies should therefore be designed not as isolated measures but as a whole coordinated with occupant control.

The reviewed evidence is nevertheless not free of contradictions, and several of the relationships above are context-dependent rather than universal. First, while studies in hospital settings report that natural ventilation can achieve higher air change rates than mechanical systems and reduce airborne infection risk (Escombe et al., 2007; Qian et al., 2010), studies on ambient air pollution show that the hours in which windows can be opened, and hence the benefits of natural ventilation, are considerably reduced in polluted urban settings (Tong et al., 2016); moreover, hospital-based evidence cannot be transferred directly to deep-plan offices. Second, window opening is reported both as a source of fresh air and thermal comfort (Haldi & Robinson, 2009; Fabi et al., 2012) and as a cause of energy losses (Rijal et al., 2007); the net effect depends on climate, season and the operating mode of the building. Third, perceived control is consistently associated with higher comfort satisfaction (Boerstra et al., 2013; Hellwig, 2015), whereas personal devices that provide such control may increase energy consumption unless they are combined with widened setpoints (Zhang et al., 2015; Hoyt et al., 2015). Fourth, the comparative findings on window opening types derive from a single climate and room geometry (Y. Wang et al., 2021), and regional studies indicate that suitable window configurations differ between climates (Abdullah & Alibaba, 2020). Finally, CO_2 is widely used as an indicator of ventilation adequacy (Peng & Jimenez, 2021), but it is an imperfect proxy because CO_2 generation varies with occupant characteristics and activity (Persily & de Jonge, 2017), and its direct effects on decision-making performance were identified under controlled exposure conditions (Satish et al., 2012). In the authors' view, these contradictions do not weaken the case for passive strategies; rather, they indicate that passive and adaptive measures should be specified conditionally, according to climate, outdoor air quality, plan depth and operating mode, instead of being prescribed as universal solutions.

The main limitation of the study is that it is based on a literature review and includes no field measurements or simulations. Although the search and selection procedure is reported in Section 2, the review is narrative rather than a full systematic review with formal quality appraisal, screening was performed by a single researcher, and the number of records at each selection stage was not logged; selection bias therefore cannot be ruled out, and restricting the corpus to English- and Turkish-language sources may have excluded relevant studies. Because a significant portion of the findings evaluated were obtained in different climate zones and building typologies, it is difficult to generalize them directly to conditions in Türkiye; the lack of nationally specific indoor environmental criteria also narrows the scope of the assessments. In future studies, it is recommended to monitor CO_2, temperature and humidity measurements in office buildings across Türkiye's different climate zones together with window use and occupant satisfaction data, to transfer occupant behavior into performance simulations through probabilistic models, and to evaluate the post-implementation performance of curtain wall retrofit modules over the long term.

In conclusion, existing office buildings should be improved in terms of indoor air quality in line with current health norms, and new projects should be designed with an approach that combines passive and hybrid strategies and incorporates operable, occupant-controlled components that allow a switch to 100% outdoor air use in the event of an outbreak. In this approach, the building should be regarded not as a static system independent of its occupants but as a dynamic system in continuous interaction with them. In this way, it will be possible in enclosed workspaces both to protect human health and to reduce energy consumption and support employee productivity.

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