Tania RUS

Indoor Environmental Quality and Wellbeing

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Preface

The built environment profoundly shapes human health, cognitive performance, and subjective wellbeing. People in technologically advanced societies spend approximately 90% of their lives indoors—in dwellings, offices, schools, healthcare facilities, and transport environments—yet the interior conditions of these spaces receive far less policy and design attention than the outdoor environment. This course book addresses that gap.

Indoor Environmental Quality (IEQ) is an integrative discipline that draws on building physics, occupational health, environmental psychology, human factors engineering, and data science. Its central premise is that well-designed indoor environments can be powerful health-promoting resources rather than mere shelters. Conversely, poor IEQ exacts measurable costs: reduced cognitive output, increased absenteeism, elevated morbidity, and diminished quality of life.

This volume is structured as a progression from foundations to applications. Chapters 1–5 establish the scientific basis of the five principal IEQ domains: thermal comfort, indoor air quality, lighting, acoustics, and psychological factors. Chapters 6–8 examine the technologies and certification frameworks that operationalize IEQ in practice. Chapters 9–10 address integrated design strategies and present extended, multi-parameter case studies drawn from real buildings across Europe, Asia, and North America. Chapters 11–12 look to future research frontiers and synthesize the book's core themes.

Each chapter includes explicit learning objectives, quantitative worked examples where appropriate, and at least one in-depth case study. Review questions at the end of each chapter are designed to test both comprehension and critical analysis. References are drawn primarily from peer-reviewed literature published between 2010 and 2025, supplemented by key standards documents and authoritative reports.

The book is intended for postgraduate students in architecture, building services engineering, environmental science, and public health, as well as for practitioners seeking a rigorous reference on IEQ science and evidence-based design. Readers are assumed to have undergraduate-level familiarity with building physics and basic statistics.

I’m grateful to the researchers, designers, and building owners whose published work underpins the case studies presented here. IEQ is ultimately a human science—its advances depend on collaboration between those who build environments and those who study how people thrive within them.

The author – Cluj – Napoca, Romania, 2026.

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Chapter 1: Introduction to indoor environmental quality and human wellbeing

Learning objectives

1. Define Indoor Environmental Quality (IEQ) and articulate its multidimensional nature.
2. Explain the relationship between IEQ parameters and occupant health, comfort, and productivity.
3. Describe the historical evolution of IEQ research and policy frameworks.
4. Identify the principal stakeholders and disciplines involved in IEQ assessment and management.
5. Critically evaluate the economic case for investing in healthy buildings.

1.1 Defining indoor environmental quality

Indoor Environmental Quality (IEQ) refers to the totality of physical, chemical, biological, and psychological conditions that characterize the internal environment of a building and that influence the health, comfort, productivity, and wellbeing of its occupants (Frontczak & Wargocki, 2011). Unlike the narrower concept of indoor air quality (IAQ), IEQ is a holistic construct that encompasses thermal comfort, luminous conditions, acoustic conditions, air quality, and the broader psychosocial milieu of interior spaces.

The built environment profoundly shapes the human condition. Epidemiological research consistently demonstrates that residents of high-income nations spend an average of 87-90% of their lives indoors, with the figure rising to over 92% in winter months in Nordic climates (Klepeis et al., 2001; Schweizer et al., 2007). Given this exposure duration, even modest degradations in IEQ can translate into significant cumulative health burdens. Conversely, purposeful design and operation of buildings to optimize IEQ can yield substantial improvements in occupant wellbeing, cognitive performance, and organizational productivity.

The World Health Organization (WHO, 2018) recognizes the built environment as a key determinant of public health, estimating that approximately 3.8 million deaths per year are attributable to household air pollution alone—primarily from the combustion of solid fuels in low-income settings. In higher-income nations, the dominant concerns shift to chronic low-level exposures: inadequate ventilation, volatile organic compound off-gassing from building materials, poor thermal regulation, suboptimal lighting, and elevated noise levels. These exposures underpin conditions ranging from sick building syndrome and building-related illness to more diffuse outcomes such as reduced cognitive performance and diminished subjective wellbeing.

1.2 Dimensions of IEQ

Contemporary scholarship identifies four principal and interrelated dimensions of IEQ, presented in Table 1.1, each of which is the subject of dedicated chapters in this course book.

Table 1.1. The four principal dimensions of IEQ, their key parameters, governing standards, and associated health outcomes.

IEQ Dimension	Key Parameters	Primary Standards	Health Outcomes
Thermal Comfort	Temperature, humidity, air speed, radiant temperature, metabolic rate, clothing insulation	ASHRAE 55, ISO 7730, EN 16798	Stress, fatigue, respiratory illness, productivity loss
Indoor Air Quality	CO_2, PM2.5, VOCs, NO_2, ozone, radon, bioaerosols, humidity	ASHRAE 62.1, WHO Guidelines, EN 13779	SBS, asthma, cancer, cognitive impairment
Visual / Lighting Comfort	Illuminance, luminance, daylight factor, glare indices	EN 12464-1, WELL Standard, CIBSE LG7	Eye strain, circadian disruption, mood disorders
Acoustic Comfort	Sound pressure level, reverberation time, speech intelligibility, vibration	ISO 3382, WHO Night Noise Guidelines, BB93	Hearing loss, sleep disruption, cardiovascular disease

Beyond these four primary dimensions, emerging research highlights the importance of biophilic connections (the integration of natural elements into the built environment), spatial factors (density, privacy, layout), and digital / electromagnetic environments. This course book adopts the four-pillar framework while acknowledging these broader contextual factors.

1.3 Historical context and evolution of IEQ research

1.3.1 Pre-modern foundations

Concerning the internal environment of buildings is not a modern preoccupation. Vitruvius, writing in the first century BCE, advised on the selection of building sites based on wind direction and proximity to marshes, recognizing that miasmatic air posed health risks. Florence Nightingale's empirical observations in Crimean War hospitals (1854-1856) demonstrated that mortality rates fell dramatically when ventilation and sanitation were improved—an early evidence-based intervention in IEQ. The British Public Health Acts of the mid-nineteenth century mandated minimum ventilation rates in tenement buildings, driven by concerns about tuberculosis transmission.

1.3.2 The twentieth century: mechanization and crisis

The advent of mechanical ventilation and air conditioning systems in the early twentieth century transformed the relationship between buildings and their environments, enabling the decoupling of interior conditions from external climate. This technological capability facilitated the energy-saving measures of the 1970s oil crisis, during which ventilation rates were dramatically reduced in commercial buildings. The consequence wave of occupant health complaints and absenteeism—prompted the coining of the term 'sick building syndrome' by the WHO in 1983 (WHO, 1983).

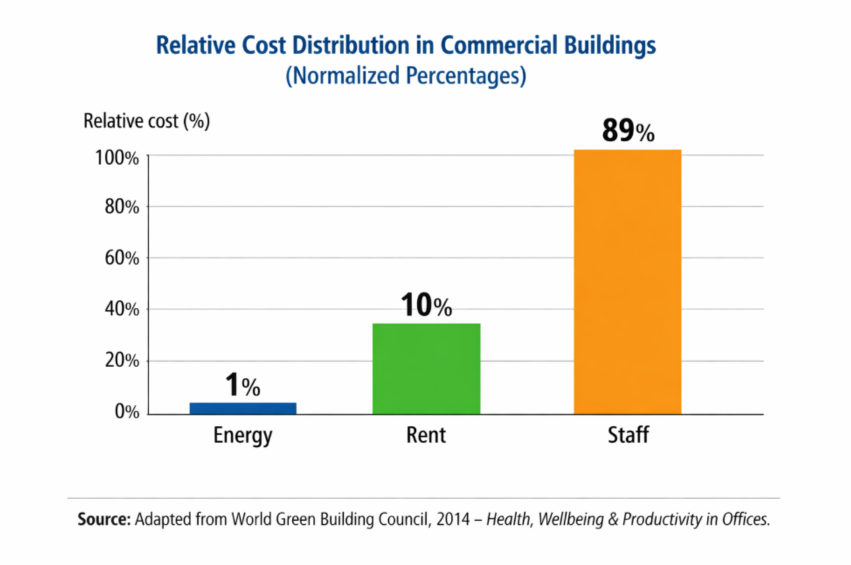
The 1980s and 1990s witnessed a proliferation of field studies, epidemiological surveys, and laboratory experiments aimed at characterizing the relationships between IEQ parameters and occupant outcomes. Landmark studies such as the Danish Town Hall Study (Skov et al., 1989), the European EUROVEN project (Wargocki et al., 2002), and the BASE (Building Assessment Survey and Evaluation) study in the United States (Apte et al., 2000) established the empirical foundations of modern IEQ science.

1.3.3 Twenty-first century: integration and digitalization

The twenty-first century has been marked by three converging trends in IEQ research: (1) the integration of IEQ considerations into green building certification frameworks (LEED, BREEAM, WELL); (2) the proliferation of low-cost sensor technologies enabling continuous, high-resolution IEQ monitoring; and (3) the growing recognition of the economic value of healthy indoor environments. Allen et al. (2016) demonstrated in the landmark COGfx study that improved ventilation and reduced chemical pollutants produced a 101% improvement in cognitive function scores, potentially translating into tens of thousands of dollars per year per worker in productivity gains.

1.4 The economics of healthy buildings

The economic case for investment in IEQ is compelling and increasingly well-quantified. The work of Woods (1989) estimated the annual cost of sick building syndrome in the United States at USD 60 billion, comprising lost productivity, absenteeism, and medical costs. More recent analyses have refined these estimates and linked them directly to specific IEQ parameters.



Source: Adapted from World Green Building Council, 2014 – *Health, Wellbeing & Productivity in Offices.*

Figure 1.1. Relative cost distribution in commercial buildings, illustrating the primacy of human capital costs (adapted from World Green Building Council, 2014).

The World Green Building Council (World GBC, 2014) synthesized evidence demonstrating that salaries and benefits account for approximately 90% of typical business operating costs, energy for 1%, and rent for 9%. Even marginal improvements in employee productivity—achievable through optimized IEQ—can far outweigh the entire energy expenditure of a building. Specific findings include:

- A 1% improvement in productivity in an office building equates to cost savings roughly equivalent to the entire annual energy bill (World GBC, 2014).
- Higher ventilation rates (above minimum code requirements) are associated with a 3-8% reduction in short-term sick leave (Wargocki et al., 2002; Sundell et al., 2011).

- Optimized thermal comfort can improve task performance by 5-15% in cognitively demanding work (Seppanen et al., 2006).
- Access to daylight and views is associated with 15-18% less absenteeism and 84% reduction in eyestrain symptoms (Heschong, 2003).
- Noise-related productivity loss in open-plan offices has been estimated at 5-15% of work output (Kim & de Dear, 2013).

These findings have catalyzed the emergence of the 'healthy buildings' movement, driven by real estate investors, employers, and insurers seeking to quantify and maximize the human capital return on building investment. The WELL Building Standard (v2, 2020) and the Fitwell certification system are market expressions of this trend.

1.5 Theoretical frameworks for IEQ and wellbeing

1.5.1 The demand-control-support model

Karasek and Theorell's (1990) demand-control-support model, originally developed to explain occupational stress, has been adapted to understand how environmental conditions in the workplace interact with psychological factors to influence wellbeing. In this framework, the built environment can function either as a stressor (excessive noise, thermal discomfort, glare) or as a resource (comfortable temperatures, access to daylight, acoustic privacy).

1.5.2 The restorative environment framework

Attention Restoration Theory (ART), proposed by Kaplan and Kaplan (1989), posits that environments rich in 'soft fascination' –

including natural light, views of nature, and moderate sensory variety – support the recovery of directed attention capacity. Indoor environments can be designed to incorporate restorative qualities through biophilic design elements, optimized daylighting, access to nature views, and acoustic variety.

1.5.3 Evidence-based design

The evidence-based design (EBD) framework, developed primarily within healthcare architecture, provides a methodology for incorporating empirical research findings into the design of buildings to achieve measurable improvements in occupant outcomes (Hamilton & Watkins, 2009). EBD aligns closely with IEQ research by insisting on the measurement and documentation of outcomes, creating a feedback loop between design decisions and their effects on building users.

1.6 IEQ assessment approaches

Assessment of IEQ may be conducted through physical measurement, occupant surveys, or a combination of both approaches as Table 1.2 shows.

Table 1.2. Comparison of IEQ assessment methodologies across key dimensions.

Assessment Method	Advantages	Limitations	Typical Application
Physical / Instrumental Measurement	Objective, quantitative, suitable for compliance assessment	Point-in-time, expensive for comprehensive coverage	Commissioning, certification, research studies

Assessment Method	Advantages	Limitations	Typical Application
Occupant Surveys (e.g., CBE Survey)	Captures subjective experience, covers multiple IEQ dimensions simultaneously	Reporting bias, context-dependent, requires large samples for reliability	Building diagnosis, post-occupancy evaluation
Continuous Sensor Monitoring	Temporal resolution, cost-effective at scale, enables dynamic management	Calibration drift, data management challenges, limited to measurable parameters	Smart buildings, ongoing operations management
Building Simulation (EnergyPlus, IDA-ICE)	Predictive, design-stage assessment, parametric analysis	Model validity depends on input assumptions, requires expertise	Design optimization, retrofit planning

1.7 Regulatory and policy framework

IEQ is governed by an extensive and evolving regulatory landscape at international, regional, and national levels. Key frameworks include:

- ASHRAE Standards 55 (Thermal Comfort), 62.1 (Ventilation), and 62.2: Published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, these are globally referenced performance standards.

- ISO 7730 and EN 16798: European standards for thermal comfort and indoor environment criteria, referenced in the EU Energy Performance of Buildings Directive.
- WHO Guidelines for Indoor Air Quality (2010, 2021): Provide evidence-based concentration limits for key pollutants including PM2.5, NO_2, ozone, formaldehyde, and radon.
- EU Directive 2010/31/EU and 2018/844/EU (EPBD): Require member states to implement minimum energy performance requirements, with provisions for indoor environment quality.
- National Building Codes: Jurisdiction-specific requirements for ventilation, acoustic insulation, and lighting in different building types.

1.8 Stakeholder perspectives

IEQ management involves a complex web of stakeholders, each with distinct priorities, decision-making authority, and information needs. Architects and engineers make IEQ-affecting decisions during design and construction. Building owners and facility managers control operational parameters. Employers and institutional administrators influence occupant behavior and expectations. Tenants and individual occupants experience IEQ outcomes directly. Public health authorities and regulators set minimum standards. Understanding these stakeholder dynamics is essential for effective IEQ improvement strategies.

1.9 Structure of this course book

This course book is organized into twelve chapters. Following this introduction, Chapter 2 addresses thermal comfort in depth, examining biophysical models, international standards, adaptive approaches, and case studies from diverse building types. Chapters 3, 4, and 5 address indoor air quality, lighting and visual comfort, and acoustic comfort respectively, following a common structure: theoretical foundations, governing standards, measurement and monitoring, design and operational strategies, and illustrative case studies.

Chapter 6 examines the psychological and behavioral dimensions of IEQ, integrating environmental psychology with building science. Chapter 7 provides a comprehensive review of measurement technologies, from traditional instruments to emerging IoT-based sensor networks. Chapter 8 analyses the treatment of IEQ within major green building certification systems. Chapters 9 and 10 address design strategies and real-world applications through extended case studies. Chapter 11 reviews future trends, including artificial intelligence, digital twins, and personalized environmental control. Chapter 12 synthesizes key insights and identifies priority areas for future research and practice.

Chapter 1 summary

This chapter has established the conceptual and historical foundations of Indoor Environmental Quality. IEQ is a multidimensional construct encompassing thermal, air quality, luminous, and acoustic conditions, each of which influences occupant health, comfort, and productivity through distinct physiological and psychological pathways. The built environment is the primary exposure setting for most of the human lifespan, making IEQ a public health priority of the first order. The economic case for healthy buildings is robust: the cost of poor IEQ – in absenteeism, presenteeism, and reduced cognitive performance – dwarfs the cost of the interventions required to achieve high standards. A clear regulatory and certification framework exists to guide assessment and improvement, though significant gaps remain in implementation and enforcement.

Review Questions

1. Distinguish between Indoor Air Quality (IAQ) and Indoor Environmental Quality (IEQ). Why is the broader IEQ framework preferred in contemporary research?

2. What historical events precipitated the emergence of 'sick building syndrome' as a recognized phenomenon? What lessons can be drawn for contemporary building design?

3. Critically evaluate the economic arguments for investing in IEQ improvements. What are the key assumptions and uncertainties in the available evidence?

4. Compare and contrast the four main IEQ assessment methodologies. Under what circumstances would you recommend a combined approach?

5. Select one of the theoretical frameworks presented in Section 1.5 and explain how it could be applied to analyze the IEQ challenges of a specific building type of your choice.

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Chapter 2: Thermal comfort

Learning Objectives

1. Explain the physiological basis of human thermoregulation and its relationship to thermal comfort.
2. Apply the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) models to realistic scenarios.
3. Critically evaluate the adaptive thermal comfort model and its applicability to naturally ventilated buildings.
4. Interpret and apply key thermal comfort standards (ASHRAE 55, ISO 7730, EN 16798).
5. Design thermal environments that satisfy the needs of diverse occupant populations, including vulnerable groups.
6. Analyze thermal comfort challenges in case studies spanning office, school, and hospital settings.

2.1 Fundamentals of human thermoregulation

The human body is a homeothermic organism that maintains core temperature within a narrow range of approximately 36.5-37.5°C to sustain normal physiological function. This thermal stability is achieved through a continuous and dynamic balance between metabolic heat generation and heat loss to the environment. The hypothalamus acts as the central thermostat, integrating signals from peripheral skin thermoreceptors and core temperature sensors to modulate effector responses including shivering, piloerection, vasoconstriction, vasodilation, and sweating.

Heat exchange between the body and its environment occurs through four principal mechanisms – radiation, convection, evaporation, and conduction (see Table 2.1) – governed by the operative temperature, mean radiant temperature, air velocity, and vapor pressure gradient respectively. Thermal comfort is defined by ASHRAE (2017) as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." This definition acknowledges that comfort is ultimately a subjective psychological state, even as its physiological underpinnings are well characterized.

Table 2.1. The four heat exchange mechanisms, their governing equations, and key determining variables

Mechanism	Process	Formula	Key variables
Radiation (R)	Electromagnetic energy exchange between body surface and surrounding surfaces	R = f_cl * epsilon * sigma * (T_sk^4 - T_mrt^4)	Skin temperature, means radiant temperature
Convection (C)	Heat transfers to air flowing over skin surface	C = f_cl * h_c * (T_sk - T_a)	Air temperature, air velocity, clothing factor
Evaporation (E)	Latent heat loss through perspiration and respiration	E = w * h_e * (p_sk - p_a)	Skin wittedness, vapor pressure gradient
Conduction (K)	Direct heat transfer to contacted surfaces	K = h_k * (T_sk - T_surface)	Contact area, conductivity, surface temperature

The gap between thermal neutrality (zero net heat flux) and thermal comfort is bridged by psychological factors including expectations, perceived control, and contextual adaptation.

2.2 The PMV-PPD model

2.2.1 Theoretical development

Povl Ole Fanger's Predicted Mean Vote (PMV) model, developed at the Technical University of Denmark in the 1960s and published in his seminal monograph 'Thermal Comfort' (1970), remains the dominant analytical framework for thermal comfort assessment in mechanically conditioned buildings. The model integrates the six primary thermal comfort variables into a single thermal sensation scale ranging from -3 (cold) to +3 (hot), with 0 representing neutrality.

The six variables are:

- Air temperature (T_a, in °C)
- Mean radiant temperature (T_{mrt}, in °C)
- Relative air velocity (v_a, in m/s)
- Relative humidity (RH, %)
- Metabolic rate (M, in W/m^2 or met, where 1 met = 58.2 W/m^2)
- Clothing insulation (I_{cl}, in clo, where 1 clo = 0.155 m^2K/W)

2.2.2 PMV equation

The PMV is derived from a complex heat balance equation. The simplified form, as presented in ISO 7730:2005, is:

$$PMV = (0.303 * \exp(-0.036 * M) + 0.028) * L$$

where L is the thermal load on the body (the difference between internal heat production and heat loss to the actual environment for a person hypothetically at skin temperature and sweat rate exactly as required for comfort at the actual activity level).

The Predicted Percentage Dissatisfied (PPD) is derived from PMV using the empirical relationship:

$$PPD = 100 - 95 * \exp(-(0.03353 * PMV^4 + 0.2179 * PMV^2))$$

This equation predicts that even at perfect thermal neutrality (PMV = 0), approximately 5% of a standard population will express dissatisfaction with the thermal environment theoretical minimum that has been confirmed empirically. ISO 7730 defines the recommended operative temperature range for Category B environments (corresponding to not more than 10% dissatisfied) as 20-24°C in winter and 23-26°C in summer, with relative humidity between 30% and 70%.

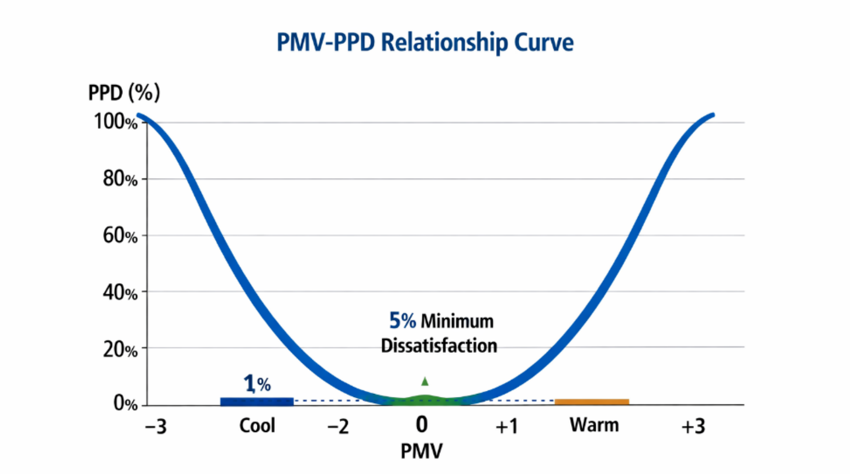

Figure 2.1. The PMV-PPD relationship, demonstrating the non-linear increase in predicted dissatisfaction with deviation from thermal neutrality.

2.2.3 Limitations and criticisms of the PMV model

Despite its widespread adoption, the PMV model has attracted substantial criticism. De Dear and Brager (2002) demonstrated that the model systematically underestimates comfort in naturally ventilated buildings, particularly in warm climates, a finding that motivated the development of the adaptive comfort model (Section 2.3). Humphreys and Nicol (2002) showed that the model's predictive accuracy decreases as thermal conditions move away from the neutral range. Yao et al. (2009) demonstrated that the model performs poorly for populations with different physiological characteristics, dietary patterns, and cultural thermal habits compared with Fanger's original Danish subjects.

More fundamental criticisms highlight that PMV was developed under steady-state laboratory conditions, whereas real occupants experience dynamic, non-uniform thermal environments. Transient exposure, asymmetric radiation, local drafts, and contact with warm or cool surfaces all influence comfort in ways that the PMV model does not capture. Standards such as ASHRAE 55 include supplementary criteria (local thermal discomfort criteria) to address some of these limitations.

2.3 Adaptive thermal comfort model

The adaptive thermal comfort model emerged from field studies conducted across diverse climatic regions and building types in the 1990s. The fundamental premise is that occupants of naturally ventilated buildings actively adapt to their thermal environments through behavioral adjustments (clothing, activity, window operation, fan use), physiological acclimatization, and psychological adjustment of expectations and preferences (de Dear & Brager, 1998).

The ASHRAE 55:2017 adaptive comfort model establishes an acceptable range of operative temperatures as a function of the prevailing mean outdoor temperature (Pout). The acceptable operative temperature range for 80% acceptability is:

T_upper = 0.31 * Pout + 21.3   (80% acceptability upper limit)

T_lower = 0.31 * Pout + 15.3   (80% acceptability lower limit)

where Pout is the prevailing mean outdoor air temperature (arithmetic average of the mean daily temperatures for the preceding 30 days). This model applies to naturally ventilated spaces where occupants have direct control over operable windows and where outdoor temperatures are between 10°C and 33.5°C.

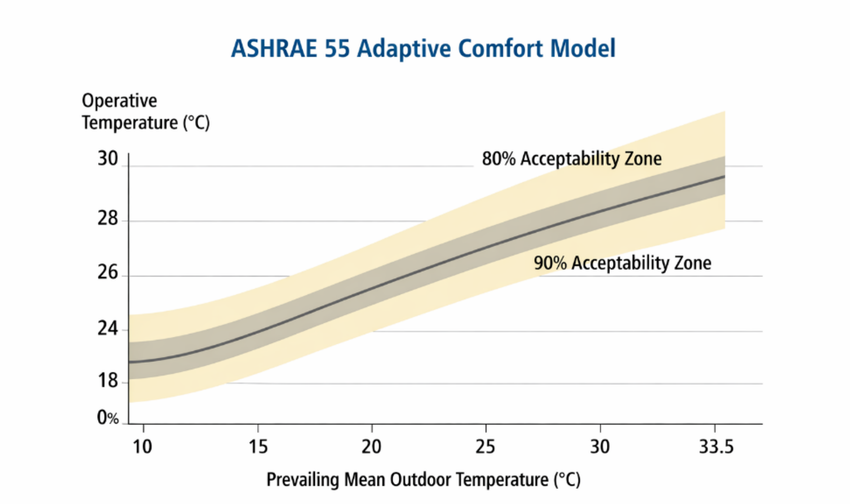

Figure 2.2. ASHRAE 55 adaptive comfort model: acceptable operative temperature ranges as a function of prevailing mean outdoor temperature.

EN 16798-1:2019 presents a parallel adaptive model, calibrated to European building stock and climate data, defining three indoor environment categories (I: exceptional, II: normal, III: moderate) with progressively wider acceptable temperature bands. The model applies when occupants have direct access to operable windows and when outdoor temperatures lie between 10 °C and 33.5 °C.

2.4 Local thermal discomfort criteria

Even when the overall thermal environment satisfies PMV-based criteria, localized thermal conditions can cause discomfort and impair performance. ASHRAE 55 and ISO 7730 specify criteria for four types of local thermal discomfort (see Table 2.2).

Table 2.2. Local thermal discomfort criteria as specified in ASHRAE 55 and ISO 7730 for Category B environments.

Discomfort Type	Cause	Criterion (Category B)	Measurement Method
Draft Risk	Air velocity fluctuations at head, neck, ankles	DR < 20% (using Draft Rating model)	Omnidirectional anemometer at ankle, neck, and head height
Vertical Air Temperature Difference	Temperature stratification between head and ankles	< 3°C between 0.1 m and 1.1 m (seated)	Temperature sensors at 0.1, 0.6, 1.1, 1.7 m
Warm/Cool Floor	Floor surface temperature extremes	Floor T: 19-29°C; comfort zone 21-28°C	Floor surface thermometer

Discomfort Type	Cause	Criterion (Category B)	Measurement Method
Radiant Asymmetry	Uneven radiant environment (warm ceiling, cold window)	Warm ceiling: < 5°C asymmetry; Cold wall: < 10°C	Radiant temperature asymmetry meter

2.5 Vulnerable populations and thermal comfort

Standard thermal comfort models are developed for a 'standard' adult, typically male, performing sedentary office work in temperate climates. This assumption systematically underserves vulnerable populations whose physiological characteristics and needs deviate from this norm.

2.5.1 Older adults

Thermoregulatory capacity declines significantly with age. Reduced sweat gland function, diminished peripheral vasoconstriction, lower basal metabolic rate, and impaired thermos-sensory perception all contribute to greater vulnerability to heat and cold stress in older adults. Studies consistently find that elderly occupants prefer higher operative temperatures (1-2°C above standard recommendations) and have narrower comfort zones (Schellen et al., 2010). This has significant implications for the thermal design of residential care facilities and sheltered housing.

2.5.2 Gender differences

Research by Karjalainen (2012) and others has documented systematic gender differences in thermal preference, with women tending to prefer slightly warmer temperatures than men (approximately 0.5-1.0°C higher optimal temperature). These differences are attributed to lower metabolic rate, different body composition, and hormonal factors. The practical implication is that gender-neutral settings in shared office environments will always produce some degree of thermal dissatisfaction in at least a portion of the workforce.

2.5.3 Children

Schoolchildren have higher surface-area-to-mass ratios and different thermoregulatory responses compared with adults. Wargocki and Wyon (2007) demonstrated significant effects of classroom temperature on children's learning speed and accuracy, with performance deteriorating above 22-23°C. The design of school buildings must balance thermal comfort with natural ventilation requirements, a challenge particularly acute in retrofit contexts.

2.5.4 Hospital patients and postpartum women

Hospitalized patients represent a particularly challenging category. Patient disease impacts thermo-physiology, thermal sensation, metabolism, and hemodynamic status, making their thermal perception different from that of the healthy population (Alotaibi et al., 2020). Standards based on healthy populations are therefore insufficient to predict or meet patient thermal needs – a finding illustrated by one of the case studies.

2.6 Thermal comfort measurement and monitoring

Field assessment of thermal comfort requires the measurement of all six comfort variables, either directly or through calculation. Standard instruments include:

- Globe thermometer: measures mean radiant temperature (Tmrt). The globe temperature (Tg) is measured by a sensor at the center of a matte black sphere (typically 150mm diameter); Tmrt is calculated from Tg, Ta, and air velocity.
- Omnidirectional hot-wire anemometer: measures air velocity with sufficient sensitivity to detect the low velocities (0.05-0.5 m/s) typical of occupied indoor spaces.
- Platinum resistance thermometer (PRT) or thermocouple: measures dry-bulb air temperature with high accuracy (±0.1°C).
- Capacitive humidity sensor: measures relative humidity.
- ASHRAE 55 Comfort Questionnaire: standardized instrument for subjective thermal comfort assessment using the ASHRAE scale (-3 to +3) and the Bedford scale.

Continuous thermal comfort monitoring in smart buildings typically employs lower-cost sensor packages that measure temperature and humidity, with operative temperature estimated through empirical corrections where direct radiant measurement is impractical. Emerging technologies include wearable physiological sensors that estimate thermal comfort from skin temperature, heart rate variability, and electrodermal activity.

2.7 Case studies

Case Study 2.1: The Powerhouse Kjorbo, Sandvika, Norway

Building Type: Retrofitted office building (energy-positive, passive house standard)

Location: Sandvika, Norway (latitude 59.9°N)

Completion: 2014 (retrofit of 1980s office building)

Designers: Snohetta / Asplan Viak

IEQ Challenge: Achieving thermal comfort in a highly insulated, airtight envelope in a continental climate with large seasonal temperature variations.

The Powerhouse Kjorbo presented a complex thermal comfort challenge. The passive house-level insulation and airtightness produced excellent thermal stability but created risks of overheating in summer (due to reduced thermal mass effect and high solar gains through enlarged window areas) and of perceived stuffiness in winter (due to very low air change rates from the MVHR system).

Thermal comfort measurements conducted by SINTEF Building and Infrastructure in 2015-2016 found mean PMV values of -0.1 to +0.3 throughout the year, with PPD typically below 10%. However, 22% of occupants reported dissatisfaction with thermal conditions in summer, concentrated in south-facing perimeter zones where operative temperatures reached 26-28°C on warm days. This was addressed through external solar shading (automated venetian blinds) and night-time natural ventilation through automated facade openings.

The adaptive comfort approach proved more predictive of occupant satisfaction than the PMV model: occupants who could open windows and adjust clothing were significantly more satisfied than those in sealed, mechanically controlled zones, even at equivalent measured thermal conditions.

Key Lessons: (1) Passive house standard buildings require careful attention to summer thermal comfort; (2) Occupant control over the thermal environment significantly enhances satisfaction independently of measured conditions; (3) The adaptive comfort model better predicts outcomes in mixed-mode buildings than PMV alone.

Case Study 2.2: Maternity Hospital, Cluj-Napoca, RO (Rus et. Al)

Building Type: Public tertiary-level maternity hospital — rooming-in department

Ward structure: 7 rooming-in wards; 3 four-bed rooms (37 m²) and 4 two-bed rooms (15.5 m²); mothers and newborns accommodated together

Location: Cluj-Napoca, Romania (Köppen–Geiger: Dfb, hemi-boreal continental climate)

Assessment Period: Summer: August 2019 (mean outdoor Ta = 23.6 °C); Winter: January 2020 (mean outdoor Ta = −2.9 °C).

During summer, the mean air temperature (27.89 °C) exceeded the upper limit of 26 °C specified by both the Romanian national standard NP-015 and ASHRAE 170. Even the minimum recorded value (26.4 °C) exceeded the upper threshold. In winter, the mean air temperature (25.91°C) complied with standards, though individual wards exceeded 26 °C on some days. Relative humidity complied with standards on average in both seasons but exceeded the 60% upper limit in some summer wards and fell below the 30% lower limit in some winter wards. Air velocity was constant at 0.11 m/s across all measurements, within the 0.15 m/s limit.

A core finding of this study is a statistically significant discrepancy between the PMV predicted by Fanger's model and the actual mean vote (TSV) of patients, in both seasons ($p < 0.001$ in both cases). In summer, PMV = 0.61 while TSV = 2.08; in winter, PMV = −0.25 while TSV = 1.36. This systematic underestimation of warmth by the PMV model indicates that the model's personal parameters — particularly metabolic rate — do not adequately represent postpartum women.

Given a 10% tolerance, the authors propose that a metabolic rate of 2.0 met should be adopted in thermal comfort standards for postpartum patients — double the current assumption. This is a significant practical recommendation that would require materially different HVAC design conditions for maternity wards.

Key lesson: (1) The PMV model is not universally applicable: it was calibrated on healthy populations and systematically underestimates warmth for postpartum patients, whose metabolic rates are elevated by lactation to approximately 2.0 met — double the standard assumption for seated adults. (2) Vulnerable populations (hospitalized patients, pregnant or postpartum women, elderly occupants) require tailored thermal comfort standards; applying generic office or residential standards to healthcare settings is scientifically unjustified. (3) The seasonal dimension matters: summer conditions posed substantially greater comfort problems than winter, driven by the absence of air conditioning in the historic hospital building. Seasonal climate analysis should be a mandatory component of healthcare building thermal comfort assessment. (4) Age and BMI are independent modifiers of thermal sensation: younger and normal-weight patients demonstrate better thermoregulatory adaptation, reinforcing the case for age- and BMI-stratified thermal comfort assessment in clinical settings.

Case Study 2.3: The Powerhouse Kjorbo, Sandvika, Norway

Building Type: Retrofitted office building (energy-positive, passive house standard)

Location: Sandvika, Norway (latitude 59.9°N)

Completion: 2014 (retrofit of 1980s office building)

Designers: Snohetta / Asplan Viak

IEQ Challenge: Achieving thermal comfort in a highly insulated, airtight envelope in a continental climate with large seasonal temperature variations.

The Powerhouse Kjorbo presented a complex thermal comfort challenge. The passive house-level insulation and airtightness produced excellent thermal stability but created risks of overheating in summer (due to reduced thermal mass effect and high solar gains through enlarged window areas) and of perceived stuffiness in winter (due to very low air change rates from the MVHR system).

Thermal comfort measurements conducted by SINTEF Building and Infrastructure in 2015-2016 found mean PMV values of -0.1 to +0.3 throughout the year, with PPD typically below 10%. However, 22% of occupants reported dissatisfaction with thermal conditions in summer, concentrated in south-facing perimeter zones where operative temperatures reached 26-28°C on warm days. This was addressed through external solar shading (automated venetian blinds) and night-time natural ventilation through automated facade openings.

The adaptive comfort approach proved more predictive of occupant satisfaction than the PMV model: occupants who could open windows and adjust clothing were significantly more satisfied than those in sealed, mechanically controlled zones, even at equivalent measured thermal conditions.

Key Lessons: (1) Passive house standard buildings require careful attention to summer thermal comfort; (2) Occupant control over the thermal environment significantly enhances satisfaction independently of measured conditions; (3) The adaptive comfort model better predicts outcomes in mixed-mode buildings than PMV alone.

Case Study 2.4: Thermal comfort assessment under pandemic safety measures, Cluj-Napoca, RO (Rus et al.)

Building Type: Two classrooms in the Faculty of Building Services Engineering, Technical University of Cluj-Napoca, Romania

Climate: Köppen–Geiger Dfb (hemi-boreal continental): cold winters (mean January Ta well below −3 °C); warm summers (warmest month mean < 22 °C)

Study 1 (no masks): January 2020; Classroom A (52 seats, 126 m^2, 504 m^3); 48 students during written examinations; 24 per session

Study 2 (with masks): January 2022 (fifth COVID-19 wave); Classroom B (300 seats, 252 m^2, 1134 m^3; social distancing); 129 students

Both classrooms complied with thermal comfort standards (PMV −0.5 to +0.5; PPD < 10%). Relative humidity in Classroom B (28.37%) was slightly below the 30% recommended lower limit, though most masked students rated it as "neutral." The outdoor conditions were very similar in both years, ensuring that seasonal variation did not confound the comparison.

Masked students experienced thermal neutrality at a significantly lower operative temperature (23.52 °C) than predicted by PMV (25.04 °C). The Wilcoxon non-parametric test confirmed significant differences between PMV and TSV in both conditions: p < 0.001 (no masks) and p = 0.012 (with masks), confirming that PMV underestimates thermal sensation in exam conditions regardless of mask use.

The finding that masked students were thermally neutral at ~23.5 °C (compared with the ~24.3 °C without masks) implies that classroom heating setpoints could be reduced by approximately 1 °C when masks are worn, without reducing thermal comfort. This translates to a measurable, cost-free energy saving achievable simply by adjusting building management system setpoints in periods when masks are required.

Key Lessons: (1) Wearing face masks shifts students' neutral operative temperature downward by approximately 1.5 °C relative to the PMV-predicted neutral point — masks effectively warm the facial microclimate, making the ambient environment feel cooler relative to unmasked conditions; (2) PMV underestimates thermal sensation during examination conditions regardless of mask use, confirming that the model does not capture the combined physiological effects of cognitive stress and face covering; (3) There is a concrete energy saving opportunity: reducing heating setpoints by 1 °C when masks are worn could achieve 5–7.5% heating energy reduction without degrading student thermal comfort — an example of how IEQ research can directly inform building energy management strategies.

Chapter 2 summary

This chapter has presented the theoretical foundations, analytical models, and practical applications of thermal comfort science. The PMV-PPD model, despite its limitations, provides the fundamental analytical framework for the design and assessment of mechanically conditioned environments. The adaptive comfort model complements this by accounting for the psychological and behavioral dimensions of thermal experience in naturally ventilated buildings. Local thermal discomfort criteria address the non-uniformities of real thermal environments that the global PMV metric overlooks. The case studies illustrate the challenges of achieving universal thermal comfort in buildings with diverse occupant populations and complex functional requirements.

Review Questions

1. A sedentary office worker (1.2 met) wearing standard office clothing (1.0 clo) is exposed to an environment with Ta = 22°C, Tmrt = 24°C, va = 0.15 m/s, and RH = 50%. Using the PMV model concepts, predict whether this person is likely to be thermally comfortable and identify the most significant thermal comfort variable in this scenario.

2. A school classroom in a temperate climate is naturally ventilated. The outdoor temperature is 28°C and the classroom temperature rises to 27°C. Using the EN 16798-1 adaptive comfort framework, determine whether this temperature is within the acceptable range for Category II.

3. Outline the design strategies you would employ to minimize local thermal discomfort in a large open-plan office with full-height south-facing glazing.

4. Critically evaluate the argument that 'personal comfort systems' (individual desk fans, heated seats, personal heaters) represent a superior approach to thermal comfort management compared with centralized HVAC systems.

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Chapter 3: Indoor Air Quality

Learning Objectives

1. Identify and classify the principal categories of indoor air pollutants and their sources.
2. Apply mass balance ventilation equations to determine minimum outdoor air supply rates.
3. Evaluate the health effects of key pollutants: CO_2, PM2.5, VOCs, NO_2, radon, and bioaerosols.
4. Compare filtration technologies and their effectiveness for different particle sizes and chemical species.
5. Design ventilation strategies appropriate for residential, office, school, and healthcare settings.
6. Interpret WHO Indoor Air Quality Guidelines and major regulatory frameworks.

3.1 The chemistry of indoor air

The chemical composition of indoor air is a complex and dynamic mixture that reflects contributions from outdoor sources, occupant activities, building materials, HVAC systems, and biological processes. Indoor air often contains higher concentrations of many pollutants than outdoor air, a counterintuitive finding that reflects the concentration effects of limited ventilation and the proliferation of synthetic materials in modern buildings (WHO, 2010).

Indoor pollutants are conventionally classified according to their physical state and chemical nature and are presented in Table 3.1.

Table 3.1. Classification of indoor air pollutants, sources, and key guideline values.

Pollutant Category	Key Compounds	Primary Indoor Sources	WHO Guideline / Limit
Inorganic gases	CO_2, CO, NO, NO_2, SO_2, O_3	Combustion appliances, traffic infiltration, HVAC	CO_2 <1000 ppm (ASHRAE); CO <10 mg/m^3 (24h WHO)
Volatile Organic Compounds (VOCs)	Formaldehyde, benzene, toluene, limonene, acetaldehyde	Building materials, furniture, cleaning products, personal care	Formaldehyde <0.1 mg/m^3 (WHO); TVOC <300 μg/m^3

Pollutant Category	Key Compounds	Primary Indoor Sources	WHO Guideline / Limit
Semi-volatile Organic Compounds (SVOCs)	Phthalates, PCBs, flame retardants, PAHs	Plasticizers, floor coverings, electronics, combustion	Compound-specific guidelines
Particulate Matter (PM)	PM10, PM2.5, PM1, ultrafine particles (UFP)	Cooking, candles, tobacco smoke, printers, re-suspension	PM2.5 <15 µg/m^3 (24h WHO 2021); PM2.5 <5 µg/m^3 (annual)
Biological agents	Bacteria, viruses, fungi, mite allergens, pet dander, pollen	Occupants, HVAC systems, building envelope moisture	No universal guideline; risk-based approach
Radon	Radon-222 (222Rn)	Soil infiltration through foundation, building materials	WHO reference level 100 Bq/m^3; IARC Group 1 carcinogen

3.2 Carbon dioxide as a proxy indicator

Carbon dioxide (CO_2) is not itself a significant health hazard at the concentrations typically encountered in occupied buildings (Satish et al., 2012 showed effects above 1000-1500 ppm, with more marked effects above 2500 ppm). Its importance in IEQ monitoring derives from its role as a proxy indicator for the adequacy of ventilation relative to occupancy: because humans are the primary source of CO_2 in non-industrial indoor settings, elevated CO_2 concentrations indicate that exhaled bioeffluents and other occupant-generated pollutants are also accumulating.

The steady-state CO_2 concentration in an occupied space can be estimated using the mass balance equation:

$$C\_indoor = C\_outdoor + (N * q\_p) / Q$$

where C_indoor is the indoor CO_2 concentration (ppm), C_outdoor is the outdoor CO_2 concentration (approximately 420 ppm in 2024), N is the number of occupants, q_p is the CO_2 generation rate per person (approximately 18,000 mL/h for sedentary adults), and Q is the outdoor air supply rate (m^3/h).

ASHRAE Standard 62.1 specifies a maximum design CO_2 concentration of 700 ppm above outdoor levels (i.e., approximately 1100-1120 ppm given current outdoor concentrations), though recent research suggests that cognitive performance benefits extend from targeting substantially lower indoor concentrations (Allen et al., 2016). The Harvard COGfx study found statistically significant improvements in cognitive function at 550 ppm compared with 945 ppm, with further improvements at 550 ppm with enhanced ventilation removing additional VOCs.

3.3 Particulate matter

3.3.1 Classification and health effects

Airborne particles are classified by aerodynamic diameter into coarse particles (PM10-2.5, 2.5-10 μm), fine particles (PM2.5, <2.5 μm), and ultrafine particles (UFP, <0.1 μm). The health significance of different size fractions is determined by their deposition sites within the respiratory tract: coarse particles deposit predominantly in the upper airways, PM2.5 penetrates to the alveoli, and UFP can translocate across the alveolar epithelium to reach the circulation. The International Agency for Research on Cancer (IARC) classifies outdoor PM as a Group 1 human carcinogen, with indoor PM having equivalent toxicological properties.

The WHO 2021 Air Quality Guidelines established revised PM2.5 guideline values significantly more stringent than previous recommendations: an annual mean guideline of 5 $\mu g/m^3$ and a 24-hour guideline of 15 $\mu g/m^3$. These values reflect the accumulating evidence linking PM2.5 exposure to cardiovascular disease, respiratory disease, lung cancer, and neurological outcomes including dementia (WHO, 2021).

3.3.2 Indoor sources and infiltration

Indoor PM sources include cooking (particularly frying and grilling, which can generate PM2.5 concentrations exceeding 1000 $\mu g/m^3$ in the breathing zone), candle and incense burning, tobacco and electronic cigarette smoke, laser printers, vacuum cleaning, and re-suspension of settled dust by occupant movement. In urban areas, infiltration of outdoor traffic-related PM typically dominates indoor concentrations in naturally ventilated buildings without filtration.

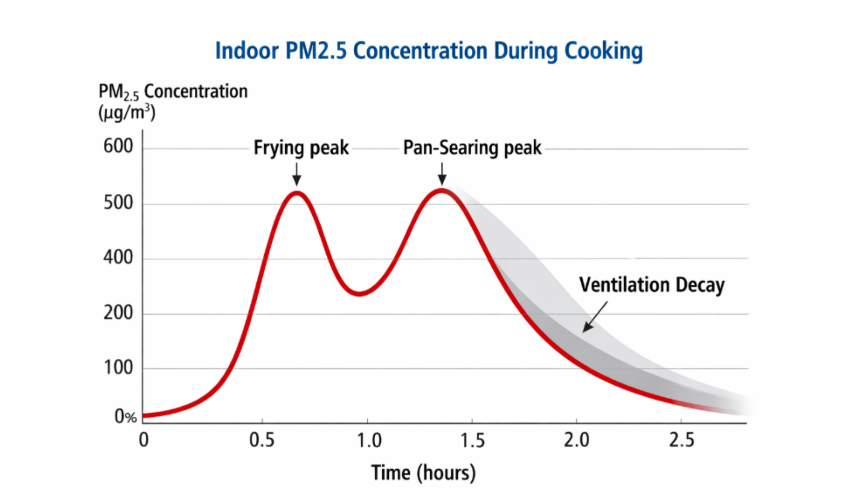

Figure 3.1. Typical indoor PM2.5 concentration profiles associated with cooking activities (schematic representation adapted based on Dennekamp et al., 2001).

3.4 Volatile organic compounds

3.4.1 Sources and emission profiles

Volatile organic compounds (VOCs) constitute a chemically diverse group of carbon-containing compounds with vapor pressures sufficient to exist as gases at room temperature. The WHO and European Commission define VOCs as organic compounds with boiling points in the range 50-260°C (WHO, 1989). The total VOC (TVOC) metric, while useful for general screening purposes, inadequately captures the toxicological significance of individual compounds, as health effects are compound specific.

Formaldehyde deserves special attention as the most toxicologically significant and widely occurring indoor VOC. It is classified as a Group 1 human carcinogen by IARC (IARC, 2012), associated with nasopharyngeal cancer and leukemia. Sources include urea-formaldehyde foam insulation, particleboard and MDF furniture (the largest single source in modern homes), carpet backings, and textiles with anti-wrinkle finishes. Formaldehyde emission rates decline exponentially over time, with the highest emissions occurring in the first 6-12 months after installation.

The key indoor VOC compounds are shown in Table 3.2.

Table 3.2. Key indoor VOC compounds: sources, health effects, and WHO guideline values.

VOC Compound	Key Sources	Health Effects	WHO Guideline
Formaldehyde (HCHO)	Particleboard, MDF, textiles, combustion	Carcinogen (nasopharyngeal, leukemia), respiratory irritant	0.1 mg/m^3 (30-min average)
Benzene (C6H6)	Tobacco smoke, garages, building materials	Carcinogen (leukemia), haematotoxin	No safe threshold; minimize
Naphthalene	Moth repellents, combustion, coal tar products	Carcinogen (nasal), hemolytic	0.01 mg/m3 (annual)
Trichloroethylene	Dry-cleaned clothing, metal degreasers, correction fluid	Carcinogen (kidney, liver, lymphoma)	No safe threshold

VOC Compound	Key Sources	Health Effects	WHO Guideline
Limonene	Citrus cleaning products, air fresheners	Ozone reaction products (secondary aerosols)	No formal guideline
Toluene	Paints, adhesives, gasoline	Neurological effects at high concentrations	No WHO indoor guideline

3.5 Ventilation principles and standards

3.5.1 The dilution ventilation principle

Ventilation is the primary engineering control for indoor air quality management. Its fundamental mechanism – dilution of pollutant-laden indoor air with cleaner outdoor air – is governed by the mass balance equation. For a well-mixed space (the standard assumption), the transient mass balance for any pollutant is:

$$V * dC/dt = S - Q*(C - C\_out) - k*V*C$$

where V is the room volume (m^3), C is the pollutant concentration (mg/m^3), S is the source strength (mg/h), Q is the outdoor air flow rate (m^3/h), C_out is the outdoor concentration, and k is the first-order decay rate (1/h) for reactive compounds.

At steady state ($dC/dt = 0$), this simplifies to:

$$C\_ss = (S + Q*C\_out) / (Q + k*V)$$

3.5.2 Ventilation effectiveness

Ventilation effectiveness describes how efficiently supplied fresh air is distributed through the occupied zone. It is characterized by two metrics: the air change efficiency (εa), which describes the evenness of air distribution, and the contaminant removal effectiveness (εC), which describes how efficiently contaminants are removed from the occupied zone. Supply-dominated mixing systems typically achieve $\varepsilon C = 1.0$, while displacement ventilation systems can achieve $\varepsilon C = 1.2$-2.0 due to the upward flow of warm, pollutant-laden air away from the occupied zone.

3.5.3 ASHRAE Standard 62.1 ventilation rates

ASHRAE Standard 62.1:2022 specifies minimum outdoor air supply rates using a two-component approach that accounts for both occupant-related loads and building-related loads:

$$Vbz = Rp * Pz + Ra * Az$$

where Vbz is the breathing zone outdoor airflow (L/s), Rp is the outdoor air rate per person (L/s/person), Pz is the zone population, Ra is the outdoor air rate per unit floor area (L/s/m^2), and Az is the zone floor area (m^2). Default values include Rp = 2.5 L/s/person and Ra = 0.3 L/s/m^2 for office spaces.

3.6 Filtration technology

Filtration is an essential complement to ventilation for particulate matter removal. Filters are characterized by their efficiency against particles of specified sizes, using rating systems including the EN 779/ISO 16890 standards (Europe) and the MERV rating system (North America). Table 3.3 presents the filter classification according to ISO 16890 standard.

Table 3.3. Filter classification according to ISO 16890 standard, with target particle sizes and typical applications

Filter Class (ISO 16890)	Target Particle Size	Efficiency (ePM2.5)	Typical Application
Coarse (G1-G4)	PM10 >10 µm	<50%	Pre-filter, dust removal in AHU
ePM10 (M5-M6)	PM10 2.5-10 µm	50-70%	General ventilation, first-stage filtration
ePM2.5 (F7-F9)	PM2.5 <2.5 µm	70-95%	Office, healthcare, schools - primary filter
ePM1 (H10-H14, HEPA)	PM1 <1 µm / UFP	>95% (HEPA >99.97%)	Hospitals, cleanrooms, immune-compromised settings
ULPA	UFP <0.12 µm	>99.999%	Pharmaceutical cleanrooms, electronics

For chemical pollutant removal, activated carbon adsorption is the primary technology, effective against VOCs, ozone, and some other gaseous pollutants. Photocatalytic oxidation (PCO), ultraviolet germicidal irradiation (UVGI), and bipolar ionization are emerging technologies for combined particulate and chemical treatment, though the evidence base for some of these is contested (particularly for bipolar ionization, which can generate ozone as a byproduct).

3.7 Mechanical ventilation with heat recovery

In energy-efficient buildings, mechanical ventilation with heat recovery (MVHR) systems have become standard practice, enabling high ventilation rates while recovering 80-95% of the heat from exhaust air. However, MVHR systems introduce specific IAQ risks if not properly designed, commissioned, and maintained:

- Filter bypass if filters are poorly maintained, damaged, or of insufficient class—allowing pollutants to penetrate to supply air.
- Microbial contamination of heat exchangers, particularly rotary wheel exchangers, if not designed to prevent cross-contamination.
- Frost protection bypasses that route cold outdoor air around the heat exchanger in extreme cold conditions, reducing ventilation effectiveness.
- Moisture carry-over from enthalpy exchangers if relative humidity is poorly controlled.

3.8 Case studies

Case Study 3.1: CO_2-Controlled Ventilation in Primary Schools, Copenhagen, Denmark

Building Type: 12 primary school classrooms, 1960s-1970s construction

Location: Copenhagen, Denmark

Intervention Year: 2016-2017

Research Team: Danish Building Research Institute (SBi) / Aalborg University

Background: Pre-intervention CO_2 monitoring revealed that 85% of classrooms exceeded 1000 ppm (the Danish guideline) for more than 50% of occupied hours during winter, with peak concentrations reaching 2800-3200 ppm in poorly ventilated rooms. Teachers reported frequent symptoms consistent with SBS (headaches, fatigue, difficulty concentrating) and standardized test performance analysis suggested a correlation between CO_2 concentration and arithmetic test scores.

Intervention: CO_2-controlled mechanical ventilation was installed in 6 of the 12 classrooms (the other 6 served as controls). The systems provided a minimum base rate of 2 L/s/person and increased automatically when CO_2 exceeded 700 ppm, up to a maximum of 7 L/s/person. HEPA-class filtration (F9) was installed to protect against outdoor particle infiltration from an adjacent main road.

Outcomes (12-month follow-up): Mean CO_2 in intervention classrooms fell from 1480 ppm to 680 ppm. Teachers' sick leave in intervention classrooms decreased by 24% compared with control classrooms. Children's scores on standardized arithmetic tests were 5.4% higher in intervention classrooms ($p < 0.05$). PM2.5 mean concentrations fell from 18 $\mu g/m^3$ to 4 $\mu g/m^3$, below the WHO annual guideline. Energy analysis found that the heat recovery system recovered approximately 82% of ventilation heat losses, resulting in a net heating energy increase of only 3.2 kWh/m^2/year despite the significant increase in outdoor air supply.

Key Lessons: CO_2-controlled demand-controlled ventilation (DCV) is highly effective in school settings. The academic performance and teacher wellbeing benefits substantially outweigh the marginal energy costs. HEPA filtration is essential in urban schools to protect against outdoor PM infiltration.

Case Study 3.2: Ultraclean Ventilation in a Teaching Hospital Operating Theatre, London

Building Type: New-built surgical center, 4 operating theatres

Location: London, UK

Completion: 2019

Challenge: Minimizing surgical site infection (SSI) risk through ventilation design.

Surgical site infections represent a major patient safety risk and economic burden, with costs per SSI episode estimated at GBP 5,000-25,000. The design of ventilation systems in operating theatres is therefore a clinical as well as an engineering priority.

The four operating theatres were designed to EN ISO 14644 Class 7 (clean room standards), using laminar flow unidirectional air supply units above the operating table, providing downward flows of HEPA-filtered air at 0.25-0.35 m/s velocity over the surgical site. This creates a protective zone of ultra-clean air (< 10 CFU/m^3) within the operating field while allowing higher particle concentrations in peripheral areas.

Continuous particle monitoring using optical particle counters confirmed sustained compliance with EN ISO 14644 Class 7 (< 352,000 particles/m^3 at 0.5 μm) in the critical zone. Microbiological settled plate sampling found <0.5 CFU/m^3 in the operative field versus 15-25 CFU/m^3 in the periphery.

The ventilation system maintains 25 air changes per hour of HEPA-filtered supply air (minimum), with positive pressure relative to adjacent corridors (+15 Pa) to prevent particulate infiltration. Operating theatre temperature is maintained at 18-22°C at 45-

65% RH, balancing patient thermal comfort with surgical team comfort and minimizing microbial growth conditions.

18-month post-occupancy SSI rate data showed a 34% reduction in SSI incidence compared with the pre-renovation theatres in the same hospital. Cost analysis found the annual saving from avoided SSI treatment exceeded the annualized capital cost of the enhanced ventilation system by a factor of 4.2.

Chapter 3 summary

This chapter examines the sources, health effects, and mitigation strategies for the principal categories of indoor air pollutants. The mass balance framework provides the conceptual and mathematical foundation for understanding pollutant concentration dynamics in ventilated spaces. CO_2 functions as the key proxy indicator for ventilation adequacy relative to occupancy. PM2.5 and formaldehyde represent the highest-priority pollutant targets in most non-industrial settings. Ventilation, filtration, and source control are complementary strategies that must be integrated in a systems approach to IAQ management. The case studies demonstrate measurable health, learning, and safety benefits from evidence-based IAQ interventions across school and healthcare settings.

Review Questions

1. A classroom of 30 students (average CO_2 generation rate 18 L/h each) has a volume of 200 m^3. If outdoor CO_2 is 420 ppm, what outdoor air supply rate (m^3/h) is needed to maintain CO_2 below 1000 ppm at steady state?

2. Distinguish between ventilation effectiveness and ventilation efficiency. How does displacement ventilation achieve superior contaminant removal compared with mixed-mode ventilation?

3. A building manager proposes replacing the F7 filters in the AHU with G4 filters to reduce energy costs. Critically evaluate this proposal from an IAQ perspective, quantifying the likely change in indoor PM2.5 concentrations.

4. What are the principal arguments for and against the use of TVOC as a measure of indoor air quality? What alternative measurement approach would you recommend?

5. Describe the pathway by which moisture infiltration into a building envelope can lead to adverse health effects for occupants. What design and operational measures can interrupt this causal chain?

References – Chapter 3

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Chapter 4: Lighting and visual comfort

Learning Objectives

1. Explain the photobiological mechanisms underlying visual comfort and circadian entrainment.
2. Apply quantitative lighting metrics (illuminance, luminance, UGR, VEEI, circadian metrics) to evaluate and specify lighting environments.
3. Distinguish between daylighting and artificial lighting strategies and their respective contributions to IEQ.
4. Design lighting environments that satisfy visual, circadian, and psychological comfort requirements for diverse occupant groups.
5. Evaluate lighting performance against EN 12464-1, WELL Standard, and CIBSE guidance.

4.1 The visual system and photobiological foundations

4.1.1 Photoreceptors and visual processing

The human visual system contains two classes of photoreceptors: rods (approximately 120 million per retina), which provide scotopic (low light) vision and detect achromatic contrast, and cones (approximately 6 million), concentrated in the fovea, which provide photopic (daylight) vision and color discrimination. The photopic luminous efficiency function V(λ) describes the spectral sensitivity of the cone system, with peak sensitivity at 555 nm (yellow green). This function underpins the definition of the lumen and other photometric quantities.

A third class of photoreceptive cell, the intrinsically photosensitive retinal ganglion cell (ipRGC), was discovered in 2002 by Berson et al. These cells contain the photopigment melanopsin, with peak sensitivity at approximately 480 nm (blue cyan). The ipRGCs project via the retina-hypothalamic tract to the suprachiasmatic nucleus (SCN) of the hypothalamus, the master circadian clock. This discovery established the neurobiological basis for the non-visual (circadian, neuroendocrine, and alerting) effects of light, which are now recognized as a critically important dimension of architectural lighting design.

4.1.2 The circadian system and architectural lighting

The human circadian system generates endogenous ~24-hour rhythms in physiology, behavior, and subjective state. Light is the primary zeitgeber (time-giver) that synchronizes the circadian clock to the solar day. The timing, intensity, duration, and spectral composition of light exposure all influence circadian entrainment. Specifically:

- Morning bright light (>1000 lux at eye, melanotic EDI >100 lux-equivalent) advances the circadian phase, promoting earlier sleep timing.
- Evening light suppresses melatonin secretion, delaying sleep onset and disrupting sleep quality.
- Blue-enriched light (high correlated color temperature, CCT > 5000K) has greater melanopsin stimulation and more potent circadian and alerting effects per unit of photopic illuminance than warm-white light (CCT < 3000K).
- Chronically insufficient daytime light exposure and excessive evening light exposure—common in office workers—contribute to circadian misalignment, sleep disruption, and associated health risks including metabolic

syndrome, depression, and cardiovascular disease (Figueiro et al., 2017).

4.2 Photometric and circadian metrics

Table 4.1. Key photometric and circadian metrics for architectural lighting assessment.

Metric	Symbol	Unit	Definition and Relevance
Illuminance	E	lux (lm/m2)	Luminous flux per unit area at a surface. The primary criterion for visual task performance in most standards.
Luminance	L	cd/m^2	Light emitted/reflected per unit area in a given direction. Determines perceived brightness and glare.
Unified Glare Rating	UGR	Dimensionless	Index of discomfort glare from luminaires. EN 12464-1 specifies maximum UGR for different tasks.

Metric	Symbol	Unit	Definition and Relevance
Daylight Factor	DF	% (ratio)	Ratio of indoor illuminance to simultaneous outdoor illuminance under overcast sky. Design tool for daylighting.
Correlated Color Temperature	CCT	Kelvin (K)	Appearance of light on warm-cool spectrum. Affects alerting, mood, and circadian response.
Color Rendering Index	Ra (CRI)	0-100 scale	Accuracy of color reproduction. Ra ≥ 80 required for most work environments.
Melanotic Equivalent Daylight Illuminance	Melanotic EDI	Lux (mel-lux)	Effective melanopsin-stimulating illuminance; key metric for circadian lighting design.
Spatial Daylight Autonomy	sDA300/50%	%	Fraction of floor area meeting 300 lux for at least 50% of occupied hours.

Metric	Symbol	Unit	Definition and Relevance
			LEED/WELL metric.

4.3 Lighting standards and recommended illuminance levels

EN 12464-1:2021 (Light and Lighting: Lighting of Workplaces) is the primary European standard for interior lighting design. It specifies maintained illuminance levels (Em), maximum UGR values, and minimum color rendering indices (see Table 4.2) for a comprehensive range of interior tasks and spaces.

Table 4.2. Selected maintained illuminance requirements from EN 12464-1:2021.

Space / Task Type	Em (lux)	UGR max	Ra min	Notes
General office work	500	19	80	On the working plane; with higher levels for demanding tasks
Drawing offices / CAD	750	16	80	Supplementary local lighting recommended
Classroom, lecture theatre	500	19	80	On the desk; blackboard 500 lux vertical

Space / Task Type	Em (lux)	UGR max	Ra min	Notes
Hospital ward (general)	100	19	80	Nighttime max 1 lux at bed to avoid sleep disruption
Hospital ward (examination)	1000	19	90	On examination surface; high CRI critical
Operating theatre	10,000-100,000	-	90	Surgical luminaire; color temperature 4000-5000K
Restaurant dining area	200	22	80	Warm white recommended for ambience
Library reading room	500	19	80	On reading surface; low UV to protect materials
Reception / entrance	300	22	80	Vertical illuminance is important for face recognition

4.4 Daylighting design

4.4.1 Benefits of daylighting

Natural daylight provides several distinct advantages over artificial light: its spectral quality closely matches the evolutionary light environment to which human physiology is adapted; it changes dynamically in intensity and color temperature through the day, supporting circadian entrainment; it provides high illuminance levels (typically 10,000-100,000 lux outdoors, 500-5000 lux indoors near windows) with relatively low energy input; and it affords visual connection to the outdoors, which has independently documented psychological benefits (Kaplan, 2001).

However, daylighting also introduces challenges: glare from direct sunlight or from bright sky, temporal and spatial variability requiring adaptive lighting controls, excessive solar heat gain (particularly problematic in summer), UV radiation that can damage materials and cause skin damage with prolonged exposure, and dependence on building orientation and geographic latitude.

4.4.2 Daylight factor method

The Daylight Factor (DF) is the most widely used metric for evaluating daylighting in the design stage. It is defined as:

$$DF = (Ei / Eo) * 100\%$$

where Ei is the indoor illuminance at a reference point (lux) and Eo is the simultaneous outdoor horizontal illuminance under an overcast sky (CIE standard overcast sky, 10,000-20,000 lux). A DF of 2% is generally considered the minimum for good daylit ambience; DF > 5% is considered well-daylit; DF > 10% risks overheating and glare.

4.4.3 Climate-based daylight modelling

Modern daylighting design has largely moved beyond the simple Daylight Factor method to climate-based daylight modelling (CBDM), which uses actual annual hourly climate data (via Perez sky model or measured TMY data) to predict dynamic illuminance distributions. Key CBDM metrics include:

- Spatial Daylight Autonomy (sDA300/50%): the percentage of floor area that receives at least 300 lux from daylight for at least 50% of occupied hours annually. LEED and WELL specify sDA ≥ 55% for partial credit and sDA ≥ 75% for full credit.
- Annual Sunlight Exposure (ASE1000/250h): the percentage of floor area that receives more than 1000 lux from direct sunlight for more than 250 occupied hours annually. High ASE values indicate glare risk and excessive solar heat gain. LEED specifies ASE ≤ 10%.
- Useful Daylight Illuminance (UDI): the proportion of occupied hours during which daylight illuminance falls in the useful range of 100-3000 lux (below 100 lux is considered insufficient; above 3000 lux risks glare).

4.5 Circadian lighting design

The WELL Building Standard (v2, Feature L07: Circadian Lighting Design) and the CIE Technical Report 218:2016 (Research Roadmap for Healthful Interior Lighting Applications) have established circadian-responsive lighting design as a professional design discipline. The core principle is to design lighting environments that deliver:

- High melanotic EDI (> 250 mel-lux equivalent) during morning and midday hours to support circadian phase advancement and daytime alertness.
- Low melanotic EDI (< 10 mel-lux) during the pre-sleep period (2-3 hours before habitual sleep time) to avoid melatonin suppression and sleep disruption.
- Dynamic CCT control to deliver blue-enriched (5000-6500K) light in morning hours and warm-white (2700-

3000K) in evening hours in residential and mixed-use environments.

This has driven the development of dynamic (tunable-white) LED luminaire systems capable of varying both CCT and light output in response to time-of-day schedules, daylight sensors, or occupancy patterns. These systems are now widely installed in healthcare environments (particularly intensive care units and dementia care settings), schools, and commercial offices.

4.6 Case studies

Case Study 4.1: Post-Occupancy Evaluation of Daylighting and Electric Lighting, Commercial Office, London

Building Type: 8-storey speculative commercial office building
Location: City of London, UK
Completion: 2018
Floor Plate: 1,850 m^2 (typical floor)
BREEAM Rating: Excellent

The building was designed with a high window-to-wall ratio (65%) on the north and south facades, with electrochromic glazing on south and west elevations to dynamically modulate solar transmission and glare. A daylight-responsive lighting control system (DALI-based dimming) was specified throughout.

Post-occupancy evaluation conducted 18 months after occupation found that sDA300/50% was 72% across the typical floor plate (LEED target: >75%). However, occupant survey using a validated visual comfort questionnaire found that 38% of workstations near the south facade reported frequent glare discomfort despite the electrochromic glazing. Lux measurement found that horizontal illuminance frequently exceeded 3000 lux on south-facing desks even with glazing in its maximum tinting state, with UGR values reaching 26-28 (significantly above the EN 12464-1 limit of 19).

Interventions included: repositioning workstations to run parallel rather than perpendicular to the facade, installing supplementary fabric light shelves at 1.5m height, and modifying the electrochromic control algorithm to respond more rapidly to high solar angles.

Post-intervention survey found glare dissatisfaction reduced from 38% to 12%, and absenteeism in the affected zone decreased by 8% in the following 12-month period. Lighting energy consumption was 31% below the BRUKL Part L2A notional building due to the daylight dimming system.

Case Study 4.2: Dynamic Circadian Lighting in a Dementia Care Unit, Netherlands

Building Type: 40-bed dementia care unit (new build)
Location: Eindhoven, Netherlands
Completion: 2017
Research Partner: Eindhoven University of Technology

Patients with dementia frequently experience disrupted circadian rhythms, manifesting as sundowning (increased agitation and confusion in late afternoon), disrupted sleep-wake cycles, and nocturnal wandering. The Circadian Stimulus (CS) framework developed by Figueiro et al. at the Lighting Research Center was applied to design a dynamic lighting system targeting CS > 0.3

during daytime hours (associated with melatonin suppression and circadian entrainment) and CS < 0.1 in the pre-sleep period.

The lighting system provided: bright, blue-enriched light (5000K, >1500 lux at eye level) in common areas from 08:00-14:00; intermediate warm-white light (3000K, 300-500 lux) from 14:00-17:00; and dim warm-white light (2700K, 50-100 lux) from 17:00 onwards. Individual bedrooms had separately controllable circadian lighting panels.

Randomized controlled study (n=40 patients, crossover design): patients under the circadian lighting protocol showed: 27% reduction in rest-activity rhythm fragmentation (actigraphy); 42% reduction in sundowning episodes (observed by behavioral ratings); 1.4-hour increase in nocturnal sleep duration (actigraphy); 31% reduction in hypnotic medication prescription.

Staff satisfaction with the new lighting was high (83% satisfied or very satisfied), with appreciation for the increased illuminance in clinical assessment areas and the reduction in challenging behaviors during evening care routines.

Chapter 4 summary

This chapter has examined the photobiological foundations of visual and non-visual effects of light, the quantitative metrics used to assess lighting environments, and the design strategies for both daylighting and electric lighting. The discovery of ipRGC-mediated non-visual effects has transformed architectural lighting from a purely visual discipline to one that must simultaneously address visibility, glare avoidance, circadian health, and psychological wellbeing. Climate-based daylight modelling provides analytical tools for dynamic daylighting assessment, while the WELL

Building Standard has formalized the requirements for circadian-responsive lighting in occupied buildings. The case studies demonstrate the breadth of application, from commercial office post-occupancy evaluation to clinical outcomes research in dementia care.

Review Questions

1. Explain why a light source with identical photopic illuminance (lux) values can have different circadian impacts. What metric would you use to compare circadian stimulation potential?

2. A north-facing office room in Berlin (52°N) has a Daylight Factor of 1.5% at the rear of the room. Using the sDA300/50% concept, predict whether this room is likely to meet the LEED minimum daylighting requirement. What design interventions could improve performance?

3. A hospital administrator proposes installing 6500K LED lighting throughout all wards to improve visual performance. Critically evaluate this proposal from a circadian lighting design perspective.

4. Explain the concept of Unified Glare Rating (UGR) and describe three design strategies that can be employed to achieve UGR ≤ 19 in an open-plan office.

5. Compare the Daylight Factor method and climate-based daylight modelling approaches. Under what circumstances would each method be the most appropriate design tool?

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Chapter 5: Acoustic comfort

Learning Objectives

1. Explain the psychoacoustic principles underlying acoustic comfort and speech intelligibility.
2. Apply acoustic metrics (SPL, RT60, STI, NR curves) to evaluate indoor acoustic environments.
3. Identify principal noise sources in buildings and the transmission pathways between them.
4. Design acoustic mitigation strategies appropriate for different building types.
5. Critically evaluate acoustic design standards and guidelines (ISO 3382, BB93, WHO Night Noise Guidelines).
6. Analyze acoustic design challenges in open-plan offices and healthcare environments through case studies.

5.1 Psychoacoustic foundations

Sound is a mechanical wave phenomenon involving periodic compression and rarefaction of the air medium. Human hearing spans a frequency range of approximately 20 Hz to 20,000 Hz, with peak sensitivity around 1000-4000 Hz as described by the equal-loudness contours (ISO 226:2003). The decibel (dB) scale is used to express sound pressure level (SPL) in terms of the ratio of measured sound pressure to the reference pressure of 20 μPa (the approximate threshold of hearing at 1000 Hz):

$$\text{SPL (dB)} = 20 * \log10 (p / p0)$$

where p is the root mean square sound pressure (Pa) and p0 = 20 μPa is the reference pressure. The A-weighting filter (dB(A)) approximates the frequency-dependent sensitivity of the human ear and is the standard metric for community noise assessment and most building acoustic applications.

Acoustic comfort is a multidimensional subjective construct that encompasses: the absence of unwanted sound (noise), the presence of wanted sound (speech intelligibility, music quality), and freedom from vibration. Unlike thermal comfort, acoustic comfort does not have a straightforward 'neutral' optimal point: what is comfort in a library (maximum quiet) is discomfort in a concert hall (insufficient reverberation and liveliness).

5.2 Key acoustic metrics

Table 5.1. Key acoustic metrics and their principal applications in building acoustics.

Metric	Symbol/Unit	Definition	Typical Application
Sound Pressure Level	SPL, dB(A)	Logarithmic measure of sound pressure relative to hearing threshold	Occupational exposure limits, ambient noise assessment
Reverberation Time	RT60 (T20/T30), seconds	Time for sound to decay 60 dB after source stops; measure of room acoustic 'dryness'	Room design for speech/music; EN ISO 3382-1/2

Metric	Symbol/Unit	Definition	Typical Application
Speech Transmission Index	STI, 0-1 scale	Objective measure of speech intelligibility; 0.75+ excellent, 0.60-0.75 good	Offices, classrooms, public address systems
Noise Rating Curve	NR number	Family of octave-band SPL curves; NR criterion determines acceptable ambient noise	Office: NR 35-40; bedroom: NR 25-30
Weighted Sound Reduction Index	Rw, dB	Airborne sound insulation of a partition; higher = better insulation	BUILDING Regulations compliance, partition design
Impact Sound Pressure Level	Ln,w, dB	Standardized impact sound transmission through floors; lower = better insulation	Building Regulations compliance, floor design
Distraction Distance	rD, meters	Distance at which intelligibility of speech falls below	Open-plan office acoustic design

Metric	Symbol/Unit	Definition	Typical Application
		discomfort threshold in open offices	

5.3 Health effects of indoor noise

The WHO (2018) Environmental Noise Guidelines for the European Region and the WHO Night Noise Guidelines (2009) provide the most comprehensive evidence review of health effects of environmental noise, with direct relevance to building acoustics. Key findings:

- Cardiovascular effects: Long-term exposure to noise levels above 53 dB(A) Lden (day-evening-night equivalent level) is associated with increased risk of ischemic heart disease. Night noise above 40 dB(A) Lnight is considered the target to avoid sleep disturbance and associated health effects.
- Sleep disruption: Noise is the primary environmental cause of sleep disruption, with effects beginning at Lnight > 40 dB(A) and progressing to include awakening, arousals, and changes in sleep architecture at higher levels.
- Cognitive impairment in children: Chronic aircraft noise exposure is associated with reading comprehension deficits of approximately 1-2 months' schooling per 5 dB(A) increase above 55 dB(A) (Stansfeld et al., 2005).
- Mental health: Long-term noise exposure is associated with increased risk of anxiety, depression, and diminished wellbeing (WHO, 2018).
- Productivity: Noise is consistently identified as the primary environmental barrier to concentration in open-plan offices.

> Kim and de Dear (2013) found that office workers' dissatisfaction with acoustic conditions is a stronger predictor of overall workplace dissatisfaction than any other IEQ parameter.

5.4 Noise sources and transmission pathways

5.4.1 Noise source classification

Indoor noise sources are classified as: (1) external sources penetrating via the building envelope (traffic, aircraft, rail, construction); (2) building services sources (HVAC equipment, lifts, plumbing); (3) occupant-generated sources (speech, movement, impact); and (4) process equipment (computers, printers, manufacturing equipment). Each category requires different mitigation strategies and is governed by different standards.

5.4.2 Sound transmission pathways

Sound transmission between adjacent spaces occurs via two principal pathways: airborne transmission (sound waves cause the partition to vibrate, re-radiating sound on the other side) and structure-borne transmission (vibration is transmitted through the building structure, bypassing the direct partition). Flanking transmission—the propagation of sound via indirect paths through junction elements such as floor-ceiling junctions, column penetrations, and service ducts—often limits the achieved field performance of acoustic partitions to levels significantly below laboratory measurements.

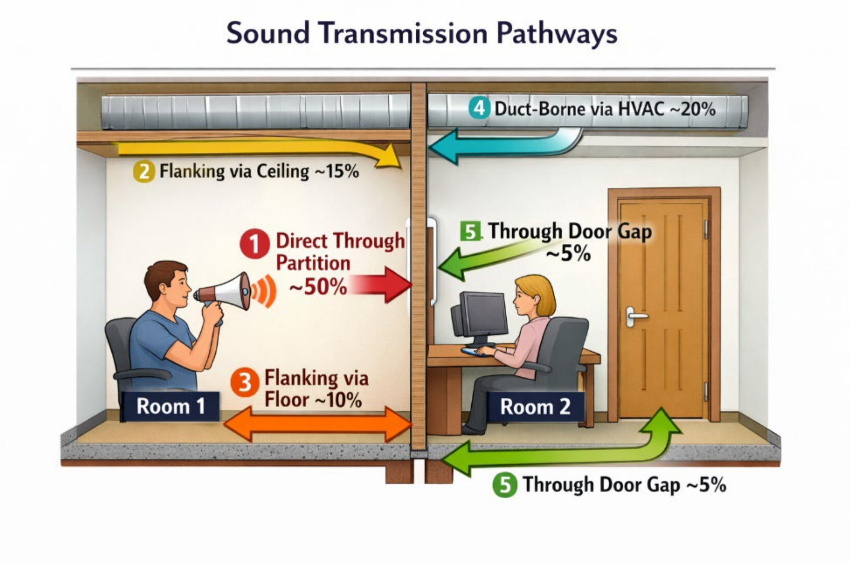

Figure 5.1. Principal sound transmission pathways between adjacent indoor spaces.

5.5 Room acoustics design

5.5.1 Reverberation time optimization

The Sabine equation provides the fundamental relationship between room acoustics parameters:

$$RT60 = 0.161 * V / A$$

where RT60 is the reverberation time (seconds), V is the room volume (m3), and A is the total sound absorption (m2, Sabins), equal to the sum of the products of each surface area and its absorption coefficient. The Eyring-Norris formula provides improved accuracy for highly absorptive rooms:

$$RT60 = -0.161 * V / (S * \ln(1 - alpha\_mean))$$

where S is the total surface area (m2) and alpha_mean is the mean absorption coefficient of all surfaces.

Recommended reverberation times vary widely between space types and are presented in Table 5.2.

Table 5.2. Recommended reverberation times for different building types.

Space Type	Recommended RT60 (seconds)	Primary Acoustic Function	Key Materials
Open-plan office	< 0.4 s	Speech privacy, reduced distraction	Suspended acoustic ceiling, carpet, acoustic panels
Cellular office (4-8 persons)	0.4-0.6 s	Speech clarity, reduced fatigue	Acoustic ceiling, soft furnishings
Classroom (unoccupied)	0.4-0.6 s	Speech intelligibility (BB93)	Acoustic ceiling tile, carpet, wall panels
Meeting room (≤10 persons)	0.4-0.6 s	Speech clarity, video conferencing	Acoustic ceiling, fabric wall panels
Lecture theatre (100+ persons)	0.6-1.0 s	Speech intelligibility at scale	Raked seating, acoustic treatment on rear and side walls

Space Type	Recommended RT60 (seconds)	Primary Acoustic Function	Key Materials
Concert hall (symphony)	1.8-2.2 s	Musical richness, envelopment	Diffusive surfaces, sound-reflecting canopy, limited absorption
Restaurant / café	0.6-1.0 s	Lively ambience, acceptable speech	Balanced hard and soft surfaces
Hospital ward	< 0.6 s	Speech intelligibility, reduced stress	Acoustic ceiling, vinyl flooring, soft furnishings

5.6 Open-plan office acoustic design

The open-plan office presents the most complex and contested acoustic design challenge in commercial architecture. The elimination of acoustic separation between workstations creates a fundamental conflict between the communication-enabling function of the open plan and the concentration-protecting function of acoustic privacy. Research consistently finds that audibility of colleagues' speech is the primary acoustic complaint in open offices, with over 60% of occupants in large open plans reporting that noise from colleagues interferes with their work (Kim & de Dear, 2013).

The acoustic design of open-plan offices requires an integrated 'ABCs' approach:

- Absorb: Maximize sound absorption to reduce reverberation time and limit sound propagation. High-absorption ceiling systems (NRC 0.85-0.95), carpet, and acoustic absorptive task screens are essential. Target RT60 < 0.4 seconds.
- Block: Provide acoustic barriers between workstations through full-height partitions in cellular zones, partial-height screens (minimum 1.5m from floor) between adjacent desks, and masking of low-partitioned zones from high-activity areas (print rooms, circulation).
- Cover: Electronic speech privacy (sound masking) systems add spectrally shaped broadband noise (typically pink noise shaped to the NC-35 to NC-40 curve) to the ambient sound field, raising the background noise floor to reduce the signal-to-noise ratio of overheard speech. Target: speech intelligibility index < 0.20 at 6-8 meter radius from source.

5.7 Case studies

Case Study 5.1: Acoustic Redesign of Open-Plan Office, Stockholm, Sweden

Building Type: 600 m^2 open-plan office, 65 workstations

Location: Stockholm, Sweden

Retrofit Year: 2019

Assessment Standard: ISO 3382-3 (Acoustics in Open-plan offices)

Pre-intervention acoustic assessment: RT60 = 0.82 seconds (highly reverberant for open plan); background noise level = 36 dB(A) (below NR 35, providing insufficient masking); Speech Transmission Index at 4 meters from a colleague = 0.65 (good intelligibility = high distraction); distraction distance (rD) = 11 meters (very large; most of the floor plate audible).

Occupant survey pre-intervention: 71% of staff reported frequent noise disturbance from colleagues' speech; 54% reported difficulty concentrating; self-reported productivity loss estimated at 8-12% per worker.

Interventions implemented: (1) Replacement of standard ceiling tiles (NRC 0.55) with high-absorption panels (NRC 0.95), reducing RT60 to 0.35 seconds; (2) Installation of floor-to-2.4m acoustically absorptive work pods for deep concentration tasks; (3) Addition of electronic sound masking system (pink noise, NC-38 level); (4) Repositioning of print/copy station to adjacent enclosed room; (5) Addition of acoustic planting screens at key locations.

Post-intervention assessment: RT60 = 0.34 s; background noise = 43 dB(A); STI at 4 meters = 0.38 (poor intelligibility = reduced distraction); rD = 5 meters (confined to immediate workstation vicinity). Occupant noise disturbance fell from 71% to 28%; self-reported concentration improved significantly; 6-month absenteeism data showed 11% reduction in short-term sick leave.

Case Study 5.2: New Primary School Design Meeting BB93, Bristol, UK

Building Type: New-build primary school, 420 pupils

Location: Bristol, UK

Completion: 2021

Standard: UK Building Bulletin 93 (BB93): Acoustic Design of Schools

BB93 specifies stringent acoustic performance standards for UK schools, reflecting the evidence that poor classroom acoustics disproportionately affects children with hearing impairment, English as an additional language, and attention deficit disorders. Key BB93 requirements: maximum ambient noise level 35 dB(A) (Leq) in unoccupied classrooms; maximum RT60 0.4-0.6 seconds in classrooms; minimum airborne sound insulation Rw 45 dB between classrooms.

Design challenges: The school site was located adjacent to a bus route generating external noise of 68 dB(A) on the facade. Internal layout required placing music rooms adjacent to standard classrooms.

Solutions: External noise mitigation through triple-glazed windows (Rw 44 dB), acoustically baffled natural ventilation intake to avoid sealed ventilation dependency, and a landscaping earth berm providing 6-8 dB additional facade attenuation. Internal: music rooms designed as acoustically isolated 'room within a room' construction with double-leaf walls, floating floors, and resilient ceiling mounts, achieving Rw 62 dB between music room and adjacent classroom.

Post-construction acoustic testing confirmed compliance with all BB93 criteria. Classroom unoccupied noise levels: 31 dB(A) (external-facing rooms), 27 dB(A) (internal rooms). RT60 in classrooms: 0.44-0.56 seconds (unoccupied). Speech Transmission Index in classrooms: 0.73-0.81 (good to excellent).

Teacher-reported outcomes (first academic year): 94% found classroom acoustics comfortable; SENCO (Special Educational Needs) staff reported marked improvement in attention and participation of hearing-impaired and EAL pupils compared with previous school building.

Chapter 5 summary

This chapter presents the psychoacoustic foundations, key metrics, health evidence, and design strategies for acoustic comfort in buildings. Noise is consistently identified as the most significant IEQ complaint in open-plan offices and one of the primary environmental barriers to sleep, cognitive performance, and cardiovascular health. The 'ABCs' framework (absorb, block, cover) provides a practical integrated approach to open-plan office acoustic design. Standards such as BB93 and ISO 3382-3 provide measurable acoustic performance targets that can guide design and post-occupancy evaluation.

Review Questions

1. A conference room has a volume of 150 m^3 and a current RT60 of 1.2 seconds. Using the Sabine equation, calculate the additional absorption area required to achieve a target RT60 of 0.6 seconds.

2. Explain why electronic sound masking systems can improve acoustic privacy in open-plan offices despite adding noise to the environment.

3. Compare the acoustic design requirements for a 30-person classroom and a 300-seat lecture theatre. Why do optimal acoustic environments differ, and what design strategies would you employ for each?

4. A developer proposes converting a 1960 office building into a residential development. Identify the primary acoustic risks and describe the investigation process you would undertake before providing design recommendations.
5. Critically evaluate the statement: 'The primary acoustic problem in modern workplaces is insufficient quiet, and the solution is to provide more cellular offices.' What evidence supports or challenges this view?

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Chapter 6: Psychological and behavioral aspects of IEQ

Learning Objectives

1. Explain key environmental psychology theories and their application to IEQ research.
2. Analyze how perceived control over the indoor environment influences comfort and wellbeing.
3. Evaluate the evidence for biophilic design as an IEQ and wellbeing strategy.
4. Describe the psychological dimensions of workplace environmental satisfaction.
5. Apply behavioral economics principles to promote pro-environmental occupant behavior.

6.1 Environmental psychology and IEQ

Environmental psychology examines the bidirectional relationships between human behavior, affect, and cognition on one hand, and the physical environment on the other. Its application to IEQ extends beyond the measurement of physical parameters to encompass the subjective experience of the indoor environment, the psychological needs that spaces must satisfy, and the behavioral responses that environmental conditions elicit (Steg et al., 2013). Three foundational theoretical frameworks are particularly relevant to IEQ.

6.1.1 Arousal theory

Arousal theory (Berlyne, 1960; Evans & Cohen, 1987) posits that environmental stimuli influence human arousal – a general state of physiological and psychological activation – which in turn affects performance and affect. The Yerkes-Dodson law describes an inverted-U relationship between arousal and performance: both under-stimulating (monotonous, uniform) and over-stimulating (noisy, thermally uncomfortable, visually complex) environments impair performance. Optimal IEQ, from an arousal perspective, provides moderate sensory stimulation with temporal variety.

6.1.2 Stress and coping framework

Lazarus and Folkman's (1984) transactional model of stress and coping provides a framework for understanding how environmental stressors – noise, heat, poor air quality – interact with individual appraisal processes and coping resources. Whether an environmental condition is experienced as stressful depends not only on its objective intensity but on the individual's cognitive appraisal of its controllability, predictability, and significance. This has important implications for IEQ management: identical physical conditions may be experienced as comfortable or stressful depending on whether the occupant feels able to exert control.

6.1.3 Biophilia hypothesis

Wilson's (1986) biophilia hypothesis proposes an innate human tendency to seek connection with nature and other living systems, rooted in evolutionary adaptation to natural environments. Kellert and Calabrese (2015) operationalized this concept into the practice of biophilic design, which seeks to integrate nature and natural processes into the built environment. Research evidence supports psychological and physiological benefits of biophilic elements including:

- Views of nature: Ulrich's (1984) landmark study found post-operative surgical patients with window views of trees had shorter hospital stays, less pain medication, and better nursing outcomes than those with views of a brick wall.

- Indoor plants: Meta-analyses (Bringslimark et al., 2009) find consistent associations between indoor plants and reduced stress, improved attention, and higher perceived air quality.
- Natural materials: Wood surfaces are associated with reduced sympathetic nervous system activation (lower skin conductance, heart rate) compared with steel or plastic surfaces at equivalent temperatures (Fell, 2010).
- Water features: Presence of water sounds and visual water features is associated with improved restoration from mental fatigue.

6.2 Perceived control and individual differences

The role of perceived control is one of the most robust findings in IEQ research. Leaman and Bordass (2007), in their analysis of the Probe (Post-occupancy Review of Buildings and their Engineering) database covering 64 UK office buildings, found that perceived control over the thermal, air, and lighting environment was consistently among the strongest predictors of overall building satisfaction – often more predictive than objectively measured environmental conditions. This finding has been replicated in numerous subsequent studies across cultural contexts.

Perceived control operates through several mechanisms: it reduces appraisal of environmental conditions as threatening, reduces physiological stress responses, enables adaptive coping strategies, and increases willingness to tolerate sub-optimal conditions. The practical implication is that building management systems designed to maximize centralized control at the expense of individual adjustment may systematically undermine occupant wellbeing, even when they succeed in maintaining objectively optimal measured conditions (see Table 6.1).

Table 6.1. Individual environmental control elements: evidence base, challenges, and design solutions.

Control Element	Evidence of Wellbeing Benefit	Implementation Challenges	Design Solutions
Operable windows	Strong: reduces dissatisfaction with thermal/air quality; increases adaptive comfort range	Conflicts with HVAC operation; security; noise ingress	Mixed-mode ventilation with automatic HVAC lockout when windows open
Individual temperature adjustment	Moderate: satisfaction effect independent of achieved temperature	HVAC zoning costs; conflict with energy targets	Personal comfort systems (fans, heated seats); fine-zone VAV control
Lighting dimming and color temperature	Moderate: satisfaction with lighting; alertness management	Cost of DALI/tunable-white systems; occupant training	Scene-based controls; occupancy-pattern learning systems

Control Element	Evidence of Wellbeing Benefit	Implementation Challenges	Design Solutions
Adjustable blinds/shading	Strong: glare control; thermal comfort; privacy	Maintenance; automated vs manual preference conflicts	Both manual and automated control; occupancy-based defaults
Acoustic privacy (movable partitions)	Strong: concentration; speech privacy	Floor plan flexibility; fire compartmentation	Acoustic phone booths; adjustable work pods

6.3 Sick Building Syndrome: A psychosocial perspective

Sick building syndrome (SBS) is characterized by non-specific symptoms including headache, eye, nose, and throat irritation, dry skin, fatigue, and difficulty concentrating, reported predominantly by occupants of specific buildings and substantially relieved upon leaving the building. While physical IEQ parameters (ventilation, VOCs, thermal comfort) contribute to SBS, a substantial literature demonstrates that psychosocial factors are equally important determinants of symptom reporting.

Hedge et al. (1992) found that job satisfaction, perceived workload, and quality of relationship with management were independent predictors of SBS symptom reporting after controlling for measured IEQ parameters. Stenberg and Wall (1995) demonstrated in a Swedish longitudinal study that the strongest predictors of SBS included work stress, poor psychosocial work environment, and individual health status—not physical IEQ variables. These findings suggest that SBS is a 'total exposure' phenomenon in which the built environment is one of several interacting exposure systems, alongside the psychosocial work environment and individual factors.

6.4 Behavioral responses to IEQ conditions

6.4.1 Adaptive behavior

Occupants of buildings respond to IEQ conditions through a range of adaptive behaviors that can substantially modify their actual exposure. In the thermal comfort domain, behavioral adaptations include adjusting clothing insulation, changing workstation location, opening/closing windows, adjusting blinds, using personal fans, and requesting HVAC adjustments. Understanding these behavioral adaptations is essential for accurate prediction of occupant comfort outcomes and for evaluating the effectiveness of passive design strategies.

6.4.2 Pro-environmental behavior

Building occupants are not merely passive recipients of IEQ conditions; they also actively influence energy consumption, ventilation performance, and IEQ through their daily behaviors. Opening windows when rooms are overheated, leaving computers and lights on when leaving rooms, propping open fire doors, and overriding HVAC settings all have significant IEQ and energy consequences. Behavioral economics approaches—including defaults (pre-setting lighting to energy-efficient levels), social norms (displaying energy use comparisons with peers), and feedback (providing real-time dashboards of indoor CO_2 and energy) have demonstrated effectiveness in promoting pro-environmental building use behaviors (Carrico & Riemer, 2011).

6.5 Case study

Case Study 6.1: Biophilic Design Integration, Amazon Spheres, Seattle, USA

Building Type: Three interconnected glass spheres forming an employee workspace

Location: Seattle, Washington, USA

Completion: 2018

Architect: NBBJ

The Amazon Spheres were designed explicitly as a biophilic workspace – a living plant-filled environment where employees could work, meet informally, and seek restorative experiences from their regular office environment. The spheres contain approximately 40,000 plants from over 400 species, sourced from temperate rainforest regions worldwide, maintained at an average temperature of 22°C and humidity of 60%.

The biophilic environment was designed to support restoration from cognitive fatigue (drawing on Attention Restoration Theory), stress recovery (informed by Ulrich's stress recovery theory), and creative thinking. The complexity, naturalness, and temporal change of the environment—with plants at different growth stages, seasonal variation, and living ecosystem dynamics—provide the 'soft fascination' described by Kaplan and Kaplan (1989) as central to restorative experience.

Post-occupancy assessment (2019 internal study): Employee self-reported creativity scores were 22% higher after 30-minute sessions in the Spheres compared with equivalent sessions in standard meeting rooms. Physiological stress measures (cortisol, heart rate variability) showed 15-18% improvement after Sphere sessions. 89% of employees reported using the Spheres as a restorative space. Employee engagement scores for employees with regular access to the Spheres were 12 points higher than for comparable employees without access.

Thermal and IAQ performance: The living plant biomass contributes to humidity regulation, reducing the humidity control load on the HVAC system. Indoor CO2 was consistently below 600 ppm due to plant photosynthesis contribution and high-volume mechanical ventilation. The planting creates localized thermal zones through transpiration cooling.

Key Lessons: Large-scale biophilic environments are technically feasible in commercial settings and yield measurable wellbeing and performance benefits. The psychological impact of biophilic spaces depends on their authenticity and ecological complexity, not merely the presence of decorative plants.

Chapter 6 Summary

This chapter examines the psychological and behavioral dimensions of IEQ, demonstrating that the experience of indoor environments is shaped as much by cognitive appraisal, perceived control, and psychosocial context as by objectively measured physical conditions. Key themes include: the importance of individual control as a determinant of environmental satisfaction; the theoretical and empirical basis for biophilic design as a wellbeing strategy; the psychosocial determinants of sick building syndrome; and the role of behavioral economics in shaping pro-environmental occupant behaviors. These insights challenge purely engineering-centric approaches to IEQ and emphasize the need for interdisciplinary integration of building science with environmental and organizational psychology.

Review Questions

1. Explain the concept of perceived control and describe three specific design features that could enhance occupants' sense of control over their indoor environment.
2. A building manager reports that occupants in a newly refurbished open-plan office are complaining of SBS symptoms despite physical measurements confirming excellent IEQ. What psychosocial factors might explain this discrepancy, and what interventions would you recommend?
3. Critically evaluate the evidence for biophilic design as an IEQ strategy. What are the methodological limitations of the available evidence, and what additional research is needed?
4. Using the arousal theory framework, design an optimal IEQ environment for (a) creative brainstorming work and (b) detailed analytical tasks. How would the optimal environments differ?
5. A large company wants to reduce energy consumption in its offices while maintaining high IEQ. Drawing on behavioral economics principles, design a three-component intervention to achieve this goal.

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Chapter 7: Measurement techniques and monitoring technologies

Learning Objectives

1. Describe the principal instruments and methods used to measure IEQ parameters.
2. Evaluate the performance characteristics, accuracy, and limitations of low-cost IEQ sensor technologies.
3. Design an IEQ monitoring protocol appropriate for a specific building type and assessment objective.
4. Explain calibration procedures and data quality assurance in continuous IEQ monitoring.
5. Interpret continuous IEQ monitoring data using appropriate statistical and visual analysis methods.

7.1 Reference instrumentation for IEQ assessment

Compliance-grade IEQ assessment relies on calibrated reference instruments meeting specified accuracy standards. The following subsections describe the key instruments for each IEQ domain.

7.1.1 Thermal environment

Table 7.1. Reference instrumentation for thermal comfort assessment.

Parameter	Instrument	Accuracy Class	Standard
Air temperature	Platinum resistance	Class A: ±0.15°C	IEC 60751

Parameter	Instrument	Accuracy Class	Standard
	thermometer (PRT/PT100)		
Mean radiant temperature	150mm matte black globe thermometer + PRT	±0.5°C (Tmrt)	ISO 7726
Air velocity	Omnidirectional hot-wire anemometer	±0.05 m/s or ±5% (>0.2 m/s)	ISO 7726
Relative humidity	Capacitive polymer sensor	±2% RH (10-90% RH)	ISO 7726
Operative temperature	Calculated from Ta, Tmrt, va; or ellipsoidal thermometer	±0.5°C combined	ISO 7730
PMV/PPD	Thermal comfort meter	Derived from measured variables	ISO 7726, ISO 7730

7.1.2 Indoor Air Quality

Table 7.2. Reference measurement methods for key indoor air quality parameters.

Pollutant	Reference Method	Detection Limit	Measurement Principle
CO_2	Non-dispersive infrared (NDIR) analyzer	< 10 ppm	Infrared absorption at 4.26 μm
PM2.5 (gravimetric)	Filter-based gravimetric sampling (24h or 7d)	~1 $\mu g/m^3$ (24h)	Mass of particles collected on PTFE filter
PM2.5 (optical)	Light-scattering photometer (nephelometer)	~2-5 $\mu g/m^3$	90° or forward light scattering
Formaldehyde	High-performance liquid chromatography (HPLC)	< 1 $\mu g/m^3$	DNPH cartridge active sampling + HPLC analysis
Total VOCs	Flame ionization detector (FID) or PID	1-10 $\mu g/m^3$	Ionization of organic molecules
Specific VOCs	GC-MS (gas chromatography-	< 0.1 $\mu g/m^3$	Chromatographic separation +

Pollutant	Reference Method	Detection Limit	Measurement Principle
	mass spectrometry)		mass spectrometry
Radon	Alpha track detector (long-term) or ionization chamber	10 Bq/m^3	Alpha particle decay measurement

7.2 Low-cost sensor technologies

The past decade has seen a proliferation of low-cost sensor technologies that enable continuous, distributed IEQ monitoring at a fraction of the cost of reference instruments. These sensors typically leverage electrochemical cells, metal oxide semiconductors, photoionization detectors, optical particle counters, or MEMS (microelectromechanical systems) transducers, integrated with microcontrollers and wireless communication modules (Bluetooth, Wi-Fi, LoRaWAN, or cellular).

The appeal of low-cost sensors for IEQ applications lies in their ability to provide high spatial and temporal resolution data that is impossible to achieve with periodic reference measurements. However, their limitations, including reduced accuracy, sensitivity to cross-interference, calibration drift, and sensitivity to environmental conditions such as temperature and humidity – must be carefully understood and managed. In Table 7.3 are presented several sensor technologies used for IEQ monitoring.

Table 7.3. Low-cost sensor technologies for IEQ monitoring: typical performance characteristics and cost ranges.

Sensor Type	Measurands	Typical Accuracy	Key Limitations	Approximate Cost
NDIR CO_2 sensor	CO_2	±50 ppm or 5%	Good; temperature compensation needed	USD 15-50 (module)
Electrochemical gas sensor	CO, NO_2, O_3, SO_2	±5-15% (well-calibrated)	High cross-sensitivity; aging; humidity effects	USD 20-100 per gas
Metal oxide semiconductor (MOS)	TVOC, H_2, NH_3	Semi-quantitative only	Very high cross-sensitivity; no compound specificity	USD 5-20
Photoionization detector (PID)	TVOC, benzene	±10% (calibrated)	Reference gas dependent; humidity sensitive	USD 50-200 (module)
OPC (optical particle counter)	PM1/2.5/10, particle count	±10-30% vs.	Hygroscopic particle swelling at high RH;	USD 20-100

Sensor Type	Measurands	Typical Accuracy	Key Limitations	Approximate Cost
		gravimetric	dust type sensitivity	
MEMS temp/ humidity	Temperature, RH	±0.3°C, ±3% RH	Sensor-to-sensor variability; drift over time	USD 2-10
MEMS sound level meter	SPL dB(A)	Class 2: ±1.5 dB	Limited low-frequency accuracy; wind noise sensitivity	USD 30-100
Photodiode lux sensor	Illuminance (lux)	±10-20%	Spectral response mismatch vs. V(λ); directional sensitivity	USD 2-10

7.3 Calibration and data quality assurance

The reliability of IEQ monitoring data – whether from reference instruments or low-cost sensors – depends critically on calibration procedures and ongoing quality assurance. Key calibration approaches include:

- Factory calibration: Performed by the manufacturer before delivery; provides initial accuracy traceable to national measurement standards. Essential for reference instruments.
- Field calibration: Comparison of sensor output with co-located reference measurement under actual deployment conditions. Required for low-cost sensors to account for site-specific environmental conditions.
- Colocation studies: Extended deployment of low-cost sensors alongside reference instruments to characterize accuracy across the full range of expected conditions. Regression-based or machine-learning correction factors can substantially improve low-cost sensor accuracy.
- Zero and span checks: Periodic exposure of sensors to zero-concentration gas (filtered air or nitrogen) and known-concentration span gas. Essential for electrochemical and NDIR sensors.
- Drift correction: Many sensors exhibit signal drift over time due to aging of sensing elements, contamination, or changes in environmental conditions. Periodic recalibration intervals should be specified based on manufacturer data and site experience.

7.4 IEQ monitoring system design

An effective IEQ monitoring system requires careful consideration of measurement objectives, spatial coverage, temporal resolution, data management, and integration with building management systems. A systematic design process follows:

1. Define objectives: Compliance assessment, occupant comfort monitoring, HVAC optimization, research, or

certification support. Each requires different sensor selections and monitoring protocols.

2. Map the space: Identify representative monitoring zones, considering occupancy patterns, HVAC supply/return locations, potential pollution sources, and spatial variability of conditions.
3. Select parameters and sensors: Match sensor technology to require accuracy, range, and durability for each parameter. Consider integrated multi-parameter devices versus single-parameter sensors.
4. Design spatial deployment: Determine sensor density. ASHRAE Standard 55 specifies measurement locations for comfort assessment (head height 1.1m seated, 1.7m standing); WELL Standard specifies sampling locations and frequencies for IAQ certification.
5. Implement data management: Select communication protocol (wired vs. wireless), data logging frequency (1-minute intervals for trend analysis; 15-minute for steady-state assessment), cloud storage, and visualization platform.
6. Establish quality assurance: Define calibration intervals, data flagging criteria (for suspect readings), gap-filling procedures, and reporting formats.

7.5 Integration with building management systems

The integration of IEQ monitoring data with building management systems (BMS) enables closed-loop environmental control – adjusting HVAC, shading, and lighting parameters in real time based on measured IEQ conditions. Common integration approaches include:

- Demand-controlled ventilation (DCV): CO_2 sensors linked to VAV (variable air volume) dampers or AHU speed controllers to modulate outdoor air supply in proportion to occupancy. Requires BACnet or Modbus integration between IEQ sensor and BMS.
- Thermal comfort-based temperature setpoint adjustment: Calculated PMV derived from multi-sensor measurements driving zone temperature setpoint, rather than fixed temperature setpoints.
- Occupancy-based lighting and HVAC: Presence sensors or CO_2-derived occupancy estimates triggering HVAC standby mode and lighting shutdown in unoccupied zones.
- Predictive maintenance alerts: Trend monitoring of filter differential pressure, heat exchanger efficiency, and fan performance to trigger maintenance before failures affect IEQ.

7.6 Case study

Case Study 7.1: IoT sensors and KNX protocol for IEQ monitoring, Technical University of Cluj-Napoca, RO

Building Type: Faculty of Building Services Engineering, Technical University of Cluj-Napoca, Romania

Classrooms studies: Two vertically aligned northwest-facing laboratories: I03 (ground floor, 20–24 seats) and I302 (third floor, 20–24 seats)

Deployment Period: April 2025 (spring semester); two consecutive weeks; 4 recording sessions

Reference instrument: Testo 400 (ISO 7726): Ta ±0.2 °C; RH ±2% RH; CO_2 ±50 ppm; placed at center of occupied zone, 1.1 m height

IoT sensors: Wall-mounted at 1.5 m; Ta ±0.5–1 °C; RH ±2% RH; CO_2 ±50 ppm; communicating via KNX middleware (v3.6.0)

Three consistent patterns emerge from the descriptive statistics. First, the Testo 400 systematically reports higher values than the KNX system for all parameters across all four sessions — confirming a systematic offset attributable to sensor placement differences. Second, relative humidity shows the largest proportional discrepancy: in I03 on 9 April, the Testo 400 reports a mean of 51.91% versus the KNX system's 43.52%, a 19.3 percentage-point difference. Third, CO_2 concentrations measured by the Testo 400 exceeded KNX readings by 16–24% across sessions, with the professional instrument consistently capturing higher peak concentrations in the occupied zone.

Despite the systematic offset in absolute values, Pearson's correlation analysis reveals a strong alignment between the temporal trends captured by both systems — meaning the KNX network reliably tracks when conditions improve or deteriorate, even if it underestimates the magnitude of changes.

Despite the objectively poor IAQ, occupant perceptions were more moderate in many sessions — a finding that illustrates the important distinction between objective IEQ and subjective IEQ. On 9 April (the overcrowding session), 33.3% of respondents rated the air as "slightly stuffy" and 11.1% as "stuffy", while 33.3% rated the air quality tolerance as "difficult to breathe" — consistent with the extreme CO_2 levels. In contrast, on 16 April (normal occupancy), 33.3% found the air "perfectly breathable" and 60% found it "breathable", despite CO_2 levels still exceeding 2,000 ppm. This suggests that students partially adapt to chronically elevated CO_2, underestimating the cognitive and health impairment they experience.

Key findings from continuous monitoring: (1) KNX wall-mounted IoT sensors are reliable trend-monitoring tools, but they systematically underestimate absolute values due to placement at the wall (1.5 m) rather than in the occupied zone (1.1 m). This offset must be understood and factored into HVAC control algorithms; (2) The KNX system successfully maintained thermal comfort for most of the study period, demonstrating that KNX-based automation can effectively control heating — but one system failure (failure to activate heating at session start, producing 17.6 °C) illustrates the need for regular system reliability testing and backup override procedures; (3) Integrating qualitative (occupant survey) and quantitative (sensor) IEQ assessment provides insights that neither method alone can offer: while sensor data revealed extreme CO_2 levels, occupant survey data showed that some degree of habituation occurs — students partially normalize to chronically elevated CO_2 — suggesting that objective measurement is essential and cannot be replaced by reliance on occupant complaint.

Chapter 7 Summary

This chapter has provided a comprehensive review of IEQ measurement technologies, from high-accuracy reference instruments to emerging low-cost sensor platforms. The key technical challenge in deploying low-cost sensors at scale is ensuring data quality through rigorous colocation studies, correction factor derivation, and ongoing quality assurance. Integration of IEQ monitoring with building management systems enables real-time closed-loop control that can maintain high environmental quality while optimizing energy efficiency. The case study illustrates the practical value of campus-scale IoT monitoring networks for identifying systematic IEQ deficiencies and supporting proactive maintenance.

Review Questions

1. You are tasked with designing an IEQ monitoring system for a 500-person open-plan office. Specify the parameters to be measured, sensor technologies to be employed, spatial deployment strategy, and data management approach. Justify each decision.

2. A low-cost PM2.5 sensor shows significant positive bias (overestimation) at relative humidity above 70% compared with co-located reference measurements. Explain the physical mechanism causing this bias and describe two approaches to correct it.

3. Compare the advantages and disadvantages of NDIR CO_2 sensors and non-NDIR alternatives (such as metal oxide sensors calibrated for CO_2) for continuous IEQ monitoring applications.

4. Describe a quality assurance protocol for a 50-node low-cost IEQ sensor network, specifying calibration intervals, data flagging criteria, and gap-filling procedures.

5. How can occupant-facing IEQ dashboards improve building performance and occupant wellbeing? What are the potential risks of providing real-time IEQ data directly to building occupants?

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Chapter 8: IEQ in green building certifications

Learning Objectives

1. Describe the IEQ provisions within the major green building certification systems: LEED, BREEAM, WELL, and Fitwel.
2. Compare the IEQ requirements, scoring mechanisms, and philosophies of these certification frameworks.
3. Evaluate the evidence for the effectiveness of green building certification in improving IEQ outcomes.
4. Critically analyze the limitations and future directions of green building certification as an IEQ governance tool.

8.1 Overview of green building certification systems

Green building certification systems emerged in the 1990s as voluntary market mechanisms to incentivize the design and construction of buildings with superior environmental performance. Initially focused primarily on energy efficiency and resource consumption, these systems have evolved to incorporate increasingly sophisticated IEQ provisions, reflecting the growing recognition of the human health and productivity dimensions of building performance. In Table 8.1 is presented an overview of most green building certification systems and their IEQ provisions.

Table 8.1. Overview of major green building certification systems and their IEQ provisions.

System	Origin	Launch Year	IEQ Category	IEQ Points/Weight	Global Reach
LEED (v4.1)	USA (USGBC)	1998	Indoor Environmental Quality (EQ)	16 credits (~15% of total)	>100 countries, >100,000 projects
BREEAM (2018)	UK (BRE)	1990	Health and Wellbeing (Hea)	12% of total weighted score	>90 countries, >600,000 projects
WELL (v2)	USA (IWBI)	2014	Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Mind	100% (IEQ is the entire standard)	>100 countries, >5,000 projects
Fitwel	USA (CDC/GSA)	2017	Multiple domains including IAQ,	Scoring matrix; ~30% IEQ-related	>60 countries

System	Origin	Launch Year	IEQ Category	IEQ Points/Weight	Global Reach
			lighting, acoustics		
DGNB (2023)	Germany (DGNB)	2009	User Comfort and Health	~15% of total criteria	Primarily European
Green Star (v1.3)	Australia (GBCA)	2003	Indoor Environment Quality (IEQ)	~20% of total	Australia, NZ, South Africa

8.2 LEED indoor environmental quality credits

LEED v4.1 (Leadership in Energy and Environmental Design) organizes IEQ provisions across 9 prerequisite and credit categories. The system uses a prescriptive-performance hybrid approach, with prerequisites establishing minimum standards and credit rewarding above-minimum performance.

8.2.1 Prerequisites

- EQ Prerequisite: Minimum Indoor Air Quality Performance – compliance with ASHRAE 62.1 ventilation rates (or equivalent regional standard) is mandatory.
- EQ Prerequisite: Environmental Tobacco Smoke (ETS) Control – prohibition of smoking within the building and within 7.5m of all entries, operable windows, and outdoor air intakes.

8.2.2 Key credits

- EQ Credit: Enhanced Indoor Air Quality Strategies (2 points) – exceeding minimum ventilation by 30%, entryway systems for particle filtration, enhanced filtration (MERV 13+), CO_2 monitoring, and other measures.
- EQ Credit: Low-Emitting Materials (3 points) – specifying low-VOC flooring, ceiling, wall, and furniture products from approved product databases (DECLARE, HPD, EPD).
- EQ Credit: Construction IAQ Management Plan (1 point) – protecting installed absorptive materials from moisture contamination and flushing out the building with outdoor air before occupancy.
- EQ Credit: Indoor Air Quality Assessment (2 points) – post-construction flush-out (14,000 ft3/ft2 with windows open at 60% RH) or IAQ testing against LEED concentration thresholds (formaldehyde <27 ppb, PM10 <50 $\mu g/m^3$, benzene <3.3 $\mu g/m^3$).
- EQ Credit: Thermal Comfort (1 point) – ASHRAE 55 compliance with individual occupant control.
- EQ Credit: Interior Lighting (2 points) – individual lighting controls, high CRI (≥80), glare control.
- EQ Credit: Daylight (3 points) – sDA300/50% ≥ 55% with ASE ≤ 10%, and simulation-verified annual sunlight exposure.
- EQ Credit: Quality Views (1 point) – direct line of sight from 75% of regularly occupied floor area to outdoors, with view quality factors (at least two of: nature, sky, human activity, or objects at least 7.5m distant).
- EQ Credit: Acoustic Performance (1 point) – compliance with ASHRAE/ANSI 2.1 background noise and sound transmission criteria, and reverberation time requirements.

8.3 BREEAM health and wellbeing

BREEAM (Building Research Establishment Environmental Assessment Method) includes a 'Health and Wellbeing' category comprising 14 issues weighted to contribute approximately 12% of the total BREEAM score. BREEAM takes a more performance-outcome oriented approach than LEED, emphasizing post-occupancy evaluation and occupant satisfaction measurement.

Key BREEAM Health and Wellbeing issues include: Hea 01 (Visual Comfort: daylight, glare control, view out, lighting control); Hea 02 (Indoor Air Quality: ventilation, indoor pollutant avoidance, VOC limits); Hea 04 (Thermal Comfort: CIBSE adaptive comfort criterion or ASHRAE 55 for mixed-mode buildings); Hea 05 (Acoustic Performance: ambient noise levels, reverberation, sound insulation performance); Hea 06 (Safety and Security: for non-residential buildings, addressing design factors affecting occupant sense of safety).

8.4 The WELL building standard

The WELL Building Standard v2 (IWBI, 2020) represents a fundamentally different philosophy from LEED and BREEAM. Rather than including health and wellbeing as one category among many (energy, materials, ecology, etc.), WELL treats human health and wellbeing as the entire purpose of the certification—all WELL credits are justified by reference to evidence of health and wellbeing impacts.

WELL v2 is organized into 10 'Concepts': Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind, and Community (see Table 8.2). Each concept contains preconditions (mandatory requirements) and optimizations (optional credits). The Air concept alone contains 9 preconditions and 11 optimizations, addressing ventilation rates, air filtration (F9/MERV

13 minimum), combustion minimization, VOC and formaldehyde limits, construction IAQ management, enhanced ventilation design, air flush-out, and CO_2 monitoring.

Table 8.2. Selected WELL Building Standard v2 concepts and their IEQ relevance.

WELL Concept	Key Requirements	IEQ Relevance
Air (A01-A09)	Minimum ventilation (ASHRAE 62.1); MERV 13 filtration; formaldehyde <27 ppb; TVOC <500 $\mu g/m^3$; CO_2 monitoring; no combustion appliances	IAQ – primary concept
Light (L01-L07)	Minimum illuminance (300 lux in work areas); max UGR 19; daylight simulation; circadian lighting design (melanotic EDI >200 mel-lux daytime)	Visual and circadian comfort
Thermal Comfort (T01-T05)	ASHRAE 55 / ISO 7730 compliance; individual thermal controls; radiant thermal comfort; humidity 30-60%	Thermal comfort
Sound (S01-S04)	Maximum background noise (HVAC: NC-35 in offices); minimum speech privacy (minimum PI of 0.20); reverberation time (0.4-0.5s in offices)	Acoustic comfort

WELL Concept	Key Requirements	IEQ Relevance
Mind (M01-M08)	Biophilic design; restorative spaces; mental health support programs; stress-reduction design features	Psychological wellbeing
Materials (X01-X06)	Low-emitting materials; hazardous material avoidance; chemical management plans; construction waste	IAQ (material emissions)

8.5 Evidence for IEQ benefits of certification

A growing body of research has examined whether green-certified buildings deliver superior IEQ outcomes compared with non-certified buildings. The findings are more nuanced than certification advocates often suggest.

Thatcher and Milner (2016) and Mendell et al. (2013) found that LEED-certified buildings did not consistently show better measured IEQ than non-certified buildings, attributing this partly to the focus on design-stage credits that do not guarantee operational performance. Allen et al. (2015) found lower VOC and PM2.5 concentrations in LEED offices compared with conventional offices, but no difference in CO_2 concentrations, suggesting that ventilation – the most critical IEQ parameter – is not reliably superior in certified buildings.

In contrast, MacNaughton et al. (2017) found that occupants of WELL-certified buildings reported significantly higher satisfaction with IEQ dimensions (air quality, lighting, acoustics, thermal comfort) than occupants of non-certified buildings, with advantages in air quality and acoustic performance. The WELL certification's combination of design requirements and post-occupancy verification may explain its superior occupant satisfaction outcomes.

These findings highlight the fundamental limitation of design-stage certification: a certificate issued at practical completion cannot guarantee that the building will perform as designed during operation. Post-occupancy evaluation and recertification mechanisms—as required by WELL (annual recertification) but not by LEED or BREEAM (one-time certification)—are essential to bridge this gap.

8.6 Case study

Case Study 8.1: WELL Platinum Office Certification – Lendlease Asia, Singapore

Building Type: Commercial office, 3,200 m^2, floors 7-9

Location: Singapore (Tropical climate: mean T 27°C, RH 84%)

WELL Certification: Platinum (2019, first in Singapore)

The certification process revealed the specific challenges of achieving WELL Platinum in a tropical climate: maintaining indoor humidity below the WELL maximum of 60% RH required significant dehumidification capacity; achieving WELL circadian lighting criteria (200+ mel-lux during core hours) required supplementing natural daylight with blue-enriched LED lighting in deep-plan areas; and the WELL materials requirements necessitated extensive product substitution, replacing 23 specified materials with compliant alternatives.

Key IEQ outcomes documented: Formaldehyde concentration reduced from a pre-renovation average of 82 μg/m^3 to 14 μg/m^3 post-construction flush-out (meeting WELL <27 ppb / 33 μg/m^3 criterion). PM2.5 maintained below 15 μg/m3 through MERV 15 filtration despite high outdoor PM in Singapore. CO2 maintained below 800 ppm through CO_2-demand-controlled ventilation. Mean thermal comfort vote: +0.2 (excellent). 91% of occupants are satisfied with visual comfort; 78% satisfied with acoustic conditions.

Business outcomes: Employee satisfaction survey scores increased 18 points (on a 100-point scale) compared with previous offices. Self-reported presenteeism (working while sick) decreased by 23%. Annual sick leave days per employee reduced from 8.2 to 6.1 days. The organization attributed the improvements primarily to improved air quality (CO_2 and pollutant reduction) and thermal comfort.

Chapter 8 summary

Green building certification frameworks have significantly advanced the mainstreaming of IEQ considerations in building design and procurement. The WELL Building Standard represents the most ambitious IEQ-specific framework, with evidence-based requirements across all key IEQ domains and a post-occupancy verification model that better bridges the gap between design intent and operational reality. However, all certification systems share the fundamental challenge that compliance at design stage does not guarantee performance in operation. Future certification frameworks will likely place greater emphasis on continuous performance monitoring, post-occupancy evaluation, and occupant-reported outcomes.

Review Questions

1. Compare the IEQ philosophies of LEED v4.1 and the WELL Building Standard v2. What are the key philosophical differences, and what practical implications do these differences have for building design and operation?

2. A building developer wants to achieve BREEAM Outstanding with maximum possible points in the Health and Wellbeing category. Outline the specific design and operational measures that would be required.

3. Why might LEED-certified buildings fail to deliver superior IAQ compared with non-certified buildings, despite the EQ credits? What changes to the certification process would improve the relationship between certification and operational IEQ performance?

4. A multinational corporation wants to certify its global portfolio of offices using a single IEQ framework. Compare the suitability of LEED, WELL, and BREEAM for this purpose, considering geographic coverage, climate adaptability, and operational requirements.

5. Critically evaluate the use of mandatory post-occupancy evaluation in green building certification. What are the barriers to implementation, and how could these be overcome?

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Chapter 9: Design strategies for healthy buildings

Learning Objectives

1. Apply integrated design principles to optimize IEQ across multiple dimensions simultaneously.
2. Design passive and active strategies for thermal comfort, IAQ, lighting, and acoustics in diverse building types.
3. Evaluate trade-offs between IEQ performance, energy efficiency, and cost in building design.
4. Develop a comprehensive Healthy Building Design Brief for a specified building type.

9.1 Integrated design approach

The delivery of high-quality IEQ requires an integrated design approach that addresses all four comfort domains simultaneously, recognizing the complex interactions between thermal, air quality, visual, and acoustic conditions. This contrasts with the traditional siloed approach in which each building service is designed independently, often resulting in sub-optimal compromises and missed opportunities for synergistic performance.

Key principles of integrated IEQ design include:

- Holistic brief development: Establishing performance targets for all IEQ domains at the outset of design, with clear allocation of responsibilities among the design team.
- Passive-first strategy: Maximizing the contribution of passive design measures (building form, orientation, thermal mass, daylighting, natural ventilation) before active

systems are specified, to minimize energy dependency and improve resilience.

- Modelling and simulation: Employing building performance simulation tools (EnergyPlus, IDA-ICE, Radiance, ODEON) to predict IEQ performance at design stage and optimize decisions before commitment to construction.
- Commissioning and verification: Rigorous commissioning of building systems against IEQ performance targets, with post-occupancy evaluation to close the feedback loop between design intent and operational reality.
- Occupant engagement: Designing occupant interfaces (controls, dashboards, apps) and operational protocols that enable and encourage active participation in IEQ management.

9.2 Building form, orientation, and envelope strategies

9.2.1 Solar orientation

Building orientation is the most fundamental passive IEQ decision, with major implications for daylighting, solar gain, natural ventilation, and thermal comfort. In the northern hemisphere:

- South-facing facades receive maximum winter solar gain and moderate summer solar gain (high sun angle); optimal for passive solar heating and daylighting with manageable glare risk.
- North-facing facades receive consistent diffuse daylight with no direct solar gain; optimal for display screens and glare-sensitive tasks but may be insufficient for circadian entrainment.

- East and west facades receive direct low-angle sun in morning and afternoon respectively; high glare risk and difficult to shade with fixed external devices.

9.2.2 Thermal mass and night cooling

Thermal mass (exposed concrete, brick, stone, or water) absorbs solar and internal heat gains during the day, releasing them slowly over time, damping peak temperatures and reducing cooling demand. In temperate climates with cool nights, night-time natural ventilation can pre-cool exposed thermal mass to extend the comfort period without mechanical cooling. Effective night cooling requires:

- Exposed thermal mass of at least 200 kg/m^2 effective thermal mass in the exposed floor area.
- Night ventilation rates of 6-12 air changes per hour, achievable by cross-ventilation (with wind-driven natural ventilation) or mechanically assisted ventilation.
- Thermal mass surface temperature difference of at least 3-4°C from peak daytime operative temperature.

9.2.3 Window and glazing design

Window design involves fundamental trade-offs between daylighting (high window area needed), solar gain control (moderate to low window area, or high-performance solar control glazing), view quality (high window area, appropriate sill and head heights), natural ventilation (openable portions), acoustic insulation (sealed or limited opening), and thermal insulation (U-value minimization). The window-to-wall ratio (WWR) should be optimized through climate-based daylight modelling and energy simulation rather than selected by rule of thumb. In Table 9.1 a glazing strategy comparison is presented by key optical and thermal performance parameters.

Table 9.1. Glazing strategy comparison by key optical and thermal performance parameters.

Glazing Strategy	G-value (SHGC)	U-value (W/m2 K)	Visible Transmittance	Best Application
Standard double low-e	0.30-0.40	1.2-1.6	0.60-0.70	North-facing facades, temperate climates
Solar control double low-e	0.20-0.30	1.1-1.5	0.40-0.55	South/east/west facades, moderate climates
Triple low-e (highly insulated)	0.35-0.50	0.6-0.9	0.55-0.65	Passive house standard, cold climates
Electrochromic (dynamic)	0.03-0.40 (variable)	0.9-1.5	0.02-0.60 (variable)	South/west facades; glare-sensitive spaces
Exterior solar shading (louvres)	Effective g-value 0.10-0.20 in summer	-	Maintains high Tvis in diffuse conditions	Best solar control for south facades

9.3 Natural and mixed-mode ventilation design

Natural ventilation utilizes pressure differences driven by wind (wind pressure) and temperature differences between interior and exterior (buoyancy or stack effect) to drive outdoor air through buildings. It is the most energy-efficient ventilation strategy when applicable but requires careful building design to be effective and reliable.

9.3.1 Wind-driven cross-ventilation

Cross-ventilation is most effective in single-sided-to-double-aspect buildings up to approximately 15m deep (5 times floor-to-ceiling height). The volumetric flow rate through a cross-ventilated space is governed by:

$$Q = Cd * A * \mathrm{sqrt}(2 * \Delta P / rho)$$

where Q is the volumetric flow rate (m^3/s), Cd is the discharge coefficient (~0.6 for sharp-edged openings), A is the effective opening area (m^2), ΔP is the pressure difference across the openings (Pa, driven by wind and buoyancy), and rho is air density (~1.2 kg/m^3). Effective cross-ventilation requires openable areas of at least 5% of floor area on each facade.

9.3.2 Stack/atrium ventilation

In deep-plan buildings, stack ventilation via central atria or wind towers can drive airflow from occupied spaces to a high-level exhaust. The stack pressure driving force is:

$$\Delta P\_stack = rho * g * H * (Ti - To) / Ti$$

where H is the vertical height between air inlet and outlet (m), Ti is indoor air temperature (K), and To is outdoor air temperature (K). Stack ventilation is most effective in warm climates where Ti > To during occupied hours.

9.3.3 Mixed-mode ventilation

Mixed-mode ventilation combines natural and mechanical ventilation, typically using natural ventilation when outdoor conditions are favorable and switching to mechanical assistance during extreme weather or when natural ventilation is insufficient. The three primary configurations are: concurrent mode (simultaneous use of natural and mechanical in different zones), changeover mode (seasonal or condition-based switching between modes), and zoned mode (natural ventilation in perimeter zones, mechanical in deep-plan zones). BMS integration with weather data and occupancy sensing enables sophisticated mixed-mode control strategies.

9.4 HVAC system selection for IEQ

9.4.1 All-air systems

All-air systems (constant air volume, CAV; variable air volume, VAV) provide excellent IEQ control capabilities: ventilation air quantity can be modulated in real time (VAV DCV), high-efficiency central filtration is straightforward, and humidity control is centralized. However, all-air systems have high distribution energy (fan power) and space requirements (ductwork). VAV systems require careful design of minimum ventilation rates to prevent under-ventilation in part-load conditions.

9.4.2 Radiant systems with dedicated outdoor air supply

Chilled beam, chilled ceiling, or radiant floor heating/cooling systems combined with a Dedicated Outdoor Air Supply (DOAS) unit provide superior IEQ in several respects: the DOAS unit can be optimized purely for ventilation and IAQ (with high-efficiency filtration, dehumidification, and heat recovery) while radiant systems handle sensible thermal loads at high COP. This decoupling of ventilation and thermal control also eliminates the draft discomfort associated with high-velocity all-air systems and reduces acoustic problems from diffuser noise.

9.5 Healthy buildings design checklist

Table 9.2. IEQ design and verification actions by project stage.

Design Stage	IEQ Action	Responsibility	Verification
Brief / Concept	Set IEQ performance targets (CO_2 <800 ppm, PM2.5 <15 µg/m3, T 20-26°C, DF >2%, RT60 <0.5s)	Client + Design Team Lead	IEQ brief document
Scheme Design	Building orientation and massing for daylighting and natural ventilation; solar analysis	Architect + Facade Engineer	Daylight simulation report (DF, sDA)
Detailed Design	HVAC system selection; filter class; ventilation rates (ASHRAE	M&E Engineer	ASHRAE 55 / ISO 7730 compliance check

Design Stage	IEQ Action	Responsibility	Verification
	62.1); radiant comfort		
Specification	Low-VOC materials specification; EC motor fans; HEPA filter specification; acoustic spec	Architect + M&E Engineer	Product EPD / HPD; filter test certificates
Construction	IAQ management plan; material protection from moisture; flush-out program	Contractor + M&E Engineer	IAQ management plan compliance photos
Commissioning	Full IEQ performance testing: CO_2, temp, lux, SPL against targets	Commissioning Engineer	CIBSE commissioning reports; WELL audit
Post-Occupancy	Occupant survey (CBE or WELL survey); continuous sensor monitoring;	Facilities Manager + Consultant	Annual POE report; WELL recertification

Design Stage	IEQ Action	Responsibility	Verification
	BMS data review		

9.6 Case study

Case Study 9.1: Passive House Standard Primary School, Hannover-Kronsberg, Germany

Building Type: Primary school (12 classrooms, 300 pupils)

Location: Hanover, Germany

Completion: 1999 (one of the first passive house schools in Europe; extensively monitored)

Standard: Certified Passive House (heating demand <15 kWh/m2/year)

The school was designed with a Passive House-standard envelope (0.15 W/m2K walls; triple glazing 0.8 W/m2K) with MVHR providing 95% heat recovery efficiency. Classroom ventilation is provided by a MVHR unit serving each classroom with 6.5 L/s/child outdoor air supply—well above the German standard minimum.

IEQ monitoring (7-year study by IBP Fraunhofer Institute): CO2 concentrations in classrooms averaged 680-820 ppm during occupied hours, consistently below 1000 ppm (compared with 1500-2000 ppm measured in conventionally ventilated classrooms in the same district). Indoor temperature was maintained within 20-23°C for 98% of occupied hours. Acoustic assessment found RT60 in classrooms of 0.42-0.48 seconds—

compliant with German DIN 18041 standard. Daylighting exceeded the 300-lux minimum at all desk locations.

No cases of SBS symptoms or moisture-related problems were reported in the seven-year monitoring period. Heating energy consumption was 89% lower than the German standard school (14 vs. 126 kWh/m2/year). Mechanical ventilation energy partially offset the heating saving, but total primary energy was still 72% below standard.

Key Lessons: Passive standard school buildings can simultaneously achieve excellent IEQ, very low energy consumption, and occupant comfort. MVHR is essential in passive house schools to maintain IAQ in airtight envelopes. The extra capital cost of the passive house measures (estimated at 7% above standard construction cost) was recovered within 8 years through energy savings.

Chapter 9 summary

This chapter has presented an integrated framework for healthy building design, from building form and orientation through to post-occupancy evaluation. The key principle is that IEQ excellence cannot be added as an afterthought: it must be embedded from the earliest stages of the design brief through a systematic, evidence-based process. Passive design strategies—solar orientation, thermal mass, natural ventilation—form the foundation of a healthy building, with active systems providing supplementary control and reliability. The healthy buildings design checklist provides a practical project-stage framework for integrating IEQ requirements into standard construction procurement processes.

Review Questions

1. Develop an IEQ design brief for a 500-person co-working office in a temperate climate. Specify quantitative performance targets for each of the four IEQ domains and justify them with reference to appropriate standards.

2. A school is to be built on a site adjacent to a motorway in an urban area. Describe the integrated design approach you would employ to achieve excellent acoustic and IAQ performance without excessive energy cost.

3. Compare the IEQ performance advantages and disadvantages of (a) a VAV all-air HVAC system and (b) a radiant cooling/heating system with dedicated outdoor air supply.

4. Explain how building thermal mass can contribute to thermal comfort and what design conditions must be met for night cooling to be an effective cooling strategy.

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Chapter 10: Case studies and real-world applications

This chapter presents extended case studies across diverse building types, demonstrating the application of IEQ principles to real-world design and operational challenges. Each case study follows a structured format: building context, IEQ challenges identified, interventions implemented, outcomes measured, and key transferable lessons.

10.1 Case study: international airport terminal

Case Study 10.1: Heathrow Airport Terminal 5, London – IEQ in High-Occupancy Transit Spaces

Building Type: Major international airport terminal (90,000 m2, 30 million passengers/year capacity)

Location: London Heathrow, UK

Completion: 2008 (extended 2011)

Architect: Richard Rogers Partnership

Background: Airport terminals present unique IEQ challenges: highly variable occupancy (peak to near-empty cycles), diverse occupant activities (sedentary waiting, walking, food service, retail), elevated PM and VOC loads from cooking and retail, and the critical health consideration of bioaerosol transmission in crowded enclosed spaces.

Thermal Comfort: The terminal's envelope combines a single-layer ETFE cushion roof with triple-glazed full-height facades, creating extensive solar gain challenges. An underfloor heating/cooling system with 18°C chilled water in summer and 35°C hot water in winter serves as the primary thermal conditioning system. Perimeter radiant panels supplement the underfloor system near glazed facades. Operative temperatures are maintained at 20-22°C in winter and 23-25°C in summer through BMS control, with the underfloor system pre-conditioning during off-peak periods.

IAQ: The terminal uses a 100% outdoor air system (no recirculation) with HEPA filtration (H14 class) in all air handling units, motivated by the elevated bioaerosol risk in the post-SARS design era. CO2 monitoring drives demand-controlled ventilation; during peak periods, CO2 approaches 800 ppm in the most densely occupied departure lounges. Extensive cooking operations in the airside dining area generate significant PM and VOC loads; dedicated exhaust systems with activated carbon filtration extract directly from kitchen zones.

Daylighting: The ETFE roof provides 40% of the terminal's daytime illuminance through diffuse natural light, reducing electric lighting energy consumption by an estimated 35% compared with a conventional opaque roof terminal of equivalent size.

Outcomes: Post-occupancy surveys found passenger thermal comfort satisfaction of 71% (above industry benchmark of 65%). Employee surveys found 84% satisfied with air quality. No infectious disease transmission events attributable to terminal air handling were recorded in the period studied.

10.2 Case study: residential building – energy-efficient retrofit

Case Study 10.2: Deep Retrofit IEQ Outcomes – Social Housing, Edinburgh, Scotland

Building Type: 48-unit 1960s concrete panel residential building (social housing)

Location: Edinburgh, Scotland, UK

Retrofit Year: 2018-2019

Energy Standard Pre/Post: EPC Band E to Band A

Background: Solid-wall 1960s social housing in Scotland presents simultaneous challenges of very poor energy performance (high heating costs for fuel-poor residents) and IEQ deficiencies (cold bridging, surface condensation, moisture damage, radon infiltration in some units, and draughts).

Retrofit Scope: External wall insulation (EPS 150mm, achieving U-value 0.18 W/m^{2}K); triple-glazed window replacement (U-value 0.8 W/m^{2}K); roof insulation; MVHR installation (replacing extract-only ventilation); replacement of gas combi-boilers with air source heat pump systems.

IEQ Monitoring (12-month pre/post): CO_2 in living rooms fell from mean 1680 ppm (pre-retrofit; inadequate ventilation) to 720 ppm (post-retrofit with MVHR). Relative humidity fell from mean 65% (pre; condensation risk) to 49% (post). Operative temperature in living areas increased from mean 18.1°C (pre; thermal discomfort for elderly residents) to 21.3°C (post). Radon concentrations in ground-floor units decreased from 145 Bq/m^3 (above UK action level of 200 Bq/m^3) to 42 Bq/m^3 after MVHR installation. PM2.5

concentrations were unchanged (15-18 μg/m^3) due to persistence of smoking in some units.

Health Outcomes: NHS Scotland data linkage for the building's residents found: 23% reduction in respiratory emergency admissions in the 18 months post-retrofit compared with the 18 months pre-retrofit; 31% reduction in cold-related GP consultations in winter months. Residents' self-reported thermal comfort improved significantly (mean ASHRAE vote from -1.1 pre to +0.2 post).

Key Lessons: MVHR is essential for maintaining IAQ in highly airtight retrofitted buildings. Radon entry points are effectively blocked by airtight retrofits combined with positive pressure MVHR systems. Deep energy retrofits of social housing can deliver significant, measurable public health benefits, justifying public investment on health as well as energy grounds.

10.3 Case study: research laboratory building

Case Study 10.3: IEQ in a Research Laboratory – Crick Institute, London

Building Type: Biomedical research laboratory complex, 93,000 m^2

Location: London, UK

Completion: 2016

Architects: HOK + PLP Architecture

Background: Biomedical research laboratories present extreme IEQ challenges. Laboratory spaces require 6-20 air changes per hour of single-pass (non-recirculated) conditioned air for fumes and chemical control; write-up (office) spaces require normal office IEQ standards; containment laboratories (BSL-1 to BSL-3) require negative pressure relative to adjacent spaces with high-efficiency exhaust filtration. The challenge at the Crick was integrating 1,250 scientists' daily movement between laboratory and office contexts while providing appropriate IEQ in each.

Ventilation Design: Laboratory modules provide 10 air changes per hour (single pass) with HEPA H14 exhaust filtration. Write-up offices adjacent to laboratories are positively pressurized relative to lab spaces to prevent chemical egress. An atrium 'heart' space (6 floors, 100m long) provides the social hub of the institute, naturally ventilated with supplementary mechanical assistance, operating at office-standard ventilation rates.

Daylighting: The design maximizes natural light penetration using a saw-tooth roof light system providing north-facing daylight to 85% of laboratory bench areas, reducing reliance on fluorescent tube task lighting. Post-occupancy illuminance measurements confirmed >500 lux on lab benches (EN 12464-1 requirement: 500-750 lux for laboratory work) in 94% of monitored locations during business hours.

Thermal Comfort: The high ventilation rates in laboratories create challenges for thermal comfort: 10 ACH of supply air requires very careful diffuser design to avoid draft discomfort (Draft Rating calculations showed DR would exceed 20% without diffuser optimization). A displacement ventilation strategy was employed in laboratory spaces, supplying cool air (16°C) at low velocity from floor-level diffusers, achieving both thermal comfort and high ventilation effectiveness for chemical contaminant removal.

Occupant Satisfaction: Post-occupancy survey (2018, n=485 scientists): 81% satisfied with air quality; 74% satisfied with thermal comfort; 88% satisfied with natural light. The main source of dissatisfaction was acoustic conditions in the open-plan write-up offices (54% satisfied), driven by noise from adjacent laboratories.

10.4 Case study: Net Zero Carbon office – urban context

Case Study 10.4: 22 Bishopsgate, London – IEQ in a Super-Tall Office Tower

Building Type: 62-floor supertall commercial office tower, 120,000 m^2

Location: City of London, UK

Completion: 2020

BREEAM Rating: Excellent (73.9%)

Bishopsgate integrates a comprehensive IEQ strategy informed by a detailed pre-design occupant needs assessment and a commitment to the WELL Building Standard's performance metrics (without formal certification). Key IEQ features:

Air Quality: The tower uses a floor-by-floor fresh air injection system delivering 2.5 L/s/person of MERV 15-filtered outdoor air, supplemented by air quality sensors (CO_2, PM2.5, TVOC) on each floor that trigger increased ventilation when pollutants are detected. The building's publicly accessible wellness dashboard displays real-time IEQ data for all tenant organizations.

Thermal Comfort: A chilled beam system serves the office floors, with underfloor air distribution in the lobby and communal floors. The facade incorporates high-performance electrochromic glazing that dynamically adjusts g-value (0.03-0.60) in response to solar irradiance, occupancy, and time-of-day. Individual zone temperature controls allow ±2°C adjustment from the setpoint.

Biophilic Design: Every floor contains a 'village green'—a planted social space with planters, natural materials, and informal seating. The building's vertical village concept integrates food, wellbeing amenities (gym, cycle storage, showers), and social spaces across multiple levels, reducing elevator travel and increasing incidental physical activity.

Post-occupancy data (2022, tenants survey): 79% of occupants satisfied with air quality; 83% satisfied with thermal comfort; 71% satisfied with natural light (lower levels have less access to daylight in the urban canyon context); 68% satisfied with acoustic conditions in open-plan areas.

10.5 Case study: Net Zero hospital outpatient department

Case Study 10.5: NHS Net Zero Outpatient Department, Bristol, UK

Building Type: New-build outpatient department, 8,500 m^2 (12 clinical specialty suites)

Location: Bristol, UK

Completion: 2022

Design Target: NHS Net Zero Carbon; BREEAM Excellent

Healthcare buildings present unique IEQ demands clinical staff require high visual acuity for examination and procedure rooms; patients in vulnerable states are more sensitive to thermal discomfort and poor air quality; infection control requires specific ventilation and surface hygiene specifications; and 24/7 operation limits opportunities for night-time passive cooling.

Ventilation: All clinical consultation rooms provide 6 ACH total air change (3 ACH outdoor air + 3 ACH recirculated HEPA-filtered air), achieving a clinical standard that exceeds the HTM 03-01 (UK Health Technical Memorandum) minimum of 3 ACH outdoors for outpatient rooms. Consultation rooms are maintained at neutral pressure; immunocompromised patient waiting areas are positively pressurized; isolation rooms (for potentially infectious patients) are negatively pressurized. Flexible pressure control enables reassignment of room function without physical reconfiguration.

Thermal Comfort: The building uses a district ground source heat pump (GSHP) array providing heating and cooling with a mean COP of 3.8 for heating and 4.2 for cooling. Radiant ceiling cooling panels in clinical spaces eliminate draft risk, critical for patient thermal comfort. Examination rooms are separately controlled to allow rapid warming for undressed patients (target 24-26°C during examination), with rapid recovery to consultation standard (21-23°C) within 5 minutes.

Acoustic: Clinical consultation room acoustic performance was designed to ensure speech privacy (minimum Sound Isolation Index SII < 0.30 through partitions to adjacent rooms), with RT60

0.4-0.5 seconds for high speech intelligibility between clinician and patient. Ambient noise in waiting areas was targeted at NR 35.

Outcomes: Post-occupancy survey (12 months): 91% of clinical staff satisfied with air quality; 88% satisfied with thermal comfort; 82% satisfied with acoustic privacy (significantly above NHS benchmark of 65% for outpatient facilities). Patient comfort scores (NHS Friends and Family Test environment rating) showed a 22% improvement over the previous outpatient facility.

10.6 Case study: educational building – IEQ, energy use and environmental impacts

Case Study 10.6: educational building – IEQ, energy use and environmental impacts, Cluj-Napoca, RO

Building Type: Faculty of Building Services Engineering, Technical University of Cluj-Napoca, same as case study 2.4

Building area: 4,806.83 m^2 total

Construction history: Originally built early 1960s; major retrofit 2005–2008: added third floor, new roof insulation, PVC double-glazed windows, modern HVAC, electrical and lighting systems

Monitoring period: October 2023 – September 2024 (full academic year)

IEQ instruments: Testo 400 (Ta, Tr, RH, Va, PMV/PPD, CO_2, illuminance); Testo 815 (sound level dB)

Energy data:

Monthly electricity and natural gas from utility billing; hourly electricity from Building Energy Management System (BEMS)

The monitoring results reveal a building with strong seasonal IEQ contrasts. During the heating season (November–February), indoor temperatures were well-controlled within the EN 16798-1 Category I range (mean 22.95 °C), PMV was in the comfortable range, and CO_2 was within Category I limits for 50% of the year (May–October). However, significant challenges emerge:

- Thermal comfort: Indoor temperatures reached 33.0 °C in summer months, far exceeding the 27 °C Category III cooling limit. The absence of centralized air conditioning in most classrooms is the primary cause, exacerbated by solar heat gains through south-facing windows with inadequate external shading.
- Air quality: In April and May, CO_2 concentrations exceeded even the Category III limit (1,200 ppm), indicating that the natural ventilation system is insufficient when classroom occupancy increases in spring. High CO_2 in these months is counterintuitive — outdoor temperatures are mild (10–20 °C) but windows remain closed for acoustic reasons (proximity to a busy road).
- Acoustic comfort: Sound levels consistently exceeded the 30–40 dB EN 15251 Category I criteria for classrooms, with a mean of 51.03 dB. This exceedance is driven by road traffic noise, occupant activity, and construction work adjacent to the building during the monitoring period.
- Visual comfort: Lighting levels below 500 lx were recorded in all months, caused by students' routine use of window blinds to reduce solar glare — a behavioral response to inadequate external shading that compromises the daylighting contribution and increases reliance on artificial lighting.

The natural gas consumption profile is sharply seasonal: zero in the warm season, rising to a peak of 72.34 MWh in January — the month when Cluj-Napoca recorded its lowest outdoor temperatures. Electricity consumption shows a flatter profile, reflecting the year-round nature of lighting, computers, and equipment loads, with a modest reduction in summer vacation months. The peak electricity day of 572 kWh was recorded on 13 December 2023, driven by maximum lighting demand (shortest daylength) combined with full academic activity.

The building's EUI of 90.19 kWh/m²/year positions it favorably within the European range for educational buildings (65–225 kWh/m²/year). However, the absence of centralized cooling means that its apparently good energy performance comes at the cost of summer thermal comfort — a classic IEQ/energy trade-off. If air conditioning were installed to address the summer overheating problem, the EUI would increase substantially.

Natural gas combustion for space heating is responsible for 61.72% of the total GWP — a disproportionate share given that natural gas is used for only approximately 5 months of the year. This is the dominant lever for environmental improvement: decarbonizing the heating system (transition to heat pump or district heating with renewable source) would reduce GWP by more than it would save by any electricity efficiency measure.

Pearson's correlation analysis of the monthly data revealed statistically significant relationships between IEQ parameters and energy/environmental variables: winter (high heating energy, high GWP, high CO_2, low temperatures) contrasts sharply with summer (low energy, low GWP, low CO_2, but thermally uncomfortable high temperatures). The near-perfect Energy use–GWP correlation ($r = 0.9995$) confirms that energy consumption is the dominant predictor of environmental impact — underscoring that IEQ improvements that also reduce energy use (e.g., the 1 °C setback) deliver double benefits.

Recommendations:

- Install passive cooling or active cooling (heat pumps) in classrooms to address summer overheating, the most significant unresolved IEQ challenge.
- Implement mechanical ventilation with heat recovery in classrooms to address CO_2 exceedances during spring and winter periods when window opening is restricted by cold or noise.
- Reduce heating setpoints by 1 °C (from ~23 °C to ~22 °C) during the heating season generating 7% natural gas savings and 4.3% GWP reduction at zero capital cost.
- Install external solar shading devices on south- and west-facing windows to enable window blinds to remain open, improving daylighting (currently below 500 lx standard) without sacrificing thermal comfort.
- Implement demand-controlled mechanical ventilation triggered by CO_2 thresholds (activate at 1,000 ppm; alarm at 1,200 ppm), with photosensor-linked artificial lighting dimming as identified in Case Study 4C.

10.7 Cross-case analysis and key themes

Analyzing the case studies presented across this course book (Chapters 2-10), several recurring themes emerge that provide transferable lessons for IEQ practice:

1. Multi-dimensional interaction: In every case study, IEQ dimensions interact significantly. Increasing ventilation (IAQ benefit) creates acoustic (fan noise), thermal (draft, temperature control), and energy consequences. Optimizing one dimension in isolation routinely creates problems in others.

2. Gap between design intent and operational reality: Multiple case studies demonstrate the critical importance of commissioning (Powerhouse Kjorbo, Terminal 5) and post-occupancy evaluation (London office, laboratory) in identifying and closing the performance gap.
3. Occupant control and engagement: Cases where occupants had control over their environment (operable windows, individual temperature controls, adjustable shading) consistently reported higher satisfaction than those with centralized, fixed control systems—even when measured physical conditions were equivalent.
4. Vulnerable populations require targeted design: Hospital ward, rooming-in ward, dementia care, and school case studies all demonstrate that standard comfort models and specifications are insufficient for populations with heightened sensitivity or specific physiological needs.
5. Economic returns from IEQ investment: Across all building types examined, investments in IEQ improvement yielded measurable returns in productivity, health outcomes, satisfaction, and reduced operational costs that substantially exceeded the investment costs.

Chapter 10 Summary

This chapter has presented six extended case studies covering airport, residential, laboratory, supertall commercial, hospital and educational building types, supplemented by shorter case studies in previous chapters covering offices, schools, and care facilities. Together, these cases demonstrate both the universality of IEQ principles and the contextual specificity of their application. The cross-case analysis highlights the importance of integrated, multidimensional IEQ design; the critical role of commissioning and post-occupancy evaluation; the primacy of occupant control;

and the compelling economic case for investment in healthy indoor environments.

Review Questions

1. Compare the IEQ challenges and design responses in the airport terminal (Case Study 10.1) and the hospital outpatient department (Case Study 10.5). What common principles apply, and where do the design approaches diverge?

2. The residential retrofit case study (10.2) demonstrated measurable public health benefits. What policy mechanisms could be used to ensure that the public health value of IEQ-improving retrofits is captured in investment decisions?

3. The research laboratory case study (10.3) found that the main occupant dissatisfaction was with acoustic conditions in write-up offices. Drawing on Chapter 5, what specific acoustic design measures could have addressed this?

4. Select two of the case studies in this chapter and evaluate the extent to which they exemplify the principles of integrated IEQ design presented in Chapter 9.

5. Propose an IEQ monitoring and post-occupancy evaluation framework for any one of the case study buildings that would enable ongoing performance management and continuous improvement.

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Chapter 11: Future trends – smart buildings, sensors, Digital Twins, and AI-driven IEQ optimization

Learning Objectives

1. Explain the concept of smart building and its relationship to IEQ management.
2. Describe digital twin technology and its application to IEQ monitoring, simulation, and optimization.
3. Evaluate the potential of artificial intelligence and machine learning for IEQ prediction and control.
4. Critically assess the opportunities and risks associated with hyper-personalized environmental control.
5. Identify emerging research frontiers in IEQ science and building technology.

11.1 The smart building paradigm

The 'smart building' concept describes a built environment in which sensing, communication, and computational intelligence are deeply integrated to enable autonomous monitoring, analysis, and optimization of building systems in response to occupant needs, environmental conditions, and operational constraints (Buckman et al., 2014). While 'smart building' technologies have been applied primarily to energy management, their application to IEQ is rapidly expanding, driven by declining sensor costs, ubiquitous wireless connectivity, and advances in data analytics and machine learning.

The smart building's IEQ management capability rests on three technological pillars: (1) a dense network of distributed sensors providing real-time measurement of environmental conditions and occupant presence; (2) a data infrastructure (cloud computing, edge computing, building information modelling) for storing, processing, and communicating sensor data; and (3) intelligent control algorithms that translate sensor data into HVAC, lighting, and shading control actions to optimize IEQ performance.

11.2 IoT and IEQ sensing

IoT refers to the network of physical devices embedded with sensors, software, and connectivity that enables them to collect and exchange data. In the building context, IoT-enabled IEQ sensors are characterized by their wireless connectivity, low power consumption (enabling battery operation or energy harvesting), small form factors (enabling deployment in diverse locations without structural modification), and integration with cloud platforms for data management and analytics (Gubbi et al., 2013, Rus et al., 2025).

Current IoT IEQ sensor platforms typically provide multi-parameter sensing (CO_2, PM2.5, TVOC, temperature, humidity, occupancy, sound level, and illuminance) in a single device the size of a smoke detector, at costs of USD 100-500 per node, enabling dense deployment densities (one sensor per 20-50 m^2) that were impractical with traditional instruments. LoRaWAN, Wi-Fi, BLE, Zigbee, and KNX are the dominant communication protocols, each with different range, bandwidth, and power consumption trade-offs.

Key research challenges in IoT IEQ sensing include sensor calibration at scale, long-term drift management without regular manual intervention, data fusion from heterogeneous sensor types, and cybersecurity of building sensor networks (which represent a potentially significant attack surface for disruption of building services).

11.3 Digital Twins for IEQ

A digital twin is a dynamic virtual replica of a physical building that is continuously synchronized with real-world sensor data and capable of simulating building performance, predicting future states, and evaluating control interventions (Grieves & Vickers, 2017). Applied to IEQ, the digital twin concept integrates building physics simulation (energy, airflow, heat transfer), occupancy modelling, weather data, and operational sensor data to create a comprehensive, real-time computational representation of the indoor environment.

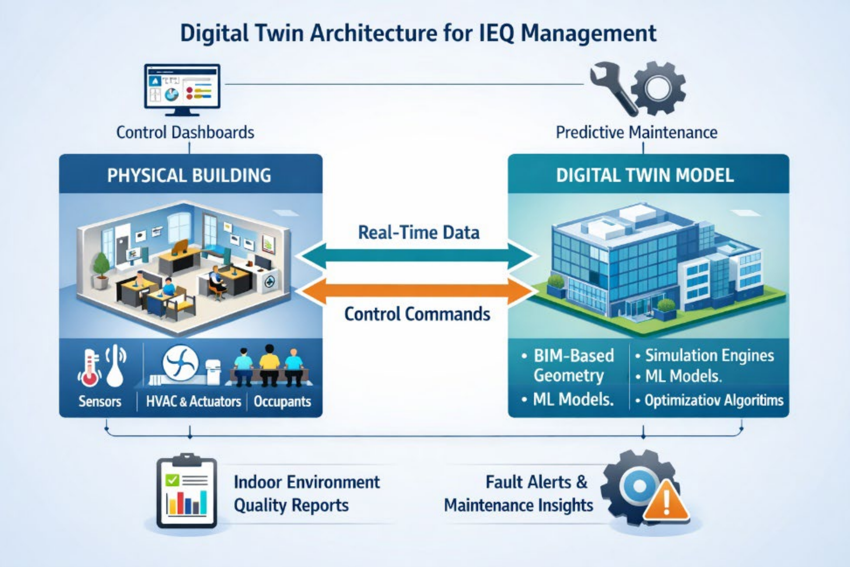

Figure 11.1. Conceptual architecture of a digital twin system for IEQ monitoring and optimization.

IEQ applications of digital twins include:

- Predictive thermal comfort control: The digital twin predicts operative temperature and PMV/PPD across the building 30-120 minutes ahead, enabling HVAC pre-conditioning that maintains comfort with lower energy consumption than reactive control.

- IAQ fault detection and diagnosis: Comparison of measured CO_2, PM2.5, and temperature against digital twin predictions enables early detection of ventilation system faults (blocked filters, failed fans, stuck dampers) before IEQ degrades.
- Renovation and retrofit planning: The validated digital twin can be used to simulate the IEQ and energy impacts of proposed retrofits under realistic occupancy and weather conditions.
- Commissioning support: Digital twin predictions during commissioning identify discrepancies between design intent and measured performance, enabling targeted investigation of underperforming systems.

11.4 Artificial intelligence and machine learning in IEQ

11.4.1 Predictive modelling

Machine learning algorithms, including artificial neural networks (ANN), gradient boosting, random forests, and long short-term memory (LSTM) networks, have demonstrated superior predictive accuracy for indoor environment parameters compared with physics-based models alone, particularly in the presence of complex occupant behavior and building operation patterns. Homod et al. (2021) demonstrated that an ANN-based thermal comfort controller reduced energy consumption by 22% compared with a standard PID controller while maintaining PMV within the ASHRAE 55 acceptable range 97% of occupied hours.

11.4.2 Reinforcement learning for HVAC optimization

Reinforcement learning (RL) offers a particularly promising approach to IEQ-energy optimization. An RL agent learns to control HVAC parameters by receiving reward signals based on measured IEQ outcomes and energy consumption, iteratively discovering control policies that maximize IEQ quality at minimum energy cost. Unlike model-predictive control (MPC), RL does not require an explicit building physics model—it learns optimal control through interaction with the real building environment. Deng et al. (2021) demonstrated an RL controller that reduced HVAC energy consumption by 17% compared with rule-based control in a commercial office building while achieving equivalent or superior thermal comfort performance.

11.4.3 Natural language processing and occupant feedback

Natural language processing (NLP) techniques enable the extraction of structured IEQ feedback from unstructured sources such as maintenance request tickets, employee survey free-text responses, and social media posts about workplace environments. This crowdsourced IEQ intelligence can complement sensor data to provide a more complete picture of occupant experience, identifying spatial and temporal patterns of discomfort that instrumented monitoring may miss.

11.5 Personalized environmental control

The heterogeneity of thermal preferences, visual comfort needs, and sensitivity to noise among building occupants (Section 2.5) motivates the development of personalized environmental control systems that adapt to individual needs rather than delivering a uniform environment based on population averages. Technologies enabling personalized IEQ include:

- Personal comfort systems: Individual desk fans, heated seats, personal radiative heaters, and task lighting that enable personal thermal and visual environment adjustment without affecting neighbors.
- Physiological comfort sensing: Wearable devices (smartwatches, fitness bands) that continuously estimate thermal comfort from skin temperature, heart rate variability, and electrodermal activity can provide continuous, passive comfort feedback to the building management system.
- Learning thermostat systems: Building on the Nest Learning Thermostat concept, room-scale systems can learn individual occupant temperature preferences from explicit feedback and adjust setpoints accordingly.
- Acoustic privacy pods and masks: Individually controllable acoustic pods, electronic hearing protection, and personalized sound masking profiles enable customization of acoustic environments.

Personalized control raises important considerations regarding equity, privacy, and energy. Granting greater individual control may benefit some occupants at the expense of others in shared spaces. The collection of continuous physiological data from wearables raises significant privacy concerns. And enabling unlimited individual customization may increase energy consumption—though this can be managed through constraint-setting within the BMS.

11.6 Post-pandemic IEQ priorities

The COVID-19 pandemic (2020-2022) fundamentally altered the discourse around IAQ, elevating the question of bioaerosol transmission and infection risk control from a specialist concern to a mainstream building management issue. The evidence that

SARS-CoV-2 (and other respiratory pathogens) is transmitted primarily via aerosols in poorly ventilated indoor spaces (Greenhalgh et al., 2021) has driven rapid adoption of HVAC upgrades (filter upgrades to MERV 13+, increased outdoor air ratios), supplementary air cleaning (HEPA portable air purifiers, UVGI upper-room systems), and CO_2-based ventilation verification as a proxy for infection risk.

Morawska et al. (2021) proposed a paradigm shift in IAQ thinking: treating clean indoor air as a fundamental public health infrastructure equivalent to clean water, with building ventilation systems held to quantitative performance standards for bioaerosol control as well as chemical pollutant dilution. This 'airborne transmission of infection' dimension of IEQ is likely to be increasingly reflected in building standards, certification systems, and operational protocols in the coming decade.

11.7 Emerging research frontiers

Table 11.1. Emerging research frontiers in IEQ science and technology.

Research Area	Current Status	Key Research Questions	Horizon
Electromagnetic fields (EMF) and IEQ	Emerging; limited evidence for chronic low-level exposure effects	Dose-response characterization; RF from building IoT networks; WHO guidelines update	2025-2030
Microbiome of the built environment	Active research; evidence for health-relevant	Design strategies for beneficial indoor microbiomes;	2025-2030

Research Area	Current Status	Key Research Questions	Horizon
	microbial communities in buildings	infection prevention; materials selection	
Neuroscience of built environments	Growing; fMRI and EEG studies of brain response to architectural features	Neural correlates of IEQ comfort; optimizing cognitive environment design	2025-2035
Hyper personal comfort models	Early stage; limited field data on wearable-based comfort prediction	Accuracy of physiological proxies for comfort; privacy-preserving personalization	2025-2030
Post-occupancy AI optimization	Prototype stage; RL demonstrations in research buildings	Scalable deployment; safety guarantees; human-AI control interfaces	2025-2028
Urban heat island and IEQ	Well-established; growing interest in adaptation strategies	Indoor overheating in urban residential buildings; vulnerability; passive adaptation	Ongoing

11.8 Case study

Case Study 11.1: AI-Driven IEQ and Energy Optimization – Keppel Bay Tower, Singapore

Building Type: 18-storey Grade-A commercial office tower, 38,000 m^2

Location: Singapore (tropical climate; year-round cooling and dehumidification required)

System Deployment: 2019-2021

Technology Partner: Keppel Land / BuildOptima AI Platform

Background: Singapore's tropical climate requires continuous HVAC operation 24/7/365. The building's HVAC system consumed approximately 45% of total electricity, with the cooling plant representing the dominant energy load. Simultaneously, occupant thermal comfort surveys showed 31% dissatisfaction with thermal conditions—paradoxically, most dissatisfied occupants complained of overcooling rather than overheating.

AI System: A deep learning model (LSTM neural network) was trained on 3 years of historical BMS data (temperature, humidity, occupancy, chiller performance, weather) plus deployed IEQ sensor data from 85 IoT nodes. The model predicts zone-level temperature and humidity 2 hours ahead, enabling HVAC pre-conditioning and setpoint optimization. A separate reinforcement learning agent continuously adjusts chiller plant staging, cooling tower operation, and AHU supply temperature to minimize energy while maintaining predicted zone conditions within the target range.

Outcomes (24-month operation): Cooling energy consumption reduced by 19% compared with the pre-AI baseline. Mean PMV improved from -0.6 (slightly cool) to -0.1 (neutral), reducing thermal dissatisfaction from 31% to 14%. CO_2 maintained below 750 ppm in 96% of occupied hours. Predicted annual energy cost saving: SGD 280,000 (approximately USD 210,000). Carbon reduction: 320 tones CO_2e/year.

Challenges: The AI system required 6 months of supervised operation before autonomous control was trusted by facilities management. Explainability of control decisions was a key stakeholder concern; the project team developed a 'recommendation' mode that presents AI-suggested setpoints to human operators for approval, building trust incrementally. Data security of the building sensor network requires significant investment in cybersecurity infrastructure.

Chapter 11 Summary

This chapter examined the emerging technological landscape of smart buildings, digital twins, IoT sensing, and artificial intelligence as applied to IEQ monitoring and optimization. These technologies represent a transformational opportunity to move from periodic assessment to continuous, predictive IEQ management at building and portfolio scale. The COVID-19 pandemic has accelerated the mainstreaming of indoor air quality as a public health priority, creating regulatory and market pressure for more stringent and transparently verified IEQ standards. However, significant challenges remain in sensor calibration, data quality, cybersecurity, occupant privacy, and the explainability and trustworthiness of AI-driven building control systems. The future of IEQ management will require building scientists, engineers, data scientists, and behavioral scientists to collaborate in developing human-centered smart building systems.

Review Questions

1. Explain how a digital twin of an office building could be used to optimize IEQ performance during the early design stage. What data inputs would be required, and what are the key sources of uncertainty?
2. Critically evaluate the use of reinforcement learning for HVAC control in buildings. What are the advantages over conventional rule-based and model-predictive control, and what risks must be managed?
3. The COVID-19 pandemic revealed significant gaps in building ventilation standards. Propose specific changes to ASHRAE Standard 62.1 or EN 16798 that would better address bioaerosol transmission risk in occupied buildings.
4. A building owner proposes deploying wearable physiological comfort sensors for all employees to enable personalized HVAC control. Identify the ethical and practical issues and propose a governance framework to address them.
5. Discuss the implications of the built environment microbiome research for building design and material selection. What design strategies might promote beneficial indoor microbial communities?

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Chapter 12: Conclusion and key takeaways

12.1 Synthesis of core themes

This course book has presented a comprehensive, evidence-based treatment of Indoor Environmental Quality and its relationship to human health, comfort, productivity, and wellbeing. Across twelve chapters, several overarching themes have emerged that transcend the individual domains of thermal comfort, air quality, lighting, and acoustics:

12.1.1 IEQ as a public health imperative

The quantitative burden of poor IEQ on human health is substantial. The WHO estimates that indoor air pollution alone causes 3.8 million premature deaths globally per year. In high-income nations, the dominant burden falls on sub-clinical outcomes, reduced cognitive performance, sleep disruption, stress, diminished wellbeing that are less visible but economically and socially significant. As populations spend an increasing proportion of their lives in built environments, the indoor environment must be recognized as a primary public health determinant, warranting the same policy attention as food safety, water quality, and outdoor air pollution.

12.1.2 The integrated nature of IEQ

No single IEQ parameter determines the quality of the indoor environment in isolation. Thermal conditions interact with air movement; ventilation affects both IAQ and acoustic performance; daylighting influences thermal comfort and circadian health; and acoustic privacy shapes psychological wellbeing independently of physical noise levels. Effective IEQ design requires a holistic, integrated approach that optimizes across all four domains simultaneously, recognizing trade-offs and synergies.

12.1.3 The performance gap

A persistent gap exists between IEQ as designed and IEQ as experienced. Buildings that achieve excellent certification ratings at practical completion frequently fail to deliver equivalent performance in operation, due to commissioning deficiencies, changes in use patterns, maintenance failures, and the complexity of real occupant behavior. Closing this gap requires mandatory post-occupancy evaluation, continuous performance monitoring, and transparent reporting of operational IEQ outcomes.

12.1.4 The human dimension

Occupant psychology, behavior, and perceived control are as important as physical IEQ parameters in determining comfort and wellbeing outcomes. The evidence for individual control, biophilic design, and psychosocial work environment as determinants of building satisfaction is robust. Future IEQ practice must integrate building science with environmental and occupational psychology to address the full complexity of human-building interaction.

12.1.5 The economic case

The economic case for investing in high-quality indoor environments is compelling and increasingly well-documented. Staff salaries represent 90% of typical office operating costs; even marginal improvements in productivity, attendance, and health outcomes yield returns that dwarf the cost of IEQ improvements. The 'healthy building' investment framework, now actively promoted by real estate investors, employers, and insurers, represents a significant opportunity to align financial incentives with human health outcomes.

12.2 Key takeaways by chapter

Table 12.1. Key takeaways by chapter: core concepts and practical implications.

Chapter	Core Concept	Key Practical Implication
1: Introduction	IEQ is a multidimensional construct encompassing thermal, air, luminous, and acoustic conditions; humans spend ~90% of their lives indoors	Holistic IEQ assessment is required; physical measurement alone is insufficient
2: Thermal comfort	PMV model provides design framework; adaptive comfort model better predicts satisfaction in naturally ventilated buildings; perceived control is critical	Provide individual thermal adjustment; use adaptive comfort for NV buildings; address local discomfort
3: Indoor Air Quality	CO_2 is the key occupancy proxy; PM2.5, VOCs, radon are priority pollutants; ventilation + filtration + source control are complementary strategies	Specify MERV 13+ filtration; target CO_2 <800 ppm; specify low-VOC materials; monitor continuously

Chapter	Core Concept	Key Practical Implication
4: Lighting	ipRGCs mediate non-visual effects; daylighting supports circadian health; dynamic lighting enables circadian optimization	Use climate-based daylight modelling; specify circadian lighting metrics (melanotic EDI); control glare (UGR ≤ 19)
5: Acoustics	Noise is the top IEQ complaint in offices; ABCs framework (absorb, block, cover) addresses open-plan offices; RT60 is the primary room acoustic parameter	Target RT60 <0.4s in open offices; use sound masking; ensure rD <8m in open-plan offices
6: Psychology	Perceived control, biophilic design, and psychosocial context are major IEQ determinants independently of physical conditions	Provide individual controls; integrate biophilic design elements; address workplace psychosocial environment
7: Monitoring	Low-cost IoT sensors enable continuous IEQ monitoring at scale; calibration and QA are essential; BMS integration enables closed-loop control	Deploy multi-parameter IoT nodes; implement colocation calibration; integrate with BMS for DCV

Chapter	Core Concept	Key Practical Implication
8: Certification	WELL Standard provides the most comprehensive IEQ certification framework; operational recertification bridges the performance gap	Seek WELL certification for health-focused buildings; mandate post-occupancy evaluation in all certifications
9: Design	Passive-first approach maximizes IEQ quality at minimum energy cost; integrated design from brief to POE is essential	Set quantitative IEQ targets in brief; use simulation for design optimization; commission against IEQ targets
10: Case Studies	IEQ principles apply across building types with context-specific adaptations; occupant control and POE are universal best practices	Learn from analogous building case studies; conduct systematic POE after occupation
11: Future trends	Digital twins, AI/ML, and IoT are transforming IEQ management; bioaerosol control and personalization are key frontier areas	Plan for IoT infrastructure in new buildings; explore AI control for HVAC optimization; address cybersecurity

12.3 Priority research and practice gaps

Despite the substantial evidence reviewed in this course book, significant gaps remain in IEQ knowledge and practice. The following priorities are identified for future research and policy attention:

- Vulnerable population thermal comfort models: The PMV and adaptive comfort models require adaptation for elderly, postpartum women, pediatric, and immunocompromised populations. Systematic data collection from these groups in real building settings is needed.
- Long-term cognitive and mental health effects of chronic IEQ exposures: Most evidence on cognitive effects of IEQ is from short-term laboratory studies. Longitudinal epidemiological studies linking chronic IEQ exposures to cognitive decline, depression, and dementia risk are needed.
- Bioaerosol control standards: Current ventilation standards do not explicitly address airborne infection risk. Quantitative standards for infectious aerosol removal efficiency – informed by the COVID-19 evidence base – are urgently needed.
- Embodied carbon versus operational IEQ trade-offs: High-performance IEQ solutions (HEPA filtration, high ventilation rates, complex glazing systems) carry embodied carbon costs that must be weighed against their operational IEQ and health benefits in whole-life carbon assessments.
- Equity and access: High-quality indoor environments are not equitably distributed. Social housing, schools in deprived areas, and workplaces in low-wage sectors routinely provide significantly worse IEQ than premium

commercial and residential buildings. Research and policy attention to IEQ equity is urgently needed.

- IEQ and climate change adaptation: Climate change is projected to increase the frequency and severity of heatwaves, which pose acute IEQ risks in existing building stock not designed for extreme heat. Adaptive strategies for maintaining thermal comfort and IAQ in a changing climate require urgent research attention.

12.4 Competencies for IEQ practitioners

Graduates of this master's course should be equipped with the following competencies for professional IEQ practice:

1. Technical competency: ability to measure, model, and evaluate all four IEQ domains using appropriate instruments, standards, and simulation tools.
2. Regulatory competency: knowledge of the principal national and international IEQ standards, building regulations, and certification frameworks applicable in their jurisdiction.
3. Design integration: ability to specify IEQ performance targets, translate these into design requirements, and verify performance through commissioning and post-occupancy evaluation.
4. Communication: ability to communicate IEQ evidence, recommendations, and performance data to diverse audiences including clients, contractors, occupants, and policymakers.
5. Interdisciplinary collaboration: understanding of the contributions of environmental psychology, occupational medicine, public health, and data science to IEQ practice,

and ability to work effectively with professionals from these disciplines.

6. Critical appraisal: ability to critically evaluate IEQ research, product claims, and technology claims, distinguishing strong evidence from weak evidence and commercial promotion.

12.5 Closing reflection

The built environment is not merely a physical container for human activity: it is a determinant of human flourishing. The evidence reviewed in this course book demonstrates that the quality of the indoor environment – the air people breathe, the light they see by, the temperature they feel, and the sounds they hear – profoundly shapes their health, their cognitive capacity, their emotional wellbeing, and their ability to connect with one another. The design, construction, and operation of healthy buildings is therefore not technical luxury or a marketing exercise: it is a moral obligation.

The transformation of the built environment towards truly healthy, human-centered indoor environments requires the integration of scientific evidence, engineering skills, regulatory ambition, and financial commitment. It requires building professionals who understand both the physics of the indoor environment and the psychology of its occupants. It requires clients and policymakers who are willing to priorities long-term health outcomes over short-term capital cost minimization. And it requires researchers who continue to advance the evidence base that underpins practice.

This course book aims to provide the foundational knowledge for this mission. The responsibility for its application rests with you.

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