Chapter 1
The Challenge of Effective Daylighting

1.1 Introduction

Effective use of daylight in buildings is a fundamental consideration for minimizing the carbon impacts of the built environment and for creating indoor environments that support the comfort, performance and well-being of building occupants. Highly glazed, "transparent" facades have become iconic images for buildings promoted as "sustainable," "green," or "high-performance," but these designs often fail to capture the claimed energy savings and may be thermally and visually uncomfortable. Little guidance exists for designers to examine how human-factors objectives such as daylight sufficiency, visual comfort and view should be defined, measured, and evaluated in context with whole-building energy objectives to establish confidence that goals for project performance can be realized after value engineering, construction, commissioning and occupancy. The integration of facade technologies, controls, and other building systems with occupant needs and the reality of building operations is a complex task, which requires a comprehensive and continuous approach. This book argues that effective daylighting requires the development of strategies and methods that acknowledge the needs and behaviors of building occupants as a critical determinant of long-term energy performance. The book defines effective daylighting with specific energy and human-factors performance objectives. It presents a range of promising daylighting design strategies and discusses them in context with simulation-based workflows and project case studies. Finally, the book presents and discusses the ongoing evolution of the glazing, shading and light control technologies and systems that underlie daylight solutions, and the applicability of emerging methodologies for optimizing and validating daylighting performance.

The following sections outline the key challenges to effective use of daylight in the design and operation of high-performance buildings to reduce carbon impacts and enhance the quality of the indoor environment for building occupants. The chapter concludes by introducing an agenda to address these issues at scale, consisting of three central transformations to contemporary design practices:

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1. From compliance-based to performance-based design.
2. From static and unresponsive to context-aware and adaptive systems.
3. From theory to validation, feedback and learning.

1.2 Effective Daylighting as a Central Driver for Low-Energy, Low-Carbon Buildings

The design of new high-performance buildings and the application of deep-energy retrofits to existing buildings will play a key role in the development of a low-carbon future. There is broad agreement that aggressive greenhouse gas (GHG) mitigation strategies are needed in order to maintain atmospheric CO_2 emissions below 450 ppm, and limit global equilibrium temperature rise to 2 °C above preindustrial levels, the threshold considered critical for avoiding irreversible effects of climate. Buildings account for more than 32% of total global energy consumption and one third of global black carbon emissions, primarily through the use of fossil fuels[1] during their operational life-cycle (Lucon et al. 2014). Looking ahead, global building energy consumption is predicted to double or even triple by 2050 as the global population increases and more consumers in the developing world gain access to energy-intensive modern buildings and operational practices. Of all sectors, (energy supply, transport, buildings, industry, agriculture, forestry, and waste), buildings have the greatest economic potential[2] for mitigation through the whole-building integration of environmentally responsive design strategies, low-energy building systems, and greater levels of energy-awareness and engagement from building occupants. A global vision that drives the existing and new building stock toward Zero Net Energy (ZNE), or even net positive performance levels would profoundly change the environmental impact of the building sector on our planet.

In commercial buildings, which account for roughly half of the energy used by all U.S. buildings (U.S. DOE 2011), decisions related to fenestration in the building envelope directly affect the largest energy end uses (HVAC and lighting) and are thus a central area of focus for performance improvements aimed at enabling low energy buildings. Replacing one square meter of opaque building envelope with a transparent element causes three fundamental changes to the energy balance of a building: (1) it admits daylight which can be used to offset electric lighting use, (2) it increases direct conductive/convective thermal losses/gains that can increase heating and cooling loads, and (3) it increases solar gain which might offset heating in winter but increase cooling in summer. Given the range of building types, sizes, and climates there is wide variability case to case. But in most instances these design decisions have significant impact on overall building loads and resultant energy use, as well as occupant comfort.

[1] Most of building GHG emissions (6.02 Gt of 9.18 $GtCO_2eq$) are indirect CO_2 emissions from the consumption of electricity.

[2] https://www.ipcc.ch/publications_and_data/ar4/syr/en/mains4-3.html (Fig. 4.2, WGIII Fig. SPM.6).

Daylight is a renewable source of high efficacy light, which makes the daylighting of buildings an attractive energy strategy compared to the standard practice of continuous electrical lighting. In the United States, lighting represents the single largest commercial building electricity end use (0.78 exajoules (EJ)) (724 Trillion Btu) (EIA 2012), and is consumed primarily during daylight hours. Of the total averages, it is estimated that 60% is consumed in perimeter zones[3] located 0–12.2 m (0–40 ft) from the building facade during typical daytime work hours (8:00–18:00) (Shehabi et al. 2013). One square meter of sunlight contains enough lumens to illuminate 200 m^2 of floor space, so the challenge is control and distribution. The luminous efficacy of daylight, as filtered through spectrally selective glazing is also good, in the same range as the best available LED lamp efficacy or ~ 120–250 lumens/watt. The key challenge of daylight is to distribute it effectively across the occupied floor area and to control glare from both sun and sky. Diffuse daylight (directly from the sky, reflected from exterior surfaces or diffused from sun control systems) can provide adequate flux to reduce electric lighting to a five-meter depth in an office. Redirecting sunlight via active and passive daylighting optics can extend that range to over ten meters.

Cooling loads represent another significant energy end use (14%), and one-third is due to electrical lighting and another one-third to solar heat gains through windows (Huang and Franconi 1999). Because low-energy projects often implement passive or low-energy cooling alternatives such as radiant systems or exposed thermal mass with night-flush ventilation, effective solar control is a requirement to avoid exceeding the cooling capacities of these systems, which are typically lower than conventional mechanical HVAC, and consequently more sensitive to peak solar heat gains. Therefore, fenestration strategies that control solar loads while transmitting sufficient daylight to minimize the need for electrical lighting in perimeter zones have the potential to significantly improve overall energy performance.

The goal in achieving dramatic reductions in building energy use is to convert building facades from their current role as a net energy cost to a net benefit. This requires converting the facade from a net energy loser to energy neutral, or even a supplier of energy on an annual basis by reducing thermal losses, actively managing thermal gains, integrating operable windows to reduce cooling and ventilation loads, utilizing daylight to offset electric lighting and integrating solar collection (e.g. solar photovoltaic or transpired solar collector systems). For example, the Lawrence Berkeley National Laboratory (LBNL) has calculated that total window area in the U.S. commercial building stock currently consumes 1.56 (EJ) but could be converted to a 1.16 EJ net energy gain if all windows were converted to high performance systems (Apte et al. 2006) (Fig. 1.1). Simulation-based studies using a standard office building located in Chicago, IL have shown that even the application of available, “off-the-shelf” fenestration technology packages can outperform opaque insulated walls (Lee et al. 2009) if intelligently designed and managed.

However, recasting the building envelope as a supportive element of the building energy concept represents a more complex challenge than a simple technology switch. Effectively utilizing the building envelope as a mechanism to

[3]Excluding non-applicable floor space such as religious worship or vacant space.

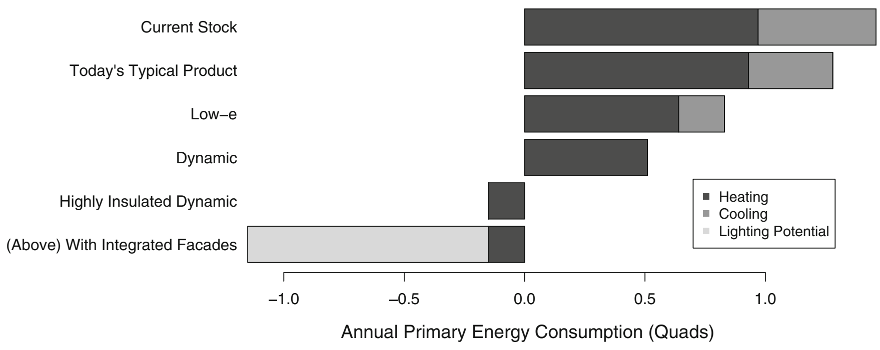

Fig. 1.1 Facade energy impacts in U.S. Commercial Building Sector (data from Apte et al. 2006). Current facade/window stock is estimated to consume ~1.56 EJ (~1.48 Quadrillion Btu (Quads)) (~$20B USD); replacement by improved technologies reduces energy as indicated; "Integrated Facades" with full daylight potential offsets lighting loads of 1.05 EJ (1.0 Quads) for a total net reduction of 1.20 EJ (1.14 Quads)

leverage environmental services available from natural systems requires fundamental changes to contemporary (i.e. Business As Usual (BAU)) design practices, particularly in regard to building form, massing, and interior organization. As one notable example, the John & Frances Angelos Law Center demonstrates the integration of building form, facade elements and building systems to minimize demand for mechanical space conditioning and electrical lighting energy in a large 17,837 m^2 (192,000 ft^2) academic building. Located in a cooling-dominated climate (Baltimore, MD), where sealed facades and air-conditioning are standard practice, the project illustrates one case study of an environmentally-responsive alternative model, which yields additional co-benefits for building occupants through the provision of greater access to daylight, visual connection to the exterior, and greater control over indoor environmental conditions.

The Law Center program is subdivided into individual volumes (Fig. 1.2), which interlock with a multi-story daylit atrium (Fig. 1.3). The void space created

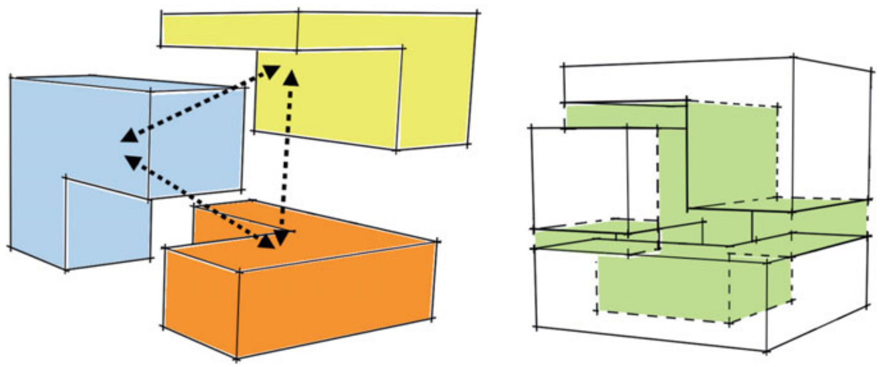

Fig. 1.2 Subdivision of the John & Frances Angelos Law Center program into individual volumes, which interlock with a multi-story daylit atrium. *Image credit* Behnisch Architekten

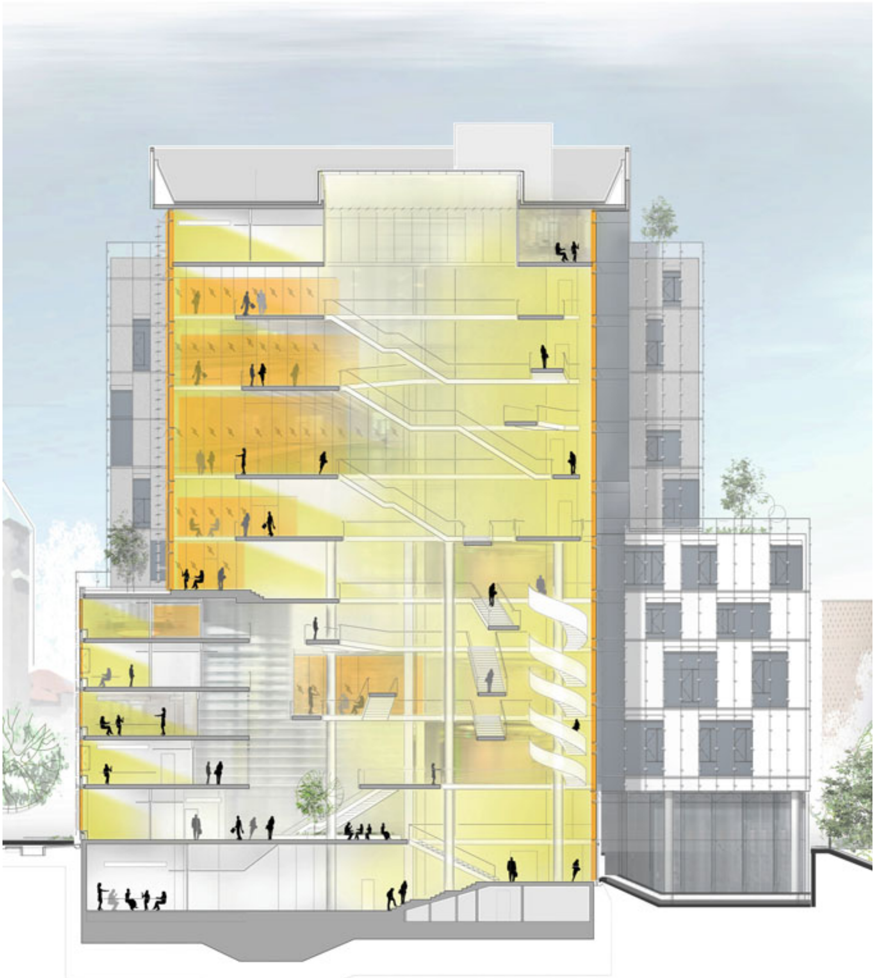

Fig. 1.3 Building section of the John & Frances Angelos Law Center showing the side and top-lit daylit atrium space that serves as the primary means of circulation. *Image credit* Behnisch Architekten

by the separation of program volumes increases the available surface area for fenestration, both on the exterior building envelope and facing the interior court-yard, enabling all regularly occupied areas of the building to have access to daylight and views, while simultaneously seeking to achieve a low whole-building energy target through the utilization of the building envelope (Fig. 1.4) for daylighting, management of solar gains, natural ventilation and space cooling. Massing and envelope strategies are supplemented with dynamic (climate responsive) facade solar shading, automated windows, thermally active interior surfaces, and

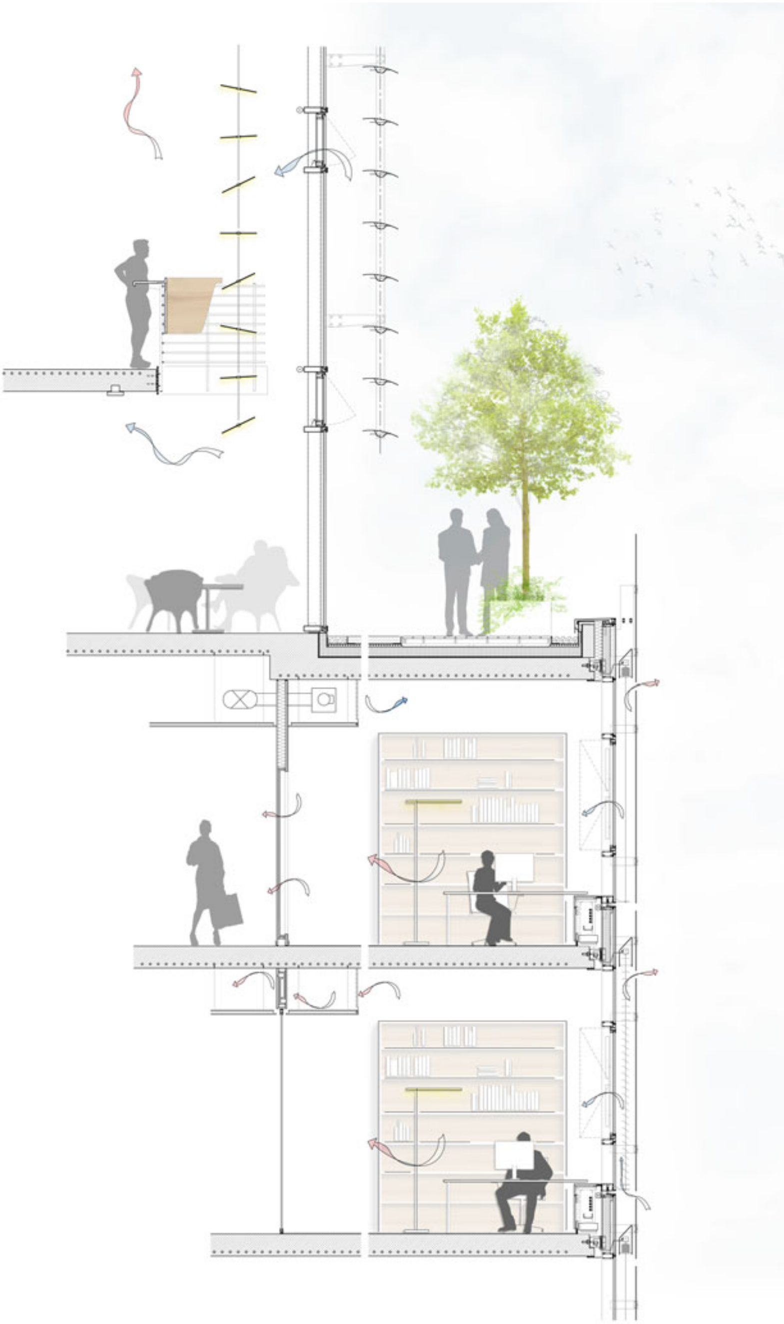

Fig. 1.4 The John & Frances Angelos Law Center atrium facade (*upper floors*) and office/classroom facade (*lower two floors*) wall section. *Image credit* Behnisch Architekten

occupant-aware, daylight-dimming electrical lighting controls. The project is predicted to achieve an Energy Use Intensity (EUI) of 126 kWh/m^2-year (40kBtu/sf-year). If this performance outcome were achieved, the project would meet the energy target of the AIA's 2030 Commitment with a 62.2% carbon emission reduction compared to the Energy Star 50th percentile building.

The concepts implemented in the John & Frances Angelos Law Center are not fundamentally new, but they are not routinely achieved in practice. There is an opportunity to better realize these underlying design approaches in virtually all buildings, not just for special case projects and not simply in the U.S. but globally. Achieving this potential requires addressing a broad set of factors for enabling effective daylighting as a central driver for low-energy, low-carbon buildings. These factors are discussed in the following sections of this chapter.

1.3 Fenestration Design Impacts on Electric Load Shape and Demand Response

Utilities are concerned as much about the timing of electrical energy use as the total use since the power plants and transmission lines are capacity limited. Accordingly, most commercial buildings pay a "demand charge" for peak power use and an "energy charge" for total energy used. Commercial building rate structures are complex, with differential rates for the same unit of energy power consumed during the day vs. night, and summer vs. winter since most utilities experience peak loads during hot summer afternoons. Utilities initially set up special "demand response" programs designed to reduce electric use during the 10–20 peak days of the year. Owners discovered that many of these demand reduction strategies could be used throughout the year. Buildings that can flexibly adjust their electric use in response to price or utility request also have added flexibility in meeting energy and cost performance goals.

Effective daylighting and solar control can play an active role achieving and optimizing the electric load management capabilities of buildings integrated into the expanding "smart grid" of advanced "time-of-day" smart meter infrastructure. This infrastructure enables time-of-use and automatic DR programs which seek to reduce consumer demand for electricity during periods of peak usage or unexpected restrictions in supply. This need will grow in the coming years due to increasing regulatory requirements, increased reliance on time-variable renewable supply and other economic drivers (Fig. 1.5).

Typical commercial building load shapes peak during the afternoon when daylight availability is greatest. Consequently, "daylight autonomous" buildings designed to operate comfortably with minimal electrical lighting during peak demand periods have the potential to significantly reduce loads on the utility grid. However, it is important to simultaneously manage cooling loads due to solar gain. Integrated control of automated solar shading systems, electrical lighting systems,

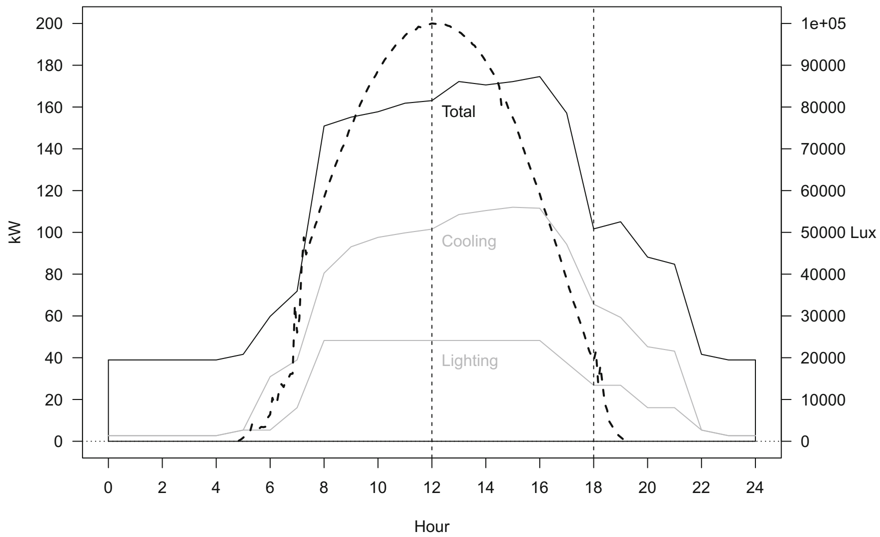

Fig. 1.5 Example load shape of a modern (2004) medium commercial office building located in Los Angeles, CA. Vertical dashed lines from 12:00 to 18:00 indicate the critical "peak" period of statewide demand. *Dashed curve* indicates daylight availability in Lux

operable windows for natural ventilation, and thermal charging/discharging of interior thermal mass has the potential to further increase load-shed and load-shifting capabilities by shifting or reducing cooling loads while maintaining occupant comfort and whole-building energy efficiency.

1.4 Daylighting Impacts on Human Health, Well-Being and Performance

While the optimal management of solar energy is a fundamental consideration for achieving low energy performance objectives, daylighting to support human needs for light in buildings is a far more complex challenge. A growing body of research in the disciplines of photochemistry, photobiology, and human physiology demonstrates that access to daylight and window views have a range of impacts on human health, well-being and performance (Fig. 1.6).

Greater emphasis on the provision of access to window views for all occupants is helping to invert conventional space planning practices for office buildings in the U.S. by placing open-plan offices along the perimeter of the floor plate and locating enclosed cellular office space in the core. For larger buildings, view requirements for the majority of regularly occupied space necessitates a transition from relatively "fat" floor plate buildings with a low surface-to-volume ratio to "thinner" more elongated and complex building forms, with a higher surface-to-volume ratio. Even

Fig. 1.6 Core zone of a large office building lacking access to daylight and views. A homogeneous and steady-state lighting condition is provided by ambient overhead fluorescent lighting. In such environments, lighting provided by electrical sources may be adequate for visual task performance but lack the appropriate spectrum and intensity required to effectively stimulate the circadian system, creating zones of "biological darkness"

in the case of deep floor plate buildings, emerging metrics aimed at quantifying and rating available views, such as the view factor adopted by the LEED rating system (U.S.G.B.C. 2014), serve as an incentive for designers to increase glazed area to achieve required view factors, creating significant technical challenges for managing thermal and visual comfort along the perimeter.

Beyond the needs of the human visual system, the discovery of a novel photoreceptor that mediates the response of the human circadian system to light has led to a growing interest in the "non–visual" effects of light on human health and well being. Much like the ear has dual functions for audition and balance, the human eye has a dual role in detecting light for vision and for adjusting the "circadian clock" which governs most 24-hour behavioral and physiological rhythms (Lockley et al. 2003). Humans possess an internal biological clock that regulates daily patterns of activity following the natural 24-hour light-dark cycle. The suprachiasmatic nuclei (SCN) hosts the circadian clock (or circadian system) responsible for orchestrating the daily timing of biological functions. These functions include sleep/wake, alertness level, mood, hormone suppression/ secretion, and core body temperature. In most people, the period of the SCN is slightly greater than 24 h and relies on patterns of light received at the retina to maintain entrainment with the 24-hour light-dark cycle of the local environment.

In indoor environments, where it is estimated that U.S. adults spend nearly 87% of their lives (Klepeis et al. 2001), lighting is often provided by electrical sources that are adequate for visual task performance, but may lack the appropriate spectrum and intensity required to effectively stimulate the circadian system. In contrast to the visual system, which is maximally sensitive to (~555 nm) "green" light, the action spectrum of light for the circadian system is shifted towards shorter wavelength (~460-480 nm) "blue" light (Brainard et al. 2001, Thapan et al. 2001). In addition to spectrum, the intensity of light required to stimulate the circadian system is significantly greater than that required for the visual system for task visibility and must be present for an extended period of time. Therefore, light that may be perceived as adequate for visual tasks may not be effective for circadian stimulus. Further, the time during the day when circadian-effective light is present is important. Bright light in the morning will advance the phase of the circadian system, while bright light in the evening will have a phase-delaying effect. Over time, lack of sufficient exposure of the retina to bright, circadian-effective light can disrupt the circadian system, which can in turn lead to poor sleep, reduced performance, and increased risk of a range of health maladies including diabetes, obesity, cardiovascular disease and cancer (Zelinski et al. 2014). While the underlying science is convincing that these are important effects, the specific cause/effect relationships, the overall impacts on occupants and the appropriate design responses are still evolving (Fig. 1.7).

Until recently, conventional light sources could not readily control the variable spectrum and intensity needed to address these biological needs. The electrical lighting industry is now beginning to promote Solid State Lighting (SSL) technologies as a vehicle to more easily change the spectral content and intensity of light than with gas discharge sources and thus should be more effective for maintaining circadian entrainment in buildings. It is now technically possible for an RGB-based LED to match any desired equivalent daylight color and intensity with the right sensors and controls, and SSL task lighting can be used to produce a circadian-effective light stimulus over a small area most relevant to an occupant's required vertical dose at the eye. However, these approaches require substantial cost and effort, and providing the vertical dose at the eye places significant restriction on occupant mobility.

Daylight is an attractive alternative to electrical lighting for maintaining human circadian entrainment indoors due to its spectrum, intensity, general availability, and potential to be introduced into spaces via windows and skylights. Enabling designers to achieve and optimize "circadian effective" daylighting strategies will require a new set of performance objectives, measurement techniques, assessment tools, and design strategies to ensure the appropriate spectrum, timing, intensity, and duration of light is delivered to maintain healthy circadian entrainment. Figure 1.8 presents an example application (described in greater detail in Sect. 2.4.3) of an emerging simulation-based approach to assess and summarize the circadian effectiveness of eye-level daylight exposures over an annual period within a space.

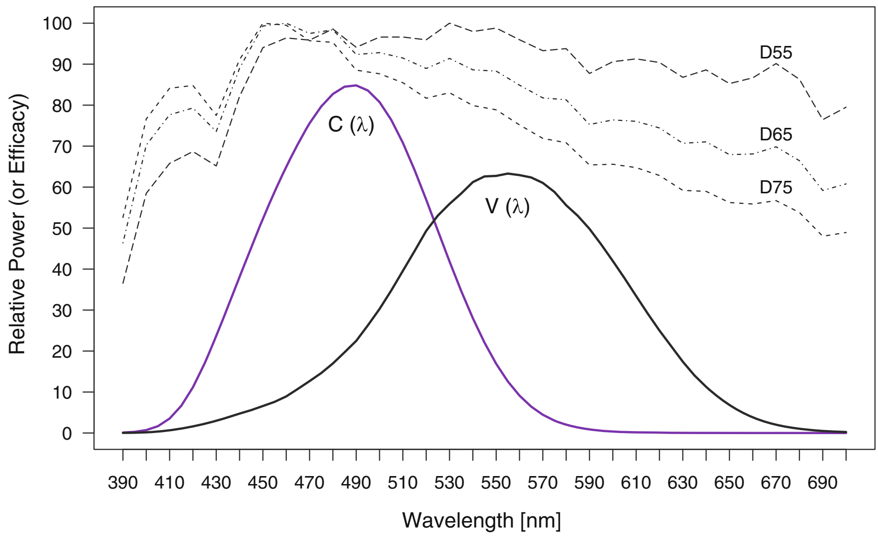

Fig. 1.7 Comparison of spectral response of the visual (photopic) system (V-Lambda) and the circadian system (C-Lambda) to the relative spectral power distributions of three CIE daylight illuminants: (D55) sunlight, (D65) overcast sky, and (D75) north sky daylight. *Note* Both *response curves* are scaled to have equal area under the curves

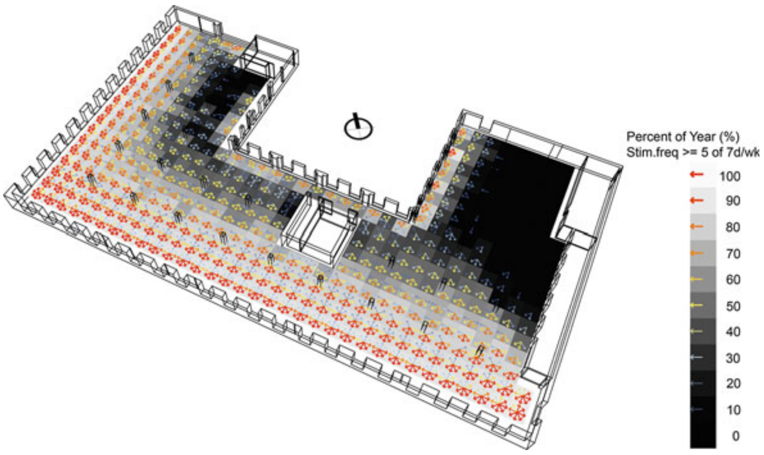

Fig. 1.8 Perspective view of building floor plate located in Downtown Los Angeles showing annual result for the percentage of analysis hours during the circadian resetting period (7:00–10:00 AM) where a minimum stimulus frequency of 71% (5 of 7 days/week) was achieved

Spatial-based exposure results can be used to identify, quantify and visually examine building zones where long-term occupancy may lead to disruption of the circadian system in the absence of supplemental electrical lighting capable of effective circadian stimulus, or other daytime exposure. While theoretical knowledge and scientific findings are sufficient to begin to propose metrics and procedures to classify indoor daylit spaces in terms of anticipated circadian effectiveness, this remains an emergent and active research area.

1.5 Design for the Next Century

The use of daylight to reduce energy consumption and enhance Indoor Environmental Quality (IEQ) is one of the most common claims made for commercial office buildings promoted as "sustainable", "energy efficient," "green," or "high performance." Claims of successful daylighting are often based on the use of large areas of high Visible Light Transmittance (VLT) facade glazing, photo-controlled electrical lighting systems, and results from lighting simulations performed during design that demonstrate compliance with green building rating system criteria (e.g. USGBC LEED Daylight and View EQ credits). Design decisions are often based on the assumption that making the building envelope as transparent as technically possible will lead to an increase in the amount of interior daylight available, leading to greater levels of occupant satisfaction and visual connection to the outdoors. But it then becomes a tremendous technical challenge to provide thermal and visual comfort immediately adjacent to a floor-to-ceiling glazing design and to address HVAC loads from the glazing.

Buildings are rarely studied in use to examine if "transparent" facades achieve design intent for overall energy and occupant comfort and performance, even if they achieve the goals of high visual transparency or daylight transmission and meet minimum code requirements. When conducted, Post Occupancy Evaluation (POE) studies often demonstrate that "unshaded", highly glazed facades produce indoor environmental conditions which are often visually and thermally uncomfortable (or, at times, intolerable) for occupants, leading to formal and informal modifications to the facade that can significantly limit anticipated energy reduction and IEQ benefits. Unshaded highly glazed facades are also likely to have high heating and cooling loads, depending further on climate and orientation. The result may be a transparent facade "design" that is made largely semi-transparent or even opaque "in operation" by occupants to reduce discomfort. Figure 1.9 shows the operational outcome for a "transparent" southwest-facing facade located in San Jose, California, a climate with predominantly clear skies. The southwest facade was photographed informally over more than four years, where interior shades were observed to occlude the majority of facade glazing, and remain static in place for months, or in some cases years (Fig. 1.10).

Fig. 1.9 Common outcome of a “transparent” facade made largely opaque by its occupants, limiting daylight transmission and views to the outdoors. South-west facing facade of commercial office building in San Jose, California, where sky conditions are typically clear. *Image credit* Prof. Charles Benton

Contemporary daylighting design practices, which favor highly glazed “transparent” facades, emerge in part from the relatively cool, heating-dominated climates of northern Europe, which have predominantly overcast skies and low demand for air conditioning. Due to a lack of effective shading, even in moderate U.S. climates with significant hours of sun, such as San Jose, CA or Los Angeles, CA, facade solar heat gains lead to significant cooling loads that are conventionally offset by the use of air conditioning. In contrast to the location of most existing “transparent” architecture, the majority of future growth in the 21st Century will be in much warmer climates. The export of contemporary “transparent” architectural design features to these locations, without any compensation for climate, will have significantly greater adverse effects on energy (and carbon) outcomes due to the level of air-conditioning needed to make such buildings operable, combined with the generally greater carbon intensity of the electricity supply in many regions. Using the simple metric of Cooling Degree Days (CDD) as an indicator of annual cooling demand, Fig. 1.11 compares the cooling demand in the U.S. cities San Jose (the location of the example shown in Figs. 1.9 and 1.10) and Los Angeles (in light blue) with the regions that are anticipated to experience the majority of urban growth in the 21st century (dark blue). The current population (in millions) of each region is shown in parenthesis.

Alternatively, integrating a high-transparency glazed envelope that provides daylight with a design that incorporates effective solar control to enable passive and

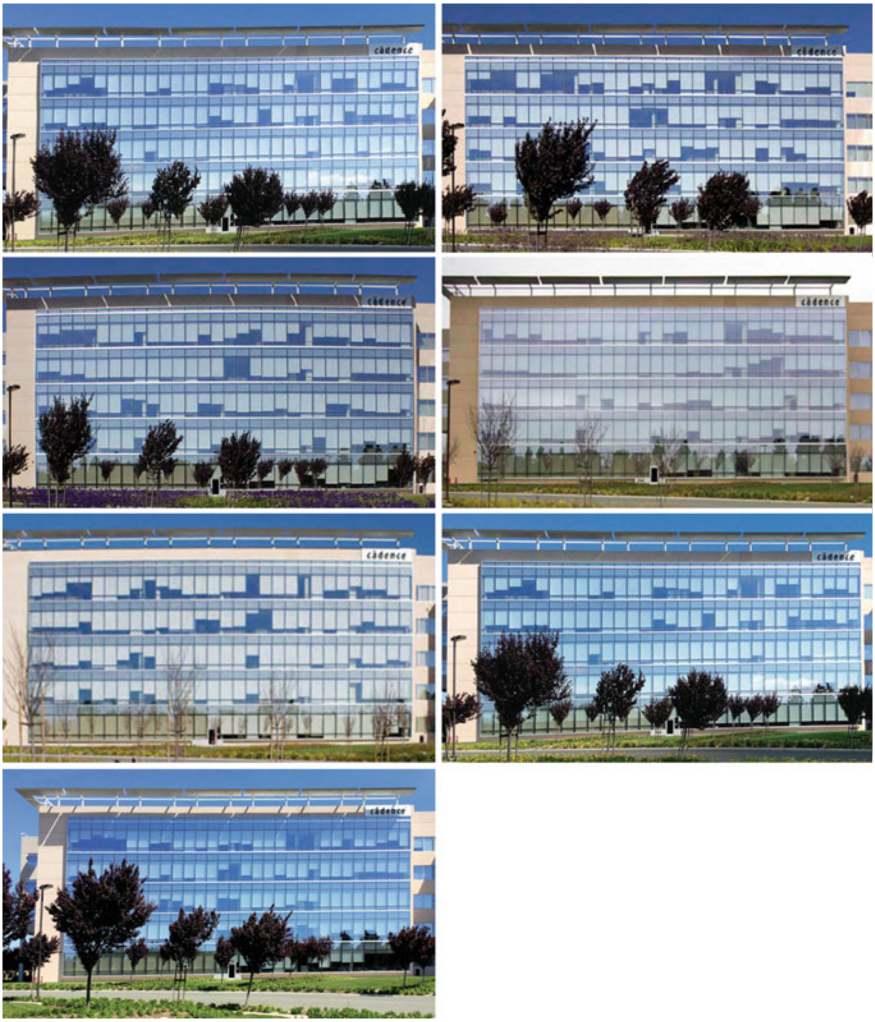

Fig. 1.10 Example operational outcome for a “transparent” facade located in San Jose, California, a climate with predominantly clear skies. Date of each image, clockwise from top left, August 2009, December 2009, January 2011, October 2012, April 2014, August 2011, August 2010. *Image credit* Prof. Charles Benton

low-energy cooling can provide not only the daylighting benefits but the co-benefit of greater operational reliability (i.e. “passive survivability”) during potential interruptions to the electricity grid as well as greater potential for demand response to manage time dependent electric load. For example, consider the floor plate of the 10-story, 22,500 m^2 office tower in Canberra, Australia, which is sidelit on three sides by a floor-to-ceiling glazed facade curtainwall (spectrally-selective low-e facade glazing (VLT 62%, SHGC 0.28, u-value 1.64 W/m^2K)). Facade glazing is

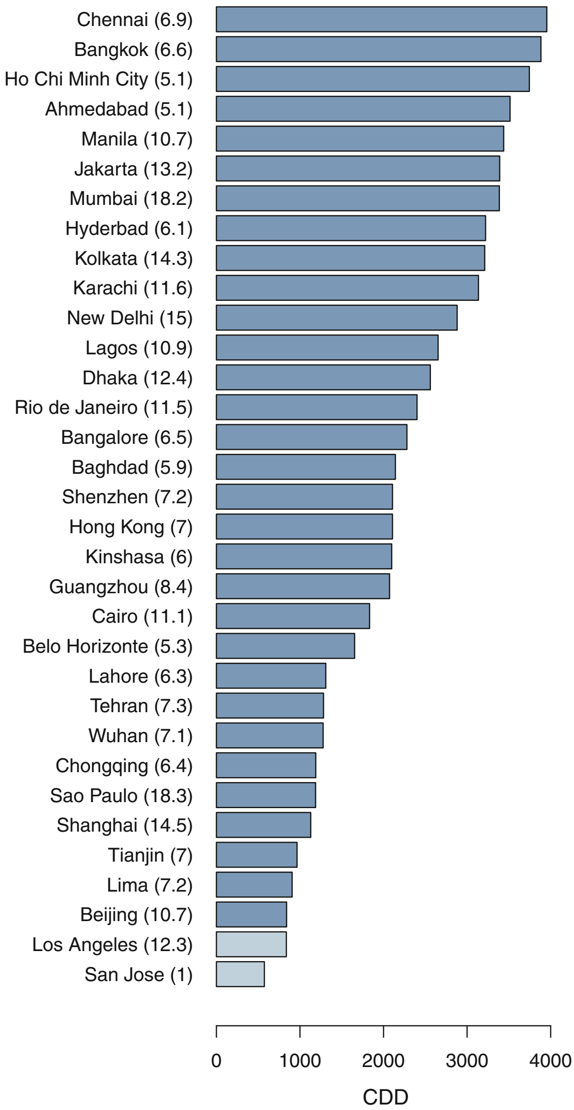

Fig. 1.11 Comparison of annual cooling demand (reported in terms of Cooling Degree Days (CDD)) for the U.S. cities San Jose and Los Angeles with the regions anticipated to experience the majority of urban growth in the 21st century. Figure after "Crank it Up," published August 18, by the New York Times (NYT 2012). Data shown in dark blue originally from Michael Sivak, University of Michigan (http://www.nytimes.com/interactive/2012/08/19/sunday-review/19rosenthal-ch-int.html?action=click&contentCollection=Sunday%20Review&module=RelatedCoverage&region=EndOfArticle&pgtype=article)

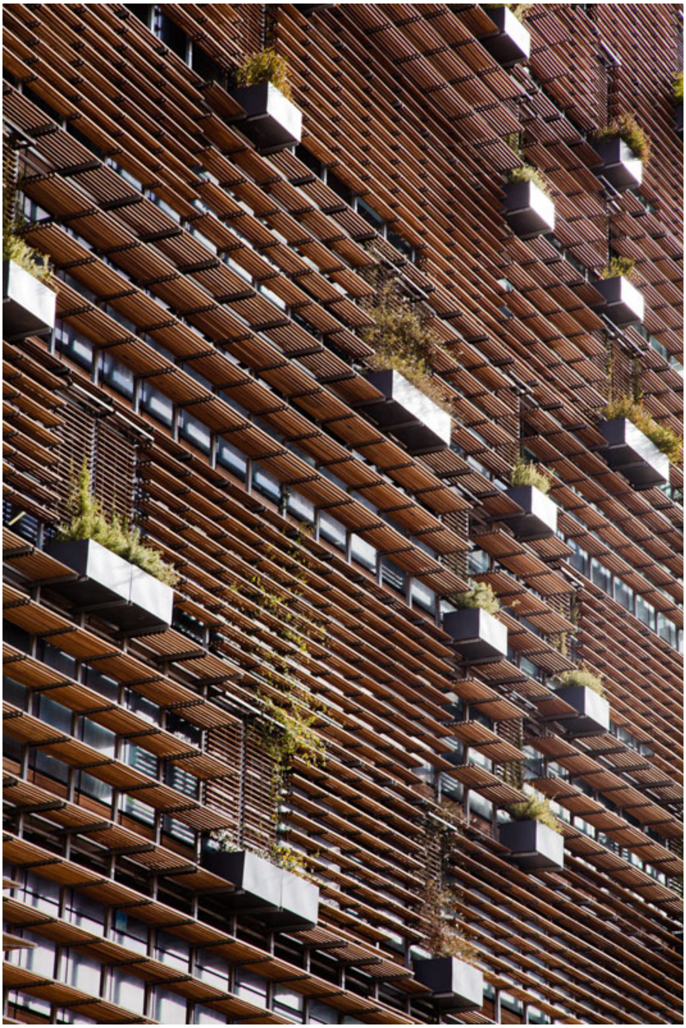

Fig. 1.12 Exterior solar control screen of the NewActon Nishi office building in Canberra Australia. The exterior screen is designed to limit peak solar radiation to 60 W/m^2, enabling the application of low-energy environmental control strategies (natural ventilation, automated night flush cooling of exposed concrete thermal mass and ventilation via an underfloor air distribution system). *Image credit* Carl Drury

shaded by external fixed horizontal wood louver screen (Fig. 1.12) engineered to provide sufficient solar control to enable the application of passive and low-energy cooling strategies as an alternative to forced-air HVAC (Fig. 1.13). The blocking angle for the louvers was calculated to limit peak solar gain to 60 W/m^2. This was done so that a high efficiency/low temperature under-floor air system, paired with natural ventilation and night-flush cooling could be utilized while still meeting peak

Fig. 1.13 View along integrated access way showing open state of automated *upper windows*. *Image credit* Carl Drury

cooling demand. Analysis was done in proprietary engineering software to study various external shading strategies (horizontal and vertical) and glazing combinations using Canberra climate data. Additional glare control is provided to occupants by manually operated interior roller shades (VLT 6-9%).

Excluding renewable energy generated on site, in 2015 the building resulted in a measured (and publicly disclosed via the Australian Government's Commercial Building Disclosure (CBD) program) annual energy consumption of 1661,000 kWh (74 kWh/m^2-year), and an annual carbon emission intensity of 46 $kgCO^2$-e/m^2, making it one of the most resource efficient commercial buildings in Australia.[4]

1.6 Challenges of Time and Scale

The challenge of effective daylighting lies not only in achieving low energy outcomes that simultaneously support end-user psychological and physiological needs for light, but in doing so rapidly and at scale to avoid locking-in the current inefficiency of Business As Usual (BAU) practices for the next 50–100 years. While the topic of daylighting in architectural publications often focuses on unique building types or newly constructed high-budget projects, addressing the problem of scale requires

[4]https://cbdportal.cbd.gov.au/Download/ShowPdf?id=B1800-2015-1.

practices that can be replicated broadly across a range of project types, regions and budgets. Scalability is necessary to meet carbon mitigation goals and important for ensuring equitable access to indoor environments that support high levels of health and well-being for occupants. Consequently, designers are faced not only with developing innovative, new prototypes and practical strategies for retrofits to the existing building stock, but in demonstrating the effectiveness of performance outcomes to stimulate market adoption. To illustrate the magnitude of the challenge using an example from California, the existing California building stock must become 40% more energy efficient by 2030 to achieve statewide greenhouse gas emission reduction targets (e.g. Executive Order S-3-05). Taking into consideration only the commercial building stock existing today (totaling ~465 million square meters (~5 billion square feet) as of the most recent survey, completed in 2006), achieving this target would require deep-energy retrofits to 36 million square meters of commercial buildings each year beginning now (i.e. 2017). Promoting widespread energy efficient design practices in the 21st century requires the creation of a body of evidence demonstrating that practices lead not only to reliable performance and more efficient resource use, but also to indoor environmental conditions that are preferred by occupants over conventional sealed and mechanically controlled environments.

1.7 Defining Effective Daylighting

One of the central barriers to effective daylighting is that daylighting *performance* is often defined differently by different stakeholders, leading to a fragmented approach to performance assessment in the design and operational life-cycle of buildings. For example, a mechanical engineer may define performance in terms of achieving low Energy Use Intensity (EUI) or Zero Net Energy (ZNE) whole-building performance. Alternatively, an architect may define performance in terms of the aesthetic qualities of daylight distribution in the space or the perceived level of visual transparency of the building facade. The client may define performance based on whether or not the project complies with the requirements of green building certification criteria for daylight sufficiency and views. Finally, building occupants may judge daylighting performance based on their perception of daylight sufficiency, visual comfort, and available views or the level of controllability provided by the design to adjust and adapt to dynamic environmental conditions at their workspace. Thus, daylighting performance encompasses a range of factors that, if considered in isolation, can lead to misleading conclusions. A space that "maximizes" daylight transmission to reduce electrical lighting energy consumption but results in visual discomfort may lead to constant use of interior shading devices as well as ad hoc and formal modifications to the facade (or workstations), which significantly changes the design intent.

At a fundamental level, effective daylighting can be defined as “building designs that deliver on performance goals.” This will require new or enhanced practices that simultaneously embrace three central elements: (1) daylighting design objectives that support a low energy concept, (2) design strategies that routinely meet end-user needs for daylight access, views, visual/thermal comfort, and personal environmental control and, (3) feedback mechanisms that are applied during the design, delivery and operational stages of the project to align performance in use with design intent.

It is common today to hear about the processes of “integrated design,” or “multi-disciplinary collaboration”, which have become widely promoted for improving whole-building energy efficiency through greater collaboration of various project team members and system integration during the design stage. Effective daylighting expands the concept in two significant ways. First, effective daylighting incorporates validation and learning during the delivery and operational stages of projects, with the goal of creating a body of empirical evidence from the field that can be leveraged by design disciplines to inform future projects and practices. The Architecture, Engineering and Construction (AEC) industry is extremely risk averse, and slow to adopt promising technologies and design strategies without proof from real buildings in use demonstrating both energy performance and high levels of end-user acceptance. Therefore, trustworthy feedback in the form of measured data that supports validation and learning are critical for differentiating innovative design practices, identifying technologies that work, correcting failures, improving market adoption, and broadly disseminating knowledge to improve design practices and technology performance specifications. Second, where integrated design is traditionally focused on a narrow objective of energy optimization, effective daylighting includes multiple human-factors performance goals as well as novel feedback mechanisms to position end-users as a central indicator of project performance (see Chaps. 2 and 6). Finally, accelerating the flow of knowledge and experience across this “design-operations” feedback loop should also pressure and encourage the building industry to innovate more rapidly and successfully to deliver new integrated facade technologies and systems that are more reliable and lower cost, thus making it easier for teams to achieve their design goals.

1.8 An Agenda for Effective Daylighting

Enabling broad application of effective daylighting requires an agenda for addressing factors that currently limit optimal utilization in contemporary design practices, project delivery and performance in use. The following sections frame an agenda within the context of three central transformations:

1. From compliance-based to performance-based design.
2. From static and unresponsive to context-aware and adaptive systems.
3. From theory to validation, feedback and learning.

1.8.1 From Compliance-Based to Performance-Based Design

Daylighting has been seen as an energy efficiency strategy since the oil embargo of the 1970s and its relative importance has evolved over time. There are a growing number of new incentives for the use of daylight as a strategy for electrical lighting energy reduction and enhanced IEQ. These include green building rating systems (e.g. LEED), standards for the design of energy efficient buildings (e.g. ANSI/ ASHRAE/USGBC/IES Standards 90.1-2013 and 189.1-2014) energy code lighting power adjustments for photocontrolled electrical lighting (CA Title 24 Building Energy Efficiency Standards for Non-Residential Buildings) and emerging standards focused on occupant health and well being (e.g. the International WELL Building Institute's WELL Building Standard). However, because these are fragmented (and often conflicting) objectives, projects designed to achieve various compliance criteria often fail to integrate daylighting goals within a whole-building energy strategy or make optimal use of the daylighting potential of the local climate to serve the diverse array of end-user needs for daylight. This is largely due to the fact that many of the design decisions occur after design development, for code-compliance purposes or to obtain green building certification rather than during the early stages of design, where the largest impacts on project performance are established. It is critical to have well-defined performance goals at the start of design and for performance evaluation to be integrated into the planning and schematic phases of design, where feedback from analysis can inform design decision-making to improve the environmental quality and energy performance of the project.

The emergence of whole-building low energy and ZNE building performance requirements combined with a growing array of human-factors objectives are driving a reversal of the conventional process of project design and performance analysis. Rather than using analysis to confirm that a predetermined design complies with various code and green building criteria, practitioners and researchers are now exploring how iterative simulation-based analysis can be used in early stages of design to rapidly identify optimal performance outcomes among multiple competing design options, and to examine trade-offs between conflicting performance goals. Performance-based design promotes the exploration of building forms, fenestration systems and controls that are "tuned" to the specific climatic, programmatic and contextual conditions of each project to optimize the use of climate for both IEQ and whole-building energy performance objectives.

At the most fundamental level, a performance-based design process is defined by a feedback mechanism utilizing analysis tools to relate prospective design strategies with measureable project outcomes (Fig. 1.14). By examining how design decisions impact project performance, particularly in early stages of design, knowledge can be generated and fed back to inform decision-making with the objective of improving the performance of future design iterations. Whole-building energy performance specifications, building energy benchmarking and public disclosure requirements, along with outcome based codes and energy-performance-based

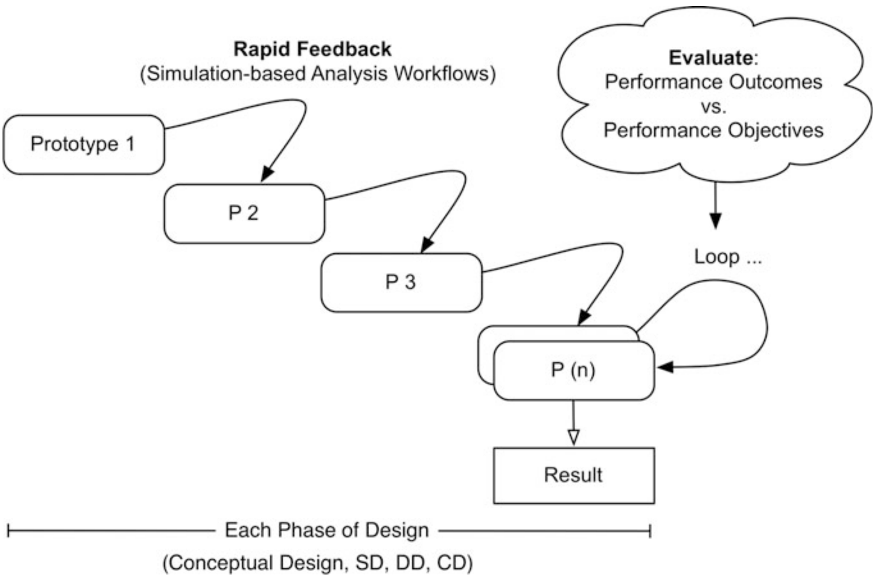

Fig. 1.14 Fundamental organization of an iterative, performance-based design process

procurement[5] adds additional incentive for design firms to seek mechanisms for reliable, early-stage performance feedback.

Implementing performance-based design in practice requires the development of new simulation-based workflows (Fig. 1.15) combining 3D authoring software with energy and lighting simulation engines, accurate thermal and optical data on all the design elements, as well as optimization and visualization tools that are capable of providing rapid and reliable analysis feedback at the pace of the design decision-making process. As projects targeting low-energy goals often implement passive environmental control strategies (e.g. solar control, natural ventilation, thermally charged/discharged mass, daylighting), which must be carefully designed in response to local climate and context, simulation tools must be capable of reliably modeling the effects of the local climate and context as well as the behavior of passive systems.

There is no single optimization tool available to translate project objectives and constraints into a holistic design outcome. Nor is there consensus for how to best manage trade-offs among various performance objectives, or how to assign relative weighting to performance metrics based on their perceived importance among various project stakeholders (e.g. design team, project manager, or end users). In the real world, one needs someone to sort the global problem into chunks that can be

[5] A procurement process where project teams are selected based on the predicted performance of a proposed design, and contractually obligated to deliver a project that performs within the range predicted.

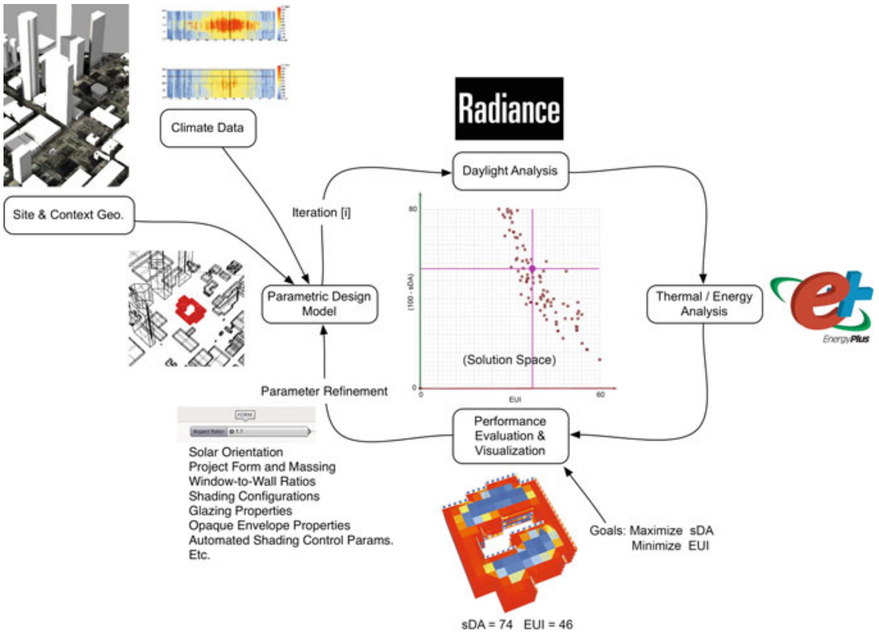

Fig. 1.15 Example performance-based design framework linking highly optimized lighting and thermal analysis with 3D parametric modeling, visual scripting and optimization tools for rapid prototype development

analyzed and optimized using available tools and guidance and then recombine those chunks into a coherent overall package. This is an ongoing and evolving process—it needs to be initiated at one level of detail in early design/schematics and then continued later (perhaps on multiple occasions) through DD, CD, VE and even late in construction. Figure 1.15, (discussed further in Chap. 4), presents an example implementation of a performance-based design framework linking highly optimized lighting (Radiance) and thermal analysis (EnergyPlus) simulation engines with 3D parametric modeling, visual scripting and optimization tools for rapid prototype development in early-stage design.

This book addresses the performance of dynamic daylit spaces from a broad perspective that includes assessment of occupant behavior, occupant subjective assessment of daylight sufficiency, view, visual and thermal comfort within a whole-building energy concept. Occupant behavior and human-factors metrics are discussed within a framework of design workflows, visualization techniques and novel "in-situ" Post Occupancy Evaluation (POE) methods capable strengthening the feedback loop between design intent and performance in use. A critical analysis of energy and human-factors performance metrics is presented in Chap. 2. Chapter 4 provides a discussion of how metrics, analysis tools and workflows are being applied within emerging performance-based design frameworks. As of the publication date of this book, all of these design processes and approaches, as well as the underlying tools, are in a continuous state of active development and refinement, promising new, enhanced options in the future.

1.8.2 From Static and Unresponsive to Context-Aware and Adaptive Systems

Contemporary approaches to daylighting design often implement static facade systems, which are incapable of responding to daily or seasonal changes in sun and sky conditions or effectively managing between the dynamic range of outdoor solar and lighting conditions and the range indoors that occupants require (or prefer). While static facade systems may serve as a practical option for some lighting and HVAC energy reduction efforts, the resulting indoor environmental conditions are often unacceptable to occupants for significant periods of time. Furthermore, while static solutions may be "adequate" for small fenestration areas that just meet compliance codes, they fall short of highly glazed designs that typify many attempts to extend daylight impacts in low energy buildings. As a result, static facades that "optimize daylight" through maximizing physical transparency often lead to retrofits and occupant modifications over the project life cycle to address glare and solar overheating which, in turn, serve to greatly reduce the anticipated energy savings and IEQ benefits. Alternatively, static facades that incorporate extensive fixed shading, small window apertures, and glazing technologies to reduce visual transparency fail to achieve energy (e.g. ASHRAE 90.1) or IEQ (e.g. LEED EQ) objectives. As the architecture, engineering and construction industries shift

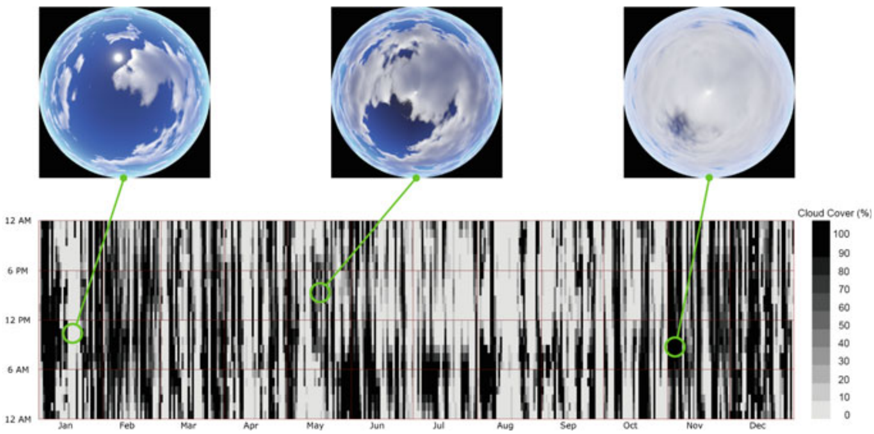

Fig. 1.16 Annual hourly cloud cover (0–100%) for San Francisco, CA

towards pursuing low and ZNE design strategies as standard practice, it is anticipated that design teams will increasingly explore the integration of dynamic, environmentally responsive facade technologies to achieve greater levels of building performance and occupant needs.

Dynamically responsive facades are needed due to the fundamentally dynamic nature of the sun and sky. Figure 1.16 shows the annual hourly cloud cover and example sky conditions for a location in San Francisco, CA. In concept, dynamic facade systems are capable of continually adjusting the envelope features to seek the optimal balance between energy and human-factors objectives for any given sky condition. However, for dynamic facade strategies to perform effectively over their life cycle requires the development of systems that are capable of modulating exterior conditions to deliver the indoor environmental conditions desired by building occupants.

Active use of the building envelope (e.g. solar control, daylighting, natural ventilation, and charging/discharging thermal mass, energy harvesting) paired with controllable lighting and HVAC systems is a complex design challenge. However, driven in part by typical building codes, application of building technology often focuses on the efficiency of individual components rather than consideration of the overall performance of multiple components working as a system. This fragmented approach needs to shift to an integrated, context-aware dynamic perspective that addresses the facade as a system that is responsive to "performance needs" at three different levels: (1) comfort and task performance needs of the occupants; (2) energy and economic needs of the building operator; and (3) the local or regional needs of the utility grid.

While significant effort has been placed on "integrated design" practices that seek to achieve greater levels of system integration during the design stage, the operational performance of integrated systems in the occupied building is limited by a number of barriers. These include (1) the lack of interoperability between various technologies, (2) challenges in deploying and maintaining large sensor arrays (e.g. unit cost, commissioning, calibration), (3) lack of detailed, granular, contextual data to drive effective real-time operation, (4) poor or non-existent mechanisms for fault detection and diagnostics, (5) lack of occupant feedback to validate controls assumptions or make adjustments, and (6) lack of holistic controls optimization frameworks (due in large part to #5). From a process point of view, design concepts may not be adequately conveyed to and implemented by the construction team, and the hand off to facility managers and occupants is often incomplete and imperfect. Improvements and innovations in the technology systems are further limited by, (1) the lack of frameworks for systems to gather and interpret performance data and learn over time, and (2) the lack of a mechanism to store and share knowledge across projects and design team members.

The result of these limitations has been failures in building performance and a resultant aversion among building designers and contractors to adopt complex but promising technologies in favor of "simple" control strategies based on the cautionary view that "simple is always better." Entirely passive, fixed solutions seem unlikely to properly address the wide range in climate and user needs in most buildings. Asking occupants to become de facto facility managers and adjust light levels, blinds, thermostats etc. seems equally unlikely in the majority of buildings. However, fully automated systems risk alienating occupants when they fail to deliver desired comfort conditions. The real world perspective also suggests that occupants may adjust building features for comfort, but will not reliably manage energy performance objectives. We suggest it is time to challenge the common knowledge that "complex controls will never work" and that hybrid models cannot be adapted to support local occupant needs.

The sensors and controls industry globally is now in the midst of a revolutionary change driven in part by the rapid advance of the "Internet of Things" (IoT) movement. The Internet of Things is the network of physical objects—devices, vehicles, appliances and other items embedded with electronics, and sensors, and linked by software-based network connectivity—that enables these objects to collect and exchange data, and then act based on that data. IoT is based on four critical elements: (1) low cost, distributed powerful sensors and embedded computing, (2) wireless communications; (3) cloud based data storage and computation, and (4) shared interoperable protocols. Much of this technology and infrastructure was created and driven initially by the smart phone industry, but is rapidly gaining traction in numerous other business realms including the building industry where the LED revolution in the lighting community is leading the way. It will likely be further accelerated by massive RD&D investments underway to develop autonomous vehicles where distributed sensing and controls-well beyond the needs of a dynamic building envelope-will need to be developed and perfected and manufactured in volume.

Figure 1.17 presents a conceptual framework for the design of IoT-enabled Perimeter Systems (IoTePS). The IoT movement can be leveraged within the building design domain to develop context-aware, interoperable building components that work to optimize the comfort and resource efficiency of buildings throughout the project operational life-cycle. The IoTePS framework is conceived as a vehicle to explore how the ubiquity of sensing, real-time data and computation will transform existing approaches towards building facade and perimeter zone technologies and the performance roles those technologies are asked to play in buildings. Of specific interest is the transformation of the building facade from a sealed and static element to a dynamic filter, operating in real time to manage a range of grid-level, building-level, and occupant-level performance goals. Charting the functional potential of dynamic behavior, informed through detailed real-time and historic sensor and occupant feedback data, will in turn serve as a basis to explore and develop new specific architectural fenestration strategies, (both technologies and design approaches), to best meet this potential.

The current challenge is to create integrated systems that are capable of delivering acceptable (or preferred) environmental conditions to occupants over an annual range of environmental conditions while simultaneously contributing to

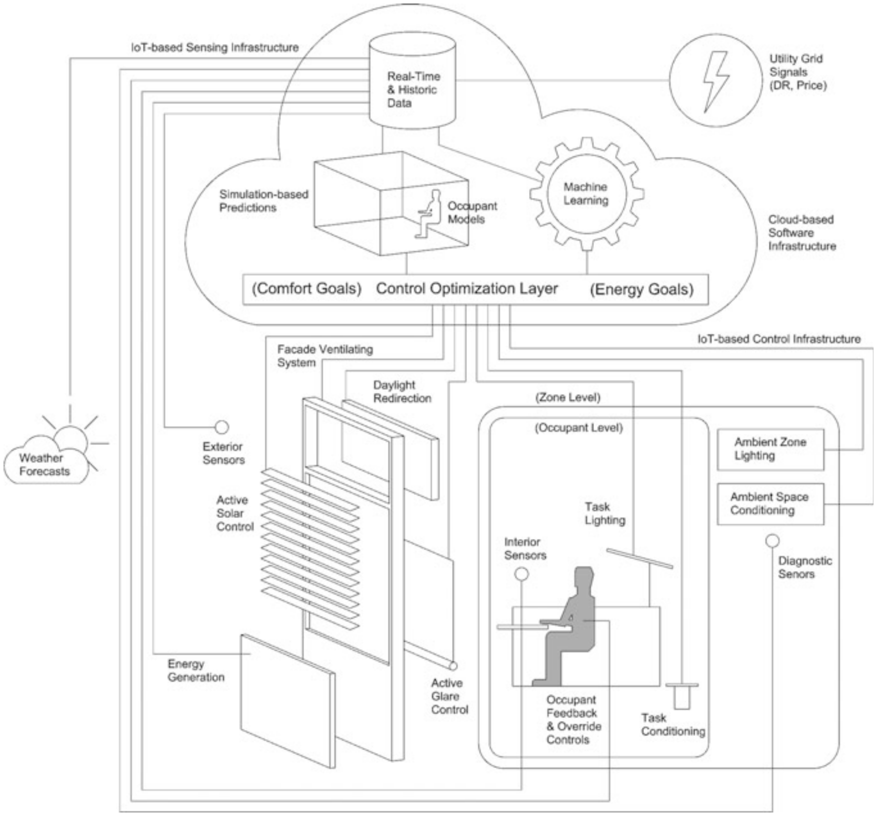

Fig. 1.17 Conceptual organization of an interconnected, human-in-the-loop facade and perimeter zone system

whole-building energy performance goals. Effective operation of automated systems requires that external and internal environmental parameters be accurately sensed, that control assumptions are validated against data-driven models of occupant behavior and subjective preferences in order to ensure long-term user acceptance, and the hardware and software solutions can be fabricated, installed and calibrated on time and on budget. As part of these solutions, appropriate user interface technologies are needed to easily integrate occupants as a mechanism for user-overrides. Achieving these objectives requires going beyond the physical integration of components in construction. The book presents emerging and novel strategies to shift from closed-loop systems and ad hoc control assumptions to context aware, humans-in-the-loop systems by leveraging the growing availability of low-cost sensing and internet-connected devices to develop interactive, interconnected systems capable of learning and adapting to changing contextual and environmental factors (e.g. Fig. 1.17). These topics are outlined and discussed in Chap. 3.

1.8.3 From Theory to Feedback, Validation and Learning

As designers seek to integrate daylighting within an efficient whole-building energy strategy, how best to manage trade-offs between objectives such as envelope thermal performance, lighting and HVAC energy demand with human factors such as visual and thermal comfort, daylight availability, visual connection to the outdoors, and personal control requires an approach informed at a fundamental level by empirical knowledge of end-user needs and behaviors. Even in the most sophisticated simulation tools and workflows, the presence and environmental preferences of occupant are often represented by crude, static and universally applied assumptions. In practice, crude application of human factors data limits the energy and carbon reduction potential of energy efficiency measures, and can lead to operational challenges and discrepancies between anticipated and measured energy consumption. Although it is unrealistic to assume that the preferences and behaviors of a specific population of building occupants can be routinely predicted with a high degree of accuracy, (particularly prior to construction of the project), it is important for designers to be aware of the large array of human-factors assumptions embedded in software-based design tools and understand the impacts these assumptions may have on anticipated performance outcomes.

Existing lighting design metrics are based on a legacy of controlled human-factors laboratory experiments yielding universal design guidance. This guidance, originally intended for electrical lighting design applications, is not well suited to the design of daylit spaces. In contrast to the static and spatially-homogeneous conditions produced from electrical lighting, daylit spaces respond dynamically to hourly, daily and seasonal changes in sun and sky conditions, and generally produce higher luminances and luminance contrasts throughout the space due to the greater intensity of light from the sun and sky as well as the location of fenestration in the occupants' vertical field of view (Fig. 1.18).

Although there is growing consensus for the importance of daylight and views in commercial buildings, there is less consensus for how performance objectives such as daylight sufficiency, visual comfort, and view should be defined, measured, relatively valued, and how results should be interpreted over an annual basis to assess success or failure. Consequently, designers are unable to reliably assess end-user outcomes during design, or optimize a design to balance energy objectives with occupant comfort. How building occupants accept, adapt to, and modify

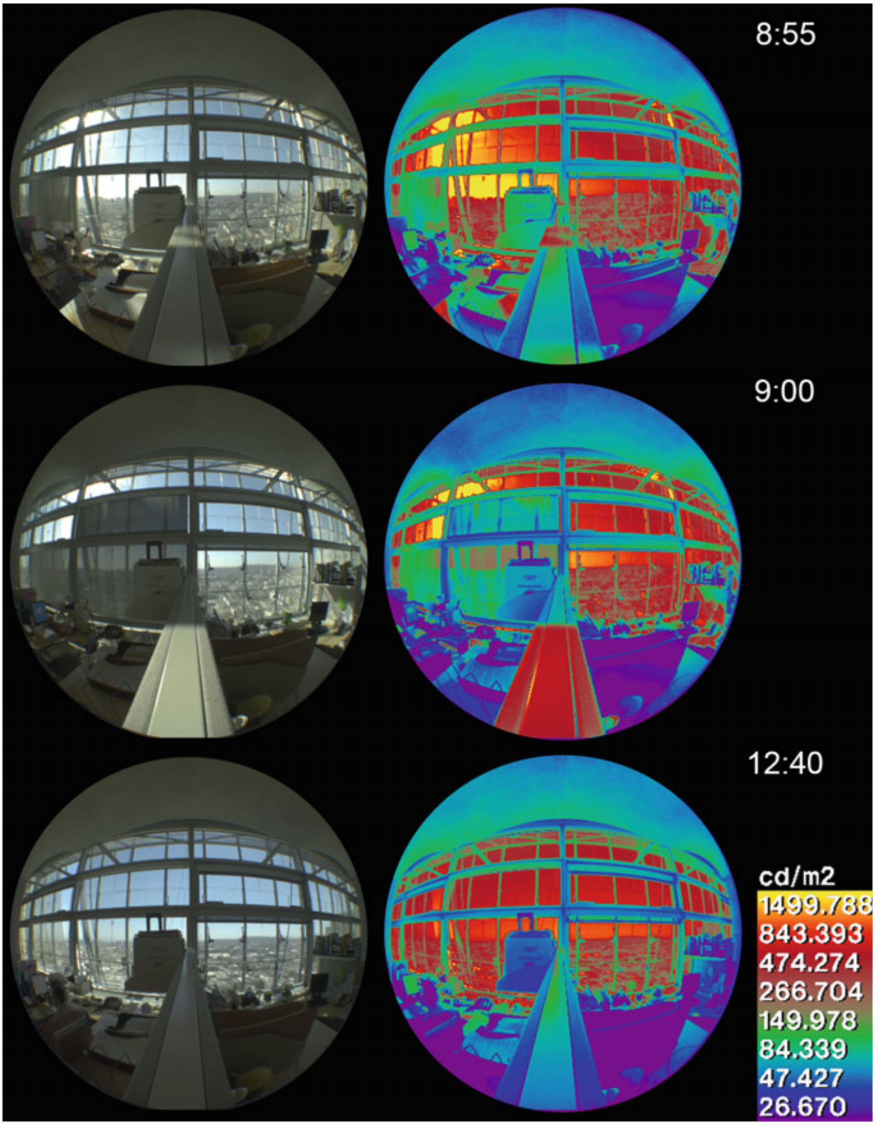

Fig. 1.18 Dynamic daylighting and glare conditions observed using "in-situ" High Dynamic Range (HDR) camera monitoring equipment in a southeast facing perimeter zone of an office building located in San Francisco, CA on August 25 under predominantly clear sky conditions. Right column display the luminance of each pixel using a falsecolor tone-mapping (logarithmic). *Horizontal rows* indicate luminance conditions (and times) before and after occupant adjustment to facade shading devices

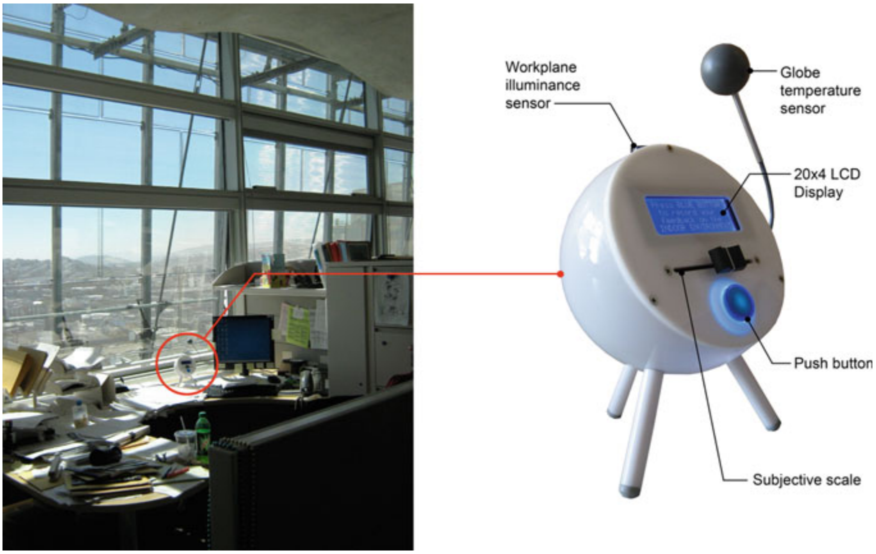

Fig. 1.19 Example "in-situ" method of human-factors data collection in buildings in use

dynamic daylighting environments over time is a difficult phenomena to examine in a controlled laboratory setting, and leads to the need for "nomadic" field research methods and continuous commissioning technologies to build a body of evidence for appropriate human-factors design parameters.

Closer consideration of occupant experience in buildings is integral to meeting the need for resource-efficient and climate-resilient buildings. Rather than passive recipients of indoor environmental conditions, occupants represent a rich multi-sensory source of information on environmental performance with the potential to serve as vital resource to better understand and respond to the complex relationship between the built environment and its inhabitants. This book discusses the application of emerging "in-situ" methods (e.g. Fig. 1.19) to collect detailed feedback data pairing physical measurements from the indoor environment with subjective feedback from building occupants in real time. Enabling real-time feedback from building occupants paired with granular physical measurements has the potential to significantly advance the ability of design teams, commissioning agents, and building operators to assess, benchmark, and learn from innovative projects and to continually optimize efficiency goals with occupant comfort. Most importantly, it has the potential to enable a greater level of input from occupants on the management of their personal environment and can serve as a systematic channel for addressing issues with IEQ related to performance. Finally, leveraging detailed feedback data across multiple projects can help enable evidence-based guidance for the AEC community in the development of more energy efficient, granular and responsive control strategies in line with achieving the dual objectives of low energy performance and enhanced IEQ.

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