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Pranab Kumar Nag

Office Buildings

Health, Safety and Environment

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Dedicated to my $\sim$88-year-old mother, and in fond memory of my father.

Preface

Office, the word stems from the Latin officium, has been transformed today to an organizational space—an entity of organizational symbolism, denoting spatial environment in which humans perform work, physical environment in and around an organization, and built environment referred to as architecture and urban locale. Relentless urbanization and anthropogenic activities and unprecedented growth of population base in office and other building typologies raise interest among public authorities, owners, and facility managers to make the infrastructure facility eco-friendly, human-friendly, and energy-friendly. In recognition of this need, from all allied academic and professional disciplines, source materials on building facilities have been researched and knowledge base developed, in order to create office buildings for effective human use. The underlying premise is to achieve a healthy office environment in which the surroundings contribute to productivity, comfort, and a sense of health and well-being of the occupants. Failure to respond effectively to the primary issues can raise negative publicity about the building.

This book, *Office Buildings: Health, Safety and Environment,* is an outcome of the author's years of interdisciplinary comprehension relating to an office building (non-industrial, non-residential), indoor workplace, and environmental assessment. The document is a convergence of the knowledge base of building science, environmental science, behavioural and health sciences, bringing insights of solution-oriented concepts applicable to buildings, and objective assessment encapsulating occupants' perspectives. The focus has been placed on the green building concepts for its sustainability to the future needs, since the building stocks today virtually bulldozed the natural resources and are responsible for emitting one-third of the total greenhouse gas emissions.

Sustainability of buildings can be achieved through a multi-pronged approach involving the adoption of bioclimatic architectural principles and energy-efficient building systems, and more importantly, addressing occupants' expectations and requirements. The effort has gone into conceptualizing and optimizing the content of the book, incorporating assimilated ideas, findings, and experiences of contemporary researchers and international agencies. Literature search strategy included electronic searching of databases, such as ScienceDirect, PubMed, Google

Scholar, and Sage as well as manually searching key-relevant journals, proceedings, standards on building design and assessment, indoor environment quality, ergonomics, health, building-related regulatory standards, energy codes, and guidelines. Source materials that were published, approximately since 1990, were scrutinized, culled, compiled, and embodied herewith, with reference to the strength and consistency of evidence on the specific domain. In other words, studies with well-designed experiments, observational studies, controlled intervention studies, and statistical validity were considered most persuasive in selecting the body of the materials. Simple narratives were grossly omitted, unless they offered specific information of value. Many proprietary documents on building assessment schemes were included despite their usual brevity in the public domain. Lists of software and simulation tools on the assessment of bioclimate, ventilation, air quality, lighting, and energy consumption were compiled for ready reference to the readers. In order to make this book understandable to a broad audience, as expected in the multidisciplinary composition of materials, potentially unfamiliar numerical and statistical methodologies have generally been avoided.

In spite of mushrooming of skyscrapers in our cities and towns, the vast majority of building facilities continue to be of smaller and medium dimensions that are operated through small- and medium-level construction agencies and developers. These operators may not be well privileged to undergo elaborate monitoring, evaluation, and accreditation due to their lack of resources as well as knowledge constraints. I hope that this book may serve as a handy reference to students and professionals in building design, architecture, urban biophysics, environmental health, and ergonomics and an inspiration to reinvigorate the zeal of professionals and policymakers to innovate our building concepts and practices.

Major part of the book was done during my tenure at the Ramakrishna Mission Vivekananda University. I express my deep gratitude to Swami Atmapriyananda, Vice Chancellor of the university, for extending kind support, and thus making possible the project to come to fruition. Apart from my own passionate commitment to the publisher, the single most important influence on the book has been that of my wife, Anjali, who displayed enviable patience with pulsating outbursts and remained an active intellectual partner in keeping me focused at trying times. A special note of thanks is owed to my students (Jayshree Sen and Tandra Mondal) for their whole-hearted involvement in preparing illustrations, and checking the body of texts and references. Thanks are due to my students, Dr. Varsha Chourashia, Dr. Kishore Madwani, and Dr. J. B. Vyas, and my colleagues from Regional Occupational Health Centre, Bangalore, namely Dr. Ravichandran and Dr. Raghavan, for helping me with critical source materials that were included herewith. I am indebted to the entire team of Springer for their untiring effort in making this publication possible.

How This Book Is Organized

This book is divided into six topics, identified as Part I to VI. Part I: *Office and Office Space* marks introductory concept of office and office space (Chap. 1) and associated spatial and behavioural attributes in office design (Chap. 2), directed towards all users of the book. Part II: *Building and Office Work-Related Illness* primarily addresses the health issues of building occupants, namely sick building syndrome and other illnesses arising from the conditions of the indoor environment (Chap. 3), and contemporary office menace of work-related musculoskeletal disorders that manifest in epidemic proportions among office goers (Chap. 4). Part III: *Office Ergonomics* brings the discussion on the fundamentals of ergonomics in relation to work design in the offices (Chap. 5) and objective ergonomics analysis of computer workstation users (Chap. 6). Strategic requirements and guidance of office lighting and visual performance in office work (Chaps. 7 and 8) are directed for better application of ergonomics at offices and improving working conditions.

Part IV: *Building Bioclimate—Indoor Environment Quality* is directed to all building stakeholders to take cognizance of the risk factors of indoor environmental quality, with emphasis on bioclimatic (thermal environment) building design (Chap. 9), in-depth knowledge and understanding of the characteristics of IEQ (Chap. 10), international acceptance of guidelines in assessing IEQ performance in buildings (Chap. 11), and the likely panacea of remedial to indoor air quality through ventilation intervention in office buildings (Chap. 12). An IEQ index is essentially a profile of building conditions from the perspective of primary bioclimatic, air quality, lighting, and acoustic characteristics. Assessment guidelines will help professionals to reveal potential indoor environmental issues and identify building areas that require special attention to prevent problems in the future.

Part V: *Building Energy Systems—Standards and Codes* focuses on the energy performance of buildings, with reference to a variety of lighting systems applied in offices (Chap. 13), and national and international building-related energy standards and codes (Chap. 14). Part VI: *Green Office Building* brings contemporary perspectives in building sustainability, embodying many proprietary assessment schemes (Chap. 15) practised globally, and exploring category, criteria, and credit rating of buildings (Chap. 16).

Some structured checklists and questionnaires for building post-occupancy evaluation and assessment of health and safety issues are included, for readers to know what type of information can be collected. Building professionals are welcome to reproduce the questionnaires for use or modify elements to reflect conditions in a particular building project; however, any modification may require a thorough understanding of the interacting factors. Some guidance points were moved up and down from basic principles to practical hints, within a chapter and across chapters. This approach was intentional to allow easy flow of information for readers to comprehend the subject matter effectively and use in suitable intervention in building projects. Communication between building management and building occupants is a critical element in innovating building concepts and practices to the stated objectives. Aspiring that if even a tiny portion of the composition is found to be useful to those concerned in creating a sustainable building, the author will feel gratified and well repaid of his labour.

Kolkata, India Pranab Kumar Nag, Ph.D., D.Sc.

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Prof. Pranab Kumar Nag, Ph.D., D.Sc. is currently associated with the Ramakrishna Mission Vivekananda University, Belur Math, Kolkata. He is former Director of the National Institute of Occupational Health (ICMR), Ahmedabad, and Regional Occupational Health Centers (Bangalore and Kolkata). Since his superannuation, he has been re-employed at the School of Environment and Disaster Management, RKMVU. He is specialized in the areas of ergonomics and human factors, environmental health and management, climate change, occupational health and safety and has teaching and research experience spanning four decades. He has written several books and reports and published 175 research articles in the journals of repute. He has professional affiliations with numerous national and international agencies in different capacities.

Part I
Office and Office Space

Chapter 1
The Concept of Office and Office Space

Concept of Office

There has been a long history of how people have been chained to office-bound life. Office work gives our functional life and living a purpose and meaning to cherish. The traits of the office goers are continually evolving by the inherent compulsions of structure and function around our offices. Our colleagues and bosses see more of us than our families do. Tomorrow, the historians might be amazed in documenting the emergence of massive concrete and glass boxes, what we call today, as *office buildings*. Equally challenging would be the task of the evolutionary psychologists to recognize how ancestral humans living in savannah-type environments transformed into today's creatures, and who knows what form the office of the future might take.

The word *Office* stems from the Latin *officium*, which is perhaps equivalent to a mobile bureau or an abstract notion of a formal position for judicial, administrative, and managerial activities. For decades now, an office has been transformed into an entity, denoting spatial environment (where humans perform work), physical environment (physical objects and bodies in and around an organization), and built environment (architecture, urban locale) (Dale and Burrell 2007). Indisputably, the meaning of office is differently understood by different people. However, the interweaving of the stated components manifests in the health, the mind, and the behaviour of humans in the organization.

Conventionally, an office is identified as a place-dependent workplace (buildings), which interchangeably expressed as a workplace, workspace, private/public space, built environment, physical environment (tangible entities). Space is also regarded as the physical entity or the imaginative materialization of power relations in the organization (Casey 2003; Spicer 2006; Taylor and Spicer 2007). The office spaces and buildings are considered as rich repositories of organizational symbolism (Taylor and Hansen 2005), created by the design of offices, physical settings, and private workplaces. Generally, an office is a place that executes and manages a

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range of processes and functions of an enterprise, encompassing human resource management, customer service, database management, process mapping, purchasing, accounting, sales and marketing, payroll, records management, facility management, and the like.

The idea, of what an office is, has continually been evolving, supplemented by the explosion of the Information and Communication Technology (ICT). The surge of knowledge work is dramatically influencing the world of work in the offices and bringing conceivable blurring of boundaries between the public spaces of work and the private spaces pushing the work into home, transit, and leisure life (Fleming and Spicer 2004; Bell and Taylor 2004). Regardless, the traditional office has been the standard for businesses for a long time, an increasing number of people in a multitude of industrial sectors are working remotely, from home offices, virtual offices, or from co-working spaces at one's schedule and setting. In specific job types, the employees might spend a more significant part of the work time outside the office premises, either working at client sites, satellite work sites, home, or when on the move. The undergoing changes necessitate in-depth look into the conceptual aspects of the design of offices and workspaces. Monotonous appearance and operational inflexibility in the conventional office setup negate the expectations of new generation workforce, who looks for a more stimulating and productive environment. Besides, there are growing health and safety concerns associated with the indoor environmental quality, and impacts of building practices and materials. The physiological and psychological stresses at work bring in hosts of health concerns, such as depression to hypertension, obesity, diabetes, and heart disease. This contribution is a modest endeavour to bring together a comprehensive view of the emergence of office buildings and the evolution of the workspace and workplace designs. Driving by contemporary requirements and expectations of office occupants, there are a considerable advance and understanding of the office design perspectives. This contribution is an embodiment of knowledge assimilated by examining credible publications from peer-reviewed journals and success stories from the corporate world.

The Emergence of Office Building

The recorded history witnesses *Office* as a segment of a palace or a temple complex, usually recognized as *libraries* where scrolls, treaties, and edicts were kept and maintained for management functions, and also the workplace where the scribes used to do their work. Evidence gathered from ruins of the Middle Egyptian city of Amarna indicates that the workplaces of the state administration in ancient Egypt (3200–525 BC) consisted of departments that controlled infrastructure, water supply, civil engineering, the military, and the economy (Jeska 2002a). During the High Middle Ages (1000–1300), the orders, laws, and proclamations of the kingdom were used to be preserved in unique rooms. Administrative complexes of the ancient Greek and Roman empires consisted of institutional buildings (councils,

Fig. 1.1 The scriptorium (sixth–twelfth-century Europe)

people's assemblies, jury courts), located at the political and social centres in the cities. During the sixth to twelfth century, the dedicated singular open spaces—*the scriptorium* (Fig. 1.1)—were set aside for ecclesiastical and university functions.

Since the Renaissance, the typical English expression of the *Offices* appeared, referring to places (stand-alone building units) where government functions—military and commerce were conducted. Since the early eighteenth century, sizeable purpose-built office buildings came into existence in UK (Hamilton 2011). Some examples of historical large office buildings are given in Fig. 1.2. The reference of the British Royal Navy, Old Admiralty (Ripley Building 1726), the East India Company, Oriel Chambers of Liverpool (1864) has often been made. A little storytelling of the office building of East India Company in Leaden Hall Street, London (built in 1729), gives us a glimpse of the early endeavour of purpose to create huge office spaces. The East India Co., began as a trading company in the early seventeenth century, was managing long-distance trade with Asia, and particularly in the Indian subcontinent. By the mid-eighteenth century, this trading company expanded to acquire entire India and transformed it into a British colony. Inevitably, the Company emerged as a complex bureaucracy, creating a massive quantity of documents on a daily basis. From thousands of kilometres away from India, these documents would arrive at London by ships at a gap of nearly eight months, and thousands of employees would attend the central office on a daily basis, to process information, compile, and make decisions.

With the Industrial Revolution, colossal office structures grew in many European regions for transacting business in railways, banking, retail, health care, insurance, petroleum, and telecommunication. The Oriel Chambers of Liverpool, UK,

Fig. 1.2 **a** East India Co., Leaden Hall Street, London (1729; 1726); **b** Oriel Chambers, Liverpool, UK (1864); **c** Sears, Roebuck and Co., Chicago, USA (1905–6); **d**, **e** Larkin Building, Buffalo, NY (1904)

the five-storey *skyscraper* office block (1864), may be deemed as a miniature by today's standards; however, its architectural ingenuity is a milestone in the development of skyscrapers. An iron- and steel-framed inner structure with the iconic glass curtain wall allowed entry of abundant natural light and making possible for more people to use a full office area with a minimal need for artificial light. This path-breaking concept got transplanted across the Atlantic in the 1880s (e.g., Missouri's Boley Building, Kansas City, 1909) and mushroomed into twentieth-century skyscrapers all over.

In the early twentieth century, the office buildings in Europe were dominated by cellular offices, that is, multiple rows of closed offices around a central corridor, around an atrium or a central room (Jeska 2002b). These building structures were adopted, due to the general building regulations on the depth of buildings to ensure daylighting and natural ventilation. During this time, however, the USA witnessed mushrooming of skyscrapers and oversized open-plan office buildings, influenced by the advanced architecture and construction technology and unrestrained statutory regulations on building structure and interior design. A significant milestone in the twentieth-century office design was the 1906 Sears, Roebuck and Co. building, which had a nine-storey, 5 million square feet office space spanning two city blocks in Chicago, accommodating nearly 22,000 employees for their mail-order operation. Sears–Roebuck building was the world's most massive business building at the time.

In 1904, in Buffalo, NY, Frank Lloyd Wright created the first *purpose-designed environment*—Larkin Building for a mail-order soap company, which for practical purposes unveiled an adaptation of the industrial production model to office building design. The Larkin Building is an infamous example of open place office building model, known as the *bullpen*, designed with a vast, spacious room with undifferentiated rows of desks, and absence of any barriers between workstations. It had six floors, and in the atrium, hundreds of employees sat in rows of the similar office desk, facing the same direction crowding the room, and answering to inquiries and processing mail orders (Hua 2007). The supervisors and managers, however, were privileged to have individual closed offices, partitioned by glass walls from the rest of the work area. The building with an artificially controlled environment with incandescent lights, conditioned and recirculated air, and devoid of external windows brought a grim look for the workers to perform in a near about sealed workplace.

Over the twentieth century, the office building and workplace floor plans in the USA, Europe, and rapidly emerging Asia-Pacific regions were greatly influenced by technological advance, sociocultural values, prevailing environmental conditions, and applicable building regulations (Arnold 2002). Notably, after the World War II, there was mushrooming of rectangular high-rise office building with noticeable features of glazed facades, also known as a *glass box* in many regions of the USA and Europe (van Meel 2000). The concepts of office space optimization through open office planning was overemphasized, to allow a maximum number of workers to fit into the same space and allow more mobility for interaction and communication among workers. The *buerolandschaft* (or office landscape) design concept (Fig. 1.3) was introduced in the first office building of Bertelsmann in Gütersloh, in the 1950s by Quickborner team in Germany (Christiansson and Eiserman 1998). Among many other contemporary open-plan office building, Osram Gmbh Administration Building (1962) Munich was very distinctive in its layout. Osram building was the first spatial expression towards achieving organizational efficiency by enhancing information flow, interaction, and transaction among colleagues (Laing 2006a, b; Hassanain 2006). Traditional furniture, curved screens, large potted plants created an organic geometry for workgroups on large and open floors. Application of central air-conditioning system, well-designed acoustic ceilings, fluorescent lights, and interior furnishings in the office buildings made this concept possible.

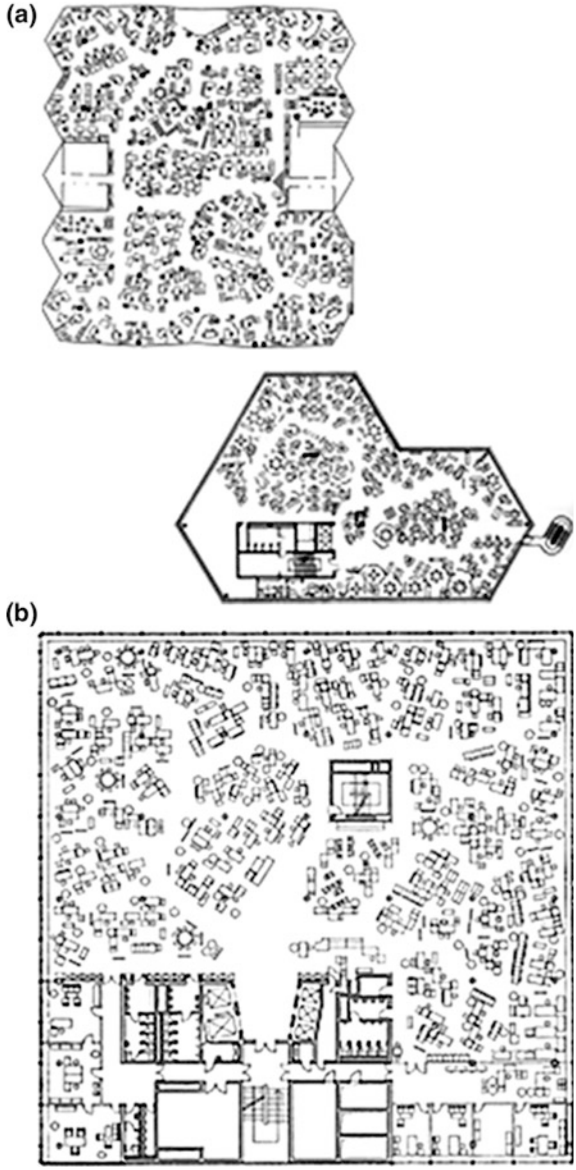

Fig. 1.3 The *buerolandschaft*—**a** first open-plan office building, Quickborner team at Bertelsmann, Gütersloh (1950); **b** Osram Gmbh Administration Building (1962), Munich, Germany

Evolution of Office Workspace Design

In the early 1920s, Frederick Winslow Taylor, a renowned mechanical engineer and management guru, made a groundbreaking contribution from his study of working methods at the Bethlehem Steel Mills, Chicago, embodied as *The Principles of*

Scientific Management (Taylor 1911). It explored the general rules, ascribing to standardizing human labour to maximize profit and efficiency. Perhaps, this foundation profoundly influenced the American office design in creating very wide open office floor plan to maximize workplace efficiency in routine-based work, however, with stringent management hierarchy (Duffy 1997). The design of office buildings and the evolution of office workspaces were the inevitable impacts resulting from the undergoing changes in the nature of office work (Danielsson 2005).

The office buildings have the general and specific type of facility requirements (for example, legal compliance to design and layout, safety, security, environmental/sustainable building features, and technical specifications including computer networking). BOMA (2012) included buildings into three classes. Class A—prestigious buildings with high-quality amenities in the best locations for premier office users. Class A buildings may have sub-categories such as prestige, AAA, AA, and A. Class B—a grade below Class A; well maintained and functional with facilities, but slightly older cost-effective buildings that attract a wide range of users. Class C—lowest grade older office buildings, having limited infrastructure and probably located on less desirable streets. These descriptions are general guidelines since no formal standard exists. However, any lack of specifics in building facilities or in interior workspace design makes difficult in defining or classifying buildings. With progression, however, there has been a transformation in the types of office plans, layout, and space use, influenced by the general management function and work culture of an organization. In corporate offices, three categories of spaces may be distinguished as workspaces, meeting spaces, and support spaces. The generic types of the workspace are:

(a) cubicle or an enclosed private office for one person, where activities demand privacy, confidentiality, and concentration;
(b) open office for about ten people, where activities require routine communication among the colleagues;
(c) team space/room, a semi-enclosed workspace for a group of four to eight people, allowing internal communication;
(d) shared/serviced office—an enclosed workspace with shared facilities, for two to three people;
(e) study booth for short-term work; and
(f) work lounge or touchdown, a workspace (may be an open space) of a small group of people for short-term activities or impromptu interaction.

Meeting spaces are (a) small and large meeting spaces to accommodate between two to twelve people, (b) brainstorm room (five to twelve people, for brainstorming sessions and workshops), and (c) meeting point for ad hoc exchanges by two to four persons. Support spaces are typically used for secondary activities, such as filing or storage space, print and copy area, pantry area and break area, locker area for storing personal belongings, separate smoking zone, library, recreation room, reception or waiting area, circulation space linking all significant functions in the organization. Besides, there can be an *executive suite* which is differentiated individual office, recognized as a furnished office, shared office/serviced office, and flexible office. Multiple organizations might occupy all such office spaces in a building, and each equipped with typical requirements, such as a reception area, meeting rooms, singular or open-plan offices, video conference facility, on-site fitness centre, and other amenities.

Analysing work modes, patterns, and spatial concepts in different enterprises, Laing et al. (1998) proposed four metaphors (Hive, Den, Cell, and Club) of office environments and emphasized on an understanding of the work structure when designing an office layout.

- Hive standardized clerical work by individuals (e.g., call centres, conventional banking, financial and administrative operations and information services, and telesales), which may include a combination of cellular or open-plan offices. In these organizations, the majority of the work can be done at a simple workstation during regular working hours.
- Den—group processes and interactive teamwork, such as law, accountancy, academic offices, and some research and consultancy organizations. This type of layout is suitable for work that requires a high level of a working group with a low level of individual work.
- Cell—designated cells where individuals can work in a concentrated fashion, such as design, insurance, media, and advertising. These cellular offices are suitable that demand a high level of intensive individual work with minimal interaction requirement.
- Club—place of communication, such as advertising, management consultancies, IT, and high-value knowledge work, which are combi offices along with hot desking facilities. It is interactive and autonomous in operation, where occupancy pattern is intermittent and may extend over regular duty hours.

Each of these working modes has typical spatial usages and workplace configurations. Activities under the *hive*-type workplaces are low in autonomy and interaction; this kind of non-interactive tasks can be found in the *bullpen* work environment. Dens are busy and interactive places where it is easy to work informally in the team, but tasks require low autonomy. Activities in *cells* are featured with high independence, privacy, and low levels of interaction. The cubicles with a variety of heights have been introduced, allowing freedom of movement around the work floor. The *Club* type of spaces is inherently built with, in making the space more useful for collaborative and autonomous work, shared by many people over time.

Open Office Planning

The open-plan office model—*Buerolandschaft*—rose in post-World War II Germany and stemmed from individual expression to create a non-hierarchical environment for increased communication and flexibility. The *Buerolandschaft* office landscape design was to reflect openness and clarity in working processes, facilitating space for collaborative work. The workstations in proximity to other amenities enhanced informal communication. The service spaces, reception lobby, interior spaces, and office furnishing systems were the useful components of the office building. However, the inherent disadvantages of the *Buerolandschaft* floor plan are well recognized, which are due to workplace conservatism, reduced symbolized hierarchy, drawbacks of lack of privacy, and visual and acoustic disruptions.

Throughout the world, the rigid location-dependent office typologies (low-rise or high-rise office buildings) are undergoing rapid changes with the changing trend in the paradigm of work. These buildings are generally located in the central financial districts, downtown, or suburban office parks, in proximity to customer or resource base. The structural organization, office infrastructure, organizational culture, standardization, and market conditions are the prevalent drivers in reconfiguring the office space, attitude towards privacy, personalization, and territorialization of space.

There has been a constant endeavour to keep employees motivated through workplace and workspace orientation and design, and thereby, they remain productive and satisfied (Earle 2003). In the contemporary office buildings, there coexists a wide variance of space layout that offers a balanced mix of focus and collaboration space. Examples of the *combi* office that have advantages of open-plan and cellular office indicate its acceptance in the corporate scenario (Arnold 2002). The design layout that incorporates both a space for private work and also provides space for group interaction emerges as a balance between the open design of office landscaping and the individual private cubicle (Laing 2006a, b). The open spaces equipped with facilities in the middle of the building might promote interaction among employees. The furniture manufacturers have their version of the cubicle and panel-based open-plan settings that include an opportunity for individual work areas, centralized filing, and acoustical privacy. Usually, panel positioning and its height adjusted at the desk to a much higher level provide for either sitting or standing visual privacy. The enclosed private offices can also be moved to the core, facing the open-plan work area along the perimeter. In such a layout design, a significant number of office occupants can enjoy a seated view to the outside and take advantage of better daylighting (Harrison et al. 2004).

The conventional office buildings are no longer the sole locations for work. There is gradual retreating from standardization and uniformity of conventional work practices, and moving towards a more creative integration of spatial configuration in workspace design. There is rising popularity in adopting casual or temporary workplaces or shared task-based setting (co-working spaces), particularly in the collaborative work environment, and that bringing in a specific change in office spatial design solutions. With the upcoming trend that more and more tasks are done remotely, the flexibility in office settings and choice of places are the critical components in the concept of workplace design. The Norwegian telecommunications giant, Telenor, introduced *hot desking* (no assigned seats), i.e., reconfiguration of spaces with task requirement and evolving teams. By this approach, the issues of space efficiency are addressed for people to share workstations with a group of employees in a team (Harrison et al. 2004). However, the new workplace concept faces issues in managing reference materials and ignoring personalization of workspace and thus can make the workplaces counterproductive in some cases.

Knowledge Work

During the industrial age, businesses competed through the proprietorship of products, equipment, and plants. In the post-industrial society, knowledge has become social wealth, and a social group recognized as knowledge workers carry a leading edge in their capability in translating ICT knowledge into profit-producing technological and organizational innovations (Drucker 2002; Myerson et al. 2010). Increasing share of inputs and outputs in the form of electronic bits, the old and conventional locational factors of work diminish in importance (Toffler and Toffler 2006). Williams (2007) explained the knowledge-based post-industrial shifting from manufacturing to service, from heavy machinery to ICT, and from large-scale setup to a more flexible organizational structure, which aptly identifying as the emergence of the information society.

Knowledge types are categorized as (a) embrained knowledge, (b) embodied knowledge, (c) encultured knowledge, (d) embedded knowledge, and (e) encoded knowledge, conveying information by signs and symbols (Blackler 1995). The knowledge workers possess a combination of embrained knowledge (conceptual and theoretical information one holds in the brain), embodied knowledge (practical and applied experiences of doing things), and embedded knowledge (regular routines to perform a task), making them focused and task-specific, along with high cognitive and technical skills. Whereas, other independent and organizational professionals, such as architects, lawyers, doctors, managers, administrators depend on embedded and encultured knowledge (shared understanding about things done in a specific situation).

The cooperative workplaces facilitate the knowledge initiating cycle, (socialization–externalization–combination–internalization) based on the codified and tacit knowledge (Nonaka and Takeuchi 1995; Nonaka et al. 2001). Although socialization emphasizes on the individual, it also refers to interaction like sharing the experience with others. However, externalization relies more on verbal communication for others to understand and apply. The combination takes issues of shared workplaces that diffuse through the organization, and generates new knowledge across groups. On the other hand, internalization is a way for preparedness, such as training and exercise that mostly take place in a workplace designed for a specific purpose.

The digital-savvy knowledge workers demand their spaces to adapt to how they work and liberation from the confines of the workstation or office building. Work can occur in any unstructured spaces or informal meeting areas, e.g., home offices and co-working spaces. However, with knowledge-intensiveness, today's office work is becoming much time-pressured and mobile (Laing 2006a, b; Kampschroer and Heerwagen 2005). Knowledge workers opt for technologically purposeful spaces so that information is more readily shared and better supported in virtual collaboration (Greene and Myerson 2011). These groups of workers chose co-working spaces, where one can work on one's schedule in a setting with all required amenities. These new work trends are proven to be more effective conditions for productivity and creativity as they enhance the worker performance and provide a valuable, stimulating setting for communication. Eventually, examples of innovative buildings are endless. Large corporations (such as Amazon's new campus in Seattle, AT&T, ING Direct, Airbnb, Adobe's Manhattan office, Telenor) mimicked the idea by creating shared space for their employees to work with all stakeholders. In AT&T Foundry, a network of research centres, engineers work side by side with handpicked start-ups and third parties to develop products faster. ING Direct Capital One 360 Cafés are the places where people can set up shops and interact with customers, sharing the space for work. Airbnb at its headquarters in San Francisco has made one of the conference rooms for free use.

Fig. 1.4 **a** Google bay (*Googleplex*); **b** Amazon's domes, Seattle, Washington; **c** Apple spaceship headquarters (proposed), Cupertino, San Francisco; **d** Facebook's a single mile-long campus, Menlo Park

With the aspiration that open offices can cure the evils of cubicles, there is a definite trend among corporates all over the world in adopting large-scale open concept offices. The Silicon Valley IT innovators stand for massive building cathedrals that are designed on the premise of the knowledge explosion and revolutionary wealth creation (Fig. 1.4). Google's *Googleplex* is a 1.1 million sq.ft structure, with nine rectangular, horizontally bent buildings, having green roofs, courtyards, and connecting bridges. Amazon's domes, admeasuring 65,000 sq.ft glass domes, are built in Seattle. Apple envisages spaceship headquarters in Silicon Valley, San Francisco. Facebook's a single mile-long campus of ~435,000 sq.ft area is probably the most discussed open-plan office in the world for 2,800 engineers and 3,400 staff; this has an underground link tunnel between the new office and its existing Menlo Park campus.

Collaborative Work

Collaboration is a process of bringing together multiple individuals or organizations on a conjoint objective. Collaborative work entails two or more people working together to accomplish interactive, high-quality group work while maintaining individual focused tasks (Brand 2009). The scale, complexity, and multidisciplinary nature of tasks, including involvement of specialized workforce, make high-quality collaboration viable to achieve efficiency and competitive advantage of organizations. In today's trend, the collaborative work environments are in a state of transition that something familiar and predictable to something not yet defined, multi-locational, virtual, and physical (Davis et al. 2011). For example, where knowledge workers carry out work, what kind of task they are engaged in, and how they spend their time are in the unpredictable state. In other words, a collaborative work environment depicts a highly diverse place, giving people lots of choices in where, when, and how one can perform their work (Becker 2005).

In collaborating work environment, people may be required to spend considerable time moving about the workplace for collaborating and impromptu meetings with co-workers in secondary office settings, rather than remain seated at their office desk. Even while one is occupied to the desk, a reasonable amount of time might be spent meeting or talking with co-workers. The workplace study by BOSTI Associates (Brill and Weidemann 2001) on 13,000 office workers in 40 business units between 1994 and 2000 revealed that people in office spend about one-fifth of their average working day away from one's workstation when people are in the office. The Steelcase 2002 Workplace Index (SWI) survey of 977 office workers, conducted by Opinion Research Corporation (Grand Rapids), as cited in Sangoi (2011), identified that only one-half of the workweek spent working at one's desk. The Steelcase SWI survey reported, on average, 7 h per week are spent in meetings. The survey indicated the essentialities for functional and flexible work environments to support people's movement and work habits in and around the office. The Microsoft Office Personal Productivity Challenge Survey (Edstrom 2005), covering over 38,000 participants worldwide, revealed that $\sim 15\%$ of the weekly working hours (i.e., 5.6 h out of 45 h workweek) are spent in meetings. While the emphasis is on collaboration as a key to productivity in the workplace, about three-fourths of the participants of Microsoft survey felt that meetings are typically unproductive. Emphasis goes on developing innovative workspaces to support flexible, group-oriented, and remote working styles (Davis et al. 2011).

A collaborative place or a workplace of an office is necessarily a combination of space, protocols, technology, and tools to support the nature of work and keep employees connected. Recognizing that different places have a different kind of utilities for interaction and collaboration, the design of office spaces must also reflect accordingly, keeping in view the brand image and management style of an organization. For collaboration work, there is a need for understanding about types of collaboration, such as situational awareness and social networking, information and knowledge transfer, coordinated work, ideation and creative development (Loftness et al. 2002; Hua 2007). That is,

(a) An organizational culture having channels of interactions for *situational awareness and social networking* contributes efficiently to task awareness and group awareness for coordination, conflict resolution, and information exchange. Importantly, better channels of communication enhance willingness to collaborate (even interdisciplinary) among co-workers towards organizational and individual goals.
(b) Organizations that allow adequate *information and knowledge transfer* among its people are aptly more productive in collaboration work. Rich information exchange and diffusion of information to all concerned trickle down organizational perspective, goals, and task objectives among members of the group. Whereas transfer of knowledge (explicit and tacit) is more complicated than information transfer, the workplace spatial design can create a conducive environment to boost the performance of knowledge transfer in organizations.
(c) *Coordinated work* in an office environment may be viewed differently to that may be found in team working on a production line. The essence of coordinated work is in recognizing requirements of multidisciplinary collaboration, making time planning, task sequencing, and material sharing. The process of coordinated work requires support from the spatial settings, including technological support, to ensure efficiency, reduce redundancy and error.
(d) Collaboration among a critical mass of multidisciplinary expertize leads to intensive *ideation and creative development* activities. Creation of new ideas, strategies, and solutions emerges from periodic brainstorming and higher iteration of problem-solving exercises.

The research goes into (a) the social dimensions of collaborative knowledge work, such as awareness, brief interaction, and also (b) the individual aspects of collaborative work, focusing on solitary work and behaviour (Heerwagen et al. 2004). The critical physical requirements to the awareness dimension are visual and

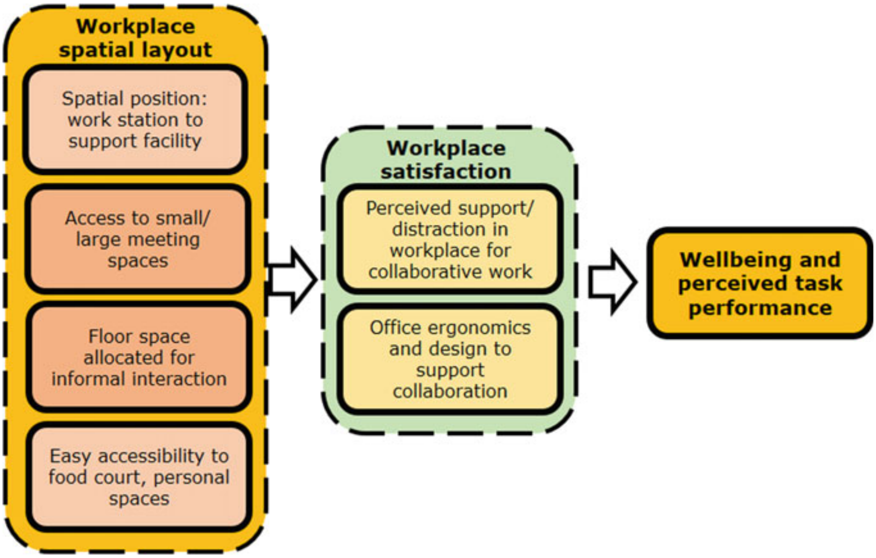

Fig. 1.5 Relationship and impacts of workplace spatial features on satisfaction and collaboration effectiveness

aural accessibility. Brief interaction includes functional communication as well as social interaction, such as quick personal exchanges. The line of sight or visibility influences the quality of interaction within the office environment. Collaboration (e.g., problem-solving sessions) can last for hours of interaction and may be occasional brief interaction. A schematic (Fig. 1.5) elucidates the interaction of components, such as physical requirements, functional communication and its influence on employee satisfaction in the knowledge work environment.

Besides, to be a productive team member, an individual must have the time, space, and tools to do work alone, for example, searching and synthesizing information into internal knowledge. Rashid et al. (2004) viewed that the need for privacy in a workplace includes the need to control access to the workspace, to limit distraction and communicate informally with others.

Office Design and Architectural Implications

Office design is not only about the layout of individual cubicles and closed offices, though they occupy a central place in planning. Workstation size defines the available amount of space for work and storage and also additional work surfaces to facilitate face-to-face communication or sideways discussion. The US GSA approach in using the balanced scorecard of pre- and post-occupancy of sites identifies the extent of alignment of workplaces with the ongoing demographic, technological, and organizational shifts. Steelcase data indicate that the size of the average executive office cubicle is remarkably coming down, since 2000. There are many other places in a work setting, which are vital layout features that support satisfaction for collaborative work and also individual task performance. For example, meeting rooms and team spaces need to be highly visible and close to neighbourhoods of workstations to enable occupants to participate in collaborative conversation efficiently. The shared services, such as copy/print and kitchen areas, take not only noise-generating activities away from workstations, and these amenity places are the active nodes of interaction and collaboration activities. For open-plan workplace design, considerations include, for example, making available a mix of individual and shared spaces for different work activities; however, these spaces should be not very close to individual workstations. In controlling occupancy density, care is needed that there is no compromise on the size of the individual workstation. Flexibility in workplace layout and enclosure is used to bring different levels of privacy and to meet needs of the distraction-free work environment. The chair–desk complex and allied furniture systems are selected that can be reconfigured, and a sense of positive feeling of the workplace can be rejuvenated.

Some research efforts have gone in *pattern language* as a design formulation methodology, to identify and emphasize the physical and socio-psychological factors to be considered in designing office space. The *pattern language* framework (Alexander et al. 1977) consists of 253 patterns; each has a description, picture/illustration, and justification. Instead of graphic standards that primarily prescribe sizes or minimum clearances, pattern language provides a methodological approach to combine socio-psychological factors in a graphic and written format, and that may be applied in architectural, urban planning, and interior design process (McLain-Kark 2001). Concerning office space design, some specific patterns are described as below:

- *Welcoming entry*: Well-designed entry of an office building with the distinctive use of materials and architecture communicates a welcoming gesture to the employees and the visitors.
- *Thoroughfare*: The thoroughfare serves as the centralized artery connecting public spaces within the office. The corridors and pathways around workstations and shared equipment such as printers/photocopiers, coffee machines provide opportunities for ad hoc encounters, interactions, and a brief exchange of information. The public spaces of the Samsung Semiconductor of its US headquarters were designed with vast outdoor areas sandwiched between floors to maximize chance collision and creative interaction among its employees (Waber et al. 2014).
- *Heads-down personal space*: Everyone needs a place to focus on a task and have a private conversation/phone call. Even in a dynamic teaming environment, it is essential to have personal work areas or zones for employees who seek privacy (Haynes and Price 2004). People assess their privacy or territory (Vischer 2007) at the functional level (separateness and freedom from

distraction to concentrate in work) and the psychological level (relating to exclusivity, status in the organization and environmental control).

- *Public spaces*: The public spaces within an office are ideal locations to tell the philosophies and goals that are embedded in the organization.
- *Social hub*: A social hub/space is the psychological centre of the workplace, creating a place for employees to interact informally and making the space more useful for collaboration (Anthony 2001). An example of social space is drawn from Telenor, a Norwegian telecommunication giant, at Oslo (Waber et al. 2014). Telenor's new open, public, and flexible spaces in office design values brainstorming exploration among employees. Earlier, Telenor workplaces were provided with roughly one coffee station for every six employees, and the same people used the same machines every day (HBR 2014). With the new space design, coffee machines are strategically placed—just one for every 120 employees in a more bigger cafeteria area that resulted in substantial improvement in communication, productivity, and creativity.
- *Town halls*: Town halls are typically friendly multifunctional congregational places to accommodate employees for different requirements (Stegmeier 2008). To a significant extent, designing town hall areas is ideal to pay attention to social *channelling* and other symbolic details to make places more rewarding to employee learning (Brand 2009).
- *Team huddle space*: There is an increasing demand for dedicated team collaboration spaces for group meetings, brainstorming, and problem-solving activities, and that may continue for days, weeks, and months at a time. These spaces allow face-to-face interaction and encourage collaboration across boundaries within the organization. Based on the study of Haworth, Inc., Brand and Augustin (2009) noted that the rate of participation in meetings seemed higher in the team area than in the conference rooms.
- *Community connections*: People in knowledge work are on sustained time pressure and job targets, and they strive to find a balance between home and work (Gibson 2003). These people are forced to handle their matters and jobs during lunch and break times, and therefore, receiving convenient access to such amenities close to their place of work is the preferred community connections.
- *Technology access*: In Google office study, Groves and Knight (2013) reiterated that access to technology at formal and informal team workspaces helps to collaborate with far-flung colleagues, to share digital information instantly. Collaborative spaces with access to such technology facilities and infrastructure are useful for everyone to share the information and interact with it.
- *Social interaction*: Workplaces vary in levels of social interaction. Informal social relationships among co-workers have both direct and moderating effects on reducing depression, facilitating greater group mentality and efficiency (Chen et al. 2009). Increasing human and animal social interaction in the workplace also help decrease stress and anxiety of employees. People who bring their pets to work and interact with them exhibit higher levels of oxytocin, a neuropeptide responsible for feelings of bonding, social interaction, and stress relief (Miller et al. 2009). The study revealed that bringing one's dog in the workplace

facilitates group cohesion, intimacy, and interpersonal trust (Christensen et al. 2012) and, in turn, adds to overall worker efficiency.

- *Work areas on wheels*: The young generation workforce has a different outlook on quality of life and living, and at workplaces, they are less constrained by privacy and personalization of the workstation. Instead, they prefer mobility and flexibility and adept with contemporary technologies (Vischer 2006). Foldable chairs and tables are no constraints for these kinds of team members to get on to the job.

  Knoll, a renowned office furniture firm, surveyed ~15,000 employees, including boomers, and those who are a generation older than the boomers, Gen Xers (the 30 s and 40 s), and Gen Yers (Thompson 2010). The boomers viewed highly about the importance of the formal office, with an emphasis on maintaining separation between work and private life, whereas for the Gen Yers the formal office settings as the least preferred design component. Product designers and ergonomists bear a significant role in designing facilities, according to the activity requirements of the Gen Yers (Thorp and Darling 2009).
- *Building windows*: Window views, unusually distant views or views of nature, influence cognitive functioning and psychological benefits in restoring one's attention capacity and the ability to concentrate (Kaplan 2001), improve worker satisfaction (Stegmeier 2008), and decrease employee discomfort (Aries et al. 2010).

  Typically, the building occupants show an overall improvement in moods and emotional tone in rooms that are lighted well with natural light (Brand 2009). The full-spectrum fluorescent lighting helps to mimic sunlight and increase mood and cognition in employees; however, its positive effects are not similar to that of natural sunlight (Vietsch and McColl 2001). Efficacy is improved in case of larger and taller windows. Loftness et al. (2008) reported that high-rise buildings could also be naturally ventilated, as demonstrated in case of the buildings, such as Commerzbank (Frankfurt) by Foster and Partners, and the RWE tower (Essen) by Christoph Ingenhoven.
- *Non-exercise activity thermogenesis (NEAT)*: In conventional office settings, people tend to be glued down to chair–desk complex for a prolonged period. Such sedentary lifestyles can be substituted with regular movements, like standing up instead of sitting down during work. Levine et al. (2005, 2011) observed that the NEAT phenomenon with actions such as fidgeting and standing could help combat obesity by raising the daily energy expenditure. Specific practical intervention, such as having raised filing desk that is forcibly compelling one to stand up or a little walk around the workplace, or walking little distances to the bathroom, cafeteria, or parking lot, may be considered as a pattern of workplace design intervention.
- *Vertical surfaces*: Access to visual displays, interactive electronic whiteboards, projection screens, either from one's workstations or when moving along the corridors, influences the effectiveness of knowledge transfer among group members (Brand and Augustin 2009; Berte 2011). Plentiful whiteboards scattered throughout Google spaces is a reminder of the value of communication and shared thinking that can happen even in the corridors (Groves and Knight

2013). The technological advances for communication through Skype, iPad, Surface, and the telepresence system (Szigeti et al. 2009) have risen in unprecedented pace for better conferencing experience with remote participants, including the global workforce (Koh 2010).

- *Comfortable work*: In conventional office settings, furniture and furnishing provide cues of the relative status of the office occupant. However, better ergonomics for workstation and spatial comfort have a direct impact on both collaborative teamwork productivity and individual task performance.
- *Wide stairways*: The wide stairways in a facility and the landing spaces increase chances of collision among colleagues on a regular basis (Groves and Knight 2013). Further, to optimize interaction and communication, the workplace strategy calls for limiting to not more than five-storey high buildings on campus (Stegmeier 2008).
- *Environmental and spatial metaphors*: The environmental and spatial metaphors (such as greenery, forests, rivers, and mountain horizons) bring visual and physical stimulation at the workplace. Such metaphors help to combat stress and increase employee well-being (Weinstein et al. 2009; Knight and Haslam 2010; Smith and Pitt 2009). The meeting rooms, heads-down spaces, shared meeting areas, open workspaces, and other work environments provide enormous options of arrangement and design, according to employee preferences. The sense of gradient and variety of material surfaces, textures, tactility, and colouration, are used in creating varying depths in elevations and dimensions in the design of offices.

  The psychometric evaluation reveals associations between natural environments and experiential feeling states. A study by Hinds and Sparks (2011) emphasized that the people with more experience of the natural environment compared with those with less experience had greater *eudemonia* (ostensibly positive feelings) and less *apprehension* (ostensibly negative feelings). Perhaps this further substantiates that access to the outdoor environment, such as courtyards or balconies, and exposure to greenery may be taken as a pattern in designing an office environment. Such exposures help improve one’s physical and mental health, release stress and anxiety (Berto 2005; Bringslimark et al. 2007), and rejuvenate one’s cognitive functioning (Berman et al. 2008).
- *Colour as a medium*: Judiciously planned use of office interior elements, such as lighting, colours, transparencies, and materials, can create a unique statement, reflecting the brand and culture of the organization. The layout of the workspace, aesthetics, lighting system, air quality, furniture, fixtures, furnishings, signage, colour planning, and art collection bring an overall feel of the space towards workers’ comfort and efficiency (Sogawa et al. 2002; Stegmeier 2008). Myerson and Ross (2003) cited the example of the open office concept of the Beacon Communications Headquarters, designed by Klein Dytham, that pursued the theme of *okarinasai* (welcome home). Every floor has its theme, with material and colour choices, and added with oversized furniture and colourful

free-flowing ribbons to distinctly separating out the spaces and functions and creating a setting for creativity and collaboration.

- *Playfulness at work*: Inherently a human being ecstasies one's childhood, and instinctively, in different phases of life and living, he adores possessing toys and playing with them. Each type of play explicitly manifests different meaning to children of different age groups, being young and old. Research emphasizes that playful or fun work environment encourages a variety of enjoyable and pleasurable activities that influence employee morale, productivity and foster innovation among individuals and groups (Ford et al. 2003). Contemporary research indicates that the early hormone differences in foetuses exert a permanent influence on brain development and gender-typical behaviour of a child (Hines 2010). The hormone-induced behavioural outcomes have a possible association with the neural mechanisms, involving hypothalamus, amygdala, as well as interhemispheric connectivity. In other words, the hormonal (testosterone/androgenic) make-up of the people has a significant effect in the development of gender-typical cognitive, motor and personality characteristics, including the type of play or toy preferences, which were earlier thought to result solely from the sociocultural influences. Therefore, playfulness at work is undoubtedly a resourceful pattern in designing collaborative and creative work environment.

  The theoretical framework embodied in *Critique of Everyday Life* by the French sociologist, Henri Lefebvre (1991), depicts work and leisure in a dialectical relationship—both are essential to sustaining life ecologically and psychologically. Findings of the Google study (Groves and Knight 2013) is a reinforcement of the strategic fun workplace setting in creating a sense of fun and passion among people through the business, with a context. The *Googleplex* has brought in innovation and dynamicity in work and leisure, embodying their office culture, creative work mandate, and employee appreciation. Its office spaces and working environment appear more like a themed adventure park, as exemplified through innovative fixtures and space designs, such as spaceships, slides, dinosaur, igloos, firemen's pole, ski gondolas, multi-user bicycles, and other artefacts.

  Groves and Knight (2013) identified four facets in the creative work environments as stimulation, reflection, collaboration, and play. Spaces for stimulation are intended to inspire unconventional creative thoughts. These instances can be effected through sensory aesthetics arising from a given leisure theme. Reflection is a period of continuous focus and filtering of information and making explicit connections. Collaboration spaces are crucial for the productive exchange of information and knowledge, and play takes a different form (e.g., active play, social play, or explorative play). Each type of play draws upon freedom and ease of communication among individuals and also to the collective group. The massive dinosaur skeleton with pink flamingos at *Googleplex* and other features of internal work environment symbolize playful nature of the workforce. This author maintained the image of Google's dinosaur skeleton as the preferred screenshot throughout the preparation of the manuscript. *Google-20%* is another example of *innovation time off* that motivates employees to spend 20% of their work time on projects of personal interest. Gmail, Google News, Orkut, AdSense are some of the innovative products of this endeavour. This symbolism has been catching up in ICT-oriented enterprises and raising interest in nurturing a playful and fun atmosphere, and exploring how this gesture informality can be translated efficiently in the creative processes of the workers. However, the playfulness of leisure and the seriousness of work are a crucial dichotomy, since different individuals respond to the object features of a play differentially. There is a potential for using the physical and psychological qualities extracted from leisure to the workplace positivism for one's performance and well-being.

- *Stay close*: Generally recognized that people communicate and collaborate more when they are nearby (Steelcase 2010). Landmark study was undertaken by Allen (1971) on communication patterns in office settings and revealed that separation by 30 m range is equivalent to being in different buildings, and even within 30 m, those nearest to one another communicate more than those at a greater distance. With the Google mandate that all employees should stay close, at Googleplex, no employee is away from more than about two-and-a-half-minute walk from another colleague, and therefore, micro-kitchens are located within 45 m (Groves and Knight 2013).
- *Multifunctional environments*: Emerging trend among Gen Yers is their likings for short-distance of commuting, perhaps using transportation modes like walking, cycling, or the public transit system instead of commuting a long distance. The concept is evolving that the workplace may be located in dense urban fabric, near housing, lifestyle amenities, and social services (Leaman 2006). Dolan (2010) defined certain design principles for live/work hybrid typologies, as live-with, live-near, and live-nearby that are classified as Zero-Commute Housing. Live-with is a conventional space with amenities that accommodate both live and work, depending on the occupant's needs. Live-near is equivalent to an apartment or townhouse where either a wall or a floor divides work and living space. Live-nearby entails a short walk separating the working and living space. These kinds of hybrid typologies support systems for the collaborative work environment.
- *Napping*: Perhaps due to the circadian rhythm, afternoon sleepiness is common across the lifespan and in different cultures. A strict work schedule, working overtime, increased work demand often infringe upon regular sleep, leading to a variety of physical and psychological complaints, in addition to potential health and safety risks at workplaces (Nishikitani et al. 2005; Buela-Casal et al. 2007). The National Sleep Foundation (2008) noted the potential benefits of napping, that is, alleviate sleepiness while improving logical reasoning, alertness, and reaction time even after nights of restricted sleep (Brooks and Lack 2006;

Mednick et al. 2008; Milner and Cote 2009). Therefore, napping as a pattern worthy of consideration for inclusion in workplace orientation and design.

The embodiment of this chapter is a brief comprehension and understanding of the emergence of the office concept, including popular location-dependent office environment to the present knowledge work environment. Since work gets executed at a location, there are apparent spatial components and environment of the workplace as necessary tools for work performance. Also, there are social contexts, such as the interactions among employees, social norms, and support systems between groups. The next chapter elucidates the behavioural and socio-spatial perspectives of the workplace and its mediating effect to achieve better use of human capital in the organization. Further, the symbolic function of the space serves as a communicator of organizational culture and values. The size of the individual space, layouts, partitions, and windows are the critical indicators of social status and expression of hierarchy. On a similar account, an open-plan workplace might indicate organizational policy towards promoting collaboration. Research is emerging in identifying the office workplace attributes and patterns of organizational effectiveness. The insights gathered from case examples of office and workplace concepts might provide direction and scope for the designers, architects, and other stakeholders to explore innovations in creating a conducive environment for collaborative work.

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Chapter 2
Spatial and Behavioural Attributes in Office Design

Introduction

We Shape Our Buildings, and Afterwards, Our Buildings Shape Us, the historical statement by Winston Churchill in his speech to the House of Commons on October 28, 1943, is remarkable for building professionals and researchers to commemorate for years to come. In rebuilding the Commons Chamber, after its destruction in World War II on 10 May 1941, there was visible debate among the Commons on the building design of the new chamber, whether to retain its adversarial rectangular pattern or to change to a semi-circular or horseshoe design with contemporary orientation. Winston Churchill insisted that shape of the new Chamber, like the old Chamber, must represent the two-party system which is the essence of British parliamentary democracy. Finally, the new Chamber was designed by Giles Gilbert Scott, and constructed, along with similar lines to the old (containing 427 seats for 646 MPs) and confrontational design to make robust and lively debates. The psychosocial constructs of the debating members were uniquely set to refrain the members from stepping over the red lines on the carpet, which are said to equal of two sword lengths.

A substantial body of literature is emerging every day on the changing pattern of the world of work in our office buildings. Transformations are visible due to the rapidly changing nature of office technology, workforce, workplace for collaboration and knowledge work. It emerges that office settings are designed or (re)designed, for physical compatibility of the workplace and also on psychosocial constructs of people involved in specific occupational pursuits. The man–machine–environment interfaces, structure and function of the organization, the behavioural processes and adaptive skills of people that influence in office performance, often form the basis of office design. This conceptual interrelatedness of organizational attributes, physical setting, and behavioural processes to organizational outcomes in office settings (Fig. 2.1) has been elucidated in this chapter.

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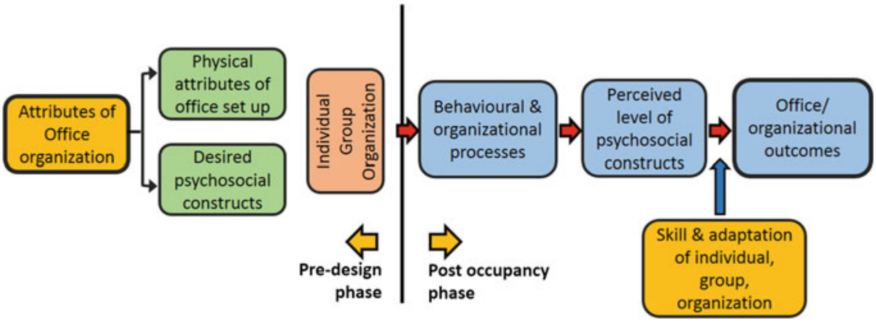

Fig. 2.1 Interrelatedness of attributes of office organization

Spatial Characteristics of Workplace

Workplace design takes different forms to generate employee satisfaction, comfort, and efficiency. The earlier chapter elaborates the emergence of different forms of office layout, corresponding to the comprehension on the demand of work. The utility of different forms of office spaces such as the enclosed cellular offices, open-plan office, co-working space, combined office space has been debated on the preference of one space over the other. The understanding of the architectural design is not about choosing between open and closed office settings, or the other, but to arrive at the right balance to the context of the organization.

The size of the workspace available for a person in a work setting termed as spatial density, the extent of enclosures around an occupants' work area and the interpersonal distance are the recognizable characteristics of the workplace. The enclosed cellular office is a private office that is arranged in rows along the façade of the building, where corridors might internally connect the rooms. An open-plan office is a large office area with no dividing walls or doors, making the workplaces equal for all. Furniture and zoning of work areas separate the office landscapes through interchangeable partition walls, wall cabinets, and room-in-room systems. The workplace openness, as a dimension, is expressed as the ratio of total area to the total length of its interior walls of the office, including partitions (Oldham and Rotchford 1983). That is, for two workplaces having the same area, the one with fewer internal boundaries is more open than the one with many walls and partitions.

Since the late 1970s, there has been a discernible trend in moving towards less hierarchical and less status-rich, more open and accessible work environment. The push towards adopting open-plan office settings is promoted by tangible drivers like cost-effectiveness, space advantage to accommodate more employees within a limited space, better communication and interaction among fellow employees, and flexibility to make changes in organizational size and structure. However, researchers have expressed reservations about the open-plan office, since it brings constant distraction, lack of privacy, including speech privacy due to workplace noise. Dissatisfaction among employees due to a variety of stated reasons leads to a negative feeling that everybody in the office is the same and the jobs are interchangeable and temporary (Vischer 2008, 2010). On the other hand, spatial isolations in a cellular or enclosed office (private space) grossly limit information flow, informal communication and knowledge exchange among fellow employees. Therefore, there is a prevailing consensus on a well-chosen mix of workspaces, private, bullpen, and open-plan offices, and to suitably realign workspaces with the evolving business needs. That is, the *combi office* brings together the features of a cellular office and an open-plan office; for example, conventionally closed offices are easily re-modelled into open-plan space, with partitions/cubic workstations in modern office designs. Such workspaces foster communication within the group and enhance the scope of speeding up decision-making. Due to the physical and environmental constraints of buildings (depth and location, noisy common spaces), however, the concept of *combi office* may not be uniformly applicable. Some of the measurable spatial characteristics of significance are elucidated below:

Office layout and workplace design—The office layout comprising of physical setting and environment is designed as a part of the organizational culture (Kallio et al. 2015; De Paoli et al. 2017). In other words, the office layout design is an indoor quality that influences work process, occupants' behaviour and performance in an organization (Wheeler and Almeida 2006; Haynes 2009). Conventionally, the closed and privatized office spaces have been created, concerning the general levels and hierarchy in the organization, whereas the open-office plan and design are more characterized by the absence of physical boundaries (Jackson and Klein 2009). Study at private corporations (El-Zeiny 2012) revealed that the females were more concerned regarding their workplace design, and furniture is the single most contributing factor to affect the performance of employees.

Density—The architectural *density* refers to the amount of workspace available to a person, which varies with office types within and across business units. Early work of Oldham et al. (1995) emphasized that the high dense work settings decrease employees' experience of control at work, and their ability to concentrate on work task, and consequently reduce one's work performance, job satisfaction and organizational commitment (Charles and Veitch 2002). Co-workers at too close proximity expose oneself to excessive stimulation, lacks control on productive interactions, and unwelcomed intrusions by others (May et al. 2005).

Proximity—The physical distance between people is a determinant of their level of communication and interaction within a workplace. Proximity is beneficial to interpersonal interaction and group functioning, due to the effects of the presence of others, shared social settings and face-to-face communication. Accordingly viewed that more team-oriented *bullpens* might enhance work effectiveness, as compared to high-partitioned cubicles or closed offices (Becker 2005, 2007). Olson et al. (2002) indicated the implications of the 30 m rule, that is, when two people reside more than 30 m apart are considered distant. The probability for two to communicate at least once a week drops unless perceived proximity achieved by the use of communication technology and other group management strategies. There are also arguments about the disadvantages of physical proximity on communication, with the view that spontaneous communication generates cognitive demand and that may not always be welcomed (Kraut et al. 2002).

Workstation—In conventional hierarchical office design, the size of a workstation is a spatial index linking to one's organizational position. Larger workstation area may be associated with higher level of privacy and satisfaction and less perceived distraction. In the contemporary computer-dominated workstations, the office employees are constrained by a fixed sitting position for a long time (Bergh and Theron 2007). Ergonomics of computer work and workplace incompatibility, and associated musculoskeletal strains and disorders have been elaborated in Chaps. 4 and 6.

Partitions and enclosures—There is a recognizable association of architectural enclosure in the workplace with the perceived privacy. The number of partitions enclosing the work area and the height of the partitions makes a difference in the level of visual and acoustic privacy (Duffy and Tanis 1999). Brand and Smith (2005) observed that the people moving from high partition ($\sim$1.6 m) to low partition ($\sim$1 m) had more negative perceptions regarding privacy and sense of control at their work surroundings. That is, the occupants behind large partitions had a better perception of privacy and also rated better in noise isolation and verbal communication. For people in workstations with low partition voted higher perception of visual appearance, colour, daylight and outdoor view quality. Goins et al. (2010) compared the physical variables (speech and visual privacy) and two symbolic attributes (home-like atmosphere and work pride). The findings are strongly indicative that the partition height was positively related to the speech privacy and visual privacy. The symbolic attributes were found to be more important than speech and visual privacy in improving work performance. Lee (2010) compared office spaces, such as enclosed private office, enclosed shared office, an open-plan office, and a *bullpen*. The study revealed that people in high cubicles had lower satisfaction regarding visual privacy and interaction with co-workers, sound privacy, job performance and perceived acoustic quality than those in enclosed shared offices. People in the *bullpen* or open-plan office layout without partitions had higher satisfaction with the noise level, work performance as well as higher perceived acoustic quality than in cubicles with high or low partitions.

Biophilia—Biophilia describes the link between nature and humans for a plausible innate human emotional affiliation to nature (Heerwagen 2009). The biophilic design appears to have a recognizable potential in office design and development. Heerwagen and Hase (2001) identified eight dimensions of the biophilic design, namely the prospect of views, refuge, water, biodiversity, sensory variability, biomimicry, playfulness, and enticement. Those of us had the privilege of experiencing office environment in the 80s can recollect the delicate use of potted plants, water features, and gardens to bring changes in the work environment. The early objective study by Ulrich (2003) of Texas A & M University was emphatic on the links between flowers and plants and workplace productivity.

Both male and female occupants in a windowed office, having a distant view of greenery, access to natural ventilation and daylighting, manifest a positive effect on their work attitude, satisfaction and productivity (Gray and Birrell 2014; Kellert et al. 2011). Employees, particularly males, may show decreased stress level in windowed offices (Menzies and Wherrett 2005; Lottrup et al. 2013). Those in a windowless office may have more job dissatisfaction, somatic distress, and fatigue, than those occupants in a windowed office. Usually, the preferred size of windows varies from 1.8 to 2.4 m in height and somewhat wider than taller (Galasiu and Veitch 2006). Passive viewing of natural stimuli through windows helps in reducing the anxiety and elevating the positive mood of occupants and well-being. Nature analogues, such as artworks, paintings, landscapes, and biomorphic forms, may arouse the feeling of living in an office environment. An innovative study by MacKerron and Mourato (2013) further strengthened the evidence of a positive relationship between subjective well-being and exposure to the green or natural environment in daily life. The researchers developed *mappiness*—a smartphone happiness mapping app that signals study participants (covered over one million responses from ~21,000 participants) with a brief questionnaire at random moments. From the analysis of response linked to GPS, coordinates indicated that the participants were happier outdoors in all green or natural habitat types than in urban environments.

Accessibility—The architectural accessibility explains the extent to which an employee's individual workspace is accessible to others. The generic property of a workplace layout regarding its relationship with interaction behaviour may be evaluated and scenario compared using the Space Syntax. The theory and application of Space Syntax were initially conceived by Hillier and Hanson (1989) in analyzing spatial configurations in the context of urban planning, street, and neighbourhood design. Generally, spaces are broken down into components and analyzed as networks of choices that are represented as maps/graphs to describe the relative connectivity and integration of the spaces. The primary conceptions of space (Fig. 2.2) are: (a) an isovist or visibility polygon, the field of view from any

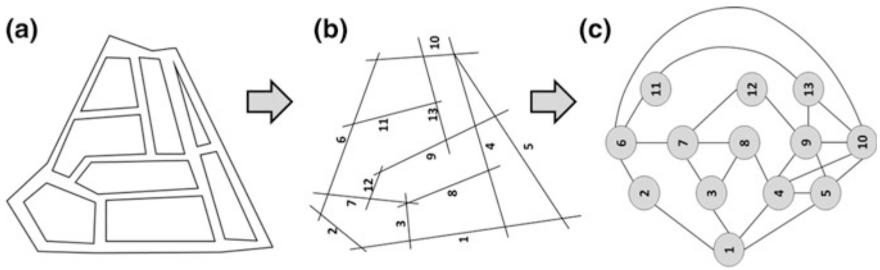

Fig. 2.2 Applying space syntax approach in urban design; **a** a fictional urban system of the neighbourhood, **b** derivation of axial map consisting of 13 axial line, with a sequence of line 1, 6, 5, 4, …, and **c** connectivity of axial lines, denoting intersections and immediate neighbourhoods (drawn from Jiang and Claramunt 2002)

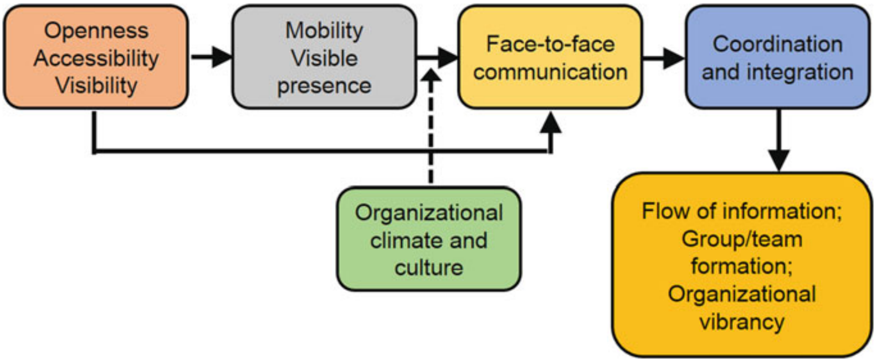

Fig. 2.3 Space syntax principle is structured as workplace interaction model (adapted from Rashid et al. 2006)

particular point; (b) axial space, a straight sight-line and possible path, and (c) convex space, an occupiable void, imagined as a wireframe diagram.

The application of Space Syntax methodology in workplace scenario opens up a newer domain in analyzing features of building interiors (Shpuza 2006), the layout of the workplace, furniture systems (Bafna 2004) in the overall human behavioural context. In a multiple-site interviews and observation-based field study, Rashid et al. (2006) recorded behavioural data, such as the number of people moving on a segment of the route, or the number of people engaged in face-to-face interactions along the route segment. The proposed interaction model is shown in Fig. 2.3.

Look and feel—Corporations around the world emphasize on the *Look and Feel* (aesthetics) of the workplace. This perspective emerges from the axiomatic truth—*better workplace yields better results* that manifest in employee productivity, performance behaviour, comfort, health, and well-being. The aesthetic value of an office design adds to the brand value of an organization. Colour schemes in an office environment have often been emphasized due to its domineering influence on the psychology of the building's occupants (Kamaruzzaman and Zawawi 2010).

In office space configuration, colour plays a significant role in influencing human psychophysiological responses that manifest in emotions and behaviour. Warm colours have a more heightened response than those of cool colours, suggesting that two rooms of same dimensions may appear differently with the choice of the colour schemes. The darker colour scheme may look the room relatively smaller, in comparison to the room with a lighter colour scheme. A long, narrow room may appear more regular in case the colour scheme of the end walls is more warm and intense and the side walls in lighter and less saturated colours. Lighter colour for a low ceiling is generally less dominant, and a high ceiling may seem lower in height when painted by a dark blue or grey (Pile 1997). O'Brien (2007) suggested that a blue office is ideal for someone who concentrates on numbers. Green is a preferred choice for a management office to provide a balancing effect, whereas yellow is suitable for sales offices. The psychological impacts of colours (Wright 2007) are briefly described herewith. That is,

- Red (exciting)—emphatic; signifies danger, excitement and strength; likely increase in cardio-respiratory responses;
- Blue (relaxing, retiring)—calming and cooling, associates to sky and ocean, concentration, comfort, harmony, unpretentious; likely slowing of heart rate and reducing blood pressure;
- Yellow (cheering)—most reflective, open, expansive, and enlightening; likely increase in cardio-respiratory activity;
- Green (relaxing, retiring)—symbolizes life, calming and natural ambience, filters out distraction, and restful to eyes;
- Purple (subduing)—mystical, playful, and grandeur;
- Orange (stimulating)—happy, soothing, radiant and glowing, excitement;
- Brown (depressing)—calm, simple, stability;
- White (neutralizing)—pure, simplicity, refreshing, open, spacious feeling;
- Black (depressing)—classic, seriousness, mysterious, sorrowful;
- Grey (neutralizing, retiring)—gloomy, respect, stability.

Either in the psychophysiological domain or interior space design, the combined effect of colour schemes, lighting, spatial features, and textures have its aesthetical appeal of a functional space (Garris and Monroe 2005). A large atrium at the entrance of an office may be welcoming among the occupants, whereas a small and narrow entrance to the building may carry an adverse feeling to both the regular and transient occupants. An experimental study (Oztürk et al. 2012) revealed that chroma significantly affects participant's performance and space appraisal of an office. The accuracy and time spent performance scores were better in the office rooms with the chromatic scheme than those in the achromatic rooms. Factor analysis indicated differences in pleasantness, harmony, dynamism, and spaciousness between the achromatic and chromatic schemes of the office rooms. At the corporate level, these outcome indicators are well recognized, and therefore, emphasis on the workplace design strategy would involve analysing the related design features using a well-structured occupant survey.

Location and amenities—Briefly, the spatial characteristics of workplaces remain at the core where all group activities are taken place. Offices located near public infrastructure have higher employee satisfaction (Duffy et al. 1992; Leaman 2006). Amenities (such as health care/clinic, childcare, recreational spaces, entertainment, sports facilities) near the workplace influence employees' satisfaction and motivation (WGBC 2014). Therefore, as corporate responsibility, organizations may decide on such amenities to gain long-term benefits of employee well-being and retention, and improvement in productivity.

Arguments (Danielsson and Bodin 2009) favour that open-plan offices have space advantages in accommodating people, promoting access and interactions with colleagues; also, the open-plan office is energy saving for lighting and ventilation. In further analysis, the impact of spatial settings on office workers may be explained by the behavioural approaches, such as the social relation, the sociotechnical and the symbolic or social value approaches. The social relation approach argues that the open-plan workplace positively influences social relationships among employees (Zahn 1991). On the other hand, the sociotechnical approach suggests that an open-plan layout removes physical work boundaries, diminishes perceived personal privacy, task identity, perceived loss of control over space (Brennan et al. 2002). Occupants feel the highest distraction in an open-plan office (65%) followed by double-room occupancy (53%), and the least in case of single occupancy (29%) (Brill and Weidemann 2001). In the symbolic or social value perspective, the environmental symbols may be taken as the representation of social order and ones' relative place in it. For example, workplace characteristics, such as size and location of the workstation, enclosures, personalization, and status markers, convey relative levels of individual recognition and responsibility.

Office designers must recognize that the privacy or publicity in the open-plan office depends on the desired identity of the group of people to achieve a sense of belonging. The concept emerges that the visually interconnected spaces create an office environment for privacy as well as separateness without isolation. The social spaces, so designed, are vital for making collaborative environment. Van der Voordt (2003) recommended articulation of innovative workplaces/combi offices, having a mix of shared and private workspaces, with the introduction of the intervention of different proximity measures and partitioned enclosures. The structure, form, and dimension of the enclosure are concerned with the degree of openness or seclusion of a space. Suckley and Dobson (2014) elaborated on the measurable dimensions of social and spatial relations in an office move. The spatial flexibility can be created by the volumetric differences, depending on the changing needs and preferences, productivity demands of the occupants, and also the technological infusion in the workspace (Al Horr et al. 2016). The occupants of large groups collaborate and communicate effectively in a centralized large shared space, whereas an individual group of the occupants makes communication more freely in the closed shared space.

Psychosocial Constructs of Work Environment

The office design presupposes that each office organization has specific needs for a psychosocial construct and expects that the design of its physical setting would meet these needs. How well the spatial setting meets the needs of a construct manifests in individual, group or organizational outcomes. One's perceived psychosocial construct may be affected by psychological processes, such as stress and overload, beliefs and attitude. On a similar note, a group's perceived psychosocial construct may be affected by multiple social and psychological processes, and an organization's psychosocial construct may be a result of the degree of congruence between organizational needs. Figure 2.4 depicts the interrelationships of spatial as

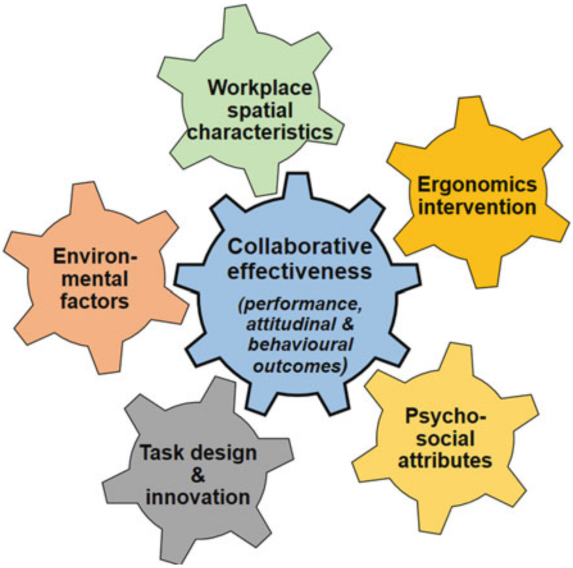

Fig. 2.4 Interrelationships of spatial as well as psychosocial components for collaborative effectiveness

well as psychosocial components, such as the task design factors, group psychosocial traits, that have direct impacts on workplace effectiveness.

Communication and Interaction—The communication structure of an organization determines how individuals and groups perform in today's office work and contribute to both individual and organizational health. Issues evolved from the literature indicate that interaction needs of an organization change regularly. Face-to-face communication is the most direct and information-rich medium for sustaining both micro- and macro-level interaction among colleagues (Nardi and Whittaker 2002). The powerfulness of face-to-face communication is evolved from language and cues like the expression, gesture, non-verbal body language, which results in effective communication (Kiesler and Cummings 2002). Besides formal interaction, informal, or unstructured information exchanges in office settings among co-workers promote and enrich social interaction and networking at work, leading to positive outcomes, such as coordination, learning, and innovation, collective performance to an optimal potential (Harrison et al. 2004).

Spatial arrangement and interconnectedness, partitions and boundaries, including physical distance influence cohesiveness among groups in work environment. Therefore, a well-designed workplace spatial setting has a direct bearing on the frequency and quality of interactions, which in turn may encourage creative teamwork (McCoy 2001). Towards facilitating interaction and collaboration, the challenge in workplace design is to create a distraction-free work environment, and impromptu interactions in and around one's workspace.

Interruptions and Distraction—It remains a sustained endeavour among the work design professionals to ensure that idle time is minimum in a work environment, and the work goes uninterrupted, irrespective of the kind of work performed. However, interruption and distraction in work are constant deterrent to work performance. Brill and Weidemann (2001) recorded that people of different administrative status spend in noise-producing activities (e.g., phone conversations, informal/formal meetings in nearby workstations) for about 1/3rd of their working time. In a survey of office workers, about 71% of the respondents viewed noise as the most significant workplace distraction (Steelcase 2007). In an open-plan work environment, distraction is considered as a severe issue of counter-productivity, comparing to a cellular office environment. For example, overhearing in low acoustic privacy condition in open-plan settings has its advantages and also disadvantages. On the one hand, one has chances of picking up useful information for work, and on the other, one may be overexposed to less relevant information.

Privacy—Privacy is a multi-layer construct in controlling access of individuals or groups to the workspace, limiting distraction and interruption, and also controlling information (Laurence et al. 2013; Rashid and Zimring 2005). The workplace privacy may be elaborated as architectural and psychological privacy (Wang and Boubekri 2011). The extent of architectural privacy may be expressed by the type of physical features, e.g., open or closed type of workstation, cubicle enclosures by opaque walls, the presence of door, the height of enclosure of the cubicles. Apart from enclosing walls/partitions, the physical barriers, such as plants, segregated dimmed lighting, may be used to achieve privacy at work partly. Visual and acoustic intrusions are controlled by visual and acoustic shields, which give occupants more control over their accessibility to others (Vischer 2006). The visual and acoustic isolations determine the level of exposure, depending on the workplace location, shape, and orientation of interior, and also passageways.

Beside the architectural privacy, the psychological privacy is related to social contact/control over ones' accessibility to information. Even in a similar office setting, a person's sense of privacy or preferences may be affected by the degree of friendliness of an office environment. Well-furnished and well-lighted rooms, cushioned chairs, and wall decors may elicit more welcoming work surroundings, than those with clumsy room arrangement.

Stress—Stress, a recognized health problem, arises when the office goer's demands exceed their ability to deal with or control the workplace requirements. Excessive stress induces fatigue, reduced productivity, increased errors and accidents, job dissatisfaction, absenteeism, workplace violence, drug abuse, increased health ailments and the like. Allowing office occupants of visual and physical access to greener outdoors is a valuable strategy for work (re)design, whereby to mitigate the perceived level of stress (Shin 2007; Lottrup et al. 2013).

Personal Control—The control refers to one's ability to either adjust, change, or regulate exposure to the physical environment or surroundings. Control over the task, resources, decision, physical environment are some recognizable dimensions of personal control. Lee and Brand (2005) explained that personal control at the objective level refers to one's ability to modify conditions of the physical environment. Personal control at the subjective level is interpreted as the effects and outcomes of applying control behaviours. Researchers (e.g., Vischer 2008; Lee and Brand 2010; Danielsson 2010) have emphasized that a higher level of personal control reflects positive psychological effects at work, including satisfaction to job and environment, group cohesiveness, and well-being. Those who have a high level of availability to control the physical environment can relate to their job satisfaction (Salama and Courtney 2013).

Vischer (2007a, b) suggested that environmental control influences office occupants on at least two levels—(a) instrumental or mechanical controlling, such as HVAC, lighting, and (b) adjustment to physical features, like reconfiguring workstations, closing/opening of doors and windows. Frontczak and Wargocki (2011) also noted that a controllable environment enhances people's thermal, visual, and acoustic satisfaction.

The Sense of Belonging—Belonging is a sense of personal involvement as a member of the group in an organization, and feeling oneself as integral to the group. Employees emotionally committed to the organization have a strong sense of belonging, and they are more encouraged to get engaged in organizational activities on longer-term perspectives. The workers who can connect their identity and ideas to the intrinsic identity of the organization, they manifest more exceptional commitment towards the organization. Jaitli and Hua (2013) examined the associations between employees' sense of belonging and their perceptions of workplace physical attributes in a corporate environment. Observations indicate the relevance of the corporate culture and environment, the perception of the workspace attributes, and familiarity with the facilities that were significantly related to the sense of belonging to employees in an organization. In a study on the virtual community, Zhao et al. (2012) demonstrated that when members of the community perceived a strong sense of belonging, they better internalized the social norms of a community and expressed in participating to its activities, like getting knowledge from others and sharing.

Territoriality—In the context of office typology, the territory is commonly understood as a physical and bounded space, including public, group, and individual territories. The sense of territory is the primary component of psychological comfort (Vischer 2008) at both individual and group level. There is an overall perception that territoriality serves to organize office behaviour by geographically placing individuals, according to requirements. Different physical features (e.g., spatial demarcation, décor) and symbolic barriers (e.g., personalization, visual imagery) are the essential elements to create office territoriality. However, the rights to a territory may be compromised depending on the degree of infringement or association of a person or group with the territory. Factors such as gender, personality, ownership, and social climate may have effects on one's perception of territoriality. However, designing of office setting might depend on the cultural influences; e.g., senior corporate executives in Japan with Kaizen culture occupy open desks on a large office floor, and a very similar approach of shared offices are more common in Italy and European corporate world.

Control and Supervision—In office settings, control is often related to one's influence over the organizational resources, including space, ideas, pace, and content of work. Taking synonymy to physical control, it describes the availability and adjustability of physical and environmental systems. About office settings, control may often be related to the sources of interference and stimulation, and organizations may use territoriality, personalization and privacy dimensions of the workplace. Supervision, on the other hand, is the direct control on employees to oversee the progress of the activity.

Home or Office Working—With the rapid change in the work practices mainly in the innovative work environment, the workplaces are fast moving from the structured offices to the home environment. Proponents of home working put forward several merits; e.g., (a) long and unpleasant commutes are avoided and maintain healthier work/life balance, and (b) organizations save money, by not investing in centralized offices, and employing best talents who prefer to serve as remote workers. On the other hand, however, the demerits of home working are the likely physical isolation and primary reliance on the technology. There are primary differences in physical and social aspects, between the office and homework environment, concerning the strategy of space planning, collaboration, and communication (Myerson and Ross 2006). Traditionally, the architectural design of buildings determines the nature of office or house environment. The house has often been regarded as a social link that reflects the cultural properties, whereas the physical aspect of office design mostly looks at the architectural attributes, such as space planning, and the social aspect addresses the use of shared spaces.

Innovative and Collaborative Workplaces

Innovative organizations need creative employees to generate novel ideas in developing new products, processes, and systems. An enterprise that value innovation needs its employees not only in achieving productivity goals but also in generating breakthrough innovations (Kakko 2009). IBM study (Tomasco 2010) on 5000 Chief Executive Officers from 60 countries and 33 industries emphasized creativity as the *crucial factor for future success*. The South Korean Government (2013) reiterated that *the global economy is moving away from the industrial and knowledge economy to the creative economy, encompassing innovation, technology, and creative ideas*.

From a variety of research efforts, a reasonable degree of knowledge is available in the psychological domain on the relationship between the characteristics of creative persons and their creative performance. The creative ability depends on the characteristics, such as personality traits (e.g., openness, toleration of ambiguity), cognitive style (e.g., divergent thinking, problem-solving), and domain knowledge (Shelley et al. 2004). The creativity in individuals can be developed in those who are potentially creative, or through training in cognitive skills (Scott et al. 2004). On the other hand, creative persons placed in traditional productivity-driven organizations with strict regulations, and rigid work routines, may remain subdued and not be able to show any creative behaviour. Seven characteristics of innovative workplaces (US GSA 2006) are spatial equity, healthfulness, flexibility, comfort, connectivity, reliability and sense of place. Steelcase Workspace Futures (2012) surveyed nearly 200 corporate real estate practitioners in investigating how workplace settings can strengthen the organization's efforts for innovation. Observations yield in making workspaces flexible, inspiring, collaborative, and making a space social. The architectural design considerations in making space flexible are (a) semi-permanent walls or movable partitions, (b) different sizes of flexible hubs for workgroups, (c) options for the user to reconfigure furniture and accessories, and (d) demarcated spaces for group meetings and privacy.

Dul and Ceylan (2011) designed a checklist—*Creativity Development Quick Scan (CDQS)* for analyzing the creativity support of the employee in a work environment. Twenty-one elements of the work environment are structured as follows:

1. Challenging job (complexity, job demands);
2. Teamwork (a group working on a joint goal);
3. Task rotation, (task scheduling to perform simultaneously);
4. Autonomy (decision latitude on the work tasks);
5. Coaching supervisor (to encourage and build trust, and to provide positive feedback);
6. Time for thinking (idea generation, with no time pressure);
7. Creative goals (produce new ideas according to goals and expectations);
8. Recognition of creative ideas (the organization recognizes new ideas);
9. Incentives for creative results (rewards, pay raises, promotion);
10. Furniture (chair–desk complex and other workplace amenities);
11. Indoor plants/flowers (potted plants, indoor flower décor);
12. Calming colours (interior colour schemes for soothing experience);
13. Inspiring colours (interior colour schemes for stimulating experience);
14. Privacy (visual and acoustic isolations);
15. Window view of nature (visual access to greenery);
16. Any window view (visual access to any outer environment);
17. The quantity of light (lighting quantity and quality);
18. Daylight (natural lighting);
19. Indoor climate (physical climate and air quality);
20. Sound (positive sound) (music, the absence of noise);
21. Smell (positive odours) (fresh air, the absence of bad smell).

In a more straightforward and easy-to-apply way, the CDQS includes elements covering the social–organizational, physical elements as well as cognitive and perceptual aspects of the work environment. The social-organisational context and physical elements are addressed in checkpoints 1–9 (Shelley et al. 2004; Hunter et al. 2007; George 2008) . Checkpoints 10–21 describe cognitive and perceptual aspects that stimulate positive mood and creativity (Küller et al. 2006; Amabile et al. 2005; Davis 2009). The CDQS allows measuring the presence of creative elements of the work environment, and each listed elements are rated of its importance on a seven-point scale (*not important at all—very important*), and the overall score is obtained by summing the scores to indicate relative support to creativity. For collective analysis, an aggregate score can be obtained by averaging scores from employees belonging to a given work environment entity. The presence score that is larger than the importance score would indicate that the environment fits the person's needs, and vice versa. By the use of CDQS, one can explore problem-solving and priorities for supporting creativity and, also, elucidate the issues of work environments for supporting comfort, health, and safety.

Questionnaire for Workplace and Workspace Analysis

The emerging literature from the organizational sciences recognizes the workplace and the workspace as symbolic representation of organization's underlying values, principles, and style of practices (Vischer 2010). The importance lies in perceiving the facets of the workplace. That is, a workplace is where one is employed or customarily does one's work (e.g., one's office, laboratory), and a workspace is the space allocated for someone to work in, especially in an office.

Researchers indicated that the architecture design and workplace spatial layout are affirmed to influence employees' well-being and job satisfaction (Wineman and Adhya 2007). The spatial experience of the workplace is contained in certain key

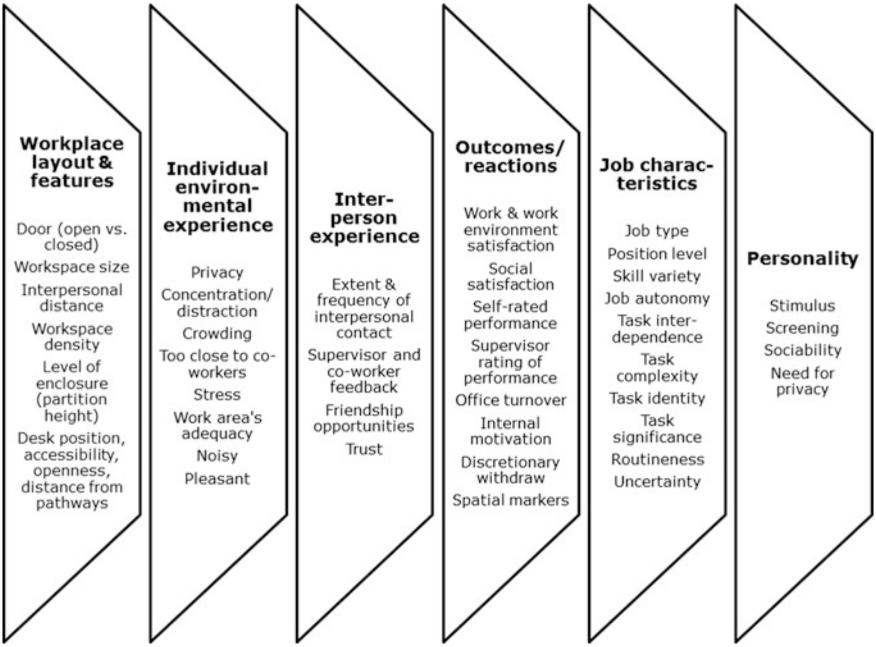

Fig. 2.5 Workplace parameters that focus on occupants' responses and outcomes

spatial design concepts, such as available space, openness, and boundaries, personalization, visual access, visual exposure, speech exposure, physical and function distance between workstations, spatial density, environmental quality. There exist complex relationships between the physical environment (acoustics, indoor climate, air quality, light, colour, space density, and arrangements) and the health, safety, performance, and behaviour at work (McCoy 2002; Gifford 2002). Different categories of workplace parameters that focus on occupants' responses and outcomes are elucidated in Fig. 2.5.

Studying the office organization involving questionnaire-based survey instrument and behavioural observations of the occupants is the widely adopted approach. In order to study the influence of workplace characteristics on knowledge worker's workspace experience, Lu and Noennig (2015), Technische Universität Dresden, introduced a structured questionnaire. The questionnaire was based on a set of peer-reviewed criteria, such as workplace experience, work motivation, job satisfaction, sense of belonging, commitment and work performance. A revised structure of the questionnaire is presented in Table 2.1. As a preamble to applying the questionnaire, the demographic information of participants is gathered, such as age range, gender, duration of work experience, and the length of time spent in enclosed/open-plan office spaces, organizational activity, and position held. A participant may be asked to respond to each question items on five-point Likert-style agreement scale, from strongly disagree to agree, reflecting one's feelings about each statement. Analysis of the workplace spatial characteristics of individual workstation and the entire floor plan layout, and associated psychosocial variables determine the relativeness of organizational outcomes, and accordingly, the workplace design implications can be ascertained.

Table 2.1 Work analysis questionnaire (adapted from Lu and Noennig 2015)

Attributes	Checkpoints	Remarks
Workplace experience: available space	Keeping one's work close to arm's reach;	*Twenty six question elements cover seven critical spatial design concepts of control, such as available space, the flexibility of using space, visual access, visual exposure, speech exposure, function distance, and environmental quality (Evan and McCoy 1998)*
	Having adequate storage space in the workstation;	
	Having sufficient space around the workstation to hold a face-to-face meeting;	
Workplace experience: flexible use of space	Having sufficient places for conversation or meeting needs;	
	Availability of a meeting room/space as and when needed;	
	Always finds a suitable place for conversation or collaborative work;	

(continued)

Table 2.1 (continued)

Attributes	Checkpoints	Remarks
Workplace experience: personalization	Makes changes in the appearance of the workplace;	*It conveys the uniqueness and identity reflecting on one's roles and responsibilities. A person having more workspace to personalize can might yield higher job satisfaction, as compared to those having less opportunity on space*
	Personalizes workplace;	
	Rearranges the workstation and allied furniture to one's preference;	
Workplace experience: visual access	Having a windowed office to see both entire room and the outdoor view;	*The windowed office is having visual and physical access to the green outdoor environment, natural ventilation and daylighting manifest a positive effect on one's work attitude and decreased stress level*
	One can see the entire room but no access to the window to see the outdoor view from one's workplace;	
	One can see outdoor view but cannot see entire room from one's workplace;	
Workplace experience: visual exposure	Everybody can see VDT at any time.	*Dense work environment and visual distraction are considered as severe counter-productivity issues. An interruption in the workstation by visual exposure has its inherent disadvantages of being visually overexposed*
	The workstation can be seen by others when they stand up	
	People passing by can always see one's work area;	
	Only co-workers from the group can see one's work area;	
	No other person can intrude on one's VDT when operating;	
Workplace experience: speech exposure	Hears the conversation with colleagues;	*Whereas speech privacy emphasizes the ways of isolating interactions from the outside, its exposure encourages passive interaction with the surroundings*
	Other people hear the conversation when one speaks on the phone or talk to others;	
	Speech isolation and privacy in one's workplace;	
	One closes the door or adjusts the partition to avoid outside noise;	
	The sound within one's workstation can be contained when one is speaking over the phone or talking to others;	
Workplace experience: function distance	The workplace is located closer to copier/printer area;	*Optimize the function distance, e.g., strategic coffee machine, micro-kitchen, copier/printer area to facilitate impromptu interaction with colleagues*
	The workplace is located closer to kitchen or coffee area;	
	The workplace is located closer to the supervisor's office;	

(continued)

Table 2.1 (continued)

Attributes	Checkpoints	Remarks
Satisfaction with the ambient environment	Satisfied with the environmental conditions in one's workspace;	*Satisfactory lighting, thermal, and acoustic situations provide conditions for health, comfort, and work performance*
Work motivation	One has an excellent clarity of the developmental plan of one's area of function;	*Motivational components are: direction (choice—what a person is trying to do), effort (intensity of a person's involvement), and persistence (duration—how long a person keeps trying) (Arnold et al. 2010)*
	Enjoys working and performing one's best in the assigned area of function;	
	The pleasure of coming to work every day;	
	Work in the assigned area makes one feel self-fulfilled;	
Job satisfaction	One would recommend one's job to a friend who is searching for a similar job;	*One's willingness to remain in the job and exert extra effort on its behalf. One has a firm belief in organization's goals and values towards job satisfaction and commitment (Lee and Brand 2005)*
	One would choose to work here again if one had to do it over;	
	Satisfied with one's current job;	
The sense of belonging	One is not very sure if one fits in with other colleagues;	*Checkpoints are adapted from the sense of belonging instrument (Hagerty and Patusky 1995); From sociological as well as psychological perspective, the sense of belonging is observable and explainable through human behaviour*
	One would describe oneself as a misfit in social engagement;	
	One thinks to make a difference to people or things around oneself, but lacks confidence that what one has to offer is valued;	
	One does not feel that there is a place in the organization where one fits well;	
	Uncomfortable with one's background and experience, as compared to those who are usually around;	
	One is not valued by the superior;	
Organizational commitment	One has a strong commitment to the assigned functions;	*Build and sustain the workers' commitment, since the organizational knowledge is embedded in the individual knowledge (Hua 2007)*
Work performance	One accomplishes work efficiently	*Criterion is associated with organizational outcome and effectiveness*

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Part II
Building and Office Work-Related Illness

Chapter 3
Sick Building Syndrome and Other Building-Related Illnesses

Introduction

Outbreaks of building-related illnesses, collectively termed as *sick building syndrome* (*SBS*) among building occupants reported in the recent decades, draw remarkable resemblance to early events of epidemic hysteria. Tarantism, the dancing mania of peasant women (animal-like squealing, obscene shouting, laughing, or weeping) during the fifteenth to seventeenth century, St. John's or St. Vitus' dances in Northern Europe, the hysterical fits of women due to smells from hemp steeped in water (Ramazzini 1713), industrial outbreak among workers in a cotton mill in the eighteenth century England (Gentleman's Magazine 1787), are historically recorded events. Many other early psychogenic illnesses reported from schools, hospitals, prisons, and in warfare, exemplify the results of various reasons, like prominent social concerns and exposure to physical, biological, or chemical agents (Bartholomew and Wessely 2002; Sirois 2013).

The SBS manifests as the complex spectrum of ill health symptoms, such as mucous membrane irritation (rhinorrhea, nasal congestion, sore throat, eye irritation), asthma symptoms (chest tightness, wheezing), neurotoxic effects (a headache, fatigue, irritability), gastrointestinal disturbance, skin dryness, sensitivity to odours. These symptoms may appear among occupants in office buildings, schools, public buildings, hospitals, and recreational facilities. The rapid spread of symptoms often leads to the virtual closure of the facility, and resolution of the illness also takes place within a short time after leaving the facility (Laumbach 2008; Takeda et al. 2009).

Building-related illnesses have been viewed as ubiquitous in modern high-rise buildings. These are designed to be airtight on energy-saving consideration—windows remain sealed, deprived of natural ventilation and daylighting, and HVAC system re-circulates the air in the building, with the minimal replacement of fresh air. Concerns about human health due to deteriorating indoor environmental quality are steadily increasing with a public outcry among the building occupants and also

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challenging lawsuits to redress grievances. The term SBS has been in use for some time now and widely recognized, in spite of suggestions for alternative names, such as problem buildings, building-related occupant complaint syndrome, abused building syndrome. Acknowledging that the incidences of SBS symptoms are straightforward, its characterization and linkages to an indoor exposure require more in-depth analysis. An impediment towards this effort is to make the primary distinction as to whether the problem is chemical, biological, physical, or psychogenic. The questions to examine are the mechanism how workplace or environmental processes trigger physical health symptoms, and whether some individuals are more prone to illnesses. Further, it calls for a review on the kind of critical work settings that precipitate illness conditions, and how the work or environmental aspects influence building occupant's psychophysiological threshold, making oneself hypersensitive even to mild irritants. Priority is placed on exploring organizational interventions to restrict the spread of the syndrome and efficiently manage causes of building-related illnesses.

Several researchers indicate the SBS as a phenomenon that occurs among building occupants, perhaps one out of five building occupants reports symptoms associated with their respective place of work and attributed to the IAQ. The interactions of a multitude of factors, such as the site, climate, building system, construction materials, building dampness, contaminant sources, activities of occupants, affect the quality of indoor air. Typically, maintaining allowable IAQ in office buildings depends on effective ventilation systems in operation. Ineffective or inadequate ventilation systems result in inefficient removal of pollutants from indoor air and display signs of SBS among the occupants.

Questionnaire Survey

Health impact assessment addresses qualitative or quantitative evaluation of the magnitude of health consequences due to measurable environmental causation or metric, and the size of the population affected (Fehr et al. 2012; Mesa-Frias et al. 2014). Apparent relationships exist between the external stimuli, kinds of human responses and about the type of building environment. Therefore, the discomfort and symptoms of occupants in the building require acknowledging that an exposure scenario exists, and the discomfort and disease have a strong association with psychologic or physiological components. A structured questionnaire (Table 3.1) may be used to ascertain the SBS of the respondents in an office building. The office workers who had at least one symptom of SBS and onset of two or more symptoms at least twice weekly, overnight resolution of symptoms after leaving the workstation or building, and the absence of known medical causes, may be defined as having SBS (Ooi et al. 1998). The prevalence of symptoms among building occupants is linked to personal exposure to the indoor environment. The symptoms may vary during the day, in the course of changes in the concentrations of indoor pollutants. Further, the prevalence of syndrome might differ with the specificity of

Table 3.1 Questionnaire on SBS (Adapted from Ooi et al. 1998)

Demographic details of the building occupant		Socio-economic aspects		
Workplace characteristics (office plan)		Work experience; working schedule (including overtime and night work)		
During the past four weeks				
Health and well-being symptoms	Daily	2–3 times weekly	Less	
Fatigue				
Headache				
Drowsiness				
Dizziness				
Shortness of breath				
Nausea/vomiting				
Stuffy nose				
Dry throat				
Skin dryness/rash				
Eye irritation				
Time of occurrence				
Do the complaints occur?	Morning	Afternoon	No noticeable trend	
Does relief occur from complaints?	On leaving workstation	On leaving building	Never	
Medical conditions	Yes	On medication (Yes)	Not on medication	No
Allergy				
Sinus				
Asthma				
Migraine				
Others (specify)				

criteria for the definitive diagnosis of a case. Accordingly, there may be a shift in the frequency distribution of affected workers when the requirements were changed to one symptom, instead of two or more symptoms (Ooi et al. 1998).

For measuring the concentration of indoor air pollutants, one may adopt area sampling by placing an environmental monitoring device in general building locations and placing a personal sampling device close to the nose of the person that better represents the inhaled dose of individuals. Chapter 10 is dedicated to indoor environmental quality (IEQ) assessment, concerning primary exposures. The exposure assessment based on area sampling and recording of symptoms of occupants from the vicinity of the samplers may indicate some dose–response relationships between exposures and symptoms. However, there are limitations to extrapolate the relation to other buildings, since the problem situations in buildings are unlikely to be similar.

SBS Epidemiology

Epidemiological evidence is abundant of the occurrence of SBS in real-world settings all over the world. Within the limited scope, and the author's comprehension on the subject, only a selected number of cross-sectional studies that have been reported in the recent years are briefly summarized in Table 3.2. Different research groups emphasized on the association of prevalence of SBS symptoms among the office workers with the organic floor dust concentration, the floor covering of the workplaces, the age of the building, and the kind of ventilation system in operation. The size of the office and the number of occupants in the office were critical, presumably because of likely rise of pollutants during the day. The shelf factor was identified as a risk factor for mucosal irritation, and the fleece factor, such as fleecy surfaces, paper, and cardboard was recognized for general symptoms in the office buildings (Skov et al. 1990; Mølhave 2011). Despite that carpets give a cozy atmosphere and an aesthetic acoustic environment in a building, carpet fibres and accumulated dust, especially the organic part of the dust, have been found to be associated with SBS, namely mucosal irritation. Further details of work and building-related respiratory illnesses are elaborated elsewhere in the chapter.

The US EPA Building Assessment Survey and Evaluation (BASE) study (Apte and Erdmann 2003) is a landmark study covering 100 large office buildings and extensive measurements of both SBS symptoms and environmental monitoring. The occupant must have reported an occurrence of one SBS symptom, at least 1–3 days per week during the month, and resolution of the symptoms when the occupant moves away from work. Analysis indicated dose-dependent associations in many of SBS symptoms with the delta change in indoor and outdoor CO_2 concentrations. VOC sources had a direct association with mucous membrane and lower respiratory irritation.

The Whitehall II SBS study is a longitudinal health survey of UK office-based civil servants, commenced with 10308 males and females, exploring the significance of the physical and psychosocial work environment to the occurrence of SBS. Analysing ten SBS symptoms among 4052 participants from 44 buildings, Marmot et al. (2006) did not observe the significant relation between most aspects of the physical work environment and SBS symptom prevalence. The features of the psychosocial work environment, such as high job demands and low support, appear to be more determining in explaining differences in the prevalence of SBS symptoms, than those attributed to local aspects of the physical environment of office buildings.

Jaakkola et al. (2007) examined the occurrence of SBS related symptoms, chronic respiratory symptoms, and respiratory infections, using a questionnaire survey of 342 office workers in Finland. A case definition of SBS was taken as symptoms of nasal (dryness or itching of nose, blocked or a runny nose, or sneezing), eye (dryness and irritation, watering, or redness), throat (dry irritative cough, sore throat, or hoarseness), skin (dryness, irritation, redness patches, itching, sore skin, or urticaria), and non-specific symptoms (headache and fatigue), which

Table 3.2 Cross-sectional studies on SBS

References	Sample population	Questionnaire survey/objective measurement	Results
Burge et al. (1987)	4373 office workers in 42 office buildings in the UK	SBS	Workers had more SBS symptoms in buildings that were humidified or air-conditioned. Complaint: lethargy (57%), nasal congestion (47%), dry throat (46%), headache (46%). Symptoms (mean building sickness index) were more in women than in men and were independently more frequent in clerical workers, secretaries than in technical and professional employees and managers
Skov et al. (1989)	4369 workers in 14 town halls and affiliated buildings in Denmark	SBS, ambient climate, CO_2, formaldehyde, VOCs, airborne dust, fibres, lighting, micro-organism, static electricity, noise, housekeeping; analysis of building material, materials used in office equipment	Employees in mechanically ventilated buildings had highest rates of mucous membrane irritation, headache, fatigue; clerical and social workers had more complaints than those of professional workers. Increased incidence of mucous irritation from exposure to photograph printing, carbonless paper, and VDT. Females had a higher prevalence of mucosal irritation and general symptoms than males
Richards et al. (1993)	2598 combat troops stationed in Saudi Arabia during the Gulf War	Investigation of respiratory illness	The type of housing (air-conditioned buildings, non-air-conditioned buildings, open warehouses, and tents) influenced the prevalence of symptoms. Ever vs. never housed in an air-conditioned building was associated with $\sim 37\%$ greater prevalence of a sore throat, and 19% greater prevalence of a cough

(continued)

Table 3.2 (continued)

References	Sample population	Questionnaire survey/objective measurement	Results
Ooi et al. (1998)	2856 office workers in 56 public and private sector buildings in Singapore	A self-administered questionnaire introduced on SBS and perception of the physical and psychosocial environment, measurement of ambient climate, respirable dust, chemicals, bioaerosol, and other variables	Health complaints included neurotoxic reactions (fatigue, headache, drowsiness, dizziness), eye irritation, irritation of the nose, throat, and airway (stuffy nose, dry throat, shortness of breath), skin irritation (dryness, rash), and other complaints (nausea, vomiting). Associations of the physical environment and work-related stress with the history of health ailments among the building occupants. SBS symptoms became more apparent over the work shift and resolved upon leaving the premises
Milton et al. (2000)	3720 workers from 40 buildings with a total of 110 independently-ventilated floors	Recorded short-term absence from work and incidences of acute respiratory illnesses.	Based on analysis of ventilation system design, occupancy, and end-of-day CO_2 measurements, the ventilation rates of buildings were classified as moderate ($\sim$12 L/sec) or high ventilation ($\sim$24 L/sec per occupant). The absence rate was 35% lower in the high-ventilation buildings
Brasche et al. (2001)	1464 (60% females) in 14 office buildings from the German ProKlimA-Project	SBS survey and ergonomics data on working conditions and job characteristics	Gender-specific SBS prevalence rates differ for the whole sample; complaints were significantly higher in females. Independent of personal, work-related and building factors, $\sim$36% of females with the most favourable job characteristic suffered SBS (male: $\sim$19%), 53% of females with the most unfavourable job characteristic suffered SBS (males: $\sim$33%)

(continued)

Table 3.2 (continued)

References	Sample population	Questionnaire survey/objective measurement	Results
Reijula and Sundman-Digert (2004)	11154 office workers from 122 workplaces in Finland during the period of 1996–99	SBS	Most common indoor problems as reported by respondents: dry air (35%), stuffy air (34%), dust or dirt in the indoor environment (25%), and draught (22%) Common work-related symptoms: irritated, stuffy, or running nose (20%), itching, burning, or eye irritation (17%), and fatigue (16%) Women reported symptoms more often than men. Allergic persons and smokers reported indoor air problems and work-related symptoms more often than non-allergic persons and non-smokers
Apte and Erdmann (2003)	US EPA Building Assessment Survey and Evaluation (BASE) study of 100 large office buildings during the period of 1994 to 1998	Environmental parameters (e.g., CO_2, CO, VOCs, air temperature, and RH), including data of jobs, perceptions about indoor environment, health, and well-being. SBS related to mucous membrane (irritation of eyes, stuffy nose/sinus, and sore throat), lower respiratory (chest tightness, shortness of breath, cough or wheezing), fatigue, headache, and dry or itchy skin	The analysis covered 36 VOC compounds (41 buildings), formaldehyde (100 buildings) and acetaldehyde (86 buildings), as analysed by gas chromatography–mass spectrometry (GC-MS). Multivariate logistic regression analyses revealed dose-dependent associations for dry eyes, sore throat, nose/sinus congestion, and wheeze symptoms with the delta change in indoor and outdoor CO_2 concentrations. VOC sources had a direct association with mucous membrane and lower respiratory irritation
Marmot et al. (2006)	4052 male and female participants from 44 office buildings in longitudinal Whitehall II SBS study in the UK	Self-reported ten SBS symptoms (i.e., headache, cough, dry eyes, blocked/runny nose, tired for no reason, rashes/itches, cold/flu, dry throat, sore throat, and wheeziness)	25% of men and 15% of women reported no symptoms, whereas 14% of men and 19% of women reported five or more symptoms. There was positive (non-significant) relationship between the aspects of the local physical environment (airborne bacteria, inhalable dust, air temperature, RH) and SBS symptoms prevalence. More significant effects were found with features of the psychosocial work environment, such as high job demands and low support

(continued)

Table 3.2 (continued)

References	Sample population	Questionnaire survey/objective measurement	Results
Karjalainen (2007)	3094 (50% females) in the home environment; 1000 (52% females) in an office environment	Telephonic interview; thermal satisfaction	In general, men reported higher thermal satisfaction. The relative percentage of people voted to uncomfortably hot or cold votes was consistently higher in females
Syazwan et al. (2009)	176 office workers in two buildings (new and old) at Kuala Lumpur	SBS and IAQ	These buildings had the same centralized air-conditioning unit, and the office was dependent only on the general ventilation. Nearly ~69% of office workers from old building recorded SBS, in comparison with 36% of office workers in the new building
Aries et al. (2010)	333 occupants (42% females) from 10 office buildings in the Netherlands	SBS, office layout, lighting, physical and psychological discomfort	The significant relationship observed between gender and office lighting, including desk lighting, physical and psychological discomfort, such as concentration problem, dullness, headache, bad vision, and dry throat/eyes
Zalejska-Jonsson and Wilhelmsson (2013)	5660 (53% female) in residential buildings in Sweden	Questionnaire; thermal comfort, IAQ, acoustics	Thermal comfort and overall IEQ satisfaction are greater among female occupants. Problems associated with IEQ (stuffy air, draught, and dust) were more among females than males

might have occurred during the past year, at least 1–3 days per week and mainly during workdays or work shifts. There were significant health effects due to office work exposures, adjusting confounders such as psychosocial factors at work. Exposures to paper dust and carbonless paper that contains solvents and colour-forming chemicals increase the risk of a headache and fatigue, chronic breathlessness, and chronic bronchitis (a chronic cough and phlegm production). Exposure to carbonless paper through its touching can cause sinus infections, middle ear infections, and increased risk of eye symptoms and diarrhoea.

Gupta et al. (2007) undertook a questionnaire-based investigation on the prevalence of the SBS at a multi-story centrally air-conditioned Airport Authority of India building in New Delhi. Qualitative analysis included the relationships between SBS score, CO_2 and other parameters related to building and work environment. Quantitative analysis included monitoring of pollutants, namely NO_x, SO_2, CO, and suspended particulate matter. Despite that the concentrations of pollutants complied with IAQ standards were generally within limits, the prevalence of SBS (a headache—51%, lethargy—50%, and dryness in body mucous—33%) was higher in the third floor as compared to other floors and the control tower. The third floor and the control tower of the airport were affected by infiltration, mainly from entrance doors.

Hengpraprom et al. (2010) showed the influence of airborne fungi on allergic rhinitis among office occupants (49%) of a high-rise building in Bangkok. Allergic rhinitis was defined as having the symptoms of nasal congestion, an itchy nose, sneezing, and running nose without a cold in the past 12 months (Teeratakulpisarn et al. 2000). Work-related allergic rhinitis was defined as (a) having the above symptoms with a cold at least twice in the past month; (b) expressing the manifestation at work or seeing it worsen at work; and (c) the frequency of manifestation occurred at least 1–3 days per week. Indoor humidity was strongly correlated with airborne fungi concentrations. However, the fungal concentration was not associated with work-related allergic rhinitis. Asthma and asthma-like symptoms among office workers, respiratory sensitization with exposure to hot or cold weather, the presence of visible mould, and carpeting resulted in a positive association with allergic rhinitis.

Syazwan et al. (2009) compared the data of SBS and IAQ of 176 office workers in old and new buildings in Kuala Lumpur City. The investigators suggested that improvement in ventilation effectiveness and increase in ventilation rates per person may reflect on the reduction of indoor pollutants and also reduction in the prevalence of SBS in buildings. Norhidayah et al. (2013) investigated associations between IAQ parameters and SBS in three buildings in Malaysia. The prevalence of SBS symptoms, having 1 to 3 symptoms per week, was similar in the buildings. The CO concentration and fungal counts were not significantly different between the buildings. However, the observed CO_2 concentration and climatic factors suggest that the predictors of SBS might be ventilation and accumulation of contaminants within the indoor environment.

Many abiotic agents from building materials and interiors like wall coverings, synthetic paints (a&b—pinene), thinners, glue, floor coatings of linoleum and PVC, solvents, such as formaldehyde, hairspray, perfume, photocopiers and printers, disinfectants and detergents (members of linear alkylbenzene sulphonates), and soap as cleaning agent (sodium or potassium salts mixed with fatty acids) add to air pollution to cause SBS symptoms (Guo 2011; McDonnell and Burke 2011). Therefore, it may be reiterated from reviewing voluminous literature that no one single cause explains most SBS complaints, but instead assumes that multiple factors interact to manifest occupant complaints. The symptoms typically grow worse during the workday and disappear or diminish after the person leaves the building.

Gender Difference in SBS

Women appeared to show a higher prevalence of SBS symptoms as compared to men in the same buildings. Individual characteristics, such as education level, working conditions, job characteristics, and other psychosocial factors, can also influence SBS prevalence positively or negatively in men and women. The technical factors associated with the increased prevalence of SBS are the building factors, such as the age of the building, indoor dampness, presence of some photocopiers and humidifiers in the building (Sundell 1996). Zweers et al. (1992) examined 7043 occupants (65% female) in 61 office buildings in the Netherlands and noted that occurrence of SBS symptoms was related to air conditioning and humidification in buildings. Females had more prevalence of SBS (e.g., skin/eye/nasal symptoms) and complaints of indoor climate, such as temperature, air quality, lighting, and noise. Carrying out of study on 4943 office workers (53% female) in Sweden, Stenberg and Wall (1995) observed a higher prevalence of SBS among females (OR = 3.4) than males.

Questionnaire survey and ergonomic data from the German ProKlimA-Project (Brasche et al. 2001) also substantiated a significantly higher prevalence of SBS symptoms among women, as compared to men folks, both under the most favourable and most unfavourable job characteristics. Undoubtedly, the physical and psychological disposition, on the one hand, and work- and job-related factors, on the other hand, are risk factors on the perception of the indoor environment and the pathogenesis of complaints. With a sample size of 368 office workers ($\sim$77% females) from 6 office buildings in the USA, Reynolds et al. (2001) observed that the psychosocial factors were positively correlated with the incidences of SBS in females. However, the environmental factors were correlated with symptoms in males. By examining 877 occupants (50% female) in 12 office buildings in Quebec, Canada, Donnini et al. (1997) observed no significant differences in thermal neutrality between males (23.5 °C) and females (23.8 °C). Females expressed significantly higher thermal dissatisfaction (63% female vs. 37% male). Nakano et al. (2002) examined 406 Japanese office workers (37% females) and noted a significant difference in thermal neutrality, i.e., females (25.1 °C) and males (22.9 °C), while females reported a higher frequency of SBS symptoms, as compared to the male group. In a study on 935 office occupants (48% female), in 22 office buildings in Australia, Cena and de Dear (1999) noted the votes of thermal unacceptability, and females complained of significantly higher thermal dissatisfaction than those of males. Choi et al. (2010) had a similar observation by studying 402 office workers (∼53% females) from 20 office buildings in the USA. Runeson et al. (2003) investigated the prevalence and change of SBS symptoms in buildings with suspected indoor air problems about Antonovsky's sense of coherence (SOC), a psychological measure of life attitude. The study was conducted on a cohort of 194 workers from 19 Swedish buildings with indoor environmental problems between 1988 and 1998. Information on 16 SBS symptoms was gathered, as well as the SOC measure was administered in a postal follow-up. After adjusting for age, gender, history of atopy, and ETS, Runeson et al. (2003) noted that SBS was more common in women, younger ones, and those with a history of atopy. A low SOC was related to a higher prevalence of ocular, nasal, and throat symptoms, tiredness, and headache. Also, subjects with a low SOC developed more symptoms during the follow-up period.

Saijo et al. (2009) undertook postal self-administered questionnaire survey to 1,582 dwellings from 40 municipal, and 24 prefectural apartment buildings in the city of Asahikawa, Japan, and 480 questionnaires were finally analysed. From the questionnaire about moisture condensation and visible mould on window panes, walls, closets, bathrooms, the perception of mouldy odour, and water leakages, a building dampness index was defined as the sum of positive dampness indicators. SBS symptoms recorded for the preceding 3-month period were—fatigue, feeling heavy-headed, headache, nausea/dizziness, difficulty in concentrating, irritation of the eyes, running nose, dry throat, cough, dry or flushed facial skin, itching of the scalp, ears, and hands. The symptoms were significantly higher among females than males. The building dampness index was also significantly related to all SBS symptoms, as also noted by Engvall et al. (2001) in the study covering 609 multi-family buildings (14,235 dwellings) in Stockholm. Saijo et al. (2009) noted allergic diseases as risk factors for SBS development, and therefore, the history of allergic diseases was taken as a confounder for SBS symptom analysis. The US NIOSH study in 80 office buildings also found a positive association between moisture and debris in the ventilation systems and lower respiratory tract symptoms (Mendell et al. 2003).

Kim et al. (2013) undertook a comprehensive literature survey, based on North American post-occupancy evaluation (POE) database (N = 38,257). The survey indicated that the satisfaction levels of female occupants were significantly lower than males on all fifteen IEQ factors (such as thermal comfort, air quality, lighting, acoustics, office layout, furnishings, cleanliness, and maintenance). The results were consistent, even after controlling the potential confounders, such as age and work characteristics.

Chronic Fatigue Syndrome

Chronic fatigue syndrome (CFS) manifests as a clinical entity characterized by prolonged severe and disabling fatigue (Fukuda et al. 1994). The syndrome usually occurs sporadically, but occasionally may appear as epidemics. Typically, the syndrome follows a cyclical course, alternating between periods of illness and relatively good health. The onset of CFS has been related to a variety of psychological, environmental, and behavioral factors (Pizzigallo et al. 1999), and exposure to pesticides, organophosphates, solvents, and other chemicals (Bell et al. 1998). In tropical areas, many CFS-like cases follow an episode of gastroenteritis due to food toxins from ciguatoxic fish (Pearn 1995). Ciguatera consists of a food-chain disease that starts with a reef-dwelling dinoflagellate, Gambierdiscus toxicus (Gillespie et al. 1986), which is heat-stable. Individuals can be poisoned from eating fresh or frozen fish, or fish products. Symptomatology of some outbreaks of SBS resembles CFS, associating with building characteristics, such as old buildings, inadequate ventilation, non-functioning windows, and inefficient HVAC system (Chester and Levine 1997). Thousands of Gulf War veterans, even 5 years after the Operation Desert Storm in 1991, remained ill with vague symptoms that resemble CFS. These veterans were exposed to an array of hazards, such as extremes of climate, dust, and smoke from oil well fires, petroleum fuels and products, depleted uranium (used in artillery shells), chemical warfare agents, pesticides, infectious diseases, and pervasive psychological and physical stress. The veterans were administered with pyridostigmine bromide (as pre-treatment for potential poison gas exposure), anthrax and botulinum toxoid vaccines (Landrigan 1997). Haley et al. (1997) identified six different syndromes among the war veterans, namely:

Syndrome 1 (impaired cognition)—reported by veterans wearing flea collars during the war than those who never wore them;
Syndrome 2 (confusion-ataxia)—reported by veterans involved in chemical exposure (e.g., pyridostigmine bromide);
Syndrome 3 (arthro-myo-neuropathy)—exposure to insecticides containing 75% DEET (N,N-diethyl-m-toluamide);
Syndrome 4 (phobia-apraxia);
Syndrome 5 (fever-adenopathy); and
Syndrome 6 (weakness-incontinence).

The case definition of CFS (Fukuda et al. 1994)

A. Persistent or recurrent fatigue (lasting >6 months)

 1. Recent and or well-defined onset;
 2. Not secondary to excessive physical activity;
 3. Not resolved by rest; and
 4. Inducing reduction of previous levels of physical and mental activities.

B. Presence of more than four symptoms (for >6 months), not previous to fatigue onset:

 1. Impaired memory or concentration;
 2. A sore throat;
 3. Tender cervical or axillary lymph nodes;

4. Muscle pain;
5. Multi-joint pain;
6. New headaches;
7. Unrefreshing sleep; and
8. Post-exertion malaise.

If the combined number of elements of A and B present exceeds 4, a case of CFS would be considered.

Environmental Stressors Associated with SBS

The multifactorial aetiology of SBS in office buildings is yet to understand clearly. Evidence favours that the accumulated effects of building characteristics and IEQ manifest in health outcomes, including SBS symptoms, allergy, asthma, and other respiratory illnesses. The health effects, in turn, cause adverse impacts on job satisfaction, work performance, productivity, and healthcare costs (Fisk 2000). The potential environmental stressors that might be responsible for causing SBS symptoms are briefly mentioned herewith. Further details of IAQ associated with different pollutants in the indoor environment are described in Chap. 10.

Indoor air pollutants include oxides of nitrogen (NO_x), CO, CO_2, VOCs, and particulates, which are emitted from building materials, office equipment, and as combustion by-products. The intrusion of pollutants from the outdoor air through leakages and ventilation systems is a critical component. The build-up of CO_2 may be considered as a surrogate for many occupant-generated pollutants in the indoor built environment. Review of studies of SBS symptoms in office buildings indicated increased indoor CO_2 levels were associated with an increase in the prevalence of one or more SBS symptoms (Seppänen et al. 1999). Findings from more mechanically ventilated and air-conditioned buildings indicated a significant association between an increase in CO_2 and SBS symptoms, and total symptom scores. As mentioned earlier, the BASE dataset (1994–98) yielded significant dose–response relationships between the delta change in indoor and outdoor CO_2 concentrations, and the SBS symptoms, such as a sore throat, nose/sinus irritation, mucous membrane symptoms, and tight chest (Apte et al. 2000).

Headaches represent the single most common symptom in almost all indoor environmental studies (Schwartz et al. 1998). The current knowledge highlights different forms and mechanisms of a headache, such as a migraine, or a tension-type headache, or any plausible exposure to chemical toxicants, e.g., CO or pesticide poisoning. Whereas, many of the events do not provide a precise characterization of the office environment (Schneider et al. 1999), such headaches are no less significant given the productivity implications, and the potential for active intervention in the office environment.

Volatile organic compounds (VOCs)—VOCs are ubiquitous indoors, due to human activities, building product emissions, including floorings, linoleum, carpets, paints, surface coatings and furniture, and infiltration of the outdoor air. For new or renovated buildings, VOCs are primarily emitted from building products. Secondary emissions of VOCs result from ageing of building products, by chemical decomposition (e.g., moisture build-up or inadequate maintenance) or physical damage due to heat and UV light (Wolkoff 1999). Furniture coatings release nearly 150 VOCs (aliphatic and aromatic aldehydes, aromatic hydrocarbons, ketones, esters, and glycols) (Salthammer 1997). Office equipment and supplies, such as laser printing toners, emit VOCs, ozone, formaldehyde, resin, and other particles. Use of perfumes indoors may release VOCs. Indoor fungi are also a source for the production of VOCs. Many VOCs are known toxic compound, with potential for carcinogenicity, mutagenicity, or teratogenicity. Documented evidence strongly affirms that occurrence of SBS follows predictable dose–response relationships with increasing concentrations of mixtures of VOCs. The VOCs, such as O-xylene, styrene, d-limonene and other terpene compounds may readily react with ozone and NO_x entrained from outdoors and produce highly reactive compounds, including aldehydes and ultrafine particles, leading to sensory irritant symptoms (Sarwar et al. 2002; Sundell 2004). These effects have been observed in case of carpet emissions, latex paint off-gassing, and other office pollutants.

It has been viewed that SBS may be related to the lost VOCs, i.e., the difference in the concentration of VOCs entering the room to that leaving the room. In California Healthy Buildings Study, Brinke et al. (1998) adopted an approach in developing VOC metrics and identified relationships between SBS symptoms and clusters of VOCs by its possible emission sources. The principal component analysis (PCA) allowed to cluster VOCs into a reduced set of principal component (PC) vectors and further estimated the association between SBS symptoms and the VOC exposure metrics, using logistic regression analysis. A similar approach was taken by Apte and Daisey (1999) in exploring the causal associations between SBS and environmental stressors, using a subset of data from 28 office buildings of the US EPA BASE study. Four source-based PC vectors were derived that identify sources as photocopiers, automotive emissions, ETS, and latex paints. Regression analyses indicated significant associations between mucous membrane-related symptoms and the photocopier vector, after adjustment for age, gender, smoking status, the presence of carpeting, and thermal exposure. Sore throat symptoms were associated with the paint vector. Analysis of dataset of all 100 BASE buildings revealed 36 VOCs, formaldehyde and acetaldehyde corresponded to 41 buildings, whereas 19 VOCs were available in all buildings. The PCA yielded ten PCs identified as the VOC sources (Apte and Erdmann 2003). Seven components referred to as furniture coatings (PC1), paint (PC2), construction materials (PC3), printing materials and processes (PC4), carpet and undercarpet (PC5), parking garage (PC6), and cleaning products (PC7) met the criterion of having eigenvectors ≥ 1.0.

Oxidative Stress and SBS—Several studies suggest that a shallow concentration of VOCs in indoor environment may cause SBS symptoms, but how such symptoms generate disability at such low levels remains unexplained. Little is known about the likely oxidative stress that can attribute to the occurrence of SBS due to exposure risks of air pollutants or other factors of the environment. Reactive oxygen species (ROS) are components found in many of the air pollutants and can cause oxidative damage to lipids, proteins, and nucleic acids. Urinary 8-hydroxydeoxyguanosine (8-OHdG) is a known biological marker of oxidative stress on DNA. Accumulation of ETS, VOCs, formaldehyde in the building due to insufficient ventilation can result in the rise of urinary 8-OHdG levels among occupants (Calderon-Garciduenas et al. 1999). Lu et al. (2007) gathered data from self-reported questionnaires and analysis of on-site air pollutants and urinary 8-OHdG of 389 employees in 87 government offices of eight high-rise buildings in Taipei city. The urinary 8-OHdG was significantly associated with VOCs and CO_2 levels in offices, and the 8-OHdG level were significantly higher among the employees with SBS symptoms than in those without such complaints. A positive dose–response effect between 8-OHdG levels and the number of symptoms was suggestive that the urinary 8-OHdG as a viable non-invasive marker can be taken as a predictor for SBS.

Office exposures and work stress**—**Office work-related exposure to paper dust emanated from carbonless copy paper and fumes from photocopiers and printers are health concerns, including respiratory illness among office occupants. Observations of Jaakkola et al. (2007) substantiated that the exposure to paper dust and carbonless papers carries potential risks of chronic respiratory symptoms, respiratory infections, and other health concerns in an office environment.

The stress of work, including extended hours of work, reflects as different work stressors and consequent health impacts among occupants in modern office buildings. There are multiple aspects of work, including physiological, motivation, technical, psychosocial, environmental, perceptual as well as organizational that attribute to work stress. As mentioned earlier, outbreaks of psychogenic illness (SBS) are perhaps a symptom of underlying stress at work and workplace (Selvamurthy and Ray 1996). Mizoue et al. (2001) carried out a cross-sectional survey of 1281 municipal employees from different buildings in a Japanese city. Findings indicated that both ETS exposure and overtime work contributed to the development of SBS. Working overtime for 30 or more hours per month was also associated with SBS symptoms, but the occurrence of SBS reduced by 1/5th after adjustment for variables associated with overtime work and about an-half after further adjustment for perceived work overload.

Runeson et al. (2006) undertook a postal questionnaire survey as regard to SBS on a sample of 1000 subjects (20–65 years of age), including the three-dimensional model of demand–control–support, regarding social support in actual work situations. Results indicated that males and females perceived psychosocial work conditions differently and reacted differently to job stressors. That is, the psychosocial work environment was as important as gender and atopy as a predictor of SBS symptoms.

Nag and Nag (2004) examined the work stresses of women VDT-cum-telephone operators in selected office buildings (telephone exchanges) and observed that the behavioural response to the work stressors, and health and well-being dimensions did vary with the work schedules. The PCA analysis of the ergonomics checkpoints yielded five aspects of work, as organizational (PC1—describing job design needs, workplace interventions, and constraints of VDT workstations), environmental (PC2—covering illumination-, climate-, and noise-related hazards), mechanistic (PC3—referring to job specialization, pace of work, information handling), perceptual and motor (PC4—describing visual and auditory displays and controls), and motivational (PC5—referring to personal job characteristics and core dimensions). The loading of the work stressors explained in PC1 to PC3 appeared autonomous, irrespective of the shift schedules at which the women were engaged. The operators in the rotating shift had higher sensitivity to the stressors related to PC4. The day workers responded greater to the stressors related to the core job dimensions that reflect growth needs (PC5). The sleep disturbance, flexibility to sleeping habits, and personality dimension (neuroticism) were negatively correlated with PC1. The digestive problems, social and domestic disruption, and languidity dimensions were positively correlated to PC4 and PC5. The operators in rotating shift had increased demand in the perceptual and motor, and the motivational aspects of work, and thus causing greater negative influence on physical health symptoms, and social and domestic disruption. The job design interventions tailoring to delay the morning shift and adjust the shift length based on the work and climatic load (that is, reduce work hours in the evening shift to avoid peak workload, and extend hours of day work during the hot summer months) might alleviate work stress and enhance health and well-being. Manifestations of work-related stress call for organizational analysis and job design interventions in structuring the workplace.

Thermal Discomfort—Exceedance beyond the thermal comfort range is associated with increased symptoms, such as a headache, fatigue, and mucosal irritation. Besides the relative effectiveness of ventilation systems, uses of increasing numbers of electronic devices in the offices add to the heat loads in buildings. In real-life work environment, a significant proportion of the population remains in uncomfortable situations and shows thermal discomfort. Clothing habits in different seasons may also contribute to the causes of thermal discomfort in a hotter environment.

Humidification—A sensation of air dryness and irritative symptoms from eyes, skin, and upper airways are common factors in the SBS (Stenberg et al. 1993). By examining 104 employees from four geriatric hospital units in southern Sweden, Nordstrom et al. (1994) evaluated the effect of steam air humidification on SBS and perceived air quality during the heating season. Air humidification was raised to 40–45% RH in two units during a four-month period, whereas the other two units were maintained at 25–35% RH. After four months of air humidification during the heating season, 24% of the employees reported a weekly sensation of dryness in humidified units, compared with 73% in controls, indicating that air humidification during the heating season in colder climates can decrease symptoms of SBS and

Table 3.3 Odours in mouldy buildings due to fungal VOCs

1-Octen-3-ol	Semiochemical; earthy, mushroomy odour
1-Butanol-3-, methyl-, acetate	Anti-fungal; banana odour
Sabinene	Unknown; peppery odour
6-Pentyl-a-pyrone	Antibiotic; coconut odour
b-Caryophyllene	Plant-growth-promoting; woody-spicy odour
Isobutyric acid, 2-heptanone	Anti-fungal; cheese-like odour
Benzyl aldehyde	Anti-microbial; almond odour
1,8-Cineole	Anti-fungal; camphor-like odour
2-Methyl-1-propanol	Fungivore attractant; mild alcohol odour
3-Methyl-butanol	Unknown; component of truffle odour

perception of dry air. In a tropical environment, RH remains at a much higher level even in an indoor office environment; therefore, incidences of SBS in such situations may be attributed to factors other than air dryness or humidification.

Odours—Odours associated with moisture and bioaerosol exposure are familiar in buildings and best considered in the context of disease with physiological indicators. The odour characteristics are the basis to investigate the possible adverse effects of moulds on human health, in what is often referred to as SBS. From mouldy buildings, the fungal VOCs (such as 1-octen-3-ol and 3-octanone) can produce a range of musty odour (Morey et al. 1997), as listed (Table 3.3).

Odour recognition thresholds are usually several orders of magnitude below the irritant thresholds (Cometto-Muniz and Cain 1996). Fanger (1988) proposed an unit of pollution, *olf* (for olfactory) for arbitrarily defining the emission rate of air pollutants from a standard person (white male, 18–30 years of age, showering 0.7 time/day, wear no perfumes, and energy expenditure equivalent of one Met for person sitting at rest). The number of olfs is indicated on the initial perception of the odour, referring to discomfort from irritation and annoyance from odour, and overall acceptability. This method was deployed in a project assessing air quality in 20 offices/assembly halls in Copenhagen, and 54 external judges adjudged the air quality in unoccupied and occupied, and with or without ventilating systems in buildings. About 42% of the perceived defects in air quality was due to ventilation systems, 38% was due to combined occupant activities and occupants themselves, and 20% due to building materials. The stated method has limitations of efficacy since the raters assess the pollution level in a site within minutes of entering the site. The majority of the occupants may not be able to rate odours consistently, and also the odour annoyance is generally perceived most severe early on first exposure and recedes over time.

Fungi in Buildings and Health Impacts

The building professionals may be amazed at recognizing how the proliferation of fungi in buildings damages the building materials and affects the health of occupants, and more importantly to the causation of SBS and building-associated illness. Inadequacy in the ventilation system, moisture controls, and dirt management thrive microbial proliferation in the HVAC systems and office carpeting. Water incursion into the building envelope is a common cause of moisture build-up and fungal growth. There could be visible mould growth on surfaces, the wall behind wallpaper or under the floor covering, suspended ceiling panels, localized damp areas between a wall and a large item of furniture, and in cavity wall spaces (Lugauskas and Krikstaponis 2004). Through the routes of inhalation or ingestion, propagules of fungi and bacteria may elicit symptoms of illness, like bronchial irritation and allergy (Britton 2003; Beezhold et al. 2008).

Broadly, bioaerosol contains fungal and bacterial cells and cellular fragments, and by-products of microbial metabolism build-up in the buildings. Particles that range in size from 1 to 5 μm remain suspended in the air, whereas larger particles are deposited on the surfaces (Martinez et al. 2004; Horner et al. 2004). It is not within the present scope to elaborate on the classification of fungi, which are grouped by phylum (division), class, order, family, genus, and species, in the order. Khan and Karuppayil (2012) indicated that ~600 species of fungi are in contact with humans and ~50 of them are frequently described in epidemiologic studies on indoor environments. In the present context, several fungal species have been referred to by the researchers about an infestation in building materials and contamination of the indoor environment. Some of the species are listed in Table 3.4.

Wood, wooden building materials, and kiln dried wood surfaces are vulnerable to fungal attack, with infestation by Cladosporium and Penicillium (*Penicillium brevicompactum* and *Penicillium expansum*) (Sailer et al. 2010). Acylated wooden furniture, plywood, and polyurethanes used in wood composites for insulation are found to be susceptible to infestation by Aspergillus, Trichoderma harzianum, *Paecilomyces variotii*, and *Penicillium* species (Yazicioglu et al. 2004; Doherty et al. 2011). Prefabricated gypsum board that is used as inner wall materials in buildings favours the growth of *Stachybotrys chartarum*.

Sterflinger et al. (2013) examined five different indoor insulation materials, i.e., bloated perlite plaster, bloated perlite board, loam and reed, soft wooden board, and sprayed cellulose, for their biosusceptibility. A. Versicolor, Alternaria, Cladosporium, and Penicillium species grow in fibreglass insulation and ceiling tiles (Erkara et al. 2008). Galvanized steel accumulated with dust or lubricant oil residues allows the growth of fungi (Rene et al. 2010; Yau and Ng 2011). Dampness can cause chemical degradation of polyvinyl chloride (PVC) floor coverings, including formation and emission of 2-ethyl-1-hexanol, 1-butanol (Tuomainen et al. 2004). Acrylic painted surfaces are attacked by Alternaria, Cladosporium, and Aspergillus (Shirakawa et al. 2011), and also *Aureobasidium pullulans* can deteriorate the paints (Lugauskas et al. 2003).

Table 3.4 Fungal species from phylum: Ascomycota

Class	Order	Family	Genus	Species
Ascomycetes	Incertae sedis	Incertae sedis	*Hymenula*	*Cephalosporium gramineum* *H. cerealis*
Dothideomycetes	Pleosporales	Pleosporaceae	*Alternaria*	*A. alternata*
	Dothideales	Aureobasidiaceae	*Aureobasidium*	*A. pullulans*
	Capnodiales	Davidiellaceae	*Cladosporium*	*C. herbarum*
	Pleosporales	Pleosporaceae	*Ulocladium*	*Ulocladium*
Eurotiomycetes	Eurotiales	Trichocomaceae	*Aspergillus*	*A. niger*
				A. Versicolor
				Aspergillus
			Paecilomyces	*P. variotii*
			Penicillium	*P. brevicompactum*
				P. chrysogenum
				P. expansum
Sordariomycetes	Hypocreales	Nectriaceae	*Fusarium*	*Fusarium*
			Gibberella	*G. fujikuroi*
		Incertae sedis	*Myrothecium*	*M. roridum*
		Stachybotryaceae	*Stachybotrys*	*S. chartarum*
				Stachybotrys
		Hypocreaceae	*Trichoderma*	*T. harzianum*
				Trichoderma
			Acremonium	*Acremonium alternatum*

Moisture damage of building frames was characterized by Meklin et al. (2003), studying 17 wooden and 15 concrete or brick school buildings. Aspergillus versicolor, Stachybotrys, and Acremonium were detected in samples from moisture-damaged buildings. Observations indicate that moisture damage of the building did not alter the fungal concentrations in wooden school buildings, whereas, in concrete schools, the effect of moisture damage was seen with higher fungal concentrations. The presence of Oidiodendron and elevated concentrations of Cladosporium and actinobacteria were associated with moisture damage in concrete schools.

Most fungi are mesophilic, and the optimum temperature for fungal sporulation (number of conidiophores and conidia formed in each conidiophore) is within the range of 20–25 °C (Burge 2006). Incidently this temperature range corresponds to the human comfort indoors, at which fungi flourish in working environments (Burge 2006). The relative humidity and air currents influence the release of conidia. Fungal growth is favoured at a water activity (a_w) of 0.95–0.99, which is a ratio of the partial vapour pressure of water in a substance to the standard state partial vapour pressure of water. pH range of 5–6.5 in building materials allows better growth of most of the fungi (Vacher et al. 2010; Hoang et al. 2010). The thermophilic and xerophilic (dry tolerant) fungi are found more in hot-dry climates, than in cooler wetter environments. In tropical and subtropical places, thermophilic and xerophilic fungi tend to be abundant in outdoors with optimal heat and moisture. However, an array of factors are necessary for optimal growth of different kinds of fungi.

Cladosporium, Penicillium, and *Aspergillus* produce high numbers of small and light spores (<10 µm in size). *Penicillium* and *Aspergillus* can grow in substrates with water activity lower than 0.80. The smaller particles can penetrate into the alveolar region when inhaled, evade phagocytosis by macrophages, and transport through systemic circulation (Reponen et al. 2007; Seo et al. 2009), whereas the larger spores and other fragments get deposited in the nasopharynx. Kildeso et al. (2003) studied the release of particles from indoor fungi growing in wetted wall-papered gypsum boards, for 46 weeks. When *Penicillium chrysogenum* were subjected to air currents, only spores were released from the colonies, but with *Aspergillus versicolor*, both spores, and fragments were released. With *Trichoderma harzianum*, particles released are—groups of spores (5–6 µm), individual spores (2–3 µm) and fragments (0.7–1 µm). Seo et al. (2009) reported the release of fragments and spores from *Aspergillus Versicolor* and *Stachybotrys chartarum* growing on the surface of ceiling tiles, wallpapered gypsum board, and culture medium. The studies are suggestive that long-term mould damage in buildings may increase the contribution of fungal fragments to the overall mould exposure.

Quantitation of Fungi

In non-culture-based methods, fungal spores in samples and its morphological identification are determined by light microscopy. Components or metabolites of fungi can also be used to quantitate fungi population. Specific assays can detect extracellular polysaccharides for partial identification of fungal genera in indoor environments (Jovanovic et al. 2004). Polyclonal antibody-based assays detect a broad range of fungal antigens but cannot detect the spores (Mitchell et al. 2007). Molecular methods for quantitation of fungi include the use of genus-/species-specific probes, polymerase chain reaction (PCR)-based methods, restriction endonuclease analysis, and karyotyping. Mitochondrial DNA can be used for restriction enzyme analysis and DNA fingerprinting for fungal identification.

Sampling Methods

The typical approach for fungal detection in a building utilizes culture and microscopy. Different surface and air sampling methods are used for detection and counting of fungi, fungal spores and fragments in ambient air and settled dust, pieces of wallboard, duct linings, carpets (Asadi et al. 2011; Reponen 2011). Surface sampling allows determining the degree and the types of microbial growth on environmental surfaces (Cabral 2010). Adhesive tape sampling method examines the fungi and the hyphal fragments in the specimens using a compound microscope (Aydogdu et al. 2010).

In air sampling of fungi, the principles of impaction, impingement, and air filtration have been used. In the impactor method, the airstream is passed through progressively narrower slits into a culture medium and microscopic glass slides covered with an adhesive substance or tape strip is used to collect the sample, and counted by optical microscopy (Zhen et al. 2009). Andersen six-stage impactor is used for collection of particles on culture medium. In Andersen sampler, in a Petri dish could grow 400 colonies. Fast-growing colonies may grow above the slow growing and hinder in counting colonies (Stetzenbach et al. 2004). The dichloran-glycerol-18 agar (DG-18) culture medium with fungistatic properties prevents the growth of the fast-growing fungi (Horner et al. 2004). Liquid impingers collect the samples into the fluid, and the micro-organisms are retained in the liquid until they are cultivated, or evaluated by techniques like biochemical or immunoassays (Jo 2011). Shipe sampler, AGT–30 glass impinger, midget, multi-stage, and micro impingers are common impinger devices (Gralton et al. 2011). Air filtration is used to collect the samples of indoor air in volume. In this method after sampling, the filters are agitated or sonicated in a solution (Bazaka et al. 2011).

Readers may refer to standard manuals for analytical details. However, the choice of air or surface sampling techniques depends on the purpose of measurement (Jung et al. 2011). Air sampling by impingement has some advantages over impaction on solid surfaces; for example, if the concentration of microbes in the atmosphere is too high, the liquid could be diluted before adding to the culture medium. Collection of the cells in a liquid avoids desiccation resulting from impaction on solid surfaces (Stetzenbach et al. 2004). Impaction directly onto agar plates may maximize survival of culturable organisms. In addition to impaction and impingement, other methods like filtration by aspiration and sedimentation sampling have been used. In filtration, three types of filter media are used, such as porous fibrous filters with overlapping fibres, porous gel membrane filters, and capillary pore filters. Filter materials include glass fibre, mixed cellulose esters, polytetrafluoroethylene, polyvinyl chloride, gelatin, and polycarbonate (Martinez et al. 2004). Membrane filters can be placed directly on the surface of culture medium or washed with a liquid, and this added to culture medium. Specific filters (namely gelatin) are dissolvable in warm liquids, and the resulting suspension can be plated on agarized medium. That is, filtration devices are adaptable for air sampling of wall cavities or roof spaces to pinpoint foci of contamination.

Sedimentary sampling (e.g., the gravity slide and the settle plate techniques) is the simplest of all methods. In the gravity slide method, microscopic glass slides, smeared with an adhesive substance, are exposed during a specified period. In the settle plate method, open petri dishes with appropriate culture medium are left open for a given time, depending on the air contamination load. After a certain period of incubation, colonies are counted. An index of microbial air (IMA) contamination was proposed; that is, a standard petri dish (dia: 9 cm) containing plate count medium is left open to the air, for 1 h, 1 m from the floor and at least 1 m away from walls. After 48 h incubation at 36 °C, the colonies are counted, and the number of colonies is the IMA. Five IMA classes were defined, as 0–5 very good; 6–25 good; 26–50 fair; 51–75 poor; and >76 very poor.

The conventional sampling apparatus gives values for fungal particles present in the atmosphere, at the time of sampling; however, other spores and fragments can be attached to the colonies and be released later. The fungal spore source strength determines the maximum amount of fungal particles that can be released from contaminated materials by the action of air currents. From the counting of released particles, the maximum fungal load for a given indoor environment can be calculated (Gorny 2004; Sivasubramani et al. 2004a, b).

Fungi and Respiratory Symptoms

Damp concrete floor and visible mould in buildings are constant sources of risk of respiratory tract symptoms, infections, and exacerbation of asthma (Lanier et al. 2010; Araki et al. 2010). Mucociliary clearance represents the first strategy for removal of fungi/mould from the human respiratory tract. *Hypersensitivity syndromes, such as* hypersensitivity pneumonitis (both acute and chronic) or extrinsic allergic alveolitis, can occur in individuals exposed to conidia, hyphae, or fungal fragments, mycotoxin (trichothecene) (Eduard 2009; Franks and Galvin 2010). Hypersensitivity pneumonitis is generally associated with high IgG antibodies concentrations in response to alveolar or bronchiolar inflammation caused by fungi or other allergens. The patients may present neutrophilic inflammation with increased production of TNFa and IL-6, and symptoms such as fever, chilliness, dry cough, dyspnoea, changes in nodular bilateral X-ray, fatigue, and headache (Eduard 2009). Aspergillus spp. develops allergic bronchopulmonary aspergillosis and pulmonary aspergilloma (Kawel et al. 2011).

Undoubtedly, exposure to fungi in indoor environments elicits an IgE-mediated hypersensitivity response that precipitates into rhinitis and other forms of the allergic syndromes, such as upper airway irritation, eye irritation, and sinusitis (Yike 2011). During this process, antigen-specific IgE is produced that attaches to receptors on mast cells which are concentrated on the gastric and respiratory mucosa. The principal fungal allergens, such as (1–3)-b-D glucan or water-soluble glycoproteins, may become airborne and when its concentration exceeds 4 ng/m^3, susceptible individuals may show non-specific inflammatory airway reactions and that affect the immune system (Kalyoncu 2010; Tercelj et al. 2011). (1–3)-b-D glucan, a cell wall component of filamentous fungi, is readily detected in moisture-damaged building materials, dust samples, and textile floor coverings (Reponen et al. 2010; Rylander 2010). Ergosterol is found in the cell membranes of fungi, but its content varies with the fungal species (Heinrich 2011).

Besides, people who inhabit mouldy buildings (presence of S. chartarum and Aspergillus spp. in air samples) were reported with cognitive defects and difficulties in concentration (Drappatz et al. 2007). In mouldy buildings, occupants complain of dermatological symptoms, gastrointestinal problems, reproductive effects, rheumatologic, and other immune diseases. Breda et al. (2010) recorded that the rheumatic diseases (inflammation and stiffness in muscles, joints, or fibrous tissues) are exacerbated by indoor environmental conditions, including dampness and fungi infestation. Rheumatoid arthritis, ankylosing spondylitis, Sjogren's syndrome, and psoriatic arthritis have been observed among occupants in water-damaged buildings with mould growth (Muise et al. 2010).

Mycotoxins and SBS

Various fungi produce mycotoxins that are low molecular weight and non-volatile compounds, and potentially carcinogenic, teratogenic, and mutagenic. Mycotoxins can also be isolated from fungi-contaminated building materials and house dust (Engelhart et al. 2002). The production of mycotoxins by indoor fungi growing in building materials is usually lower than that cultivated in vitro in building materials (e.g., gypsum board, chipboard) (Nielsen 2003; Nieminen et al. 2002). Aflatoxins, trichothecenes, and ochratoxins are common mycotoxins in indoor environments (Zain 2011; Halios and Helmis 2010). Other toxins (e.g., T-2, HT-2, deoxynivalenol (DON), nivalenol, diacetoxyscirpenol, satratoxins, trichoverrols, verrucarol, verrucarins, trichoverrins) have been described in this group. Trichothecenes are a family of mycotoxins produced by species such as *Cladosporium, Aspergillus, Penicillium, Fusarium*, *Trichoderma, Myrothecium*, *Trichothecium*, *Stachybotrys, Cephalosporium*, *Giberella*, *Memnoniella* (Tuomi et al. 2000).

A possible causal relationship exists between mycotoxin exposure and building related illnesses (Sen and Asan 2009; Di Giulio et al. 2010). The effects of trichothecenes exposure in humans include internal burning, vomiting, and diarrhoea with blood, cutaneous necrosis, and internal haemorrhages. Evidence gathered that exposure to higher concentrations of *Penicillium* and *Aspergillus* in the indoor environment could induce health problems and SBS symptoms. Severe asthma and acute exacerbations of asthma have been associated with *Alternaria* sensitivity and increased airborne concentrations of *Alternaria* spores (Salo et al. 2005). Vance and Weissfeld (2007) warned that the presence of *S. chartarum* indoors is a concern since its growth requires water saturation of cellulose-based materials such as paper, cardboard, wood, and gypsum board (Menetrez and Foarde 2004; Gottschalk et al. 2006). It is likely that plumbing and roof leaks provide the needed moisture for the fungus to grow. The small size, ellipsoid shape *Stachybotrys* spores can reach the lower respiratory tract (Murtoniemi et al. 2003). The causal relationship between S. chartarum and SBS has been debated, with the view that health effects may be due to the presence of other pollutants, like VOCs (MVOCs), endotoxins, respirable dust, and other compounds in the indoor environment (Bloom et al. 2007). DON, a trichothecene mycotoxin mainly produced by Fusarium molds, like other mycotoxins, is an immunomodulator that can enhance or suppress the immune system depending upon the dose and duration of exposure (Lee et al. 1999; Zhou et al. 1999). The T2-toxin, which is produced by species of Fusarium and diacetoxyscirpenol, has been shown to modulate apoptosis in human promyelocytic leukaemia cells (Yoshino et al. 1996; Yang et al. 2000).

Several types of research explore the potential association of SBS with particular microbes, biotoxins, or other complex exposure mixture components observed in the water-damaged buildings (Shoemaker et al. 2005). *Trichothecene* mycotoxins produced by *Stachybotrys*, satratoxin, and roridin have been identified in serum using an ELISA assay. Generally viewed that the mixture components, including fungi, bacteria, mycotoxins, endotoxins, and lipopolysaccharides, interact synergistically, through the feedback control of pro-inflammatory cytokine production and induce SBS (Huttunen et al. 2004). The onset of SBS is typically observed following chronic exposure in water-damaged buildings, extending for many months. Needless to mention that health risk assessment for SBS has many uncertainties, such as the extent of toxin accumulation in tissues, interspecies differences in susceptibility, and threshold shifts of the repair mechanisms during chronic exposure (Shoemaker and House 2005; Shoemaker et al. 2005). There is an evident need to make the focus on innovative and effective therapeutic interventions (e.g., Cholestyramine (CSM) therapy) to remove biotoxins from the body, caused by toxic mould exposure.

Fungal VOCs and SBS

There are nearly 250 VOCs of fungal origin that often referred to as microbial VOCs (MVOCs). These MVOCs produce mixtures of simple hydrocarbons, heterocycles, aldehydes, ketones, alcohols, phenols, thioalcohols, thioesters, and their derivatives, including benzene derivatives, and cyclohexanes (Korpi et al. 2009; Ortiz-Castro et al. 2009). Currently, gas chromatography–mass spectrometry (GC-MS) is the primary method for the detection of MVOCs (Matysik et al. 2009). The electronic nose (E-nose) is an alternative non-invasive technique to detect essential fungi and MVOCs. The instrument combines an array of electronic chemical sensors, a pattern recognition processing unit, and a reference library for recognizing odours (Wilson and Baietto 2009, 2011).

Molhave (2008) emphasized the exposure to MVOCs as the aetiological agents associated with SBS, including lethargy, headache, as well as irritation of the mucous membranes. However, the types and concentrations of MVOCs in mould-infested buildings vary with the ventilation rate indoors, moisture level, the composition of mould population, and other parameters (Schleibinger et al. 2008). For example, *Penicillium, Aspergillus,* and *Stachybotrys* are VOCs as well as mycotoxin producers (Matysik et al. 2008). MVOCs are produced by the cells and released to the indoor environment, whereas mycotoxins are present inside the cells and fragments (Reponen et al. 2007). In healthy individuals, the fungal spores and fragments are destroyed by cells of the immune system, but a small number of mycotoxins can still enter in the systemic circulation with possible chronic or sub-chronic toxic effects (Straus 2009).

The fungal release of VOCs is sometimes referred to like products of secondary metabolism, and these compounds remain reasonably stable in a range of growth media and conditions (Moularat et al. 2011). Moularat et al. (2008a, b) described the assay of VOCs produced by *Aspergillus niger*, *A. versicolor,* and *Penicillium brevicompactum* and identified nineteen compounds resulting from fungal metabolism. MVOCs also cause indirect metabolic effects. Fungal colonization in urea formaldehyde insulation materials results in the cleavage of urea from the polymer releasing formaldehyde (Shinoj et al. 2011; Asan et al. 2010). Like other sources of VOCs, the exposure of MVOCs even at deficient concentrations has been linked to symptoms such as a headache, nasal irritation, dizziness, fatigue, and nausea, independent of exposure to other allergenic fragments and toxins (Weinhold 2007; Burton et al. 2008).

Respiratory Illness in Buildings

Researchers have attempted to distinguish between the SBS and building-associated illness (Jaakkola et al. 2007; Tsai et al. 2012). As discussed, the SBS represents multiple non-specific symptoms among the building occupants, but its occurrence is correlated with some factors, such as the type of ventilation and the condensation or the leakage of water in building indoors. On the other hand, building-associated illness consists of different diseases with known aetiologies (Craig and Mindell 2011); for example, allergic alveolitis, with specific aetiologies, is usually linked to ventilation-based, wet microbial breeding places, such as humidifiers, air washers, heater/cooler units. In multifactorial causal situations, however, several components attribute to creating complex environmental conditions. Ventilation inadequacy in indoor spaces may aggravate IEQ, resulting in health symptoms, SBS or BR and other communicable respiratory illnesses, such as allergy and asthma symptoms, respiratory infections and cardiovascular diseases. The literature emphasizes association of building characteristics, IAQ, and inhaling of bioaerosol with the prevalence of respiratory illnesses among building occupants. For easy understanding by the professionals from other building sciences, some common forms of respiratory illnesses are briefly described herewith. Details of the respiratory illnesses are found in several online sources, e.g., http://www.mayoclinic.org/diseases-conditions/copd/symptoms-causes/dxc-20204886.

Asthma and Asthma-Like Disorders

Increased prevalence of asthma has long been known as the impacts of outdoor and indoor exposures to air pollutants, and lifestyle habits, as well (Eder et al. 2006).

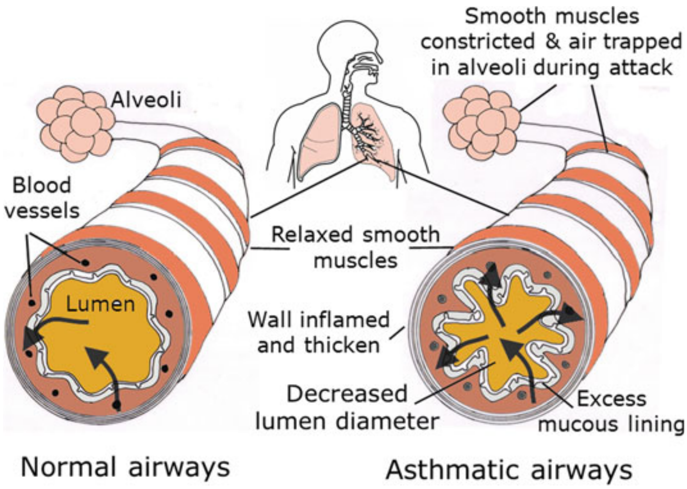

Fig. 3.1 Illustrated normal and bronchial asthmatic airways

Asthma can be adult onset or occupational in origin. From a clinical point of view, bronchial asthma is a well-known lung condition, defined as a chronic inflammatory disease, due to the contraction of the bronchial muscles, increased mucous production or decreased clearance, and muscle tightening, causing variable airflow obstruction (Fig. 3.1). Coughing, wheezing, chest tightness, shortness and shallow breathing, anxiety, and tachycardia are the common signs and symptoms of asthma. The inflammation causes airway hyper-responsiveness and is the reason for the appearance of variable and reversible airflow obstruction. Occupational asthma is caused by breathing substances present at workplaces, such as chemical fumes, gases or dust which are irritating or sensitizing. Exposure to these substances develops an immune response either to respiratory irritants (gas, fume, or vapour), usually of low molecular mass at high concentration, referred to as *irritant-induced occupational asthma, or to* sensitizing agents (e.g., high molecular mass—glycoproteins of biological origin), referred to as *sensitizer-induced occupational asthma*. These exposures are characteristically associated with symptoms at work with relief on weekends and holidays. With early diagnosis and treatment, occupational asthma may be reversible. Table 3.5 includes the most common asthmagen agents.

Irritant-induced acute occupational asthma (also termed as reactive airway dysfunction syndrome—RADS) may occur following a short-duration single high-level irritant exposure to substances, such as chlorine or oxides of nitrogen, or multiple exposures to gas, smoke, fume, or vapour characterized by irritant capacity. Respiratory symptoms (a cough, wheezing, chest tightness, and dyspnea) may persist for 3 months. Low-molecular mass agents probably become antigenic after conjugation with a body protein (e.g., serum albumin), and its response clinically manifest as direct epithelial cell injury. The procedure to diagnose RADS includes analysis of occupational history, inventory of exposures in the workplace,

Table 3.5 Common most asthmagen agents

Classification	Sub-groups	Sources	Occupational activity
High-molecular-weight protein antigens	Animal-derived substances; plant-derived substances	Laboratory animals, seafood, grain mites/insects; grain dust, natural rubber/latex gloves, bacterial enzymes, vegetable gums	Animal handlers, food processing; bakeries, healthcare workers, detergent making;
Low-molecular-weight/chemical sensitizers	Plasticizers, paints, adhesives, wood dust, foams, metals, drugs and pharmaceuticals	Isocyanates (e.g., toluene diisocyanate), acid anhydrides (e.g., phthalic anhydride), amines (e.g., ethylenediamine), fluxes (e.g., colophony), metals (e.g., platinum salts), drugs (e.g., penicillin), plastics (e.g., acrylates), wood dust (e.g., western red cedar)	Auto-spray painting, varnishing, metal grinding, platinum refineries, pharmaceutical manufacturing, sawmill work, woodworking,
Other chemicals		Biocides (e.g., glutaraldehyde), polyvinyl chloride fumes, organophosphate insecticides	Janitorial work, meat packaging

pulmonary function tests (PFT), serial peak expiratory flow measurement on work days and days off, histamine or methacholine challenge, and immunological tests, such as specific IgE and skin prick, epicutaneous tests (Fishwick et al. 2008; Tarlo et al. 2008). The PFT may show evidence of airway obstruction (FEV_1/FVC ratio less than 0.7), although the absence of airway obstruction does not exclude a diagnosis of the disease. For irritant-induced asthma due to indoor environmental exposures, specific bronchial challenges may not diagnose; also the peak expiratory flow (PEF) is not diagnostically specific. However, conventional approach of observing an elevated diurnal variation in PEF might suggest the presence of asthma. Bronchodilator response may be seen in individuals with acute irritant-induced asthma. A chest radiograph is usually normal, although it may show no specific signs associated with coexisting respiratory infection. A bronchial biopsy may indicate possible inflammation with lymphocytes and plasma cells, as a manifestation of epithelial cell injury.

Sensitizer-induced occupational asthma is characterized by a latency period, which may last from several weeks to months or years, between first occupational exposure to a respiratory sensitizer and the development of immunologically mediated symptoms. Once the subject is sensitized, asthma attacks are provoked even with exposure to a shallow concentration of the sensitizing agent. Diagnosis is typically achieved from the evidence of reversible variable airway limitations, along with asthmatic trends between periods of work and rest. PFT may become normal rapidly after the cessation of the exposure. A serial PEF (about four recordings a day) over three weeks has high specificity and sensitivity in making the diagnosis of occupational asthma. Serum-specific IgE may assist in making a diagnosis, due to its likely presence in persons exposed to allergens with high molecular weight and some chemical agents. Skin prick tests may also be positive for the workplace allergen. Increased bronchial reactivity to challenge with the agents, such as histamine, methacholine, is evidence of sensitizer-induced occupational asthma, and this may be carried out sequentially over time. Allergens that cause occupational asthma can also cause allergic rhinitis (nasal symptoms) that may precede the onset of occupational asthma symptoms or may commence at the same time as asthma symptoms.

Simoni et al. (2010) showed that upper respiratory tract symptoms were more prevalent in poorly ventilated classrooms. That is, with CO_2 levels exceeding 1000 ppm had a higher risk of a dry cough and rhinitis. Increased ventilation rate ($>0.7\ \mathrm{l\ h^{-1}}$) was associated with a decreased prevalence of allergic symptoms among college students living in dorms in China (Sun et al. 2011a). The occurrence of wheeze decreased with the increase in ventilation rates when CO_2 concentration reduced from 1359 to 915 ppm.

The prevention of occupational asthma requires environmental intervention and medical management. The primary prevention of exposure, such as improved ventilation and dust control for elimination of the formation of dust, and localized aspiration, is the direct approach towards reducing the incidences of the disease. Avoiding cold temperature and air dryness, wearing PPE, and in some cases, adopting prophylactic pharmacological treatments can mitigate asthma symptoms. Population screening for early detection is the secondary prevention.

The term *Asthma-like* (suspected asthma) is indicative that all asthma-like symptoms are not associated with asthma. These include chronic obstructive pulmonary disease, chronic bronchitis, chronic cough, hyperventilation, mechanical obstruction of the airways, congestive heart failure, pulmonary embolism, gastro-oesophageal reflux, multiple chemical sensitivity/idiopathic environmental illness, SBS, Sjogren's syndrome, vocal cord dysfunction. *The chronic obstructive pulmonary disease* is characterized by a slowly progressive reduction of pulmonary ventilation due to a combination of emphysema and bronchiolitis with obstruction of the small airways. ETS is a critical aetiological factor. *Chronic cough* has different aetiologies—a cough at night or associated with physical exercise may be indications of asthma. The asthma tests such as reversibility to a bronchodilator and increased levels of exhaled nitric oxide should be positive (Chatkin et al. 1999). *Hyperventilation syndrome* is indicated by symptoms induced by physiologically inappropriate hyperventilation or voluntary hyperventilation. Shortness of breath, accelerated/deepened breathing, and feeling of inability to breathe deeply are asthma-like. Symptoms reproduced by a hyperventilation test and a slow recovery of CO_2 in blood or expired air are the two criteria for establishing the diagnosis (Ringsberg and Akerlind 1999). *RADS* is an illness with asthma-like symptoms that may occur as the direct consequence of excessive toxic inhalation exposure. The bronchial histological changes show an increase in inflammatory cells. However, eosinophils and mast cells do not dominate. *Multiple chemical sensitivity* (also named as idiopathic environmental intolerance) is a disease caused due to some low dose of exposure to chemical toxicants, manifesting diverse symptoms (e.g., headache, weakness, memory problems, inability to concentrate, throat soreness, abdominal pain, and discomfort). One may suffer from nasal congestion and asthma-like symptoms such as cough and chest tightness. As elaborated earlier, *SBS* is a complex disease caused primarily due to building characteristics of the indoor environment, including inadequacies in air-handling systems. *Sjogren's syndrome* is a systemic rheumatic disease. *Vocal cord dysfunction* is characterized by episodic or acute attacks of breathing troubles similar to attacks of asthma. In asthma-like disorder, treatment compliance with conventional therapy is low (Schmier and Leidy 1998; Chan et al. 1998). Medication with steroids are the most potent drugs in the treatment of asthma.

Sensory hyper-reactivity (earlier referred to as functional breathing disorder) manifests common symptoms, such as heavy breathing, cough, and increased secretion, difficulty in getting air, and chest pressure (Lowhagen et al. 1997). The symptoms are often induced by trigger factors, such as allergens, chemical irritants, ETS and strong scents, cold air, viral infections, physical exercise (Millqvist and Lowhagen 1998). Symptoms, such as difficulty in breathing and breathlessness, which indicate asthma, may also be indicators of sensory hyper-reactivity. The diagnosis of sensory hyper-reactivity is a clinical challenge; PFT is sometimes difficult to obtain due to inability to perform an adequate forced expiration, giving a false indication of bronchoconstriction (Ringsberg et al. 1997). Asthma-like symptoms can be provoked by a sensory nerve-mediated disturbance of the respiratory pattern; for example, a capsaicin inhalation test provokes these kinds of symptoms (Millqvist et al. 1998).

Extrinsic allergic alveolitis (EAA, also termed as hypersensitivity pneumonitis) is type III and IV hypersensitivity reaction of the alveolar and bronchiolar tissue and interstitium of the lungs, in response to inhaled antigens. A range of environmental allergens, including fungi, bacteria, plant proteins, and other reactive chemicals, may be related to the occurrence of EAA (Simon-Nobbe et al. 2008; Robertson et al. 2007). Farmer's lung caused by mouldy forage is a well-studied form of EAA. Microbiological contamination of air conditioners or humidifiers has been reported to cause of EAA in an office environment. The EAA may manifest as an acute, sub-acute, and chronic form. The former form is more natural to recognize, with symptoms, like a cough, chest tightness, febrile chills, and flu-like illness appear 3–8 h after exposure, fades away gradually over a few hours, and may reappear on subsequent exposure. The sub-acute form presents as progressive shortness of breath, dry cough, and weight loss. The chronic form may show the slow development of interstitial fibrosis.

Diagnosing EAA requires identifying the source of exposure to contaminants, recording exposure history, including worksite visit and environmental measurements. In physical examination, crackles in the lower fields of the lungs may be noticed. A chest X-ray may show fine interstitial infiltrates in acute and sub-acute forms of the disease, whereas in the chronic form, irregular scarring may indicate diffuse pulmonary fibrosis. In PFT, typically patients may show restrictive impairment, i.e., the FEV_1/FVC ratio reduced in comparison with its normal range. The EAA is a diffuse parenchymal disease, and thus, the diffusion capacity of the lungs is affected (both DL_{co} and K_{co}). Bronchoscopy with bronchoalveolar lavage (BAL) and transbronchial biopsy may be carried out when investigating a patient with suspected EAA. BAL typically shows increased total cell count, with an increased proportion of lymphocytes (>40%). T-helper to T-suppressor ratio is usually reduced to less than 1. After acute exposure, neutrophils are transiently increased. The histopathologic findings include diffuse interstitial infiltrate, scattered non-caseating granulomas, and cellular inflammation of the bronchioles. An inhalation provocation test with the specific antigen can be performed to confirm the diagnosis; a worksite challenge test is a conventional approach, with PFT before and after workplace exposure. Management of EAA primarily demands to remove the affected persons from the source of exposure. Drug intervention with corticosteroids is given at the acute episodes. Any dampness or mould problems in buildings should be repaired promptly.

Humidifier fever, like in EAA, is also termed as a disease related to bioaerosol exposure from contaminated humidifier water, often referred to as Monday morning fever. The affected person experiences fever, nausea, sweating, and myalgia, sometimes with breathlessness, about 3–8 h after exposure, which is very similar to those described in outbreaks of EAA. The symptoms diminish towards the end of the working week, and over the weekend, for example, the episode may be worse again. Humidifier fever differs from EAA in that the affected person may have specific IgG antibodies to the micro-organisms growing in water reservoirs as a sign of exposure. Regular maintenance of humidifiers and air conditioners is the best approach to prevent humidifier fever (Pal et al. 2000).

Legionnaires' disease presents as pneumonia, due to infection with *Legionella pneumophila,* a bacterial micro-organism that may be found in wet surroundings and capable of forming colonies in cooling towers and hot water systems in hospitals and office buildings. An outbreak of *Legionella pneumophila* in Philadelphia in 1976 (Fraser et al. 1977) with the source identified at the ventilation and humidification system of a hotel, affected 221 persons, with about 20% mortality. The incubation period of the disease is about a week. The early symptoms include illness, headache, myalgia, fever and mild cough, blood in the sputum, and watery diarrhoea (Cunha 2008). There may be a neurological symptom of severe encephalopathy. A chest X-ray may show unilateral lobe infiltrate, with rapidly progressive infiltrations of Legionella. Complete recovery of the infiltrates may take several weeks to months. Urinary antigen detection is a rapid test. However, it is less sensitive than culturing respiratory secretion. Superheating of hot water to >50 °C and flushing the water distribution systems are crucial to prevent Legionella infections.

Other Office Environment Exposures

Office environment exposures through handling of self-copying paper that contains ink, solvent and dust, acrylate glues used in flooring, PVC, phthalate compounds, and wall-to-wall carpet might induce airway inflammation in humans (Jaakkola et al. 2006; Jaakkola and Jaakkola 2007; Jaakkola and Knight 2008). Professional cleaners in buildings are regularly exposed to cleaning chemicals containing ammonium, bleach, chlorine, and some disinfecting substances, and these people may develop irritant-induced asthma (Zock 2005). Table 3.6 includes different

Table 3.6 Environmental exposures to cause signs and symptoms related to SBS and other respiratory illnesses

Sources	Potential exposures/factor
Physical environment	High indoor temperature (>23 °C); low relative humidity; low air change
Water damage or leakage	Dampness and mould
Paints	Toluene, propylene, glycol, ethylene glycol, butyl propionate, methyl propanol
Furniture (plywood, plastic)	Formaldehyde, 2-pentyl furan, benzaldehyde, hexanal, pentanal
Carpets	Particles, vinyl acetate, styrene, dodecanol, acetaldehyde
Plastic wall, PVC flooring	Phthalates
Photocopying	Xylenes, benzene, 2-ethyl-1-hexanol
Cleaning agents (Detergents)	Fatty acid salts, organic sulphonates
Cleaning agents (water softeners)	EDTA (ethylenediaminetetraacetic acid), tripolyphosphates
Cleaning agents (Alkaline agents)	Silicates, carbonates, sodium hydroxide, ammonia
Cleaning agents (Acids)	Phosphoric, acetic, citric, sulphamic, hydrochloric acid
Disinfectants	Hypochlorite, aldehydes, quaternary ammonium compounds
Carbonless copy paper	Crystal violet lactone, trimellitic anhydride (TMA), phenol-formaldehyde resins, azo dyes, diisopropyl naphthalenes (DIPN), formaldehyde, isocyanates, hydrocarbon-based solvents, epoxy resins, aliphatic isocyanates, Bisphenol A, diethylenetriamine
Smoking	Environmental tobacco smoke (ETS)

environmental, physical, and social factors, which may cause one or more signs and symptoms related to SBS.

Second-hand tobacco smoke exposure (SHS), containing irritant substances, can potentially induce mucus hypersecretion and inflammation in the airways (Jaakkola et al. 2003; Gilmour et al. 2006). In adults with asthma, SHS exposure is related to increased occurrence of respiratory symptoms, reduced lung functions, increased use of bronchodilator and steroid medications, and increased bronchial hyper-responsiveness (Jaakkola and Jaakkola 2002). Fisk et al. (2007) from a meta-analysis of 33 epidemiological studies on dampness and mould problems revealed 30–50% increased risk of asthma about indoor dampness and mould problems in buildings. The IgE-mediated hypersensitivity reactions to fungal allergens (Jaakkola et al. 2006) and mycotoxins produced by fungi and inflammatory reactions caused by fungal cell wall components (1,3-β-D-glucan, ergosterol) are the suggested mechanisms that could lead to asthma.

Airborne Transmission of Pathogens

There is a whole range of airborne pathogens, such as Aspergillus and Bacillus spp., that may be found in the built environment and also during construction or renovation activities (Balm et al. 2012; Fournel et al. 2010). Particular focus is on hospitals and healthcare buildings, to create healthy conditions. Natural ventilation and availability of sunlight in buildings serve as effective strategies in infection control of diseases, such as measles, tuberculosis, smallpox, chickenpox, influenza, SARS and H1N1 (Li et al. 2007).

The transmission of pathogen takes place through contact, dust, respiratory droplets, and droplet nuclei, e.g., inhalation of large droplets from contagious individuals or contaminated surfaces. The transmission depends upon the number and size of particles produced, the velocity at which they are produced, micro-organisms contained within the droplets, and proximity of a susceptible target (Gralton et al. 2011). The longevity of the pathogens depends on temperature and humidity, ultraviolet (UV) radiation, and atmospheric pollutants (Tang 2009). Depending on the size and density, residues of suspended droplet nuclei can remain suspended and penetrate deep into the lung tissues. Droplet nuclei that are exhaled during normal breathing are only a small fraction than those aerosols produced when coughing or sneezing (Gralton et al. 2011). Factors, such as local ventilation, the activity of occupants indoors, and thermal gradients produced due to office equipment influence the movement of the suspended droplets (Nielsen 2009; Eames et al. 2009; Clark and de Calcina-Goff 2009). Towards controlling infection in healthcare and other building facilities through sunlight and natural ventilation, transmission and control of some pathogens are briefly described herewith.

Influenza is assumed to be transmitted by large droplets. However, the aerosol transmission, such as H5N1 avian influenza that demonstrates high virulence and lethality involves the lower respiratory tract (Tellier 2009; Tang and Li 2007).

Direct contact with diseased poultry and other birds may cause H5N1 transmission through the air, without recombination in an intermediate host (Herfst et al. 2012).

Severe acute respiratory syndrome (SARS) epidemic in 2003 was assumed direct contact as the primary transmission route. The Hong Kong, Amoy Gardens outbreak, is an affirmative indication of the airborne transmission of the SARS virus (McKinney et al. 2006), such as transmission of virus-laden aerosol through inadequate ventilation, the ventilating shaft of adjacent buildings, floor drainage. Before the SARS epidemic, hantavirus transmission causing the pulmonary syndrome in humans has been demonstrated, due to the inhalation of aerosolized excreta and saliva from wild rodents (Kimmel et al. 2010; Clement et al. 2008). The primary prevention is to clean the ventilation system of buildings that show signs of rodent infestation. Norovirus that causes gastrointestinal illness is transmitted via contact with food materials, contaminated surfaces, and the spread of aerosolized particles from vomiting or liquid diarrhoea (Marshall and Bruggink 2011; Greig and Lee 2012) .

Tuberculosis is mainly contracted through airborne droplets; that is, transmission of M. tuberculosis to a non-infected person is possible if there are overcrowding and confined environment, and poor indoor ventilation (Beggs et al. 2003). Earlier it was presumed that *smallpox* virus spreads by face-to-face contact. However, airborne transmission of the virus is evident now. Occupants in hospital, health care, and allied facilities are at potential risk from *Staphylococcus aureus* (Kerr 2010) that get deposited throughout a room. Nasal cavities of susceptible adults become colonized with S. aureus by inhaling particles from the air. There are many other pathogens found in an aerial spread in building facilities, such as Escherichia coli, Klebsiella, Acinetobacter, Pseudomonas, Clostridium difficile (Wu et al. 2011). Persons infected with C. difficile may shed spores in faeces, and therefore, when a toilet is flushed without a closed lid, aerosol production may contaminate the surrounding environment (Best et al. 2012).

SBS: Intervention and Management

Office goers and building occupants are usually not exposed to high levels of physical, chemical, or biological compounds potentially hazardous to health. Office environments have traditionally been considered as safe. However, an ample body of the literature is available on SBS and building-associated illnesses (BRI) from different kinds of studies, including epidemiological cohort and cross-sectional studies, population questionnaire surveys, and experimental studies. The risk of SBS may occur at different levels, for example, (a) building level—indoor environmental quality, different sources pollutants, and exposure to bioaerosols, (b) personal level—interpersonal differences (women, younger and the elderly people, persons predisposed with chronic disease show more SBS related complaints), and (c) workplace stressors—aspects of work and psychosocial environment of the building occupants, and ones' ability to cope with the conditions of workplace and workspace. Since all these levels are simultaneously present, one major problem emerges in SBS and BRI is its lack of generalizability. On a simplistic way, the overall impression of the building environment may be rated by the occupants on an ordinal 100 point scale, against the stated levels of IEQ, personal characteristics, aspects of work and the psychosocial environment. The summated scores are scaled into an overall dissatisfaction score for the building occupants.

Mitigation of IAQ problems may require the involvement of building management and related people of responsibility in facility operation and maintenance, housekeeping, policy-making, and staff training. Three methods have been suggested to improve the IAQ, namely source control, increase ventilation, and air cleaning. The source control is the most cost-effective approach to mitigating IAQ problems in which point sources of contaminants can be identified. Conventional pollution source control method, such as adsorption by microporous activated carbon and chemical scrubbers, has reasonable efficacy to mitigate pollutants. Thermal catalytic oxidation (Everaert and Baeyens 2004; Roark et al. 2004) and photocatalytic oxidation (Carp et al. 2004) are promising technologies for air purification. However, the former is not economically feasible at low pollutant concentrations. Photodegradation may be more cost-effective for air purification since the process takes place at room temperature and pressure. TiO_2, a popular photocatalyst, is employed for removal of VOCs from indoor air (Wang et al. 2006, 2007). By incorporating TiO_2 catalyst with adsorbent may yield better results for adsorption of pollutants and oxidation efficiency. This type of catalyst, however, exhibits high catalytic activity at UV light.

Building Ventilation—Health Relationships

The literature suggests a robust affirmative link between ventilation and the respiratory health of building occupants (Seppänen and Fisk 2004). Due to the random character of natural ventilation during different seasons of the year, emphasis among the building designers goes in installing mechanical ventilation and HVAC systems. The natural ventilation no longer provides optimal distribution of fresh air in the buildings. However, several views have been put forward with regard to mechanical ventilation systems and acute health symptoms (SBS/BR), asthma and allergy symptoms among occupants in buildings. Mendel et al. (2003, 2006), examining US NIOSH data of 80 office building, emphasized that improperly maintained ventilation systems increase the adverse health effects among the occupants, particularly the asthmatics, due to exposure to accumulated pollutants and microbiological growth. Comparing with naturally ventilated systems, the presence of air-conditioning increased respiratory symptoms in office buildings located in a hot and humid climate (Graudenz et al. 2005). Takahashi et al. (2008) reported that the presence of a ventilation system was associated with increased allergic symptoms, probably due to the entry of large quantities of pollen into the dwellings through the air ducts and other factors, not directly related to the ventilation system. Dwellings installed with air conditioners, and those had poor maintenance of ventilation systems, resulted in increased prevalence of SBS (Wong et al. 2004; Coelho et al. 2005), as compared to those in naturally ventilated dwellings. Some multidisciplinary reviews on relationships between ventilation rate and health outcomes are summarized in Table 3.7.

Table 3.7 Case studies on the influence of indoor ventilation rate on health outcomes

Godish and Spengler (1996)	Increasing the ventilation rate up to 10 l/s per person may be useful in reducing the prevalence of SBS symptoms and occupant dissatisfaction with air quality. The use of ventilation as a mitigation measure for IAQ problems should be dealt with factors that may limit its effectiveness
Seppanen et al. (1999)	Ventilation rates below 10 l/s per person in different building types were associated with significant worsening in one or more health or perceived air quality outcomes. Some studies determined that increasing ventilation rates above 10 l/s to ∼20 l/s per person significantly decreases the prevalence of acute health symptoms or improvement in the perceived air quality. The SBS symptoms continued to decrease significantly with decreasing CO_2 concentrations below 800 ppm
Wargocki et al. (2002, 2004)	Ventilation rates below 25 l/s per person increase the risk of acute health (SBS) symptoms, increase short-term sick leave, and decrease productivity
Mendell and Heath (2005)	No substantial evidence on the causal relationships between indoor pollutants or thermal conditions in schools and the performance of students. Suggestive evidence links low ventilation rates in buildings to decreased performance in children and adults
Seppanen et al. (2006)	A 1–3% improvement in average performance was associated with an increase in ventilation rate by 10 l/s per person. The performance increase per unit increase in ventilation was more substantial with ventilation rates in the range 15–17 l/s per person, and almost negligible with ventilation rates over 45 l/s per person
Li et al. (2007)	Strong evidence of the association between ventilation, air movements in buildings, and the transmission/spread of infectious diseases. Data insufficiency to define the ventilation rates that can reduce the spread of infectious diseases via the airborne route in hospitals, schools, offices, homes, and isolation rooms. Overcrowding is a risk factor related to the ventilation of buildings and also infection transmission via direct contact
Fisk et al. (2009)	Reduction in ventilation rate from 10 to 5 l/s per person led to increased prevalence of SBS symptoms by ∼23% (12–32%). Increase in ventilation rate from 10 to 25 l/s per person led to the decreased prevalence of acute symptoms by 29% (15–42%)
Sundell et al. (2011)	Ventilation rates, up toper person, were associated with reduced prevalence of SBS symptoms in offices. Ventilation rates in homes above 0.5 ACH are associated with a reduced risk of allergic manifestations among children in a Nordic climate

The above stated studies provide a fair understanding that ventilation (air change in a built environment) plays a central role to exhaust pollutants of both non-biological and biological agents of the occupied space or generate pollutants within systems. Chapter 12 elucidates the design, installation, operation, and maintenance of ventilation systems in buildings. Ventilation inadequacy may be due to poor building design, inadequate ventilation system, and its improper maintenance and operational strategies. Lack of control of HVAC systems aggravates the growth of microorganisms. Besides, the quality of outdoor air, building materials, and accumulated dust are also sources of microbial contaminants in indoor environments. The presence of mould, spores, musty smell, and water intrusion are warning signs, reflecting the inefficiency of a building's ventilation system (Radon et al. 2008).

It is emphasized that the strength of elimination of pollutants from building space is the determinant of exposure-associated adverse health effects of occupants. In spite of differing views, ventilation rates below 10 l/s per person would increase the risk of symptoms of SBS (Jaakkola and Miettinen 1995). The assertion from the BASE study of the association of SBS with the increasing difference in concentration of CO_2 between indoor and outdoor brings forward the suggestion that a relative increase in the ventilation rates per person in an office building may reduce the prevalence of SBS symptoms. A concentration of CO_2 (800 ppm) has been suggested as a control limit value. Erdmann and Apte (2004) observed a remarkable reduction in mucosal symptoms ranging from 65 to 85% when CO_2 levels in offices dropped in the range from 610 to 40 ppm above outdoor levels.

Frequent contributors to biological pollutants are water damage in buildings, leaks in plumbing, roofs or air conditioners, and humidifiers (McKernan et al. 2008; Li et al. 2010). Given that some airborne moulds may always be present in the indoor environment, various guidance limits and remediation measures have been proposed (Baubiologie Maes 2008). EC guidelines state that mould count greater than 500 CFU/m^3 may be considered an intermediate level of exposure for a building occupant, whereas >1000 CFU/m^3 is a high level of exposure in indoor non-industrial workplaces. Levels more than these guidelines do not necessarily imply unsafe or hazardous conditions. In the USA, there are no exposure levels for airborne concentrations of mould (US OSHA 2003). Every country must establish the requisite legislation and environmental standards and guidance concerning building maintenance specifications.

Also, building-associated illnesses manifest in multiple forms of symptoms, and often in combinations of asthma, hypersensitivity pneumonitis, and interstitial pneumonitis (Bornehag et al. 2001). Evidence of markers for individual susceptibility might separate normal from more sensitive groups. Symptoms of allergy and asthma may be triggered by allergens in the indoor air including those from house dust mites, pets, fungi, insects, and pollens. As elaborated earlier, asthma symptoms can be evoked by irritating chemicals or sensitizing agents. There are approaches to reducing allergy and asthma symptoms via changes in buildings and indoor environments. Reductions in allergy and asthma symptoms would be expected by a substantial reduction in the associated allergens and irritants, from indoors.

Overall, intervention and management of SBS and BRI may encompass measures, as described herewith. For new buildings, the prevention measures in reducing mould contamination include, for example, (a) minimizing moisture accumulation in construction materials, (b) maintaining the integrity of building impermeable envelope, and (c) ensuring the effectiveness of HVAC system to control thermal comfort and relative humidity. In the existing buildings, corrective measures include (a) repair and maintenance of water leakage in ceilings, walls, and draining systems, (b) deep cleaning of building interiors and HVAC systems, (c) control of the reservoirs of visible mould in ceiling and carpets, and (d) periodic assessment of IAQ. Once a mould problem is established, a well-documented action plan may be followed to notify people for (a) rectifying the underlying moisture problem, (b) minimizing spread of contamination, by cleaning of ventilation pathways and enhancing ventilation to exhaust the relevant pollutants from indoors, and (c) removing mouldy materials. It is important to consider that fungal spores are continually entering into the indoor environment and a remedial measure to fungal contamination is the maintenance of dry conditions in a building. As part of remediation, an entire or part of a building may be heated to a temperature that should kill most of the fungal spores. Caution is needed that heat may not damage specific equipment and plastic materials.

Ventilation and Pathogen Infection Control

Apart from dilution of airborne pathogens, high ventilation of outdoor air results in an adverse effect on viability and virulence of micro-organisms, including influenza and the Category IV pathogen, Francisella tularensis (Hood 2009). Infection of rhinoviruses causes adults to suffer the frequent *common cold*. Myatt et al. (2004) provided evidence of aerosol transmission of rhinovirus in mechanically ventilated office buildings that resulted in an increased risk of inhaling infectious droplets. In student rooms having a ventilation rate of about 1 l/s per person, the frequency of common colds was six times more among 35% of the students. The number of common colds was higher in winter. Reported common colds were higher when some students shared a room. By increasing the ventilation rate to 5 l/s per person, the self-reported common colds dropped to a mere 5% (Sun et al. 2011b), suggesting that ventilation from outdoor-to-indoor bears greater significance in diluting and dispersing virus-laden droplets (Mendell et al. 2002). Milton et al. (2000) observed a reduction in short-term sick leave among office workers when the outdoor air supply rates increased from 12 to 24 l/s per person in an office building. Mendell et al. (2013) reported the relative decrease of illness absence of about 1.6% for each additional ventilation rate of 1 l/s per person.

Natural ventilation brings many advantages, whereas entry of unfiltered air containing free contaminants such as fungal spores (Bartley et al. 2010; Phares et al. 2007) is a possible disadvantage of natural ventilation. Natural ventilation can be more effective than mechanical systems for preventing transmission (Kembel et al.

2012). Despite that an outbreak of infectious disease is an outcome of several factors, as stated above, the evidence is supportive that ventilation is a modifying factor in the transmission of infection. Following the 2001 incidents of anthrax attacks, preventive intervention is to relocate air intakes to publicly inaccessible locations, e.g., secure roofs.

Coughing and sneezing activities can carry infectious aerosols a long distance within a built environment (Zhu et al. 2006). Intervention in building ventilation airflow patterns (Chen and Zhao 2010) can thwart particle transport from a source to a receiver. The exposed concentration of aerosol from sneezing, at the breathing zone of a receiver occupant is slightly higher under displacement ventilation, DV than mixing ventilation, MV system (Seepana and Lai 2012), due to its low local air velocities. High discharge velocity air curtains provide a strong momentum to redirect coughing and sneezing jets and minimize cross infection (Aubert and Solliec 2011; Nino et al. 2011), and also influence heat gain/loss in a facility (Foster et al. 2006). With a protected occupied zone ventilation, POV system, the intake fraction of coughed particles in the breathing zone of the receiver occupant decreased to a significant extent, as compared to an MV system (Liu et al. 2014). A narrowly concentrated plane jet was more effective at reducing the direct exposure to expiratory particles than with multiple low-velocity jets.

Preventing Infection by Sunlight

The majority of micro-organisms that cause airborne infections cannot tolerate sunlight. Direct sunlight passing through an ordinary window can kill M. tuberculosis and Meningococci within a few hours. Streptococcus pyogenes cannot survive more than 5 min under sunlight, compared with more than an hour in diffuse daylight. Lethality of sunlight against staphylococci is due to radiation at 300–380 nm; in addition to bactericidal effect, solar radiation is mutagenic. Ordinary window glass absorbs solar radiation at <300 nm, which permits entry of solar UV-A and small amounts of UV-B. Research indicates that UV wavelengths inactivate microbes by causing cross-links between constituent nucleic acids; the formation of intra-strand cyclobutyl-pyrimidine dimers within DNA leads to mutations and cell death (Maclean et al. 2010). Exposure to high-intensity visible violet light at 405 nm is likely to be associated with photoexcitation of porphyrin molecules, resulting in the production of reactive oxidative species that are strongly bactericidal (Hamblin et al. 2005).

The contemporary modern building envelopes have an overdependence on mechanical ventilation and HVAC systems. As insulation levels increase, there is a risk of overheating and poor IAQ (Bone et al. 2010). Typically, in cold climate, the heating in new buildings is provided by warm air, whereas heating in older ones was often from a radiant source (Hobday 2011). Any exclusion of sunlight in buildings, for example, in hospital and healthcare facilities increases the risk of infection, and a variety of other health problems (Castro et al. 2011; Hobday and Dancer 2013). The design of buildings that allow increased exposure to sunlight and outdoor air may discourage survival and spread of infectious agents with considerable health benefits to occupants.

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Chapter 4
Musculoskeletal Disorders: Office Menace

Introduction

Sometime in 1713, Bernardino Ramazzini, the father of occupational medicine, recognized the severe disease of the upper limb caused by *violent and irregular motions and unnatural postures of the body*. Ramazzini explained that *the incessant driving of the pen over paper*, by copyists and clerks, resulted in intense fatigue of the arm and hand, because of a continuous strain of the muscles and tendons. Similar injuries were found amongst artists, musicians, dressmakers, milkmaids, and smiths. Since the late 1970s, reports were piling up from several countries, such as Australia, Japan, the USA, and the UK, of musculoskeletal conditions of epidemic proportions amongst telegraphy, typists, and computer operators. Today, musculoskeletal disorders are the predominant cause of physical disability worldwide (Woolf et al. 2012; Riihimäki 2014). The stress injuries caused by physically stressing a body part encompass several terminologies (Putz-Anderson et al. 1997; NRC 2001; European Agency for Safety and Health at Work 2010), such as *Repetitive Stress Injury/Disorder*, *Repetitive Strain Injury/Disorder, and Repetitive Motion Injury/Disorder.* That is, the *repetitive injury* is termed an injury caused by repetition, irrespective of whether it is stress, strain, or motion (Hagberg et al. 1995). *Overuse Syndrome is* a condition when a person has overused some parts of the body to the point of injury, in which, however, repetitiveness is not a necessary condition. Accordingly, *Cumulative Trauma Disorder* (CTD) occurs through the building up of trauma over time.

On the one hand, there has been a debate on the terms to describe the entirety of musculoskeletal disorder, and on the other hand, the literature is amassed with terminologies in defining the real entity of a musculoskeletal condition, and the specific difference which sets it apart. A technical definition, to be useful, must be directed towards for whom it is intended so that the broader meaning of the definition is interpretable. It should describe, expound, interpret, and use metaphor to clarify precise meaning, or a collective, all-inclusive term to describe the

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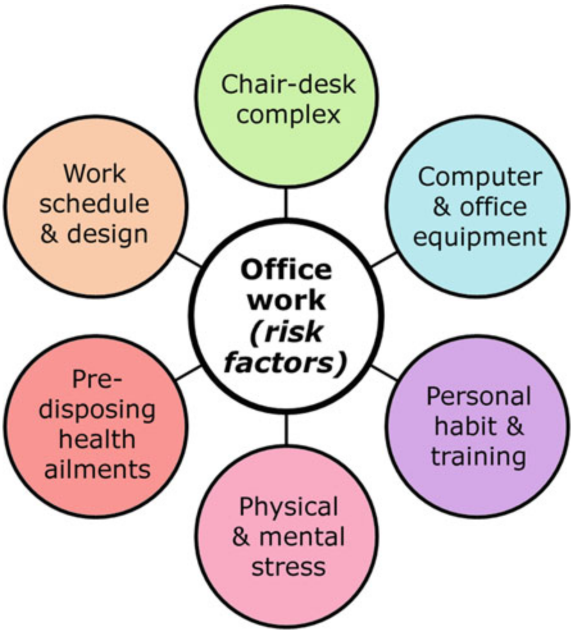
phenomena. It is not unlikely that several subtle words very close in meaning may encroach upon with some shades of difference. On a broader meaning, injuries or disorders of the soft tissues, including muscles, tendons, ligaments, blood vessels or nerves, and also joints that arise from exposure to risk factors, are termed as musculoskeletal injuries or disorders (MSD). Associating MSDs with the phrase *work-related* implies that workplace factors may not be the primary cause of the disorder or injury. These injuries can be acute or cumulative. Muscle sprain is an injury to a ligament, caused by sudden overstretching; muscle strain is excessive stretching of muscle, resulting in pain and inflammation. The MSDs are not the same as localized sprains or strains; these involve an extended latency period, months, or years. In repetitive strain injury, magnitude and frequency of repeated strain may exceed the muscle tissue's ability to repair.

Office work and working with computers are common risk factors behind the prevalence of MSD, due to workplace design incompatibilities, constraints and behaviour among the office workers (Fig. 4.1). Upper limb and neck disorders among computer users are the fallout of prolonged uninterrupted keying, raised shoulder and unsupported forearm position, about the workspace and monitor height (Babski-Reeves et al. 2005; Straker et al. 2008). In brief, the workplace factors, such as the dimension of seated place, work surface, placement of input devices, are all interconnected for comfort, health, and well-being of people working with computers (Szeto et al. 2005). Other risk factors that may cause MSD include the poor physical condition and lack of flexibility of the operator, and any pre-disposing medical conditions (joint injury, diabetes, and pregnancy). Work-related MSDs may be classified as (a) nerve-related, (b) tendon-related,

Fig. 4.1 Tangible workplace risk factors behind the prevalence of MSD



(c) bursa-related, (d) circulatory, and (e) muscle- and joint-related disorders. The commonest work-related MSDs are briefly described herewith. Several authorities (e.g., http://www.mayoclinic.org) provide details of the above disorders.

Nerve-Related Disorders

The nerves that supply to muscles, tendons, and other tissues can be entrapped or compressed along the pathways to the wrist, arms, neck, and shoulder (Fig. 4.2).

Carpal tunnel syndrome (CTS)—The carpal tunnel is a narrow passageway located on the palm side of the wrist. The median nerve provides a sensory function to thumb and fingers, excepting the little finger. Any pressure within the carpal tunnel due to the repetitive flexing and extending of the tendons in the hands and wrists (e.g., uninterrupted computer keyboarding), a sore arm and hand condition may be caused. It produces the tingling or numbness, pain and eventually, hand weakness (Thomsen et al. 2008; Palmer et al. 2007). Van Rijn et al. (2009) reviewed data to indicate that the CTS is associated with arm force exertion greater than 4 kgf, work repetitiveness cycle less than 10 s, or 50% of the cycle time performing the same movement, and 8 hourly frequency-weighted acceleration of about 4 m/s^2. The CTS is more common in women since they have a smaller carpal tunnel area. Other risk factors attributed to the development of the condition include rheumatoid arthritis, wrist fracture or dislocation, diabetes, obesity, thyroid disorders, menopause, and fluid retention during pregnancy.

Guyon's canal syndrome—Guyon's canal, about 4 cm long, is situated on the palmar side of the wrist. The ulnar nerve that originates from C8 to T1 nerve roots runs down the arm crossing the medial epicondyle (cubital tunnel) at the elbow and reaches to the hand and digits through the Guyon's canal. Because of the unique location of the Guyon's canal, the ulnar nerve is vulnerable to compressive injury to overuse of the wrist, heavy gripping, and repeated wrist and hand motions (Aleksenko and Dulebohn 2018). Guyon's canal zones of sensory and motor branches of ulnar nerve are depicted in the illustration.

Cubital tunnel syndrome—A condition, also called as cell phone elbow is caused due to pressure and stretching of the ulnar nerve (funny bone nerve) through its path along the cubital tunnel (ASSH 2015). Elbow flexion greater than 90^o while sitting at a computer workstation or during prolonged use of cell phone can cause cubital tunnel syndrome. Symptoms include aching in the forearm, numbness of the ring and small fingers, loss of muscle strength and mobility of the hand (Palmer and Hughes 2010).

Pronator teres syndrome (PTS)—m. Pronator teres is attached to the lower humerus and the inner ulna bone and is used in the act of turning or pronating the hand, so the palm faces downwards. The PTS is a rare medical condition when the median nerve gets entrapped within the two heads of m. Pronator teres, during forceful gripping and twisting. A deep ache in the forearm radiates down the wrist and hand, and localized numbness and tingling in the thumb, index, long, and ring fingers. Symptoms of PTS can be very similar to CTS. In the case of CTS, one may

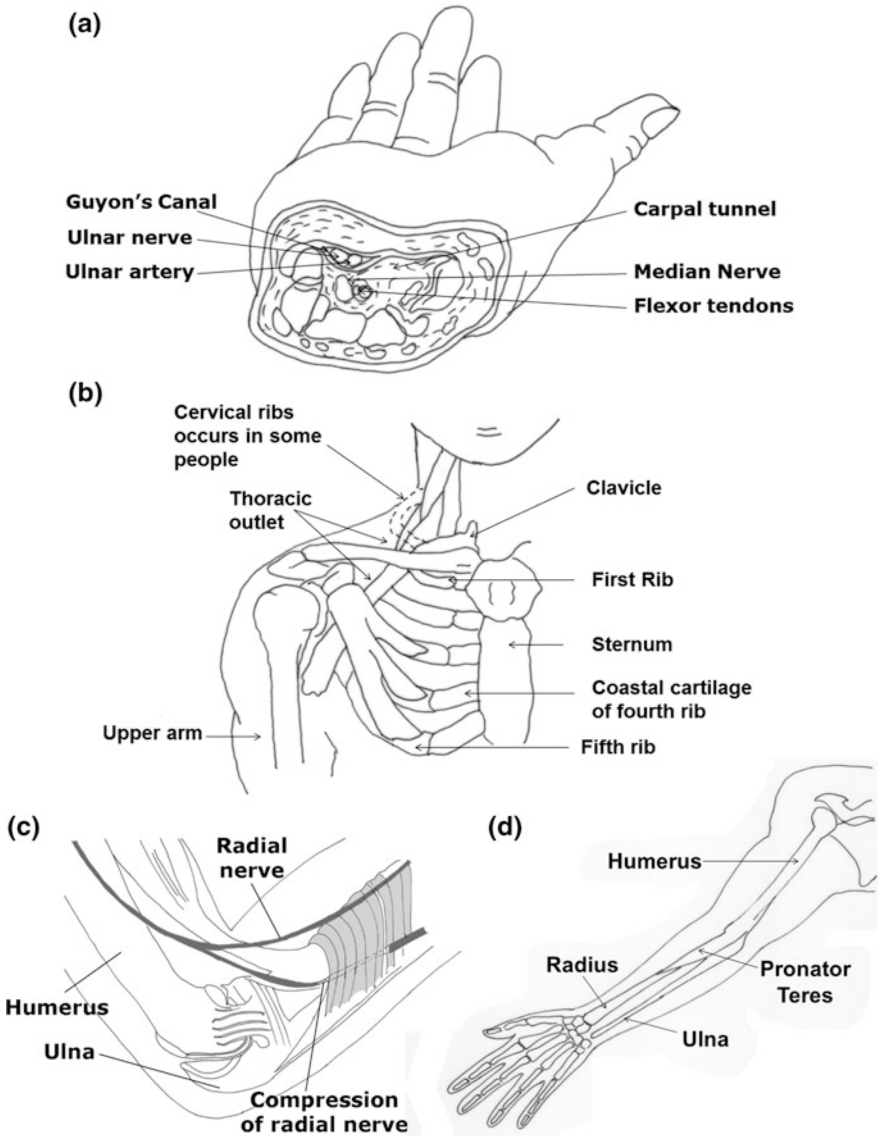


Fig. 4.2 Nerve-related MSDs; **a** carpal tunnel and Guyon's tunnel syndrome, **b** thoracic outlet syndrome, **c** radial tunnel syndrome, **d** pronator teres syndrome

not have weakness or pain upon pronation of palm, and in PTS, there is no tenderness to touch (Bridgeman et al. 2007). PTS is often difficult to diagnose among other proximal median neuropathies (Lee et al. 2014).

Radial tunnel syndrome (RTS)—A nerve compression pathology when the radial nerve is squeezed in the radial tunnel near the elbow. At distal to the elbow, the radial nerve divides into superficial (sensory) and deeper branches, carrying along the two divisions of the supinator muscle as it enters the radial tunnel. The deeper one comprises the posterior interosseous nerve (PIN, predominantly a motor nerve), which is involved in RTS (Naam and Nemani 2012). Repetitive and forceful pushing and pulling, constant twisting of the arm and repetitive bending of the wrist can stretch the radial nerve leading to RTS. Pain, muscle weakness, or difficulties with upper extremity dexterity are common. The extensor muscles of wrist and fingers are primarily affected. The PIN controls finger and wrist extension. Since one branch of the supinator originates from the lateral epicondyle of the humerus, and the other from on the supinator crest and the fossa of the ulna, the RTS may be confused for lateral epicondylitis. The pain pattern in RTS is different from that of epicondylitis where the tenderness is close to the tendon attachments at the lateral epicondyle. Damage to the anterior interosseous nerve (AIN) causes AIN syndrome with pain in the forearm and weakness in a pincer movement of the thumb and index finger. Based on the clinical analysis and follow up of eleven surgical cases, Park et al. (2013) noted that the most common structure of nerve compression was a fibrous band of the flexor digitorum sublimis muscle.

Thoracic outlet syndrome (TOS)—The condition is produced from compression of nerves and vessels running through the thoracic outlet. This is a narrow passageway between the collarbone (clavicle) and the first rib, which is crowded with blood vessels, muscles, and nerves. Often TOS is described as the clinically most challenging entrapment neuropathy (Huang and Zager 2004). The cause of TOS may include drooping of the shoulders, drawing the head in a forward position, continuously repeating a movement, like a computer keyboarding, and lifting of things above the head. Symptoms vary depending on whether nerves or blood vessels are compressed. Pressure on the nerves (brachial plexus) may cause throbbing pain in the trunk area, forearm, including numbness and tingling in the ring and little fingers. Pressure on the blood vessels can reduce blood flow to the arms, resulting in swelling and discoloration. In TOS, the range of motion becomes very limited.

Cervical syndrome—Cervical disc disorders and displacements are the typical conditions, involving high cervical, mid-cervical, and cervicothoracic regions. The pathological condition of the cervical disc (neck area) occurs when the intervertebral discs degenerate or deform due to repetitive shoulder movements or maintaining rigid neck during repetitive hand motions. Stiff neck is a common symptom. Cervical spondylosis and cervical spondylitis are commonly referred to degeneration of the vertebrae and inflammation of the synovial joints between the vertebrae (Binder 2007). The disc herniation occurs when the inner core of a disc herniates or leaks out of the disc. Severe pain radiates along the nerve pathway to the arms. There are conditions referred to as cervical disc disorders with myelopathy or radiculopathy, and in the former, the disorder results when the spinal cord gets compressed, and symptoms reflect hand incoordination, heavy feeling, or numbness and tingling in the legs. The radiculopathy refers to the condition in which the nerve roots from the spinal cord are pinched due to herniated disc or overgrowth of bone. Each of these conditions is identified by WHO ICD 10.

Sciatica—Sciatica refers to pain that affects only one side of the body and radiates along the path of the sciatic nerve and its branches. Being the longest nerve, it runs from the spinal cord to the buttock and hip areas and down to the back of each leg. The condition of nerve compression occurs due to a herniated disk, bone growth, and spinal stenosis. Pain varies from a mild ache to a sharp, burning sensation, and discomfort aggravates with prolonged sitting (http://www.mayoclinic.org/diseases-conditions/sciatica/basics/definition/con-20026478). In most cases, mild sciatica resolves over time. With severe sciatica, however, one may show leg weakness and difficulty in controlling bowels or bladder. Untreated sciatica can cause permanent nerve damage.

Tendon-Related Disorders

Tendons connect muscles to bones to facilitate movements of joints. Overused tendons may result in microscopic tears, leading to inflammation. Tendon swelling is usually referred to as tendinitis (also *tendonitis*); i.e., the suffix *-itis* characterizes the disease condition by inflammation. Tendinitis is commonly reported in the shoulders, the wrists, and elbows. For example, Achilles tendinitis and patellar tendinitis are common injuries in basketball and volleyball playing, due to vigorous jumping and landing (Almekinders and Temple 1998). Symptoms include local joint stiffness, pain, and burning around the inflamed tendons. There may be visible knots surrounding the joint. Where the symptoms of tendinitis are chronic, it is probably *tendinosis*, i.e., chronic tendinopathy or chronic tendon injury, due to micro tear in the tissues in and around the tendon. The suffix -osis implies a pathologic condition of chronic degeneration, without inflammation.

Epicondylitis—A kind of muscle lesion or inflammation of tendons of the elbow joint. Lateral epicondylitis (Tennis elbow) is caused by the repeated motions and force exertion, resulting in micro tears of tendons that attach to forearm muscles at the bony prominence outside of the right elbow (Fig. 4.3). Medial epicondylitis (*Golfer's elbow*, hammering, keyboarding) is caused by the damage of muscles and tendons on the inner side of the unspecified elbow, due to repetitive and forceful motions of wrist and fingers. Nordander et al. (2009) affirmed that repetitive/constrained work results in elevated risks similarly among males and females in work settings, such as industrial/non-industrial, and office settings.

Tenosynovitis—The gliding surfaces of the tendon and the fluid-filled sheaths (the synovium) may become roughened and inflamed due to overuse. The condition manifests as pain, tenderness, and swelling surrounding the tendons of hand, wrist, and arms, and other sites. Tenosynovitis is commonly linked to bacterial infection of a sheath, overuse strain, and injury of the tendon (Biundo 2016). If the tendon is damaged, recovery from the chronic condition is slow, and the affected joint can become stiff.

Dupuytren's contracture—A hand disorder in which the fingers becomes stiff and curl towards the palm (ring and little fingers are commonly affected). Scar tissue grows under the skin on the palm; the fascia thickens and shortens and as a result limits free movement of fingers and hand. Such condition can occur in the soles of the feet. The disease condition gets worsen slowly and is usually painless. Regular gentle stretching exercises help to get rid of tightness.

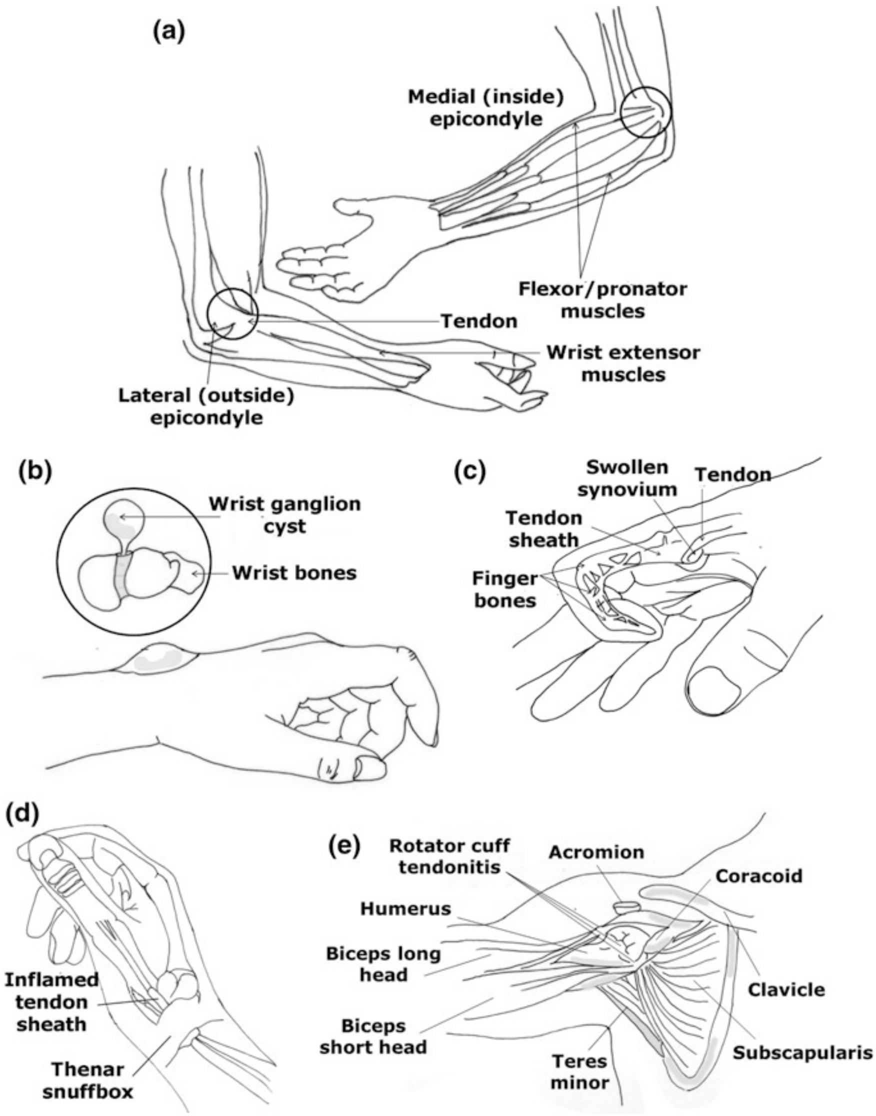


Fig. 4.3 Tendon-related MSDs; **a** epicondylitis (lateral and medial), **b** ganglion cyst, **c** trigger finger/thumb, **d** De Quervain's tenosynovitis, **e** rotator cuff impingement syndrome

Rotator cuff impingement syndrome—The rotator cuff is encircled by m. Subscapularis, m. Supraspinatus, m. Infraspinatus, and m. Teres minor. Tendons connect the humerus bone with the scapula. These muscles along with other extrinsic muscles of the upper arm are responsible for rotation and other actions of the glenohumeral joint, along with humeral abduction. The impingement syndrome occurs when the neck and shoulders of a person repeatedly slump forward, or a person lifts heavy objects repeatedly above the head (Fig. 4.3). Due to such acts, the tendons of the rotator cuff muscles become inflamed as they passage through the subacromial space, underneath the acromial process. Symptoms are pain that lingers for a prolonged period, weakness, loss of movement, or a grinding or popping sensation during shoulder movement (Pedowitz et al. 2012; Chen et al. 2003).

Ganglion cyst—Small, round lumps filled with a viscous synovial fluid may usually be formed over a joint or tendon of the wrist, fingers, and also on ankles or soles of the feet. Symptoms of a ganglion cyst are pain and discomfort, tenderness, and restrict joint movements.

De Quervain's syndrome—The condition of tenosynovitis surrounds the tendons of m. Extensor pollicis brevis and m. Abductor pollicis longus that course from the forearm into the hand by the side of the thumb. The m. Extensor pollicis brevis moves the thumb outwards radially, and m. Abductor pollicis longus moves the thumb forward away from the palm. De Quervain's syndrome, the radial-sided wrist pain, swelling, and burning sensation over the thumb side of the wrist, emanates from chronic overuse of the wrist (Martin and Awan 2017), in which the coverings of the tendon may become inflamed and thus, restrict movement of the tendons. The syndrome is common in middle-aged women. Intensive mouse/trackball use, computer keyboarding, sewing, and knitting that involve wrist bending and twisting movements are the potential risk factors associated with the disease.

Trigger finger/thumb—Each tendon is lined with synovium fluid to allow smooth gliding of tendon within its protective sheath as fingers move. Trigger finger, a painful condition happens when tendons in the finger or thumb, becomes inflamed due to a repeated movement and powerful use of the finger or thumb and forming of tissue fibrosis and bumps (nodules). That is, the space within the tendon sheath becomes restricted, causing trigger finger/thumb.

Bursa-Related Disorders

Bursae are small fluid-filled sacs (like a cyst), that cushion friction between the bones, tendons, and muscles near the joints (Fig. 4.4). Inflammation or irritation of a bursa (Bursitis) may result in a painful condition, having symptoms of swelling in the joint, stiffness, tenderness, and warmth around the affected joint. Over 150 bursae have been identified in the human body (McAfee and Smith 1988). Bursitis is often caused by repetitive movement and excessive pressure on the joint. Prolonged sitting on hard surfaces may exert pressure on the bursas in the buttock region. High-risk activities are, for example, carpentry, painting, scrubbing, shovelling, throwing, and pitching. In the shoulder region, overuse, injury, or aging may cause *subacromial bursitis* (Gotoh et al. 1998). *Olecranon bursitis* (McAfee and Smith 1988) are located at the back of the elbow over the olecranon bone. Bursitis is also common in the hips, knee, heel, and the base of the big toe. Severe loss of motion in the shoulder referred to as *Frozen shoulder (adhesive capsulitis)* results

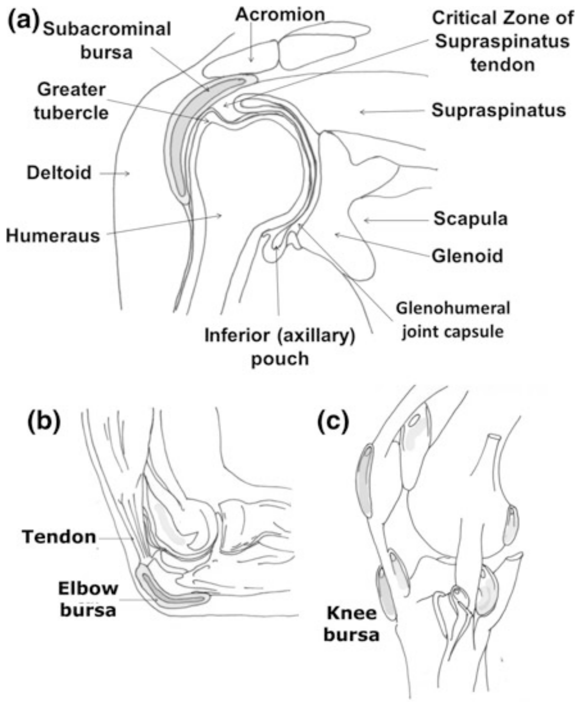


Fig. 4.4 Bursa-related disorders; **a** subacromial bursitis, **b** elbow bursitis, **c** knee bursitis

from immobility and pain associated with shoulder bursitis. The range-of-motion exercises are commonly adopted physical therapy treatment option.

Circulatory Disorders

A disorder in the circulatory system is an indication of serious health implications, due to reduced nutrient supply to the body cells and tissues. An interruption in the blood flow in a region of the body can result from mechanical compression of a nerve due to repetitive body movements and swollen tissues (Fig. 4.5).

Raynaud's disease (White finger)—Raynaud's disease, syndrome, or phenomena manifest as a colour change under the skin (namely hand and fingers, and toes), due to brief episodes of vasospasm. Raynaud's disease, primary and secondary types, may be caused in response to cold or stress (LeRoy and Medsger 1992). The primary ones are more common and less severe than secondary ones, often called as Raynaud's phenomenon. With the narrowing of blood vessels, and reduced blood flow to the affected areas, the skin turns white at first, and then, the affected areas turn blue (feeling cold and numb), and with improvement in circulation, the skin areas may turn red, throb, and swell. Women suffer more from such conditions. Repetitive actions, like typing, using keyboard devices, or repetitive impacts,

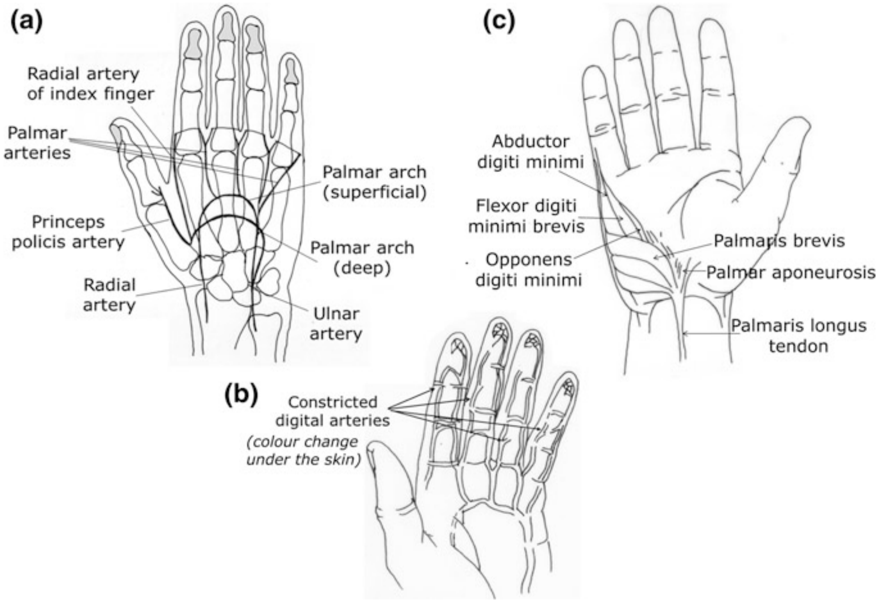


Fig. 4.5 Circulatory disorders; **a** arteries over the palm; **b** white finger; **c** hypothenar eminence

damage the arteries or the nerves in the hands and feet, leading to secondary Raynaud's. In *hand-arm vibration syndrome (Vibration white finger)* the blood supply is interrupted due to prolonged exposure to vibration. Exposure to chemicals, like vinyl chloride used in plastic processing, can be linked to Raynaud's phenomenon. An episode may last less than a minute to several hours. In case of severe Raynaud's phenomenon, there may be tissue necrosis.

Hypothenar hammer syndrome—The hypothenar eminence is referred to as the fleshy edge of the palm. The ulnar artery passes along the hypothenar area and supplies blood to the fingers. Repeated pounding of the hypothenar eminence region, like hammering, can damage the ulnar artery, resulting in reduced blood flow to the fingers. This condition is termed as hypothenar hammer syndrome (Ablett and Hackett 2008). The occupational groups, such as carpenters, butchers, operators using vibrating tools, are at risk of such syndrome.

Deep venous thrombosis (DVT)—The DVT is the formation of blood clots (thrombus) in the deep veins of the body. Common symptoms include pain or tenderness, swelling, redness, usually in the legs. Symptoms appear as engorged superficial veins among persons who remain seated for a long time or travelling on the long flight. Ultrasound of the suspected veins is used for diagnosis. The Wells score (Scarvelis and Wells 2006; Geersing et al. 2014) is a prediction rule for clinical assessment of the probability of a suspected DVT. The criteria for Wells score include nine items (such as active cancer, calf swelling of calf/entire leg, unilateral pitting edema and swollen superficial veins, localized tenderness, documented DVT, immobilization of lower extremities, bedridden for days), and each carries one point, with the maximum scoring of nine. There is the tenth item of an alternative diagnosis that carries negative two points. The score higher than two would indicate over one-half of the likelihood of having DVT.

Sometimes, DVT can be a potentially life-threatening medical condition. There is a risk of pulmonary embolism when a blood clot in a vein breaks loose and travels to the lungs. Chinsakchai et al. (2011) emphasized the management of Phlegmasiaceruleadolens, which is a very critical type of DVT, characterized by nearly total venous occlusion in the extremity. The leg is painful, swollen, and discoloured, with a risk of venous gangrene (Barham and Shah 2007). For people who are susceptible, the preventive intervention includes periodic walking and calf exercises, wearing graduated compression stockings, use of aspirin, and anticoagulants.

Muscle-Related Disorders

The excessive and repetitive exertion of muscles, including postural stress, can cause a range of muscle disorders, pain, and discomfort. With overuse injuries, the fascia that wraps muscles under the skin may lose its elasticity and cause less efficient contraction of muscles. The work-related muscle disorders are:

Tension neck syndrome—A condition results from some factors, including static workload. Tension neck syndrome encompasses a variety of disorders or syndromes, such as posture-related neck pain, trapezius myalgia, tension myalgia, myofascial syndrome, cervical strain (Fig. 4.6a). These terminologies are generally vague. However, the syndrome indicates the pain and discomfort of cervicobrachial areas (Buckle and Devereux 2002), as commonly experienced by office and factory workers, computer operators, due to postural stress, workplace incompatibility, fatigue and also psychological factors, such as emotional stress. Sustained contraction of muscle groups is felt as tight bands or nodules, and spasms and these trigger points cause pain and numbness and radiate to regions of neck–shoulder and head. Any work posture that demands arms and shoulders raised and unsupported seating for long hours may cause neck tension and muscle fatigue in the adjacent areas. Any unsupported elbow and forearm position maintained for a long period, for example, in continous computer keying and use of mouse, may culminate into tension neck syndrome (Mekhora et al. 2000).

Myalgia is a symptom of muscle pain, resulting from overuse, overstretching, injury, or trauma including sprains and strains. Pain ranges from mild to excruciating and develops almost in any parts of the body, whereas *fibromyalgia is* a chronic condition characterized by widespread pain in the muscles, ligaments, and tendons. *A myofascial pain syndrome is a* chronic form of myalgia that centers on sensitive points called trigger points in the muscles (Gerwin 2010). The active trigger point has identifiable pathophysiologic changes, with a measurably elevated concentration of substances, such as substance P, CGRP, bradykinin, and cytokines, indicative of a chemical inflammatory response. The trigger points manifest as

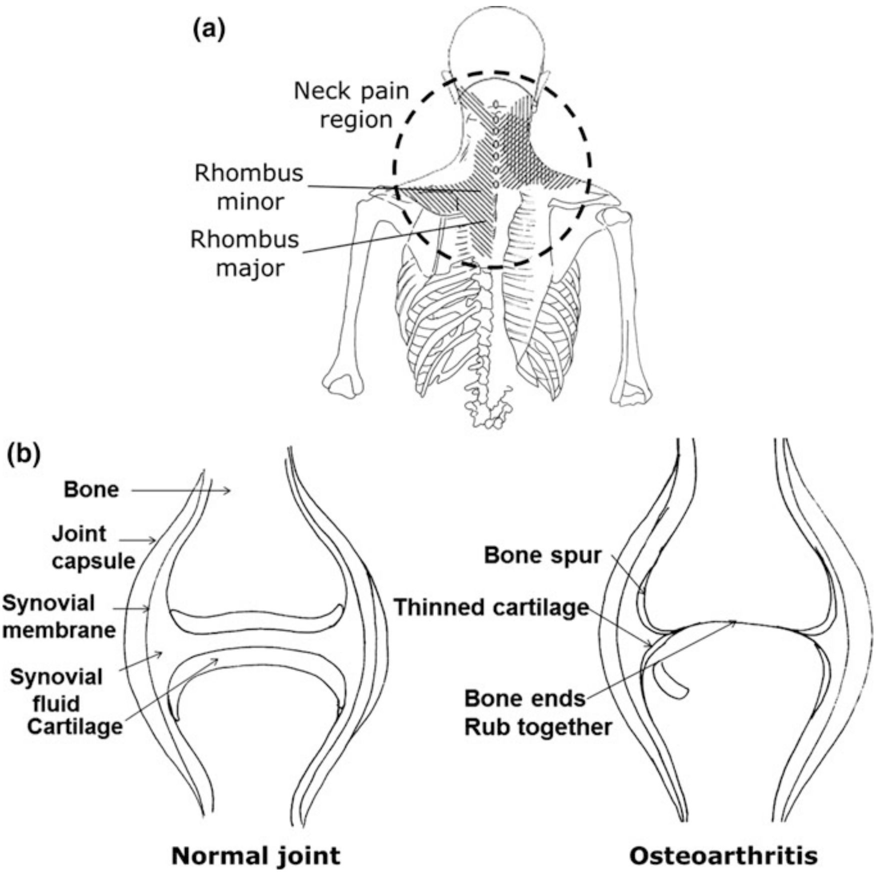


Fig. 4.6 Muscle related disorders; **a** tension neck syndrome; **b** normal and osteoarthritic joint

persistent, low-amplitude, high-frequency EMG discharges, like endplate potentials. The myofascial pain syndrome may be termed as primary and secondary syndromes (Gerwin 2010). Usually, the primary syndromes are the overuse myogenic syndromes of specific regions of neck and shoulder or other areas. Myofascial pain can spread to seemingly unrelated parts of the body. The secondary syndrome occurs in conjunction with other medical conditions, such as chronic whiplash neck pain, cervical and lumbar spondylosis, osteoarthritis, chronic infection. The pain and discomfort may persist or worsen unless appropriate treatment interventions (medication, physical therapy, relaxation) are introduced. *Dystonia (Writer's cramp)* presents itself as a lingering tension and discomfort in the hand or forearm, due to a malfunction of the CNS; specific symptoms are excessive gripping of the pen, the involuntary extension of fingers, hand tremors, and muscle spasms.

Apart from work-related MSD specific to nerve-, tendon-, bursa-, circulatory-, and muscle-related disorders, other types of overuse disorders are osteoarthritis, back pain, eye strain, migraine, stress, and depression. *Osteoarthritis is* a medical condition of excruciating pain. The condition occurs when the cartilage cushioning the bones in the joints wears down, and the ends of the bones become damaged due to rubbing bone on bone (Fig. 4.6b). Back pain is a complex manifestation that can arise from strained muscles and ligaments, prolonged manual materials handling, and after a sudden awkward movement. Eyestrain may appear due to extended periods of intense focus and concentration, e.g., computer work and exposure to bright light sources or straining from working under dim light.

People often complain of a chronic headache (a migraine) that may last for hours or even days. A migraine may be accompanied by nausea, vomiting, and extreme sensitivity to light and sound. A t*ension headache, on* the other hand, *is* a diffuse, mild to moderate pain witnessed by people, who are under stress and anxiety, and sustained postural stress. Humans perceive stress when exposed to inherently stressful interactions of the work environment, referred to as work overload or under load, long hours of work, and psychosocial stress. Strain develops when stress exceeds their adaptive capacities. Anxiety and depression are two distinct disorders, and both appear at the same time. Anxiety disorders include generalized anxiety, panic, phobias, and obsessive–compulsive disorder, whereas depression shows more profound symptoms, such as feeling of sadness, fatigue, irritability, sleep disturbances, and some of these may be observed with anxiety disorders. Also, there are apparent relationships exist between pre-disposing conditions, due to vitamin B-6 deficiency, diabetes, obesity, rheumatoid arthritis, gynecological surgery, to the occurrence of MSD.

With the evidence of work-relatedness to the occurrence of neck and upper limb MSD, workplace intervention would need focus on work design strategies to mitigate the menace (Buckle and Devereux 2002; Brewer et al. 2006). The MSDs can be confirmed from (a) the medical history, clinical progression of the disease, (b) evidence of occupational exposure to risk factors, (c) the report of functional ability, and (d) the confirmatory tests (X-rays, strength and endurance testing, nerve conduction tests), as appropriate. Early recognizing of symptoms of work-related MSD among the office workers could prevent increasing strain by making changes to the job, work practices, or workstation. The European Foundation for the Improvement of Living and Working Conditions Survey (2005) indicated that about 1/4th of the workforce reported work-related neck/shoulder pain. Together, MSD and traumatic injuries bear a significant implication to reduce medical costs, minimize productivity loss, reduce lost-time compensation claims of affected workers and increase morale (Kennedy et al. 2010). The causes of MSD are complex and not often predictable. However, the employer and office facility manager may make use of the annexed MSD study questionnaire as a proactive measure for assessment of the scenario and intervention in the workplaces. The employer may be responsible for compensatory cost coverage for temporary total or partial disablement, as stipulated by the appropriate regulatory authority.

Annexure: MSD Study Questionnaire

Demographic information	ID.	Gender (M/F)	Age (yrs)
Type of organization/Industry	• General government offices • Finance and services • Academic • Communication and transport		• Wholesale/retail, automobile, hotels • Electricity, gas, and water • Engineering and manufacturing • Other (specify)
Type of office work			
Home office/small office	Mobile office/alternative workspace		Tele Centre/Telecommuting/Tele-business
Flexitime/flexi-work	Hot-desking		Hoteling
Desk sharing	Just in time		Interactive service delivery/operations centers
Work experience in the current office/organization	– (years)	Previous work experience in similar office/other organization	– (years)
Work scheduled for current work (hours/week)	– (hours)	Work schedule in previous work (hours/week)	– (hours)
Furniture/equipment and support systems used in office work/telework	• Workstation/desk/chair • Desktop PC, laptop, tablets, notebook • Printer/scanner, etc.		• Telephone, smartphone • Internet, remote access VPN, WiFi router. • Social networks (Skype, Facebook, Twitter)
Employee training	Occupational Health and Safety Act		• Yes • No
	Occupational Injury Compensation Act		• Yes • No
	Ergonomics policies and guidelines		• Yes • No
	Telework/alternative worksite safety, and guidance on health		• Yes • No

(continued)

(continued)

Reporting of work-related MSD	• Yes • No		If yes (How many times in the last year)	
Occupational risk factors	Never (1)	Occasional (2)	Often (3)	Always (4)
Force exertion and movement (e.g., manual materials handling)				
Awkward or non-neutral postures (movements at extreme ranges)				
Repetitive motions (same body parts are repeatedly used)				
Static muscle loading for an extended period				
Mechanical/local contact stress (pressing hard with a body part on sharp edges)				
Extreme climate (heat or cold)				
Poor lighting				
Hazardous environment (noise, toxic substances)				
Task-related stressor (time pressure, work overload)				
Work schedules (night work, shift work, overtime)				
Social stressors (interpersonal conflicts, workplace violence)				
Role stressors (ambiguity, conflict)				
Career-related stressors (lack of recognition and promotion)				

(continued)

(continued)

Poor work design and organization (low level of control)				
Organizational stressors (restructuring, technology pressure)				
Traumatic stressors (accidents, unsafe acts, and conditions)				
Predisposing medical conditions (joint injury, diabetes, hypertension)				
Other (specify)				
The occurrence of work-related MSD symptom	Never (1)	Occasional (2)	Often (3)	Always (4)
Reduced range of motion, stiffness, muscle spasm				
Loss of grip strength, muscle weakness, and fatigue				
Loss of normal sensation				
Tender trigger points in muscles				
Tingling/pain				
Other (specify)				
Ergonomics incompatibility and related factor(s) resulting to work-related MSD	Strongly disagree (1)	Disagree (2)	Agree (3)	Strongly agree (4)
Table/desk/workstation/chair				
Desktop computer/laptop computer				
Monitor (height)				
Keyboard/mouse use				

(continued)

(continued)

Lack of computer accessories (monitor risers, wrist/palm rest, armrest, footrest)				
Insufficient space allocation, the layout of furniture, workstation				
Lighting (glare, luminance)				
Temperature (heat, cold)				
Floor surfaces (slippery, uneven)				
Noise (co-workers, ventilation systems, office equipment, outdoors)				
Job design (task variety, work pace)				
Work scheduling (overtime, shift work)				
Lack of rest/recovery breaks/lack of exercise/ stretch breaks				
Overweight/obesity				
Other (specify)				
Did suffering from MSD result in:				
Temporary job, job rotation	Workstation re-design	Tools and equipment adaptation		Job-task modification
Work schedule modification	Job enlargement, job enrichment	Retraining and re-assignment		Other
Work-related MSD (Use Figs. 4.2–4.6, to guide the physical locations of complaints)	Type of disorders	Cause of injury	Medical costs for treatment	Yearly loss of work days due to medical intervention

(continued)

(continued)

Nerve-related disorder	Carpal tunnel syndrome			
	Guyon's tunnel syndrome			
	Cubital tunnel syndrome			
	Pronator teres syndrome			
	Radial tunnel syndrome			
	Anterior interosseous nerve syndrome			
	Posterior interosseous nerve syndrome			
	Thoracic outlet syndrome			
	Cervical syndrome			
	Sciatica/Back pain			
Tendon-related disorder	Tendonitis hand/wrist; tendinosis			
	Epicondylitis			
	Tennis elbow *(lateral epicondylitis)*			
	Golfer's elbow *(medial epicondylitis)*			
	Tenosynovitis/De Quervain's syndrome			
	Dupuytren's contracture			
	Rotator cuff impingement syndrome/shoulder pain			
	Ganglion cyst			
	Trigger finger/thumb			

(continued)

(continued)

Bursa-related disorder	Bursitis			
	Olecranon bursitis			
	Subacromial bursitis			
	Frozen shoulder (adhesive capsulitis)			
Circulatory disorder	Raynaud's disease (White finger) : cold-induced			
	Hand-arm vibration syndrome (vibration white finger)			
	Hypothenar hammer syndrome			
	Deep vein thrombosis			
Muscle-related disorder	Tension syndrome neck			
	Muscle sprain and strain			
	Myofascial pain syndrome			
	Myalgia/Muscle pain			
	Fibromyalgia			
	Dystonia (Writer's cramp) :			

(continued)

(continued)

Other disorders			Osteoarthritis			
			A migraine/tension headache			
			Back pain			
			Neck pain			
			Eye strain			
			Stress, depression			
			Other (not listed above)			
Healthcare provider						
General practitioner	Orthopedist	Biokineticist/ chiropractor	Optometrist	Exercise physiologist/ physiotherapist	Psychologist	Other (specify)
Compensation claims due to MSD			Was the claim successful?	Yes	No	Not applicable
			Financial benefit?	Yes	No	Not applicable
			Medical reimbursement?	Yes	No	Not applicable
			Work environment improvement?	Yes	No	Not applicable
			Other (specify)			

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Part III
Office Ergonomics

Chapter 5
Fundamentals of Office Ergonomics

Introduction

Today, our offices have the overflowing presence of computerized systems, dramatically changing the world of work. The massive infusion of computers in the offices has brought in a simultaneous explosion of computer-based tertiary services such as computer institutions, software companies, and call centres services like banking, BPOs and telecommunication sectors, start-ups and online marketing and allied services. Estimated number of PCs in use, as on 2012, in the top five countries (USA, China, Japan, Germany, and India) reaches over 732 million, which is sharing about little less than the half of the world's total. The global population of Internet users perhaps represent as the surrogate marker of the extensive infusion of computer in different functions of our life (Fig. 5.1). As of June 2016, Asia contributes half of the world total Internet user population, ranking China, India, and the USA in order with over 721, 462, and 287 million users, respectively (http://www.internetworldstats.com/).

Computers in our offices have brought in a sea change in the look of the contemporary offices, how easy way the work is executed, and diversity instilled in the organizational work processes. Office managers, safety, and health personnel recognize the immediate necessity of making workplaces comfortable and safer. The emphasis of the discipline of ergonomics in computer work is a way forward to understand the human physical and mental capabilities, as one interacts with the allied equipment, work methods, and the working environment. The science of ergonomics brings in a proactive approach to work design to enhance work performance at minimal health and safety implications, and deliver quality business process, products and services.

P. K. Nag, *Office Buildings*, Design Science and Innovation,
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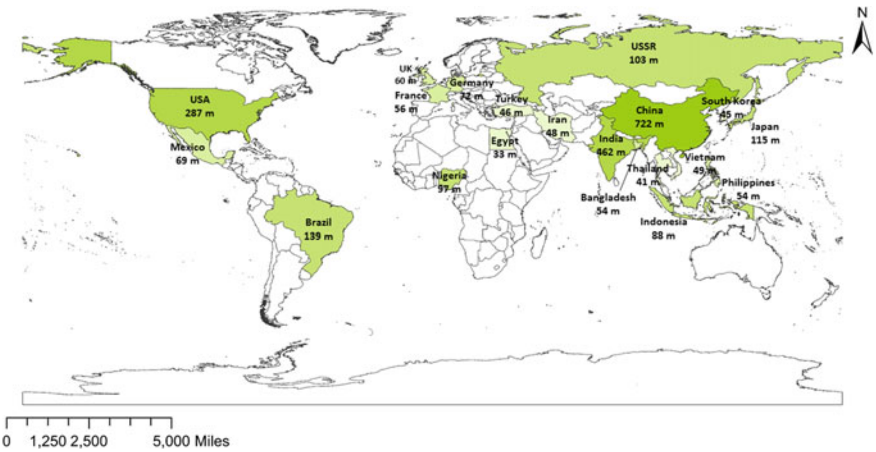


Fig. 5.1 Global distribution of Internet (first twenty countries)

A Brief Note on Ergonomics

In the prophetic treatise entitled *Rys ergonomji czyli nauki o pracy* (An Outline of Ergonomics, or the Science of Work), W. B. Jastrzebowski, a natural scientist, created the foundations and premise of ergonomics (*Przyroda i Przemysl, Poznari*, Poland 1857; Fig. 5.2). The Science of Work that ventured to call ergonomics was derived from Greek ergon (epyov)—work, and nomos (voμoς)—principle or law. *Work* is performed by man's forces and faculties that have been endowed by our *Maker* for the common good. In philosophic understanding, the *Work* is viewed in its comprehensive and integral sense, encompassing labour, entertainment, reasoning, and dedication. That is, the concept of *Work* is not merely physical labour, but physical, aesthetic, rational, and moral work. This prophetic message might find an equivalence to ancient Vedic sayings *work is worship*, conveying an untarnished sense of personal dignity.

Over a century of hibernation, the term ergonomics was independently reinvented by Murrell in 1949, as the discipline that assembles knowledge on human properties and capabilities to apply in the design of products, workplaces, equipment, and achieve benchmark in work (re)design. The re-emergence of the Science of Work in contemporary understanding has become evident from the magnificent and inspiring storytelling by Edholm and Murrell (1974) about the history of ergonomics research society. The classical application of micro-ergonomics in physical nature of work, and relevant human factors concerns in the man–machine–environment system (Singleton 1974), gradually led to broader visibility to the macro-ergonomics, with systems-oriented perspective (Hendrick 2002; Siemieniuch and Sinclair 2006; Kleiner 2006).

Fig. 5.2 Jastrzebowski's writings on the Science of Work (third part), published in the polish journal "Przyroda i Przemysl, Poznari"

In describing the body of knowledge, several terminologies and definitions emerged independently and in combinations, namely ergonomics, applied/industrial ergonomics, human factors, human factors engineering, human engineering, engineering psychology, applied experimental psychology, human factors psychology, biomechanics, occupational health. These have been viewed as synonymous with the interdisciplinary character. However, it is imperative to determine the real nature of an entity that it includes, and the specific differences which set it distinctively apart. In other words, a technical or scientific definition is usable for the intended purpose, with the provision that the broader meaning of the definition is interpretable to the all concerned. It describes, expounds, interprets, and uses metaphor to clarify precise meaning. It is not unlikely that several synonyms having subtle words very close in meaning may encroach upon in the process. A search of the literature, books, and materials, databases, including source-based Web searches, using keywords, yielded a variety of viewpoints on the subject matter, with considerable shades of difference in meaning, emphasis, and interpretation. These viewpoints are scrutinized, culled, compiled, and embodied herewith (Table 5.1).

Towards consensus building of a unifying expression, three main categories, namely ergonomics, human factors, and human factors engineering, have been amply described by the researchers. The study of ergonomics is emphasized to the relation between man and his occupation, equipment, and environment, with the application of anatomical, physiological, and psychological knowledge (Murrell 1965, 2012; Singleton et al. 1967; Tichauer 1978). As the name implies, ergonomics is an area of study and application that devoted to the problem of fit between user and machine or tool, whereas the goal of human factors directs to apply knowledge in designing systems that work, wherewith accommodating limits of the human operator in exploiting better performance (Meister and Rabideau 1965; Chapanis 1986). Ergonomics profoundly incorporates anatomical, physiological, and medical component and pays attention to health, well-being, and efficiency, and human factors is a psychology and engineering partnership towards increasing system efficiency (Salvendy 1997).

In contrast to ergonomics and human factors, the study of human factors engineering places emphasis on the design as the medium to effect change on an end system, that is, to optimize the relationship between people and their activities by systematic application of the human sciences, integrated into the framework of systems engineering. The readers may refer to the writings of leading authorities (e.g., Sheridan and Ferrell 1974; Rasmussen 1997; Rouse 2007) who introduced the concepts of man–machine systems-level models in ergonomics/human factors. Also, the literature on human engineering elucidates its foundation as the analysis of factors that help a man perform his job with speed, accuracy, and efficiency. It encompasses the design of human tasks, man–machine systems, and specific items of man-operated equipment for the useful accomplishment of the job in complex man–machine systems (Hertzberg 1955; Chapanis 1959). Often, this branch of study has been referred to as engineering psychology, as a hybrid of engineering and psychological knowledge (Fitts 1963). It seeks to understand how human performance is related to task variables and to formulate principles of human performance in the design of the physical conditions and environments, machinery, and devices about human capabilities, learning capacities, efficiency, reliability, and comfort (Park 1987). In essence, human engineering/engineering psychology calls for broad interdisciplinary knowledge, aiming at optimum man–machine functional interrelationship.

The synonymy or the diversity of the disciplines is vividly recognized, with the convergence that the ergonomics implies the study of a man at work, while the human factors refers to the study of a man about equipment and environment. The human factors engineering converges on user behavioural orientation to the human–machine system. Undoubtedly, the perception and acceptance of the meaningfulness of the discipline have many milestones of progression in delineating its perspectives, limitations, and variations. The federative science and technology of man at work forms the foundation for development and adjustment of technology for rational utilization of human potentials under the favourable environmental and social conditions

Table 5.1 Diversity in defining ergonomics, human factors, and human factors engineering

Ergonomics	References
The relationship between man and his working environment; the term environment covers not only the ambient environment, but also his tools and materials, methods of work, and the organization; these are related to the nature of the man himself, his abilities, capacities, and limitations	Murrell (1965)
Application of psychology, physiology, and anatomy to the study of and the design of human tasks, workplaces, machines, and environments; "systems design [is] an organized approach to the business of decision-making in any design context" that is regarded as an emphasis on human factors	Singleton et al. (1967)
"The interaction—physical as well as behavioral between man, his workplace, his tools, and the general environment"; "it utilizes, as tributaries, so many aspects of the biological, behavioral, medical, and technological sciences"	Tichauer (1978)
A study of man's behaviour in relation to his work, based on theories of physiology, psychology, anthropometry, and aspects of engineering; "(i) fitting the demands of work to the efficiency of man in order to reduce stress; (ii) designing machines, equipment, and installations so that they can be operated with great efficiency, accurately, and safely; (iii) working out proportions and conditions of the workplace to ensure correct body posture; (iv) adapting lighting, air conditioning, noise, to suit man's physical requirements"	Grandjean (1980)
Devoted to alleviating the rigours of the workplace and the improvement of the persons' performance on the job; "application of those sciences relating human performance to the improvement of the work system, consisting of the person, the job, the tools and equipment, the workplace and workspace, and the immediate environment"	Alexander (1986)
Human factors	
(1) The characteristics (capabilities and limitations) of man, (2) characteristics (design features) of machines and machine systems, and (3) the relationship between them; Application of variables in the development and evaluation of man–machine systems, and to improving the performance of men in the operation of their machines, so that resulting system operations meet specified performance requirements	Meister and Rabideau (1965)
Concerned with virtually every consideration of the human in the system, covering functions and tasks, the design of jobs for various personnel, training, and evaluation; • improved human performance and comfort as shown by increased speed, accuracy, and safety, and less energy expenditure and fatigue; • less training and reduced training costs; • improved use of manpower through minimizing the need for specialized skills and aptitudes; • reduced loss of time and equipment as accidents due to human errors are minimized	Huchingson (1981)

(continued)

Table 5.1 (continued)

Ergonomics	References
Human factors engineering	
Considering man/machine combination as a total system to ensure that the operational requirements of equipment do not exceed human abilities; Considering the human performance tolerance, to ensure optimal speed, accuracy, and quality of performance, and eliminate hazards to operating personnel, and maximizing their comfort	Behan and Wendhausen (1973)
Concerned with designing products, processes, and equipment used in manufacturing to maximize human ability, comfort, and safety; Application of data and principles about human characteristics, capabilities, and limitations, referring to the conception of designing machines, machine systems, work methods, and environments for safety, comfort, and productiveness of human users and operators; Drawing knowledge of anatomy, anthropometry, applied physiology, environmental medicine, psychology, sociology, and toxicology, as well as parts of engineering, industrial design, and operations research	Chapanis (1986, 1996)
Deals with the capabilities and limitations of human performance about the design of machines, jobs, and other modifications of the physical environment; it seeks to ensure that humans' tools and environment are matched to their physical size and strength, and the capabilities of the senses, memory, cognitive skill, and psychomotor preferences	Sheridan (1987)
Synonymy of the discipline	
Describing, analysing, measuring, predicting, and controlling the functioning of the real world of systems, i.e., studying the relationship between the personnel sub-system and other system elements, including the terminal system output	Meister (1985)
Consideration of human characteristics, expectations, and behaviours in the design of things people use in everyday lives and environments in which they work and live; Considerations in (1) the design and creation of man-made objects, products, equipment, facilities, and environments that people use; (2) development of procedures for performing work and other human activities; (3) providing services to people; and (4) evaluating things in terms of the suitability for people use	McCormick and Sanders (1982)
A repository and source of data and principles that are applied to the specification, design, evaluation, and operation of products and systems for safe, effective, satisfying use by individuals, groups, and organizations	Christensen (1988)

(Nag 1996). Both micro- and macro-ergonomics developments (Kleiner 2006) broaden the scope of understanding at human–machine–environment–organization relationships. At the micro-level, ergonomics has been emphasized on the relation of engineering and design, with central consideration of the human characteristics and behaviour to the design of objects, facilities, and environment. At the macro-level, the micro-ergonomics developments broaden the system's effectiveness goals, whereby the integrated concepts and practices exemplify work system development and management in the organization. The International Ergonomics Association (2000) takes up the discipline as *the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design to optimize well-being and overall system performance*.

Systems Approach

The literature shows a clear chronological trend towards broadening of considerations of ergonomics/human factors, with noticeable opening up towards systems orientation. Insight brings out twofold objectives, i.e., (1) to enhance the effectiveness and efficiency with which work and activities are carried out, and (2) to maintain or enhance desirable human values (health, safety, satisfaction). Reference has been drawn to the primary functions of humans in complex systems to the design of equipment and facilities, and the development of environments for human comfort and safe use (Fig. 5.3). The positive interactions of the sub-systems at all possible interface levels are the necessary conditions for organizational effectiveness. An easy way to look into that systems ergonomics/human factors accounts for the interacting combination of people, materials, tools, machines, software,

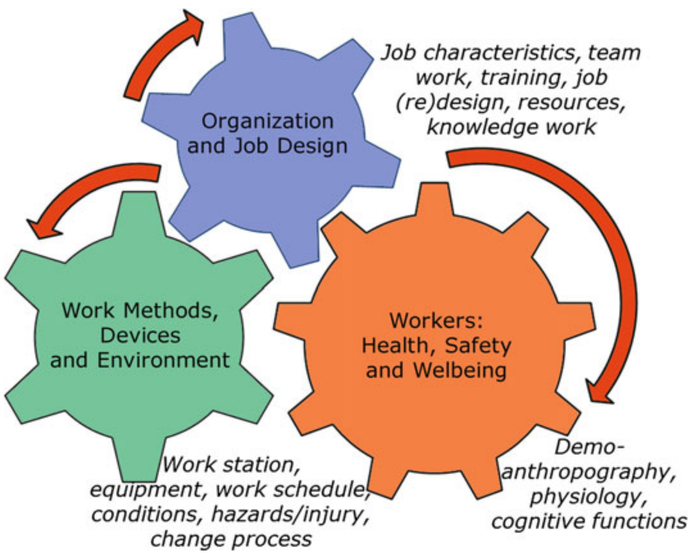


Fig. 5.3 System components in ergonomics/human factors study and application

facilities, and procedures designed to work together for some common goal (Chapanis 1996).

The interdependent components are defined about one another, concerning the technical and human components, their attributes and relationships (Luzeaux and Ruault 2008; Stasinopoulos et al. 2009). Wilson (2014) elucidated the systems ergonomics/human factors by defining features, such as systems focus, context, interactions (including complexity), holism, emergence, and embedding.

- *Systems focus:* on viewing as a system with interacting combination of other materials, information, and function/process components. Since *human* is at the centre of attention, our clear focus of interest is in the *design* of people's interaction with or within the broader socio-technical system domain.
- *Context*: Since all behaviour and performance take place in a setting or a context, the setting of the boundaries of the system is used for the analysis of complex socio-technical systems, and systematic representation of operations of system boundaries, and how each can provide context for others (e.g., Waterson 2009).
- *Interactions*: The fundamental view of interaction lies at the core of ergonomics/human factors approaches, concerning human–machine systems, socio-technical systems, cognitive, health and safety systems. The underlying purpose is to optimize the interactions involved with the integration of human, technical, information, social, political, economic, and organizational components.
- *Holism*: The discipline of ergonomics/human factors by very nature is holistic; it seeks to understand the physical, cognitive, and social/emotional characteristics of people, in enhancing the interactions they have with objects, information, environments, and other people.
- *Emergence*: That is to recognize the emergent properties of systems (Johnson 2006), including those of the human components. All systems in real use, with users under the constraints of time, space, pressures, and the like, might display and operate unexpectedly, and therefore, appropriate familiarization of the components is the job of the ergonomics/human factors professionals. Thereby, the impact of poor designs may be obviated through the well-recognized ability of users in making the system work despite its shortcomings.
- *Embedding*: This means the way ergonomics fits within the organizational system and is embedded within the practice, thus calling participatory role with all key stakeholders (Haines et al. 2002) in operations, design, engineering, safety, and training.

Interested readers may refer to selected peer publications (Hollnagel 2001; Stanton and Stammers 2008), projecting the future of ergonomics regarding expected developments and effects on the content of the discipline, or in specific regions (Dul et al. 2012). There is no denying that ergonomics is inherently imbibed with a strong value proposition (well-being) and interactivity with other stakeholder groups (Carayon 2006). In an integrative sense, the performance of the system is based on the performance of the work system (including worker, working methods,

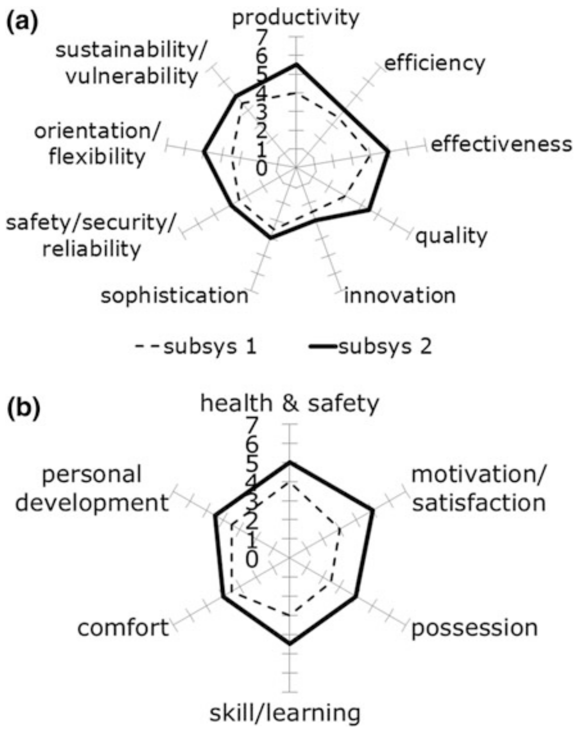


Fig. 5.4 Ergonomics attributes of **a** system performance and **b** human well-being

and the working environment) and the product/service system (consumer, service receiver, including the environment where the product is used or services received) (Fig. 5.4). The author has expressed his comprehension on the subject matter, and further enjoins that by fitting the work environment to the human, two related systems outcomes (performance and well-being) can be achieved (Wilson et al. 2009; Neumann and Dul 2010). The performance dimension covers, for example, productivity, efficiency, effectiveness, quality, innovativeness, flexibility, (systems) safety and security, reliability, sustainability, whereas the well-being dimension covers, for example, health and safety, satisfaction, pleasure, learning, personal development. These dimensions are intertwined and powerfully connected, and the way forward for the widespread acceptance and application of the knowledge.

In the relevant context, *Office Ergonomics* emerges as a newer domain, both in abstract and in examples. The conventional office environment and traditional office organization are fast replaced by the newer office envrionment, such as VDT workstations, instructions, and procedures, physical environment, the activities carried out, material interfaces, operator–equipment–environment–customer interaction. Whereas, the computer-enabled technology has created immense possibilities in office organization, it has brought along a host of human issues, ranging at the societal level from the perennial ethical issues about the use of technology, to individual level issues relating to physical and mental health. The proliferation of

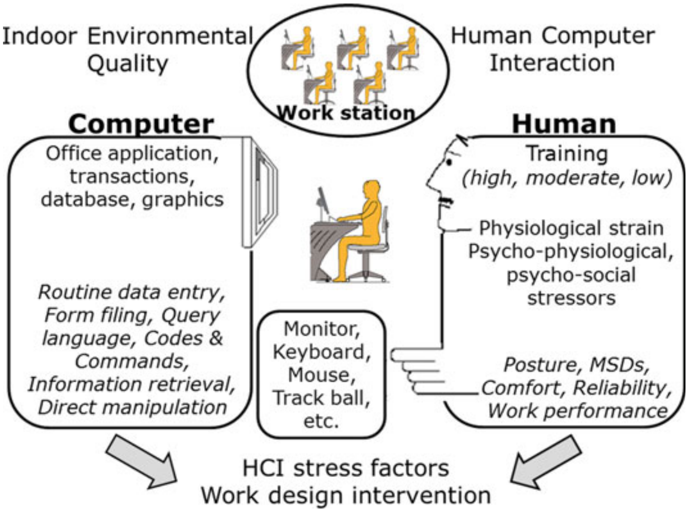


Fig. 5.5 Characteristics of human–computer task components and interfaces

VDTs in workplaces has resulted in a malaise of musculoskeletal disorders (MSDs) among the computer operators, with gigantic compensation claims in individual countries. Multiple aspects of VDT work, such as the characteristics of human–computer task components, the interfaces, viz. the type of monitor, input/pointing devices being used, and the tasks performed, have long-term health, performance, and safety consequences, as illustrated in Fig. 5.5. There is a tangible and intangible impact on the worker's perception of work, and an increased incidence of visual discomfort, postural load, and psychophysical as well as psychosocial stressors among the computer users. To help understand certain fundamental ergonomics aspects to be considered in the context of the office environment, this chapter examines the interaction issues, potential hazards, and interventions that may be taken up to prevent or reduce the potential health and safety concerns of the office workers.

Risk Factors in Computer Work

A complex set of conditions, such as individual physiology, the work environment, technology, organizational impacts, psychosocial factors, as well as non-work activities and environments, present the risk factors in computer-associated office work (Brewer et al. 2006; Miller 2001). Overall, the risk factors can be split into two general groups: (a) physical factors and exposure condition, and (b) psychosocial and cognitive stressors.

Physical factors and exposure condition—Physical factors, such as sustained force exertion, uncomfortable work posture, static loading, mechanical/local contact stress, repetitiveness, long duration of work, poor working environment, are present in computer and office work, some or all of that may be present at the same time. A range of manual handling activities, such as lifting, lowering, carrying, pushing or pulling, gripping, and manipulating objects, exert physical strain on the musculoskeletal structure and the spinal column. Epidemic proportion of work-related MSDs among people in the offices culminates from cumulative exposures, and partly modulated by individual differences, regarding one's body size, age, health, and disabilities. Individuals may differ in their perception of risks and attitude towards reporting any symptoms. The incidences of MSDs in the offices vary to a great extent, indicating the relative influence of the workplace stressors.

Routine office tasks require a moderate amount of force to be applied. However, there is a likelihood of sustained postural stress in the computerized office. Static postural load and lack of movement reduce blood circulation and cause increased muscle tension that can contribute to or aggravate an injury. Unsupported sitting, sitting on the hard surface, or any pressure on the soft tissues (the tendons, nerves, and blood vessels) are the risk factors of MSDs over time. Repetitiveness in a task is a recognized risk factor, leading to fatigue, tissue damage, and, eventually, pain and discomfort (Kennedy et al. 2010; Nordander et al. 2009). However, the speed at which the job becomes risky depends on the task itself. Complaints of discomfort and injury are higher among employees who spend long hours daily doing repetitive keying tasks, compared to those who might spend ~ 2 h daily in repetitive keying work. Repetitive arm motions in using the mouse that is placed beyond the keyboard might result in a shoulder injury since the employee is forced to elevate their arms and work in an awkward posture.

Psychosocial and cognitive stressors—Today's office workers, and sectors with primary dependence on computer-based services, like call centres/BPO, banking, and other financial services, are exposed to repetitive, intensive, and stressful work. These, in turn, are the primary causes of physical and psychological distress, with individual variability to one's coping efforts. Survey on a community sample of men and women (Johnstone and Feeney 2015) indicated workplace stress appraisal as a mediator between attachment anxiety and less adaptive coping and established both mediating and moderating effects of perceived coping resources. Dimensions of stressors in the workplaces are identified (Shaver 2010) as follows:

(a) task-related (cognitive) stressors—excessive workload, time pressure, cognitive demands, work complexity, monotony;
(b) work-schedule stressors—night work, shift work, overtime that can affect one's sleep patterns, social and domestic interactions;
(c) environmental stressors—physical and chemical environment;
(d) psychosocial stressors—interaction with co-employees, isolation and alienation, interpersonal conflicts;
(e) role stressors—ambiguity, lack of job clarity;

(f) career-related stressors—job insecurity, lack of promotion;
(g) traumatic stressors—disasters and accidents; and
(h) organizational stressors.

The resultant impacts of these stressors lead to a multitude of organizational issues, such as absenteeism, decreased employee performance, workplace errors and accidents, healthcare costs, increased employee turnover, workplace dissension. Thus, the emphasis goes into the holistic job design through identifying and mitigating the job stressors in computer-related work.

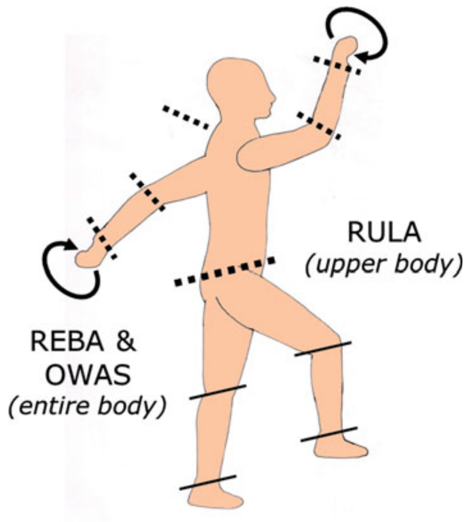
Ergonomics Survey at Workplaces

Creating good ergonomics in workstation arrangement is vital to protect the user's health and maintain workplace wellness. Timely assessment is required to evaluate workplaces. Therefore, the steps to be followed include (a) conducting a thorough workplace and task analysis covering the individual workstation, the psychosocial and environmental factors, and office work design, and (b) exploring ergonomics interventions to the identified problem areas. The workplace analysis identifies workplace risk factors, and simultaneous task analysis elucidates activities executed by the individual employees on a daily basis. That is, for each task, exposure details, the associated risk factors, records of discomfort, and the likely causes, including the environmental and organizational factors, can be explored, and scope of feasible intervention can be determined. Many ergonomics toolkits like OWAS (Louhevaara and Suurnakki 1992), RULA (McAtamney and Corlett 1993), REBA (Hignett and McAtamney 2000), ROSA (Sonne et al. 2012) have been developed for body posture analysis, workplace evaluation, and design intervention. Generally, these easy-to-use methods attach numbers to different body orientation, joint angles, and movements, along with considering physical loads, and based on accrued ranking, suggestions are provided for action.

OWAS, *the* Ovako working posture analysis system, is a pictorial four-digit classification of body postures and physical loads, during a work cycle. Scoring arises from three body regions of back, arms, and legs when the load is handled (between 0, 10, and 20 kg). Each body posture has a predetermined gradation regarding the physical load and action required. The categories are no action, action in the near future, action as soon as possible, and immediate action.

RULA, Rapid Upper Limb Assessment, is very close to the assessment as OWAS, however, with the emphasis more on upper body work, including hand/arm intensive work. Positions of seven body regions, i.e., upper arm, forearm, wrists, twisted wrists, neck, upper body, and legs (Fig. 5.6), are assessed using numerical codes. An overall score is arrived at based on the body part assessment, load handled, and static or dynamic movements. The higher the assessment score, the higher the risk of injury, and accordingly, an action scale for intervention is suggested. Software application tools are available in public domain for use. *REBA*,

Fig. 5.6 Body regions assessed by RULA (upper part of the body), REBA and OWAS methods (include entire body)

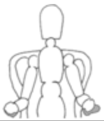
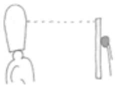


Rapid Entire Body Analysis, is a whole-body orientated method than RULA, to evaluate unpredictable body postures within health care (Hignett and McAtamney 2000). REBA considers load couplings, including the person's hand grip on the load, and also dynamicity of body posture. The scoring of REBA is linked to an action category for intervention.

ROSA, Rapid Office Strain Assessment, was designed to analyse operators' discomfort and risks associated with computer work, with reference to chair–desk complex, including computer accessories (Sonne et al. 2012). The risk factors were coded between 1 and 3, and the final scores ranged from 1 to 10, indicating each successive score as an increased presence of risk factors, and needs of action. The readers may refer to Sonne et al. (2012) for details of the risk factors and scoring of strain, as briefly presented herewith (Table 5.2). The stated risk factors of computer operators in office work are further elucidated in Chap. 6.

The checklists-based cross-sectional investigation is a straightforward approach to analyse jobs in computer work (e.g., Nordic questionnaire, Kuorinka et al. 1987). One such work analysis methodology, namely Multi-Method Ergonomics Review Technique (MMERT) , may be utilized (Nag 1998) for the cross-sectional survey at office complexes and to elucidate the aspects of ergonomics work design (Nag and Nag 2004). The framework of the checkpoints consists of 20 modules (Table 5.3). These have been applied for apportionment of work stressors in different workplace applications, such as computer-based telecom services (Nag et al. 2005), weaving (Nag et al. 2010), and fish processing industry (Nag et al. 2012). The structure of the modules consists of primary and secondary statements/checkpoints that took account of multiple responses to one or more questions.

Table 5.2 Scoring and risk factors listed in Rapid Office Strain Assessment (adapted from Sonne et al. 2012)

Seat pan height 	Knees at 90° (1)	Too low—knee angle < 90° (2)	Too high—knee angle > 90° (2)	No foot contact on the ground (3)	Insufficient space under the desk—ability to cross legs (+1)	Non-adjustable (+1)
Seat pan depth 	Approximately 8 cm of space between knee and edge of the seat (1)	Too long—less than 8 cm of space (2)	Too short—more than 8 cm of space (2)			Non-adjustable (+1)
Armrest 	Elbows supported in line with the shoulder—shoulders relaxed (1)	Too high (shoulders shrugged)/low (arms unsupported) (2)	Hard/damaged surface (+1)	Too wide (+1)		Non-adjustable (+1)
Back support 	Adequate lumbar support—chair reclined between 95 and 110° (1)	No lumbar support or lumbar support not positioned in small of back (2)	Angled too far back (greater than 110) or angled too far forward (less than 95°) (2)	No back support (i.e., stool or worker leaning forward) (2)	Work surface too high (shoulders shrugged) (+1)	Back support non-adjustable (+1)
Monitor 	Arm's length distance (40–75 cm)/screen at eye level (1)	Too low (30° below eye level) (2) Too far (+1)	Too high (neck extension) (3)	Neck twisted (+1)	Glare on screen (+1)	Documents—no holder but required (+1)

(continued)

Table 5.2 (continued)

Seat pan height 	Knees at 90° (1)	Too low—knee angle < 90° (2)	Too high—knee angle > 90° (2)	No foot contact on the ground (3)	Insufficient space under the desk—ability to cross legs (+1)	Non-adjustable (+1)
Keyboard 	Wrists straight, shoulders relaxed (1)	Wrists extended/ keyboard on a positive angle (>15° wrist extension) (2)	Hand deviation while typing (+1)	Keyboard too high —shoulders shrugged (+1)	Reaching to overhead items (+1)	Platform non-adjustable (+1)
Mouse 	Mouse in line with the shoulder (1)	Reaching to mouse (2)	Mouse/keyboard on different surfaces (+2)	Pinch grip on the mouse (+1)		Palm rest in front of the mouse (+1)
Telephone 	Headset/one hand on phone and neutral neck posture (1)	Too far off reach (outside of 30 cm) (2)	Neck and shoulder hold (+2)			No hands—free options (+1)

Table 5.3 Survey checkpoints administered to the VDT operators

Section	Details of checkpoints
Job specialization	Specific job, tools and methods, production, quality of work, multiple tasks
Job skill	Skill requirement, mistakes, job rotation, machine-paced work
Physical work, shift work	Work target, repetition, night shift, overtime, uneven work pressure, predetermined pace, work–rest pattern
Work posture	Arm stretch, wrist deviation, neck, and shoulder angle, back bent and twisting, hips and legs support, body movement
Workplace design	Work distance, work desk height, body and thigh clearance, shoulder and arm alignment, desk surface, keyboard tray, leg room, placement of accessories, storage space, entrance/exit
Seating arrangement	Chair height, the spacing of seat pan, back support, backrest curvature, upholstery, arm and footrest, knee movement
Pointing device	Placement of keyboard and keying, wrist pad, keyboard drawer, document holder, mouse, trackball
Monitor	Position and placement, neck position, visual distance, screen contrast, glare
Eyewear	Head adjustment, visual distance
Lighting	Illumination, light intensity, and source, reflective surface, diffuser
Noise	Noise and annoyance, sound isolation, emergence measures
Climate	Ambiance, ventilation, drinking fountain
Exercise	Intermittent task, rest break, exercises
Task variety	Start/finish time, organizational support, number of staff, work method/condition
Autonomy	Participation, work constraints, communication, attention, acknowledgement of job performance
Feedback	Job roles and goals, person–machine relationship, stimulation, boredom, job enlargement
Task significance	Task planning, significance, recognition
Mental load	Information load, attention to other information, software/screen orientation, risk judgment
Training	Periodic training, incentives
Organization	The organizational role, feeling of tightness, medical and administrative services, OSH management, inspection, and monitoring

The MMERT application is further illustrated about the work analysis in telecom exchanges (Nag et al. 2006). The VDT operators (N = 315) belonged to different work groups, e.g., call centre, data entry, customer care, office work, and fault repair. The principal component analysis (PCA) allowed clustering the work stressors into five principal components (Table 5.4), showing different work stressors to different work patterns. The work stressors, including physical interfaces, such as the VDT devices, workplace design, and other workplace stressors, appeared to reflect on the incidences of MSD. The lower back complaints and upper back and shoulder discomfort were reported by about 45 and 33% of the operators,

Table 5.4 Principal component analysis of work stressors of VDT telecom workers

	PC 1	PC 2	PC 3	PC 4	PC 5
Call centre	Variance exp (21.1%)	Variance exp (20.1%)	Variance exp (10.7%)	Variance exp (7.7%)	Variance exp (6.6%)
	Training and recognition Job feedback Monitor Task variety Organizational issues Lighting	Keyboard and pointing devices Workplace design Job autonomy Physical activity and shift work Mental load	Corrective eyewear Noise and annoyance Task significance Climate	Job specialization Job-related exercise	Skill requirement Work posture
Data entry	Variance exp (16.4%)	Variance exp (15.6%)	Variance exp (12.9%)	Variance exp (9.5%)	Variance exp (8.1%)
	Workplace design Job autonomy Job feedback Lighting Monitor Job-related exercise	Mental load Organizational issues Training and recognition Corrective eyewear Physical activity and shift work Noise and annoyance	Climate Keyboard and pointing devices Work posture	Task significance Skill requirement Task variety	Job specialization
Customer care	Variance exp (17.5%)	Variance exp (15.9%)	Variance exp (13.2%)	Variance exp (11.7%)	Variance exp (11.5%)
	Keyboard and pointing devices Skill requirement Job-related exercise Climate	Training and recognition Organizational issues Corrective eyewear Physical activity and shift work	Monitor Job specialization Work posture Noise and annoyance	Mental load Job autonomy Job feedback	Task significance Lighting Task variety Workplace design
Office work	Variance exp (23.6%)	Variance exp (16.3%)	Variance exp (14.9%)	Variance exp (13.7%)	Variance exp (10.9%)
	Skill requirement Noise and annoyance Mental load Corrective eyewear Monitor Job feedback	Task significance Climate Physical activity and shift work Workplace design Lighting	Organizational issues Job autonomy Job specialization	Job-related exercise Keyboard and pointing devices Work posture Training and recognition	Task variety

(continued)

Table 5.4 (continued)

	PC 1	PC 2	PC 3	PC 4	PC 5
Fault repair	Variance exp (18.7%)	Variance exp (17.9%)	Variance exp (17.4%)	Variance exp (15.4%)	Variance exp (11.4%)
	Mental load Climate Job specialization Noise and annoyance	Skill requirement Task variety Lighting Training and recognition Work posture	Monitor Task significance Keyboard and pointing devices Physical activity and shift work	Job autonomy Workplace design Job feedback Organizational issues	Corrective eyewear Job-related exercise

respectively. Nearly 8% of the computer operators developed severe spinal cord-related problems. Visual problems such as a headache, eye strain, and irritation were among the most frequently reported complaints by the operators. Apart from the concerns of physical interfaces, there was obvious importance to the human–computer interaction environment and significantly to the shift schedules of work (Nag and Nag 2004). The modification in the work habit and the design of workplace and workspace were clear priorities to reduce postural stresses among the operators, irrespective of the type of work concerned.

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Chapter 6
Ergonomics of Computer Workstation

Introduction

A vast number of people in offices and other places of work have been compelled to, or increasingly constrained to remain seated in a chair–desk complex (Clemes et al. 2014). Anthropometric dimensions vary across the population, and therefore, one workstation/desk or one chair does not fit everyone. Selection of workstation layouts (Fig. 6.1) calls for population-specific optimal dimensions and adjustability, for people to effectively perform work. Due to compulsive office organization, the workstations may look exactly alike, and the employees forced to get adjusted to their workstations. There are several options of adjustability, i.e., the workstation may have a regular work desk and an adjustable or separate space for the computer monitor, the keyboard and mouse, and other accessories. The way the workstations are organized for computer, and other office equipment influences the employee's orientation to body position.

In a workstation, each person tends to develop unique postural dynamics relating to one's physiology, habits, the product use, and the circumstances of sitting. Sitting is a body position in which the weight of the body is transferred to supporting areas primarily by the ischial tuberosity (seat bone) of the pelvis and their surrounding soft tissue. The concentration of forces acting on intervertebral structures, ligaments, and link joints are the critical issues of their susceptibility to damage. There is no single ideal sitting posture since the resultant posture is influenced by height and slope of the seat pan of a chair, shape, and inclination of the backrest, and the presence of armrest and footrest. How we sit and what we sit on exert a load on the musculoskeletal and spinal structures. In turn, it carries the risk of spinal and paraspinal discomfort, including joint impairments (arthritis), inflammation of tendons and tendon sheaths, chronic muscle pain and joint degeneration (arthroses). Prolonged sitting in one position causes local build-up of pressures and interrupts blood flow in proportion to the load acting on the muscles. Leg swelling (oedema), more prevalent among women, is associated with the lack

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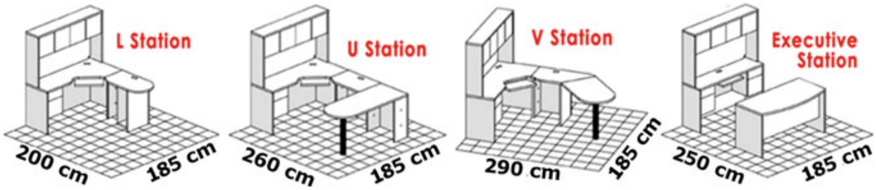

Fig. 6.1 Common forms of workstation layouts in the offices

of movement. Long hours of the seated position can cause local pooling of the blood, thus increase venous pressure to the heart, and in turn, are at risk of peripheral venous disorders, such as bilateral or unilateral oedema, varicose veins, deep venous thrombosis (Scarvelis and Wells 2006). From a study on continuous rotary seat pan movements, Van Deursen et al. (2000) observed that seated persons even in prolonged sitting experience much less oedema than inactive sitters. The user-seat dynamics has been evaluated using a multitude of approaches, e.g., anthropometric (human size compatibility), biomechanical, electromyographic (Chiari et al. 2002; Rocchi et al. 2004) and stabilometric analysis (Nag et al. 2008), comfort rating (Helander and Zhang 1997) and materials' construction. Herewith, the discussion covers biomechanics of sitting, analysis of sitting modes and seated features, chair–desk complex, ergonomics aspects of seat design, and also, human-seat interface analysis.

Biomechanics of Sitting

There are primary and secondary variations in sitting postures. The focus has been placed on the lumbar spine, which is usually lordotic (concave, towards the stomach). The rotation of the pelvis affects lumbar vertebrae and overall deviation in the posture. Hamstring muscles that cross from lower leg to pelvis, the hip and knee joints influence sitting posture and configuration of the lumbar spine. The neutral body posture in space assumes the thigh–torso angle of about 125–130° (Leivseth and Drerup 1997). In chair sitting, the thigh–torso angle at $\sim 110°$, to a great extent reinstate the natural lordotic curve of the lumbar spine. Illustration (Fig. 6.2) includes three broad patterns of pelvis rotation, referred to as (a) anterior forwards rotation, (b) middle relaxed position and (c) backwards posterior rotation.

For chair–desk complex, there is a likelihood of postural variations, influenced by the sitting habits and preferences (Fig. 6.3). The centre of gravity (CG) is as depicted by a "*" about the location of the seat bone. Seated variations about chair–desk complex (Fig. 6.4) have an indirect influence on the spinal curvature.

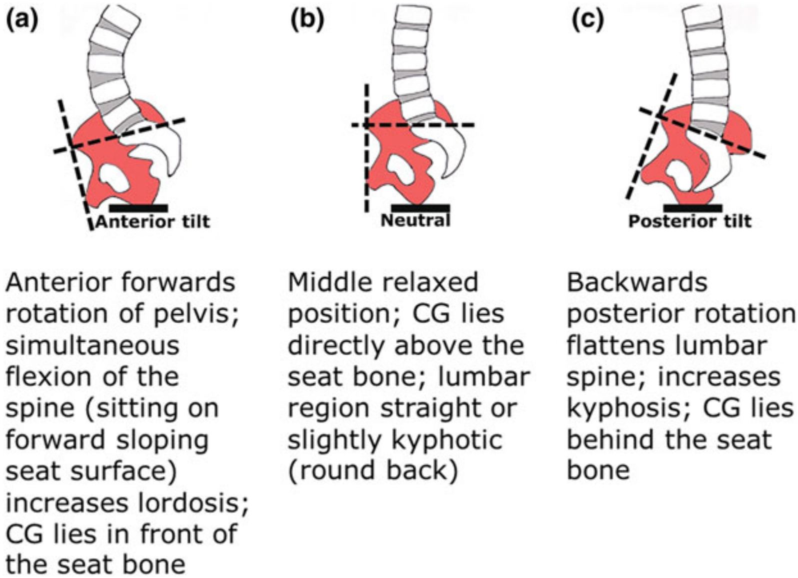

Fig. 6.2 Pelvis motion (lateral view) during sitting

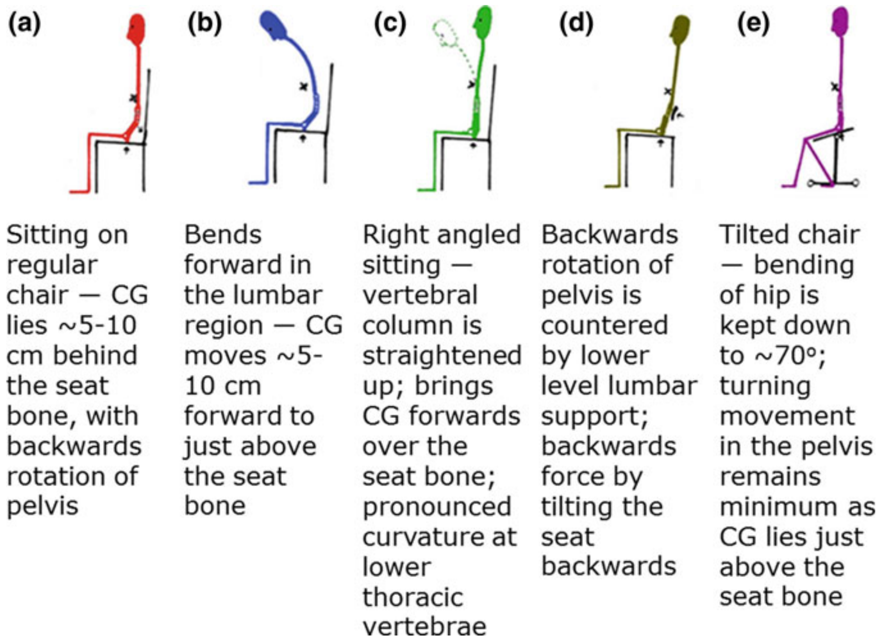

Fig. 6.3 Seated variations in chair–desk complex, influenced by the sitting habits and preferences

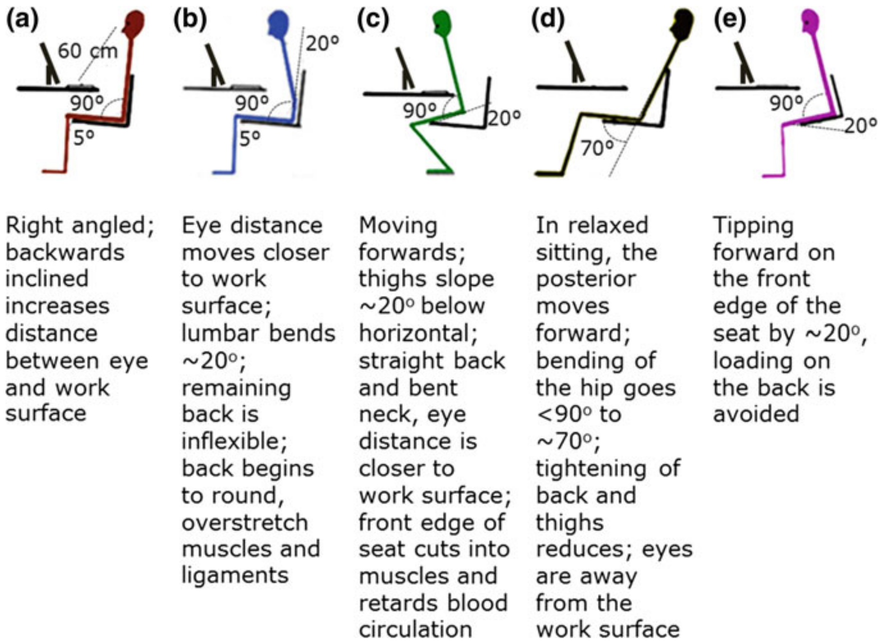

Fig. 6.4 Seated variations about chair–desk complex

Kinematics: Sitting Posture

The primary focus is on the lumbar spine and associated flexion at the hips and rotation of the pelvis, in adopting a sitting posture. The angle of the lumbar spine depends on the kinematics of both lower and upper limbs (Keegan 1953). Hip flexion appears to have a more significant impact on lumbar lordosis than those at the knee (Eklund and Liew 1991). Using MRI study, Alexander et al. (2007) documented the rotation of the pelvis and flattening of the lumbar spine in a regular chair sitting. There was a decrease in lumbar lordosis angle of $\sim 40°$ in sitting, as compared to standing. The posterior migration of the nucleus pulposus was also noted during sitting.

It appears that gender differences exist in seated low back posture, i.e., women tend to adopt a more upright trunk posture in a chair sitting than men. Beach et al. (2008) observed lumbar flexion angles of about 55–60% of maximum flexion in office chairs and automobile seats for males, whereas lumbar flexion angles in females had about 45% in office chairs and 59% in automobile seats. Literature is not conclusive to indicate any age-related influence on lumbar lordosis angle (Been and Kalichman 2014; Youdas et al. 2006). However, Lee et al. (2014) observed that older individuals develop a more lumbar lordosis in the supine, 60° and 90° sitting postures.

Sustained flexed low back posture has been linked to a variety of negative consequences, such as increased disc pressure (Wilke et al. 1999), altered muscle control (Mörl and Bradl 2013), pain and injury (Pope et al. 2002). With the decreased postural control and proprioception (O'Sullivan et al. 2003), the affected sitter may adopt a more flexed lumbar spine and posterior rotation of the pelvis (Dankaerts et al. 2006). As mentioned, adopting a posture is greatly influenced by the habit and circumstances. Therefore, even a pain-free individual may adopt a posture with more flexed lumbar spine and consider ideal or more neutral (O'Sullivan et al. 2010). Also, the type and extent of movement in sitting differ between populations. Dunk and Callaghan (2010) suggested that people with low back pain had a more significant shift movement during prolonged sitting. In general, however, the females make more frequent shifts of position, than males (Rohlmann et al. 2014).

Kinetics: Stress and Strain in the Spine

The intervertebral discs of the human spine undergo both compressive and shear loading, depending on the postural orientation, and supported and unsupported sitting (Callaghan and McGill 2001a, b). While the compressive load in sitting posture may be about one-fourth of the intra-discal (L4/L5) breaking point, the biomechanical analysis does indicate that postural variations in different chair sitting modes exert a load on the spine differently (McGill 2004; Jans et al. 2007). Sitting modes and seated features (e.g., components of chair design) have direct implication in raising or reducing spinal load and injury risks in sitting. Rohlmann et al. (2001) measured loads on an implant spinal fixation device during sitting in the stool, standard chair, office chair, exercise ball, knee stool, stool with a padded wedge angled (9.5°). The investigators observed that different seat types had minimal effect on implant loads. However, the upright sitting caused about 11% increase in loads compared to slumped posture.

However, low-level impacts (e.g., constrained posture due to sitting habits and circumstances) over long-term are potent stressors to cause degenerative spinal changes. Several factors, such as increased disc pressure, static spinal loading, the strain on muscles and passive tissues, have been implicated as potential sources of pain and spinal injury. In the first place, prolonged sitting reduces blood flow to the lumbar muscles, resulting in accumulation of metabolic waste products, and generating pain from the postural muscles. Prolonged flexion of the lumbar spine can induce creep in viscoelastic passive and active tissues, including ligaments, disc, and joint capsule. The resulting creep deformation of the ligamentous structures and intervertebral discs causes increased laxity in the joint, with associated pain (Sánchez-Zuriaga et al. 2010; Adams and Dolan 2005). Besides, muscle spasm and delayed ligamento-muscular reflexes in the lumbar spine, (Solomonow et al. 2003a, b) are the other likely physiological mechanisms to alter muscle activation reflexes and impair muscles in stabilizing the spine. Rest allows the creep and laxity in the viscoelastic tissues to recover and restore the reflexive muscular activity (Gedalia et al. 1999). However, the duration of rest for recovery may depend on the nature of loading (point of application and direction) of the spine.

Ergonomics in Seat Design

Ergo-design of an office chair helps to maintain good posture in sitting. The first office chair, known as the typewriter's chair, was introduced in 1902. Since then, various forms and construct of the office chairs have found its place with aesthetic and brand value consideration to organizations (Pynt 2015). On a broader implication, the usefulness of seat design lies in (a) the comfort, stability, and balance to body orientation, (b) minimal stress on lower extremities, and (c) backrest, lumbar support, and armrest to better distribute body loads. Primarily, ergo-design of an office chair involves establishing the type of work to be performed and related anthropometric compatibility matching to the percentile distribution of anthropometric dimensions of the user population (Fig. 6.5). A brief description of the dimensions (Table 6.1) may be useful in selection of the chairs. However, dimensions vary with the user population groups that may be appropriately considered.

Mostly, a chair design for office use (Fig. 6.6) has the following features:

- *Seat height* allows the user to place the feet firmly on the floor or a supportive footrest. The seat height so adjusted that the hips and knees are at a 90° angle when sitting; that is, one may stand in front of the chair, and the seat edge should touch right behind the knees. The minimum height should be based on the 5th percentile value of the popliteal height of women and a correction for the

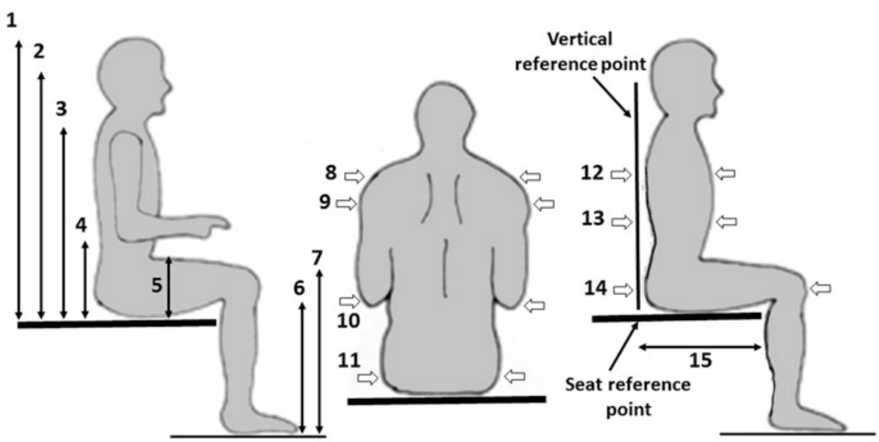

Fig. 6.5 Anthropometric dimensions in relation to chair design

Table 6.1 Anthropometric dimensions

1 plus 6	Sitting height	The vertical distance from the floor to the horizontal midpoint of the head; person sitting upright and barefoot flat on the floor; the back of the thigh is in contact with the backrest; the popliteal fold 2–3 cm above the seat pan and knee flexed at 90°
2 plus 6	Eye height	The vertical distance from the level of the floor to the horizontal eye level, when seated and the back straight
3 plus 6	Shoulder height	The vertical distance from the floor to the superior aspect of the acromial process
4	Elbow height	The vertical distance between the seat pan and the tip of the olecranon, when the arm is flexed to 90° at the elbow and shoulder relaxed
5	Thigh height	Vertical height from the seat surface to the highest part of the thigh
6	Seat pan height	Vertical height between the floor and seat pan
7	Patellar height	Vertical height between the floor and superior tip of the patella
8	Shoulder width (bi-acromial breadth)	The maximum transverse distance at the shoulders
9	Upper arm width (bi-deltoid breadth)	The maximum transverse distance at the upper arms
10	External elbow width	The maximum transverse distance between the tips of the olecranon, with the arms abducted
11	Buttock width (sitting breadth)	The maximum transverse distance at the buttocks
12	Chest depth (buttock–chest)	Sagittal distance from the anterior chest wall to the posterior of the buttock
13	Abdominal depth (buttock–abdomen)	The sagittal distance between the anterior abdominal wall to the posterior part of the buttock
14	Sitting depth (external) (buttock–patella)	The sagittal distance between the anterior aspect of the knee to the posterior of the buttock
15	Sitting depth (internal) (Buttock–popliteal)	The sagittal distance between the posterior aspect of the popliteal fold to the posterior of the buttock

average heel height. With a too high seat, height can cause increased pressure on the underside of knees and decreased blood flow. When the height is too low, load falls on the ischial tuberosities increases.

- *Seat pan depth* (~38–43 cm) maintains contact with the backrest in the lumbar area. For a seat depth higher than the buttock-popliteal length (5th percentile value for a woman), a sitter cannot suitably use the backrest. Horizontal adjustment of the backrest permits to reach the effective seat pan depth. A positive seat pan angle (5–10°) helps the user to maintain good contact with backrest. Tilting seat pans facilitate a more neutral low back postures (Grondin et al. 2013; McGill and Fenwick 2009). A *waterfall* or rounded front edge of the seat pan can minimize pressure on the back of the legs.

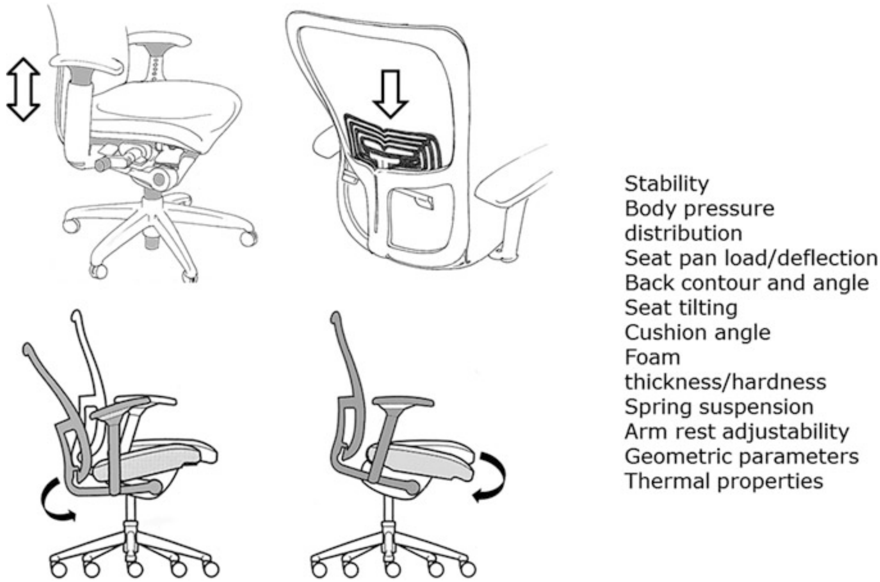

Fig. 6.6 Features of chair design for office use

- *Seat pan* contouring is used to distribute pressure over a larger area and to allow smooth shifting of position. Over two-fifth of the body weight is supported at the seat pan, and if the seat is hard and flat, the load distribution can be higher. Seat cushioning ($\sim$3–4 cm), i.e., making it firmer and thicker at the back, and less firm and thinner at the front half, or softer top layer and firmer bottom layer helps for better distribution of body weight on the seat pan. Too much cushioning that causes the body to sink into the seat retards blood circulation and increases compression under thighs. The cushion compressibility expressed as indentation load deflection can be about 25% for the soft top layer and about 65% for the firm bottom layer, with a ratio higher than 2.6 is ideal for better quality support.
- *Backrest* stabilizes posture by freeing shoulder space for retraction of the shoulder blades, reduce muscle activity and low back flexion (Callaghan 2006). The weight of the torso shifts back against the backrest, and the angle between torso and the legs increases. The backrest of a chair has three categories: as low, medium and high levels. That is, the low-level backrest supports the lumbar region; medium-level backrest supports full shoulder, having $\sim$60 cm high (e.g., regular purpose office chairs), and the high-level backrest, about $\sim$90 cm high, provides full support to head and neck (e.g., executive chairs). These dimensions may accommodate 95th percentile man. The spring-tensioned

reclining backrest should be adjustable to suit user needs. The backrest can have a width of 36–48 cm. There may be the curved surface of the backrest or multiple zones of the backrest for proper adjustment. The tilt angle of the backrest may be fixed (103° ± 1°) or adjustable (95–110°).

Research shows that lumbar support imparts extension to the low back and reduces muscle activity (De Carvalho and Callaghan 2012; Grondin et al. 2013). Bendix (1996) viewed that facilitation of lumbar lordosis by a backrest may not be true, and on the other hand, it might increase kyphosis with the support of the lower back. Dolan and Adams (2001) noted that in a prolonged sitting, as in case of an intensive computer user, one may tend to slump against the backrest, locking in the pelvis and causing them to reverse the lumbar curve. Such situations may lead to increased disc pressure, stretching of muscles and ligaments and increased wedging at the forward edges of the discs. In exploring the extent that lumbar supports (backrest) can reduce intra-discal loads, Brodeur and Reynolds (1990) used cadavers to analyse the vertebral motions and observed that the lumbar curve was minimally affected by the lumbar support. Instead, it results from the position of the thorax relative to the pelvis, and its' impact on the pelvic angle.

- *Chair armrest* is the component that provides lower arm support and aid in standing up and sitting down. Adjustable armrests (in horizontal and vertical planes) are recommended for correcting the elbow angle (~90°) concerning the work surface and keyboard operation. The horizontal distance between the right and left armrests should exceed 95th percentile value of thigh breadth of women; primarily, this distance determines the seat width to accommodate clothed persons. Importantly, the armrests should not limit chair access in a chair–desk complex. The armrest should be at 20–25 cm above the seat pan, with a gap of about 10 cm between the armrest and the edge of the backrest. Wider armrest avoids pressuring the elbow and supports well the fleshy part of the forearm.
- *Five-pronged chair base* with casters allows easier mobility to raise oneself from a seated position and reduce twisting stresses on the spine. The selection of casters corresponds to the floor surface, such as hard casters for soft floors or soft casters for hard floors.
- *Chair mechanism* placed underneath the seat regulates the chair for the user to push, pull or twist. Different chair tilting mechanisms (Fig. 6.7) have been introduced for seat adjustability, such as permanent contact, front or centre pivot, forward tilt, synchro, dynamic and zero gravity seat mechanism. The multifunction mechanism (multi-lock levers, backrest and knee tilt, and synchronization) is most prevalent for a wide selection of adjustability. The synchro-tilt mechanism allows coupled tilting of backrest and seat pan, which can be both centre pivoted and front-pivoted. Dynamic kind of mechanism is widespread; once one reclines, the seat can move forward and down. Lengsfeld et al. (2000a, b) reported that a dynamic seat allowed the seat pan to tilt forward and facilitate some degree of recline to increase lumbar lordosis. This effect was

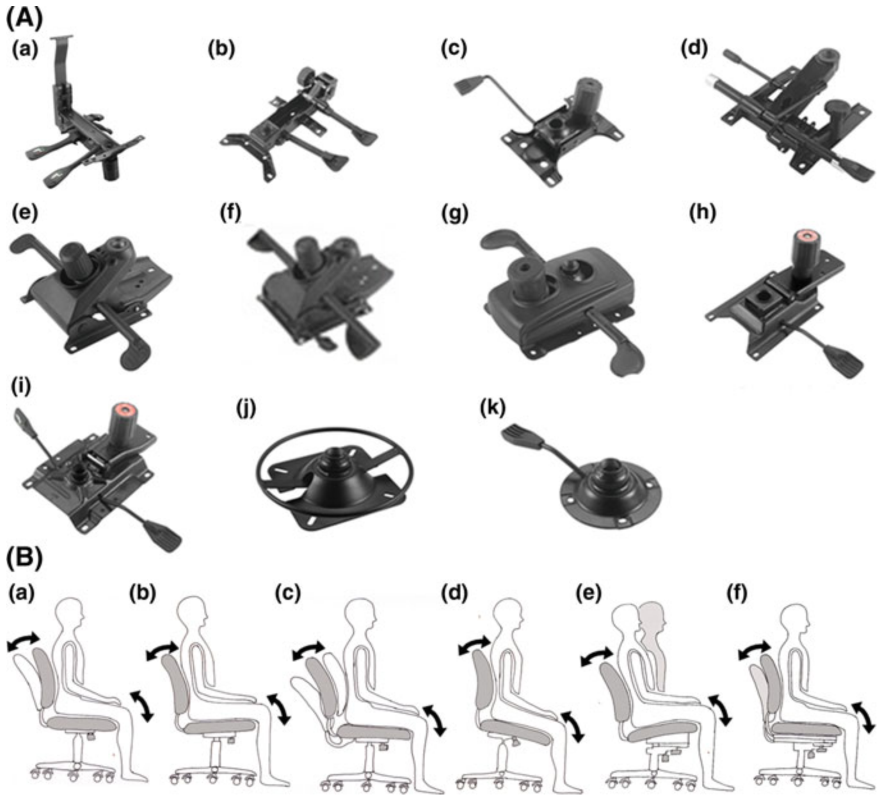

Fig. 6.7 **A** Hardware of chair pivot tilting mechanisms, and **B** Seat–backrest tilt adjustments: **a** Back angle, **b** Tilt lock, **c** Tilt tension, **d** Back–seat tilt, **e** Centre tilt, **f** Synchro tilt

superior to a synchro chair that tilted the seat pan back as the backrest reclined. The knee-tilt mechanism allows tilt from just below the knee. However, it usually does not embody seat depth adjustment. The back tilt tension adjustment permits the sitter to regulate the force needed to recline according to one's body weight.

For the office goers, interventions aiming at reducing stress and strain at the lumbar spine can minimize or mitigate the risks of pain and injury. Therefore, making office workers or computer users aware of the ergonomics may help in their perceived comfort concerning various workplace and workstation features (Amick III et al. 2012). Mueller and Hassenzahl (2010) explored user comfort ratings of office chairs in a field study when the users were not instructed on the seat features that can improve comfort, and as a result, the users rated ergonomically superior chairs lower than chairs with inferior features. Conducting a cluster randomized controlled trial among computer users on the provision of ergonomics training in reducing MSD, Mahmud et al. (2011) found a significant improvement in workstation habits. The differences remained significant at the follow-up time for keyboard, mouse, chair and desk use. Consistent reductions in all MSDs were noted at the follow-up time point. These improvements, however, did not translate into the reduction in loss of work days or any improvement in psychological well-being.

Balans Chairs

For office sitting activities, a backrest angle beyond 90° is an inherent limitation for better contact of the thoracic support, simultaneous to adjustment in seat pan tilt. Design constraint exists in chair mechanism that can allow making use of backrest support coupled with the 10° tilt in the seat pan. As alternatives to the traditional office chairs, newer Balans group of chairs, kneeling, saddle, exercise ball chairs, generated interest among the professionals of its utility in creating good support and promoting comfort. Some observations of researchers (McGill et al. 2006; Kingma and van Dieen 2009) suggest that sitting on an exercise ball results in higher spinal shrinkage, trunk muscle activation, and pain.

The Balans chairs (Fig. 6.8) are the tipping forwards or the forward sloping seats (Mandal 1985). Forward sloping, knee rest chair with no backrest improves reach, facilitates rising from a chair and prevents leg oedema by facilitating leg movability. Colombini et al. (1985) documented the benefits of the design feature as lower back muscle activity (with a 20° forward tilt) and intra-discal pressures. The proponents of forward tilting seat maintained that such sitting positions reinstate

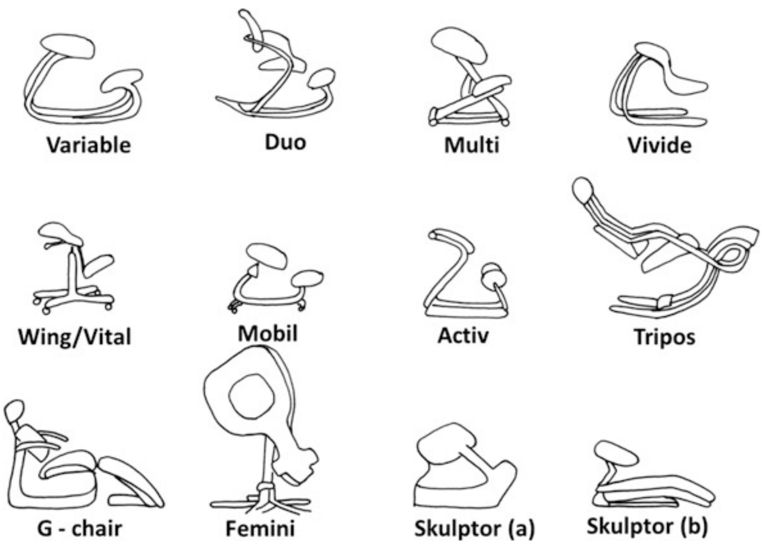

Fig. 6.8 Balans group of chairs (alternative designs)

lumbar lordosis by tilting the pelvis (Frey and Tecklin 1986; Link et al. 1990). The sitter may be least kyphotic in the lumbar area and opposite in the upper torso when sitting at forward sloping seats. However, increased load on the lumbar spine (Ericson and Goldie 1989), and potential balance issues, such as sliding forward on the seat pan and loading of the feet (Bendix et al. 1985; Shenoy and Aruin 2007) outweigh any benefits of the in knee-rest chair designs.

Human–Seat–Desk Interface (HSDI) Analysis

Apart from understanding and design of different features of the seat, the emphasis remains to systematically explore the core issues of compatibility of chair–desk complex, and health and safety concerns of the sitters. The office going population, including computer professional groups amassing in a proportion, are at high risk of MSD and spinal injuries, in spite of their sedentary nature of activity in a chair–desk complex. Besides elucidating the related aspects in recognizing the goodness or badness of the seated features, it is very much warranted to understand the influence of the characteristics of the sitter and sitting modes, concerning body oscillation, postural stability, and stress and strain of upper and lower back, and other body segments. In other words, the HSDI analysis and understanding of the amount of body weight distributed to the components of seat bear significance in evaluating the design and functional consequences for persons using the seat.

A simulated seat–desk system is described herewith (Fig. 6.9) that included an adjustable chair–desk complex, comprising of two piezoelectric force platform (Kistler, Switzerland). One force platform was placed at the height of a chair seat pan, stabled and vertically adjusted by a heavy-duty mechanical jacking mechanism, and the other platform placed horizontally on the floor surface, served as a footrest (Nag et al. 2008). The simulated chair included a seat pan with back inclinations at 75, 80, 90, 95, 105 and 115°, and without and with armrests at 62, 64, 66 and 68 cm height. The chair could be adjusted for forward and backward sloping of the seat pan by 5°, supported and unsupported back, and seated hip position at upline or downline. The work desk had two separate surfaces, and each was adjustable for placing monitor at different heights, and another surface was adjusted for placing the keyboard and pointing devices. The simulated chair set-up was unattached to the seat pan placed on the force platform, thus making possible to study the influence of seat features, regarding sitting modes, sitting orientation, armrest, back reclines, and influence of different work desk and VDT components, such as a monitor, keyboard/mouse placement.

Electromyography—The experimental set up included a multichannel electromyographic (EMG) machine for recording the EMG activity of forearm and back muscles during VDT tasks, such as text or data entry, and graphics. Since the seated VDT work is not a burdensome task, the reference muscle activation was recorded every 30 s at a reference position of seated upright with the arms at right angled at the elbow.

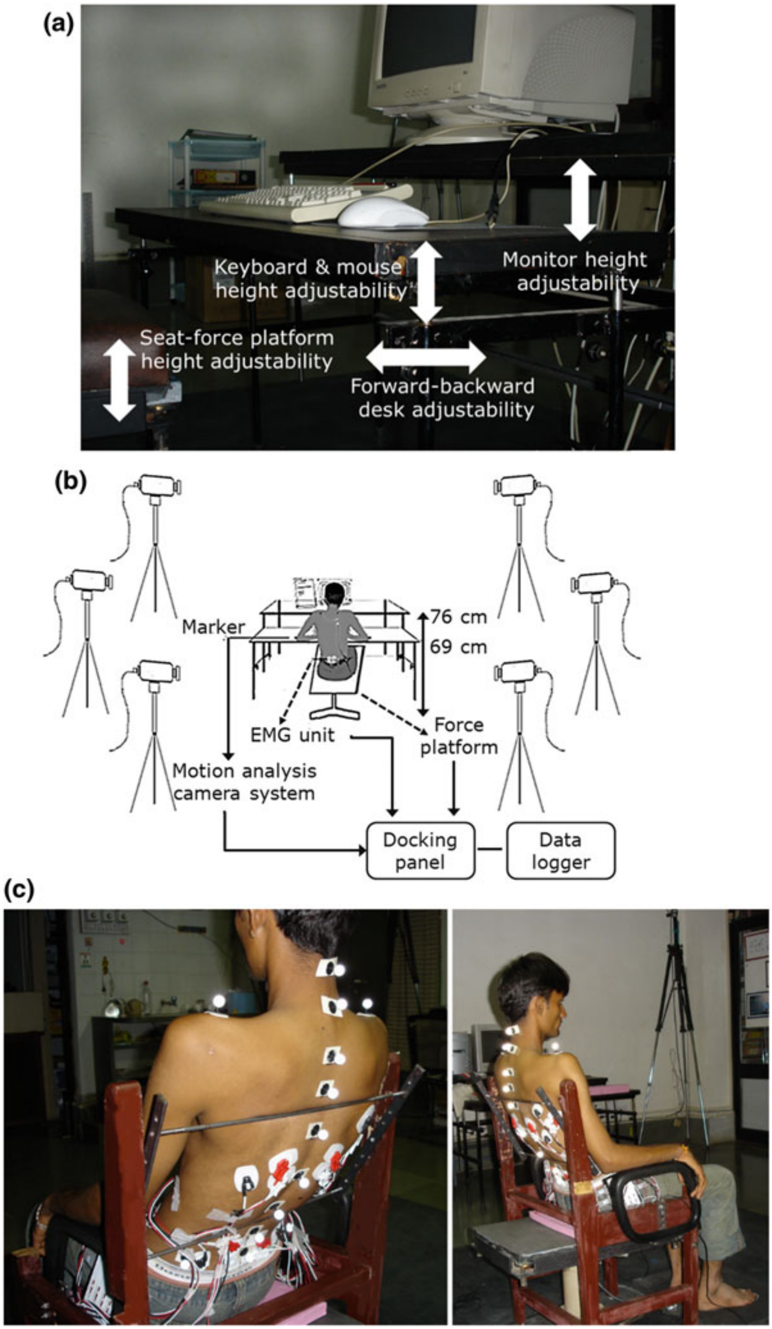

Fig. 6.9 An experimental seat–desk system to make multiple adjustments of the chair–desk–keyboard complex; **a** seat–desk adjustability, **b** human motion analysis camera system, **c** volunteer in the experimental setup

The quantitative analysis of EMG requires recognizing activity patterns in terms of signal amplitude as well as the embedded frequency contents, due to the type of muscle fibres involved and its nature of activation over time. The muscle activities are conventionally analysed concerning timing and amplitude characteristics, as well as analysing the frequency contents (spectral density) using fast Fourier transforms (FFT) or short-time windowed Fourier transform (STFT). The force/EMG signal relationship and the power spectral density signal provide amplitude and frequency representation of EMG signal. In conventional FFT analysis, and also in case of STFT, the EMG signal windows become static, and the dynamic components are virtually lost over time. The time–frequency representation (continuous wavelets transformation, WT) has been used to characterize the EMG activity pattern, in which rapidly varying high-frequency components are superimposed on slowly varying low-frequency components. The mathematical procedure in WT adopts a prototype function, called as analysing wavelet or mother wavelet, and the wavelets analysis of the EMG signals may be performed, using MATLAB open-source toolbox on signal processing.

Motion analysis—A 3D motion analysis of six infrared camera system (Elite plus, SMART, BTS Engineering, Italy) recorded tracking of movements of the reflected markers placed at different anatomical landmarks of the wrist, elbow, shoulder and along the vertebral column, and measured the joint angles. Data acquisitions were sampled at 100 Hz. The continuously recorded angle measurements were further processed in a computer routine to obtain different joint angles between segments, and deviations along the spinal curve from C7 to the lumbar region.

Stabilometry (centre of pressure displacement)—The stabilometry is an approach for postural stability analysis in seating research. It recognizes that the upper body including a part of the upper leg is supported by the seat pan, backrest, and the armrest, and the lower leg and a part of the upper leg are supported at the floor surface. Reducing the load on the seat, by transferring the load to other support surfaces might reduce spinal and other musculoskeletal strains and enhance comfort to the sitter. The force platforms placed as the seat pan and as footplate allowed recording the displacement of the centre of pressure (CoP) of the body due to sitting in chair–desk complex. The platform recorded three counteracting forces along the three orthogonal axes—Fx, Fy, and Fz, and the three moments around the three axes—Mx, My, and Mz. The outputs of the forces and moments are commonly used to obtain the x- and y-coordinates of the CoP. The oscillation in x-direction corresponded to mediolateral (ML) time series and the movements in y-direction corresponded to anterio-posterior (AP) time series. These low-level body oscillations indicate the intricate mechanism of body balance and stability (Fenety et al. 2000; Chiari et al. 2002) during simulated computer work. The CoP parameters are the mean and range of AP and ML directions of CoP displacement, CoP trajectory length, the velocity of the CoP displacement, and radius of the stabilogram. Based on x- and y-coordinates of CoP displacement, and the polar star graph (based on distance and angle between the CoP points and the barycentre), CoP spread patterns are identified in different sitting modes, like ML, AP, centralized, diffused and multi-centric type of CoP displacements.

HSDI analysis: Body weight distribution—Analysis of the orthogonal force components recorded from the force platforms yielded quantification of the body force distribution to the components of the seat, including the seat pan, backrest, armrest, and footrest. Apart from the analysis of the CoP displacement characteristics, the resultant forces exerted on the platforms due to different modes of sitting were derived by weighting the three force components as:

$$Weight\,(kgf) = \frac{\sqrt{Fx^2 + Fy^2 + Fz^2}}{9.81}$$

The weight distribution at two platforms—feet level and seat pan, and the *deviation* derived as the difference in the estimated body weight to the total of forces at two platforms reflected the extent of body weight taken over by the components of seat features (Fig. 6.10).

- *Backrest at different inclinations*: analysis of unsupported and supported back inclines showed that in leaning forward at 75°–80° (i.e., back unsupported sitting), the load at seat pan was about 10% less than at 90° upright sitting. The load deviation increased with the increase in the height of the armrest. In forward-leaning posture; however, there might be a reduction in the angle between the torso and the legs, with a consequent reduction in lumbar lordosis and the associated increase in intra-discal pressures and ligamentous load (Dolan and Adams 2001). Back unsupported sitting may not be endured for long. Strong abdominal muscles can absorb part of the pressure in stabilizing posture. The posterior characteristics of the lumbar vertebrae may be adversely affected by reversing the lumbar curve (lumbar kyphosis), and prolonged

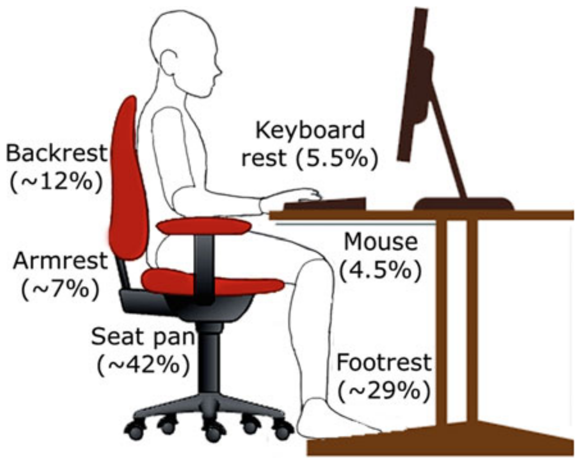

Fig. 6.10 Bodyweight distribution to the components of seat–desk features

compression of the facet joints may increase the risk of damage to the spine and joints.

By increasing the inclination of the backrest from 90 to 115°, it appeared that the load at seat decreased gradually, with a corresponding increase of load at feet. At an inclination beyond 95°, the load on seat decreased to about 8% at 115°. Analysis indicates that backrest helps to reduce load at the seat. The extent of load gets reduced from the seat might proportionately reduce stress on the spine (Nag et al. 2008) and relieve the amount of effort required to support against gravity (Makhsous et al. 2003).

- *Armrest—with and without backrest*: As a matter of fact, the armrest of a chair contributes to reducing load at the seat. HSDI analysis indicated that the load at seat pan was minimal (~60% of body weight) at 68 cm height of the armrest, and the load at feet was about 33% of body weight at different heights of the armrest. That is, the remaining 7% of the body weight was estimated to be transferred to the armrest. Depending on the anthropometrics of the chair users, the height of the armrest may be optimized at about 40% of the body height.
- *The slope of the seat pan*: There was a perception that forward seat positions shift the body weight to the lower extremities (Corlett 1999). However, the stabilometric analysis yielded that the load at seat pan was minimal at horizontal as well as 5° forward tilted seat pans and was maximum at 5° backward tilted seats, irrespective of unsupported or supported back at different inclinations (Nag et al. 2008). The load at seat pan was minimal in case of 90 and 115° back inclinations at 5° forward sloping of the seat pan, implying that the horizontal, as well as 5° forward tilted seat, might be the preferred choice, as against backward tilted seat. This observation strongly supports the proponents of forward sloping seats, regarding its utility to increase the thigh-to-torso angle.
- *Upright and slouch sitting*: With the demand of the task, the sitter might continue to move between upright and slump position of the back. In slumped forward sitting, the lumbar curve gets reversed from lordosis to kyphosis. When the back was maintained 90° upright, the load exerted at seat pan was about 6% higher, and the load at feet was about 13% less than in slouched back. This observation is a corollary to findings of Callaghan and Dunk (2002) that the slumped position causes less back muscle activation as compared to the upright sitting.

As far as the body weight distribution is concerned, in the backward tilted seat, the load on the seat pan was highest, and therefore, such postural position may be avoided by all sitters. On the other hand, the maintaining of the seat pan at the horizontal level might be beneficial to reduce the body load on the seat and the spine. The backrest has utility at inclination beyond 95–115°, with a significant reduction of load from the seat. For every 10° backrest incline from 95° onwards, an approximate 4% load was reduced at the seat. Overall, the backrest and armrest have conjoint influence in reducing the load at the seat, which in turn, might indicate mitigation of stress on the spinal and other paraspinal structures. The present may be useful for the designers to optimize chair design features for better distribution of body load to the components of the seat.

Placement of Desktop and Laptop Computers

Uses of laptop computers have advantages because of being lightweight and portable. These design features carry inherent ergonomics issues for moderate and intensive computer users. The design and construction of laptops violate the essential ergonomics requirement for computer users that the keyboard and screen cannot be positioned independently. With a fixed design of the laptop (e.g., the low position of the screen and flat design of the keyboard), postural compromises are unavoidable. Even contemporary laptop or notebook computer designs fail to satisfy the essential positioning requirement. The users must pay attention to how they use their laptop to avoid neck and shoulder complaints. Using a separate keyboard and mouse or getting a laptop docking station are the possible interventions. Several ergo-design products have been marketed, such as:

(a) keyboard and mouse tray that may be attached to the chair and position the desktop computers in maintaining neutral body position;
(b) laptop stand as an extension of an office chair; and
(c) laptop riser that allows tilting the laptop from a flat position, whereby a user can keep head up, and back and neck in a relaxed position.

The workstation should be sufficiently spaced to accommodate all sizes of computer monitors and other related accessories (Fig. 6.11). The flat screen monitors allow better space use and flexibility. The easily turnable monitor makes possible to place the device directly in front of the user and adjust the top of the screen at one's eye level. Too low monitor height, like in case laptop on a lap forces the neck to move forwards, whereas too high placement of monitor may tilt the head backward. The horizontal viewing distance should be about an arm's length, since improper viewing distance may be physically as well as visually fatiguing. Screen quality is an issue that has a discernible influence on user's viewing. The text characters on the screen should look sharp and of comfortable size. There are some uses of an anti-glare glass filter or an LCD (like a laptop screen). A computer operator who wears bifocals may tilt the head back to view the monitor through the bottom, close-vision part of the glasses. In such cases, a computer monitor can be lowered, whereby the head is in a neutral position for viewing. One may wear single-focus glasses with the focal distance chosen for the viewing distance between the sitter and the computer monitor. A document holder should also be positioned at the same viewing distance. Other options in selecting spectacles are graduated bifocals, trifocals, or the use of reverse bifocal lenses, as suitable for computer work.

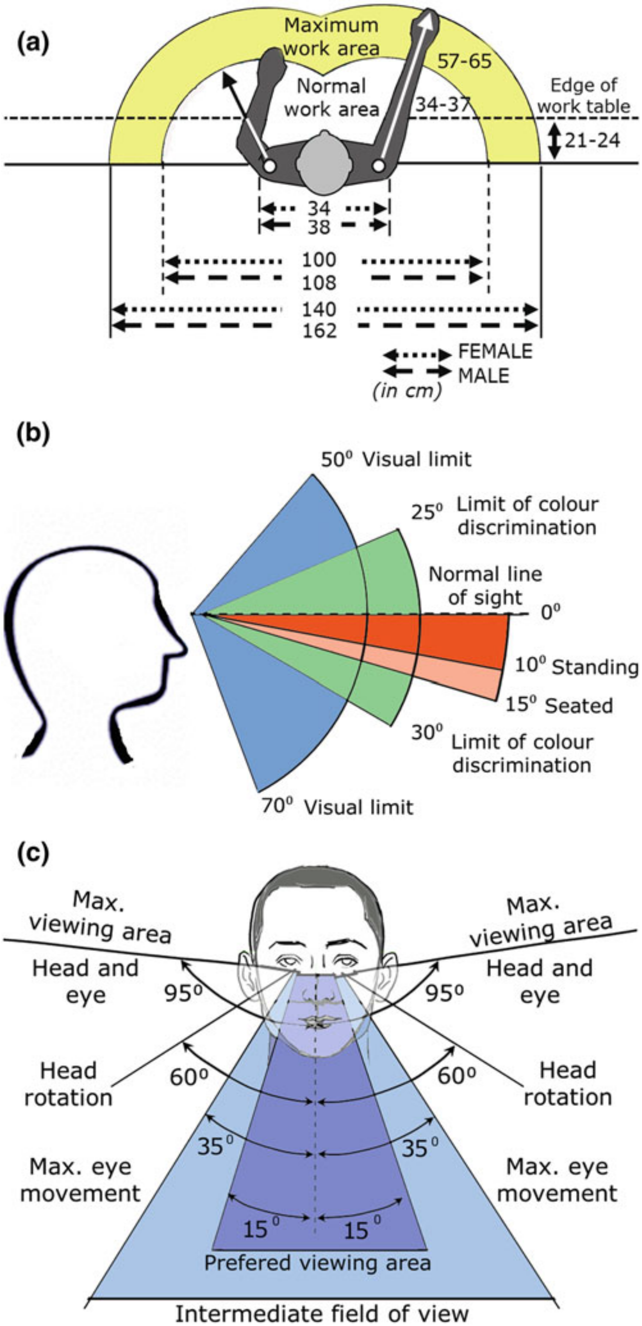

Fig. 6.11 Limits of **a** reach on the work surface, **b** vision in a vertical plane and **c** vision in the horizontal plane

Keyboard Design

The keyboard is the standard mode of data entry in computer application. The QWERTY typewriter layout was the remarkable discovery of Christopher Latham Sholes in 1868 (Liebowitz and Margolis 1990) and the standard layout consists of 101–104 keys, named after the home row sequence of letters that begins in the upper left corner of the keyboard. Computer keyboard includes a separate numeric keypad and other function keys. On ergonomics consideration of the keyboard users, the problem issues of the QWERTY design include forearm pronation, ulnar deviation, wrist extension, upper arm/shoulder abduction, and shoulder and hand/wrist discomfort. Recommended dimensions of keyboard components and position of the monitor are included in Table 6.2. Many alternative keyboard designs (Fig. 6.12), such as tented, supportive, scooped, split keyboard have been evolved with the premise to reduce muscular stress in keyboarding (Tittiranonda et al. 2000, 1999). Dvorak keyboard, an example of the alternative keyboard layout in which the most common letters are located at the home row. (Dvorak and Dealey 1936). The QWERTY keyboard layout has about 52% of usage on the top row, 32% on the middle row, and 16% of usage on the bottom row. Left hand does two-third of keying work. In Dvorak keyboard layout both hands do comparable work, and the distance of hand movement is significantly less since 70% of the keying is done on the middle row. The early development of split keyboard design (Klockenberg 1926) has undergone research refinement. Historically, the first split keyboard was used in a typewriter in 1886 (Louis Crandall, Syracuse, NY). Grandjean (1978) developed a split keyboard that supported the whole forearm (including curved keys).

Table 6.2 Recommended dimensions of computer keyboards and monitor

	Components	Dimensions	Remarks
Keyboard	Height	60–85 cm	Adequate leg clearance and comfortable arm posture
	Slope	5–30°	Based on operator's preference and keyboard height
	Thickness	3–5 cm	Measured from the home row
	Key width	6–8 mm	
	Key spacing	19 mm	
	Reach	17.5–25 cm	Home row of the keyboard to the edge of the desk
Screen	Viewing distance	41–93 cm	Depend on legibility and operator preference
	Height	90–70 cm	Measured from floor to centre of the screen

(ANSI 1988; Drury and Hoffman 1992; Jaschinski-Kruza 1990)

Fig. 6.12 Alternative keyboard designs (such as tented, supportive, scooped, split keyboard)

Despite claims of superiority of alternate keyboard layouts, there is a greater subjective preference in choosing a keyboard. The standard flat or negatively sloped QWERTY layout predominantly continues in all spheres of computer activities. The design features of the split keyboards include:

(a) Horizontal rotation of the right and left halves of the keyboard to reduce forearm pronation and abduction of the upper arms;
(b) Lateral inclination of the keyboard halves to reduce forearm pronation and abduction of the upper arms; and
(c) crescent-shaped key rows, rather than parallel, to conform to the anatomical shape of the hand.

A detachable keyboard reduces awkward wrist postures (Nakaseko et al. 1985), and alleviates fatigue (ANSI 1988). The muscular strain can be minimized with 13° lateral angles and splitting the keyboard and rotating it in a horizontal plane for a 20° opening angle.

EMG analysis—Types of keyboard exert postural load differently, as evident from EMG activity of arm and back muscles, and upper extremity joint angle deviations. An experimental study by Nag et al. (2008) covered four keyboards, e.g., membrane tactile key switches, mechanical keys with sculptured keycaps, light touch sensitive, and ergo-shaped, curved, ultra-thin, flat keyboards. The study yielded that the EMG activity of forearm (m. flexor digitorum superficialis, FDS, and m. extensor digitorum, ED); and back muscles (m. upper trapezius, UT and m. erector spinae, ES) were least with the use of a curved ergo-shaped keyboard.

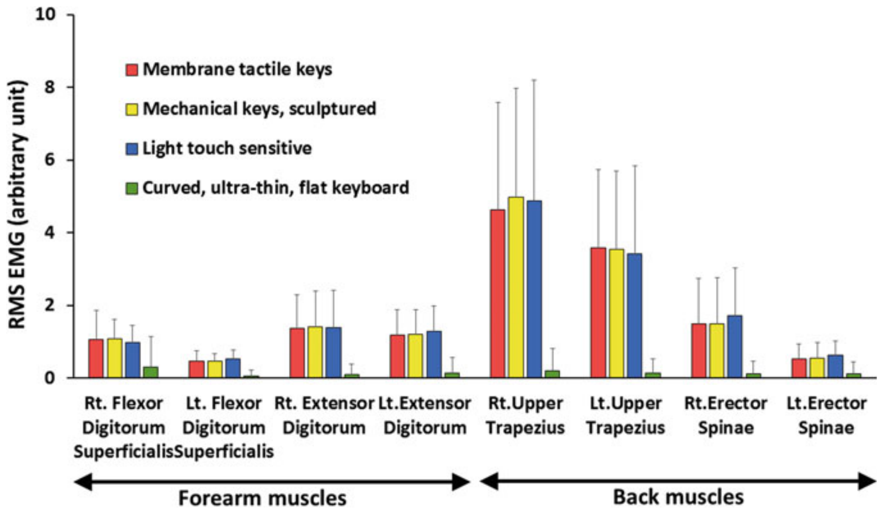

Fig. 6.13 Influence of types of the keyboard on the EMG activity of arm and back muscles

The activity of the forearm muscles was maximum in a keyboard with mechanical keys (Fig. 6.13).

Elbow and wrist extension—The elbow extension was referred to as the angle between upper arm and forearm (movement in a posterior direction from fully bent to a straight elbow). The wrist extension was taken as the angle between the dorsum surface of the hand and posterior surface of the forearm (movement in a posterior direction, starting with the straight wrist as anatomical zero position). These joint angles were recorded from the movements of the reflected markers in 3D motion analysis system. Predominantly, the bilateral wrist extensions were within the range 20–25° for membrane tactile key switches, and ultra-thin ergo-shaped keyboards; wrist extensions were more in case keying in mechanical keys keyboard, wrist angles ranged between 30 and 35° (Fig. 6.14).

Generally, the wrist extension and flexion pose a risk of wrist injury for CTS than radial or ulnar deviation (Gilad and Harel 2000). Carpal tunnel pressure (CTP) is lowest when the hand is in the neutral operating zone of about 15° wrist extension and less than 20° wrist flexion. The elbow extensions (80–85°) were similar in mechanical keys and ultra-thin, ergo-shaped keyboards, whereas in other membrane tactile keyboards, the mean elbow extensions were in the range of 94–97°, which corresponded to observations—92° (Green et al. 1991) or 99° (Grandjean et al. 1983). The preferred elbow angle was suggested as 99°, and shoulder flexion as 9° (Grandjean et al. 1983), elbow angle of 81° and shoulder flexion of 14° (Starr et al. 1985). The preferred trunk extension was suggested as 2° (Grandjean et al. 1983), 4° (Starr et al. 1985), and 14° (Green et al. 1991).

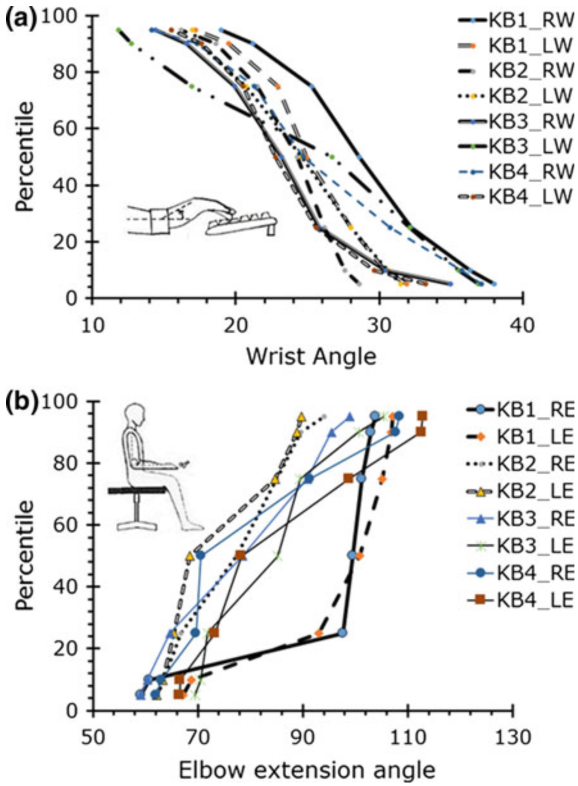

Fig. 6.14 Percentile distribution of **a** Wrist angles and **b** elbow angles during different keyboarding operations

Keyboard Inclination

Keyboard inclination influences the text keying frequency. Sample volunteers had keying frequency of 68 ± 15 characters per minute for flat keyboard (i.e., 0° inclined or flat). The further incline of the keyboard (i.e., 10° inclined) increased keying frequency by 6%, and with further incline (i.e., 25° inclined) the keying frequency decreased by 18%, in comparison with keyboard placed at 0° inclined or flat. The keyboard inclination influenced the radius and speed of the mediolateral and anteroposterior centre of pressure (CoP) displacement. The radius of the stabilogram was minimum when the keyboard was flat 0° incline, and it increased with increasing inclination, maximum being noted at 25° keyboard inclination. The sitting posture appeared more stable with the use of flat 0° incline keyboard, with regard to having least velocity of CoP displacement. EMG activities of forearm muscles increased with increase in keyboard inclination. On the contrary, bilateral ES load increased with a decrease in inclination (Nag and Pal 2008).

With the flat 0° incline of the keyboard, the mean elbow extension ranged between 84 and 86°, whereas extension increased by 1.5° for every degree increase of keyboard inclination. The wrist extension differed marginally between 25 and

30° with keyboard inclination of 0° and 10°, whereas the range of wrist extension varied from 25 and 35° with 25° keyboard inclination. The wrist extension decreased by 4–8° from 10° inclined keyboard to flat keyboard (Nag and Pal 2008). The same observation was made by Simoneau and Marklin (2001).

Gilad and Harel (2000) observed that the activities of m. Trapezius and m. Deltoid was low with flat keyboard (0°), and the muscle load increased with the increase of keyboard inclination. The perceived comfort level is higher in flat and negative designs keyboard slope. Load on m. Extensor carpi ulnaris decreased with the decrease in keyboard slope (Simoneau et al. 2003). The negatively sloped keyboards allow the hand and fingers to assume a neutral wrist posture (Hedge et al. 1995). The positioning of neutral wrist posture has a geometrical advantage, and CTP was lowest up to 15° wrist extension, less than 20° wrist flexion, and average ulnar deviation. Users reported higher comfort in shoulders with flat and negative designs, and EMG suggested that m. Trapezius and m. Deltoid activities lowered with a flat keyboard. The wrist extension angle decreased approximately 12° of extension (with 7.5° slope) to 3° of flexion (with −15° slope) (Simoneau et al. 2003), whereas Simoneau and Marklin (2001) stated that wrist extension decreased approximately 1° for every 2° of change in downward slope.

Placement of Keyboard and Mouse

The equipment and object that are used most frequently should be placed closest to the user, for comfortable use. Most joints are in a neutral posture in the middle of their full range of motion. When the joint moves away from the neutral posture, the posture becomes more awkward with a likely more strain on the muscles, tendons, and ligaments around the joint. Input devices such as computer mouse, trackballs and digitizing tablets are used to perform a variety of screen pointing devices. Primarily, the VDT pointing device/mouse should be positioned next to the keyboard on one's dominant side, and at a height for the upper arm to hang relaxed by the side, align the forearm to achieve a neutral wrist position.

The selection of mouse is based on considerations of hand sizes for comfortable holding and clicking. A mouse pad is used for moving the mouse smoothly. Even for an optical sensor mouse, the mouse pad is used for easy detection of movement of the mouse.

The effectiveness of the keyboards (standard and alternative designs) and screen pointing devices/mouse depends on the type of work performed by the users. Several risk factors, such as seating system, repetitive use of input devices, narrow keyboard table, chair without armrests or armrests with no adjustability, and work desk with a smaller area of support of the forearm, are all interconnected to affect the comfort of the VDT operator (Eklof et al. 2004; Szeto et al. 2005), and recognized as contributing to the epidemics of CTD (Sandfeld and Jensen 2005;

Fagarasanu et al. 2005). Floating forearm posture, keyboard placement, the non-optimal location of the mouse, monitor height are the added stressors (Babski-Reeves et al. 2005).

When keyboarding, the upper arms are hanging naturally from the shoulders, and the elbows bent at about 90° angle. Thus, putting the arms and wrists in a natural position exerts least amount of physical stress on muscles and joints. If desk height is too high, raising of arms and shoulders is a fatiguing static load in the arms and shoulders; any hindrance in blood flow add to the discomfort and risk of injury. If the work desk is too low, leaning forward puts stress on the arms and back. Therefore, one should ensure that wrists are in a neutral position, close to the keyboard. The wrists are straight and the home row of keys at elbow height. The keyboard height and angle should be adjustable in allowing the upper and lower arms to form a right angle. Wherever the keyboard trays are used, this should be wide enough to accommodate mouse by the side of the keyboard at the same level, and the height of the tray to be adjusted at elbow height. However, the keyboard trays should not restrict leg movement.

The keyboard height influences the activity of the forearm and shoulder muscles, whereas the hand position was necessary for the extensor muscles of the forearm (Gustafsson and Hagberg 2003). Nag et al. (2009) examined the possible impact of keyboard placement on multiple stressors, i.e., forearm and backs muscle activities and associated upper extremity joint angles with reference to the horizontal and vertical positioning of the keyboard on work surface. Load on both m. Upper trapezius (UT) and m. Erector spinae (ES) increased with the increase in the height of the work surface (61, 69 and 76 cm). Bilateral UT activity increased with upline placement (at the inner edge of the table, closer to the display unit) than downline (at the outer edge of the table) (Fig. 6.15). Both the forearm (FDS and ED) muscle loads were greater with upline placement than downline, at 69 cm vertical height. In contrast, bilateral FDS and ED activity were less with upline placement than downline at 76 cm height. The study suggested that the work surface height of

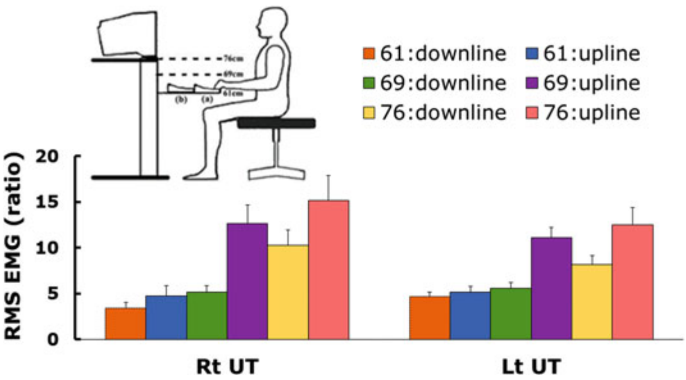

Fig. 6.15 Effect of keyboard placement on bilateral UT muscles

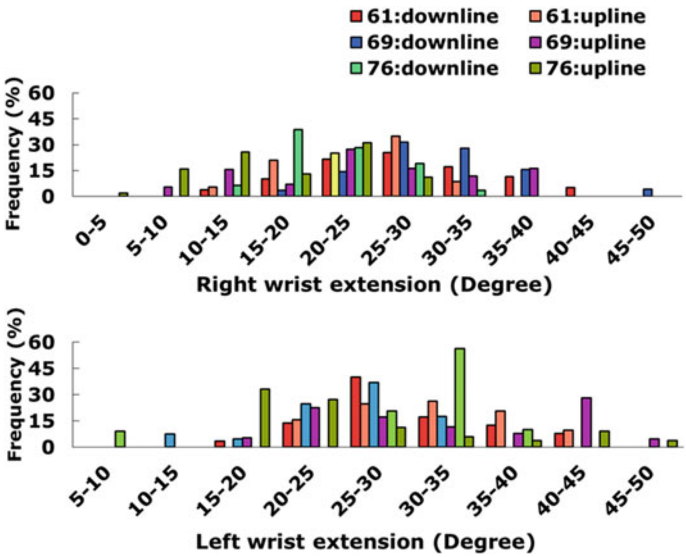

Fig. 6.16 Effect of keyboard placement on the bilateral wrist angles

76 cm yielded lesser forearm muscle load when the keyboard was placed upline. At the work surface height of 69 cm, forearm muscle load was less at downline position. The load on shoulder muscle, i.e., bilateral UT activity increased with the increase in vertical height and at a particular height UT load increased with upline (at the inner edge of the table) than downline (at the outer edge of the table). Reeves et al. (2005) also reported that workstation height affected the back muscles activity; upper trapezius and flexor carpi radialis load changed according to the workstation height (Gustafsson and Hagberg 2003). Overall analysis indicated that the upline (close to the screen) position was preferable for comfort (Tepper et al. 2003).

Also, the joint angle analysis indicated that elbow extension increased approaching towards the anatomical posture of the elbow (upper arm and forearm at 90°) with a decrease in height for both upline and downline placement of the keyboard. Elbow extension was more significant at upline than the downline placement for all the vertical height, i.e., 61, 69 and 76 cm. The bilateral wrist extension was minimum at 76 cm height and maximum of 69 cm (Fig. 6.16).

Forearm and Wrist Support

The placement of the keyboard, mouse and other input devices are the compelling components that add to workplace constraints in computer work. The forearms and wrist support have been suggested as preferred for comfort in keyboard/mouse usage (Cook and Burgess-Limerick 2002; Nag and Pal 2008). However, the evidence is inconclusive to what extent the use of forearm support and wrist rests in keyboard usage can influence the reduction of arms, neck, and shoulder discomfort. Cook et al. (2004a, b)viewed that the forearm supports resulted in greater elbow extension over floating condition, whereas wrist support resulted in less m. trapezius and anterior deltoid activity. From an intervention study in a real work situation, Aaras et al. (1998) observed that support of forearm on the desk significantly reduced the intensity of shoulder pain. It is presumed that support of the wrist on the work surface might reduce the wrist flexion and extension resulting in more neutral wrist posture, as well as, low CTP (Cook et al. 2004a). Serina et al. (1999) reported that in a workstation set-up, the majority of wrist extension angle in keying was greater than 15°, whereas more than one-fourth of participants typed at greater than 30° wrist extension angle. Dickerson and Erdil (1999) indicated that the CTP could increase for wrist extension greater than 15°, due to mechanical friction on the tendons that pass over the wrists to the fingers. Observations do indicate that the wrist pads (Hedge 1994) or inbuilt keyboard wrist rest (Cobb et al. 1995) resulted in substantial increase in CTP. Broad palm rest supporting the major part of the weight of the hand can decrease the amount of weight placed directly on the keys (Hedge and Powers 1995). Smith et al. (1998) advocated the use of detachable palm rest of around 5 cm wide with padding and a rounded front. Parsons (1991) examined nine wrist rests, in which none of the palm rest showed a decrease in shoulder or forearm muscle strain in keyboard work. Cook et al. (2004b) also observed that forearm support resulted in greater shoulder flexion and elbow extension bilaterally, but ulnar deviation and discomforts were significantly less over floating condition. Whereas, there are other observations (Albin 1997; Serina et al. 1999) that the wrist extensions decreased with both forearm/wrist supports, resulting in more neutral wrist postures. Based on a 6-year intervention study, Aarås et al. (2001) emphasized that the static trapezius load, and neck and shoulder pain decreased when the volunteers were able to support their whole forearm and hand on the work desk. Nag and Pal (2008) and Nag et al. (2009) favoured that the forearm and wrist supports were useful in maintaining the elbow in anatomical position nearly at 90°, whereas body stability of the keyboard operators was not influenced by the upper extremity support. Supporting the wrists on the work surface reduced the load on the upper extremities (Albin 2014), with the primary aim of wrist rests to place the wrist in a neutral flexion/extension posture in pointing or keying. The forearm support reduced EMG activity of the forearm and the back muscles, bilaterally. The composition of the wrist rest was an important factor. The gel-filled wrist rest was advantageous in reducing forearm muscle load, in comparison with the use of bead-packed wrist rest.

Scheduling Rest Breaks in Computer Work

Confinement to chair–desk complex in various computer-based professional spheres causes a gamut of MSD-related signs and symptoms, besides other short- and long-term health effects, such as swelling of feet and ankles resulted from less blood circulation. The issues of computer users are of immediate concern if the device is used more than 4 h per day. The literature is abundant that the physical and mental strain in computer work can substantially be relieved by introducing frequent short rest breaks combined with stretching exercises during work hours (Henning et al. 1997). Apart from the commonly negotiated rest breaks (mid-morning, lunch and mid-afternoon) agreed upon among the employee unions and the facility occupier, mainly, in highly repetitive keying tasks, adjusting the work schedule by intermittent rest breaks (micro-pauses) may help to reduce discomfort and improve productivity. Little walking interspaced in prolonged seated work may result in lesser spinal shrinkage, as compared to sitting with no breaks (Helander and Quance 1990). The primary purpose of negotiated rest breaks is to take care of personal needs, which, however, does not take into account recovery time from the potential physical and mental demands of one's jobs.

The VDT work is associated with eye discomfort, including the symptoms of gritty feeling or redness of the eye as well as sensitivity to light. Apart from intermittent rest breaks for VDT work, other suggestions are (a) interrupting keyboarding tasks with other jobs, (b) occasionally moving around the workstation to change body position, and (c) frequently looking at objects far away at least 20 feet away, and blinking eyes to refresh the tear film and relax eye muscles. One may take a 10-min rest break after every 2 h of VDT work under moderate visual demands, and a 15-min rest break every hour of continuous VDT work for a high visual demand or repetitive work task.

Stretching and gentle exercises, as depicted (Fig. 6.17), every 1–2 h may be useful to relieve muscle fatigue. The effect of stretching-type exercises has been tested in a field study by Fenety and Walker (2002). The intervention of in-chair stretches at 30-min intervals throughout the testing period resulted in a significant decrease in body discomfort, compared to increases in discomfort during the trials with no exercises.

In the overall analysis, the office job design is imperative for organizational effectiveness. Importance has been placed on the organizational requirements and the physical and mental needs of the office workers. Issues of concern are (a) task variety, job enlargement, job rotation, teamwork, (b) work pace, work schedules, (c) work and rest breaks, micro-pauses, (d) adjustment to a new job, extended illness, and (e) training and education, techniques of work, performance and safety. Employee participation is essential in designing jobs and framing the structure and content of one's jobs. Good job design should include a periodic rotation of tasks,

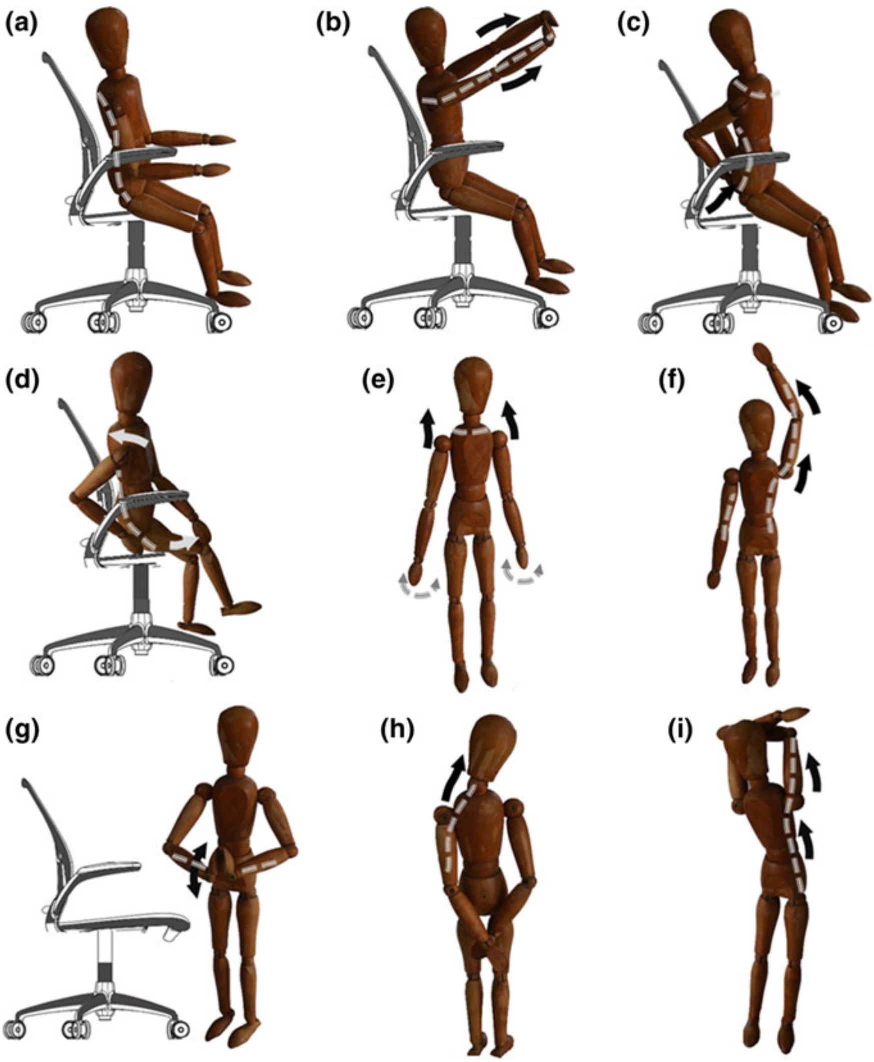

Fig. 6.17 Some examples of gentle exercises for office workers. Black bold arrows indicate the direction of stretching and pressure exertion. Dashed lines indicate muscular areas influenced by the exercise. Each exercise may be repeated $\sim$10 s couple of times, and about 3–4 times during the workday

to provide office workers with job variety and increased job satisfaction. Job enlargement is a way to add meaningfulness to tasks and improve morale. Jobs can be enriched by giving employees more control over the issues and, in turn, the employees gain responsibility and ownership in their jobs.

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Chapter 7
Strategic Office Lighting

Introduction

Worldwide, the lighting accounts for a substantial fraction of electricity consumption. Estimated that the grid-based electric lighting consumes one-fifth of total global electricity production. Lighting accounts for about one-third of the tertiary sector electricity consumption in OECD countries (Waide and Tanishima 2006). In the USA, commercial buildings account for one-third of the nation's primary energy consumption, and the lighting utilizes nearly 25–45% of the total energy consumption of commercial buildings (Krarti et al. 2005; Dubois and Blomsterberg 2011). The extent of consumption varies from one building to another. To target better energy efficiency in buildings, energy use for space heating and cooling, ventilation, hot water, and lighting should substantially be reduced. Various building rating systems have emphasized the necessary lighting requirements in buildings, relating to health, comfort, safety, and productivity of people at work. As described elsewhere, LEED included lighting as a critical parameter in high-performance buildings. LEED assessment involves lighting in four areas, such as

(a) Sustainable sites (lamp and luminaire efficiency, lighting layout);
(b) Energy and atmosphere (energy optimization issues, including lighting load in buildings);
(c) IEQ (daylighting and the control of artificial lighting systems); and
(d) Innovation in design solutions of lighting.

The key factors that influence energy consumption in a building are depicted in Fig. 7.1. A sound organizational initiative is essential in managing the lighting systems at workplaces, with a balance between energy efficiency, and quantity and quality of illumination to perform the visual task. Strategic lighting in the offices requires an understanding of the parameters that impact on the occupants. Good office lighting promotes work and other activities carried out in the building, health

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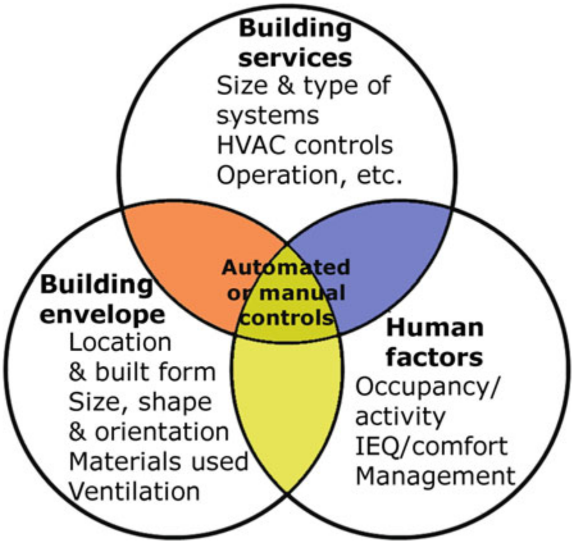


Fig. 7.1 Key factors that influence energy consumption in the building

and safety and creates a pleasing environment for the occupants. Daylight and quality of artificial lighting in the offices, energy efficiency in lighting, the lighting standards and recommended illumination levels are the essential concerns for different task environment.

With the view that human comfort in an environmental context is highly a sociocultural construct (Chappells and Shove 2005), practical realization of good lighting involves:

- Planning of the brightness and colour pattern in the interior space and thus making work areas refreshing and free from any sense of gloom;
- Using directional lighting to assist in the perception of task details and controlling glare to eliminate visual discomfort;
- Minimizing flicker from the artificial light sources and focusing on the colour rendering properties of the light; and
- Optimizing illuminance in different areas of the building, preventing extreme differences between adjacent areas, and installing emergency lighting systems, as necessary.

Lighting Design Criteria

Lighting requirements are determined by three basic human needs, such as visual comfort, visual performance, and visual safety. For efficient lighting design, necessary lighting criteria, such as luminous distribution, illuminance for the interior and task areas, direct and reflected glare, the directionality of lighting and modelling, colour rendering and colour appearance of the light, flicker and stroboscopic effects, and quality of daylight are briefly stated herewith. Other visual parameters that influence operators' performance include (a) the intrinsic task properties, such as size, shape, colour, and reflectance of detail and (b) ophthalmic capacity of the operator, such as visual acuity, colour perception.

Luminance Distribution

The luminance (brightness) distribution in the visual field influences task visibility and visual comfort. This photometric measure of the brightness of a light source is expressed in the unit, as nit or candela/sq. m, equals 0.29 foot-lamberts. The measure equals luminous intensity per unit solid angle emitted per unit projected area of the source or reflected from a surface. An appropriately bright interior surface, the walls and ceiling raises comfort levels of people in buildings. A balanced luminance distribution increases visual acuity (sharpness), contrast sensitivity (discrimination), and efficiency of the visual functions (accommodation, convergence, pupillary contraction, movements). Sharp shadows may cause uncomfortable luminance ratio and reduce visibility by reducing task luminance. Using indirect lighting that can reflect the light to a variety of directions can soften the shadows.

The luminance can be determined by the reflectance and the illuminance on the surfaces. Reflectance or reflection factor is the ratio of the luminous flux reflected by a body (with or without diffusion) to that flux it receives. Recommended reflectance for the building interior diffusely reflecting surfaces is ceiling—0.7–0.9, walls—0.5–0.8, working plane—0.2–0.6, floor—0.2–0.4, and furniture, machinery —0.2–0.7.

Illuminance and Maintained Illuminance

Illuminance level (measured in *foot-candles* or *lux*) impacts on the ease and reliability of the visual tasks performed. One foot-candle is equal to one lumen of light density per sq. ft, and one lux is equal to one lumen per sq. m. The recommended levels of the illuminance of various tasks and activities, given in Chap. 8, are the maintained illuminances (E_m), below which the illuminance on a reference surface should not fall. In defining illuminance of workstations, the visual performance depends on the size and location-specific illuminance on the workstation, the task area, immediate surroundings and background area. Illuminance is determined according to the angle of inclination of the visual task reference surface (horizontal, vertical).

In general, prolonged computer work results in visual symptoms, such as eye strain and fatigue, due to improper lighting, glare, and reflection from the monitor. The VDUs may be placed to the side of the light source, and not directly underneath, and ensure that the VDUs and the operators do not face the window. In the offices having fluorescent strip lighting, the arrangement of work desks should be parallel to the lights. Glare and reflection on the monitor reduce contrast and sharpness of the display that can be avoided by tilting the monitor downward. Thus, the reflections are directed below eye level. LCD monitors or those with the light diffusing surface or anti-glare may help reducing glare. Eye discomfort of computer users may be mitigated by adjusting the screen brightness and changing the character and background colours. Suggested combinations are black characters on white or yellow background, white on black and blue, yellow on black, and green on white. Moreover, it is suggested to avoid red and green and yellow on white.

The scale of illuminance—About 20 lx of horizontal illuminance is required to discern features of the human face, and this is the lowest level in the scale of illuminance. According to EN 12665, the steps of illuminance are 20–30–50–75–100–150–200–300–500–750–1000–1500–2000–3000–5000 lx. A factor of about 1.5 represents the smallest perceptual difference to recognize the subjective effect of illuminance. The maintained illuminance may require being increased in case (a) the visual capacity of a person is below normal, (b) there is an unusually low contrast in the task, and (c) the visual work demands accuracy and productivity.

The maintained illuminance of 200 lx is the cut-off below which continuous work in an area may not be desirable. The illuminance of immediate surroundings of the task areas including a border of $\sim$0.5 m width around the task area may be adjusted to a step in reverse scale, in comparison with the task illuminance. However, if the task illuminance is <200 lx, the immediate surroundings should be equally illuminated to the task level. In indoor workplaces, many workstations are not regularly manned (e.g., in a call centre). In such a situation, a background area of about 3.0 m widths, adjacent to the immediate surrounding area, may be considered (Fig. 7.2) and area to be illuminated with a maintained illuminance of one-third the value of the immediate surrounding area. There are two measures need to be analysed, i.e., illuminance uniformity and diversity.

Illuminance uniformity (U_0)—The ratio of the minimum illuminance (E_{min}) to the average illuminance ($E_{average}$) in the illuminance grid determines the relative uniformity of light. The diversity is the ratio of minimum to the maximum illuminance over the core working plane. The U_0 may also be expressed as the ratio between the E_{min} and the maximum illuminance (E_{max}) on the given plane (EN 12464-1 2011). The U_0 values have been recommended for electric lighting (such as walls and ceiling) to make the areas brighter. This ratio may range from 0.7 (min/max) to 0.8 (min/average). For immediate surroundings, minimum U_0 values range from 0.4 to 0.7 for the visual tasks and 0.1 for background areas.

Illuminance grid: All E_m and U_0 values are dependent upon the grid definition, based on the size of the reference surface, the geometry of the lighting installation, and the luminous distribution of the luminaires. Grid systems are designed to indicate the points at which the illuminance levels are measured and verified, referring to the workstations, immediate surroundings and background. Rectangular reference surfaces are subdivided into squared grid cells, having the calculation

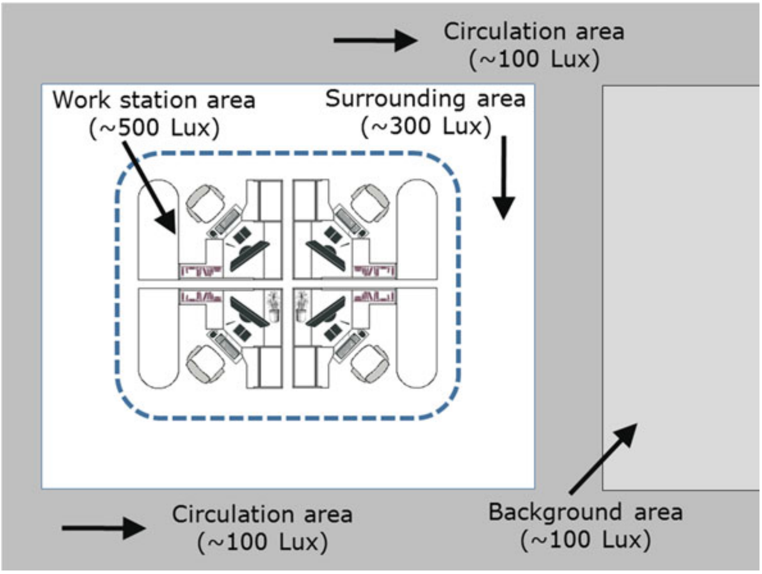


Fig. 7.2 Relative illuminance distribution about the workstation, the task area, immediate surrounding, and the background area

points at the centre. Usually, a 0.5 m of space along the walls is excluded from the calculation. The maximum grid size shall be:

$$p = 0.2 \times 5^{\log_{10} d}$$

where p is the grid size and *d* is the relevant dimension of the reference surface. For a reference surface having a length-to-width ratio between 0.5 and 2.0, the grid size and the number of points (nearest whole number of *d/p*) are determined by the larger dimension *d* of the reference area. In other cases, the shorter dimension is taken into account to establish the spacing between grid points (EN 12193 and EN 12464-2). For small- to medium-sized office spaces (5–10 m), the grid size ranges from 0.6 to 1 m. For large open office spaces (about 50 m), the grid size may as large as 3 m. Importantly, the spacing of luminaires and grid point spacing are not identical, as illustrated in Fig. 7.3a, b. The spacing between measurement points should be less than the mounting height of lighting installations. The arithmetic mean for all calculation points is the average illuminance. For non-rectangular reference surfaces (e.g., irregular polygons), grid size can be determined using approximately defining rectangles. For ribbon-like reference surfaces, the dimension of the ribbon at its widest point is taken to decide the grid size. For a workstation area (workspace plus movement space) extending to the marginal strip along the wall, calculation points may be ignored where the projecting area is a movement space. However, calculation points are duly considered, where the marginal strip is a workspace.

Maintenance factor (*MF*)—The ratio of initial illuminance to the maintained illuminance is expressed as MF. Guidance to derive MF is given in CIE 97-2005. The artificial lighting systems are designed from an overall MF calculated referring

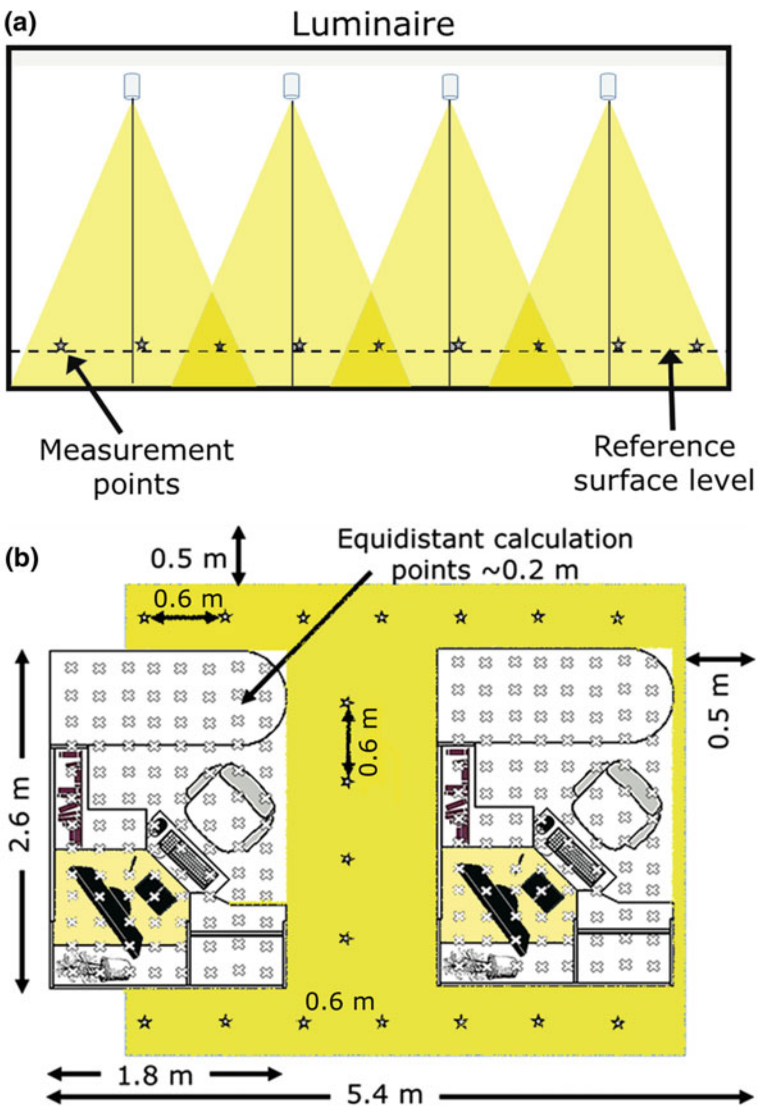


Fig. 7.3 Spacing of **a** luminaires. **b** Calculation grid points

to the lighting equipment, environment, and maintenance schedule, including the frequency of lamp replacement, luminaire, room, glazing, cleaning intervals and method. That is, the MF is calculated as the multiplication of factors, i.e.,

$$MF = LLMF \cdot LSF \cdot LMF \cdot RMF$$

where *LLMF* (lamp lumen maintenance factor), *LSF* (lamp survival factor), *LMF* (luminaire maintenance factor), and *RMF* (room maintenance factor). The MF should not be less than 0.70. With usage and ageing of a lamp, its lumen output decreases. The LLMF is indicated by the ratio of luminous flux after given hours of burning to the luminous flux when the lamp is new. The LSF expresses the probability that about half of the observed group of lamps remains operative after specified burning hours. The LSF of different lighting systems, like fluorescent lamps, is usually calculated by a switching frequency 2.75 h ON and 0.25 h OFF. In many cases, LSF can be assumed equal to unity, since the failure of individual lamps results in drastic fall in lighting level unless the lamp is replaced. Since lamps and luminaires accumulate dust and dirt, the LMF is estimated as a function of the time luminaires are in the lighting system since last cleaned. Due to indoor dust and dirt get deposited on the ceiling, walls, floor and furnishings, the room size, the reflectance of the room surfaces and the luminous flux distribution influence the RMF.

Determination of the luminous flux—The luminous flux (Φ) is a quantity characteristic of radiant flux that can produce visual sensation based on the luminous efficiency for the light-adapted eye. The ratio of the total luminous flux at the working plane to that of the luminous flux of the light sources is expressed as utilization factor (μ). For every luminaire, the measurement comprises the luminous flux radiated by the luminaires and reflected by the ceiling, walls, and other surface interiors and objects. These measurements are taken for different reflection factors of ceilings and walls, i.e., white and very light colours—0.7, light colours—0.5, middle tints—0.3, and dark colours—0.1, respectively. Derivation to arrive at the luminous flux and the required number of lamps and luminaires in a room can be described as:

$$E_{av} = \frac{\mu\Phi}{A} \quad N_{lamp} = \frac{E_{av}A}{\mu \cdot MF \cdot \Phi_{lamp}} \quad N_{luminaires} = \frac{E_{av}A}{\mu \cdot MF \cdot \Phi_{luminaires}}$$

where E_{av} is the average illumination (lux) required for the area of the working plane A (m^2), μ, utilization factor, Φ, luminous flux of the light sources installed in the room (lumen), *MF,* maintenance factor, N_{lamp} *and* $N_{luminaires}$ are numbers of lamps and luminaires, Φ_{lamp} *and* $\Phi_{luminaire}$ are luminous flux of each lamp and luminaire, respectively. Room index is used to determine the utilization factor. The arrangement of luminaires for interior lighting depends upon the layouts and dimensions of the rooms. The room index (k_r) is calculated as:

$$k_r = (L \cdot W)/(L + W)H_m$$
$$\text{(direct, semi-direct and diffuse light distribution) and}$$
$$k_r = [3(L \cdot W)]/[(L + W) \cdot (2H_c)]$$
$$\text{(semi-indirect and indirect light distribution)}$$

where L and W are the length and width of the rectangular interior; H_m and H_c are the mounting height of the luminaires, and the ceiling height above the working plane, respectively. For rooms where the length exceeds five times the width, L may be taken as L = 5 W.

Flicker and stroboscopic effects cause a visual distraction in workplaces. Electromagnetic ballasts of fluorescent luminaires often produce flicker. In Chap. 13, different lighting systems have been described. High-frequency electronic ballasts, however, can eliminate flicker and audible hum (IES 2011).

Directionality

Apart from task lighting, the entire workspace is required to be illuminated to highlight objects, reveal textures, and improve the appearance of people occupied in the space. The mean cylindrical illuminance, modelling, and directional lighting describe the lighting conditions.

Mean cylindrical illuminance—Good visual communication within a volume of space can be attained by providing adequate mean cylindrical illuminance (E_z). The maintained mean cylindrical illuminance (average vertical plane illuminance) in the task area and interior space shall be not less than 150 lx with $U_o > 0.10$, on a horizontal plane at a specified height of 1.2 m (sitting) and 1.6 m (standing) above the floor.

Directional lighting reveals details within a visual task, increases visibility, and makes the task easier to perform. However, veiling reflections and reflected glare should be avoided. ***Modelling*** refers to the balance between diffuse and directional light. The ratio of cylindrical to horizontal illuminance at a point is an indicator of modelling; a value ranging between 0.30 and 0.60 is an indicator of good modelling. By clearly revealing the structural features, form, and texture, the interior appearance is enhanced. Preferably, the lighting should not be too directional thereby to avoid confused multiple shadows and visual effects.

Energy Efficiency Requirements

Energy requirements for lighting in buildings increase with proportional more substantial dependence on artificial lighting, occupancy, lack of control on the lighting pattern, and minimal maintenance of the installation. Needless to mention that the availability of daylight varies depending upon climate conditions and distance from the side windows. Switching and dimming controls are the features to ensure a balance between artificial lighting and daylight. The energy efficiency actions in achieving the lighting design involve:

- Ascertaining the design maintained illuminance, colour rendering index, and glare rating required for the visual tasks and surroundings;
- Maximizing the use of daylight and planning the energy effective maintenance programme throughout the life of the lighting installations;
- Selecting the preferred type of lighting system, the efficient lamp, ballast and luminaire that meet the optical, control, and design requirements;
- Installing the appropriate controls to ensure switching and dimming, as required; and
- Calculating the installed power density and maintaining within the recommended range.

Power density—The installed power density, a quantifiable dimension of the power (W/m^2), needed per unit floor area to achieve 100 lx of maintained illuminance on a working area with the general interior lighting. The overall lighting benchmarks for typical and good practice performance in office buildings (CIBSE Guide 2004) include parameters, such as the installed capacity of treated floor area, annual running hours, and the percentage utilization of the plant (Table 7.1). Accordingly, the energy use indicator (EUI) is obtained as the product of the mentioned parameters. The installed power density is estimated by adding up all the lamp wattages in a built area and control gear losses (10–20%), against the floor area. The best practice benchmark of 12 W/m^2 (British Council of Offices 2000) is based on 350–450 lx at a luminous efficacy of 3 W/m^2 per 100 lx.

Linhart and Scartezzini (2011) compared two lighting scenarios for evening office lighting, i.e., reference scenario with LPD of 4.5 W/m^2 and test scenario with LPD of 3.9 W/m^2. The reference scenario was used in office rooms of the Swiss Federal Institute of Technology in Lausanne for years. Investigators observed that the two scenarios were comparable regarding personal visual comfort, such as preferring the test scenario to that of the reference scenario. The test scenario was

Table 7.1 Overall lighting benchmarks for offices

	Naturally ventilated cellular office		Naturally ventilated open-plan office		AC standard office		AC prestige office	
	Good practice	Typical	Good practice	Typical	Good practice	Typical	Good practice	Typical
Installed capacity (W/m^2)	12	15	12	18	12	20	12	20
Running hours (h/year)	2500	2500	3000	3000	3200	3200	3500	3500
Utilization (%)	45	60	60	70	70	85	70	85
Energy use indicator (EUI) (kW-h)/m^2)/year	14	23	22	38	27	54	29	60

Source CIBSE guide (2004)

providing higher illuminance, however, with an increased risk of discomfort glare. Visual performance of the participants in a paper-based task was significantly better under the test scenario, as compared to the reference scenario. Accordingly, Linhart and Scartezzini (2011) viewed that with right luminaires and high-frequency lighting, with a small allowance for decorative lighting, the energy-efficient lighting with a power density of about 5 W/m^2 may be achieved in our offices, without jeopardizing visual comfort and performance

Visual Comfort Indices

Lighting Design Criteria, described above, cover the necessary lighting parameters for efficient lighting design in office buildings. Literature provides several indices aiming at evaluating the luminous quality, visual comfort, and performance in the built environment (Reinhart and Wienold 2011; Carlucci et al. 2015). There are different terminologies in describing the type of assessment achieved by the indices. Reinhart et al. (2006) categorized indices as *dynamic* and *static*, based on time series of illuminance, or as a representative climatic condition of a situation. The dynamic indices are grouped into (a) *time series indices,* providing an immediate assessment based on hourly values in the annual weather dataset and (b) *cumulative indices* predicting aggregated measures of daylight over time (Mardaljevic et al. 2009). Carlucci et al. (2015) assessed visual comfort indices as *short-term* (an immediate assessment of a lighting environment), and *long-term indices* (summarizing assessment into a single value for an extended period). Overall, a given lighting environment is assessed by comparing the indices to actual physical quantities with given reference values. The illuminance-based indices indicate threshold values about determining whether a given luminous environment may be considered comfortable, whereas the indices on glare, colour rendering, and lighting uniformity compare physical quantities to reference values, indicating visual performance (Nabil and Mardaljevic 2006). To compare buildings or building variants, visual indices that expressed as percentages are more useful to create illuminance maps over a defined space grid and making annual evaluation easier. EN 12464-1 (2011) presents reference values of illuminance, glare (UGR), uniformity of light (U_0), and colour rendering quality (CRI or R_a) for different areas and tasks, as described in Chap. 8.

Daylighting

In many green building rating systems, such as BREAM, LEED, daylighting has been recognized as a cost-effective alternative to artificial lighting. The daylight closely matches the human visual response. The quality and colour rendering of daylight are better than artificial lighting, and thus daylight creates a more pleasant indoor environment (Lim et al. 2012). Daylighting in the living and working spaces has implied benefits to health and well-being of occupants, work satisfaction, and productivity, as compared to electrical lighting (Cantin and Dubois 2011).

The sunlight that reaches the earth surface consists of direct solar illuminance and sky illuminance. To daylight design, only sky illuminance is considered as contributing to building illumination during the day. The amount of sky illuminance depends on the position of the sun defined by its altitude, latitude of the locality, date, and time. The external horizontal sky illuminance (diffuse illuminance) varies with the climatic regions, such as 6800 lx (cold climate), 8000 lx (composite climate), 9000 lx (warm–humid climate and temperate climate) and 10,500 lx (hot–dry climate). Other than the sky component, there are externally and internally reflected components of daylighting. Whereas the sky component is the amount of light that directly comes into an indoor reference point from the sky, the sunlight that gets reflected from an exterior building/walls, and reaching to the reference point is termed as the externally reflected component. The part of the daylight reaches the indoor reference point after inter-reflections from the internal objects and surfaces. The summation of three components gives the measure of daylight factor, as described elsewhere.

An ample body of literature is available on daylight fundamentals and its determination in buildings (Alrubaih et al. 2013). Research elucidates the energy-saving potentials of daylight in buildings (Li 2010; Dubois and Blomsterberg 2011) and application of window glazing, solar shading on the daylight harvesting (Colaco et al. 2008). There is an emphasis on exploring occupant preference and satisfaction of daylight in offices (Guo et al. 2010; Galasiu and Veitch 2006). Yu and Su (2015) provided an extensive review of the daylight metrics and its potential in energy-saving estimations. Invariably, the daylight entry into the building is influenced by factors, such as geographic location, climate, building geometry and orientation, window properties, window-to-wall ratio, and obstructions from nearby buildings. The evaluation of indoor daylight performance covers (a) assessing the indoor daylight availability by either field measurements or software simulation and (b) estimating energy implication when sufficient daylight is available, and partially replacing artificial lighting. Despite implied advantages of daylight elucidated in the context of building design criteria (CIBSE 2008; IESNA 2010), daylight schemes are not yet well integrated with the artificial lighting in buildings (IES 2013).

Daylight Illuminance (E_p) is referred to as illuminance at a point (p) of a given surface. Illuminance thresholds vary with the building typologies, kind of use of space and user's task requirement in a building. In a typical office, the suggested reference value on the work plane is about 500 lx (EN 12464-1 2011). IESNA committee favours a target illuminance of 300 lx for offices and library-type spaces (Reinhart and Wienold 2011). Such approach has the advantage of being simple and immediate. However, it has limitations in evaluating the overall performance of space regarding the nature of light, glare, and time trend of changes.

Daylight Factor (DF) is a commonly used measure to indicate the subjective daylight quality in an indoor space. The amount of daylight received at a reference point in an internal space can be analysed by measuring illuminance on a grid or undertaking a daylight factor calculation. The DF describes the ratio of the indoor daylight illuminance to that of the outdoor illuminance at a point under the same unobstructed overcast sky (Rea 2000), i.e., the summation of sky component, and externally and internally reflected components of daylight. Typical values of DF may be derived assuming that the outside illuminance is around 10,500 lx (hot-dry climate) while about 500 lx as an averaging level on the work plane for office work, and thus arriving the ratio at about 5%. This level of *DF* values is suggested for *not too deep or obstructed office rooms* (CIBSE Lighting guide 10 1999).

From architectural consideration, maximizing DF may lead to admitting more daylight as possible. However, this may affect the thermal comfort performance of the building (Reinhart et al. 2006). A very high daylight availability in an office environment can cause a high level of lighting or a non-uniform environment. Maintaining a proper level of reflectance factors for ceilings, walls, and floors is desirable. The DF should not fall less than 1% on the working plane 3 m from window wall and 1 m from side walls. The illumination levels in a given room can be raised by a light coloured painting of the walls, as compared to dark coloured ones.

Daylight Coefficient (*DC*) is a method to perform annual daylight illuminance simulation (Laouadi et al. 2008). It considers dynamic changes of indoor daylight illuminance from knowing the sky luminance under various sky conditions and solar positions (Li et al. 2004) . The DC method assumes that the sky is divided into patches and each patch contributes to the internal illuminance (Mardaljevic 2000). Simulation methods allow calculating a set of coefficients for a given room space even under dissimilar fenestration systems, e.g., windows with movable shades.

Daylight Autonomy (DA) represents the percentage of annual daytime hours during which all or part of a building's lighting requirement meets through daylighting alone, that is, meeting a specified minimum daylight illuminance threshold (Reinhart and Walkenhors 2001). The measure aims at quantifying lighting needs in designing a space to maximize the amount of useful daylight and minimize the demand for supplemental electric light.

The occupied building space with the DA exceeding 50% would be considered as daylit area (Reinhart and Weissman 2012). The metrics consider geographic location-specific weather information on an annual basis. Olbina and Beliveau (2009) suggested the illuminance limit value at 500 lx. The weightage ranges between 0 (when daylight illuminance is less than the set limit value) and 1 (when daylight illuminance exceeds the set limit value). The DA may be of limited significance when the daylight illuminance values fall below the threshold (Nabil and Mardaljevic 2006).

Continuous Daylight Autonomy (DA_{CON}) and Daylight Autonomy max (DA_{max}) are other modifications of DA (Dubois and Flodberg 2013). DA_{CON} linearly introduces percentage credits when indoor illuminance falls below the user-defined threshold, whereas DA_{max} expresses as the percentage of the time when daylight is about 10 times the recommended illuminance, indicating the moments of the risk of glare. These measures include glaze-to-wall ratio, internal surface reflectance, glazing transmittance, climate, and spatial orientation.

Spatial Daylight Autonomy (*sDA*), on the other hand, examines whether space receives annual sufficiency of daylight in interior environments. That is, the percentage of floor area receives daylighting illuminance exceeding a specified illuminance level for a specified fraction of the operating hours over a typical meteorological year (IESNA 2012, Yu et al. 2014).

All of these metrics apply to an annual evaluation taking into consideration climatic data of respective geographical zones and setting a minimum or maximum threshold of illuminance as the design target. The sDA metrics is calculated virtually through computational simulation, using many commonly used lighting analysis and design software, such as Radiance, Daysim. IESNA (2012) recommended $sDA_{300}/_{50}\%$ for analysis of daylight sufficiency, i.e., the percentage of points of the analysed area having illuminance threshold of 300 lx for $\sim$50% of the daytime occupied hours.

Daylight Autonomy (DA) Reinhart and Walkenhorst (2001)	$= \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i}$	where t_i is each occupied hour in a year; wf_i is a weighting factor derived from the horizontal daylight illuminance at a given point; the illuminance limit value (500 lx); x is the reference illuminance level, y is the time fraction, p_i is the points belonging to the calculation grid
Spatial Daylight Autonomy $\left(sDA_{x/y\%}\right)$ (IESNA 2012, Yu et al. 2014).	$= \frac{\sum_i (wf_i \cdot DA)}{\sum_i p_i}$	

Useful Daylight Illuminance (UDI) is a concept that defines a range of horizontal daylight illuminance as the useful levels of illumination at a given point. Generally, it incorporates the lower and upper threshold limits (100 and 2000 lx) to divide the annual illuminance distribution into three bins (Nabil and Mardaljevic 2006). The upper bin presents the percentage of the time the daylight is in oversupply that can lead to visual discomfort. The intermediate bin represents the percentage of the time the daylight falls in the illuminance level between 100 and 2000 lx (supplementary range, 100–500 lx; autonomous range, 500–2000 lx (Mardaljevic et al. 2009), whereas the lower bin takes the percentage of time with the insufficient supply of daylight. A very close to the concept of UDI intermediate bin, *Frequency of Visual Comfort* (*FVC*) is expressed as the percentage of the time within a given period, daylight alone delivers appropriate illuminance (Sicurella et al. 2012). The FVC higher than 0.8 is assumed as satisfactory when illuminance levels at most for 20% of the time are outside the range (insufficient, 150 lx—excessive, 750 lx). Further, Mardaljevic et al. (2012) introduced a new series of UDI, as

- Fell short (UDI-f)—illuminance < 100 lx;
- Supplementary (UDI-s)—illuminance > 100 < 300 lx;
- Autonomous (UDI-a)—illuminance > 300 < 3000 lx;
- Combined (UDI-c)—illuminance > 100 < 3000 lx; and
- Exceeded (UDI-e)—illuminance > 3000 lx.

Setting the same upper and lower thresholds of illumination, as in FVC, Sicurella, et al. (2012) also proposed an index, *Intensity of Visual Discomfort* (*IVD*), which is the time integral of the difference between the spatial average of daylight illuminance and the upper and lower limits of visual comfort. Generally, from different spatial and temporal combinations, the different daylight indices have been evolved. However, the ones that are expressed with a reduced number of values as output are preferred for simulations and optimization. *UDI* and FVC metrics are very much analogous to provide information about the levels of daylight illuminance, and the frequency of occurrence of an oversupply of daylight, causing glare and visual discomfort. The DC, UDI, and DA metrics have been incorporated in lighting simulation software, such as RADIANCE and DAYSIM (Reinhart and Herkel 2000; Reinhart and Wienold 2011).

Building Openings for Good Daylighting

Design of buildings with a focus on natural ventilation and daylighting is interrelated. Chapter 12 elucidates the positioning of windows and openings and also its utility in natural ventilation. Generally, taller openings give greater daylight penetration, whereas broader openings give a better distribution of light. By placing the window at a high sill level (30–60 cm above the working plane) may allow entry of natural light, with a likely compromise in reducing ventilation at work levels. Instead of placing one large opening, multiple small openings positioned along the same, adjacent, or opposite walls bring the better distribution of illumination. Where the width of the room is greater than two times the distance from the floor to the top of the opening, unilateral lighting from side openings is not preferred. Openings on two opposite sides allow uniform distribution of illumination, especially when the room is 7 m or more across. The diffused lighting in a room may be increased by cross-lighting with openings on adjacent walls.

As described, the daylight of the sky component is the part of the illuminance received directly from the sky, and this component should not usually be less than half the total area of the room. The target can be ensured on the working plane at (a) a distance of $\sim$3.5 m from the window along the central line perpendicular to the window, (b) the centre of the room, and (c) at fixed locations of workstations. Direct sunlight can increase room illuminance. However, there is a risk of glare if it falls on walls at low angles. Openings provided with louvres, baffles, or other shading devices avoid entering direct sunlight. Translucent glass panes, for example, prismatic glass, tinted glass, corrugated glass, are often used in the upper portions of the openings. Such fixtures reduce the sky component to a significant extent and are used to reflect part of the light on to the roof, enhance diffuse lighting in the interior space. Blinds can be used to deflect and control the amount of natural light.

Colour in an Office Environment

Of a vast electromagnetic energy spectrum, the colour is visible to human eyes from 400 to 700 nm. Inherently, one might perceive colours as calmness, comfort, or stimulation (Chebat and Morrin 2007; Nurlelawati et al. 2012). A variety of factors (gender, age, cultural aspects, education, background, and experience) influence individual preferences (Baniani and Yamamoto 2015), and therefore, colour preference may not be universal (Taylor et al. 2013). Men are very similar in their colour preference than women (Al-Rasheed 2015; Sorokowski et al. 2014). A comprehensive review by Savavibool et al. (2016) describes the subtle effects of workplace colour on mood and emotion, stress and physiological outcomes, and cognition and performance. Choosing the right colour scheme for a workplace, regarding hue, saturation and brightness, and also colour preferences, can have positive effects on human emotions and behaviour, work performance, productivity, and creativity (Kamaruzzaman and Zawawi 2010; Kwallek et al. 2007). Colour also affects the physiological response (e.g., cardiovascular responses), as well as anxiety and human comfort (Kuller et al. 2009).

Colour Preference

Colour ranges at shorter wavelength such as blue, green, and purple are fresh and cool. Red is having the longest wavelength perceived by our eyes. Red, orange, and yellow are warm colours; however, the colour preferences of individuals are associated with their emotional response to the environment (Gao et al. 2007). Most studies on colour effects were conducted in laboratory settings and on a selected group of volunteers. Challenge remains in exploring multiple combinations of colours in real-life workplace interiors.

Park and Park (2013) examined the effects of culture and gender on colour preferences and observed that Korean paediatric patients had a higher preference for white compared to Americans, whereas blue and green were the most preferred colours for both Korean and American groups. Overall, females had a higher preference for red and purple than those of males. The choice of colour also has religious aspects. White is the favourite neutral colour (Poursafar et al. 2016). One may notice that most public building is white, and many people accept white as professional quality (Kamaruzzaman and Zawawi 2010). However, Kurt and Osueke (2014) noted that interior white walls might be perceived as dull and uninteresting. In general, blue and green are the most favourite colours (Liu et al. 2014; Poursafar et al. 2016), due to their association with a sense of well-being. Green evokes a positive emotional response and is associated with relaxation, calmness, and freshness (Lengen 2015). Red can be perceived as stimulating and also highly rated as distracting (Kwallek et al. 1997). Red may cause avoidance behaviour (Elliot et al. 2007) and one perceives red as a warning cue in performance-related tasks (Maier et al. 2008).

Physiology of the visual system is significantly influenced by the colour, with both neural and photochemical adjustment at the retinal level. A very colourful workplace brings visual complexity, and thus the central nervous system undergoes into a more exciting state, as may be observed from EEG activity. O'Brien (2007) suggested that a blue office is ideal for someone focusing and concentrating on numbers in their work routines. Due to a balancing effect, green is a preferred choice for people working in the management office, and yellow for sales offices. The level of performance, however, depends on the type of task and task demand (Stone 2003), and also one's stimulus screening ability (Kwallek et al. 2007). Red enhances cognitive task performance, whereas blue enhances creative task performance (Mehta and Zhu 2009; Dul et al. 2011). Therefore, a right balance of warm and cool colours can positively induce a response to the visual system, increase comfort (Lebedkova et al. 2012), influence work performance and productivity (Ozturk et al. 2012).

Assessment Methodology

Besides, the colour rendering metrics to assess visual and colour comfort, there are physiological as well as psychophysical approaches to evaluate human responses to colour. These are (a) emotion and environment assessment, (b) performance or non-performance analysis, (c) objective physiological assessment, and (d) actual or simulated scenario assessment. Since the effects of colour on human responses depend on the duration of exposure, any deviation in the emotional or psychophysiological state are evaluated with a temporal factor in consideration (Jin et al. 2005; Küller et al. 2006; Stone 2003). The assessment may include:

- *Emotion and environment assessment*—using checklist technique, mood state fluctuations are explored about the visual environment. The multiple effect adjective checklist, the pleasure–displeasure, arousal–non-arousal, and dominance–submissiveness) are the subjective measures of mood and emotion.
- *Performance or non-performance analysis*—performance characteristics are evaluated using structured, psychological tests, such as learning performance, achievement task, IQ test, motor task and productivity (Tsunetsugu et al. 2005; Jin et al. 2005).
- *Objective physiological assessment—e*xperimentation may include recording EEG, neuroimaging with optical topography, and near-infrared spectroscopy to study the cerebral hemodynamic responses to the central nervous system activity (Tsunetsugu et al. 2005). Using neuroimaging technique, Aoki et al. (2011) viewed that the brain's prefrontal cortex activity has an association with mood–cognition interaction in human behaviour. Besides, cardiorespiratory responses

and skin conductance indicate the sympathetic and parasympathetic activity (Jin et al. 2005).

- *Actual or simulated scenario*—examining actual settings, such as offices or working area, and also under simulated settings (Elliot et al. 2009; He et al. 2011; Read 2010).

Colour Rendering: Metrics and Indices

Colours in the environment, of objects and human skin, shall be rendered naturally and correctly. The chromaticity and the colour rendering properties are the two metrics, concerning colour and light sources. The colour appearance of a near-white lamp or transmitted daylight refers to the chromaticity of the light emitted, which is described by the correlated colour temperature (CCT). The CCT is expressed as the temperature of the black body Planckian radiator whose perceived colour resembled a given stimulus at the same brightness and specified viewing conditions (CIE/IEC 1987). Accordingly, lamps are divided into three groups (IES 2011), i.e.,

- Higher CCT makes the light look cooler (CCT > 4100 K, cold white perception);
- Lower CCT makes the light look warmer (CCT < 3000 K, warm perception); and
- Neutral (CCT at 3000–3500 K, white perception.

The standard Kruithof curve (Fig. 7.4) indicates colour temperature/illuminance combinations and the related response. The lower and upper shaded areas of the

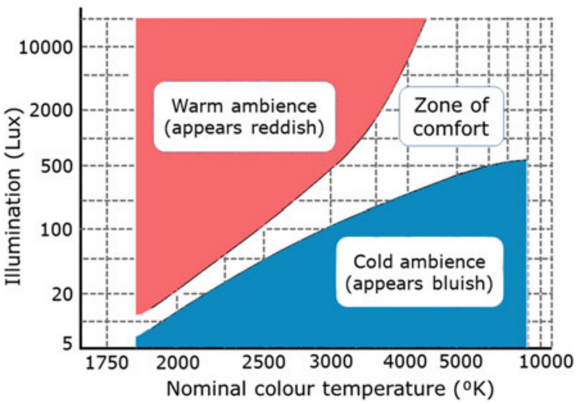


Fig. 7.4 Kruithof curve, indicating colour temperature/illuminance combinations and related perception

curve are believed to produce cold (bluish) and warm (reddish) ambience, respectively, and the white area represents the preferred zone of the comfort (Boyce 2014).

Different metrics have been proposed to more objectively describe the colour rendering properties of a white light source, such as the colour rendering index, CRI (CIE 1995), the (general) colour quality scale (Davis and Ohno 2010; Davis et al. 2011), the colour rendering capacity (Xu 1984) and the feeling of contrast index (Hashimoto et al. 2007). Readers may refer to some apt documents, e.g., Houser et al. (2013); Smet et al. (2013), and Carlucci et al. (2015), for a brief account of different indices related to assessing the quality of light. Derivation of some of the indices is tabulated below:

Colour rendering index (CRI or R_a) CIE (1974, 1995)	$R_i = 100 - 4.6\,\Delta E_i$ $R_a = \frac{1}{8}\sum_{i=1}^{8} R_i$
Colour quality scale (Q_a) Davis and Ohno (2009)	$\Delta E_{RMS} = \sqrt{\frac{1}{15}\sum_{i=1}^{15}\Delta E_i^2}$ $Q_{a,RMS} = 100 - 3.1\Delta E_{RMS}$ $Q_{a,0-100} = 10 \cdot \mathrm{In}\left[\exp\left(\frac{Q_{a,RMS}}{10}\right) + 1\right]$ $Q_a = M_{CCT} \cdot Q_{a,0-100}$
The feeling of contrast index(*FCI*) (Hashimoto et al. 2007)	$FCI = 100\left[\frac{G(Test)}{G(D65)}\right]^{\frac{3}{2}}$

Most metrics describe subjective aspects of the colour rendition or colour quality of a light source. However, for some precise applications, such as health care, colour reproduction, the colour fidelity has high significance. Poor colour fidelity causes colour distortion and affects critical colour judgement. Also, the lamp manufacturers may require objective measures about a standard reference illuminant, thereby to quantify the influence of a light source on the colour appearance of objects.

CIE Colour Rendering Index (*CRI or R_a*) is a standard metric to characterize a light source to reveal the colours faithfully in comparison with that illuminated an object by an ideal or natural light source. The chromaticity shifts of eight standard colour chips illuminated by a test and reference light sources are determined. A blackbody Planckian radiator is the reference source at *CCT* < 5000 K; otherwise, a CIE daylight illuminant is matched to the *CCT* of the test source. Accordingly, the chromaticity between each of the eight standard colour chips, ΔE_i, R_i, and C*RIs* (R_a) is computed and averaged.

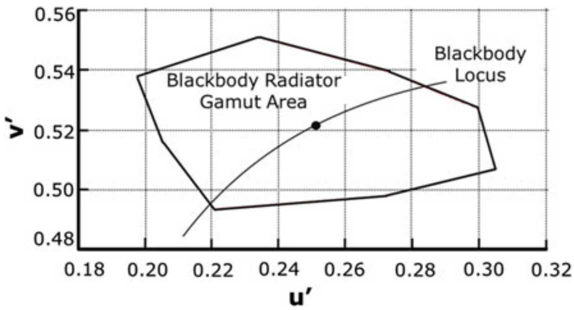
When a lamp renders the colour of the chips identical to the reference light source or a black body, its R_a value is 100, and numerically, this is the highest possible. A light source that does not render the colour points precisely as rendered by the black body, the R_a falls below 100. CRI of fluorescent lamps ranges from $\sim$50 to >90 for the best multi-phosphor lamps. Typical LEDs have R_a exceeding 80 to >95. The importance of R_a depends on the extent to which colour distinction is critical to the visual tasks, and R_a > 70 is needed to achieve visual comfort. The values >90 are considered excellent, which may be required to perform colour critical tasks, 80–89 as good, and 70–79 as acceptable (US-DoE 2012).

Colour rendering properties of a light source vary with applications and human personal perception. Therefore, the design specifications of lamps may be examined against the authenticated R_a and CCT data. The CRI has some limitations since the test colour samples are not very saturated. The ability of CRI to predict colour appearance has been criticized (Sándor and Schanda 2006; Smet et al. 2011, 2013) due to its limitation in correlating well with the visual colour rendition of spiked or narrow band sources such as tri-band fluorescent lamps and LED.

Gamut area is another measure of colour rendering, defining the bounded polygon of the rendered colour points in a two-dimensional space (Fig. 7.5). Different sets of colours generate different gamut areas. *Gamut Area Index* (*GAI*) is usually calculated from the gamut area formed by the chromaticity coordinates of colour samples to that of the gamut area formed by the reference eight colour sources used to calculate CRI. A light source with CRI of 100 would also have corresponding GAI. The larger gamut area usually means higher GAI. Halonen et al. (2010) viewed that CRI in conjunction with GAI may be useful to predict subjective judgements of colour discrimination and saturation of colours. This metric is fast becoming popular in evaluating light sources, and particularly in printing sectors to evaluate the amount of colour that is reproduced.

(*General*) *Colour Quality Scale* (Q_a) derives a single number output, in which the reference light source is matched to the *CCT* of the test source. The root-mean-square deviation (ΔE_{RMS}) of the colour differences ΔE_i is computed, taking 15 colour sample illuminated by the test source and the reference illuminant corrected with the saturation factor. The $Q_{a,RMS}$ is computed similarly to the one used in *CRI*. The scaling factor (3.1) has been chosen to Q_a equal to *CRI* for standard fluorescent lamps. Using a normalized equation, $Q_{a,0-100}$ is derived, and adjusting with the *CCT* factor (M_{CCT}) for those illuminant characterized by a *CCT* < 3500 K, the Q_a as the single value output is obtained. Further, Davis and Ohno (2013) proposed other two indices, namely the *colour fidelity scale* to assess the faithfulness of object colour appearances and *colour preference scale*. It is noted that people's preferences in the magnitude and direction of chromaticity shift vary at different CCTs.

Fig. 7.5 Gamut area of a blackbody radiator with a CRI of 100. The bounded area represents colour rendering references of eight standard colour chips which represented in x-y-axis as u′ and v′ colour space



The feeling of contrast index (*FCI*) estimates colour discrimination or visual clarity of a light source. As shown in the derivation above, the FCI is computed by scaling the gamut area of a test light source, G (Test) to that of the D65 reference light source, G (D65). Both are assessed for an illuminance level (E) of 1000 lx produced on a given colour sample. The two gamut areas are calculated for four saturated colours (red, yellow, green, and blue), corresponding to the Munsell notation: 5R 4/12, 5Y 8.2/10, 5.5G 5/8, and 4.5PB 3.2/6, respectively.

Discomfort Glare in Office Interiors

Glare is a light phenomenon that defines "*the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility*" (IESNA 2000). Direct glare occurs due to poorly positioned light sources in the field of vision. Indirect glare, also known as (a) reflected glare may be caused by reflections from light sources or surfaces of excessive brightness, and (b) veiling glare as bright light is reflected from polished, shiny or glossy surfaces and computer screens. Both direct and indirect glare can cause annoyance, discomfort and other health symptoms such as a headache, visual fatigue, and a decrease in visual performance (Osterhaus 2005).

Disability glare or physiological glare is familiar in exterior lighting. In interior workplaces, *discomfort glare* or *psychological glare* may arise from bright luminaries or windows. This disturbance of glare gets mitigated by the reduction in the retinal illuminance, for example, darkening the too bright part of the visual field and lowering the luminance of the entire field of view. Indirect lighting systems, such as shielding of lamps and luminaires, dimming the general and task lighting, substantially reduce glare in the office interiors (IES 2011). Example of glare sources in daylighting is the view of the bright sky through a window or skylight, and this can be minimized using shielding the open sky by louvres, other shading devices, curtains or cross-lighting of the surroundings.

Sitting at a chair–desk complex, one may look straight at a distant object easily, where there is no glare on the light path. With the blocking of the light path, one may find more comfortable to see distant objects, indicating that the light fixtures are probably producing glare (Fig. 7.6). Also, when one looks at the task from sitting position, it can be easily seen if there is no reflected glare. Where the details of work on the work surface can be seen much easier by blocking the light falling on the surface, either from the front or above, this would indicate the reflection glare as a likely problem source.

By placing a mirror face up on the work surface, if the mirror reflects light from above, the light fixture is probably producing glare. The glare situations can be obviated using several simple workplace practices, for example,

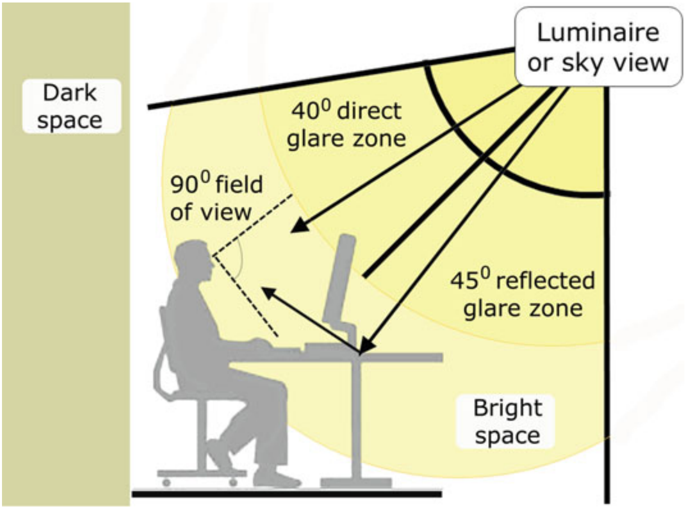


Fig. 7.6 Direct and reflected glare

- Using some small low-intensity light fixtures rather than one large high-intensity light fixture; using indirect light fixtures or direct light fixtures with parabolic louvres;
- Reflected and veiling glare can be minimized by workplace design, with respect to luminance control of luminaires, windows, and roof lights. The light fixtures should not be in the front or directly overhead, to reduce reflected light that is directed on the eyes. Workstations may be positioned in the manner that windows and overhead fluorescent tubes are parallel to the person's line of sight.
- The brightness around the area of glare source may be increased. Adjustable local lighting with brightness controls is useful. Highly polished and shiny objects/surfaces may be replaced with semi-gloss paint and matte finishes.

Assessing Glare

Individuals have high variability about discomfort glare perceptions. Different discomfort glare indices essentially attempt towards estimating the degree of perceived discomfort. Four physical quantities are primarily considered in the assessment and prediction of the degree of perceived discomfort glare. These are (a) the luminance of the glare source, (b) the adaptation of the eyes against the luminous flux reaching the eyes, (c) the solid angle subtended by the glare source, and (d) the position index concerning the displacement of glare sources from the field of vision. A general form of glare indices combine these factors (Osterhaus 2005), i.e.,

$$G = \left(\frac{L_s^e \cdot \omega_s^f}{L_b^g \cdot f(P)} \right)$$

where

- L_s is the luminance of the glare source (maximum luminance from the observer's point of view);
- L_b is the background luminance (average luminance in the field of view with removing the glare source);
- ω_s is the solid angle (steradian) subtended by the source or the size of glare source to the observer's eye;
- P is the Guth position index that accounts for the location of individual luminaires from the line of sight; and
- exponents (e, f, and g) are the weightings to different factors.

This general model applies to most glare indices, such as British Glare Index (*BGI*), Daylight Glare Index (*DGI*), CIE Glare Index (*CGI*), CIE Unified Glare Index (*UGR*), indicating that the glaring risk increases with the more significant and brighter light sources. The glare risk decreases by moving the glare source away from the centre of the visual field and making the background luminance brighter.

Luminance ratio—The human visual system cannot adequately adapt to varying luminance levels at the same time. The concept of the luminance ratio is about the luminance between any two areas in the visual field. The ratio has to remain in a reasonable level to prevent glare caused from any massive contrast. The visual field may be subdivided into zones, as (a) the *central zone,* where the visual task takes place; (b) the *adjacent zone* delimited by a cone of 60°; and (c) the *non-adjacent zone*, delimited by a cone of 120°.

The luminance ratio "1:3:10" is a rule of thumb in different standards. According to IES (2011), to maintain proper lighting quality, the luminance ratios should not exceed:

- 3:1 or 1:3 between a paper task and an adjacent VDT screen, or between a visual task and the adjacent surfaces; and
- 10:1 or 1:10 between a visual task and remote surfaces.

To minimize VDT glare/veiling reflections, the luminance ratios between a brighter ceiling and wall zone and a dimmer ceiling and wall zone should not exceed 4:1 in a critical situation and 8:1 in a typical normal situation. However, there exists a relationship between the preferred luminance ratios and the visual interest of a scene. Situations like daylight or artificial light may not have the same effects on people's perception, suggesting that the stated rule of thumb has personal influence.

Besides luminance ratio, the emphasis has also been placed on the absolute luminance in defining an upper limit of the glare factor in a glare scene (Suk et al. 2013). In predicting and quantifying levels of daylight glare in office spaces, Suk et al. (2016) described the absolute and relative glare factor-based equations to evaluate perceived glare levels. Absolute and relative glare factor zones displayed on a scatter plot visually explain which factor is more dominant to cause discomfort glare, and this approach was used to understand causes of daylight glare and solutions to avoid glare issues in buildings. Shin et al. (2012) proposed 3200, 5600, and 10,000 cd/m^2, respectively, as thresholds for *acceptable, just uncomfortable and intolerable glare*. Wienold and Christoffersen (2006) proposed 2000, 4000, and 6000 cd/m^2 for the corresponding three categories. Several widely used glare indices are elaborated in Table 7.2.

British Glare Index (*BGI*)*, also* referred to as the IES glare index, was developed for small light sources, particularly for artificial light sources (Hopkinson and Collins 1963). *BGI* is a three-step scale, such as 10, 28, and 30 indicating imperceptible glare, just intolerable (Osterhaus 2005; Fisekis et al. 2003), and intolerable glare (Boyce et al. 2006), respectively. *CIE Glare Index* (*CGI*) *is a* new index for BGI of multiple glare sources that ranges between 10 (imperceptible glare) to 34 (intolerable glare). *Daylight Glare Index* (*DGI*) is an amendment of the CGI to predict glare from large sources (e.g., window). DGI values indicate several levels of glare discomfort, and a level of 22 is considered a reasonable acceptability threshold, referring to uniform light sources.

Chaiwiwatworakul et al. (2009) devised a programme controlled horizontal Venetian blind system, integrated onto the glazed windows and found that such window system with automated blind enabled over three-fourth of energy savings and attained the quality of interior daylight illuminance and maintained associated glare.

DGI is not reliable in case of non-uniform sources. *New Discomfort Glare Index* (DGI_N) is a modified index of DGI. The form of expression of BGI closely resembles the CIE (1995) proposed *Unified Glare Rating* (*U*GR). The UGR reference values for different visual tasks and activities are listed in Chap. 8, according to EN 12464-1 (2011). The UGR is suitable to assess small glare sources due to artificial light sources. Similar to CGI, the values of the UGR form a series ranging from 10 (imperceptible) at increments of 3 indicating noticeable changes in the glare, up to 34 (intolerable), (CIE 117 1995). Like *CGI*, a UGR value of 19 is typically the central frontier between comfort and discomfort glare (Cai and Chung 2013). *The* UGR_{small} is proposed for use with small light sources with A_0 lower than 0.005 m^2. For large light sources (luminaires with the area greater than 1.5 m^2), Great-room Glare Rating (*GGR*) has been suggested (CIE 146/147 2002). The indices, *UGR, GGR,* and UGR_{small}, however, provide the same level of discomfort glare.

The working groups of the IESNA have maintained some approaches that differ from those of the CIE, regarding glare rating issues (Rea 2000). IESNA used the term *visual comfort probability* (*VCP*) index, as against to UGR (CIE 1995). The VCP aims at a rating of a lighting system as the percentage of people who,

Table 7.2 Numerical derivation and approximation of glare indices

Indices	Equations	Abbreviations used
BGI (British Glare Index) Petherbridge and Hopkinson(1950)	$= 10\log_{10}\left[0.478\sum_{i=1}^{n}\left(\frac{L_{s,i}^{1.6}\cdot\omega_{s,i}^{0.8}}{L_b\cdot P_i^{1.6}}\right)\right]$	Where subscript *s* and *i* are the quantities depending on the observer position and the light sources; $\omega_{s,i}$ is the solid angle subtending each source from the observer; *P* is the Guth position index expressing the dependence of perceived discomfort glare on the position of the source *i* with respect to the observer; $L_{s,i}$ is the luminance in the direction connecting the observer with each light source; L_b is the background luminance that, for windows, is the average luminance of the wall excluding the window; E_d and E_i are the illuminances due to direct and diffuse light, respectively
CGI (CIE Glare Index) Einhorn (1979)	$= 8\log_{10}\left[2\frac{1+(E_d/500)}{E_d+E_i}\sum_{i=1}^{n}\left(\frac{L_{s,i}^{2}\cdot\omega_{s,i}}{P_i^{2}}\right)\right]$	
DGI (Discomfort Glare Index)	$DGI = 10\log_{10}\left[0.478\sum_{i=1}^{n}\left(\frac{L_{s,i}^{1.6}.\omega_{s,i}^{0.8}}{L_b+0.07\omega^{0.5}.L_{win}.P_i^{1.6}}\right)\right]$	$\omega_{s,i}$ is the solid angle subtending each source from the observer, modified with respect to the field of view and Guth position index of each luminaire, *i*; L_{win}, the luminance from large sources (e.g., window)
DGI_N (New Discomfort Glare Index) Nazzal (2005)	$DGI_N = 8\log_{10}\left\{0.25\frac{\sum_{i=1}^{n}L_{exterior,i}^{2}.\Omega_{pN}}{L_{adaptation}+0.07\left[\sum_{i=1}^{n}\left(\omega_{N,i}.L_{window,i}^{2}\right)\right]^{0.5}}\right\}$	$\omega_{N,i}$ is the apparent solid angle of each source, from the point of observation; Ω_{pN} is the corrected solid angle subtended by the source; L_{window}, $L_{adaptation}$, $L_{exterior}$, respectively, are the vertical luminance of the window surface, surroundings, and outdoors due to direct sunlight, diffuse light from the sky and reflected light from other external sources; $L_{adaptation}$ replaces background luminance (L_b)
UGR *(Unified Glare Rating)* (CIE 117, 1995)	$UGR = 8\log_{10}\left[\frac{0.25}{L_b}\sum_{i=1}^{n}\left(\frac{L_{s,i}^{2}.\omega_{s,i}}{P_i^{2}}\right)\right]$	$L_{s,i}$ is the luminance of the luminous parts of each luminaire in the direction of the observer's eye; $\omega_{s,i}$ and *P* are the solid angle (steradian) and Guth position index of each luminaire

(continued)

Table 7.2 (continued)

Indices	Equations	Abbreviations used
Great-room Glare Rating (GGR) and UGR_{small} *CIE 146/147* (2002)	$GGR = UGR + 8\left(1.18 - 0.18\frac{A_1}{A_0}\right)\log_{10}\left[\frac{2.55\left(1+\frac{E_d}{220}\right)}{1+\frac{E_d}{E_i}}\right]$ $UGR_{small} = 8\log_{10}\left[\frac{0.25}{L_b}\sum_{i=1}^{n}\left(200\frac{I_i^2}{r_i^2.P_i^2}\right)\right]$	A_0 is the projected area of the glare source towards the nadir and A_1 *is* the room floor area divided by the number of glare sources. UGR_{small} applies to small light sources with A0 lower than 0.005 m^2; I_i is the luminous intensity of the light source causing glare, and r_i is the distance between the light source and observer's eyes
Visual Comfort Probability (VCP) index IESNA (2000)	$M = \frac{0.5L_{s,i}}{P.L_{vf}^{0.44}}\left(20.4\omega_{s,i} + 1.52\omega_{s,i}^{0.2} - 0.075\right)$ $L_{vf} = \frac{L_w.\omega_w + L_{fc}.\omega_f + L_{cc}.\left(\omega_c - \sum_{i=1}^{n}\omega_{s,i}\right) + \sum_{i=1}^{n}\left(L_{s,i}.\omega_{s,i}\right)}{5}$ $DGR = \left(\sum_{I=1}^{n} M_i\right)^{n^{-0.0914}}$ $VCP = 279 - 110(\log_{10} DGR) + C$	$\omega_{s,i}$ is the solid angle subtended by luminaires from observer's position, in sr; L_{vf} is the average luminance (cd/m^2) of the visual field, assuming that the amplitude of the entire field of view is 5 sr; L_w, L_{fc}, L_{cc} are the wall, floor cavity, and ceiling cavity luminance, ω_s, ω_f, ω_c are the solid angles subtended by walls, floor, and ceiling. The constant C varies with the DGR (IESNA 2000). $C = 0, when\, 55 \leq DGR \leq 200$ $C = 350(log_{10}DGR - 2.08)^5 when\, DGR\langle 55\rangle 200$
Discomfort Glare Probability (DGP) Wienold and Christoffersen (2006)	$= 5.87.10^{-5}E_V + 0.0918.\log_{10}\left[1 + \sum_{i=1}^{n}\left(\frac{L_{s,i}^2.\omega_{s,i}}{E_v^{1.87}.P_i^2}\right)\right] + 0.16$	E_v is the vertical eye illuminance, produced by the light source (lux);
Simplifications of DGP (DGP_s)	$DGPs = 6.22 \cdot 10^{-5} \cdot E_V + 0.184$ (Wienold et al. 2007) $DGPs = 5.87 \cdot 10^{-5} \cdot E_V + 0.16$ (Hviid et al. 2008)	
J-Index Meyer et al. (1993)	$= \frac{(A_{max} - A)}{A_{max}}$ $A = A_{max} \cdot \check{r}_1 \cdot (C_1) \cdot \check{r}_2 \cdot (C_2) \cdot \check{r}_3(E_P)$	A_{max} is the maximum possible visual acuity; A is the visual acuity that a person would reach in a given light condition; C_1 and C_2 are the contrasts between the target and the background, and between the background and its surroundings, respectively; Ep is the pupil illuminance, and r_1, r_2, and r_3 are the relative influences of C_1, C_2, and E_p on the visual acuity

when viewing from a specified location and direction would consider comfortable to a given luminous environment. Arriving at VCP estimates, there are several intermediate steps of numerical approximation (as elucidated in Table 7.2), beginning to estimating glare sensation index (*M*). Summating *M* values for *n* glare sources within the visual field, the *discomfort glare rating* (*DGR*) is obtained, from which VCP is estimated. *VCP* was developed to assess ceiling-mounted luminaires with uniform luminance (Harrold and Mennie 2003) and accompanied with an assessment scale (0–100). VCP may not be useful in evaluating glare with non-uniform, very large or small light sources, or daylight. Differences in the *VCP* values of two lighting systems higher than 5 units would be taken as significant.

Most glare indices focus on the contrast ratio between the glare source luminance and average background luminance. *Discomfort Glare Probability* (DGP) has a distinctive formulation with the inclusion of the level of E_v perceived by the observer (Wienold and Christoffersen 2006). Further *simplifications of DGP* (*DGP_s*) *have been suggested by* Wienold (2007) and Hviid et al. (2008). Refer to the mathematical derivation given in Table 7.2, where the middle logarithmic expression of DGP relating luminance and solid angle of the source, has been neglected in the simplifications, whereby the derivation is formed as a linear equation based on the level of E_v. This simplified index may be useful when there is no direct sun or specular reflection in the visual field. *J-Index* (Meyer et al. 1993) applies to express the difference between the maximum possible visual acuity (A_{max}) and the visual acuity (A) a person reaches in a given light condition. In other words, the J-Index refers to evaluating discomfort glare to the effects of non-optimal light conditions, i.e., insufficient or excessive luminance and non-adapted contrast.

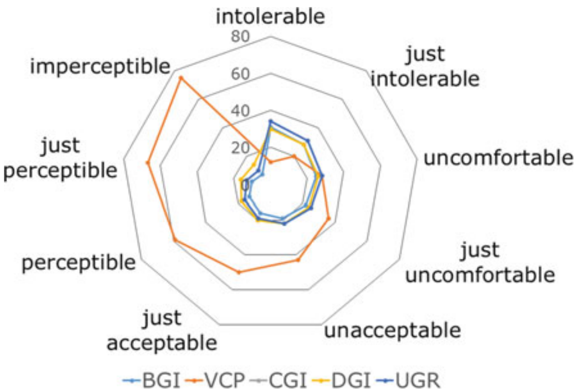


Fig. 7.7 Comparison of discomfort glare-related indices

The glare-related indices described above may be arranged on a nine-point glare sensation scale on three-unit increment (Carlucci et al. 2015), and normalized in 100-point scale in a polar graph, as shown in Fig. 7.7. Analysis substantiates that there is a general agreement on the factors that cause glare. Different formula evaluate discomfort glare differently, making difficult to generalize. The rating by VCP deviates widely from other indices. Glare ratings using UGR of the CIE are widely used in different countries, whereas the VCP of the IESNA is proposed in the case of USA and Brazil.

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Chapter 8
Visual Performance in Office

Introduction

Lighting is a recognized concern in our office environment. Towards optimizing energy use for lighting in an office building, emphasis focuses on the lighting levels and characteristics, and also of the efficiency and utilization factor with which the lighting is provided. On the one hand, optimal use of lighting has physical, physiological, and psychological effects on employee comfort, satisfaction, and visual performances, and overall organizational productivity through reduced operational costs. On the other hand, inappropriate lighting characteristics, such as level of lighting patterns and distribution, glare, shadows, flicker, and colour appearance, culminate into one's physical discomfort, health effects (such as visual fatigue, eye strain, cognitive dysfunctions) and negative influence on satisfaction and task performance.

Physiology of the visual system amply indicated the human quality of visual perception is the function of photoreception, depending on the distribution of the photoreceptors, such as cones and rods on our retinal surface. Cones are more active at high light levels, whereas rods are more active low light levels, and all the rod photoreceptors have similar spectral sensitivity. There are three different types of cones (S-, M-, and L-cones), having different photopigments, spectral sensitivities, and wavelengths. The distribution of photoreceptors varies along the retinal surface, with cones densely populated at the centre of the retina (fovea), gradually diminishes its density along the peripheral end of the retinal surface. There is no presence of rods in the fovea region. The presence of high density of cones results in finer resolution and colour vision in the fovea region of the retina. For better visual acuity and colour perception, therefore, office illumination should be kept within cones dominated photopic vision (i.e., adaptation luminance >3 cd/m^2). In other words, the tasks should be held in the central area of the visual field so that the retinal images of tasks fall in the fovea. Where both cones and rods are active (mesopic vision), the adaptation luminance is between 0.001–3 cd/m^2, which may

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not be very common in offices. Rods are dominant at the peripheral end of the retinal surface (scotopic vision), where the adaptation luminance is lower than 0.001 cd/m^2. The condition creates poor acuity and no recognition of colour.

The human visual system employs the process of adaptation, such as the neural and photochemical adaptation, in adjusting to lighting conditions. When a person is exposed to a new lighting condition, the size of the iris gets constricted or dilated in fractions of second, to decrease or increase retinal illumination. Both neural and photochemical adaptation simultaneously set in to adjust to retinal illumination. While the neural adaptation involves faster process (<250 ms) of synaptic interactions in the retina, photochemical adaptation takes place depending on the light absorption and reactions of pigments in the photoreceptors (Boyce 2014). As long as the changes of retinal illumination are within the range of photopic vision, the adaptation gets completed in less than a minute. For the foveal adaptation, sensitivity increases rapidly, and after about 100 s, the sensitivity remains constant. When the light level changes beyond the range of photopic vision, photochemical adaptation is necessary, and as a result, the adaptation time may be much longer. Usually, dark adaptation requires a longer time (about 20 min). The lighting conditions have effects on visual performance. Coloured objects appear differently at different illumination in typical colour rendering situations (Davis and Ohno 2009). This phenomenon is consistent with the Hunt effect (i.e., the colour saturation decreases with the lowering of light intensity) and Bezold–Brucke effect (hues shift with changes in luminance).

Aberration and imperfection of human eyes affect visual performance. Ageing affects visual acuity with peaks in the twenties and declines with the advancing age. The abnormal colour vision includes anomalous trichromatopsia, achromatopsia, and dichromatopsia. The majority of people who have abnormal colour vision are anomalous trichromats, and their colour vision differs from the normal one. Monochromats have no colour vision. However, there may be some people with partial achromatopsia that can be identified through anomaloscope or 100 hue testing (Pickford et al. 1980; Bose et al. 1984). These groups of people can match lights, only by adjusting the intensities. Dichromats can match any light with a mixture of two primary lights.

Lighting Conditions and Performance

The changing nature of office activities and the development of new electric lighting designs suggest potential linkages between lighting characteristics, energy saving, task effectiveness, and organizational productivity. A holistic approach is called for an affirmative understanding of the implications of different kinds of light choices on visual performance, including health, and comfort of occupants in an office building. Over the decades, a substantial amount of experimental research has gone into the variable light and colour patterns, creating different kinds of visual interest. Generally viewed that office occupants prefer higher luminance surfaces, provided there is no glare on the work surface, however, considerable variation in luminance may create adaptation difficulties for the eye and possible dissatisfaction. Concerning the practices of office lighting systems, quality of lighting, and colour characteristics of office interiors, some findings of contemporary research are briefly described herewith.

Veitch and Newsham (1998) tested nine lighting systems, in combinations of three lighting power densities (LPDs) and three designer lighting qualities. That is, (i) recessed troffers with prismatic lenses, (ii) recessed troffers with parabolic louvers, and (iii) indirect or direct/indirect luminaires. A total of 150 men and 142 women (aged 18–61 years) volunteered to perform work in an open-plan office space containing six workstations, for a single day at one of the nine lighting conditions. The volunteers underwent visual performance tests in the morning and afternoon and performed computer- and paper-based office tasks. They completed questionnaires to assess satisfaction about lighting quality, mood, comfort, and social behaviours. The study indicated that the energy-efficient and good-quality lightings were compatible. In computer-based work, men and women had better verbal intellectual and clerical task performance in parabolic-louvered luminaires, as compared to those in recessed prismatic lensed luminaires.

Boyce et al. (2006a, b) described two experiments about the effects of lighting quality on office worker performance, health, and well-being. In one experiment, four lighting conditions were chosen. That is, (i) regular array of fully direct recessed parabolic luminaires, (ii) direct/indirect luminaires with no control, (iii) direct/indirect luminaires with a switchable desk lamp, and (iv) workstation-specific direct/indirect luminaires with control on the direct luminaires. The second experiment covered two conditions, i.e., a regular array of recessed prismatic lensed luminaires and suspended direct/indirect luminaires, with no lighting control. Generally, direct–indirect lighting system and personal control were favoured by the workers, in comparison to the direct-only systems. While the investigators did not observe simple main effects of lighting quality on task performance, however, interactions between lighting quality and individual control of lighting influenced motivation and vigilance over the day. Veitch et al. (2008) reported regression analysis of the two experiments (six conditions) and showed that improvement in visibility by the lighting conditions improved the task performance. The office lighting perceived by temporary workers as having higher quality was rated as more attractive and pleasant, and also these workers showed greater well-being at the end of the day.

Newsham et al. (2008b) examined the relationship between illuminance and occupant satisfaction, from the study on 779 workstations in nine buildings. The study observed that illuminance in the range of 300–500 lx reduced the risk of dissatisfaction with lighting. The presence of veiling reflections from VDT screen and one’s lack of access to a window were recognized as the most significant risk factor for dissatisfaction. However, present-day workstation/laptop LCD screens have lower reflectivity, and thus obviate the stated problem issue.

Buchner and Baumgartner (2007) used a proofreading task presented on a TFT monitor, to test if text-background polarity, such as dark text on light background or light text on dark background affects performance. The subjects performed the task without a time limit and then repeated with a time limit. The task performance with positive polarity, i.e., dark text on a light background, was found better. Kwallek et al. (2007) conducted a large-scale study focusing on the effects of interior colour schemes, such as white, predominately red, and predominately blue-green on week-long worker productivity regarding task performance and accuracy. The workers were assigned to perform simulated office tasks for four consecutive days. In three different office tasks, the influence of interior colours on productivity was dependent upon the individual's environmental sensitivity, such as stimulus screening ability, and time of exposure to interior colours.

Ample literature explores the efficacy of different lighting control systems, such as daylight-linked automatic lighting control, dimming control, and occupancy-based lighting controls at different spatial levels, namely individual workspace, room and building zones. A lighting system linked with occupancy sensors has been found to save energy between 20 and 60%. Savings depend on the lighting system configuration, type of space, occupancy pattern, and type of sensors used (Chung and Burnett 2009; de Bakker et al. 2017). Review by Haq et al. (2014) and Guo et al. (2010) elucidated different occupancy detection techniques and their energy saving. Passive infrared sensors are the dominant detection systems used in office buildings. However, advanced detection techniques, such as chair sensors (Timilehin et al. 2015), radio-frequency identification (Manzoor et al. 2012) are available to track occupants at different building zones and, accordingly, enable light control (Li et al. 2012).

In the context of examining the controls of electric lighting in a daylit space, Newsham et al. (2008a) involved 40 participants who were asked to use dimming control every 30 min over electric lighting, according to one's preferred light level in a glare-free, daylit laboratory for the whole day. Luminance maps were generated using a high-dynamic range digital camera. Findings of the study depicted the negative correlation between the prevailing desktop illuminance and change in dimmer setting. However, manual dimming control reduced energy use by one-fourth, as compared to a fixed electric lighting (500 lx) on the desktop. Galasiu et al. (2007) carried out a study in an open-plan office building equipped with suspended direct–indirect luminaires attached with occupancy daylight sensors, located at cubicle workstations, and dimming controls were done through occupants' computer screens. Observations from 86 workstations over a year indicated that the energy savings and power reduction were attributable to the controls used. The installed lighting power was 42 and 47% lower with the combined use of three sensor controls, compared to the same lights used at full power during work hours. There were an overall energy savings of about 66% (35% for occupancy sensors; 20% for light sensors; and 11% for dimming control), and higher occupant satisfaction, as compared to the conventional fluorescent lighting system. Thereby, an average effective LPD was 3 W/m^2.

Questionnaire Survey

The questionnaire survey is a practice to evaluate satisfaction and physical comfort, concerning the effects of lighting environment. Subjects may be asked to rate their satisfaction, comfort, and aesthetic impression of the room on a defined scale. Newsham and Veitch (2001) rated the task difficulty, productivity, mood, and satisfaction of subjects towards the work environment and workspace lighting. Newsham et al. (2004) asked open-ended questions to subjects to rate their pleasure, arousal, and dominance factors on an 8-point scale, the room appraisal on a 0–100 scale, the workplace satisfaction on a 4-point scale, lighting control quality on a 5-point scale, and two-choice lighting preferences. Moore et al. (2004) used questionnaires to evaluate user attitudes towards lighting conditions and controls in 14 office buildings in the UK. Sheedy et al. (2005) conducted a study about visual effects of the luminance surrounding a computer screen. The subjects rated symptoms including pulling, burning, ache, strain, irritation, and pain on a 0–100 scale. A simplified questionnaire, containing eight sub-sections and 21 items of inquiry, is given here for undertaking a survey of lighting quality and task satisfaction in an office environment (Table 8.1). The questionnaire may also be adopted by suitably incorporating a rating scale.

Table 8.1 Questionnaire on lighting quality and task satisfaction survey

Lighting survey		Response (5-point Likert agreement scale), as applicable
Light level	Uncomfortable bright light at the work surface	—
	Uncomfortable dim light at the work surface	—
Light distribution	Non-uniform and poorly distributed lighting	—
	Deep shadows in the work areas	—
	The marked contrast between the task and background	—
Glare	Reflections from the light fixtures	—
	A too bright light fixtures	—
	Glare from window-workstation positions (in front, behind, and to the side)	Mention window location
	The absence of glare filter (glass/mesh) on the VDT	—
CRI	An unnatural tone of human skin under the lighting	—
	Coloured objects look unreal or less legible	—

(continued)

Table 8.1 (continued)

Lighting survey				Response (5-point Likert agreement scale), as applicable
CCT	Lighting is too warm			—
	Lighting is too cold			—
	Lighting colour temperature is inappropriate			—
Other physical factors	Lights flicker (including VDT)			—
	Humming noise from the lighting system			—
	Window light control: (curtains, blinds, desk lamp/task light)			Mention, as applicable
Overall attitudes	Lighting is comfortable			—
	Lighting in the workplace/workstation is acceptable			—
	One likes to live and work in the present lighting environment			—
	Adjustability of height and slope of the VDT			—
Task satisfactions	Colour of the text characters on the VDT			Mention, as applicable
	Colour of the background of the VDT			
	Daily working hours in computer viewing			— hours
	Level of difficulty in the VDT task			—
	Level of satisfaction in task performance			—
	Difficulty in the colour matching task			—
	Level of satisfaction in colour matching task performance			—
	Viewing distance of the VDT screen from eye level			— cm
Ocular symptoms	Eye strain	Double vision	Headaches	Neck/shoulder ache
	Blurred near vision	Blurred distant vision	Colour distortion	A backache
	Dry eye	Irritated eyes	Light sensitivity	
	Wearing glasses while working on the computer (single vision, bifocal, progressive)			Mention, as applicable
	Wearing contact lenses while working on the computer (soft, gas permeable, hard lenses)			Mention, as applicable

Lighting Regulation for VDT

Long hours of viewing desktop, laptop and tablet computers, electronic book readers, and other hand-held display devices may result in eye strain, headaches, ocular discomfort, dry eye, diplopia, and blurred vision. These symptoms are collectively referred to as computer vision syndrome (CVS). The lighting regulation at VDT workplaces intends to optimizing conditions so that no disturbing reflections and discomfort glare are created from display screens, and work surfaces. As described in Chap. 7, lighting contrasts arise when there is a substantial difference in the illumination from one area to another, and colour contrast of objects. The immediate work area of VDT workstation should usually be brighter than the surrounding areas. Too little contrast between characters on a VDT screen and the background, makes difficult for one to work on the VDT. Such situations can be avoided by (a) increasing the contrast between objects and the background and (b) decreasing reflected glare, for example, using of matte finishes on surfaces and moving away from any shiny objects.

About health and safety requirements for VDT operators, the US OSHA states that the preferred viewing distance for a desktop monitor is between 50 and 100 cm. This distance corresponds to an accommodative stimulus in a corrected individual between 1 and 2 D. The centre of the computer monitor should generally be located 15–20° below the horizontal eye level. The VDT should be so positioned that the downward viewing angle is within 60° (http://63.234.227.130/SLTC/etools/computerworkstations/components_monitors.html). The UK Health and Safety Executive (http://www.direct.gov.uk/en/Employment/HealthAndSafetyAtWork/DG_10026668) and Australian Standards (http://www.gamc.nsw.gov.au/workplace-guidelines/1_GuidelineContent/guidelines_1_07.htm) include guidelines for computer setup and operation.

Limits have been specified (EN 12464-1) for VDT work in an office environment. That is, for VDT where background luminance is ≤ 200 cd/m^2, luminaire luminance may be limited to 1500 cd/m^2; for screens having background luminance >200 cd/m^2, luminaire luminance up to 3000 cd/m^2 is permissible (Fig. 8.1). These levels apply to flat-screen monitors with an excellent anti-glare, i.e., diffusely reflecting finish. For the operators spending long hours at VDT workstations, highly reflecting screens should not be used. Since the laptops and tablet PCs can be set up in multiple angles and direction, users can adjust the position of the screen to avoid disturbing reflections.

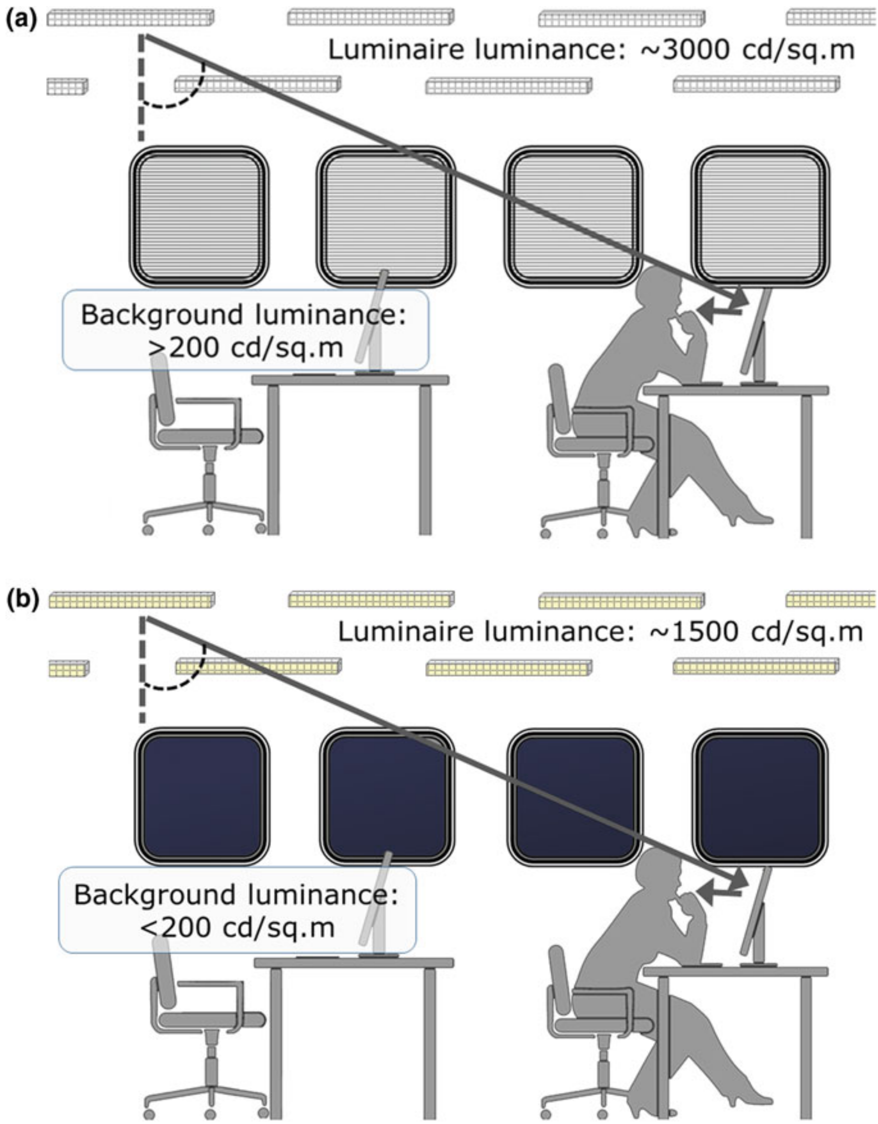

Fig. 8.1 Background and luminaire luminance for VDT work in office environment (EN 12464-1); **a** For VDT with background luminance >200 cd/m^2 (good office lighting), luminaire luminance up to 3000 cd/m^2 is permissible; **b** For VDT with background luminance <200 cd/m^2 (typical offices with average daylight supply), luminaire luminance up to 1500 cd/m^2 is permissible

Computer Vision Syndrome

Computer vision syndrome (CVS), as the name implies, relates to ocular symptoms arising out of ocular (ocular-surface abnormalities or accommodative spasms) and extraocular aetiologies, e.g., incompatible visual environment associated to tedious visual tasks (Blehm et al. 2005). The well-recognized syndrome is prevalent among IT professionals, call centre operators, people in banking and other financial services. Asthenopia (eye strain) is a major complaint among people with CVS, and females have a higher prevalence of such condition (Wiholm et al. 2007; Bhanderi et al. 2008). Symptoms fall into two broad categories, such as external and internal symptoms. The external symptoms, such as eye burning, irritation, ocular dryness, and tearing, are related to dry eye. On the other hand, refractive, accommodative, or vergence anomalies generally cause the symptoms, such as eye strain, headache, eye ache, diplopia, and blur.

Ocular Factors of CVS

The ocular factors, namely inappropriate oculomotor responses and dry eye, may lead to CVS. About 90% of the people who spend three or more hours a day at a computer may be affected by CVS. Inappropriate lighting and excessive glare at workstation are the other factors attributed to CVS (Sheedy and Shaw-McMinn 2003). Uncorrected refractive errors of the eye aggravate the magnitude of CVS symptoms.

Accommodation—Inaccurate accommodative response of the eye, like in case of long hours of viewing at VDT and a fixed viewing distance, may result in CVS symptoms. The presence of any refractive or accommodative anomaly could impact the visual comfort of the computer operators. Investigations have emphasized that when concentrating on an intense visual task at a near fixed distance, the contraction of the ciliary muscle, which adjusts the curvature of the crystalline lens, can cause the eyes to get irritated. Richter et al. (2010) attempted to vary the accommodative stimulus by using the plus and minus lenses and noted that increase in the accommodative response was coupled with increased activity in trapezius muscle and also MSD symptoms. Wiholm et al. (2007) examined 1183 call centre operators and observed a positive association between eye strain and neck–shoulder pain symptoms. There is a possible conjoint relationship of these complaints, for instance, the visual demands at VDT work may result in changes in postural orientation, leading to MSD complaints. However, there is a likelihood that oculomotor fatigue can affect neuromuscular junctions to the neck, shoulder, and back muscles. If one looks at distances periodically, that may result in reducing the accommodation and vergence responses and alleviate the CVS problems.

Vergence—Vergence is referred to as the simultaneous movement of the eyes in opposite directions, and thereby the projection of the image is at the centre of the retina in both eyes (maintaining single binocular vision). As opposed to saccadic movements, vergence is slower. Spending long hours in VDT work would cause vergence anomaly (Watten et al. 1994). Under such condition, clinical assessment includes the near point of convergence, near heterophoria, horizontal and vertical fixation disparity, and vergence ranges.

Dry eye—Corneal drying and eye burning are common symptoms due to an extended period of computer work (Blehm et al. 2005). There might be reduced rate of blinking if the font sizes and contrast are reduced (Gowrisankaran et al. 2007). Apart from reduced or incomplete blinking, there are alternating shorter and longer inter-blink periods (Schlote et al. 2004), indicating possible cognitive adaptation effort (Jansen et al. 2010). Other work environment factors, such as low humidity, forced hot air, excess static electricity, airborne contaminants, may exacerbate symptoms of dry eye. Other clinical conditions may also be present among the CVS-affected computer workers. For example, dry eye conditions can result from reflex hyposecretion of the lacrimal glands or excessive evaporation.

Astigmatism—Some degree of astigmatism are present in most people. However, the presence of uncorrected astigmatism (<1.0 D) may increase CVS. Astigmatism is a condition that causes blurred vision. This condition is

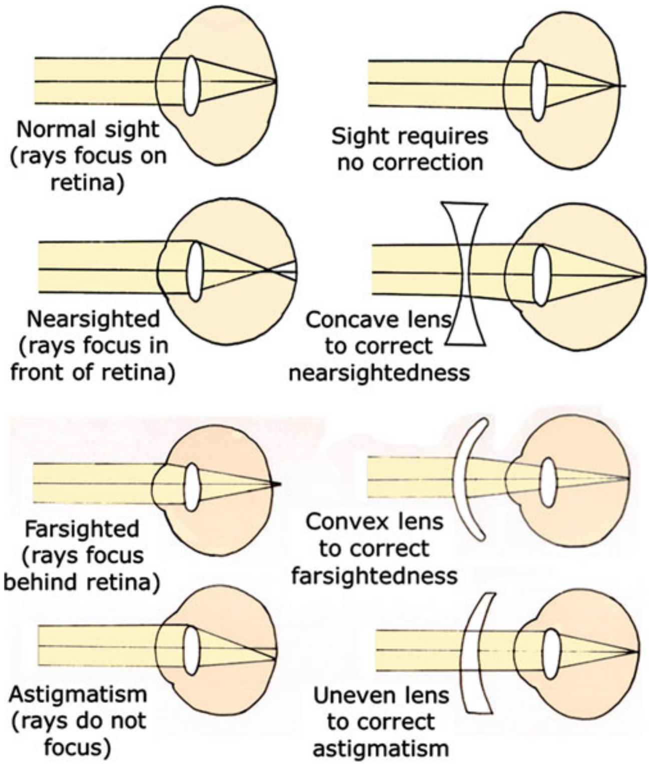

Fig. 8.2 Irregular corneal shape or the curvature of the lens

developed due to the irregular shape of the cornea or the curvature of the lens (Fig. 8.2). Such condition prevents light from focusing appropriately on the retina. Astigmatism occurs with vision conditions, like myopia (nearsightedness) and hyperopia (farsightedness). So that the VDT is focused appropriately, the astigmatic errors may be obviated by suitable selection of the contact lens, spectacle correction, or a non-invasive corneal procedure (orthokeratology). Laser surgery can also treat some types of astigmatism. Persons suffering from astigmatism are generally asked to wear spherical lenses. Wearing contact lens may increase the blinking rate, particularly among new contact lens wearers. With adaptation, however, the blink rate gets lessened. Nichols et al. (2005) affirmatively noted that contact lens wearers are 12 and 5 times more likely than emmetropes (normal refractive condition of the eye) and spectacle wearers, respectively, to report dry eye symptoms.

Presbyopia—Presbyopia is a natural occurrence when the near vision becomes blurred and thus causing difficulty to focus on things. With ageing, the crystalline lens of the eye gets harden and loses elasticity. One loses the accommodative flexibility of the lens to adjust appropriately to focus near objects. Treatment options for people entering into presbyopia include using magnifiers, bifocal or

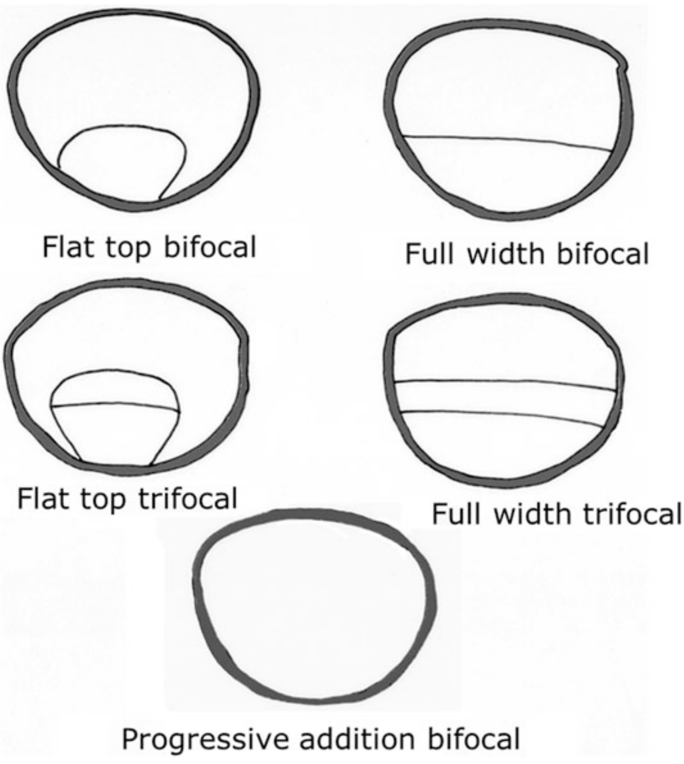

Fig. 8.3 Forms of spectacle corrections

varifocal spectacles, reading glasses, contact lenses, and intra-ocular lenses (Bennett 2008). For people working on the desktop computer, laptop, or other hand-held devices, the correction of presbyopia can be a challenge since these units may be placed at different levels away from the primary gaze. The use of a bifocal spectacle lens for a downward gaze, with a viewing distance of $\sim$40 cm may not be appropriate. For an appropriate spectacle correction (Fig. 8.3), including monovision correction, both horizontal and vertical gaze angle and the viewing distance are considered. Other forms of presbyopic correction include multifocal and simultaneous vision-type lenses (various lens powers are positioned before the pupil) (Wolffsohn and Davies 2010).

Guidance on Illuminance Levels

An emphatic view on lighting design prevails that more lighting is not necessarily better lighting. Different visual tasks need different levels of lighting for the same visual efficiency, and therefore, there is a discernible trend towards more precise focusing of task lighting over ambient lighting. The amount of light required is determined by (a) the characteristics and details of the tasks, contrast, and background, closeness to the eyes, (b) the speed and accuracy required in performing the work, and (c) the ease and comfort of working. Chapter 13 includes different categories of standards that have been evolved from various national and international standards bodies and agencies. Apart from the influence of updated lighting technology, there is no consensus across standards bodies as to the *right* light level for a specific task and building type.

It is understood that the quality of illumination is a function of many factors, including horizontal versus vertical illuminance, glare, contrast, colour rendition, colour temperature, and flicker. Also, human beings differ in their preferences for illumination intensity and quality, about retinal photopic and scotopic sensitivity, and pupillary size (an indicator of brightness perception). Also, age and gender profoundly affect the desired illuminance levels. Human perception of quality of lighting as to one's comfort may also be influenced by the luminance variations of walls and ceilings, immediate and background of workspaces. The recommended lighting levels vary to a great extent with the type of tasks and activities in office and non-residential buildings, residential, school and industrial applications, across countries (Table 8.2). However, new technologies such as daylight-linked controls for artificial lighting systems, occupancy sensors, lighting controls with dimming options, and glazing with variable transmittance are opening up new possibilities for control of lighting to the occupants of buildings. There is a trend towards specifying illuminance for specific types of activities under different work settings. A more holistic approach would demand to combine task varieties and architectural settings to arriving at suitable building illuminance.

One may note the substantial variation in the recommended lighting levels of different task activities and also the differences across countries of Asia-Pacific and

Table 8.2 Recommended lighting levels of different countries for selected building areas

	Standards	General office	VDT tasks	Office desk	Retail store	Hospital—common areas	Hospital—operating room
Australia	AS 1680.2.0 (1990)	160	160	320	160	240	500
Brazil	NBR 5413/82: 1990	750–1000	–	200–500	300–750	75–150	300–750
China	Min et al. (1997)	100–150–200	150–200–300	150	75–100–150	50–200	–
European Union	EN 12464-1 (2011)	500	500	500	300	200	1000
India	CED 46(8030)WC (2015)	300–500–750	300–500–750	300–500–750	300–500–750	200–300–500	750–1000–1500
Japan	JIS 9110 (1979)	300–750	300–750	300–750	150–750	150–300	750–1500
United Kingdom	CIBSE (1994)	500	300–500	500	500–1000	–	400–500
USA/Canada	IESNA 1993	200–300–500	300	200–300–500	200–300–500	100–150–200	1000–1500–2000

Table 8.3 Recommended illuminance levels for selected tasks in the office or allied activities, including industrial applications

Building type	Type of area, task or activity	E_m (lux)	UGR	U_o	R_a
Educational buildings	Circulation areas, corridors, stockrooms for teaching materials, stairs	100	25	0.40	80
	Entrance halls, common rooms, assembly halls, canteens, library bookshelves	200	22	0.60	80
	Classrooms, computer practice rooms, language laboratory, teachers rooms, gymnasium, swimming pools	300	19	0.60	80
	Classroom for evening classes, auditorium, lecture halls, art rooms, laboratories, workshops, handicraft rooms, library reading area	500	19	0.60	80
	Black, green and whiteboards, demonstration table, workshops	500	22	0.70	80
Airports	Arrival and departure, waiting areas, lounge storerooms	200	22	0.40	80
	Security check areas	300	19	0.60	80
	Information desks, check-in and passport control desks	500	19	0.70	80
	The air traffic control tower, testing and repair hangars, engine test areas	500	22	0.60	80
General areas (GA) inside buildings—control rooms	Plant rooms, switch gear rooms	200	25	0.40	60
	Switchboard	500	19	0.60	80
GA—storerooms, cold stores	Dispatch packing handling areas	300	25	0.60	60
GA—storage rack areas	Gangways: manned, control stations	150	22	0.40	60
Healthcare premises (HC)	Corridors, elevators, lifts	100	22	0.40	80
	Corridors, dayrooms, service lifts, waiting areas	200	22	0.60	80
HC—exam. rooms (eye, ear, dermatology), pharmacy	General lighting	500	19	0.60	90
HC—delivery rooms	Examination and treatment	1000	19	0.70	80
	Scanner room: general lighting	300	19	0.60	80
HC—dentists	General lighting	500	19	0.60	90
	At the patient	1000	–	0.70	90

(continued)

Table 8.3 (continued)

Building type	Type of area, task or activity	E_m (lux)	UGR	U_o	R_a
HC—eye/ear examination rooms	Examination of ear/outer eye	1000	–	–	90
	Reading and colour vision tests	500	16	0.70	90
HC—intensive care unit, maternity wards	Simple examinations	300	19	0.60	90
HC—laboratory, pharmacy, operating areas	Colour inspection	1000	19	0.70	90
	Pre-op and recovery rooms	500	19	0.60	90
	Operating theatre	1000	19	0.60	90
HC—scanner rooms	Scanners with image enhancers and television systems	500	19	–	80
HC—treatment rooms	Endoscopy rooms, medical baths, massage and radiotherapy	300	19	0.60	80
	Dialysis, plaster rooms	500	19	0.60	80
HC—wards, maternity wards, ICU	Bathrooms and toilets	200	22	0.40	80
	Examination and treatment	1000	19	0.70	90
HC—autopsy rooms and mortuaries	Autopsy table and a dissecting table	5000	–	–	90
HC—decontamination rooms	Sterilisation rooms, disinfection rooms	300	22	0.60	80
Industry—bakeries	Preparation and baking	300	22	0.60	80
	Finishing, glazing, decorating	500	22	0.70	80
Industry—cement, cement goods, concrete, bricks	Material preparation, work on kilns and mixers	200	28	0.40	40
	General machine work	300	25	0.60	80
Industry—ceramics, tiles, glass, glassware	Machine work, enamelling, rolling, pressing, glazing, glass blowing	300	25	0.60	80
	Grinding of optical glass, crystal, hand grinding, and engraving, glass polishing	750	19	0.70	80
	Precision work—decorative grinding, hand painting	1000	16	0.70	90
	Manufacture of synthetic precious stones	1500	16	0.70	90

(continued)

Table 8.3 (continued)

Building type	Type of area, task or activity	E_m (lux)	UGR	U_o	R_a
Chemical, plastics, and rubber industry	Processing installations with limited manual intervention	150	28	0.40	40
	Manned work stations in processing installations	300	25	0.60	80
	Pharmaceutical production, tyre production, precision measuring, laboratories	500	22	0.60	80
	Cutting, finishing, inspection	750	19	0.70	80
	Colour inspection	1000	16	0.70	90
Electrical and electronic industry	Cable and wire manufacture, winding large coils, coil impregnating, galvanizing, assembly work—large transformers	300	25	0.60	80
	Assembly work—medium-sized coil, switch boards	500	22	0.60	80
	Assembly work—small coils, fine work, e.g., telephone, IT	750	19	0.70	80
	Equipment (computers)—measuring equipment, PCBs	1000	16	0.70	80
	Electronic workshops, testing	1500	16	0.70	80
Foodstuff and luxury food industry	Breweries, malting floor, barrel filling, sieving, peeling, chocolate/sugar factories, drying and fermenting raw tobacco	200	25	0.40	80
	Sorting of products, milling, mixing, packing, cutting and sorting of fruits and vegetables	300	25	0.60	80
	Manufacture of delicatessen foods, cigars and cigarettes, inspection of glasses, product control, trimming, decoration	500	22	0.60	80
	Workstations in slaughterhouses, butchers, dairies, filtering in sugar refineries	500	25	0.60	80
	Colour inspection	1000	16	0.70	90
Foundries and metal casting	Man-size underfloor tunnels, cellars	50	–	0.40	20
	Platforms	100	25	0.40	40
	Sand preparation, workstations at cupola and mixer, machine moulding	200	25	0.40	80
	Hand and core moulding, die casting,	300	25	0.60	80
	Model building	500	22	0.60	80

(continued)

Table 8.3 (continued)

Building type	Type of area, task or activity	E_m (lux)	UGR	U_o	R_a
Jewellery manufacturing	Watch making (automatic)	500	19	0.60	80
	Manufacture of jewellery	1000	16	0.70	90
	Watch making (manual)	1500	16	0.70	80
	Working with precious stones	1500	16	0.70	90
Laundries and dry cleaning	Inspection and repairs	750	19	0.70	80
Industry—leather and leather goods	Work on vats, barrels, pits	200	25	0.40	40
	Fleshing, skiving, rubbing, tumbling of skins	300	25	0.40	80
	Saddlery work, shoe manufacturing, stitching, polishing, cutting, leather dyeing (machine)	500	22	0.60	80
	Sorting	500	22	0.60	90
	Colour inspection	1000	16	0.70	90
	Quality control	1000	19	0.70	80
Metalworking and processing	Open die forging, plate machining: thickness >5 mm, assembly: rough	200	25	0.60	80
	Rough machining: tolerance >0.1 mm; sheet metalwork: thickness <5 mm	300	22	0.60	80
	Drop forging, welding, wire, and pipe drawing shops; cold forming, galvanizing	300	25	0.60	80
	Precision machining; grinding: tolerance <0.1 mm	500	19	0.70	80
	Inspection, precision work, tool making: cutting equipment	750	19	0.70	80
	Tool, template and jig making, precision mechanics, micro-mechanics	1000	19	0.70	80
Industry—paper and paper goods	Edge runners, pulp mills	200	25	0.40	80
	Paper manufacture and processing, corrugating machines, cardboard manufacture	300	25	0.60	80
	Bookbinding work, such as folding, sorting, gluing, cutting, embossing, sewing	500	22	0.60	80

(continued)

Table 8.3 (continued)

Building type	Type of area, task or activity	E_m (lux)	UGR	U_o	R_a
Power stations	Boiler house	100	28	0.40	40
	Machine halls, pump rooms, condenser rooms, switchboards	200	25	0.40	80
	Control rooms	500	16	0.70	80
Industry—printers	Cutting, gilding, embossing, block engraving, work on stones, printing machines, matrix making, paper sorting and hand printing	500	19	0.60	80
	Type setting, retouching, lithography	1000	19	0.70	80
	Colour inspection in multicoloured printing	1500	16	0.70	90
	Steel and copper engraving	2000	16	0.70	80
Rolling mills, iron and steel works	Production plants—occasional manual operation	150	28	0.40	40
	Production plants—continuous manual operation, furnaces	200	25	0.60	80
	Control platforms, control panels	300	22	0.60	80
	Mill train; coiler; shear line	300	25	0.60	40
	Test, measurement and inspection	500	22	0.60	80
Textile manufacture and processing	Drying room	100	28	0.40	60
	Workstations and zones in bale opening	200	25	0.60	60
	Carding, washing, ironing, devilling machine work, drawing, combing, sizing	300	22	0.60	80
	Spinning, plying, reeling, winding, warping, weaving, braiding, knitting, finishing, dyeing, automatic fabric printing	500	22	0.60	80
	Sewing, fine knitting, manual design, drawing patterns	750	22	0.70	80
	Colour inspection; fabric control, burling, picking, trimming	1000	16	0.70	90
	Invisible mending	1500	19	0.70	90
Vehicle construction and repair	General vehicle services, repair	300	22	0.60	80
	Bodywork and assembly	500	22	0.60	80
	Painting, spraying, polishing chamber	750	22	0.70	80
	Upholstery manufacture (manned), painting: touch-up, inspection	1000	19	0.70	80

(continued)

Table 8.3 (continued)

Building type	Type of area, task or activity	E_m (lux)	UGR	U_o	R_a
Woodworking and processing	Automatic processing, plywood manufacturing	50	28	0.40	40
	Steam pits	150	28	0.40	40
	saw frame, work at joiner's bench, gluing, assembly	300	25	0.60	60
	Woodworking machines, such as turning, fluting, dressing, rebating, grooving, cutting, sawing, sinking	500	19	0.60	80
	Polishing, painting, fancy joinery; selection of veneer woods, marquetry, surface preparation	750	22	0.70	80
	Quality control, inspection	1000	19	0.70	90
Interior areas, tasks/activities	Stairs, escalators, elevators, lifts, restrooms	100	25	0.40	40
	Circulation areas and corridors	100	28	0.40	40
	Loading ramps/bays	150	25	0.40	40
	Cloakrooms, washrooms, toilets, canteens, pantries	200	25	0.40	80
	Rooms for physical exercise	300	22	0.40	80
	Rooms for medical attention	500	16	0.60	90
Offices	Filing, copying, reception desk	300	22	0.40	80
	Writing, typing, reading, data processing, CAD workstations, conference and meeting rooms	500	19	0.60	80
	Technical drawing	750	16	0.70	80
	Archives, cloakrooms, lounges, bookshelves	200	25	0.40	80
Places of public assembly (PA)	General areas: entrance halls	100	22	0.40	80
	General areas: ticket offices	300	22	0.60	80
PA—libraries	Reading area, counters	500	19	0.60	80

(continued)

Table 8.3 (continued)

Building type	Type of area, task or activity	E_m (lux)	UGR	U_o	R_a
PA—public car parks (indoor)	In/out ramps (at night), traffic lanes, parking areas	75	25	0.40	40
	Handicraft room, ticket office	300	19	0.60	80
	Play room, nursery	300	22	0.40	80
	In/out ramps (during day time)	300	25	0.40	40
PA—restaurants and hotels	Self-service restaurant, seating areas	200	22	0.40	80
	Reception/cashier desk, buffet	300	22	0.60	80
	Conference rooms, kitchen	500	19	0.60	80
PA—theatres, concert halls, cinemas	Practice rooms, dressing rooms	300	22	0.60	80
	Stage area	300	25	0.40	80
Retail premises	Sales area	300	22	0.40	80
	Till area, wrapper table	500	19	0.60	80

Source European Standard, EN 12464-1:2011

Table 8.4 LPD allowances and occupancy sensor reductions using the space-by-space method (ANSI/ASHRAE/IES 90.1 2016)

	LPD (W/ft^2)	Occupancy sensor reduction
Common space types		
Auditorium	0.90	10%
Convention centre	0.70	10%
Gymnasium/sports arena	0.40	10%
Motion picture theatre	1.20	10%
Penitentiary	0.70	10%
Performing arts theatre	2.60	10%
Religious facility	1.70	10%
Transport facility	0.50	10%
Audience seating area	0.90	10%
Banking activity area	1.50	10%
Penitentiary	1.30	None
Classroom/lecture hall/training room	1.40	None
Conference/meeting/multipurpose room	1.30	None
Confinement cells/copy/print room	0.90	10%
Facility for visually impaired	1.15	25%
Hospital	1.00	25%
Manufacturing facility	0.50	25%
Courtroom	1.90	10%
Computer room	2.14	35%
Bar/lounge or leisure dining	1.40	35%
Cafeteria or fast food dining	0.90	35%
Electrical/mechanical room	1.50	30%
Emergency vehicle garage	0.80	10%
Food preparation area	1.20	30%
Judges chambers	1.30	30%
Laundry/washing area	0.6	0.1
Loading dock, interior	0.59	0.1
Elevator	0.8	0.25
Healthcare facility	0.8	None
Office: enclosed	1.1	0.3
Office: open plan	1.1	15%
Parking area, interior	0.2	0.15
Restroom facility	0.9	0.45
Seating area, general	0.7	0.1
Hospital	0.9	0.45
Workshop	1.9	0.1
Building type-specific space types		

(continued)

Table 8.4 (continued)

	LPD (W/ft^2)	Occupancy sensor reduction
Health care: emergency room	2.7	0.1
Health care: exam/treatment room	1.5	0.1
Health care: medical supply room	1.4	0.45
Operating room	2.2	0.1
Physical therapy room	0.9	0.1
Patient room	0.7	0.1
Library: reading area	1.2	0.15
Library: stacks	1.7	0.15
Manufacturing facility		
Extra-high bay area (>50 ft floor-to-ceiling height)	1.32	0.1
High bay area (25–50 ft floor-to-ceiling height)	1.7	0.1
Low bay area (<25 ft floor-to-ceiling height)	1.2	0.1
Post office: sorting area	1.2	0.1
Retail facilities: dressing/fitting room	0.89	0.1
Museum: general exhibition area	1	0.1
Museum: restoration room	1.7	0.1

North America. Concerning updated European Standard, EN 12464-1 (2011) (adopted as the ISO standard), this contribution compiles recommended illuminance levels for selected tasks in the office or allied activities, including industrial applications (Table 8.3). Besides, ANSI/ASHRAE/IES Standard 90.1 (2016) is a benchmark energy code for commercial buildings in the USA, which has been adopted by many countries in North America and other regions. Section 9 of the Standard 90.1 (2016) regulates the energy-efficient design of lighting systems, including installations for new construction, major renovation, and retrofit projects.

The standard includes maximum LPD allowances (Table 8.4) and occupancy sensor reductions for both a common space type and a building area-specific space type (DiLouie 2017). For occupancy sensors controlling special workstation lighting, occupancy sensor reduction factor shall be 30%. For example, maximum LPD was reduced from 0.9 to 0.82 W/sq.ft for office buildings. For hospitals, it is maintained at 1.05 W/sq.ft. The reduction in LPD allowances is based on growing popularity of LED lamps and luminaires. For manual ON or partial-auto-ON occupancy sensors, the occupancy sensor reduction factor shall be multiplied by 1.25. The Standard 90.1:2016 requires daylight-responsive controls for both primary and secondary daylight zones, with suitable control for lighting flexibility. In case of both a common space type and a building area-specific space type are listed, the latter shall apply.

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Part IV
Building Bioclimate—Indoor Environment Quality

Chapter 9
Bioclimatic Approach: Thermal Environment

Introduction

More than half of the world's population now live in cities and towns, and there are nearly 200 cities in the world with people over a million. Cities have a significant impact on the local climate, and the vulnerability of these population might appear insurmountable unless the scale and magnitude of the effects of the urban environment are better understood and strategies to mitigate them are implemented. International emphasis goes in evolving approaches to the sustainability of the human habitat and the environment, towards ensuring minimal impacts in the future. Undoubtedly, building design and building environment have significant implications on the comprehensiveness of sustainability. That is, building design process must address energy demand, building form, construction, materials, operation and maintenance, and above all, the long-term needs of the user population, throughout the life cycle of buildings (William 2007). Sustainable design aims at maximizing the quality of the built environment and minimizing or eliminating negative impacts on the natural environment (McLennan 2004).

Bioclimatic Building Design

The building design process may be seen as a system consisting of sub-systems that appropriately accommodate the elements of bioclimatic perspectives. That is (a) building to be eco-friendly that have minimal impact on the environment; (b) building focusing on human-friendliness, with attention to human health, comfort, and safety; and (c) making the building energy-friendly to achieve efficiency and conserve energy (Guy and Farmer 2001).

Eco-friendly—Strategies include (a) s*ite selection relating spatial planning, building utilization*, (b) *material selection with* consideration of the local practices

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and the environmental impact, (c) efficient use of water, recycled wastewater, as well as green area and watershed planning, and (d) pollution control throughout project life cycle (Abidin and Powmya 2014).

Human-friendly—The primary emphasis is on health, comfort, and safety of building users. The comfort is not just a matter of physical conditions and environment (thermal, auditory, visual, chemical) but also the intermediaries, such as architectural features, space design, physiological and demographic indicators, and safety features embedded in the design of the building (Zr and Mochtar 2013; Bougdah 2010).

Energy-friendly—Ventilation and HVAC systems are the primary energy demanding in the building. Optimization of energy use strategies in building design (Sarté 2010) refers to a reduction in energy demand, efficient use of energy, selection of a sustainable energy source, and reduction in CO_2 emissions.

The interrelationship of the bioclimatic perspectives (Fig. 9.1) has been viewed at the micro-level analysis in the process of building design. These considerations are furthermore necessary for responding to the climatic conditions of the tropical areas. The abundance of sunlight and heat conditions in the humid tropics set the building design criteria, in contrast to those in the subtropical climate. The energy saving is achieved through the use of daylighting and natural ventilation, and optimizing the use of electrical energy. The dimension of the building openings, the presence of shading device, and the building façade installations influence the extent of sunlight and natural ventilation available in the building space. The acoustic condition in the building may be affected by the origin and sources of noise (internal and external). In accordance with the sound levels in the building interiors, the exterior facades and the interior features (walls and ceiling, furniture) may be planned. With the concerns that pollutants may originate from multiple sources and

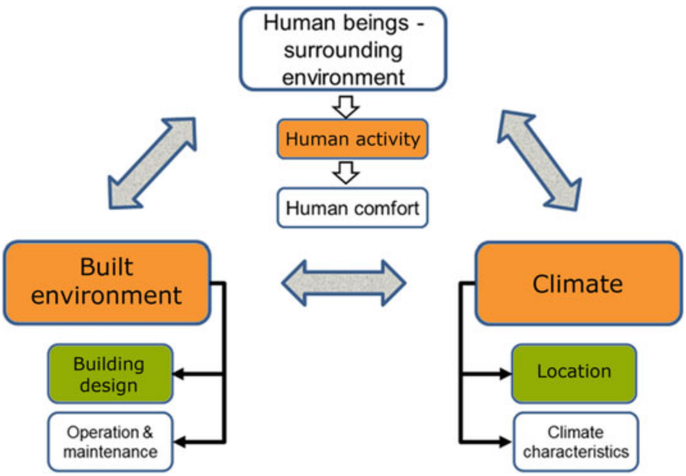

Fig. 9.1 Bioclimatic perspectives of human–climate–built environment interrelationships

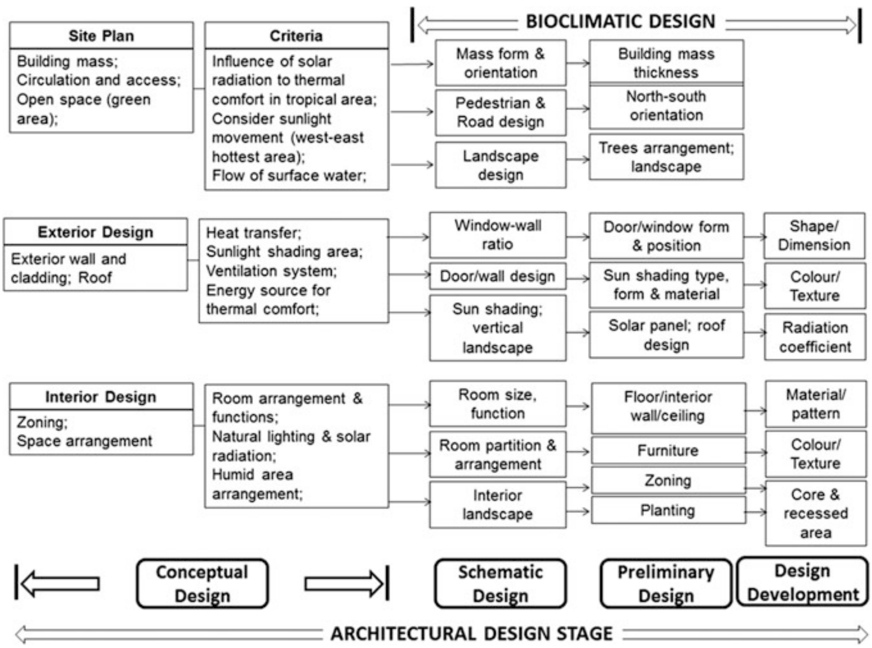

Fig. 9.2 Bioclimatic components at different stages and processes of building design

energy use characteristics in the building, the indoor air quality (IAQ) must be conducive to support the functions of occupants. In summary, the bioclimatic approach adopts the passive building design to create comfortable conditions for occupants (Fig. 9.2). The primary strategies include site design, landscape elements (such as plants, water), building orientation, building form and envelope, openings for ventilation, sunshading and window/façade design. It addresses to bring balance between the climate and the built environment, with interrelated considerations, such as the climate variables, human health, comfort and safety requirements, and technological and architectural solutions. This contribution is a modest effort to bring together different facets of bioclimate, focusing on the indoor thermal environment, urban climate, human health, and comfort, concerning rational warmth assessment in the microclimate environment.

Environmental Warmth and Human Comfort

Humans exposed to varying climatic and behavioural conditions and dynamically respond to as one’s sense of warmth and comfort to both indoor and outdoor environment (Pantavou et al. 2011; Taleghani et al. 2013). A generally agreed definition of thermal comfort is a *condition of mind that expresses satisfaction with*

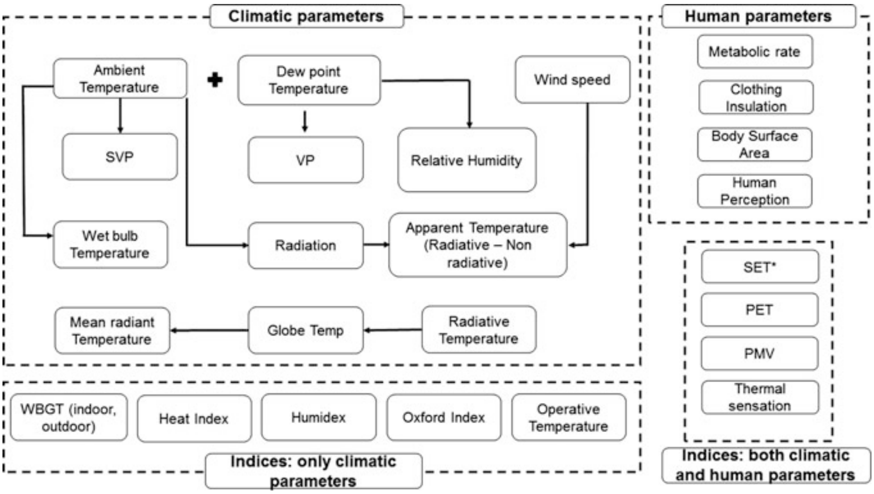

Fig. 9.3 Linkages and climatic and human behavioural parameters in assessing human thermal indices

the thermal environment and is assessed mainly by subjective evaluation (ASHRAE 55: 2004). Such a definition emphasizes on the comfort as a psychological phenomenon, subject to caveat on the physical environment and the human physiological state under consideration. Basic understanding of bioclimatic aspects, covering physiology, psychology, building physics, and engineering, has high relevance in evaluating thermal comfort in a building environment and providing a satisfactory condition for building occupants, controlling energy consumption, and improving IEQ.

Emphasis has been placed to identify the most useful parameters (climatic, physical, biophysical) which can predict human thermal comfort or better to say, human warmth assessment (Fig. 9.3). Human body undergoes complex thermoregulatory processes, duly influenced by intrinsic and extrinsic factors, like external climatic variability, microclimate conditions, human behavioural patterns. The early endeavour of Blagden (1775) in understanding the human thermoregulatory ability to endure high temperatures in a heated room is perhaps the starting point of the concept of human body heat transfer (Hill et al. 1897) and foundation to the rationality of evolving a unified physical dimension of heat stress and strain. Accordingly, endeavours have gone into devising human thermal indices, integrating the environmental and behavioural parameters, and also the human perception of warmth and comfort. The primary premise in designing human thermal index is to combine the heat-related aspects of the environment and the human body in a way that gives simple meaning to the thermal signature of the overall condition. It takes into account the parameters or indicators that represent or signify the state of the thermal environment for an individual or group of individuals. Over the decades, there has been considerable development in human thermal indices, from multidisciplinary specialty.

Types of Human Thermal Indices

Professionals and researchers from different academic disciplines, such as atmospheric science, biological science, and environmental hygiene, use the climatic and behavioural dimensions differently, and accordingly, different types of indices have been adopted for related application. A brief account is given herewith to make readers acquainted with the development of indices, indicating broad approaches and its utilities. The methods in the construction of the index vary according to the number of variables taken into account, the rationale employed and relative sophistication in measurement. The evaluation criteria include the range of climatic conditions at which the indices may be applied, and the human activity state, such as metabolic rate, clothing worn, and whether the indices assess the thermal environmental stress and thermophysiological strain.

These indices have multiple application, such as environmental warmth assessment, heat exchange phenomena, physiological and biophysical strain assessment, perceived thermal comfort, tolerance limits, and risk assessment for both indoor and outdoor conditions. Particularly in case of hot climates, thermal indices are used to evaluate the extent of cooling achieved in indoor environments through interventions like air-conditioning systems, increased air movement, and in case of colder climates, consideration is given for heating requirement to deliver thermal comfort. NIOSH (1986) grouped the thermal indices based on:

(a) Direct measurement of climatic parameters (direct indices), such as WBGT, AT;
(b) Human heat balance (rational indices), such as the heat stress index for warmth weather (Belding and Hatch 1955), the clothing insulation required (IREQ) for cold environment (Holmer 1984); and
(c) Objective and subjective strain (empirical indices), such as the physiological strain index (Moran et al. 1998).

Bethea and Parsons (2002) grouped them as (a) heat balance (rational indices), (b) physiological strain (empirical indices), and (c) environmental parameters (direct indices). Further refinement has gone into a grouping of the indices, for possible robustness of reasoning in the groupings, and aligning to international standards and guidelines. Carlucci and Pagliano (2012) grouped 15 indices for evaluation of thermal comfort conditions in a building into homogenous families, namely (a) percentage indices, (b) cumulative indices, (c) risk indices, and (d) averaging indices. De Freitas and Grigorieva (2015) categorized eight classes of indices. These are (a) simulation devices for integrated measurement, (b) single-sensor (single-parameter) index, (c) algebraic or statistical model, (d) proxy thermal strain index, (e) proxy thermal stress index, (f) energy balance stress index, (g) energy balance strain index, and (h) special purpose index.

Based on the comprehension of the human warmth assessment in the built environment, however, the thermal stress and strain indices may be broadly grouped into three categories. These are (a) direct/empirical indices that are derived from environmental variables, (b) rational indices, referred to as the human heat balance model, and (c) perception indices using comfort thermal voting and sensation of warmth. Readers may refer to Parsons (2014) for a detailed description of human health, comfort, and performance of thermal environments.

Direct Indices

Climatic parameters, such as ambient temperature, wet-bulb temperature, humidity, wind speed, solar radiation, are used to derive direct indices with simplified formulae, as described in Table 9.1. Earlier, to define human comfort, kata thermometer was developed (Hill et al. 1916) that measured the rate of cooling due to the wind effect on the human body. Since then, several environmental indicators and indices have been proposed, such as the equivalent temperature (Dufton 1929), the effective temperature (ET) (Houghton and Yaglou 1923), corrected effective temperature (CET) (Vernon and Warner 1932), heat stress indices (HSI) (Epstein and Moran 2006). The wet-bulb globe temperature (WBGT) (Yaglou and Minard 1957) determines heat exposure of the industrial workers, with the wet-bulb temperature and radiant temperature measured by 6-in. diameter black globe. WBGT was further proposed as an international standard, ISO 7243 (2003), which as on date extensively applied in industrial hygiene and occupational health applications. Botsford (1971) described wet globe temperature (WGT) as the temperature of a black globe of 2.5 in. diameter. The apparent temperature (AT), either expressed as radiative and non-radiative version, has been applied to predict the physiological heat stress and discomfort about heat index (HI) for warm environment and wind chill index (WCI) for the cold environment (Steadman 1979). Temperature–humidity index (THI) (Thom 1959), as a measure of human comfort, was developed with temperature and humidity in Fahrenheit scale. Discomfort index was developed by the US National Weather Service as a more sophisticated and straightforward index and also referred as a temperature–humidity index (Schoen 2005) that eliminates the limitation of AT. Humisery (Weiss 1982) and weather stress index (WSI) (Kalkstein and Valimont 1987) were used to calculate the thermal discomfort by the readily available climatic parameters, thereby obviating the constraint of indices, like THI and humiture (Hevener 1959). The Humidex describes the perceived temperature of people in everyday conditions (Masterson and Richardson 1979). There are other indices which have been introduced to measure the severity of climate as well as the discomfort under varied climatic characteristics. For example, summer severity index (McLaughlin and Shulman 1977) used weather parameters to convey the severity in humid continental warm summer climate; the equatorial comfort index (Webb 1960) considered the thermal comfort of a subject, acclimatized in the equatorial climatic conditions. The spatial synoptic classification (Kalkstein et al. 1996) was used to compare the daily air masses of different inter-site over a vast region to analyse air quality considering climatic and geomorphological factors.

Table 9.1 Direct heat stress indices

Index	Description	Formulae	
Air enthalpy (Gregorczuk 1968)	Only consider the air temperature and humidity for human health and comfort assessment without considering other physical and biometeorological parameters	$i = 0.24\left(T_w + \frac{1.555}{p} E_t\right)$	i = air enthalpy in kcal/kg; p = atmospheric pressure in mm Hg; E_t = saturated air pressure in a given air temperature; Q = net radiation absorbed per unit body surface area (W/m^2); v_0 = wind speed (m/s) at 10 m above ground level; T_a = air temperature (°C); T_w = wet-bulb temperature (°C); T_{dp} = dew point Temp (°C); v_t = wind speed (m/s) at 1.2 m above ground; T_r = mean radiant temperature (°C); T_g = globe temperature (°C); RH = Relative Humidity; SR = Solar radiation; v_2 = wind speed (m/s) at 2 m above ground level; B for black and S for silver measured by eupatheoscope; MO = Moderate overcast; DS = Direct Sunlight; T_{pwb} = ground psychrometric wet-bulb temperature; T_{db} = ground psychrometric dry-bulb temperature; vp = vapour pressure; WBT = wet-bulb temp (°C); v = air velocity (m/s); t'_H = corresponds to wet-bulb temperature about cooling power temperature t_h, and it can be computed by means of t_h and relative humidity; E_{t_h} = saturated water vapour pressure at a temperature t_h in hPa
Apparent temperature (Steadman 1971)	Combination of ambient temperature, wind speed, vapour pressure in radiant and non-radiant version to calculate total thermal resistance	$AT(\text{radiative}) = T_a + 0.348 * e - 0.70 * v_0 + 0.70 \frac{Q}{v_0 + 10} - 4.25$ Where, $e = \frac{RH}{100} * 6.105 * e^{\frac{17.27 * T_a}{237.7 + T_a}}$ $AT(\text{non-radiative}) = T_a + 0.33 * e - 0.70 * v_0 - 4.00$	
Weather severity index (Bodman 1908)	Used for bioclimatic evaluation in winter	Bodman's weather severity Index $= (1 - 0.04T_a)(1 + 0.272v_0)$	
Discomfort index or temperature–humidity index (Thom 1959)	Physiological thermal stress indicator for people, based on dry-bulb and wet-bulb temperature	$THI = 0.4(T_a + T_w) + 15$	
Discomfort index (Ono and Kawamura 1991)	Based on Thom's formulae, only altered wet-bulb temperature by water vapour pressure and dew point temperature	$DIK = 0.99T_a + 0.36T_{dp} + 41.5$	
Effective temperature (Houghton and Yaglou 1923)	Used by occupational physiologist to determine the relative comfort due to temperature, humidity, and wind	$ET = \left(37 - \frac{37 - T_a}{0.68 - 0.0014.RH + \frac{1}{1.76 + 1.4V_t^{0.75}}}\right) - 0.29T_a(1 - 0.01RH)$	
Effective temperature (Missenard 1933) cited by Gregorczuk and Cena (1967)	The temperature of saturated air having the same level of comfort or discomfort due to ambient temperature and humidity at minimal air movement	$ET = T_a - 0.4(T_a - 10)\left(1 - \frac{RH}{100}\right)$	
Environmental stress index (Moran et al. 2001)	Alternatively used with WBGT	$ESI = 0.63 * T_a - 0.03 * RH + 0.002 * SR + 0.0054(T_a * RH) - 0.073(0.1 + SR)^{-1}$	
Equivalent effective temperature (Aizenshtat and Lukina 1982)	Temperature perception of a person in stationary and saturated moisture air as same as the prevailing condition	$EET = t_a[1 - 0.003(100 - RH)] - 0.385v_2^{0.59}[(36.6 - t_a) + 0.622(v_2 - 1)] + [(0.0015v_2 + 0.0008)(36.6 - t_a)]$	
Equivalent temperature (Dufton 1929)	Usually measured by eupatheoscope and determined by the different emissivity of the surface	$\text{Equivalent Temperature} = 75.2 - 546\left(\frac{2.35}{B + 3.5} - \frac{1}{S}\right)$	
Fighter index of thermal stress (Stribley and Nunneley 1978)	Predicts the thermal stress in the cockpit with the help of WBGT and solar heating	$FITS_{DS} = 0.8281T_{pwb} + 0.3549T_{db} + 5.08\,°C$ $FITS_{MO} = 0.8281T_{pwb} + 0.3549T_{db} + 2.23\,°C$	
Humidex (Masterson and Richardson 1979)	Widely used by Canadian meteorologist for the weather forecast. Based on temperature and vapour pressure	$\text{Humidex}(°C) = T_a + 0.5555(vp - 10)$ $vp\ (hpa) = 6.11 * \exp\left(5417.7530 * \left(\frac{1}{273.16} - \frac{1}{(273.16 + T_{dp})}\right)\right)$	

Table 9.1 (continued)

Modified discomfort index (Moran et al. 1998a)	The alternative of WBGT that calculates heat stress based on ambient and wet-bulb temp	$MDI = 0.30t_a + 0.75T_w$	
Operative temperature (Winslow et al. 1937)	The temperature of an isothermal blackbody enclosure with the same convection (wind) conditions as the actual environment. It indicates same net sensible heat flow to or from the same animal having the same surface	$OT = \left(T_r + \left(T_a * \sqrt{10v}\right)\right)/\left(1 + \sqrt{10v}\right)$	
Oxford index or Wet-Dry Index (Lind and Hellon 1957)	More emphasis on wet-bulb temperature, than ambient temperature	$WD = 0.8 * T_w + 0.15T_a$	
Subjective temperature (McIntyre 1973)	Predicts the warmth of an environment more precisely and differentiate it from environmental temperature	$ST = 0.56T_a + 0.44T_r^9$	
Tropical summer index (Bureau of Indian Standards 1987)	Used in a tropical area to define the thermal sensation by a defined temperature with 50% relative humidity in the still air	$TSI = 0.308WBT + 0.745T_g - 2.06\sqrt{v + 0.841}$	
Temperature-wind Speed–humidity index (TWH) (Zaninovic 1992)	Based on measured values of temperature, wind speed, and air humidity, on Hill's equations for cooling power to assess thermal sensation	$TWH = 1.004\left(t'_H + \frac{1555}{P}E_{t_h}\right)$	
Wet Bulb Globe Temperature (Yaglou and Minard 1957)	Developed by US navy to calculate for both indoor and outdoor environment by the wet-bulb and globe temperature	$WBGT\_in = 0.7 * T_w + 0.3 * T_g$ $WBGT\_in = 0.567 * T_a + 0.393 * e + 3.94$, Where, $e(hpa) = \frac{RH}{100} * 6.105 * \exp[17.27 * T_a/(237.7 + T_a)]$ $WBGT\_out = 0.7 * T_w + 0.2 * T_g + 0.1 * T_a$	
Wet Globe temperature or botsball (Botsford 1971)	Consists of a dial thermometer with the heat sensor of a 6 cm diameter copper sphere, covered with a wet black cloth	$WGT\ (°F) = 0.958WBGT - 3.2$	
Heat index (Rothfusz 1990)		$HI = -8.784695 + 1.61139411 * T_a + 2.338549 * RH - 0.14611605 * T_a * RH - 1.2308094 * 10^{-2} * T_a^2 - 1.6424828 * 10^{-2} * RH^2 + 2.211732 * 10^{-3} * T_a^2 * RH + 7.2546 * 10^{-4} * T_a * RH^2 - 3.582 * 10^{-6} * T_a^2 * RH^2$	

Rational Indices

Rational indices described below (Table 9.2) are primarily based on the energy balance model of the human body. It considers human comfort by effective heat exchange over various environmental and behavioural avenues. Appropriate selection of the indices might be useful for the building professionals to apply in climate zone assessment in buildings. The energy or heat balance of the human body is evolved from integrating multiple avenues of heat transfer between the human body and environment, which is grossly expressed as:

$$M - W + R + C - E_{\mathrm{D}} + E_{\mathrm{Re}} - E_{\mathrm{Sw}} = \mathrm{S}$$

where M (metabolic rate), W (physical work output), R (heat exchange by short-wave and long-wave radiation), C (convective heat *transfer),* E_{D} (latent heat flow—imperceptible perspiration), E_{Re} (heat flows for heating and humidifying the inspired air), E_{Sw} (heat flow due to evaporation of sweat), and S (heat storage of the body mass). Several intermediate steps are involved in the quantification of the heat balance; for example, the convective and evaporative heat transfers in the stated heat balance equation may be obtained from convective and evaporative heat transfer coefficients of body segments (Nag 1984), which are influenced by the nature and type of body movements. Some of the rational indices are briefly mentioned herewith.

Belgian effective temperature (Bidlot and Ledent 1947) was developed to assess the strain in hot and humid climate in coal mining industry. Lee (1958) developed thermal strain index (TSI) following the psychometric chart analysing heat transfer mechanisms. Effective heat strain index (Kamon and Ryan 1981) evaluates strain calculating total heat balance. Cumulative heat strain index (Frank et al. 1996) calculates total physiological thermoregulatory strain at the time of exercise. According to the strain factor, thermal work limit (TWL) (Brake and Bates 2002) equates to predict a safe, sustainable metabolic rate, mainly in the underground environment. The degree of heat tolerance of unacclimatized subject was determined by numerical heat tolerance index (Hori 1978). Integral index of cooling conditions (IICC), (Afanasieva et al. 2009) was designed to determine risk in cooling condition. Similarly, biometeorological comfort index (Rodriguez et al. 1985) and comfort chart (Mochida 1979) were used to assess human thermal comfort. The predicted four-hour sweat rate index (P4SR), established by McArdle et al. (1947), quantifies the amount of sweat rate considering all the underlying environmental and behavioural parameters.

A new effective temperature index (ET*) was proposed (Gagge 1971) based on the two-node model, covering heat exchange through radiation, convection, and evaporation, including degrees of clothing insulation and metabolic rate of diverse activities. The thermal effects of meteorological conditions were analysed against the conditions in a standardized room with a mean radiant temperature (Tmrt = T_a) and relative humidity at 50%. With further improvement in ET*, Gagge et al. (1986)

Table 9.2 Rational indices (heat strain indices)

Index	Description	Formulae	Parameters
Acclimatization thermal strain index (de Freitas and Grigorieva 2009)	Assesses short-term acclimatization, thermal loading from the difference between respiratory heat losses of the recreational traveller's home location and trip destination upon first arriving. Developed in Siberia	$ATSI = \frac{(Res_d - Res_h)}{Res_h} \cdot 100$	Res_h = heat loss by respiration at home location; Res_d = heat loss by respiration at the studied
Cold strain index (Moran et al. 1999)	Refers to severe cold strain based on core and mean skin temperatures	$CSI = 6.67(T_{coret} - T_{core0}) \cdot (35 - T_{core0})^{-1} + 3.33(\bar{T}_{skt} - \bar{T}_{sk0}) \cdot (20 - \bar{T}_{sk0})^{-1}$ When, $T_{coret} > T_{core0}$, then $T_{coret} - T_{core0} = 0$	destination T_{core0} & $\bar{T}_{sk0}$ are initial
Physiological strain index (Moran et al. 1998b)	Predicts heat strain based on rectal temperature and heart rate and uses a rating scale of 0–10	$PSI = 5(T_{re_t} - T_{re_0})(39.5 - T_{re_0}) + 5(HR_t - HR_0)(180 - HR_0)^{-1}$	measurements; T_{coret}, $\bar{T}_{skt}$, T_{re_t} & HR simultaneous measurements
Subjective temperature index, (Blazejczyk 2005)	Defines objective and subjective interactions between man and environment. It considers mean radiant temperature and heat exchange for cooling of the skin by evaporation	1 $STI = Mrt - [\lvert S^* \rvert 0.75/(5.39 * 10^{-8}) + 273^4]^{-0.25}\} - 273$, at $S^* < 0$, S = man–environment heat exchange 2 $STI = Mrt + [\lvert S^* \rvert 0.75/(5.39 * 10^{-8}) + 273^4]^{0.25}\} - 273$, at $S^* \geq 0$	were taken at any time t; Ha = heat acceptance of environment; M = rate of heat
Thermal acceptance ratio (Ionides et al. 1945)	A measure of heat stress, which can be calculated by the amount of heat transfer in a hot environment for the unclothed subject	Thermal acceptance ratio = Ha/M	production of the body; T_0 = operative temp (°C);
Thermal sensation index (de Paula and Lamberts 2000)	Analysis between sensation and environmental variable in free running buildings. It is very similar to PMV	$TSNI = 0.219T_0 + 0.012RH - 0.547V_a - 5.83$	T_r = mean radiant temperature (°C); RH = relative humidity (%);
Universal thermal climate index (Bröde et al. 2010)	Considers the necessary parameters of environment as well as human thermal comfort factors	$UTCI = 0.995 * T_a + 0.27(T_r - T_a)$	V_a = air velocity (m/s); T = air temp. (°C) at 1.50 m;
Wind chill equivalent temperature (Steadman 1971)	Calculates winter clothing based on heat loss due to cold and wind of a walking adult	$WCET = 1.41 - 1.162 * W + 0.98 * T + 0.0124 * W^2 + 0.0185 * W * T$	W = wind speed (m/s) at 10 m; T_s = 33 °C is the exposed skin temp
Wind chill index (Siple and Passel 1945)	Instantaneous rate of heat loss from the bare skin at the moment of exposure	$WCI\ (w/m^2) = (10\sqrt{v} + 10.45 - v)(T_s - T_a)$	

proposed the new standard effective temperature (SET*) which is defined as the T_a of a reference environment in which a person has the same mean skin temperature (T_{sk}) and skin wettedness as in real-life exposure conditions.

There are two distinct approaches to human warmth and comfort assessment, referred to as steady-state and non-steady-state approaches. It is understood that human thermal adaptation better represents a non-steady-state real-world dynamic environmental situation, including varied nature of the physical activity. Most methods for assessing this dynamic aspect of human thermal adaptation use the approach similar to Gagge's two-node model, considering that the human body as two isothermal parts, skin (shell) and core. Core temperature, skin temperature, sweating rate, skin blood flow, and heat exchange through the skin surface are derived concerning the set points of environmental conditions.

There have been several related developments of rational indices, based on the heat balance model. A close to the approach of ET*, the physiological equivalent temperature (PET) was formulated based on the Munich energy balance model for individuals (MEMI) (Höppe 1994, 1999). PET provides the equivalent temperature of a isothermal reference environment at an indoor setting ($T_{mrt} = T_a$; airspeed 0.1 m/s; water vapour pressure 12 hPa (50% RH at T_a = 20 °C; metabolic rate for light activity (80 W) added to basal metabolism, heat resistance of clothing 0.9 clo) and maintained by the T_{sk}, T_{cr}, and E_{sw} equal to those under the conditions to be assessed. Besides, PET allows assessing the thermal component of climate with reference to personal experience and behavioural adaptation of an individual.

The PET has been incorporated as one of the recommended indices in German guidelines for use by the urban and regional planners (VDI 1998). This has been examined in various climatic conditions in indoor as well as outdoor areas. Matzarakis and Nastos (2011) applied PET for heat stress analysis in Athens. Thorsson et al. (2007) examined the subjective outdoor thermal comfort of 1192 people during activities in a park and a square in a satellite city near Tokyo. They used a nine-point scale to evaluate the thermal sensations. The PET curve was more skewed towards the warm zone, suggesting that people tended to stay longer (19–21 min) when their perception was within the acceptable comfort zone than when their perception was outside of the zone ($\sim$11 min).

Predicted heat strain (PHS) (ISO 7933 2004) was proposed (Malchaire et al. 2001) as the revision of required sweat rate (ISO 7933 1989) and the index of thermal stress (Givoni 1969). PHS was a significantly improved version that included the extreme condition of basic environmental parameters, clothing, and individual differences to make guidance for the better work environment. Nag et al. (2007) adopted the evaporative heat exchange through the skin (E_{skin}), a quantitative derivation in the heat balance model, as a thermoregulatory indicator of human heat strain. A schematic (Fig. 9.4) shows the heat exchange layers in proportion to the volumes of different fractions of body components. The generalized

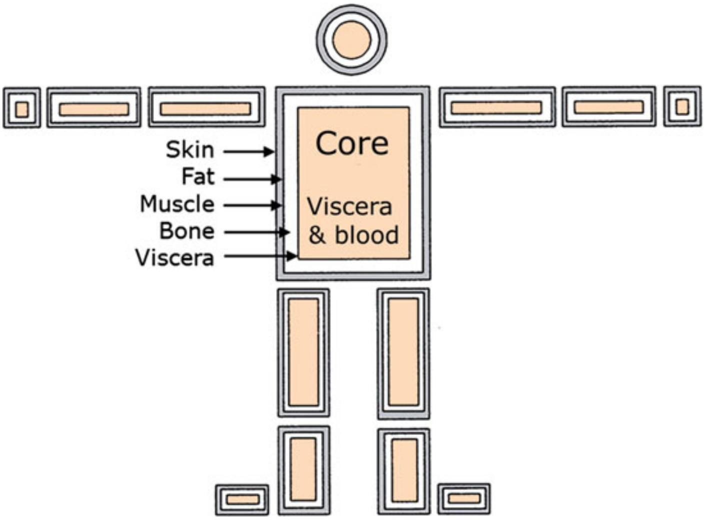

Fig. 9.4 Heat exchange across the body segments along the adjacent compartments

equation is:

$$
\begin{aligned}
Y\Delta T/\Delta t = {} & (V_\rho \times S) \times T_{blood} + \Delta M - [\{K_{blood-core}(T_{blood} - T_{core}) \\
& + K_{core-muscle}(T_{core} - T_{muscle}) + K_{muscle-fat}(T_{muscle} - T_{fat}) \\
& + K_{fat-skin}(T_{fat} - T_{skin}) + H(i)(T_{skin} - T_{environment})\} \times BSA \\
& + (C_{res} + E_{res} + E_{skin})]
\end{aligned}
$$

where Y = product of mass and specific heat; $\Delta T/\Delta t$ = change in temperature over time; V = volume (l); ρ = density of blood (kg/l); S = specific heat of blood (W.h/kg °C); T = resultant temperature of body compartment (°C); ΔM = total metabolic energy—basal metabolic energy (W.h); K = heat conductance (W/m^2 °C); H(i) = combined heat transfer coefficients (W/m^2 °C); BSA = body surface area (m^2); C_{res} = respiratory heat loss through convection (W.h); E_{res} = respiratory heat loss through evaporation (W.h); E_{skin} = evaporative heat loss through the skin (W.h). The effective heat load manifests in increase or decrease in body core temperature, as a function of its gradient to the thermographic profile of the skin. The classification of E_{skin} regarding the range of comfort, warm, hot, and very hot, in turn, may determine exposure tolerance time at a given indoor or outdoor environment.

The man–environment heat exchange model (MENEX) (Blazejczyk 1992), which was used to obtain heat exchange rates in steady-state as well as non-steady-state conditions, led to the development of the physiological subjective temperature (PST) (Blazejczyk and Matzarakis 2007) . The universal thermal index (UTCI) (Jendritzky et al. 2008; Blazejczyk et al. 2012) assesses the outdoor thermal conditions for both cold and heat stress. The UTCI considers the necessary parameters of the environment as well as the elements related to human thermal comfort, based on Fiala simulation model (Fiala et al. 1999, 2012).

There are other indices and models to evaluate regional and specific effects. For example, bioclimatic distance index (Mateeva and Filipov 2003) takes into account the human heat balance over a variety of bioclimatic location in Bulgaria. Watts and Kalkstein (2004) applied the relative thermal stress level from the daily maximum and minimum Steadman AT values and expressed as heat stress index (HSI_{WK}), and thereby, overcome the limitation of weather stress index (WSI) (Kalkstein and Valimont 1986). Bioclimatic contrast index (Blazejczyk 2011) was used to assess bioclimatic contrasts in locations of Poland to overcome the constraints of ATSI (de Freitas and Grigorieva 2009). Rational models, such as the still shade temperature (Burton and Edholm 1955), fuzzy-PMV (Hamdi et al. 1999), the OUT-SET (Pickup and De Dear 2000), and the COMFA outdoor thermal comfort model (Kenny et al. 2009), have been differently used to assess human thermal responses to the local thermal environment.

Thermal Perception Index

Warm sensation or thermal comfort in an urban environment, whether outdoor or indoor, is much affected by the environmental stimulus, and behavioural characteristics of the exposed population. On the one hand, the natural acclimatization of humans is ambient thermal condition-specific and the period of retention to a thermal condition. For example, there is a comparison of the thermal response of a street vendor to that of a passer-by, depending upon their retention in a situation. Therefore, the sensation of warmth and comfort may not always be consistent with the objective climatic or biometeorological condition. Besides the climatic conditions, human perceptions of thermal comfort in urban space or indoor environment encompass other aspects, such as physical, physiological, psychological, and social/behavioural attributes. A questionnaire-based thermal survey of indoor or outdoor spaces is useful to draw objective information from thermal exposure and associated strain (Yau et al. 2012).

To study the condition of comfort and well-being in indoor environments, Fanger (1970) proposed predicted mean vote (PMV) using perception and sensation of the environment as perceived by individuals. The empirical laboratory-based experiment was conducted in a simulated environmental chamber exposing 128 Danish students in the constant climatic condition, without having any uncontrollable interference. An equal number (64 each) of males and females were exposed to eight set point conditions, and a total of 32 tests were conducted with three hours of exposure each. After every half an hour of exposure, besides physiological measurements, the volunteers were introduced to a questionnaire to score ambient conditions subjectively. Based on the votes of a thermal sensation of volunteers, and the analysis of the environmental, physiological, and behavioural parameters, an elaborate PMV equation was introduced to express a score on the level of comfort that one gives to an environment. The perception of volunteers was also presented on a psychometric chart. The PMV was expressed on a seven-point scale (+3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, 1 = slightly cool, 2 = cool, 3 = cold).

$$\mathrm{PMV} = \left(0.303\mathrm{e}^{-0.036\mathrm{M}} + 0.028\right)\left\{\begin{array}{l} (\mathrm{M}-\mathrm{W}) - 3.96\mathrm{E}^{-8}\mathrm{f}_{\mathrm{cl}}\left[(\mathrm{t}_{\mathrm{cl}}+273)^4 - (\mathrm{t}_{\mathrm{r}}+273)^4\right] \\ -\mathrm{f}_{\mathrm{cl}}\mathrm{h}_{\mathrm{c}}(\mathrm{t}_{\mathrm{cl}}-\mathrm{t}_{\mathrm{a}}) - 3.05[5.73 - 0.007(\mathrm{M}-\mathrm{W}) - \mathrm{p}_{\mathrm{a}}] \\ -0.42[(\mathrm{M}-\mathrm{W}) - 58.15] - 0.0173\mathrm{M}(5.87-\mathrm{p}_{\mathrm{a}}) - 0.0014\mathrm{M}(34-\mathrm{t}_{\mathrm{a}}) \end{array}\right\}$$

$$\mathrm{PPD} = 100 - 95 * \exp(-0.03353 * \mathrm{PMV}^4 - 0.2179 * \mathrm{PMV}^2$$

In essence, PMV expresses the opinion of the people regarding well-being at a given climatic zone, but not as an assessment of the acceptable comfort range. Accordingly, Fanger proposed predicted percentage of dissatisfied (PPD), i.e., the percentage of the thermally dissatisfied people at each PMV level.

The PMV and PPD have been implemented in indoor thermal comfort standards, such as ISO 7730: 2005 and ASHRAE 55: 2010. Based on the PMV-PPD approach, several other comfort standards, like exceedance metrics, were developed, denoting the time duration that falls within or beyond the comfort condition in a building (Borgeson and Brager 2011). Overheating risk (Nicol et al. 2009) was used to derive building comfort (e.g., health care facilities) of occupants, based on adaptive thermal comfort, as referred in EN 15251 (2007). The climate index (Becker 2000) was introduced concerning the discomfort level quantified by PMV to the monthly frequency of hot or cold days.

Though PMV initially developed as an indoor thermal comfort index, this was also applied in outdoor thermal comfort studies (Cheng et al. 2012). Following a study about the influence of thermal bioclimatic conditions on behavioural patterns of people in an urban park (the Gothenburg, Sweden), Thorsson et al. (2004) viewed discrepancy between actual perception vote and PMV. The study indicated that transient exposure and thermal expectations influenced the subjective assessment. However, PMV being a steady-state model, the short-term outdoor thermal comfort assessment from PMV prediction may have its limitations. Hodder and Parsons (2007) indicated that the total solar load was the critical factor to affect thermal comfort. Besides people of different habitats and climates have different thermal preferences and adaptation, and therefore, those in cold or moderate climate regions, any available warm conditions and sunlight have a positive influence in using the outdoor spaces, and context would undoubtedly be different in hot and humid climates. Lin (2009) studied the thermal perception of 505 people about their using of a public square in a hot and humid subtropical climate in Taichung City, Taiwan. From high-resolution photographs, the density of people in the square was counted. Based on a seven-point scale of the thermal sensation vote, the acceptable thermal range of the whole year was observed as 21.3–28.5 °C PET, in comparison with the range of 18–23 °C PET in Europe.

From the derivation of PMV, the perceived temperature (Staiger et al. 2012) was proposed, using Klima–Michel model in complex atmospheric conditions for a long

Table 9.3 Corresponding PMV and PET levels to thermal perception and grade of physiological stress

PMV	PET (°C)	Thermal perception	A grade of physiological stress
–3.5	4	Cold	Strong cold stress
–2.5	8	Cool	Moderate cold stress
–1.5	13	Slightly cool	Slight cold stress
–0.5	18	Comfortable	No thermal stress
0.5	23	Slightly warm	Slight heat stress
1.5	29	Warm	Moderate heat stress
2.5	35	Hot	Strong heat stress
3.5	41	Very hot	Extreme heat stress

time. Alexandri and Jones (2008) used PET to evaluate thermal comfort, concerning the effect of the greening of walls and roofs of urban canyons in a simulation model. However, there exists a correspondence of PMV and PET levels (Table 9.3) of thermal perception.

There are other perception indices, such as draught risk index (Fanger et al. 1988) to assess the discomfort due to undesired cooling effect (referred as draught) in indoor climate by air temperature, air velocity, and turbulence measuring the heat loss. Summer Simmer Index, amended as new Summer Simmer index (Pepi 1999) was used to identify thermal comfort in the dry season with the help of the physiological model.

Adaptive Thermal Comfort Standards

With further progression in thermal indices to apply in the indoor and outdoor environment, adaptive comfort standards have been evolved, aiming at the real world dynamic situation (Tokunaga and Shukuya 2011; Nicol et al. 2012). Examples are the ASHRAE 55: 2010, EN-15251: 2007, CIBSE Guide A (2006). In this context, a building is said to be freerunning that does not consume energy for heating or cooling. These standards have been evolved with the concept that near sedentary individuals adapt to the thermal conditions of their recent exposures. Also, the thermal comfort envelopes depend on the recent exposures, about the upper and lower thresholds of indoor operative temperature.

ASHRAE 55: 2010—The standard specifies the combination of indoor climatic and personal parameters that produce thermal conditions acceptable to a majority of the building occupants. deDear and Brager (1997, 2002) gathered data from the field studies conducted in several countries (USA, Australia, UK, Greece, Pakistan, Singapore, Canada, Indonesia, and Thailand) and showed that the thermal responses of occupants in freerunning spaces depend on the outdoor temperature, thermal experiences and expectations, clothing worn, and availability of control.

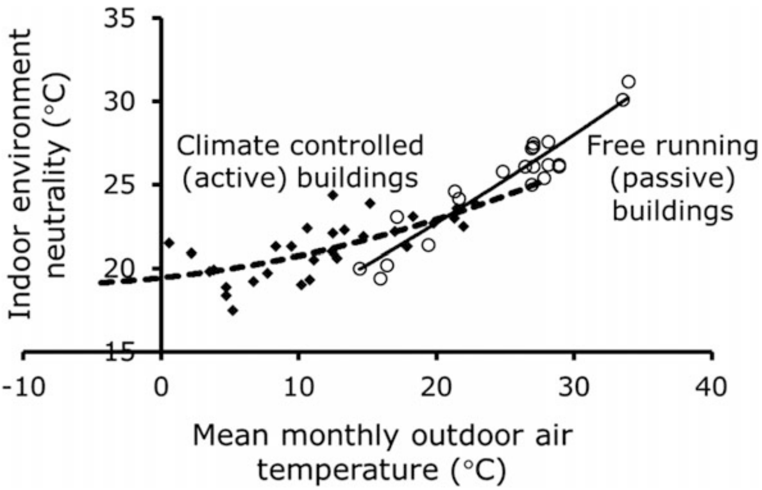

Fig. 9.5 Adaptive comfort temperature

Taking more than 21,000 measurements from around the world, primarily in office buildings, the following equation was suggested:

$$T_{co}(^{\circ}C) = 0.31 * T_{ref} + 17.8$$

where T_{co} and T_{ref} are the comfort temperature and current mean outdoor air temperature (for a period of last 7–30 days before the day in question). The ASHRAE databases were divided into two categories, i.e., naturally ventilated buildings (passive control), and centrally conditioned buildings (active control) (Fig. 9.5). The SET* and PMV prediction fitted closely to centrally conditioned buildings, in comparison with the naturally ventilated buildings (deDear and Brager 2002).

ASHRAE 55: 2010 has undergone further recent revision that includes computer model method for general indoor applications and further to evaluate the impacts of behavioural factors, clothing value, and high air movement on the comfort range of operative temperatures. In combinations of ambient indoor temperatures and behavioural factors, the occupants' preference for more air movement is higher than it is for less air movement. The approach of the adaptive model has been widely used in defining the range of indoor thermal environmental conditions acceptable to a majority of occupants. The adaptive model, accordingly, has been accommodated as design imperatives for sustainable buildings (e.g., thermal comfort compliance with LEED requirements).

EN 15251: 2007—The European standard establishes environmental input parameters for non-industrial buildings (offices, educational buildings, apartment buildings) for design and energy performance calculations. The guidelines of thermal comfort are based on the Smart Control and Thermal Comfort (SCATs) project, commissioned by the European Commission (McCartney and Nicol 2002). The survey covered 26 European buildings from France, the UK, Greece, Portugal, and

Sweden for three years covering free-running, air-conditioned, and mixed-mode buildings. For naturally ventilated buildings, EN 15251: 2007 included the equation:

$$T_{co}(°C) = 0.33 * Trm_7 + 18.8$$
$$Trm_7 = (T_{-1} + 0.8T_{-2} + 0.6T_{-3} + 0.5T_{-4} + 0.4T_{-5} + 0.3T_{-6} + 0.2T_{-7})/3.8$$

where Trm_7 is the exponentially weighted running mean of the daily outdoor temperature of the previous seven days. In EN 15251: 2007, the comfort temperature was divided into four categories, based on the range of acceptability (refer to Chap. 11, Table 11.1). Comparisons of the standards indicate some difference in the T_{co} due to differences in the intercepts by 1 °C and a marginal difference in the slopes of the equations.

Aynsley (1999) estimated thermal neutrality (T_n) for south-east Asia, based on the mean monthly dry-bulb temperature (T_m). That is,

$$T_n(°C) = 0.31T_m + 17.6$$

With the decadal average T_a for Kuala Lumpur as 28 °C, the thermal neutrality (T_n) arrived at 26.3 °C. For the comfort zone of 80 and 90% acceptability, the suggested T_n were ±3.5 and ±2.5 °C, respectively, and the T_{co} ranged within (26.3 + 2.5 = 28.8 °C) and (26.3 + 3.5 = 29.8 °C), respectively. The airflow (m/s) to offset the excess temperature was arrived at:

$$V = (\text{excess temperature}/3.67) + 0.2$$

Thus, for an excess T_a of 2 °C, the airflow required is ~0.7 m/s for the upper limit, and to compensate for the temperature of thermal neutrality, the suggested the airflow is 1.5 m/s (Zain et al. 2007).

CIBSE Guide A (Chartered Institution of Building Services Engineers 2006)—The British CIBSE Guide A (Environmental Criteria for Design) applies to free-running buildings, in which environmental control may be exercised via operable windows, the use of fans, or by changes to clothing worn. The guide presents an envelope of acceptable indoor operative temperature (T_o) that is relevant to normal healthy individuals. T_o increases with the exponentially weighted running mean of the daily mean ambient air temperature (T_{rm}) at a rate of 0.33 °C per °C. The upper and lower bounds are 4 °C apart and are applicable between limits of 8 °C < T_{rm} < 25 °C. That is, during warm summer, 25 °C is taken as an acceptable temperature, and for non-air-conditioned office buildings, the overheating criterion is *1% annual occupied hours over T_o of* 28 °C. The T_o drifting over 2 °C above the upper boundary might attract complaints. The CIBSE Guide notes that the thermal comfort and quality of sleep might be affected if room temperature rises much above 24 °C, and at night it should not exceed 26 °C unless ceiling fans are available.

Besides, the buildings may be recognized by the characteristics of thermal susceptibility, depending on the geographical location, the building types, functions, and vulnerability of the occupants to elevated temperatures. Notably, people

Table 9.4 Recommended thermal comfort criteria for selected applications

	Winter			Summer		
	T_o (°C)	Activity (Met)	Clothing (Clo)	T_o (°C)	Activity (Met)	Clothing (Clo)
Airport terminals						
• Check-in and customs areas	18–20	1.4	1.15	21–23	1.4	0.65
• Concourse (no seats)	19–24	1.8	1.15	21–25	1.8	0.65
• Departure lounge	19–21	1.3	1.15	22–24	1.3	0.65
*Banks, post offices (*counters, public areas)	19–21	1.4	1.0	21–23	1.4	0.65
Bars/lounges	20–22	1.3	1.0	22–24	1.3	0.65
Churches	19–21	1.3	1.15	22–24	1.3	0.65
Computer rooms, drawing offices	19–21	1.4	1.0	21–23	1.4	0.65
Conference/board rooms	22–23	1.1	1.0	23–25	1.1	0.65
Educational buildings (lecture/seminar room, exhibition hall)	19–21	1.4	1.0	21–23	1.4	0.65
Factories (sedentary work)	19–21	1.4	1.0	21–23	1.4	0.65
Fire/ambulance stations (watch room)	22–23	1.1	1.0	24–26	1.1	0.65
Garages (servicing)	16–19	1.8	0.85	–	–	–
General building areas						
• Entrance halls/lobbies, corridors, waiting areas, toilets	19–21	1.4	1.0	21–23	1.4	0.65
• kitchens (commercial)	15–18	1.8	1.0	18–21	1.8	0.65
Hospitals and healthcare buildings						
• Bedheads/wards	22–24	0.9	1.4	23–25	0.9	1.2
• Circulation spaces (wards)	19–24	1.8	0.75	21–25	1.8	0.65
• Consulting/treatment rooms	22–24	1.4	0.55	23–25	1.4	0.45
• Nurses' station	19–22	1.4	0.9	21–23	1.4	0.65
• Operating theatres	17–19	1.8	0.8	17–19	1.8	0.8
Hotel (bedrooms)	19–21	1.0	1.0	21–23	1.0	1.2
Law courts	19–21	1.4	1.0	21–23	1.4	0.65
Libraries, Museums and art galleries						
• Reference areas, museum display and storage	19–21	1.4	1.0	21–23	1.4	0.65
• Reading rooms	22–23	1.1	1.0	24–25	1.1	0.65
Offices (general, open-plan)	21–23	1.2	0.85	22–24	1.2	0.7
Places of public assembly						
• Auditoria	22–23	1.0	1.0	24–25	1.1	0.65
• Circulation spaces, foyers	13–20	1.8	1.0	21–25	1.8	0.65
Prison cells	19–21	1.0	1.7	21–23	1.0	1.2

(continued)

Table 9.4 (continued)

	Winter			Summer		
	T_o (°C)	Activity (Met)	Clothing (Clo)	T_o (°C)	Activity (Met)	Clothing (Clo)
Railway/coach stations						
• Ticket office	18–20	1.4	1.15	21–23	1.4	0.65
• Waiting room	21–22	1.1	1.15	24–25	1.1	0.65
Restaurants/dining rooms	21–23	1.1	1.0	24–25	1.1	0.65
Retailing (shopping malls)	12–19	1.8	1.15	21–25	1.8	0.65
Television studios	19–21	1.4	1.0	21–23	1.4	0.65

in hospital buildings (patients, vulnerable individuals, and other usual occupants, such as clinicians, nursing staff, visitors, and maintenance staff) differ in their thermal comfort requirements. Lomas and Giridharan (2012) reported the monitoring of 111 spaces in 9 healthcare buildings in the UK, over a two-year period, indicating that the buildings were either passively cooled with the use of operable windows or by the installations of mechanical cooling and air conditioning. CIBSE Guide A suggests the recommended thermal comfort criteria of selected building areas (Table 9.4).

Simulation Models in Evaluating Building Microclimate

Assessment of the relationships among microclimatic environment, subjective thermal response, and social behaviour require integration of weather parameters as well as the behavioural and activity patterns of occupants in and around the built environment (Nikolopoulou and Steemers 2003). The weather parameters include T_a, RH, wind speed, direct and diffuse solar irradiation, exchange of long-wave radiation between a person and the environment. Several field techniques represent measurements of the specific urban meteorological context. Techniques, such as wind tunnel measurements and CFD simulations, are used in both building indoor and outdoor studies (Schatzmann and Leitl 2011). Roelofsen (2016) presented an overview of the mathematical relationship between the performance loss and the thermal comfort/discomfort of people at workplaces. The goal was to present a single computer model and flexible design tool for use by building professionals, to analyse the indoor environment of buildings and improve conditions of the workplace. The proposed mathematical model was an assembly of human thermophysiological model and wet-bulb globe temperature index model, along with performance (loss) models. Every laboratory engaged in human–environment heat exchange research might have their in-house simulation tools and models, of varying level of efficacy and applicability.

A wind tunnel is a tool consisting of a tubular passage with solid objects mounted in the middle, and air moves past the object by a powerful fan or other means. The application of wind tunnel received importance to study the effects of wind on the built environment how the building structures alter the wind forces and directions. The wind tunnel measurement includes estimating the velocity, the pressure, and the scalar concentration. The velocities are measured by thermal anemometry, laser Doppler velocimetry, and particle imaging velocimetry. These measurements have been applied to determine wind loads on the facades and roof of a low-rise building (Uematsu and Isyumov 1999), to assess outdoor wind comfort in passages and near high-rise buildings (Kubota et al. 2008), and to analyse pollutant dispersion in street canyons and intersections (Ahmad et al. 2005).

Fluid flows are commonly observed in everyday meteorological phenomena (such as wind, rain, wind, floods), dispersion of air pollutants, HVAC in buildings, environment–human body heat transfers). Computational fluid dynamics (CFD) provides a qualitative and quantitative prediction of fluid flows using (i) mathematical modelling (partial differential equations), (ii) numerical methods (discretization and solution techniques), and (iii) software tools (solvers, pre- and post-processing utilities). CFD models, such as RayMan (Matzarakis 2007), SOLWEIG (Lindberg et al. 2008), BOTworld (Bruse 2007, 2009), ENVI-met (Bruse 2010), are in use for multi-agent thermal outdoor comfort assessment. The RayMan and SOLWEIG are based on radiation modelling of the outdoor environment (Robinson and Stone 2005). The RayMan calculates human thermal comfort indices, such as PMV, PET, and SET*, taking into consideration outdoor conditions and inputs of personal characteristics, clothing worn, and the physical activity performed. The ENVI-met is a three-dimensional non-hydrostatic microclimate model, which includes a simple one-dimensional soil model, a radiative heat transfer model, a vegetation model, as well as an airflow model. It is designed to simulate the interaction between surfaces, plants, and air in an urban environment with a typical resolution of 0.5–10 m in space and 10 s in time. The schematic (Fig. 9.6) of the BOTworld multi-agent system illustrates the interaction of component parameters, including import modules for microclimate data, human movement details, dynamics of thermoregulatory systems towards thermal comfort assessment (Bruse 2009). DesignBuilder, an interface model for EnergyPlus, can simulate the indoor environment and examine building performance (Wasilowski and Reinhart 2009). Simulation allows determining long- and shortwave radiative exchange, plant canopy effects on convective heat transfer, evapotranspiration from the soil and plants, and heat conduction (and storage) in the soil layer.

CFD tools and techniques have been applied to various applications. Ono et al. (2008) measured the convective heat transfer coefficient of human body parts by wind tunnel experiments using a thermal manikin, and compared with the CFD model, and used for the calculation of SET* distribution. There is a diversity of indoor and outdoor application of CFD models, such as pedestrian wind and thermal comfort (Tominaga et al. 2008), design of natural ventilation of buildings (Karava et al. 2011; van Hooff et al. 2011), solar chimneys (Harris and Helwig 2007) and hygrothermal analysis of building envelopes and envelope materials

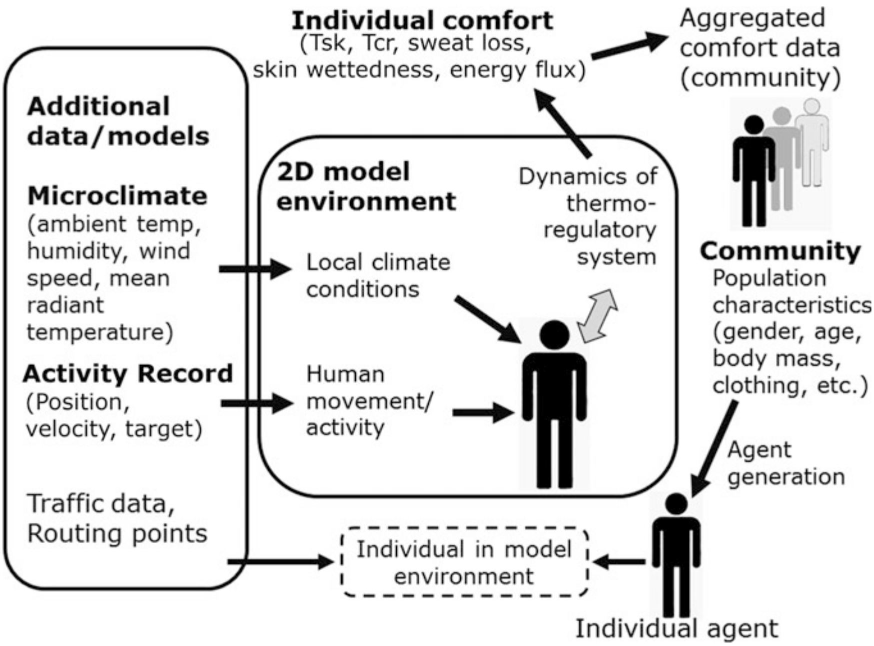

Fig. 9.6 Botsworld environmental simulation system

(Carmeliet et al. 2011; Defraeye et al. 2012). Besides, other CFD applications include pollutants dispersion and deposition (Tominaga and Stathopoulos 2011), urban heat island effects (Sasaki et al. 2008), wind-driven rain (Blocken and Carmeliet 2010; Blocken et al. 2010), and energy performance analysis of buildings (Barmpas et al. 2009; Defraeye and Carmeliet 2010).

With the CFD model and genetic algorithm, Ooka et al. (2008) simulated the optimum arrangement of trees, and Chen et al. (2008) simulated the influence of the arrangement of buildings on the outdoor thermal environment. From thermal comfort analysis in 14 cities across Europe, under the RUROS project (Rediscovering the Urban Realm and Open Spaces), Nikolopoulou (2004) revealed that the mean radiant temperature and wind speed are the two dominant factors affecting thermal perception. Yoshida (2011) developed a numerical method to assess pedestrian comfort along with a walking trajectory and found a significant effect of the walking direction on pedestrian thermal comfort, using SET*. Integration of the environmental tools with the human physiological modelling tools and geographical information system (Kántor and Unger 2010) opens up a gamut of avenues in understanding the influences of the outdoor thermal environment in comfort assessment and the planning implications for people to effectively use the outdoor space.

Heat Island

The heat island is a well-documented phenomenon of having localized elevated surface and air temperatures. Urbanization and mushrooming of tall building structures along narrow streets, and more surfaces paved or covered with buildings, often create a phenomenon known as the urban heat island (UHI). The likely causes of the phenomenon include (a) trapping of short- and long-wave radiation in between buildings, (b) decreased long-wave radiative heat losses due to reduced sky-view factors, (c) increased storage of sensible heat in the construction materials, (d) anthropogenic heat released from combustion of fuels, domestic heating, and vehicular traffic, (e) reduced evapotranspiration and convective heat removal due to the reduction of wind speed. Properties of urban materials, in particular, solar reflectance, thermal emissivity, and heat capacity, influence the development of UHI. While impermeable and dry surfaces result in elevated surface and air temperatures, ground green covers, and vegetated areas have more cooling surface and air temperatures.

Mainly, elevated temperatures, burning of fossil fuel for electricity generation, emissions of air pollutants, and greenhouse gases directly impact UHI intensity. Santamouris (2001) reported a wide range of heat island intensities around the world, i.e., 1 °C (Singapore), ~2 °C (Johannesburg and Sao Paulo), 2.5 °C (London), 4 °C (Cairo), ~10 °C (Pune and Calgary), and 14 °C (Paris). Surface temperature measurement is a useful way to identify UHI, and at a local level, infrared thermography is a handy technique to identify temperature gradients. Radiometers and other remote sensing devices can measure surface thermal energy from the surface emitted wavelengths. Air temperatures at little above the ground indicate thermal properties of surfaces, both within a city and in non-urban areas.

In hot climates, UHI can exemplify the potential risk of exposure of inhabitants to discomfort and heat exposure-related morbidity and mortality. Sensitive populations, particularly children, elderly, and those with existing health conditions, are at higher risk from these events.

A review by Santamouris (2014) on the UHI mitigation technologies revealed the promise of increasing the albedo of cities, and the use of vegetative green roofs. Available data are mostly from simulation studies on mesoscale modelling, with a paucity of experimental data. Considering a global increase of the city's albedo, the expected decrease in T_a temperature is close to 0.3 °C per 0.1 rises of the albedo, and the decrease in peak T_a is close to 0.9 °C. When cool roofs were considered, the expected depression rate in the T_a varies between 0.1 and 0.33 °C per 0.1 increase of the roofs albedo. With green roofs, T_a can be reduced between 0.3 and 3 °C.

Evaporative cooling from ground-level ponds (Kruger and Pearlmutter 2008), roof ponds (Runsheng et al. 2003), surfaces wetted by wind-driven rain (Blocken et al. 2007), vegetated surfaces (Alexandri and Jones 2008), and controlling the solar gains by applying high-albedo materials at horizontal surfaces (Erell et al. 2012) are other UHI mitigation approaches. A high solar reflectance or albedo of a roof (*cool roofs*) can reflect sunlight and heat away from a building and reduce roof temperatures. Cool roofing of a building transfers less heat to the level below, and thus building stays cooler resulting in net energy savings.

Increasing strategic *trees and vegetation* covers around buildings, to shade pavements, streets and public areas are effective in reducing UHI. Planting deciduous trees to the west is an effective way of cooling a building, especially if they shade windows and part of the building's roof. Evapotranspiration alone or in combination with shading might reduce peak summer temperatures by 1–5 °C.

Cool pavements can be created using different paving technologies. Permeable pavements, grass paving, coating, and reflective pavements reflect more solar energy and enhance water evaporation to remain cooler than conventionally used paving materials (such as asphalt and concrete). Permeable pavements allow storm water to soak into the pavement and soil, reducing run-off and filtering pollutants. Reflective pavements can enhance visibility at night. Cool pavements in parking and other public open areas (e.g., populated religious complexes) can provide a more comfortable environment.

Wind Comfort

Empirically, wind performance, the velocity of wind flow around a built structure or other facility were evaluated using, for example, the *Beaufort scale* or Beaufort wind force scale. The scale was proposed in 1805 by Francis Beaufort, to predict weather warning—cyclonic or hurricane wind conditions (Beer 2013). The original scale was limited to force 1–12 scale and extended up to 17 in 1946 Beaufort scale (http://www.rmets.org/weather-and-climate/observing/beaufort-scale). Wind speed (m/s) on the 1946 Beaufort scale can be derived using the relationship:

$$v = 0.836\,\mathrm{B}^{3/2}$$

where v is the equivalent wind speed (m/s) at 10 m above the sea surface and B is Beaufort scale number; i.e., for B = 6, the corresponding wind speed is 12.3 m/s. The WMO Manual on Marine Meteorological Services (2012) included the scale value, only up to the original 12 scale, as given in Table 9.5 (refer to http://www.britannica.com/science/Beaufort-scale, *Encyclopedia Britannica*).

The Beaufort scale was developed based on visual and subjective observation of a ship and the sea, and therefore, it is not an exact scale. Since the integral wind speeds were determined later, the scale values could not be made an equivalent. The merit of the Beaufort scale is its simplicity. However, surroundings of high-rise buildings can produce high wind speed at pedestrian level, which can lead to uncomfortable conditions. These buildings deviate wind differently (Fig. 9.7), partly guided over the building, and around the vertical edges, and a more significant part deviates to the ground level. A standing vortex and corner streams develop at the ground level and also create low wind speed pockets.

Table 9.5 Beaufort scale about wind speed

Beaufort no.	Scale		Wind speed
0	Light winds	Calm	<1 mph; <1 knot; <0.3 m/s
1		Light air	1–3 mph; 1–3 knots; 0.31–0.5 m/s
2		Light breeze	4–7 mph; 4–6 knots; 1.63–3 m/s
3		Gentle breeze	8–12 mph; 7–10 knots; 3.4–5.5 m/s
4		Moderate breeze	13–18 mph; 11–16 knots; 5.5–7.9 m/s
5		Fresh breeze	18–24 mph; 17–21 knots; 8.0–10.7 m/s
6	High winds	Strong breeze	25–31 mph; 22–27 knots; 10.8–13.8 m/s
7		Near gale	31–38 mph 28–33 knots; 13.9–17.1 m/s
8	Gale force	Gale	39–46 mph; 34–40 knots; 17.2–20.7 m/s
9		Strong gale	47–54 mph; 41–47 knots; 20.8–24.4 m/s
10	Storm force	Storm	55–63 mph; 48–55 knots; 24.5–28.4 m/s
11		Violent storm	64–72 mph; 56–56–63 knots; 28.5–32.6 m/s
12	Hurricane force	Hurricane force	>73 mph; >63 knots; >32.7 m/s

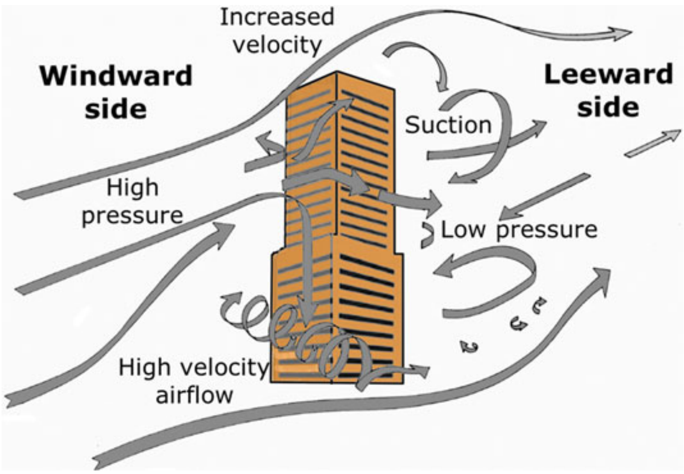

Fig. 9.7 Wind flow pattern around a high-rise building

Pedestrian-level wind conditions around buildings can be analysed by on-site wind tunnel measurements or by CFD, as described above. Wind conditions affect the ventilation of buildings, as described in Chap. 12, and the required rate of air exchange in a building space is obtained from the ratio of volumetric flow rate of air and space volume.

Green Roof

Green roofs are an attractive greening strategy in office buildings and many other built facilities. A green roof, a vegetative layer grown on a rooftop, can be as simple as a few centimetres of ground cover that facilitates absorbing heat and acting as insulators for buildings. The plant growth is related to the substrate composition, plant material, and the relative depth of the substrate layer to provide support for plant growth (Fang 2012; Getter and Rowe 2009). Intensive and extensive green roofs have been built, with appropriate deeper or thinner depth of substrate layer. Roof garden, for instance, is an intensive type, having a deeper substrate layer; an extensive green roof, however, has a thinner substrate layer (Castleton et al. 2010).

Green roofs mitigate possible UHI phenomenon—the vegetation influences the indoor thermal condition of the buildings and removes air pollutants and greenhouse gas emissions through dry deposition, carbon sequestration, and storage. By investigating the behaviours of 50 major metropolitan areas, Stone et al. (2012) observed that roof greening and tree planting facilitate increasing (a) the urban planting and the green coverage, (b) the urban albedo, and (c) improving the efficiency of energy use. Lundholm et al. (2010) examined green roof system planted with monocultures or mixtures containing one to five life forms, and quantified summer roof cooling and water capture, besides properties/processes of albedo, evapotranspiration, and temporal variability of biomass. Mixtures containing three to five life form groups, e.g., combinations of tall forbs, grasses, and succulents, optimized several green roof ecosystem functions.

Energy saving from the green roof—The heating and cooling load, that is, increased energy demand of a building depend on the climate to which the building is exposed. Various studies on UHI, covering cities like Athens (Santamouris et al. 2001), London (Kolokotroni et al. 2010), and Tokyo (Hirano and Fujita 2012) indicated a substantial impact of the increased urban temperature on the energy consumption of buildings. Akbari (2005) estimated that the UHI effect is responsible for 5–10% of peak electricity demand for cooling buildings in cities.

Ohashi et al. (2016) undertook simulations of summertime outdoor heat stress and disorder risks, studying possible influence of UHI mitigation measures on outdoor human heat stress in the 23 wards of Tokyo, about city's 2010 extremely hot kinds of weather. Taking WBGT as a heat stress indicator, simulations were applied to evaluate the effects of building greening, high-albedo coating, and roof-level emissions of waste heat by air conditioning. Results indicated that high-albedo coating increased the daily maximum WBGT by ~0.6 °C, to a maximum of ~1.7 °C, with possible 1.4–3.3 times higher heat hazard and disorder risks, in comparison towards with no mitigation scenario.

By studying the residential buildings, Sfakianaki et al. (2009) showed that a green roof in the Mediterranean climate (Athens, Greece) could provide limited insulation effect, whereas it was useful to reduce the cooling load by about 11% for thermostatically controlled buildings. A green roof improved heat comfort in summer for the ordinary buildings, with a temperature drop of ~0.6 °C between the roof surface and interior. Spala et al. (2008) studied commercial buildings in Athens and observed that a green roof reduced the electricity consumption for air conditioning in summer by about 40%. Castleton et al. (2010) noted that old buildings with poor insulation received the most considerable benefit from a green roof. The annual energy usage of modern buildings, built with high standard insulation layer specifications, gained little from the construction of a green roof.

Cooling effect**—**With the growing UHI phenomenon, different types of cooling roof approaches have also been advocated, in place of a green roof. Different levels of insulation of the roof slab result in different cooling effectiveness. Greening styles, plant materials, plant types, and substrate formulations may all affect the cooling effectiveness (Nardini et al. 2012; Ouldboukhitine et al. 2012). Experimental study of extensive green roofs in subtropical and tropical island climate regions of Taiwan (Lin et al. 2013) revealed that the green roofs might reduce the increase of outdoor temperature by about 42% and indoor temperature by 8% during the daytime. The daytime cooling effectiveness was higher in the tropical island climate in summer, and the night-time insulation effectiveness was *more* pronounced in the subtropical climate. A simulation study using DOE2 on a hypothetical high-rise commercial building in Singapore (Wong et al. 2003) indicated potential benefits of green roofs in the reduction of surface temperature. Onmura et al. (2001) conducted a field measurement, investigating the evaporative cooling effect from roof lawn gardens during summer in Japan and observed a reduction in the amount of heat coming into the rooms due to the roof lawn garden. The surface temperature of the roof slab decreased substantially from during daytime, amounting equivalent of a 50% reduction in heat flux into the room. The evaporative cooling effect of the lawn garden was substantiated by a wind tunnel experiment in a room and numerical prediction of the extent of transport of heat and moisture.

D’Orazio et al. (2012) compared the effectiveness of the green roof and other types of cool roof, concerning the degree of insulation in an experimental house near Ancona, Italy. The installation of a green roof could reduce the surface temperature in summer and stabilize the daily variation of temperature. Teemusk and Mander (2010) compared the temperature changes of a green roof, a turf roof, a modified bituminous membrane roof, and a steel sheet roof in Tartu, Estonia, in different seasons. The green (100 mm) and turf roofs (150 mm) behaved similarly during summer, and on the other hand, during autumn and spring, the temperature of the substrate layer for the turf roof was higher than that of the green roof. In winter, the temperature below the substrate of the green roof was higher than the surface temperature of the non-greening roof. The heat storage of the non-greening roof was about 75% higher than that of the green roof, as studied in Hong Kong (Tsang and Jim 2011). In the overall analysis, the green roofs unquestionably contribute to ecosystem services. The green roofs brought in reduction in summer roof temperature, storm water management (Tan and Sia 2009; Lundholm et al. 2010), reduction in thermal load applied to buildings, cooling effectiveness and optimization of building energy use (Fioretti et al. 2010), and improvement in the microclimate.

The bioclimate analysis included in this chapter primarily focused on the human warmth and comfort characteristics with respect to the indoor and outdoor environment, and particularly for occupant's comfort and safety in the building environment. In summary, the comfort/discomfort of the microclimate scenario depends on the uneven distribution of environmental parameters, particularly in indoor and in confined spaces, such as homes, hospital, schools and buildings, and also transportation. The discomfort might arise due to the temperature difference between the floor and the ceiling, the radial asymmetry, non-homogeneous distribution of the skin temperature of different body regions due to the difference in convective and evaporative heat exchange coefficients, leading to the uncomfortable feeling of having hot/cold. The beckoning by the work of Fanger (1970) has gone deep into the understanding of the physiological basis of comfort, dynamics of the human thermoregulatory system, thermal comfort models and techniques, and ongoing efforts in adaptive approach (Djongyang et al. 2010; Frontczak and Wargocki 2011). Naturally, the concept finds its place in exploring the relationship between the architectural form of the buildings and the related climatic heat exchange. Issues raised provide firm support and evidence of deploying bioclimatic principles and approaches to building design and achieve comfort and well-being to the occupants. This chapter is linked to Chap. 11, describing assessment guidelines of IEQ performance in buildings. The architectural design, solar architecture, passive architecture (or passive buildings), green architecture, and bioclimatic architecture are the separate domains about human thermal comfort and energy optimization in buildings.

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Chapter 10
Characteristics of Indoor Environmental Quality

Introduction

Indoor environmental quality (IEQ) in an office/non-residential building is expressed in term of occupants' health and safety, determined by environmental aspects, covering the physical, chemical, and biological origins. The physical factors include lighting, acoustics, thermal conditions, and the chemical factors include indoor air quality (IAQ). The biological factors include the presence of microorganisms in the indoor environment. Inhalation of bacterial, fungal, and microalgal spores have been recognized to cause an allergic reaction. Each of these environmental aspects demands elucidation for a comprehensive assessment of IEQ about different types of building spaces. Building types under commercial or non-residential categories that are of concern include:

(a) office buildings along with banking and other financial service buildings, R&D facilities;
(b) retail and food stores, such as grocery stores, liquor stores, convenience stores, restaurant, cafeteria;
(c) hospitals and healthcare buildings;
(d) commercial facilities, hotels;
(e) services, such as beauty salons, gas stations, automobile garage; and
(f) public utilities, such as post offices, police and fire stations;
(g) public assembly, such as health/fitness centres, libraries, conference rooms.

Generally, small- and medium-sized commercial buildings (less than four stories, floor area ranging from 1,000 to 50,000 ft^2) make up the vast majority of the commercial buildings all over the world (Bennett et al. 2011). From a total of 476 telephone and 71 additional mail-back surveys of small- and medium-sized commercial buildings of California (floor area of $\sim 60\%$ buildings ranged within 10,000–50,000 ft^2), Piazza and Apte (2010) noted a broad array of air contaminant sources in the premises. This chapter brings an analysis of IAQ, i.e., the particulate

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matter (PM) and gaseous contaminant sources from indoor and outdoor sources. The contaminants from outdoors can enter indoor via both mechanical and natural ventilation processes. These contaminants also get generated from building materials, products, and processes (office equipment, solvents), ETS, and bioeffluents from the occupants and remain suspended in the indoor air (Bluyssen 2009; Kim and Haberl 2012a, b).

Sources of Indoor Air Pollutants

The relative dominance of the air pollutants depends on how hazardous and how much emissions generated from multiple sources, the occupant proximity to emission sources, and the efficacy of the ventilation system to exhaust contaminants. For example, the building site or location at the proximity of industrial activity, or a land area with high water table having risks of leaching chemical pollutants into the building, busy urban activity or highways are the potential sources of particulates and other contaminants to buildings. Doors and windows, roofs and facades, are the avenues of pollutant intrusion in buildings. Products of combustion, waste generation, and vehicle idling are the recognized outdoor pollutant sources that may enter the building. Building exhaust carries particulates and other contaminants, and that may re-enter into the building due to inappropriately designed or improperly functioning HVAC system. Maintenance shops, photocopy, parking garages, kitchen, and toilets are the potential sources of pollutants if the areas are appropriately not equipped with local exhaust ventilation. In different forms of repair, renovation and painting activities, dust or other by-products of the construction materials circulate through the building. Isolation by barriers and increased ventilation to minimize the contaminants are alternative options to control pollutants. Thermal insulation or acoustical material, wet structural (walls, ceilings) and non-structural surfaces (carpets) promote microbial growth. Building furnishings, furniture made of pressed-wood products, pesticides, cleaning products, occupants using personal care products, perfumes or other synthetic fragrance are the source of indoor air pollutants.

IEQ Measurement

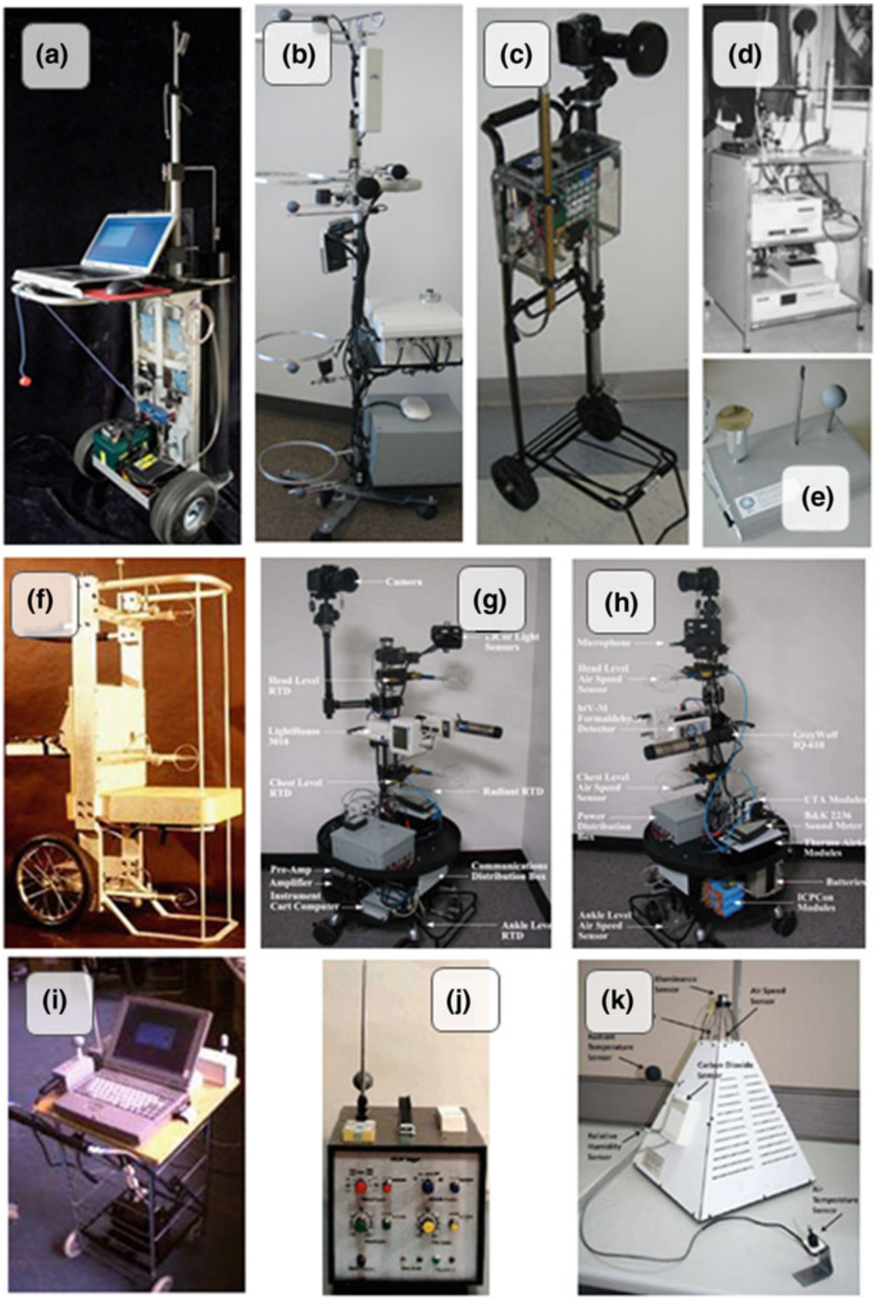
Different environmental attributes of building space can be objectively measured using suitable environmental monitoring devices and sensors. Measurements cover chemical and physical parameters, particulates—PM_{10}, $PM_{2.5}$, aerosols, carbon dioxide (ppm), carbon monoxide (CO), volatile organic compounds (VOCs) , black carbon, radon concentration, climatic factors—ambient temperature, relative humidity, radiant temperature, air movement, acoustic, lighting, fungal, and other microbial contaminants. The laser printers in operation can generate a substantial amount of ultrafine particles in office and commercial buildings. In Chap. 3, details of quantification of fungal growth in buildings and building materials are described. It is not intended to mention the prospective manufacturers of different equipment and devices. However, the literature evidence indicates equipment of relative efficacy, smooth operation, the range of capabilities, precision, and accuracy. Heinzerling et al. (2013) have made an updated compilation of different IEQ measurement carts and desktop devices (Fig. 10.1) that have been used by various researchers. Carts, housing with multiple sensors in a unit are useful for easy movement to locations, and schedule sampling of IEQ parameters.

There are issues of skill requirements for accuracy testing, calibration, and operation of equipment. Moreover, deploying of sensor devices in a large building, for IAQ, HVAC, occupancy sensors, safety and security sensors, weather stations, is often expensive and then analysing the vast amount of data is time-consuming. Developing portable, easy-to-use, accurate, and inexpensive equipment is an inherent challenge in IEQ performance evaluation. With the availability of improved measurement technology and computer-based application, the indoor environment attributes from multiple locations can be remotely accessed on a temporal scale, by synchronizing with the building information modelling (BIM) tools, and meaningfully evaluated the building performance.

Indoor Contaminant Sources

Particulate matter (PM)—PMs in an indoor environment comprise of mixtures of organic and inorganic substances from outdoor air infiltration and indoor sources in buildings. The respirable particulate matter, i.e., 1–10 μm in size, may be inhaled deep into the lungs, and the exposure can result in respiratory illness, depending on the characteristics of particles. Different types of devices, such as cascading impactors may be used for sample collection, e.g., $PM_{2.5}$ and PM_{10} (Demokritou et al. 2004). These impactors include multiple stages, and each stage gravimetrically collects PMs of different size fractions onto a small piece of polyurethane foam, and the tiniest size fraction collected onto a Teflon filter. Condensation particle counter, for example, Model 3781 (TSI) is a primarily used method for measuring ultrafine PMs (Mullen et al. 2011; Wallace and Ott 2011). This device uses water vapour to enlarge particles and detect down to 6 nanometers (nm) in diameter and count concentrations up to 50,000 particles/cm^3, by a laser-based optical detector.

In general, office and commercial buildings have a relatively lower PM concentration indoors than those of outdoors. This is achieved due to installing mechanical ventilation systems, use of filters, and better sealing of buildings (CARB 2005). The extensive US BASE study, examining 100 randomly selected office buildings, recorded geometric mean $PM_{2.5}$ and PM_{10} concentration as 7.2 and 11.4 μg/m^3 (Burton et al. 2000). $PM_{2.5}$ concentration in offices and café in Iran ranged from 7.3 to 19.8 μg/m^3 (Mohammadyan et al. 2010). Buonanno et al. (2010) reported the extremely high concentration of ultrafine particles, with an average of 170,000/cc in


(a)
(b)
(c)
(d)
(e)
(f)
(g)
Camera
Head Level RTD
Lighthouse 3016
Chest Level RTD
Radiant RTD
Pre-Amp
Amplifier
Instrument Cart Computer
Communications Distribution Box
RTD
(h)
Microphone
Head Level Air Speed Sensor
Chest Level Air Speed Sensor
Power Distribution Box
GrayWolf IQ-610
B&K 2236 Sound Meter
Modules
ICPCon Modules
Ankle Level Air Speed Sensor
(i)
(j)
(k)
Illuminance Sensor
Air Speed Sensor
Radiant Temperature Sensor
Carbon Dioxide Sensor
Relative Humidity Sensor
Air Temperature Sensor

◂**Fig. 10.1** Air monitoring carts: **a** UFAD commissioning cart (Webster et al. 2007), **b** Comprehensive IEQ monitoring cart (Kim and Haberl 2012a, b), **c** EnviroBot (Choi et al. 2012), **d** IEQ cart (Chiang et al. 2001), **e** Indoor climate monitor desktop device (Paliaga 2004), **f** Instrumented chair-like cart (Benton et al. 1990), **g** NICE instrumented cart part 1 (Newsham et al. 2012), **h** NICE instrumented cart part 2 (Newsham et al. 2012), **i** SCATs instrumented cart (Nicol and McCartney 2000), **j** IEQ logger (Mui and Chan 2005), **k** Pyramid desktop device (Newsham et al. 2012)

a pizzeria, Italy. Bennett et al. (2011) observed $PM_{2.5}$ concentration in small- and medium-sized buildings (California, USA), ranging from 8.6 to 10.1 µg/m^3. Indoor/outdoor ratios of ultrafine PMs, and those smaller than 2.5 µm were less than 1.0 in most buildings, excepting the facilities, such as restaurants, hair salons, dental offices, which have known sources of ultrafine PMs. The penetration efficiency of black carbon in the buildings was 0.72, indicating that the building shell and HVAC system provided only partial protection from outdoor particulates.

The dental practices (such as drilling and polishing, and the aerosolized saliva emitted from patients' mouths during treatment) are said to generate high concentrations of ultrafine particles (Helmis et al. 2007; Sotiriou et al. 2008; Bennett et al. 2011). In hair salons, use of hair dryers, curling irons, and hair straighteners release ultrafine particles (Wallace and Ott 2011). Other sources of high particles in hair salons are, for example, small pieces of hair, particles re-suspended while sweeping floors, particles generated during oxidation reactions from products containing compounds such as d-limonene.

Heavy metals—Indoor dust is a repository for pollutants such as heavy metals that get accumulated indoors (Hunt et al. 2008). Heavy metals can get bioaccumulated through inhalation, ingestion as a result of hand-to-mouth activity, and dermal contact absorption.

Carbon dioxide (CO_2)—CO_2 is considered as a critical parameter (Syazwan et al. 2009) in assessing indoor IAQ and ventilation efficiency. It gets accumulated in the indoor space from human respiration, ETS, gas stoves, ovens, and other activities. The concentration of CO_2 exceeding 3% can cause a headache, dizziness, and nausea, and concentration above 6% may be fatal. A building space that has insufficient fresh air ventilation can contribute to increasing the level of CO_2. Increase in the ventilation rate improves the effectiveness in providing clean air and reducing CO_2 concentration in the building.

Carbon monoxide (CO)—CO, a by-product of incomplete combustion of carbon-containing materials, is an odourless and colourless gas. On exposure, CO disrupts oxygen transport. Concentration above 5 ppm of CO within the airspace may result in adverse health effects, including a headache, sore eyes, runny nose, dizziness, vomiting, and loss of consciousness. CO concentration above 10 ppm is significantly associated with SBS symptoms (Samet and Krewski 2007). The US OSHA recommended 8-hr TWA PEL of CO is 50 ppm.

Oxides of Nitrogen (NO_x)—The sources of NO_x include kerosene heaters, gas stoves, and ETS. NO_x act as mucous membrane irritant, affecting the eyes, nose, throat, and respiratory tract. Continued exposure at the high level of NO_x can lead to acute bronchitis. Extremely high-dose exposure in case of situations like fire incident may result in pulmonary oedema and lung injury.

Black carbon—Ultrafine particles of outdoor origin may penetrate buildings through doors and windows, air handlers, cracks, and gaps in the building envelope (Meng et al. 2007). The US OSHA recommended 8-hr TWA PEL of black carbon is 3.5 μg/m^3. Black carbon concentration can be estimated by placing aethalometer at different locations, such as the roof, indoors, air handler units, outside the building (Sarnat et al. 2006). The fraction of outdoor particles penetrating into the building is expressed as the penetration efficiency. However, penetration factors of particle size fractions vary due to the geometry and shape of the cracks, the air exchange rates, and temperature differentials between the air and surfaces (Tian et al. 2008; Chen and Zhao 2011). Accordingly, the rate of deposition of particles onto indoor surfaces varies between buildings, depending on airflow patterns, furnishings of interiors, interior surface-to-volume ratio, temperature differentials, particle size and roughness (Lai 2006). The indoor/outdoor ratio of black carbon indicates the effectiveness of the building shell and filtration system. The ratio greater than 1 would indicate that the black carbon concentration might vary between sides of the building, and re-suspension of dust particles from furniture and furnishings. There may be the presence of an indoor source that changes the reflectance very similar to that of black carbon (products used in the hairstyling processes).

Radon—A radioactive gas that found in soils, coal, rocks contains uranium, granite, shale, and phosphate. Radon decays form radioactive particles, which can enter the body by inhalation. Radon deposition in the lungs carries an increased risk of developing cancers in the respiratory system. Estimated that 15,400–21,800 people in the USA die each year from lung cancer attributable to radon, although the fatality could range from 3,000 to as high as 32,000 (NAS 1998). Death of about 1100 people in the UK every year is attributable to radon exposure (HPA 2009). Radon is of less concern in a naturally ventilated buildings.

Volatile organic compounds (VOCs)—VOCs are all organic compounds at the boiling point range of 50–260 °C and excluding pesticides. The VOCs are estimated from the indoor air by sampling air analysing by thermal desorption gas chromatography/mass spectrometry (TD-GC/MS). This contribution is beyond the scope to elaborate the procedures of indoor air sampling and analytical methods of estimation of different air toxicants. Readers may refer to a standard analytical chemistry manual for detailed methodological procedures. Since VOCs exhibit diverse physiochemical properties, developing standard measures for sampling and analysis of VOCs has obvious analytical challenges. A review by Panagiotaras et al. (2014) examined various sampling strategies and analytical methods to determine VOCs and aldehydes with reference to the indoor environment. The most commonly used methods are the US EPA compendium of methods for the determination of toxic organic compounds (TO methods) (US EPA 1984, 1999), and air pollutants in indoor air (IP methods) (US EPA 1990). The TO methods (TO 1–TO 17) developed for ambient air studies can be adapted to the indoor application; the IP methods are also same as the comparable TO methods (MADEP 2002). The ISO 16000 standards, having several parts (ISO 16000-6:2011, ISO 16000-28:2012) are of particular interest for determination of VOCs in indoor test chambers and emission testing from building products.

Most of the analytical methods use GC or HPLC techniques to separate analytes in a mixture of compounds. In GC, the mobile phase is used as a carrier gas to move chemical compounds along the long, flexible, capillary columns, whereas in HPLC, liquids are used as mobile phases. On separation of a mixture of chemicals, each compound can then be identified by passing the air sample through a detector. The choice of the detector (e.g., a flame ionization detector, FID; photoionization detector, PID; electron capture detector, ECD) depends on the structural characteristics of the compounds to be identified, in terms of selectivity, sensitivity, and the required detection limits. Mass spectrometry (MS) coupled with high-resolution gas chromatography (GC/MS) has superiority over other detectors in the identification of unknown analytes, since MS generates a unique mass spectrum of each compound and discriminates between the compounds. Most of the TO methods use a mass spectrometer as the detector.

Hundreds of VOCs have been identified in indoor air. However, researchers have identified target VOCs that are found in measurable quantities in commercial buildings. The VOCs estimated from building in selected studies are tabulated herewith, in the order of concentration levels (Table 10.1). The total VOC emission indoors varies widely, since the emission rates depend on the construction and decorating materials, such as textile carpet, paint, dyes, and glue, and also cleaning products present in the indoor environment (Brown et al. 1994). Formaldehyde (a known human carcinogen) is usually emitted from carpet, laminated wood products, and furniture coating (Singer et al. 2006). Naphthalene has been used as a fumigant. Presence of d-limonene, 2-butoxyethanol, and toluene in buildings corresponds to the sources of cleaning and polishing agents, paints, and solvent-containing materials (Nazaroff and Weschler 2004).

Different range of concentrations of the VOC classes might indicate source apportionment of indoor VOCs. The analysis has often been undertaken using the principal factor analysis technique (Logue et al. 2009), assuming that the variance explained by the factor components of the VOC concentrations attribute to specific sources or activities in buildings. Taking data from 37 buildings, Bennett et al. (2011) estimated source apportionment of 30 aldehydes and VOCs indoors and outdoors. The analysis yielded five factors, cumulatively explaining 63% of the total variance of the indoor VOC concentrations. Factor 1 represented outside sources, with high loadings of benzene, toluene, ethylbenzene, and xylenes (BTEX), and n-hexane that emits from automatable sources. Factor 2 was from high loadings of d-limonene, a-terpineol, and D5-siloxane, which were related to cleaning products. Factor 3 covered high molecular weight aldehydes; Factor 4 explained high loadings of TXIB and diethyl phthalate (plasticizers) and Factor 5 due to low molecular weight aldehydes. Chloroform concentration was higher in restaurants and grocery stores (due to frequent water use). Diethyl phthalate was higher in dental offices, healthcare establishments, hair salons, and gyms (due to frequent cleaning and personal care product use), whereas m/p-xylene were higher at automobile and gas stations (due to volatile components of gasoline).

Table 10.1 VOCs estimated in building-related studies

37 Small and medium-sized US buildings (Bennett et al. 2011)	Call centre (Hodgson et al. 2003)	100 BASE buildings (EHE 2002)	US BASE study (Girman et al. 1999)	Swedish housing stock (Bornehag and Stridh 2000)	Australian review (Brown 1999)	A German study (Reitzig et al. 1998)	US review (Holcomb and Seabrook 1995)	European audit (Bernhard et al. 1995)
2-Butoxyethanol	D5-siloxane	Acetone	Acetone	Toluene	Benzene	Phenoxyethanol	o-xylene	Acetone
Acetone	Acetone	Formaldehyde	Hexane	Decane	PCE	Butyldiglycol acetate	Benzene	Isoprene
D-limonene	2-Butoxyethanol	Toluene	Toluene	Dodecane	1,4-DCB	Longifolene	TCE	2-Methyl pentane
D5-siloxane	Formaldehyde	Acetaldehyde	1,1,1-Trichloroethane	Nonanal	Ethylbenzene	Dimethyl phthalate	m-, p-xylenes	Hexane
Decanal	Acetaldehyde	d-limonene	Methyl chloride	Undecane	m-, p-xylenes	a-pinene	Ethylbenzene	2-Methyl hexane/ benzene
Formaldehyde	Hexanal	m/p-xylene	Benzene	Limonene	1,1,1-Trichloroethane	Camphene	Trichloroethane	Heptane
Acetaldehyde	Toluene	2-Butoxyethanol	Ethanol	C_{1r}Alkane	o-xylene	b-Pinene	Toluene	Toluene
Toluene	d-limonene	Hexanal	2-Propanol	C_{j2}-Alkane	Decane	3-Carene	1,4-DCB	m-, p-xylenes
m/p-xylene	m/p-xylene	Nonanal	Dichlorofluoromethane	Xylenes	Toluene	Styrene	Styrene	o-xylene
Nonanal	a-pinene	Benzene	m-, p-xylenes	Cio-Alkane	1,2,4-Trimethyl benzene	o-xylene	Undecane	Decane
Hexanal		n-Hexane	2-Butanone	Trimethylbenzenes	Hexane	C_{12}-Alkanes	Dodecane	Trimethylbenzene
n-Hexane		o-xylene	Trichlorofluoromethane	Butoxyethoxyethanol	Nonane	1.2.3-Trimethylbenzene	Octane	Limonene
Ethylbenzene		PCE	o-xylene	Butoxypropanol	Limonene	1.2.4-Trimethyl benzene		
TXIB		Phenol	Undecane	C7-Alkane		Methylcyclohexane		

(continued)

Table 10.1 (continued)

37 Small and medium-sized US buildings (Bennett et al. 2011)	Call centre (Hodgson et al. 2003)	100 BASE buildings (EHE 2002)	US BASE study (Girman et al. 1999)	Swedish housing stock (Bornehag and Stridh 2000)	Australian review (Brown 1999)	A German study (Reitzig et al. 1998)	US review (Holcomb and Seabrook 1995)	European audit (Bernhard et al. 1995)
a-pinene		Ethylbenzene	PCE					
PCE		Methylene Chloride	1,2,4-Trimethyl benzene					
Octanal		CTet	Decane					
Phenol		Styrene						
Methyl chloride		TXIB						
o-xylene		1,4-DCB						
CTet		Naphthalene						
a-terpineol		a-pinene						
Chloroform		Chloroform						
Styrene		TCE						
DEP								
Benzaldehyde								

Abbreviations: carbon tetrachloride (CTet); trichloroethylene (TCE); tetrachloroethylene (PCE); 1,4-dichlorobenzene (1,4-DCB); diethyl phthalate (DEP); decamethylcyclopentasiloxane (D5-siloxane); and 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TXIB)

There are several sources of semi-volatile compounds in the indoors. Flame retardants are used in the foam of upholstered furniture and electronic equipment (Harrad et al. 2010; Rose et al. 2010); phthalates used is polyvinyl chloride and other plastics (Bornehag et al. 2005; Hauser and Calafat 2005). Use of pesticides is widespread to control indoor pests (Morgan et al. 2007; Julien et al. 2008). There is also the anticipation of seasonal variations in VOC concentrations in buildings. Increase in indoor temperature in summer months can cause increased emission of aldehydes, chlorinated compounds, and esters (such as formaldehyde, acetone, nonanal, trichloroethylene, phenol). Intense generation of aldehydes is likely during the summer due to photochemical reactions with ozone (Morrison and Nazaroff 2002).

VOCs and Potential Health Effects

The individual VOC in an indoor environment is usually lower than 50 μg/m^3. The cumulative load of total VOCs indoors can be much higher. ASHRAE (2009) recommended the threshold limit for VOCs in the airspace to be below 3 ppm. Possible health effects of the classes of VOCs are briefly summarized in Table 10.2. The VOCs (including those of microbiological origin) deteriorate the perceived air quality (Clausen et al. 2000) and following inhalation exposure attributes to a range of health conditions, including the mucous membrane irritation, exacerbation of asthma, odour annoying, liver, and kidney damage and increased cancer risks. Exposure to reactive indoor VOCs (formaldehyde, acrolein) is known to cause eye and airway irritation. Several studies cited in Chap. 3, indicated that the VOCs may provoke symptoms typical of SBS, and multiple chemical sensitivities. Generally, repeated exposure to VOCs and long-term exposure might result in apparent adaptation to odour threshold and modulate the physiological and psychological response (Wilkins et al. 1998; Hummel et al. 2000).

Unsaturated terpenes are abundant in cleaning and air freshener products, such as a-pinene (pine scent), and d-limonene (lemon scent), and other terpene-related compounds, such as a-terpineol, linalool, and linalyl acetate. Reactions of these compounds with oxidants, such as ozone and nitrogen oxides release hydroxyl radicals, and form aldehydes, ketones (Singer et al. 2006) and hydrogen peroxide (Li et al. 2002). Secondary organic aerosols remain suspended as fine and ultrafine particles (Weschler 2006; Nøjgaard et al. 2006; Vartiainen et al. 2006). Exposure of ozone-initiated monoterpene reaction products can cause eye symptoms, upper airway (nose, throat), and lower airway complaints (Apte et al. 2008; Brightman et al. 2008), skin irritation and sensitization (Anderson et al. 2010) among people in office environments. Limonene reaction products increase eye blinking frequency, indicating possible trigeminal (fifth cranial nerve) stimulation (Klenø and Wolkoff 2004). Experimental analysis of sensitization potentials (Forester and Wells 2009) and findings of dermal and pharyngeal aspiration studies (Anderson et al. 2012) hypothesized that terpene reaction products with multiple oxygen groups such as dicarbonyls might exhibit inflammatory and respiratory sensitizing properties.

Table 10.2 Classes of VOCs that emit from indoor sources and its possible health effects

Class	Substance	Indoor use and Sources	Potential health effects	Carcinogenic classification
Alcohol	2-Propanol	Used widely as a solvent, cleaning fluid, especially for dissolving oils; less toxic to that of formaldehyde and other preservatives	Poisoning can occur from ingestion, inhalation, or skin absorption; over doses may cause a fruity odour on the breath, due to its metabolism to acetone; CNS depressants; symptoms of poisoning—flushing, headache, dizziness, nausea, vomiting	
Alcohol	a-terpineol	Used as solvents, plasticizers, and to manufacture insecticides and synthetic pine oil; a pleasant odour similar to lilac; an ingredient in perfumes, cosmetics, and flavours	No known health impacts from its direct exposure; chemical reactions lead to indoor pollution of concern	Not classified
Alcohol	Ethanol	Widely used as a solvent and fuel; principally found in alcoholic beverages	Characteristic intoxication—drunkenness and neurotoxicity when consumed in sufficient quantities	
Alcohol	Phenol	Used as a disinfectant and consumer products—mouthwash, throat sprays	Short-term, high-level inhalation may cause respiratory irritation; long-term exposure may cause damage to vital systems	Not classified
Aldehyde	Acetaldehyde	Emission from composite/pressed-wood furniture, building materials, ETS and automobile exhaust; emits from carpet due to photochemical reactions of other compounds with ozone (Morrison and Nazaroff 2002). Used as a preservative in some fruits	Acute exposure causes skin, eye, and respiratory irritation. Long-term or chronic exposure may lead to damage to the respiratory tract	Probable human carcinogen

(continued)

Table 10.2 (continued)

Class	Substance	Indoor use and Sources	Potential health effects	Carcinogenic classification
Aldehyde	Formaldehyde	Building materials, pressed-wood products, particle board, plywood, foam, carpet, paints, and varnishes; ETS, automobile exhaust	At low concentration—irritation of the mucous membranes, burning sensations in the eyes, nausea, coughing, chest tightness, and allergic reactions. At high concentrations, it may trigger asthma attacks	Known human carcinogen
		Photochemical reaction of ozone and other secondary reactions of unsaturated compounds in carpet are familiar indoor sources of formaldehyde (Morrison 2008)		
Aldehyde	n-Hexanal, Nonanal, Octanal, Decanal, Benzaldehyde	Fragrant liquid with a fruit-like odour; used as a component in perfumes (nonanal, octanal) and in flavour production for the food industry; scent (n-Hexanal) resembles freshly cut grass; benzaldehyde adds almond flavour to foods and scented products and sometimes used in cosmetics products	May result in skin, eye, and respiratory irritation	Not classified
Alkane	Heptane (n-Heptane)	A solvent with a high vapour pressure; Available as mixed isomers, used in paints and coatings, as the rubber cement solvent	Inhalation exposure causes acute toxic effects on the CNS, typical of lipophilic solvent vapour; Irritation of the respiratory passages and likely loss of auditory sensitivity	
Alkane	n-Hexane	Used as cleaning agents in printing, textile, and furniture industries; quick-drying glues used in shoes and leather products; used in gasoline and automobiles	Breathing in large amount can cause numbness in the extremities and muscle weakness	Not classified

(continued)

Table 10.2 (continued)

Class	Substance	Indoor use and Sources	Potential health effects	Carcinogenic classification
Alkane	Nonane	A flammable liquid in the component of the petroleum distillate fraction (kerosene); used as a solvent, fuel additive, and an ingredient in biodegradable detergents	Corrosive and toxic gases; inhalation or contact with material may irritate or burn skin and eyes. Vapours may cause dizziness or suffocation	
Alkane	Octane	Used as a component of gasoline. Octane rating is an index of a fuel's ability to resist engine knocking at high compression ratios. Gasoline rating is equal to that of heptane/octane scale. Isomers of octane influence the rating, i.e., n-octane (straight chain of 8 carbon atoms, no branching) has 10 (negative); pure 2,2,4-trimethylpentane (highly branched octane) has 100 octane rating	Very harmful to people if inhaled or swallowed; a respiratory and eye irritant	
Alkane	Undecane	Used as a mild sex attractant for moths and cockroaches, and an alert signal for a variety of ants	Slightly hazardous with skin contact (irritant, permeator), eye contact (irritant), of ingestion, of inhalation. Prolonged exposure is not known to aggravate medical condition	
Aromatic	Benzene	Emits from ETS, gasoline, and automobiles	Low-level inhalation may cause drowsiness, headaches, rapid heart rate, tremors, and unconsciousness; prolonged exposure may result in anaemia and immune system depression	Known human carcinogen

(continued)

Table 10.2 (continued)

Class	Substance	Indoor use and Sources	Potential health effects	Carcinogenic classification
Aromatic	Ethylbenzene	Emits from gasoline and automobiles, inks and paints	Exposure at high levels even for a short period can cause eye and throat irritation, and dizziness	Possible human carcinogen
Aromatic	Naphthalene	Used as in mothballs and additive to spray pesticides; smoking	Exposure at high levels may lead to anaemia; symptoms include fatigue, lack of appetite, and a pale appearance to the skin	Possible human carcinogen (IARC and US EPA)
Aromatic	Styrene	Used in consumer products (rubber, plastics, insulation, textiles, disinfectants, paints, packaging materials, carpet backing); emits from photocopiers, ETS, gasoline and automobile exhaust	Toxic to the central nervous system and upper respiratory tract; inhalation exposure may cause throat and nasal irritation, drunkenness and concentration problems	Possible human carcinogen
Aromatic	Toluene	Used in consumer products like paints, paint thinners, lacquers, adhesives, and rubber; emits from ETS, gasoline and automobile exhaust	Low to moderate term exposure can cause weakness, nausea, memory loss; exposure to large amounts may cause damage to vital systems, including CNS	Not classified
Aromatic	Xylenes (o-, m-, p-isomers)	Xylene is an aromatic hydrocarbon, as part of the BTX aromatics (benzene, toluene, and xylenes); used in consumer products (cleaning agent, paint thinner, varnishes); emits from ETS, gasoline, and automobiles	A skin irritant; inhalation exposure may cause CNS depression; symptoms are a headache, nausea (at 100 ppm exposure), and dizziness, irritability, vomiting, slow reaction time (at 200–500 ppm). Long-term low-level exposure may lead to a decrease in balance, coordination, and reaction times (often referred to as organic solvent syndrome)	Not classified

(continued)

Table 10.2 (continued)

Class	Substance	Indoor use and Sources	Potential health effects	Carcinogenic classification
Chlorofluorocarbon	Dichlorofluoromethane, trichlorofluoromethane	Used as a propellant and refrigerant. Due to high ozone depletion potential, and possible harmful effects on the environment, its productions have been set to be phased out by 2015, according to Montreal Protocol	Short-term emergency exposure guidance levels (EEGLs) of dichlorofluoromethane are 10,000 ppm (1 hour) and 1,000 ppm (24 h). At 50,000 ppm, it may induce dizziness in humans	
			Irritating or toxic fumes of Trichlorofluoromethane can cause cardiac arrhythmia, confusion, drowsiness, and unconsciousness	
Ester	Diethyl phthalate (DEP)	Used in the plasticizer, e.g., toothbrushes, toys and food packaging; used in cosmetics, insecticides, and aspirin	No information available	Not classified
Ester	TXIB (2,2,4-trimethyl-1,3-pentanediol diisobutyrate)	Used as a plasticizer in certain vinyl products	No known health impacts	Not classified
Glycol ether	2-Butoxyethanol	Used in paint thinners and strippers, varnish and spot removers, and herbicide; used in liquid soaps, cosmetics, dry-cleaning compounds	Breathing in large amounts may result in irritation of the nose and eyes, headache, and vomiting	Not classified
Halo	Carbon Tetrachloride	Used as a dry-cleaning solvent; industrial strength cleaners	High exposure can cause liver, kidney, and CNS damage. The liver is especially sensitive—liver gets enlarged, and cells are damaged; kidneys are damaged	Probable human carcinogen (US EPA, IARC)

(continued)

Table 10.2 (continued)

Class	Substance	Indoor use and Sources	Potential health effects	Carcinogenic classification
Halo	Chloroform	Water contaminant released when water is flashed (showering, washing clothes, dishes)	Inhalation with higher exposure may result in dizziness, headache, unconsciousness. Prolonged exposure may be damaging to the liver and kidneys	Reasonably anticipated as a carcinogen (DHHS)
Halo	Methylene chloride	Paint removers, solvent usage; found in some aerosol and pesticide products	Breathing in large amounts can damage the CNS; contact with eyes or skin can result in burns	Probable human carcinogen (US EPA)
Halo	Tetrachloroethylene	Used as a dry-cleaning solvent; also used in some consumer products	Exposure at a high concentration in poorly ventilated areas can cause a headache, sleepiness, difficulty in speaking and walking, unconsciousness and may be fatal	Reasonably anticipated as a carcinogen (DHHS)
Ketone	Acetone	Used in a variety of medical and cosmetic applications; cleaning agents, e.g., nail polish remover, and also used in food additives and packaging; emits from ETS and vehicle exhaust	Inhalation at moderate to high levels for a short period can cause mucous membrane eye irritation; symptoms are headaches, light-headedness, tachycardia, nausea; vomiting, unconsciousness and possibly coma; and shortening of the menstrual cycle in women	Not classified

(continued)

Table 10.2 (continued)

Class	Substance	Indoor use and Sources	Potential health effects	Carcinogenic classification
Terpenes	a-pinene, d-limonene	Commonly used as scented deodorizers, room air fresheners, a solvent for cleaning purposes, personal care products, polishes, food beverages	Irritates mucous membranes, skin, and lungs; Symptoms are a headache, nausea, vomiting, skin allergy, and damage to kidneys; high exposure may affect CNS, causing loss of coordination, dizziness, seizures, and coma	Not classified
Misc.	decamethylcyclopentasiloxane (D5-siloxane)	Primarily comes from personal care products, such as underarm deodorants and antiperspirants; also used as a by-product in silicone-based caulks and lubricants	No known health impacts	Not classified

Detailed information may be available from different agencies, such as US OSHA, US EPA (US Environmental Protection Agency), DHHS (United States Department of Health and Human Services), IARC (International Agency for Research on Cancer), WHO (World Health Organization)

Studies indicate an increased prevalence of lung symptoms due to repeated exposure to high concentrations of terpenoid fragrances and cleaning spray products (e.g., Zock et al. 2010).

Standards and Guidelines

Presence of air pollutants in the indoor environment is a global issue due to its adverse effects on human health. US EPA ranked indoor air pollution as one of the top five environmental health risks to the public. Limit values of exposure to pollutants represent the concentration of specific chemical compounds in the indoor environment that pose no health hazard to the occupants. Assessment of hazards, however, necessitates making a distinction between absolute safety and acceptable risk. Setting a guideline that can provide complete safety, however, involves extensive experimental investigation of the dose–response relationships, and toxicological effects elicited by the sources of pollutants (single or combined), sensitivity and thresholds for toxicological effects. Such comprehensive data on indoor pollutants are evolving with the concerted effort of various research groups and international agencies. Multiple standards and limit values of exposure to contaminants have been proposed, as given in Tables 10.3 and 10.4. There is apparent understanding that exposures are always in combinations, and data dealing with the effects of co-exposures are scarce. While there are approaches towards quantitative risk assessment using numerical methods and simulations, no recommended guidelines on combined pollutant exposures are yet available. Guidelines on particulate matter based on the evaluation of mass concentration of particles have been attempted as regard to control strategy, i.e., measures are taken to mitigate pollution lead to eliminating concentrations of more than one pollutant.

Ventilation Standards—The ASHRAE 62.1:2010 specifies ventilation for acceptable IAQ, with both a prescriptive and performance-based minimum ventilation rates for commercial building applications. Chapter 12 includes other relevant ventilation standards. The building air supply rates are expressed as (a) rate of airflow per occupant multiplied by the number of occupants in a defined space (ranging from 5 to 20 cfm/person) and (b) rate of airflow per floor area times the conditioned space floor area. Depending upon the building use categories, the per area air supply rate ranges from 0.06 to 0.48 cfm/ft^2. The whole-building ventilation rate was classified as below:

>18 cfm/person (>20% higher than the standard, considered significantly higher);
12–18 cfm/person (within ±20% different from the standard); and
<12 cfm/person (>20% lower than the standard, considered significantly lower).

Carbon Dioxide Standards—The US OSHA (1994) have established Permissible Exposure Limits (PELs), based on 8-hourly time-weighted averages (TWA). The PEL value of CO_2 was set at 5000 ppm (9000 μg/m^3). ASHRAE 62.1:2007

Table 10.3 Various standards and limit values of exposure to pollutants

Pollutant	Duration	WHO IAQ guidelines 2010	ACGIH (2001)	US OSHA (1994)	US EPA/ NAAQS (2007)	MAK (Germany)	Threshold values in green building rating schemes
Benzene (μg/m³)	Annual	No safe level determined					2–5; HQE
Carbon monoxide (μg/m³)	1 h	35 ppm			35 ppm		
	8 h	10 ppm	25 ppm	50 ppm	9 ppm	30 ppm	10–100,000 μg/m³ or +2 ppm over outside; GREENSHIP, IGBC, HQE, NABERS
Lead (Pb) (μg/m³)	annual	0.5	0.5	1.5 pg/m³	0.15	0.1	
Formaldehyde (μg/m³)	30 min	100	0.3 ppm	0.75 ppm		0.3 ppm	10–120; IGBC, HQE, BREEAM, DGNB, KLIMA, LEED, NABERS
Nitrogen dioxide (μg/m³)	Annual	40			53 ppb		40–5600; GREENSHIP, HQE
	1 h	300			100 ppb		
	24 h		3 ppm	5 ppm (8 h)		5 ppm	1500 (WB, USEPA); 85 (EU)
Ammonia (μg/m³)	Annual						17,000; GREENSHIP
Radon	24 h	100 Bq/m³ (sometimes 300 mg/m³, country-specific)					
Tetrachloroethylene (μg/m³)	Annual	250					
Sulphur dioxide (μg/m³)	Annual				75 ppb		20–5200; GREENSHIP, HQE
	24 h	20	2 ppm	5 ppm (8 h)	140 ppb	0.5 ppm	150 (WB, USEPA, EU)

(continued)

Table 10.3 (continued)

Pollutant	Duration	WHO IAQ guidelines 2010	ACGIH (2001)	US OSHA (1994)	US EPA/ NAAQS (2007)	MAK (Germany)	Threshold values in green building rating schemes
CO_2	Annual						530–1500 μg/m^3; GREENSHIP, IGBC, Pearl, KLIMA, NABERS
	8 h	10	5000 ppm	5000 ppm		5000 ppm	
Ozone (μg/m^3)	8 h	100	0.05 ppm	0.1 ppm	0.07 ppm	Carcinogenic (no max value)	
Particulate Matter $PM_{2.5}$ (μg/m^3)	Annual	10	3	5 (resp)	12–15	1.5	10–25; HQE, LEED
	24 h	25			35		
Particulate Matter PM_{10} (μg/m^3)	Annual	20		15		4	20–50; IGBC, HQE, LEED, NABERS
	24 h	50	10		150		150 (WB, USEPA, EU)
TVOC (μg/m^3)							300–25,000 μg/m^3; IGBC, HQE, BREEAM, DGNB, KLIMA, LEED, NABERS
Microbes							Indoor/outdoor = 1; NABERS
Total suspended particulate matter (TSP)	Annual						80 μg/m^3 (WB, USEPA, EU)
	24 h						230 μg/m^3 (WB, USEPA, EU)

Unless otherwise specified, values are given in μg/m^3; these limit values undergo periodic revisions
Abbreviation: World Bank (WB)

Table 10.4 Standards limit values of exposure to VOCs

Class	Substance	OSHA 8-hr TWA: PEL (ppm)	OSHA 8-hr TWA: PEL (μg/m^3)	Acceptable ceiling conc. (ppm)	Acceptable max above acceptable ceiling conc. for 8 hr shift (ppm)	Max. duration	IDLH (ppm)	OEHHA: Acute REL (pg/m^3)	OEHHA: Chronic REL (pg/m^3)	USEPA: Non-carcinogenic: RfC for chronic inhalation (μg/m^3)	USEPA: Carcinogenic: Inhalation risk level (1 in 1,000,000) (μg/m^3)
Alcohol	2-Propanol	400	980				2000				
Alcohol	Phenol	5	19					5800	200		
Aldehyde	Acetaldehyde	200	360					470	140	0.009	0.5
Aldehyde	Formaldehyde							55	9	N/A	0.08
Alkane	Heptane (n-Heptane)	500	2000			15 min	750	85–440 ppm (350–1800 μg/m^3)			
Alkane	n-Hexane	500	1800						7,000	0.7	
Alkane	Nonane							200 ppm (1050 μg/m^3)			
Alkane	Octane	500	2350			15 min	1000	75–385 ppm (350–1800 μg/m^3)			
Aromatic	Benzene	10		25	50	10 min		1300	60	0.03	0.13
Aromatic	Ethylbenzene	100	435						2000	1	
Aromatic	Naphthalene	10	50						9	0.003	
Aromatic	p-Dichlorobenzene	75	450								
Aromatic	Styrene	100		200	600	5 min in 3 h		21,000	900	1	

(continued)

Table 10.4 (continued)

Class	Substance	OSHA 8-hr TWA: PEL (ppm)	OSHA 8-hr TWA: PEL (μg/m^3)	Acceptable ceiling conc. (ppm)	Acceptable max above acceptable ceiling conc. for 8 hr shift (ppm)	Max. duration	IDLH (ppm)	OEHHA: Acute REL (pg/m^3)	OEHHA: Chronic REL (pg/m^3)	USEPA: Non-carcinogenic: RfC for chronic inhalation (μg/m^3)	USEPA: Carcinogenic: Inhalation risk level (1 in 1,000,000) (μg/m^3)
Aromatic	Toluene	200		300	500	10 min		37,000	300	5	
Aromatic	o-, m-, p-xylenes	100	435					100	800	0.8	
Ester	Diethyl phthalate (DEP)		5								
Glycol ether	2-Butoxyethanol	50	240							1.6	
Halo	Carbon Tetrachloride	10		25	200	5 min in 4 h		1900	40	0.1	0.17
Halo	Chloroform	50	240					150	300	N/A	0.04
Halo	Methylene Chloride	100		200	300	5 min in 3 h	2000	14,000	400	N/A	2
Halo	Trichloroethylene	100		200	300	5 min in 2 h.			600		
Ketone	2-Butanone (Methyl ethyl ketone)	200	590								
Ketone	Acetone	1000	2400								
Misc.	Methylcyclohexane	500	2000								
	Benzyl chloride	1	5								

These limit values undergo periodic revisions, for indoor, outdoor, and occupational exposure scenario, and hundreds of substances have been included on a continual basis. Primarily, the VOCs identified in building interiors are listed herewith. The updated information is available from different organizations, US ATSDR—Agency for Toxic Substances and Disease Registry; CDC—Centres for Disease Control and Prevention; IRIS—Integrated Risk Information System; US EPA—US Environmental Protection Agency; DHHS—United States Department of Health and Human Services; IARC—International Agency for Research on Cancer sets the CO_2 level at 700 ppm (steady-state condition) above the outdoor level, which is assumed to vary between 300 and 500 ppm. Thresholds of indoor CO_2 proposed in building rating schemes GREENSHIP, IGBC, Pearl, KLIMA, NABERS range between 530 and 1500 μg/m^3;

Temperature and Relative Humidity Standards—ASHRAE Standard 55: 2009 defined comfort levels regarding operative temperature, which is based on either monthly or weekly average outdoor air temperature and an exponentially weighted running mean of the daily temperature. The summertime comfort standard is based on the assumption that people would wear a short-sleeve shirt and cotton pants, the equivalent of clothing insulation value (Clo) of 0.5. The wintertime standard is based on the assumption that people would wear a business suit, the equivalent of 1 Clo. Different persons have different thermal sensation, as subjectively described by feelings termed as hot, warm, slightly warm, neutral, slightly cool, cool and cold. The setting of the standard of a thermal environment specifies the condition, which is acceptable to at least 80% of the employees working in a given area. Predicted percentage of dissatisfied (PPD) is used to estimate the thermal satisfaction of the occupants (refer to Chap. 11, for different recommended categories).

Particulate Matter Standards—Inhaling particulate matter goes deep into the lung and the bloodstream, carrying substantial risk to cause a multitude of health problems, including acute and chronic respiratory illnesses. People of the different age range and predisposing with heart or lung diseases are more likely to be affected by PM exposure. PM affects cellular functions, through oxidative stress and inflammatory mechanisms (Valavanidis et al. 2008). Country-specific national ambient air quality standards regulate the outdoor and indoor PM concentrations. The US EPA (2007) specifies 24-hour standards for PM_{10} and $PM_{2.5}$ as 150 and 35 μg/m^3. Currently, there are no standards for the ultrafine particulate matter. The ultrafine particles penetrate more deep into the lungs and translocation of particles are the likely imminent danger of increased cardiovascular and respiratory diseases, and all-cause mortality (Knol et al. 2009). The presence of these particles in the circulation could affect blood coagulation and heart rate control (Stewart et al. 2010).

Air Toxic Health Standards—The concentrations below US OSHA (1994) recommended PELs are considered not to cause adverse health effects during specified periods. The US EPA (Integrated Risk Information System—IRIS 2010) provides toxicity information of chemicals, including toxicity data, reference concentrations (RfC) for non-carcinogenic chronic inhalation exposure and inhalation risk level concentrations for one case per 1,000,000 persons (refer to Table 10.3). ISO 14644 clean room classification states the status of air cleanliness in clean rooms and clean zones. Regarding laboratory standards, the air quality of laboratory area needs to satisfy ISO 14644 Class 7 where the ambient air contains less than 352,000 particles/m^3 of air (0.5 μm in diameter).

IAQ Management—Green Building Ratings

The building sustainability assessment schemes take into account the building energy consumption, environmental impacts particularly during the operation phase, and likely effects on human health. Later in Chaps. 15 and 16, green building schemes and its credit rating criteria are described. These assessment tools have been developed according to country-specific features, objectives, and standards requirements. Due to the health concerns, IEQ requirements have been differently included in most of the building assessment systems. As for relevance to the discussion, the characteristics of IAQ and threshold limit values of target indoor air pollutants are briefly included here. In managing IAQ, there are preferred pathways, such as (a) emission source control, aiming at designing and choosing low-emission indoor materials, and building construction/renovation practices, (b) ventilation to provide an appropriate indoor/outdoor air exchange rate, and (c) indoor air measurement to periodically monitor whether air IAQ comply with the given thresholds (e.g., refer to Tables 10.3 and 10.4). Comparing 31 green building certification schemes from 30 countries, Wei et al. (2015) recorded mechanical or natural means of ventilation as the dominant strategy for IAQ management, and about two-third of the rating systems emphasize emission source control and indoor air measurement. Generally, Asian and American countries include emission source control requirements, whereas indoor air measurement is strongly recommended in European and American certifications. About two-fifth of the green building certifications use the ASHRAE 62.1 standard to specify minimum ventilation rates, whereas approximately one-fourth of the systems, mostly in European countries rely on EN 15251 and EN 13779 standards, and the remaining one-third of the building rating schemes usually adopt national building ventilation codes and guidelines.

Indoor air pollutants included in different assessment systems vary widely (Fig. 10.2). The contaminants such as PM_{10}, CO, CO_2, formaldehyde, and TVOCs are significantly emphasized, however, indoor air measurement is optional in specific schemes, such as BREEAM, LEED, and HQE. VOCs are taken into account in 84% of the green building certifications. CASBEE, LEED, HQE IGBC listed VOC species, including benzene and toluene. CO_2 is considered an indoor pollutant in two-third of the schemes and the risk of asbestos pollution is included in over half of the assessment schemes, primarily in the European schemes.

Generally, assessment schemes do not indicate indoor air sampling and measurement (Table 10.5), however, for CO_2 and CO, continuous monitoring devices are commonly used. The ISO 16000-3:2011 standard is chosen as suitable in schemes such as BREEAM, LEED, DGNB, IGBC, for determination of VOCs, including formaldehyde concentrations. The measurement procedure involves air

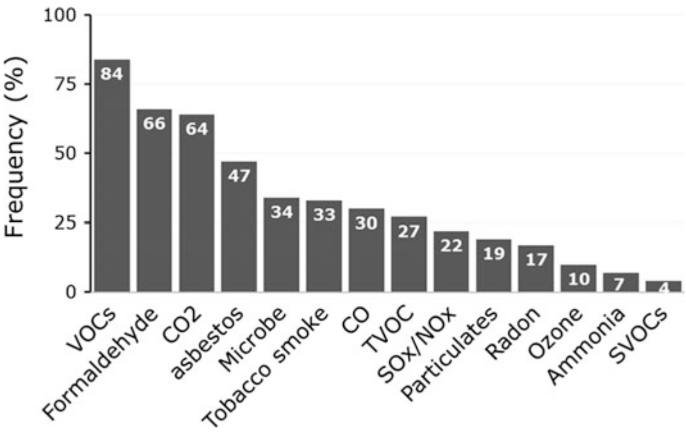


Fig. 10.2 Frequency of indoor air pollutants included in different assessment systems (data are taken from Wei et al. 2015)

sampling of VOCs on Tenax TA sorbent and subsequent thermal desorption and gas chromatographic (GC) analysis. In case of formaldehyde, the procedure involves active air sampling through adsorbent cartridges coated with 2,4-dinitrophenylhydrazine (DNPH) and analysis using HPLC. Source control requirements may include measures on ventilation filtration for outdoor air intakes (Table 10.5) to prevent pollutants from entering the building. National building air quality regulatory guidelines cover requirements for emission control of indoor pollutants and that probably takes the provision of source control of pollutants, such as formaldehyde from composite wood products. WHO (2010) guidelines (Table 10.3) may also be used, in case of non-availability of national guidelines. As regard to indoor particle concentration, assessment schemes (e.g., HQE, LEED IGBC) require measurement compliance of indoor PM_{10} and $PM_{2.5}$ concentrations. However, these building assessment schemes only took note of indoor ozone contamination. Semi-VOCs include pesticides, plasticizers, flame retardants, have potential health risks, including cancer and endocrine disruption. However, provisions and technology to control indoor contaminants are not sufficiently elaborated in the certification schemes. Austrian KLIMA for new office buildings introduced emission control requirement of indoor SVOC sources that include paint, sealant, plaster and filler, and wooden materials, with emissions not to exceed 100 mg/m^3.

Table 10.5 Requirements of ventilation filtration for outdoor air intake, and indoor air sampling strategies

Certification	Air intakes and ventilation filtration	Indoor air sampling
BREEAM	Building's air supply intakes and exhausts are >10 m apart; inputs are about 20 m away from sources of external pollution	Measurements are taken before occupancy; a statistical sampling of occupiable rooms with ventilation and heating systems ON
LEED	A ventilation system supplying outdoor air to an occupied space must have particle filters installed	Measurements are taken during regular occupied hours; the ventilation system remains operational at the minimum outdoor airflow rate throughout the test
	Filtration media are installed at return air grille and transfer duct inlet opening to avoid bypass	US EPA or ISO methods, as indicated above, may be applied; testing VOCs and formaldehyde may be carried out by the laboratories accredited under ISO/IEC 17025; the testing to be conducted within 14 days of occupancy
Green Globes	Exhaust outlets and vent stacks should be about 6 m away from outdoor air intakes, and about 9 m away from the sources of pollution; Outdoor air intakes may be protected with 6.4 mm or smaller mesh screens	
IGBC	Outdoor air intakes located a minimum of 7.6 m away from outdoor smoking areas; installing air filtering media after building flush-out, using at least MERV 13, EU 7 or equivalent	Same as LEED
Pearl	Outdoor air intakes and discharge points should be separated by 25-m smoke-free zones; installing air filters of MERV 8 or G4 class in return air grille	
HK-BEAM	Air intakes must be away from pollutant sources; any short-circuiting with exhausts may be avoided; filters to be sufficient to remove outdoor pollutants	Samples collected at the lowest outdoor air intake location
HQE		Sampling devices may be placed at the centres of rooms, or at a distance of nearly half-a-metre away from the walls
NABERS		The prescriptive methodology follows ISO 17025 standard; sampling locations depend on the size of the building and number of ventilation systems installed and operational

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Chapter 11
Assessing IEQ Performance in Buildings

Introduction

An office building is a workplace where the building features, characteristics of the workplace, and the indoor environment are created to perform functions of the office. The causal links of an indoor building environment with the occupant's comfort and performance are well acknowledged. The elements of the indoor environment include IAQ, acoustics, lighting, temperature, physical layout, and utility. These elements influence employee attitude, behaviour, and satisfaction, and indirectly affect employees' morale, health, well-being, and productivity in the organization (Kamarulzaman et al. 2011; Frontczak et al. 2012). Different methodologies, both subjective and objective, have been proposed in indicating indoor environmental quality (IEQ) performance in office buildings. The objective and experimental measurements in evaluating the characteristics of IEQ have been elaborated in Chap. 10. The subjective evaluation using survey method is often the most straightforward and least-expensive method for evaluating IEQ concerns in a building. Post-occupancy evaluation (POE) is an approach in evaluating building energy consumption, maintenance systems and in identifying occupant comfort after the built facility has been occupied (Gocer et al. 2015). Primarily, the POE uses (a) direct feedback from occupants through questionnaires and interviews (subjective assessment) and (b) objective assessment, including the physical measurement of the environment (Dykes and Baird 2013).

Several different survey instruments (BOSTI 1977; US EPA BASE study; BUS, Cohen et al. 2001; CBE 2008; HOPE, Bluyssen et al. 2011) have been applied in office, educational and other types of buildings. In general, the questionnaire survey, either as the paper-based method or via an online survey, includes documenting occupant complaints relating to the building environment, and also, information about the frequency of occurrence of the complaints (daily, weekly, monthly, quarterly, once, or never). These methods provide guidelines for building practitioners to transform subjective measures into quantifiable environmental

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indicators of building performance. There are limitations, however, that the approach of the survey methods and phrasing of survey questions may not be similar between surveys.

Buffalo Organization for Social and Technological Innovation (BOSTI)—BOSTI Associates (Brill 1984, 1985) is probably the earliest to introduce survey instrument for analysis of office workplace design and productivity. BOSTI services cover workplace research and analysis, workplace diagnostics, and post-occupancy evaluation. Workplace research is based on quantitative and qualitative data gathering, and analyzing one's business goals and challenges, workplace culture, and employees' work behaviours, and developing situation-specific recommendation for workplace designs.

MM040 Questionnaires—MM040 (Andersson et al. 1993) developed initially at Örebro University Hospital, Sweden, has different versions for workplace and problem building analysis, for specific environments such as schools, day care centres, offices, hospitals, and residential dwellings (www.inomhusklimatproblem.se). The primary module includes elements, such as:

(a) Questionnaire for the workplace, and background factors;
(b) Physical environmental factors, and psychosocial factors at the workplace; and
(c) Medical history of allergic diseases, symptoms usually reported in buildings about problems of indoor climate, and building-related symptoms reported by the occupants.

The manual includes a graphics technique to present results of the elements of the questionnaire. An illustration of radar graph (Fig. 11.1a, b) represents a sample comparison of (a) IEQ and working environment and (b) building-related symptoms of occupants in two telecom exchanges.

Building Use Studies (BUS)—BUS occupant survey methodology (Cohen et al. 2001) uses a structured questionnaire and rating occupants' responses on a 1–7 point scale, for overall building performance. The evaluation includes nearly 45 aspects, such as thermal comfort, lighting, noise, IAQ, ventilation, personal control, space design. The occupant satisfaction evaluation using the BUS methodology can be commissioned by licensed professionals, such as architects, contractors, and facilities managers.

US EPA BASE (Building Assessment Survey and Evaluation)—A standardized study protocol of public and commercial office buildings covers three major areas, such as (a) environmental and comfort measurements, (b) building and HVAC systems characterization, and (c) building occupant demographics, symptoms and perceptions. Data gathered from 100 office buildings in the USA, from 10 climatic regions in 37 cities and 25 states, provided guidance on the design, construction, operation, and maintenance of buildings. The standardized protocol may be useful for future IAQ benchmarking studies. A further description of the BASE study is given elsewhere in this contribution.

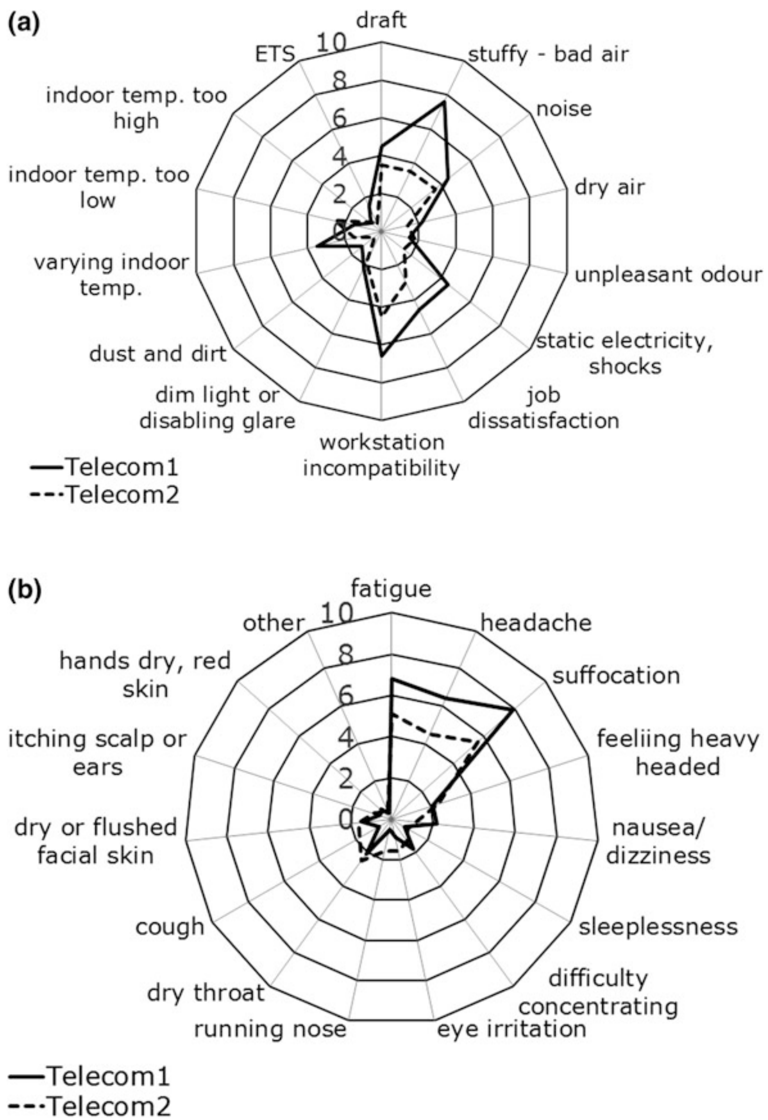

Fig. 11.1 MM040-based graphical presentation of **a** working environment dimensions and **b** building-related symptoms of occupants in telecom exchanges

Office Productivity Network (OPN)—Initially, a paper-based questionnaire (Oseland and Bartlett 1999) elucidates the response of the building occupants to rate different aspects of work setting, such as office facility, environmental conditions, and controls, productivity, downtime factors. The technique is very similar to the BUS methodology, however, with more emphasis on self-assessed productivity of occupants. Currently, an online questionnaire has been introduced, and the respondents can rate each section of the questions against a scale. A walkthrough and follow-up workshops accompany the survey.

Stockholm Indoor Environment Questionnaire (SIEQ)—A standardized questionnaire primarily developed for dwellings (Engvall et al. 2004) was based on the sociological principles, exploring individual behaviour and personal factors about the dwelling. The interview questionnaire was transformed into a postal self-administered questionnaire, in which the indicators of environmental factors included the perception of IAQ, climate, noise, and illumination, and making a general judgement of the variables. The symptoms of SBS were also included as indicators of health.

Design Quality Indicator (DQI)—A Web-based assessment toolkit (Prasad 2004) assesses design quality of buildings, regarding functionality, build quality, and building impact. The functionality refers to the design and arrangement of space to be useful for all. The build quality considers the structural stability, safety, robustness, and other engineering performance criteria of the building. The building impact addresses the likely positive effect of the building on the local community and environment. Through a proprietary algorithm, the DQI tool converts individual subjective perceptions into objective, measurable results, and rates a building on a six-point scale.

CBE Survey (Centre for the Built Environment)—The CBE at the University of California, Berkeley, developed a Web-based IEQ survey in 2009, to measure occupants' perception of the quality of the workplace environment, including core questions on IAQ, thermal comfort, lighting, and acoustics. The procedure allows adding custom modules to address issues of the quality of the building process, from planning to the occupancy phase. The survey instrument has been tested and validated on an extensive sample survey, as indicated later in the chapter.

EU project HOPE (Health Optimization Protocol for Energy-efficient Buildings) (Bluyssen et al. 2011)—The project involved assessment of buildings by checklist and occupant questionnaire (first stage), and physical measurements (second stage) to highlight potential hazards. Occupant questionnaire, referring to Building Symptom Index (Raw 1995), covers (a) location and orientation of workspace, (b) personal health and well-being, (c) comfort associated to environmental factors, (d) privacy, layout, décor, cleanliness, and view, (e) duration of work on VDT, (f) smoking behaviour, and (g) occupants' response about the office building. Health hazard algorithms included specific building related hazard (asbestos, CO, fungi, etc.).

IEQ Criteria and Energy Performance of Buildings

Indoor environmental quality is a perceived indoor experience about the building environment. This includes aspects of design, analysis, and operation of energy-efficient, healthy, and comfortable buildings. Overall comfort in a building environment is defined by an absence of unpleasant sensations. Several dimensions, such as physical comfort (e.g., IEQ), functional comfort (proximity, availability of resources, ergonomics, and aesthetics) and psychological comfort (privacy, territoriality in office activity), are in view to evaluate comfort in a building environment (Feige et al. 2013). Inevitably, these are the manifestations of physiological and psychological responses of the occupants to the complex interaction of factors. To achieve an acceptable IEQ, policies, strategies, and guidelines have been developed. The standard EN 15251 (2007) (revised draft prEN 16798-1 2015) in accordance with the European directive (EPDB 2002, 2010), and US ASHRAE 55 (2010)/(2013) are the extensively referred guidance on IEQ imperatives to deal with the design and assessment of energy performance of buildings. The EN 15251 (2007) focuses on establishing IEQ parameters for building system design and energy performance calculations (Olesen 2007). The revised draft prEN 16798-1 (2015) has widened the scope of applicability where human occupancy sets the criteria for the indoor environment. The prEN 16798-1 (2015) includes four categories to express levels of expectation from occupants (category I, being the highest level of expectation, and also recommended for persons with special requirements (disability, sick, very young, elderly persons). Category IV is having the lowest level of expectation and should only be accepted for a limited part of the year. That is, a primary aspect of the standard is in specifying how different categories of criteria for the indoor environment can be used. National regulations may specify requirements. It does not prescribe design methods but gives input IEQ parameters to the design of buildings. There exists other related national and international guidance documents to influence the energy demand. ISO 7730 specifies criteria for thermal comfort and IAQ.

Design Input Criteria

The prEN 16798-1 (2015) has been issued for circulation and comments from the concerned agencies. By the time, this publication is released, and it is likely that the final standard may be available. For awareness of the readers, the criteria specified in the document are briefly embodied in Table 11.1.

Thermal environment—The thermal comfort criteria included PMV-PPD indices, with assumed typical levels of activity and thermal insulation for clothing for winter and summer, corresponding to specified design operative temperatures. As described in ISO 7730, the values for dimensioning of cooling systems are the upper levels of the comfort range during summer. The lower levels of the comfort range are applied for dimensioning of heating systems. These design criteria are to be used in the design of buildings (windows, solar shading, building mass) and also HVAC systems. Apart from the operative temperature (T_o) as the design criterion, the standard prEN 16798-1 (2015) prescribes that PMV-PPD levels can be used directly, which takes into account the effects of wind speed and clothing. The standard includes criteria for local thermal discomfort, such as draught, vertical air temperature differences, floor surface temperatures, and radiant temperature

Table 11.1 Recommended categories and criteria of IEQ specified in the prEN 16798-1 (2015)

			Recommended categories				
			I	II	III	IV	
			High level of expectation	Normal level of expectation	Acceptable, moderate level of expectation	Low level of expectation	Remarks
Design of mechanical heated and cooled buildings							
Thermal state of the human body as a whole	PPD (%)		<6	<10	<15	<25	Changes in category IV, to that of EN15251
	Predicted mean vote		−0.2 < PMV < +0.2	−0.5 < PMV < +0.5	−0.7 < PMV < +0.7	−1.0 < PMV < +1.0	
Operative temp (°C) (activity level ~1.2 met)	Single office, open-plan office, auditorium, restaurant	Min for heating (winter); ~1.0 clo	21	20	19	18	Category IV included in prEN 16798-1 (2015) (E); Residential buildings not included here; Assumed: 50% RH; airspeed: < 0.1 m/s
		Max for cooling (summer); ~0.5 clo	25.5	26	27	28	
Local thermal discomfort: (a) Draught	PD (draught rate) (%)		10	20	30		
	Max. air velocity (m/s)	Winter	0.1	0.16	0.21	Assumed: turbulence intensity—40%, air temp. ~20 °C (winter), 23 °C (summer)	
	Max. air velocity (m/s)	Summer	0.12	0.19	0.24	When air temp. is >25 °C, higher airspeeds are allowed and often preferred (draught becomes pleasurable breeze); but under this condition, occupants have direct control over the airspeed	
(b) Vertical air temp. difference (head-ankle)	PD (%)		3	5	10		
	Temp. difference (°C)		2	3	4	Difference between 1.1 and 0.1 m above the floor	
(c) Range of floor temperature	PD (%)		10	10	15		
	Floor surface temp. (°C)		19–29	19–29	17–31		
(d) Radiant temperature asymmetry	PD (%)		5	5	10		
	Warm ceiling (°C)		<5	<5	<7		
	Cool wall (°C)		<10	<10	<13		
	Cool ceiling (°C)		<14	<14	<18		
	Warm wall (°C)		<23	<23	<35		

(continued)

Table 11.1 (continued)

			Recommended categories				
			I	II	III	IV	
			High level of expectation	Normal level of expectation	Acceptable, moderate level of expectation	Low level of expectation	Remarks
Temperature ranges for hourly calculation of cooling and heating energy (Sedentary activity ~1.2 met)	Offices and spaces—single offices, open-plan offices, auditorium, restaurant	Temp. (°C) for heating; clothing ~1 clo	21.0–23.0	20.0–24.0	19.0–25.0	17.0–25.0	Air velocity: <0.1 m/s; RH ~ 40% for heating season; 60% for cooling season Mean design operative temp; can vary to take account of local custom and energy saving
		Temp. (°C) for cooling; clothing ~0.5 clo	23.5–25.5	23.0–26.0	22.0–27.0	21.0–28.0	
IAQ and ventilation rates							
Design ventilation air flow rates (for a non-adapted person)	Ventilation for diluting emissions (bioeffluents)	Expected %age dissatisfied	15	20	30	40	Note the changes in category IV. Criteria assumed to be independent of seasons
		Airflow (l/s per person)	10	7	4	2.5	
	ventilation rates (l/(s m^2) for diluting emissions from different type of buildings	Very low polluting (<1000 $\mu g/m^3$)	0.5	0.35	0.2	0.15	Minimum total ventilation rate (4 l/s per person)
		Low polluting (<300 $\mu g/m^3$)	1	0.7	0.4	0.3	
		Non-low polluting	2	1.4	0.8	0.6	
	Example of design ventilation air flow rates for a single-person office of 10 m^2 (non-adapted person)	Low polluting (l/s m^2)	1	0.7	0.4	0.3	
		Airflow (l/s per person)	10	7	4	2.5	Non-adapted person
		Total design ventilation (l/s per person)	20	14	8	5.5	
Design CO_2 conc. above	CO_2 conc.	ppm	550 (10)	800 (7)	1350 (4)	1350 (4)	Assumed: CO_2 emission of 20 l/h per person

(continued)

Table 11.1 (continued)

			Recommended categories				
			I	II	III	IV	
			High level of expectation	Normal level of expectation	Acceptable, moderate level of expectation	Low level of expectation	Remarks
outdoor concentration							
Pre-defined ventilation air flow rates	Total ventilation including air infiltration	(l/s m^2)	0.49	0.42	0.35	0.23	
		(ach)	0.7	0.6	0.5	0.4	
	Supply air flow	(l/s per person)	10	7	4		
	Supply air flow (perceived IAQ)		3.5	2.5	1.5		Adapted persons
		(l/s m^2)	0.25	0.15	0.1		
	Exhaust air flow	Kitchen (l/s)	28	20	14	10	
		Bathroom/toilet (l/s)	14–20	10–15	7–10	4–6	
Humidity	Design relative humidity (%)	Dehumidification	50	60	70		Recommended limit of the absolute humidity (12 g/kg)
		Humidification	*30*	*25*	*20*		
Noise levels							
	Type of space						
Equivalent continuous sound Level Leq, nT, A —dB(A)	Places of assembly	Libraries	<25	<30	<35		
		Museums	<28	<32	<36		
	Commercial	Supermarkets	<40	<45	<50		
	Hospital	Wards	<32	<36	<40		
		Operating theatres	<35	<40	<45		
	Offices	Small offices	<30	<35	<40		
		Landscaped offices	<35	<40	<45		
		Conference rooms	<30	<35	<40		
	General	Service rooms, corridors	<35	<40	<45		

asymmetry for category level I–III. These criteria were primarily evolved from the Smart Control and Thermal Comfort (SCATs) project, commissioned by the European Commission (McCartney and Nicol 2002), described in Chap. 9, Bioclimatic approach: thermal environment.

For buildings *without mechanical cooling systems*, the dimensioning of the heating system follows the same criteria to those for mechanically ventilated, cooled, and heated buildings. However, in buildings without mechanical cooling, the criteria for the thermal environment are specified differently. Refer to the description given in Chap. 9 that the acceptable range of indoor operative temperatures in buildings without mechanical cooling systems may be arrived at as a function of the exponentially weighted running mean of external, ambient temperatures, or as a weighted weekly running average of the daily mean external, ambient temperature (T_{rm7}, °C). Instead of weekly running mean, the ASHRAE Standard 55-2005 was based on a monthly average outdoor temperature. Taking the optimal T_o (°C) equals to the linear regression ($0.33 * T_{rm7} + 18.8$), for the summer, spring, and autumn, the recommended adaptive criteria of T_o for different categories are given in Table 11.2.

These criteria apply for human occupancy with sedentary activities and regular clothing, in the offices, and other similar buildings where thermal conditions are regulated primarily by the adjustability in the opening and closing of windows. The upper limits of T_o may be used to design buildings and to introduce passive controls to prevent overheating. The passive thermal controls are executed by appropriate orientation of glazing and solar shading, and utilization of the building thermal capacity. When indoor T_o exceeds 25 °C, air velocity may be personally adjusted to compensate for the raised air temperatures. The correction values of T_o are 1.2, 1.8, and 2.2 °C for the corresponding air velocities of 0.6, 0.9, and 1.2 m/s, respectively, for buildings equipped with fans or personal systems at occupant level.

With reference to 2007 version of the standard EN 15251, concerns have been raised on the rationale of the IEQ categories and its colour codings as white, green, yellow, and red, for category I–IV (Nicol and Wilson 2011; Marino et al. 2012). One may favour that the categories provide flexibility in design decisions on building types, and to evaluate the performance of a building over time (Raimondo et al. 2012), and motivate the building designers and operators to strive for IEQ conditions on both subjective and objective indicators (Schiavon and Melikov 2008). Since the occupant expectations might differ from those measurable

Table 11.2 Recommended adaptive criteria of T_o for different categories

	Upper limit (T_o) (°C)	Lower limit (T_o) (°C)
Category I (high level of expectation)	$(0.33 * T_{rm7} + 18.8) + 2$	$(0.33 * T_{rm7} + 18.8) - 3$
Category II (normal level of expectation)	$(0.33 * T_{rm7} + 18.8) + 3$	$(0.33 * T_{rm7} + 18.8) - 4$
Category III (an acceptable, moderate level of expectation)	$(0.33 * T_{rm7} + 18.8) + 4$	$(0.33 * T_{rm7} + 18.8) - 5$

differences in environmental parameters, categorizing building with occupant expectations would be much more complicated where the climates of a region or country are very different. Arens et al. (2010) indicated that the EN 15251-2007 categories for thermal comfort do not align with perceptible changes in occupant satisfaction. Raimondo et al. (2012) suggested that the categories to indicate how the building performance changes are evaluated among classes over time but do not force the operation of a building into the class limits. With the revision of the standard, further research is warranted to establish whether the hypothesized energy performance and potential energy saving may be affirmatively associated with the IEQ criteria and the newer categories of expectations.

IAQ and ventilation rates—Source control, ventilation, filtration, air cleaning are the well-recognized means to control IAQ in buildings. However, the former two are the effective strategies for controlling indoor air pollutants. For the design of ventilation systems (refer to Chap. 12) and the calculation of heating and cooling loads, the required ventilation rate must be documented based on national requirements or using the methods defined in prEN 16798-1 (2015). Design parameters for IAQ are derived in relation to the methods applied to (a) perceived air quality (perceiving fresh and pleasant air), (b) pollutant concentrations, and (c) pre-defined ventilation airflow rates (Olesen 2007). In case of the method based on perceived air quality, air dilution required to reduce indoor pollution load to the desired level of expectation or perceived comfort may be evaluated from the ventilation rates. The design ventilation rate is calculated from two components, i.e., (a) the occupants (bioeffluents) and (b) the contaminants arise from the building and systems, and accordingly, the total ventilation rate at the breathing zone can be estimated as:

$$q_{tot} = n \cdot q_p + A_R \cdot q_B$$

where q_{tot}—total ventilation rate at the breathing zone (l/s), n—design value for the number of persons in the room, q_p—ventilation rate for occupancy per person (l/s per person), A_R—floor area (m^2), and q_B—ventilation rate for emissions from building (l/s m^2).

In case of the method using criteria for pollutant concentration (e.g., CO_2 represents a tracer gas of human occupancy), the ventilation rate required to dilute a pollutant can be estimated as:

$$\mathrm{Q_h} = \left(\mathrm{G_h}/\left(\mathrm{C_{h,i}} - \mathrm{C_{h,o}}\right) \cdot (1/\mathrm{E_v}\right)$$

where $\mathrm{Q_h}$—ventilation rate required for dilution (l/s), $\mathrm{G_h}$—pollution load of a pollutant (μg/s), $\mathrm{C_{h,i}}$—guideline value of a pollutant (μg/m^3 or ppm), $\mathrm{C_{h,o}}$—supply concentration of pollutants at the air intake (μg/m^3 or ppm), and $\mathrm{E_v}$—ventilation effectiveness. Whereas, the pre-defined ventilation airflow rates refers to minimum ventilation rate, meeting both perceived air quality of occupants in the occupied zone, and dimension of the ventilation system. In summary, to calculate required ventilation rates, both the people part (density of occupancy) and building part (types of the building) are taken as criteria. The standard also includes ventilation airflow rates during unoccupied periods (to deliver the minimum ventilation before occupation). The intent of installation of filtration and air cleaning technologies in the building ventilation system is to remove odorous and gaseous particulates of the incoming outdoor air. The prEN 16798-1 (2015) indicated an informative example regarding the building as low or very low polluted if the interior building materials are low or very low emitting. The threshold values of IAQ given in WHO (2010) guidelines (refer to Chap. 10) are indicative of the indoor pollution, with emphasis on the VOCs which are high emitting from different kinds of building materials. The building IAQ test report from an accredited testing laboratory may be considered as a valid attestation of compliance to requirements, as applicable.

Humidity—The priority remains in setting the humidity criteria since the extent of humidification or dehumidification directly depends on the requirements for thermal comfort and perceived IAQ. Research studies elucidated in Chap. 3 evidently suggest that a long-term, very low humidity ($\sim$20%) exposure is the recognized factor of causation of SBS among the building occupants. On the other hand, long-term high humidity indoors due to water leakage and condensation creates a favourable environment for microbial growth, which in turn may result in building-related illnesses. That is, indoor air shall not be dehumidified to a lower humidity than the design values and not humidified into higher humidity than the design values. Usually, humidification or dehumidification may be needed only in special individual buildings (such as museums, churches) and in part of the year in some climatic zones. Generally, unoccupied buildings shall not be humidified (with some exceptions such as museums).

Lighting—The design illuminance levels of buildings are achieved by deploying means of daylight, electric light, or a combination of both. The visibility and visual comfort to perform visual tasks are governed by the activity type of the occupants and duration of lighting required. Earlier in Chap. 7, details of illumination, glare, and colour rendering index have been given. For reasons of comfort and energy saving, the prEN 16798-1 (2015) emphasizes on the default values for daylighting, with reference to daylight factors, $D_{ca,j}$ of the raw building envelop opening and D_{SNA}, EN 15193 (Table 11.3).

Noise—The noise from different systems and areas of the building often severely hampers the intended use of the space and affects work performance, health, and

Table 11.3 Daylight availability classification (prEN 16798-1 2015)

Classification	Daylight factor $D_{ca,j}$	Daylight factor D_{SNA}
	Vertical facades	Roof lights
Strong	$D_{ca,j} > 6\%$	$7\% < D_{SNA}$
Medium	$6\% > D_{ca,j} > 4\%$	$7\% > D_{SNA} > 4\%$
Low	$4\% > D_{ca,j} > 2\%$	$4\% > D_{SNA} > 2\%$
None	$D_{ca,j} < 2\%$	$2\% > D_{SNA} > 0\%$

$D_{SNA} > 10\%$ should be avoided due to the danger of overheating well-being of the occupants (Fig. 11.2a, b). The standard specifies the sound levels that apply to the sources inside the building as well as sound generated from other mechanical and service equipments. The criteria set the limit of the sound pressure level and also sound insulation requirements of noise from adjacent areas and outdoors. Default values for three categories listed in Table 11.1 can be exceeded for a short-term period by 5–10 dB(A), in case, the occupant can control the operation of the equipment or the windows. It is noted that the ventilation should not rely on operable windows if the outside noise level is too high, as compared to the level one wishes to achieve indoors.

In the overall analysis, to perform building design energy calculations, Olesen (2007) provided a stepwise description of IEQ parameters, concerning EN 15251-

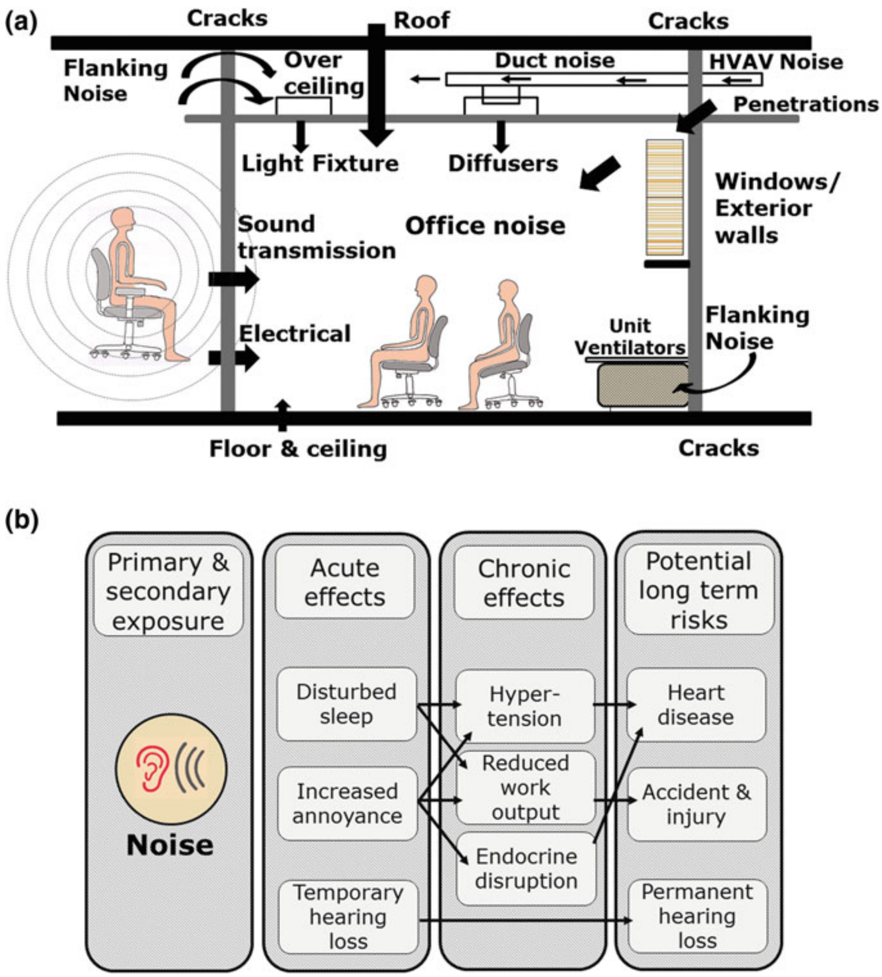

Fig. 11.2 **a** Exposure to noise in offices and **b** noise-related health impacts

2007. In case of prEN 16798-1, the objective design inputs given in Table 11.1 may be applied. For seasonal and monthly energy calculations of heating and cooling requirements, the indoor T_o specified for the design of the heating and cooling systems may be used. In the dynamic simulation, the energy consumption is calculated on an hourly basis. The acceptable range of indoor temperatures for heating and cooling is recommended based on the range of the PMV index. For non-residential, commercial, and office buildings, the ventilation rates for energy calculations are usually the same as design load and dimensioning of the ventilation system specified. Depending on the air change indicated in different recommended categories, the outdoor airflow should be delivered to space before occupancy. Where no national guidelines are available, the minimum ventilation rate of 0.1–0.2 l/s m^2 is recommended that may be delivered to the indoor space during unoccupied times. In systems with variable airflow controlled ventilation, the rate of ventilation depends on the minimum to maximum of occupancy. In case of CO_2 controlled ventilation, the CO_2 concentration requires to maintain below the design values indicated. The energy demand due to the ventilation system, humidification, or dehumidification and the energy load from the overall use of the lighting in and around the building are quantified and ensured that the energy demand of the building project is optimized. Chapter 13 and 14 are dedicated to lighting and energy requirements and related international standards.

Issues of Concern

The energy burden due to buildings has become increasingly significant, primarily because of tight envelope specifications of office and non-residential buildings, and its overdependence on mechanical ventilation and HVAC systems (Offerman 2009). With evidence that windows are seldom or almost never used in high-rise office buildings, the majority of building energy goes to conditioning the air for maintaining the healthy indoor environment. Establishing building codes for construction of buildings, and implementing and enforcing standards to optimize energy use and preserve IEQ are the national imperatives. The International Mechanical Code (IMC), ASHRAE Standards 62.1, 55: 2010, EPDB (2002, 2010), EN15251: 2007 (prEN 16798-1 2015), ISO 7730, ISO EN 13790 (2008), ANSI/ASHRAE/IES Standard 90.1-2016 are the related guidance documents on IEQ imperatives to deal with the design and assessment of energy performance in office and non-residential buildings. Provisions of these standards are differently incorporated in building codes. Improving the thermal performance of the building envelope, minimizing ventilation or air change requirements, including passive ventilation through windows or infiltration, and using the high-rated energy-efficient equipment and appliances are the principal mechanisms that building codes come in effect to address IEQ concerns.

Building design and construction practices are highly localized, influenced by the climate, topography, the availability of resources, choices of the local builders, and the character of local communities. The balancing of the energy and IEQ options are becoming increasingly necessary due to an overemphasis on cost considerations and stringent energy practices. However, a considerable lacuna prevails at the local level for interpretation and enforcement of building code provisions to energy optimization and system improvement in IEQ in buildings. The ISO proposed a building code effectiveness grading schedule to evaluate communities on a ten-point scale, (http://www.isomitigation.com/bcegs/1000/bcegs1001.html), with 1 indicating exemplary administration and enforcement of the building code, and 10 that have little or no quality administration and enforcement.

There are reasons for occupants to turn off the mechanical ventilation system during some parts of the day, for example, poor outdoor air quality, and reduce energy use as a cost-cutting measure. It may appear rational to allow the intermittent use of the building ventilation system. However, it may not be justifiable to meet requirements of IAQ. The practices of tightening building envelopes and restriction of entry of the excess fresh outdoor air are the issues of concern about degradation of IAQ. Building tightness limits and depressurization tightness limits are the proposed target levels to achieve the needed infiltration rates for different climate zones and to ensure against back drafting (ASHRAE 62-1989). The climate change is evident, and its impacts are perceived both at the local level and in a global context. The building occupants are not generally very knowledgeable about the role they play in protecting the IEQ. A strong education campaign at the building community levels is needed to adopt building codes and construction practices, for the energy conservation, energy efficiency of the building system, and effective IEQ interventions.

The Emergence of IEQ Model

In general term, an IEQ model or IEQ index combines multiple environmental parameters (IAQ, thermal environment, lighting, and acoustics) into a scoring/rating unit to evaluate IEQ performance (Ncube and Riffat 2012; Marino et al. 2012; Cao et al. 2012). In practice, however, objective environmental measurements are integrated with subjective occupant response and, accordingly, arrived at a numerical rating or index as an outcome of an IEQ model. Design recommendations of energy performance of the building as elucidated above are perhaps the foundation for many of the IEQ models. Literature review reveals that IEQ models and indices have been developed, broadly using two approaches (Heinzerling et al. 2013), that is (Fig. 11.3):

(a) Regression analysis between subjective and objective measures, and deriving prediction of occupant satisfaction for each category of IEQ objective measurements, and expressing as a combination of each sub-index (Ncube and Riffat 2012; Cao et al. 2012; Wong et al. 2008; Lai et al. 2009). The overall

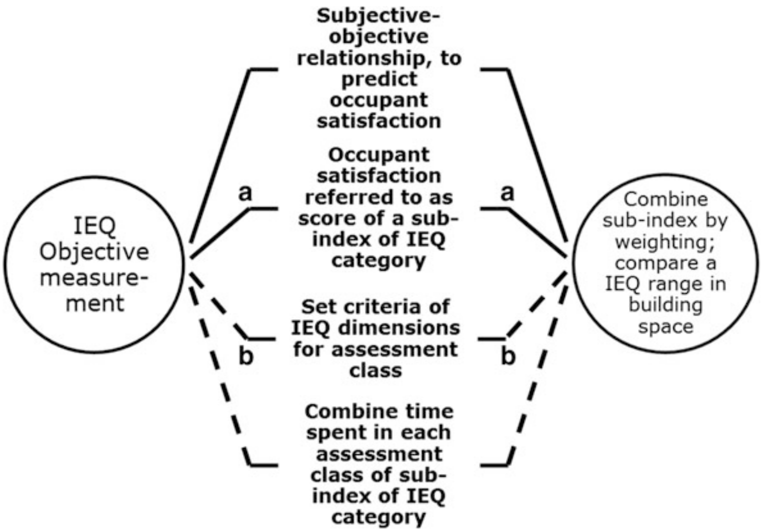

Fig. 11.3 Two primary approaches (a and b) in developing IEQ models and indices

IEQ index is compared against a fixed set of ranges that define the level of IEQ in a given building.

(b) IEQ objective measurements are compared against a fixed set of criteria to determine an assessment class under which the measurement falls and expressed as single values for each IEQ category and overall IEQ (Marino et al. 2012; Chiang et al. 2001). In this approach, the subjective measurements are not included as part of the overall IEQ index.

For general understanding to readers, the approach of IEQ index, described by Ncube and Riffat (2012) and mathematical derivations of sub-indices, are briefly reproduced herewith. A generalized expression of $\mathrm{IEQ_{index}}$ integrates objective assessment of thermal and acoustic comfort, IAQ and lighting, as below:

$$\mathrm{IEQ_{index}} = \beta_1 \times \mathrm{TC_{index}} + \beta_2 \times \mathrm{IAQ_{index}} + \beta_3 \times \mathrm{AC_{index}} + \beta_4 \times L_{\mathrm{index}}$$

The weighting coefficients (β1–β4) were derived by fitting multiple regression models to questionnaire data obtained from the responses of 68 occupants from two selected air-conditioned office buildings in the UK.

Thermal comfort sub-index—This was based on Fanger's thermal comfort model (Fanger 1973; ISO 7730-2005), called the predicted mean vote (PMV) and predicted the number of people dissatisfied with the thermal environment (PPD), with reference to exposure at moderate thermal environments in mechanically ventilated offices. The detailed derivation of PMV and PPD is given in Chap. 9. The Thermal Comfort Index ($\mathrm{TC_{index}}$) was expressed as the percentage of people accepting the thermal environment, i.e., deducting PPD from 100.

Acoustic comfort sub-index—Acoustic comfort relates to the ability of the building that has minimal unwanted noise, which may emanate from the HVAC systems, sources external to the building or distractions from fellow occupants. The percentage of people dissatisfied (PD_{AC}) to the background noise in dB (A) was obtained as:

$$PD_{AC} = 2\left(\mathrm{Actual}_{\text{sound pressure level}} - \mathrm{Design}_{\text{sound pressure level}}\right)$$

The A-weighted continuous equivalent sound pressure level (LeqA) was used for evaluating indoor acoustic comfort in offices (Wong et al. 2007). Design sound pressure level may be obtained from Table 11.1. Based on the number of persons dissatisfied with the acoustic environment, the AC index was obtained by deducting PD_{AC} from 100.

Lighting comfort sub-index—Lighting quality relates satisfaction of occupants to illuminance, luminance distribution, colour characteristics, daylighting factors, and room surface reflectance and glare. Chap. 8 describes the detailed guidance on lighting requirements and lighting levels for the indoor office environment. The lighting index (L_{index}) was expressed based on the amount of light falling on the working plane, as below:

$$L_{index} = -176.16X^2 + 738.4X - 690.29$$

where $X = \{\ln(\ln(\mathrm{lux}))\}$.

IAQ sub-index—IAQ relates to the level of pollution in the building and ventilation effectiveness. The IAQ index was evolved from the consideration that the IAQ in an office building can be determined from calculating percentage dissatisfied (PD), regarding (a) ventilation rates, (b) CO_2 concentration above outdoors, or (c) air pollution levels (decipol) (EN 13779-2006). The quality of indoor air (PD_{IAQ}), in terms of ventilation rates (q), was expressed as:

$$\begin{aligned} PD_{IAQ} &= 395 \times \exp\left(-1.83q^{0.25}\right) \text{for } q \geq 0.32 \mathrm{l/s} \times \mathrm{olf} \\ PD_{IAQ} &= 100 \text{ for } q < 0.32 \mathrm{l/s} \times \mathrm{olf}, \end{aligned}$$

where olf is expressed as a unit to measure the strength of a pollution source, which is equivalent to the emission rate of the air pollutant from one standard person. The use of olf, name derived from the Latin word olfactus, meaning smelled (Fanger 1988), is not restricted to people as sources. It takes into account sum of all sorts of sources, such as building furnishing materials, photocopiers that emit air pollutants. Emissions of building materials have been estimated at 0.1—0.2 olf/m^2. The percentage of occupants dissatisfied with the quality of air in a building can also be estimated from indoor CO_2 as:

$$\mathrm{PD_{IAQ}} = 395 \times \exp\left(-15.15\,C_{\mathrm{CO_2}}^{-0.25}\right)$$

In this case, acceptable indoor CO_2 level shall not exceed the design values indicated, i.e., to keep less than 1000 ppm (650 ppm above the ambient level) to prevent excessive accumulation of pollutants. The PD can further be expressed for perceived air quality measured as decipol (in C_i) (Fanger 1988). That is,

$$C_i(\mathrm{decipol}) = -112\{\ln(\mathrm{PD_{IAQ}}) - 5.98\}^{-4}$$

One decipol corresponds to the perceived air quality with a sensory load of one olf, for one standard person ventilated a space by 10 l/s of fresh air. From the $\mathrm{PD_{IAQ}}$, the $\mathrm{IAQ_{index}}$ (comfort) was obtained by deducting $\mathrm{PD_{IAQ}}$ from 100. By adjusting the weighting coefficients of sub-indices, against their integrated contribution to IEQ as 100%, the overall IEQ index was yielded as:

$$\mathrm{IEQ_{index}} = 0.30 \times \mathrm{TC_{index}} + 0.36 \times \mathrm{IAQ_{index}} + 0.16 \times L_{\mathrm{index}} + 0.18 \times \mathrm{AC_{index}}$$

where IAQ contributed highest to the perceived IEQ analysis, followed by thermal comfort, acoustic, and lighting in the decreasing order of contribution. Accordingly, the IEQ assessment categories were suggested for rating office complexes, with weighted assessment against the floor space occupied for each type of office. The IEQ scores were categorized as I–V, i.e., scoring between 80 and 100 (very high quality), and intermediates 60–80 (high), 40–60 (medium), 20–40 (low), and 0–20 as very low quality, respectively. Depending on the IEQ measurement options available and information at hand of the comparative energy demand, the assessments can be presented on a real-time, daily, weekly, monthly, or annual basis.

Potential of IEQ Models

The approach of IEQ model is useful in providing an overall evaluative picture of IEQ in a cluster of office and non-residential building. There is a lack of consensus on the IEQ measurement protocols, scaling criteria to be used, and level of accuracy the models can achieve in comparing buildings. Depending on the building characteristics, such as location, size, types of occupants, climatic zones, the design of HVAC systems, the comfort weightings of the sub-indices would vary. Chiang et al. (2001) used a consultative, analytical hierarchy process to develop a linear IEQ model, based on the health-risk outcomes, and determine the appropriate weights. Like Ncube and Riffat (2012), Wong et al. (2008) and Cao et al. (2012) used multivariate linear regression of occupant responses to determine weights of the categories.

The weightings obtained in different aspects (Table 11.4) indicate a vast difference in terms of human comfort. For example, findings of Chiang et al. (2001)

Table 11.4 Weighting coefficients regarding relative occupant response to different IEQ parameters

	Thermal comfort	IAQ	Acoustics	Lighting
Chiang et al. (2001)	0.21 (0.24)	0.21 (0.34)	0.20 (0.23)	0.16 (0.19)
Mui and Chan (2005)	0.42	0.09	0.28	–
Wong et al. (2008), Lai et al. (2009); N = 293	6.09 (0.31)	4.88 (0.25)	4.74 (0.24)	3.7 (0.19)
Cao et al. (2012); N = 500	0.32 (0.38)	0.12 (0.14)	0.22 (0.27)	0.17 (0.21)
Ncube and Riffat (2012); N = 68	0.30	0.36	0.18	0.16
Marino et al. (2012)	0.19 (0.29)	0.15 (0.23)	0.16 (0.25)	0.15 (0.23)
Heinzerling et al. (2013); N = 52,980	0.12	0.2	0.39	0.29

show that the lighting comfort was least important and IAQ was most important. Ncube and Riffat (2012) also noted IAQ as being the most important, whereas both lighting and acoustic comfort were the least important. The observation of CBE study from a considerably large building database indicated acoustic comfort has a very high weight, in comparison to other aspects (Heinzerling et al. 2013). In spite of emphasis given that buildings are characterized by an overall influence of several environmental factors, devising a universal IEQ index for assessment buildings using a single number has its challenges. From analysis of indoor environment of 26 offices under SCAT project in Europe, Humphreys (2005) noted that dissatisfaction in one or more aspects of the indoor environment is no indication to manifest dissatisfaction with the overall environment, however, satisfaction with warmth and IAQ appeared to be relatively more important than satisfaction with lighting or humidity. Lai et al. (2009) developed an IEQ logger for continuous monitoring of the IEQ parameters, which has been validated by large-scale surveys in air-conditioned buildings in Hong Kong. The logger was used for the development of an IEQ comfort model—a composite IEQ index integrating responses of all the indoor environmental qualifiers.

Frontczak and Wargocki (2011) summarized the literature on IEQ category weightings, based on the ranking of the building users as being the most critical determinants of comfort. Building occupants placed greater importance on thermal comfort, as compared to the visual and acoustic comfort and good air quality. The occupants provided with options to control the indoor environment seem to influence a higher degree of overall satisfaction with IEQ. Further, Frontczak et al. (2012) used a mixed model logistic regression to analyze the relative importance of IEQ categories and building features (office type, distance from windows) to the workplace and overall building occupant satisfaction. Kim and De Dear (2012), using the CBE database, looked at the relationships between IEQ categories and overall workspace satisfaction. Kim and De Dear used Kano's model of customer satisfaction to breakdown IEQ category performance into more complicated relationships with satisfaction (basic factors, bonus factors, and proportional factors).

The European Directive 2002/91/EC (recently replaced by 2010/31/EU) indicates the member countries to draw up a methodology for buildings energy certification. The directive emphasizes the evaluation of both energy consumptions and pollution impacts, taking into account comfort conditions of indoor environment and outside climate. Marino et al. (2012) suggested an approach of the IEQ classification on seven-point comfort scale to apply in unique single environments or the whole building. The ranking was based on the calculation of two indoor quality indices, i.e., the environmental quality index (EQI) and the building quality index (BQI). Candido et al. (2016) introduced the Building Occupants Survey System Australia (BOSSA) including a scoring system to meaningfully communicate occupant survey on IEQ to the key stakeholders. The scoring system is comprised of nine IEQ dimensions (such as spatial comfort, IAQ, thermal comfort, visual comfort noise distraction, individual space, privacy, personal control, connect to the outdoor, building image and maintenance) and its association with four independent variables (such as work area comfort, building satisfaction, productivity, and health). Since different green building certification schemes prioritize on issues of IEQ in building assessment, better IEQ models with quality criteria and rating scores would be useful in comparing building performance across countries.

IEQ: Occupants' Performance and Productivity

Building characteristics, indoor physical parameters, and IEQ have plausible links on occupants' health, comfort, satisfaction, performance, and productivity (Fig. 11.4). An office building is considered as a healthy environment when over 3/4th of its occupants are satisfied with the complex workplace settings. Multiple factors present itself with many possibilities to inspire, energize, and motivate occupants to feel like of the space where they always belong. Research studies indicate physical factors, such as thermal comfort (Djongyang et al. 2010; Lan et al. 2011), lighting and daylighting (Alrubaih et al. 2013; Sivaji et al. 2013), IAQ and ventilation (Fisk et al. 2012), noise and acoustics (Banbury and Berry 2005; Mui and Wong 2006), office layout (Haynes 2009), biophilia and views (Bright 2012; Heerwagen 2009), location and amenities (WGBC 2014; Gordon-Larsen et al. 2009) have direct bearing on occupant's health and well-being in an organizational environment. Most of these elements are also differently incorporated in green building certification schemes.

IAQ and ventilation—The constituents of IAQ in building environment are affected by the building conditions (material, structure and construction, HVAC systems), indoor space arrangements (workplace layout, ergonomics, furniture, and equipment), occupants' activity patterns and outdoor climate. Emissions of VOCs from sources like paints, furniture, and other indoor materials are ongoing concerns of poor IAQ and its consequent effects on human health (Wolkoff 2013). Refer to

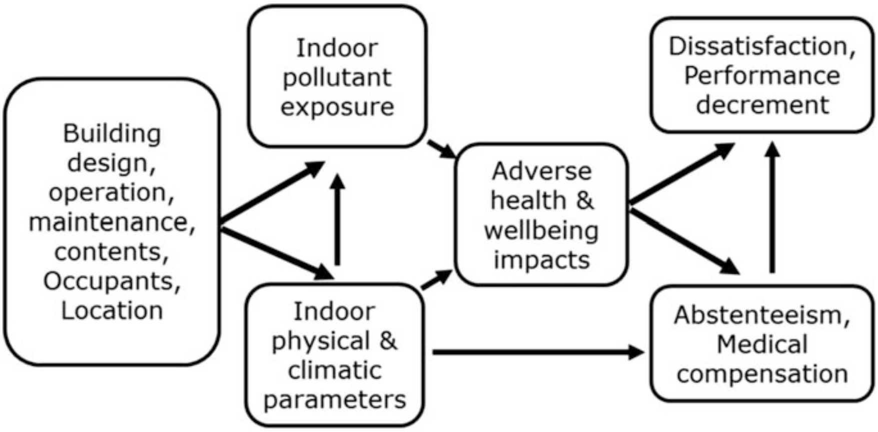

Fig. 11.4 Plausible links between building characteristics, indoor physical parameters and IEQ on occupants' health, comfort, satisfaction, performance, and productivity

Table 10.2 for a variety of health effects due to different indoor pollutants. Building-related illness, SBS, hypersensitivity pneumonitis, asthma among building users, and decrement in productivity and performance due to poor IAQ have been documented (Zheng et al. 2009; Tham et al. 2015).

Thus, assessment of IAQ encompasses evaluating ventilation effectiveness. Appropriate application of ventilation can exchange the indoor air and remove CO_2 and other air pollutants. Ventilation rates below 10 l/s are associated with higher prevalence of SBS and other health risks (Dimitroulopoulou and Bartzis 2014). Whereas higher ventilation rates result in higher energy demand, better IAQ better might lead to beneficial effects on health and productivity of the occupants (Ezzeldin and Rees 2013) and overall economic benefits. The US study (Fisk et al. 2012) revealed that by increasing minimum ventilation rates from 8 to 10 or 15 l/s yielded annual economic benefit of nearly three times, from US$ 13 billion to 38 billion. The ventilation systems, such as naturally or mechanically ventilated system, hybrid/mix mode system, are chosen considering building typology and architectural features, climatic and behavioural components. Personalized ventilation (PV) used as a secondary system in conjunction with the primary air distribution system results in higher satisfaction and acceptability by the occupants, and better energy savings than other HVAC systems (Ezzeldin and Rees 2013; Gou et al. 2014).

Indoor climate and performance—Hot-dry and hot-humid climatic conditions directly affect thermo-regulatory and cardiovascular systems, with a consequent effect on health, comfort, and performance. In case of high effective heat load, dehydration may ensue, and one may feel fatigued and exhausted. ASHRAE 55-2004 standard elucidates thermal comfort as a state of mind that expresses one's satisfaction with the thermal environment. There are two facets of thermal comfort referred to as (a) the thermal state (combined expression of air temperature, humidity, air velocity, and mean radiant temperature) and (b) the human aspect (thermal sensation, thermal acceptability, and preference towards a thermal state) (Langevin et al. 2013). A thermal state can trigger human responses, and the degree of reaction is modulated by factors, such as age, gender, clothing worn, a metabolic rate about activity pattern of the occupants, and microclimate (ASHRAE 55-2010). The subjective thermal sensation is often expressed, for example, on a seven-point scale from −3 (cold) to +3 (warm) in the direction and magnitude of one's sensory perception of the environment. Whereas thermal acceptability is the degree of an occupant's approval to the climatic situation, the thermal preference is the preferred and ideal thermal state of the climate (Langevin et al. 2013). Therefore, the judgement of overall comfort in a building is the resultant of the combined effect of the thermal state and the human aspects (Quang et al. 2014).

Research on thermal comfort underlines two major approaches, that is, (a) Fanger's (1984) rational approach, as described in EN 15251-2007 (prEN 16798-1 2015) and (b) de Dear's adaptive standard approach (Brager and de Dear 1998). Readers may refer to Chap. 9 for details of these approaches. Fanger's analytical model (PMV—predicted mean voting on a scale of +3 to −3, and PPD—the predicted percentage of dissatisfied occupants) combines climatic and the human variables. The adaptive approach (Brager and de Dear 1998; de Dear and Brager 2002) analyses human thermal acceptability of an environment, depending on one's adaptive behaviour, physiological, and psychological state. There has been a debate on the efficacy of the above approaches, as incorporated in thermal comfort standards, such as ASHRAE (2005), ISO 7730 (2005). In any case, thermal comfort standards are a good starting point for designing heating and ventilation system in a built environment (Humphreys et al. 2007; Nicol et al. 2012).

Dissatisfaction in a thermal environment implicates loss of productivity and performance (Akimoto et al. 2010; Roelofsen 2016). The indoor temperature range of 21–25 °C is a stable range for better productivity in sedentary, office work. For each degree rise in indoor temperature over 25 °C, there might be a productivity drop by 2% in the range of 25–30 °C (Seppanen and Fisk 2006). Studies indicate that females feel more dissatisfaction than males and are more sensitive to deviations from an optimal thermal environment (Karjalainen 2012)

Importance of lighting and daylighting—In essence, a good lighting system in a building should maximize the availability of natural light and optimize the artificial lighting energy load. Despite that most workplace in the offices are illuminated by artificial lighting, the occupants generally prefer natural light/sunlight over artificial light (Elzeyadi 2011; Galaxia and Veitch 2006); however, excess direct sunlight is disliked. Organizations paying attention to the importance of daylighting tend to achieve better occupant satisfaction (Yang and Nam 2010). Access to windows brings aesthetically delightful visual information of the surroundings. However, the extent of daylight entry distinctively influences the occupant preferences and responses due to the effects of solar radiation (Zhang and Barrett 2012a, b). Geographical location, the season of the year, time of a day, and the occupancy pattern of the office play a role in defining the size, the position of the window, or type of glass façade (Lim et al. 2012) .

Chapter 7 includes a detailed analysis of daylight availability and possible causes of glare in the building. A glare-free workspace contributes to improving occupant productivity (Hemphala and Eklund 2012). The office areas are recommended to have Daylight Glare Index (DGI) level of 22 for good visual comfort (Cantin and Dubois 2011). Switching controls, either manual ON and OFF or relays controlled by occupancy sensors contribute to reducing a building's energy consumption (Pomponi et al. 2015). For example, the strategy of continuous dimming uses sensors to regulate the exterior illuminance and accordingly controls the artificial lights in the indoor space. Automated shading devices in buildings minimize solar gains and excessive daylight indoors.

Noise as psychosocial stress—In an office environment, any unwanted sound is recognized as noise, since such sound disrupts human performance and affects health. External building elements and sources of noise (vehicular movement, running machinery), and internal office layout and sources (speech, office equipment, HVAC systems) can influence the interior noise level in the office environment. The type of sound, the intensity of noise, technological complexity of the office environment produce annoyance and dissatisfaction among the office occupants and affect their performance (Frontczak et al. 2012; Balazova et al. 2008). Noise annoyance manifests as health implications, like hypertension, and the release of increased stress hormones among the occupants (Ayr et al. 2003). Pellerin and Candas (2004) viewed that acoustic and thermal sensation have an equivalent effect on an employee's productivity; that is, a change in air temperature of 1 °C in a building has the same effect as of 2.6 dBA change in the noise level.

Employees in open-plan offices are more prone to privacy issues and disturbances due to the noise sources around them (Balazova et al. 2008), with a risk of adverse impact on their motivation and performance (Jahncke and Halin 2012). McLaughlin (2000) revealed that a lack of acoustical privacy in open-plan offices can reduce productivity by about 40% and increase errors by about 27%. Different interventions may be taken to minimize noise level in an office, such as use of sound absorbent material on the ceiling, walls, and floors at specific office locations (Payne 2013). Installing thick curtains on the windows is a way to reduce unwanted noise. In an open-plan office, acoustic discomfort can be reduced by lowering the background noise. Suitable application of sound masking might be useful in maintaining the primary sound levels in an office.

Pollution Control

The World Health Organization (WHO 2010) laid out that the indoor pollution causes over 1/3rd of the respiratory diseases, 22% of chronic disease, each 5% of bronchial catarrh, cancer, and leukemia. The amount of time occupied in a building space is a likely factor of contraction of diseases. The assessment of lifetime risk of cumulative exposure to indoor pollutants sets the thresholds or permissible limits of exposure (refer to Chap. 10). All concerned deal with office and other types of buildings seek to reduce health risks from indoor air pollutants through public education, including the development of IEQ guidelines to support related control measures. The primary recommendation is to execute a well-defined building inspection procedure that includes determining whether the ventilation systems meet the requirement to supply outdoor air at the required rate (adjustment is made in case of a partial dependence on the options of natural ventilation). Small- and medium-size commercial buildings constitute the significant chunk of the building stock, and most of these buildings might have installed non-commercial HVAC units, and often these units are not routinely maintained, filters might not have changed for a long time, and thus, the building indoors are heavily loaded with particulate matter. For building occupants, both short- and long-term exposure to indoor pollutants, particularly the VOCs, are health concerns because some sources of these pollutants typically require months or years to fully off-gas. Ample body of literature reveals that VOCs are generally emitted from the use of cleaners, paints, flooring materials, and adhesives during the renovation, remodelling, repair, and regular building maintenance. Presence of significant concentration formaldehyde in carpeted buildings is a potential health risk, and therefore, this is a logical starting point in reducing formaldehyde building source strengths, but emissions of other products also carry considerable health risks.

Particulates and bioaerosols are of different dimensions (Fig. 11.5), and the control of these particles or dust control in buildings consists of removal of the source, local exhaust, dilution ventilation, filtration, wetting, and use of personal protective equipment, such as respirators; however, the latter two options are mostly adopted in industrial units, as necessary. Broadly, office and commercial buildings are designed and operated, maintaining air handling system partly pressurized to push the outdoor air into the building. Building technologies, such as increased

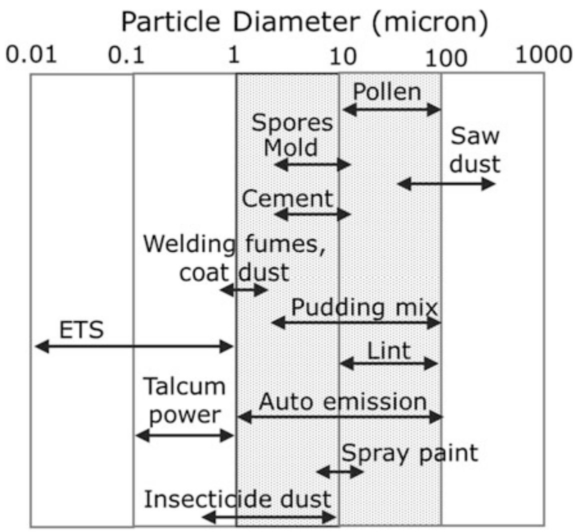

Fig. 11.5 Diameter of different kinds of particles

ventilation, reduced air recirculation, selection of appropriate filtration devices and ultraviolet disinfection of air, have potential to reduce inhalation exposures to toxicants and infectious aerosols. Filtration devices installed in the air handling system are useful controls to remove contaminants from the incoming outdoor air (Fig. 11.6). The filtration is performed in combinations of multiple mechanisms,

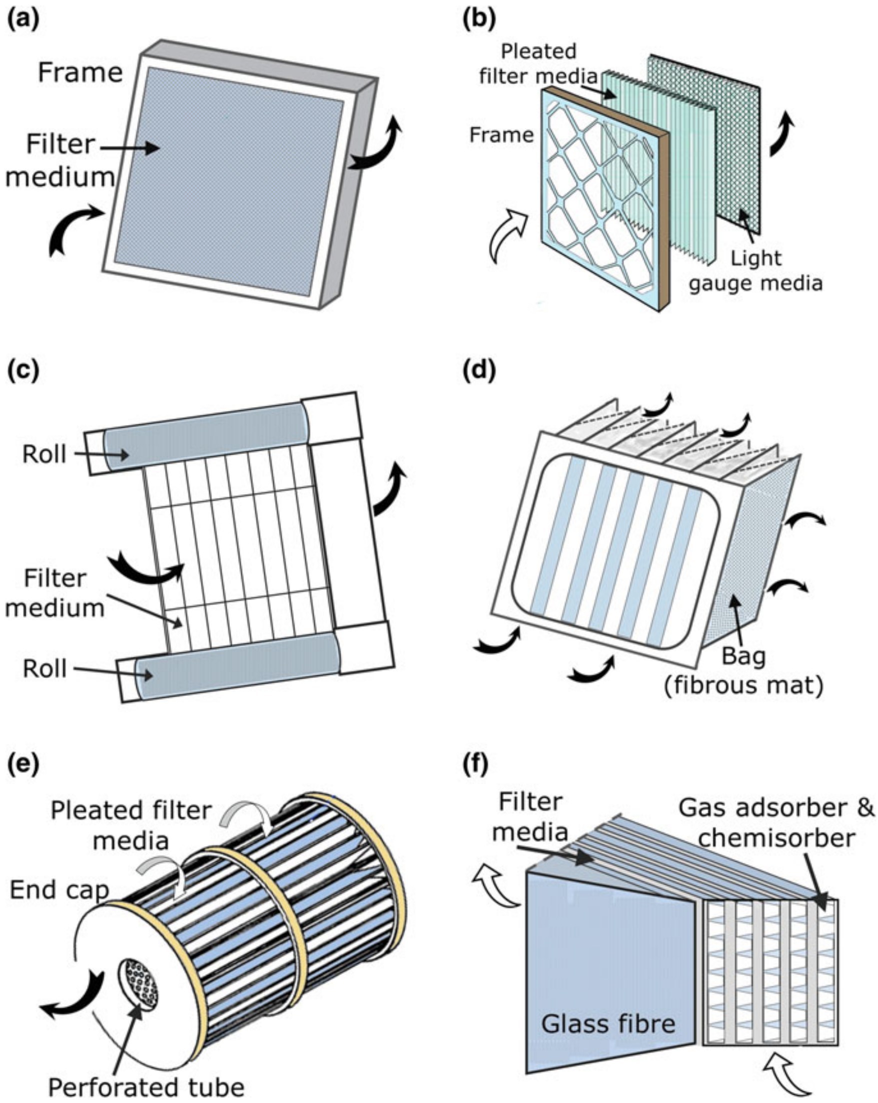

Fig. 11.6 Filtration devices in the air handling system to remove contaminants from the incoming outdoor air; **a** panel filter, **b** pleated filter, **c** renewable rolling filter, **d** extended surface bag type filter, **e** rotary pleated filter, **f** HEPA/ULPA filter

such as (i) inertial impaction (collision between dust particles and fibrous media), (ii) straining (dust particles trapped in the filter spaces of different sizes), (iii) diffusion (Brownian movement causes fine particles to settle), (iv) interception (along the air stream, particles may contact fibrous media and remain there), (v) electrostatic effects (dust gets collected when the particles and filter medium are charged). Low-, medium-, and high-efficiency filters are characterized by the efficacy of removal of particles of different sizes—dust, spores, moulds, bacteria, coal dust, welding fumes, ETS, and other smokes. Ultrahigh-efficiency filters include high-efficiency particulate air (HEPA) and ultralow penetration air (ULPA) filters. The extent and efficacy of filtration depend on the filter efficiency, the rate of air change to the building interior, the particulate concentration of the outdoor air passes through the filters, and any likely internal generation of particulates. That is, the buildings that are anticipated to have high particulate matter sources, and airborne microorganisms would benefit from the use of HEPA filters (Fisk et al. 2002). A review of particle filtration intervention studies in homes and commercial buildings (Fisk 2013) is strongly suggestive of improvement in allergic or asthmatic persons by the delivery of filtered air to the breathing zone. In most ventilation systems, the recirculated air is also filtered to minimize particulates in the incoming air, and some special purpose buildings use gaseous and chemical absorbents.

Apart from the methods of source control, filtration, and increased ventilation in a building zone, proper installation of air cleaning system also significantly contributes to improving the IAQ in buildings. Conventional pollution control methods, such as activated carbon adsorption and chemical scrubbers, have limited utility since pollutants are merely phase transferred. Advanced oxidation processes, such as thermal oxidation destruction (Everaert and Baeyens 2004; Roark et al. 2004) and photocatalytic oxidation (Carp et al. 2004), are promising technologies for air purification. Many of the VOCs in the indoor environment are in the sub-ppm or parts per billion (ppb) levels, and therefore, the method selection of air cleaning, regarding economic feasibility, is worthy of consideration. Removal of VOCs from the indoor air can be achieved using photo-catalytic oxidation (Wang et al. 2007). The TiO_2 is a useful catalyst in photo-catalytic oxidation. However, this type of catalyst exhibits high catalytic activity at UV light. Therefore, pollution control and IEQ performance in indoor environment, with particular reference to office buildings, can be addressed through structured methodology and approach, and thereby to mitigate the risks of harmful or unpleasant substances.

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Chapter 12
Ventilation in Office Buildings

Introduction

Ventilation is a process of circulation of air within the building and exchanging the contaminant air to the outside. This process is accomplished passively through natural ventilation, or actively through mechanical/forced air distribution systems. Natural ventilation has been the adopted approach in a great many historic buildings for ages. The architectural design included provisions of air infiltration through the doors and windows, as well as through building orientation and openings in building envelopes and uniformly distributed ventilation in different building zones. Mechanical ventilation (exhaust only, supply only, and balanced) has become an additional means in contemporary buildings, particularly in non-residential and office buildings. The buildings that have a high dependence on mechanical ventilation consume more electricity in comparison with other building types. Several authorities have emphasized that over two-thirds of total energy is used in general lighting and HVAC requirements in office buildings (Juan et al. 2010). The utilization of energy depends on the location of office buildings, dimensions, and the types of equipment used, and that ranges from 100 to 1000 kW.h/sq.m. With the increased awareness to make buildings more energy efficient and less impact to the environment, the application of natural ventilation to building structures is a justifiable imperative towards reducing energy usage, achieving acceptable IEQ, and decreasing the ventilation operation costs.

Natural Ventilation Effects

Natural ventilation depends on pressure difference through the natural forces of wind and buoyancy to deliver fresh air into buildings. The direction and velocity of wind, disposition of windows and openings (wind action), the convection effects

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due to thermal forces between inside and outside, and the difference of height between the outlet and inlet openings (stack effect) determine the rate of ventilation in buildings (Ghiaus and Roulet 2005). That is, in large buildings, warm air may rise and escape to the outside through upper openings, and fresh outside air is drawn through low building openings. The climatic factors, such as air velocity, ambient temperature, relative humidity, and pollutant airflow pattern, are essential to determine ventilation requirements, thermal comfort, and IAQ in buildings (Chen 2009).

Wind action—Wind causes a positive pressure on the windward side of the building. Negative pressure on the leeward side sucks the air out through the leeward openings and the roof. The volume of airflow induced by wind (Q_{wind}, m^3/h) is:

$$Q_{\text{wind}} = K \cdot A \cdot V$$

where A—area of inlet openings, m^2, V—outdoor wind speed, m/h, and K—coefficient of effectiveness. The value of K depends on the angle of the wind, the relative size of entry and exit openings, which may range from 0.3 to 0.6. Wind-induced ventilation is maximal when the building elevation is positioned perpendicular to the summer winds. Where the prevailing wind is either from east or west, the building may be oriented at 45° to the incident wind. This orientation allows diminishing solar heat with not much compromise in reducing airflow indoors.

Buoyancy—Buoyancy ventilation results from the difference in air density, either as temperature-induced (stack ventilation) or humidity-induced (cooling tower). Heat and humidity that build up within, from various sources, require to be released out through the ceiling or roof openings, and the cold air enters indoor through lower openings. The rate of airflow induced by the stack effect (Q_{stack}, m^3/h) is:

$$Q_{\text{stack}} = 7.0\,A\sqrt{h(t_{\text{indoor}} - t_{\text{outdoor}})}$$

where h—vertical distance between inlet and outlet, m, and t_{indoor} and t_{outdoor}—air temperatures of indoor and outdoor, °C. The discharge coefficient may be taken as 0.50–0.65, and the lower value is taken when conditions are not favourable. That is, separate supply and exhaust openings at higher levels maximize stack effect. In a building, windows across the room and partially offset from each other maximize airflow performance than other window arrangements. Open staircases also provide stack effect ventilation.

Natural Ventilation Systems

The elements of passive natural ventilation systems that ensure sufficient air change in buildings have both physical elements and non-physical elements.

Physical elements—The categories of physical elements and designs are in five groups, such as air wells, façade designs, ventilation openings, corridors and shadings, blockage and partitions.

- *Air well design*: This is one of the most ancient passive construction designs. Air tower, atrium, or wind catcher helps to circulate the airflow vertically to replace the hot air with cold and fresh air. Through this stack effect, the polluted indoor air can be disposed of effectively (Jafarian et al. 2010). Chimneys and stack air duct serve specific building zones. For taller buildings, the space of atrium can be increased to ensure that there is sufficient space for air circulation. The passive cooling effect can also be created through designs of the fountain in open areas of a building or introducing a suitable evaporative cooling mechanism to provide cooled airstream into the buildings (Ghiaus and Roulet 2005).
- *Façade design*: The building façades consisting of roof, walls, and other openings, such as doors and windows, serve as the alternatives to ensure the mixing of indoor air with fresh outdoor air. Effective façade designs can significantly minimize the building energy load, by reducing the size of mechanical components. Double-skin façade designs can reduce the transmission of heat due to the protection of reflective glass wall and air barrier (Heiselberg 2002; Haase et al. 2009). Projected wing walls next to windows are used to create a pressure differential and allow the breeze to flow through an open window into the building. Wing walls are useful on sites with low outdoor air velocity and variable wind directions.
- *Ventilation openings*: Windward ventilation openings allow entry of fresh air and discharge of the polluted air outside, by the air pressure difference between indoor and outdoor areas. Window openings are the main components to control the access to ventilation and daylight (Tian et al. 2010). Apart from the sizes of the openings, the placement, and orientation of the windows determine the air distribution within a building zone (Gratia et al. 2004; Roulet and Ghiaus 2005). Vents and louvers are other openings for natural ventilation, and their locations depend on the architectural design requirements.
- *Corridors and shading*: Building corridors and balcony play the function of channelling the air from outdoors into the interior zones. Its effectiveness is influenced by the strength of airflow and the draught levels. Corridor opening surrounding the building facades is preferred that it produces an air pressure zone to cause increased air movement, for most of the orientations of the building. However, such provision in office buildings is always a challenge due to space constraints. For the buildings ventilated by HVAC system, any air leakage and heat transfer from the gaps and openings reduce the operational efficiency of HVAC. Creating more green space around the corridors can minimize these shortcomings. Besides, the energy efficiency of a building can substantially be improved through the process of reducing the absorption of external heat, such as solar heat, by installing thermal insulation materials in the walls, tinted glasses, and passive solar shading elements (Roulet 2005; Zhou et al. 2008).

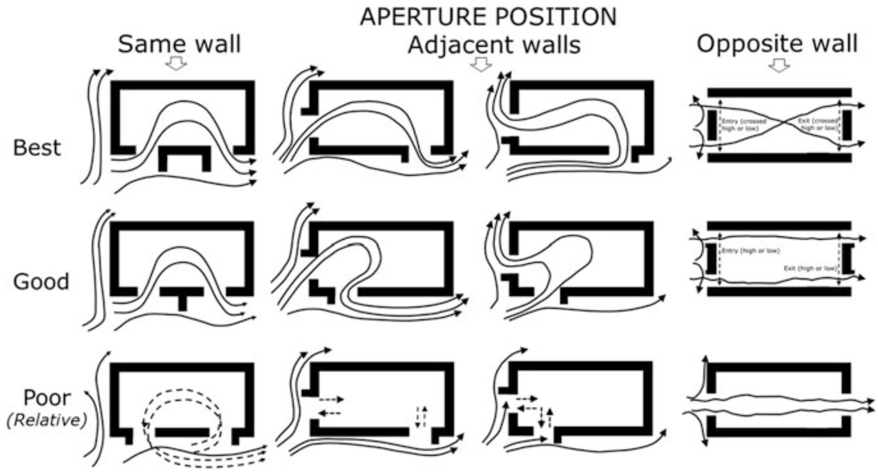

Fig. 12.1 A schematic of the architectural strategies for passive ventilation in a room (redrawn from Brown and DeKay 2001)

- *Blockage and partitions walls*: Due to the essential requirement of human activities, such as zoning or grouping of operations, privacy, and storage, various forms of partitioning in office design are required. These physical elements may retard the airflow circulation, and therefore, the focus of interior design goes in efficiently utilizing the space by avoiding partitions between the windward inlets and leeward exhaust openings. Provision of a partition with a spacing of 0.3 m underneath helps to augment air movement near floor level in the leeward side of large buildings. Different architectural design strategies (Brown and DeKay 2001) of window/inlet-outlet orientations (Fig. 12.1) have been applied, depending on the building orientation, and preferably to avoid inlet and outlet windows directly across.

Non-physical elements: While physical elements impose direct impacts onto the airflow distribution, the non-physical elements include the management policies and procedures, practices and habits of building occupants to minimize the energy usage with no compromise to indoor comfort. For instance, night ventilation can improve the cooling effect of the indoor environment. Also, occupants may opt to adjust themselves at their end by selecting the types of clothing worn, and operating windows or switch on fans, depending on the level of comfort required.

Good Practices of Natural Ventilation

The performance of natural ventilation depends on the characteristics and clusters of buildings of the surrounding areas. The factors of wind direction (wind rose diagram), topography and open areas, building shapes, stack effect, and the clusters of nearby buildings influence the ventilation performance (Omer 2008). To achieve the optimum natural ventilation effects, the building architects emphasize on the site feasibility and building orientation. For the entire building to be naturally ventilated, it should preferably be narrow, for the best use of the directional airflow. Anselm (2006) suggested that the ratio between the length and width of an office building in hot and humid climate should be 1:1.7, and the building should orient to north or south to avoid the sunlight exposure to the significant opening. The specific approaches to passive ventilation design may vary with the building typology and local climate. However, some good practices of natural ventilation are embodied herewith.

- In hot-dry climates, the temperature difference between day and night being high, a closed-building approach works better. That is, building openings are closed during the daytime, and ventilated at night. On the other hand, in warm and humid climates, when temperature condition does not change much between day and night, an open-building approach works better.
- When the areas of inlet and outlet openings are nearly equal, and at the same level, better airflow per unit area of openings is attained. Wide windows of similar in size on opposite walls at an approximate height of 1.1 m are beneficial. In the regions and zones where the wind direction is nearly constant, the maximum average wind velocity in indoors does not exceed 2/5th of outdoor velocity. Since the wind direction is variable in most places, the openings are arranged on all sides for adequate air movement. Cross ventilation is suitable in small buildings up to about 12–15 m in depth, i.e., five times the floor to ceiling height; for depth of building about 2.5 times the floor to ceiling height, openings may be on one side. In more larger buildings, the inclusion of internal courtyards and atriums combines cross ventilation and stack effects. Horizontal louvers that are a sunshade, atop a window deflects the incident wind upward and reduces air movement in the zone of occupancy. Provision of inverted L-type (Γ) louver increases the room air movement, provided that the vertical projection does not obstruct the incident wind.
- Buildings should be oriented in a way that summer wind obstructions are minimal. Air movement in a building is not very much affected by another building on the leeward side unless the leeward building is taller than the windward one, whereas air movement in a building having windows tangential to the incident wind is augmented when another building is positioned to an end on the downstream side. Suitable planting of trees promotes air movement; for example, air movement on the leeward side of a building can be enhanced by planting a low hedgerow in proximity to the building.

In spite of several options and opportunities of including natural ventilation system in the building, using mechanical cooling in hot, humid climates is inevitable to meet requirements of the occupants in contemporary buildings. Drawing cue from the historical statement by Winston Churchill that our buildings shape us the way we build it, the modern building architects understand the criticality of the challenge in combining natural and mechanical ventilation in building design. Needless to mention, the most effective natural ventilation strategies can be found in our regional construction practices.

Ventilation: Mechanical (HVAC System)

Heating, ventilating, and air conditioning (HVAC), as the abbreviations imply, encompass three interrelated functions of heating, ventilating, and air- conditioning that regulate the system operation to meeting the design goals of thermal comfort, IEQ, and cost-effective operation in a build environment. Multiple inventions and discoveries have been associated with today's HVAC system. The first rudimentary ice system, designed by McKin, Mead, and White, was installed in Madison Square Garden (New York) in 1880. In a decade later, Alfred R. Wolf used ice at the outside air intake of the heating and ventilating system in Carnegie Hall of the city. Other central ice systems were also installed at about the same time (1890–1900s) in the New York Stock Exchange (cited in Cooper 2002), Auditorium Hotel in Chicago (cited in Wang 2000). Early central heating and ventilating systems used steam-engine-driven fans to discharge air. The first systematically developed process of air-conditioning (AC) system was in 1902 by Willis H. Carrier. This equipped the Sacketts-Wilhems Printing Company, establishing the control relationship of the system between temperature and humidity. As mentioned in Chap. 1, Larkin Administration Building, designed by Frank L. Wright, was perhaps the first air-conditioned office (1906) that used a refrigeration plant to distribute 10 °C cooling water to air-cooling coils in air-handling systems.

Carrier's patenting of air conditioner impacted hugely in the modernization of building design and industrial workplaces. The significant expansion of AC systems, as individualized window air conditioners units, happened during the building boom in the period of post-World War II. Central AC systems were popularized in the 1970s. In large buildings, the design, fabrication, and commission of HVAC systems require in-depth analysis of the overall requirement, considering the building size, occupants' density in the interior spaces, and the prevailing climate. Accordingly, the capacity and the type of air distribution system are determined. Ever since the boom of HVAC industry, there has been constant awareness related to the reduction of energy usage, and endeavour goes towards developing building codes and standards to optimize energy consumption.

The heating component can be executed by heating the air within the air supply systems or heating through floor/ceiling/wall radiation. The central heating system contains a boiler, furnace, or heat pump to heat water/steam, or air, and the heat gets exchanged through different avenues, such as convection, conduction, and radiation. Heaters exist for different types of fuel (solid fuels, liquids, gases, or electricity) to heat ribbons composed of high-resistance wire, e.g., nichrome coil. Electrical heaters are usually available as a backup or supplemental heat for heat pump systems to extract heat from environmental air or exhaust air out of the building.

The Boilers generate steam, and these units can be coal-fired or fired by natural gas and fuel oil. The combustion efficiencies of boilers, such as firetube, watertube, or cast iron boilers, range between 75 and 85%. Cast iron boilers are composed of precast sections, and they can be more readily field-assembled than watertube or firetube boilers. The cast iron boilers are typically used in small installations (steam output >10 million Btu/h), whereas watertube steel boilers range from small, low-pressure units ($\sim$10 million Btu/h) to massive, high-pressure units ($\sim$300 million Btu/h). Condensing boilers, fired with natural gas, achieve high efficiencies to extract heat from the flue gases. These boilers are available in capacities ranging between 0.3 and 2 million Btu/h and can be connected in modular installations. Devices of heating controls intensify energy efficiency by reducing ON/OFF cycling of boilers. Besides, oxygen trim systems adjust the combustion of air to achieve higher efficiency. They are usually cost-effective for large boilers that have modulating flame controls. Most hot water boiler heating systems have an inbuilt pump to circulate water through the distribution system, and heat gets transferred through heat exchangers, radiators, and hot water coils.

The Refrigerators and air conditioners are the types of the heat pump to extract heat from a cooler, conditioned space, and exhaust to the outdoors. Heating and cooling can be achieved by reversing the refrigeration cycle. Two principal types of heat pumps are packaged (air-source) and water-source (conventional or geothermal). Indoor heating using space heaters or boilers may cause incomplete combustion due to oxygen insufficiency, and indoor air may be contaminated by the emissions of CO, NO_X, VOC_S, and other harmful by-products. In case of warm air systems, heated air flows through the supply and return air ducts, where the supply air is filtered through air cleaners to remove dust and microbial particles.

The Ventilating maintains the process to exchange clean air, control temperature, and remove moisture, odours, and air contaminants of the interior spaces. An air handler unit (AHU) is a component of HVAC system to maintain mechanical or forced ventilation in the system. In designing a ventilating system, the flow rate is a function of the fan speed and exhaust vent size. Ceiling fans and table/floor fans are the conventional devices to circulate air within a room. Different kinds of air distribution systems applied in building situations are described later in the section.

Air conditioning (AC), combined with refrigeration, involves in both sensible and latent cooling, and thereby to control air temperature as well as humidity. The room air cooling is taken place by exchanging heat via air-cooling or water-cooling mechanism. There are both stand-alone air conditioners and larger air-conditioning systems. A refrigerant is used either in a heat pump system, and a compressor pump that drives the fluid into the refrigeration cycle, or in a free cooling system, a cooling refrigerant (water or a glycol mix) that is pumped to circulate. Ozone-depleting chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which became common refrigerants in the twentieth century, are being substituted by other substances, such as perfluorocarbons (FCs) and hydrofluorocarbons (HFCs) that were included in the Kyoto Protocol (UNCED 1997) to the Framework Convention on Climate Change.

A refrigeration cycle (Fig. 12.2) consists of four essential elements, such as (1) condensing coil (heat exchanger), (2) expansion valve (metering valve), (3) evaporating coil, and (4) compressor pump. At high pressure and temperature, the heated refrigerant gas exchanges heat to the outside through the condensing coil and condenses into the liquid phase. The expansion valve regulates the flow of the refrigerant liquid to the evaporating coil, and in the process of evaporation, the refrigerant absorbs heat from the inside air and returns to the compressor, and the cycle gets repeated. By the absorption of heat from indoors and exhaustion to outdoors, cooling of the interior building takes place. The refrigeration cycle, that is, the flow of refrigerant may be reversed to change the system from cooling to heating or vice versa. A humidifier or a dehumidifier controls the humidity in a building. In an AC system, moisture condenses on the evaporator coils, and finally removed by ducting to the outside. The central AC or package systems with a combined outdoor condenser/evaporator unit are often installed with large air ducts in offices and public buildings. An alternative to packaged systems is the split systems, in which the evaporator coil connects to a remote condenser unit through refrigerant piping. Indoor units with directional vents may be mounted onto walls, or into the ceiling.

Chillers—In large buildings, chilled water from the chillers is pumped into AHU, and through the process of mechanical refrigeration or absorption, the interior air is cold. Mechanical refrigeration chillers, having one or more types of compressors, are powered by electric motors, fossil fuel engines, or turbines. Whereas the centrifugal compressors (100–7000 tons) and rotary screw compressors (70–500 tons) are the large-capacity chillers, reciprocating (10–200 tons) and scroll compressors (1–15 tons) in multiple units can be employed in a single system.

Absorption chillers are heat-operated devices to produce chilled water via an absorption cycle. Absorption chillers can be direct-fired using natural gas/fuel oil. The indirect-fired chillers use hot water or steam from a boiler or waste heat. Evaporative coolers are package units in which the air is cooled through

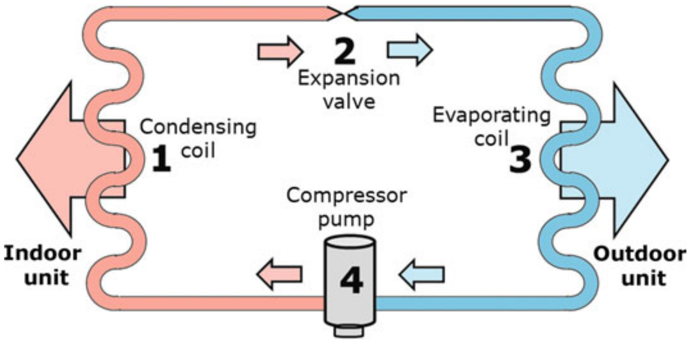

Fig. 12.2 Refrigeration cycle

humidifying and evaporating the moisture. *The full-load operating efficiencies of chillers*, in terms of coefficient of performance (COP), vary widely; lower values of chillers (0.6–0.5 kW/ton) with a COP of 5.9–7.0 would indicate energy-efficient equipment. The COP of large- and medium-sized air-cooled electric chillers (0.95–0.85 kW/ton) ranges from 3.7 to 4.1, whereas the COP of water-cooled electric chillers (0.8–0.7 kW/ton) ranges COP of 4.4–5.0, respectively (Graham 2016).

The condensers (air-cooled or water-cooled heat exchangers) exhaust heat from the conditioned spaces. *Air-cooled condensers* are attached with the smaller, packaged systems (2–120 tons). Water-cooled condensers often rely on rooftop cooling towers for exhausting heat into the environment.

Most readers recognize that the HVAC technology has undergone enormous depth of development. Needless to reiterate, this contribution is beyond its scope to elaborate the technological changes of HVAC systems. A schematic is shown herewith (Fig. 12.3) to briefly identify the critical components of HVAC systems, which may require appropriately being maintained on a regular basis to meet the design goals of user thermal comfort, improved IEQ, and energy efficiency in a building environment.

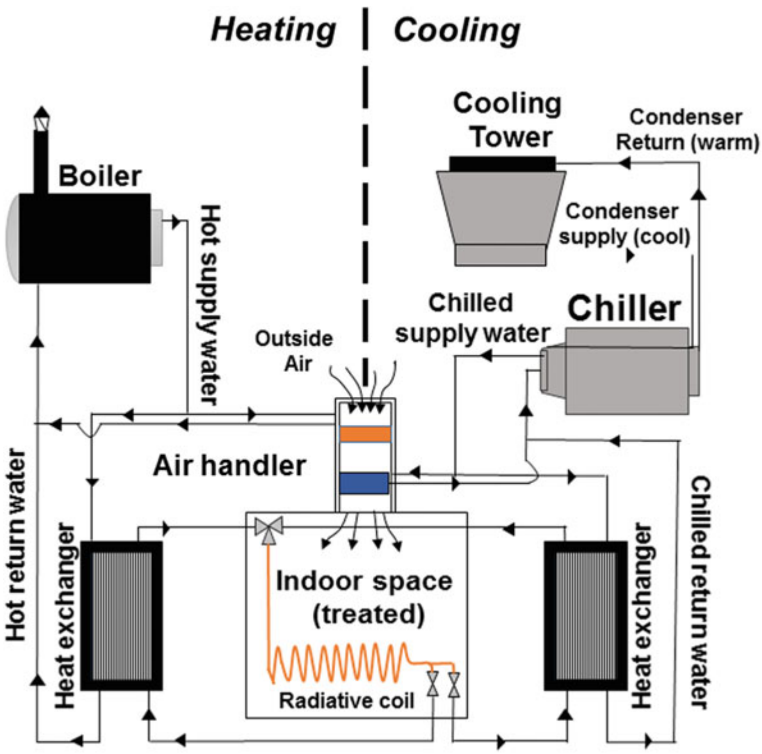

Fig. 12.3 A schematic showing the critical components of HVAC system

The ASHRAE guideline (ANSI/ASHRAE 1989/2007/2010/2-13) of outside air ventilation equivalent to 20 ft^3/min/person is a sufficient amount of air to dilute building contaminants in an office environment. The AC systems (including small window units) are equipped with internal air filters (lightweight gauzy materials), which are required to be routinely replaced or washed for better heat exchange. Besides replacing the air filter at the evaporator coil, the condenser coil also requires regular maintenance to discharge the indoor heat and the heat generated by the electric motor to drive the compressor. Poorly maintained HVAC/AC systems in building culminate in deteriorating IAQ in buildings, with obvious health consequences among the building occupants.

Ventilation and Airflow Distribution Systems

The ventilation systems in building premises are primarily chosen depending on the pollution load, the location of the air supply/exhaust device, and the mixed use of natural and mechanical ventilation (Cao et al. 2014a, b). However, in office spaces, where there are large numbers of obstacles and heat sources, such as occupants, computers, and other equipment, air distribution in such rooms is more complicated and challenging. Inevitably, the effectiveness of the system is determined from its utility in the removal of heat and pollutants, supply of fresh air to the breathing zone and the overall efficiency of the energy use. Different forms of ventilation systems that are deployed in office buildings are schematically illustrated (Figs. 12.4 and 12.5), including the historical illustrations of airflow pattern of MV, given in Boyle Son (1899).

Mixing ventilation (MV)—The ventilation approach is based on the principle of diluting the contaminated indoor air by mixing the fresh inlet air. A REHVA guidebook introduces the various application of MV (Muller et al. 2013). The MV systems are market-dominant, in spite of its relatively poor ventilation efficiency and less energy efficiency (Karimipanah and Moshfegh 2007).

Displacement ventilation (DV)—The system works on the principle of displacing contaminated indoor air by pushing fresh air from outside. A low-velocity (<0.5 m/s) fresh air is supplied at about the floor level, and the warm air moves up as thermal plumes through creating gradients of temperature, air velocity, and

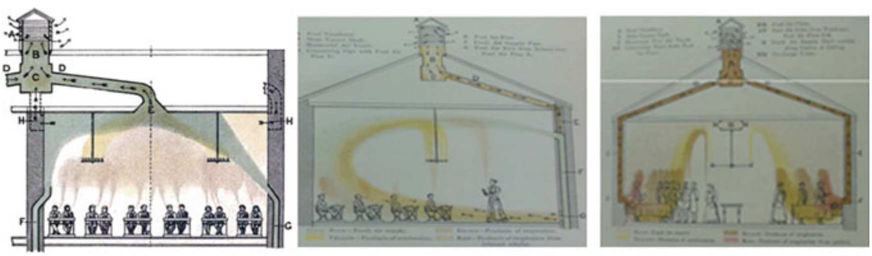

Fig. 12.4 Airflow pattern of MV (given in Boyle Son 1899)

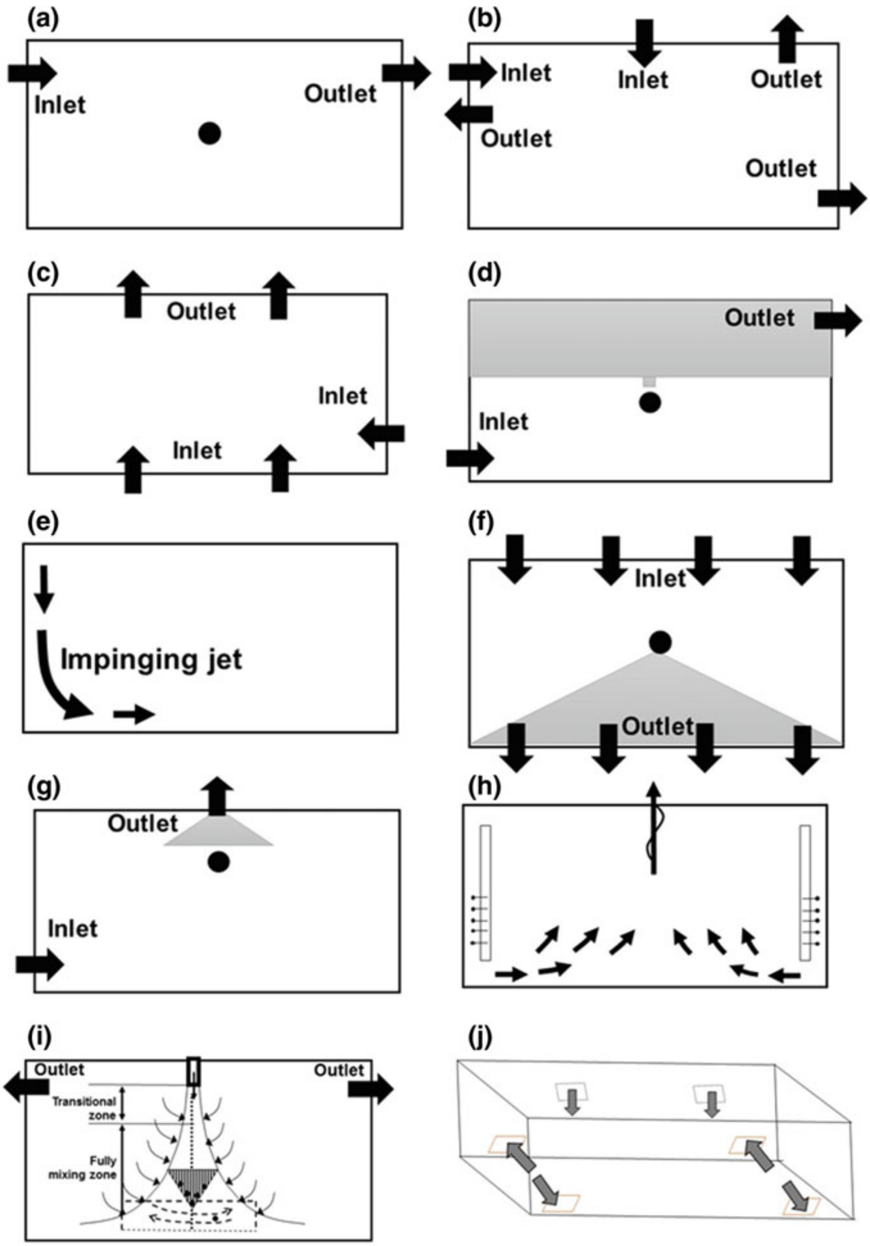

Fig. 12.5 Air distribution systems (Cao et al. 2014a, b): **a** mixing ventilation (Awbi 2011); **b** mixing ventilation (Krajcik et al. 2012); **c** displacement ventilation (Lee et al. 2009); **d** displacement ventilation (Awbi 2008); **e** impinging jet (Awbi 2011); **f** confluent jet ventilation; **g** piston ventilation (Awbi 2011); **h** piston ventilation; **i** protected occupied zone ventilation; **j** stratum ventilation

contaminant concentration (Lee et al. 2009; Tomasi et al. 2013). The DV system can only be used for cooling and is not suitable for winter heating.

Personalized ventilation (PV)—That is, air distribution is directly in the breathing zone of a person. Different types of air supply devices have been adopted to supply fresh and filtered air directly to the exposure region. Cao et al. (2011) summarized the performance effectiveness of PV, which over 3/4th of the inhaled air would consist of fresh, personalized air (<3 l/s).

Hybrid ventilation (HV)—The impinging jet ventilation (IJV) system (Awbi 2011) and the confluent jet ventilation (CJV) system (Awbi 2008; Cho et al. 2008) combine the characteristics of both MV and DV systems. In IJV, an infinite stream of a fragile layer of airflow impinges onto the floor and gradually spreads over a large area. The *confluent jet ventilation* (CJV) system blows air to the wall at the corners of the occupied space, through the supply duct with circular nozzles in multiple rows ($\sim$6 rows). The jets at some distance downstream coalesce to a single jet and produce a greater horizontal spread over the floor (Cho et al. 2008).

Besides, *local exhaust ventilation* (LEV) is an extract ventilation system installed in a building zone where the sources of localized contaminants can be identified. An extraction hood is placed firmly above the source to exhaust the pollution before it can spread into the room. In *piston ventilation* (PiV), air is supplied vertically or horizontally at low velocity (0.2—0.4 m/s) into a room, that is, creating a piston-type turbulent flow to remove contaminants from an enclosed space. The PiV requires a very high ACH (200–600), which is used in specific application areas, such as hospital operating theatres, pharmaceutical clean rooms (Awbi 2003). The *stratum ventilation* (SV) has been proposed to accommodate any elevation at room temperature. The critical issue is to evaluate whether this air distribution method offers performance advantage in combating airborne infection (Lin et al. 2011; Tian et al. 2011).

Protected occupied zone ventilation (POV)—A protected occupied zone (POZ) in a room consists of the breathing zone and working zone of building occupants. A POV system consists of a low turbulent jet air curtain at the ceiling or located above the height of the people working in the office. An exhaust grill at the floor level separates an indoor space or an office environment into sub-zones, e.g., a source zone and a target zone (Cao et al. 2014a, b). Such air curtains are installed in facilities (such as open-plan office, smoking zones, and departmental store check-outs), where more interpersonal exposures are anticipated and with a likely risk of respiratory infection by contaminated air.

Ventilation Codes and Standards

Ventilation has often been viewed as the panacea to control contaminants, and in turn to influence health and well-being outcomes of building occupants. Von Pettenkofer's (1858) early endeavour of associating build-up of CO_2 concentration in homes to people's common sickness was probably the starting point towards establishing ventilation standards, often referring to Pettenkofer number of 1000 ppm CO_2. Ventilation standard is imperative to attain perceived IAQ in buildings, with due consideration to indoor pollutants emanated from the occupants and building functions, outdoor air quality, airborne pollutant limits, and performance-based design (Persily 2015). Standards have been formulated by the national standards bodies and also international agencies. Many of the HVAC standards are based on the ASHRAE data. Other reference source materials are available from SMACNA, ACGIH, International Mechanical Code, and the like. ASHRAE Handbook, updated every four years, is a fundamental knowledge base on HAVC design practices. Some of the ventilation standards are listed below:

- ASHRAE 55 (2004,2007,2009-10, 2013)—Standards for building thermal comfort;
- ASHRAE 62: 2001—Ventilation for acceptable IAQ;
- ACGIH (2001/2003) yearbooks provide TLVs for chemical substances, physical agents, and biological exposure indices;
- OSHA (1989)—Air contaminants-Permissible Exposure limits (Title 29, Code of Federal Regulations, Part 1910.1000);
- ASHRAE 90.1: 2010—Energy standard for buildings except for low-rise residential buildings (updated 2016);
- ASHRAE 90.2-2004 (2004)—Energy-efficient design of low-rise residential buildings;
- ASHRAE 100-2006 (2006)—Energy conservation in existing buildings;
- US Federal standard, 10 CFR 434—Energy code for new federal commercial and multi-family high rise residential buildings, and US Federal energy standards, 10 CFR 435;
- Life-cycle cost analysis (10 CFR 436) (US Federal Regulation).

The conventional approach in establishing ventilation standards is in using sensory discomfort referred to as percentage dissatisfied (PD) with IAQ as an outcome (refer to ASHRAE 62.1:2013; EN 15251:2007, as described in Chap. 11) . ASHRAE 62.1 prescribes a minimum ACH of 0.35 for occupants, whereas a rate of 0.5 ACH can influence in reducing the frequency of respiratory symptoms. Many countries have adopted this standard. ISO 16813:2006 forms the general principles of building environment design to provide a healthy indoor for the occupants, protect the environment for future generation, and promote collaboration among stakeholders. The Chartered Institution of Building Services Engineers, UK (CIBSE 2008) publishes guides of HVAC design relevant to the UK, the Republic of Ireland, Australia, New Zealand, and Hong Kong. These guides include recommended design criteria and standards, such as:

- Guide A: Environmental design;
- Guide B: Heating, ventilating, air conditioning, and refrigeration;
- Guide C: Reference data;
- Guide D: Transportation systems in buildings;
- Guide E: Fire safety engineering;

- Guide F: Energy efficiency in buildings;
- Guide G: Public health engineering;
- Guide H: Building control systems;
- Guide J: Weather, solar and illuminance data;
- Guide K: Electricity in buildings;
- Guide L: Sustainability;
- Guide M: Maintenance engineering and management.

Ventilation Design Recommendations

Ventilation in a building is achieved through (a) natural supply and exhaust of air, (b) natural supply and mechanical exhaust of air, (c) mechanical supply and natural exhaust of air, and (d) mechanical supply and exhaust of air. The building design should incorporate possible features that reduce heating and cooling loads. Wherever possible, passive heating or cooling strategies in buildings (sun control, shading devices, and thermal mass) may be employed. The buildings installed with HVAC systems must be of *Right Size*, that is, to avoid systems that have more capacity than currently required. The load allowances, safety factors, performance rating for space-heating/cooling, heat rejection, fans and other HVAC components, as stated in ANSI/ASHRAE/IES 90.1-2016 (I-P), may be considered as an upper limit (refer to Chap. 14). The systems that can operate at part load, such as variable speed drive and volume control fan systems, variable capacity boiler plants/chiller plants, cooling towers (e.g., multiple cell towers) and temperature reset controls, are the preferred selection. Low-cost fuel sources (such as natural gas vs. fuel oil; dual-fuel boilers) may be considered for heating and cooling systems. The CFD tools (DOE2, BLAST, Energy Plus) are effective to anticipate the load distribution, reduce uncertainty, eliminate excess oversizing, and minimize energy demand and cost overrun.

Measuring ventilation—Different methods have been applied (U.S.EPA 2003; Wang 2005; Bennett et al. 2011) for measuring ventilation pattern in buildings. The steady-state method includes the release of a perfluorocarbon tracer gas that creates a homogeneous distribution per occupied floor area of the building and measurement of its concentration. The bag samplers are placed at multiple locations within the building space for sampling of the trace gas, and samples are analysed in gas chromatography (GC-ECD). The effective steady outside airflow rate (Q_{wb}) is computed from the measured tracer gas concentration and the emission rates (Fisk et al. 1993), using the equation, as below:

$$Q_{wb} = \frac{N \cdot E_{avg}}{C_{avg}}$$

where N is the number of tracer gas sources, E_{avg} is the average emission rate of tracer gas per source, and C_{avg} is the average tracer gas concentration measured during the sampling period.

In the *tracer step-up* approach, a tracer (e.g., sulphur hexafluoride) is injected into the air handlers, in proportion to the outdoor airflow in the building. From the analysis of samples drawn from the bag samplers, and determining the rate of increase of the tracer concentration, one can arrive at the air exchange rate. This method is useful where there are only a limited number of air handlers, and all operate simultaneously (ASTM 2000). Due to difficulty in achieving well-mixed condition throughout the building space, the evaluation of the ventilation system in large office spaces has limited practicality. Moreover, there is a cost component for discharging a large volume of tracer gas.

Alternatively, in the step-down or *decay method*, instead of filling up the entire space, the tracer gas is injected into a small control volume or recirculating to a ventilation system (Chow et al. 2002; Cui et al. 2015). The localized age of air gets measured from the transient decay in the concentration of the tracer gas, and accordingly, the ventilation rate is determined. The tracer release can be made simultaneously from several positions or multiple air handlers to evaluate ventilation in vast space. The decay method may be useful in open-plan offices. Tracer gases are measured continuously using a device like Miran infrared gas analyser, and analysing the gases in GC-ECD. The following equation may be used to estimate the decay of tracer gas:

$$C(t) = C_\infty + (C_0 - C_\infty) \cdot e^{\frac{-Q_{wb}}{V}t}$$

where $C(t)$ is the tracer gas concentration at a given time (t, hour) after the start of decay (C_0), C_∞ is the background concentration of tracer (ppm), and Q_{wb}/V is the steady-state ventilation rate/hour. Accordingly, the Q_{wb} is calculated. The tracer decay method provides a better reflection of building ventilation when occupancy is maintained (Bennett et al. 2011).

The *equilibrium method* includes determining the steady-state concentration of CO_2, taking into account the number of occupants in the building (ASTM 2000). The difference in the indoor and outdoor concentration of CO_2 is proportional to ventilation rate per person. Similar to the steady-state tracer method, the Q_{wb} is calculated as:

$$Q_{wb} = \frac{N \cdot E_{CO_2}}{C_{CO_2\_avg}}$$

where N, the number of people; E_{CO_2}, the typical emission rate of CO_2 per person; and $C_{CO_2\_avg}$, the average CO_2 concentration measured during the sampling period. The equilibrium method works well when there is a stable occupancy in the building.

There are other approaches, such as directly measuring tracer gas at HVAC outdoor air intake, using single or multiple duct blasters (Fisk et al. 2005), and calculating the total supply flow rate. Such approach can be used in buildings where outdoor air is supplied mechanically through a rooftop intake. In case the capacity of duct blaster does not match to requirements, the alternative is to use balometer to measure the flow rate at each AHU in the building.

Simplest of all, the multi-directional air movement in a building space can be measured using a kata thermometer (dry silvered typeof different temperature ranges), heated thermometer or thermocouple anemometer. The kata thermometer and heated thermometer give the cooling power of the air, and the rate of air movement is calculated from the kata cooling time, kata factor, and the ambient temperature. The anemometer gives a direct reading of the air velocity. There have been attempts to determine the air velocity in around a human body in a room from the rate of convective heat transfer, using naphthalene sublimation (Nishi and Gagge 1971; Nag 1984). The computational fluid dynamics (CFD) methods are also applicable in profiling ventilation rate in a building space, as described elsewhere.

Fan-forced ventilation—In places where wind-induced natural ventilation does not meet the requirement, installing of fan-forced ventilation (ceiling or wall-mounted) is a conventional approach. The quantity of fans required in a room depends on the climatic conditions of the regions. The size of the ceiling fan may be chosen about the actual usable area of a room. The power consumption of large fans is high; however, the consumption per unit floor area is less. Therefore, proper installation of fans and its use is necessary, with respect to room dimensions. Draft Indian national building code (BIS, 2015) listed the optimum size and number of fans for different room dimensions. For example, room dimensions of 5 × 10 m and 10 × 10 m, the corresponding number of fans of 1400 mm, arrived at 2 and 4, respectively; for a room size of 14 × 14 m, the number arrived at 9 for the same size of fans. The minimum distance between fan blades and the ceiling should be maintained at about 0.3 m.

Infiltration and exfiltration of air—Infiltration of air from outside into the buildings can disrupt the air pressure relationships that HVAC systems create in indoor spaces. In comparison with diffusion of moisture, air pressure differentials can result in faster transport of water vapour through air leaks (Quirouette 1985; Anis 2016) and can condense within the enclosure. Air leaks can take different forms, such as orifice flow, diffuse flow, or channel flow. The orifice flow covers the entry and exit of air through cracks in the window frames. Diffuse flow is effected through poor quality enclosure materials (e.g., fibreboard) (Figure 12.6a). Channel flow takes place where air entry and exit points are distant from each other (Fig. 12.6b), thus making possible deposition of moisture in the enclosures (www.wbdg.org/resources/air-barrier-systems-buildings). There are obvious negative consequences if the HVAC installed buildings are not adequately taken care of air leaks. Problems of IAQ and health problems may arise due to infiltration of pollutants and moisture through the building enclosures. Tian et al. (2008), using a simulation model, emphasized that exposure to pollutants of outdoor origin depends substantially on the penetration of particles through the building envelope. The particle penetration through cracks with rough inner surfaces enhances deposition for the particles larger than 0.04 μm diameter, in comparison with ultrafine particles. The intervention against air infiltration and exfiltration of air is to create air barrier system. For example, walls can be air tightened using an elastomeric (flexible) coating and air barrier sheet products. Peel-and-stick membranes are commonly used at window and door perimeters.

Besides, wind-driven rain is an avenue for penetration of rainwater through the building facades, windows leaks, and other structural cracks, leading to moisture accumulation, efflorescence, and discolouration (Moonen et al. 2010). Through this process, the internally held salt in water or any other solvents can migrate through porous layers of the building and emit solvent by-products indoors.

Ventilation maintenance—Mechanical ventilation combined with natural ventilation is a complementary measure in the air purification strategy, such as control of contaminant emissions at source, ventilation of workspaces, maintenance of the ventilation system. Operation of the mechanical ventilation system without proper

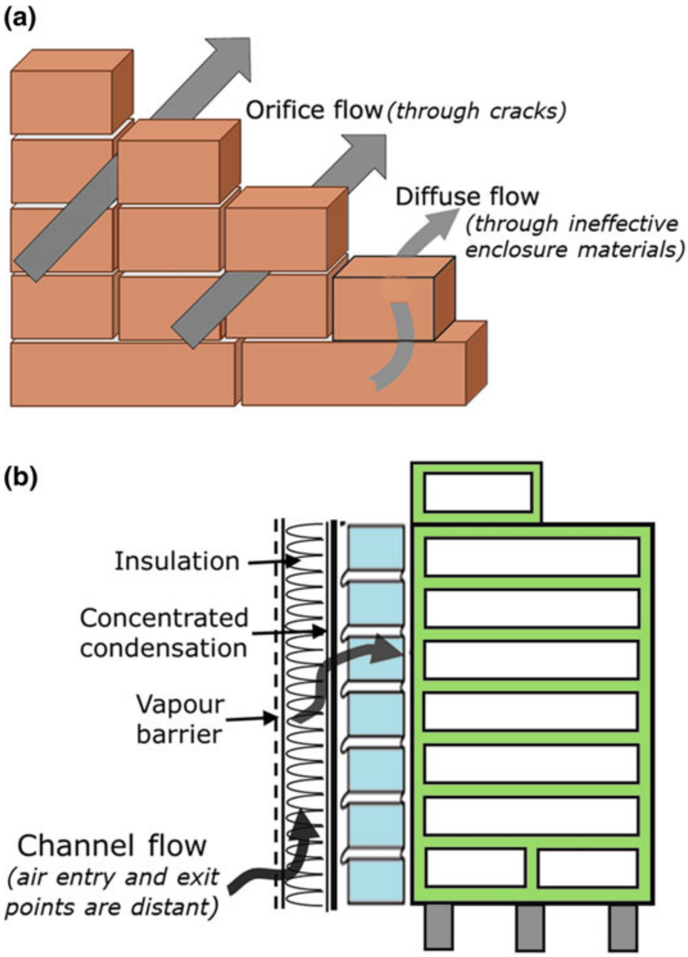

Fig. 12.6 Schematic air barriers and leaks through building enclosures; **a** orifice flow and diffuse flow; **b** channel flow

operational procedures, periodic maintenance, cleaning and efficient filtration, the ventilation system itself may become a potent source of pollution and health risks. In such cases, supplying the air indoor using natural means may be more beneficial, provided the outdoor air is not too polluted, or there are extreme climatic reasons, e.g., too low temperatures (in cold and moderate climates) or too high and humid outdoor air (in tropical and subtropical climates).

Performance of ventilation systems—The primary tasks of a ventilation system refer to exchanging room air, removal of heat and indoor contaminants, and protecting local occupants. The performance evaluation of ventilation systems is based on the usages of the indoor space, and airflow distribution (Lomas 2007). Related indices to air distribution, air change effectiveness, heat and pollutant removal are described herewith. Building exhaust, carrying particulates and other contaminants, and re-entering into the building result from inappropriately designed or improperly functioning HVAC system. Filter efficiency reflects the extent the HVAC system can remove particulates and contaminants from the outdoor and recirculating air. Minimum efficiency reporting value (MERV) is a measurement scale to rate the effectiveness of air filters in the range of 1 to 16, and a value of 4 or less would indicate relatively lower filter efficiency (ASHRAE 52.2:2007). Maintenance shops, photocopying areas, parking garages, kitchens, and toilets are the sources of pollution if these areas are not equipped with adequate local exhaust ventilation.

Air distribution system—Different systems of air distribution have relative utility on the ventilation performance and IEQ parameters (ANSI/ASHRAE 113-2013). The performance of air distribution system may be assessed from the effective draught created by the system. The effective draught temperature, E_{DT} (Kelvin) is a function of local air temperature (T_a) and air velocity (v, *m/s*), average (control) air temperature (T_{c}) recorded at equispaced points in an occupied zone or through a vertical, centre-line plane of the air supply outlet (ASHRAE 62.1-2010; ASHRAE 55-2007) , i.e.,

$$E_{DT} = (T_a - T_c) - 8(v - 0.15)$$

The number of points of E_{DT} that satisfies a specified comfort limit to the total number of points measured is expressed as the air diffusion performance index (ADPI). For assessing the effectiveness of an air distribution system, an *air distribution index* (ADI) has been proposed from the estimation of the effectiveness for heat removal (ε_t) and removal of contaminant (ε_c) (Karimipanah and Moshfegh 2007; Karimipanah and Awbi 2002), as below:

$$\varepsilon_t = \frac{T_{outlet} - T_{inlet}}{T_{avg} - T_{inlet}}$$

$$\varepsilon_c = \frac{C_{outlet} - C_{inlet}}{C_{avg} - C_{inlet}}$$

Corresponding air temperature (T, °C) and contaminant concentration (C, ppm) refer to the outlet, inlet, and the average levels, respectively, in the occupied zone at the height of 1.8 m. Here, the readers may refer to Chap. 11, describing the percentage of dissatisfied (PD) with the IAQ, and PPD concerning PMV of comfort in a thermal environment. The percentage values of heat removal (ε_t) and contaminant removal (ε_c) are further used to obtain thermal comfort (N_t) and air quality (N_c) numbers, as below:

$$N_t = \frac{\varepsilon_t}{PPD}$$

$$N_c = \frac{\varepsilon_c}{PD}$$

The square root of the resultant multiplication of these two numbers (N_t and N_c) is expressed as Air Distribution Index (ADI) that indicates the system effectiveness to arrive at thermal comfort and air quality.

Air exchange effectiveness—This is a measure of the effectiveness of ventilation systems in delivering the supply air in the ventilated space, expressed as:

$$\varepsilon_a = \frac{\tau_n}{2\tau_p}$$

where ε_a, the local air change effectiveness; τ_n, the nominal time constant for the room, which is the reciprocal of the ACH, e.g., the ratio of the hourly rate of ventilation to the room volume; τ_p, the local mean age of air. With reference to tracer gas concentration in a building space, as described earlier, Cao et al. (2014a, b) expressed τ_p as:

$$\tau_p = \frac{1}{C_0}\int_0^\infty C_p(t)\mathrm{d}t$$

where C_0 is the concentration of the tracer gas at the initial level, and $C_p(t)$ is the concentration at a point at time t. The ratio of τ_n to τ_p is referred to as the local air change index (ε_p).

Comparison of the Air Distribution Systems

Descriptions given above indicate that different indices can assess the effectiveness and efficiency of ventilation systems. Cao et al. (2014a, b) provided a review account of different indices, and the range values of the indices are given in Table 12.1 about different air distribution systems. The ventilation effectiveness depends on the task of the ventilation system, such as removal of contaminants, air exchange, heat removal, and occupant's protection. Since the task goal of ventilation may change with the circumstances, the selection of ventilation system bears importance. The designers should take cognizance of the fact that for MV (high supply, low exhaust) and PV, the ventilation effectiveness for removal of contamination decreases when the temperature difference decreases, whereas the effectiveness increases in case of high-supply and high-exhaust systems. The MV can achieve a ventilation effectiveness value of 1 (perfect mixing) when the supply air temperature is 2 °C higher than room temperature (heating conditions). The DV system can achieve ventilation effectiveness higher than 1 when the supply air temperature is lower than the room temperature (cooling conditions). The PV can save about a half of the energy consumption, as compared to MV in cold and hot climates (Schiavon et al. 2010). The use of filtration further improves its performance. The overall performance of the HV (CJV) system having high momentum jets (<12 m/s) has some positive aspects over the MV, DV, and HV (IJV) systems. With higher air exchange, CJV produces a sub-zone of clean air in the lower part of the occupied zone. However, in this system, heated air can be supplied, in contrast to a DV system which is used only for cooling. Karimipanah et al. (2008) indicated a very similar level of ADI for MV, DV, and HV (CJV) systems. For MV and POV systems, the supply air inlets may be located outside the occupied zone, and thereby, the draught problem is avoided.

The indoor contaminant sources can be active or passive. Active sources are those associated with heat sources, and the passive sources are from building materials. Novoselac and Srebric (2002) noted that the DV system might be more useful to remove active sources than the passive sources. There are risks of airborne cross-infection in case of vertical low-velocity ventilation (Olmedo et al. 2013). Generally, the combination of ventilation systems in a facility, such as MV with DV, or DV with PV, may be more effective than using only one method. Kaczmarczyk et al. (2004) observed that a PV system that provided fresh air directly to the breathing zone significantly reduced SBS symptoms, as compared to a traditional MV system with re-circulated air. Smedje et al. (2011) reported that the classrooms equipped with DV system had relatively less acute SBS symptoms to those with MV. Chapter 3 includes details of SBS about building characteristics and IAQ in office buildings.

Recommended Levels of Air Change

The general levels of ventilation in buildings are recommended based on maintenance required for optimal IEQ and thermal balance. The air change rate per hour (ACH), e.g., the hourly rate of ventilation divided by the volume of the space, varies with the type of workplace/built facilities. BIS-recommended ACH values (Table 12.2) may be suitable for different building facilities in a tropical climate.

Table 12.1 Range of values of ventilation indices in different ventilation systems

Ventilation system	Air exchange		Pollutant removal			Heat removal	Exposure to contaminant/protection efficiency		Airflow distribution
	ε_a	ACH	ε_a	VE	ε_a (%)	ε_t (%)	ε_p	ADPI	ADI
MV	0.42–0.53 (Novoselac and Srebric 2003)	4–6 (ASHRAE 62)	0.6–0.72 (circular supply and rectangular exhaust); 0.75–0.86 (rectangular supply and exhaust); 1.14–1.2 (circular supply and exhaust), (Krajcik et al. 2012)	0.8–1.0 (ASHRAE 62)	50 (Mundt 2004)	99 (Karimipanah et al. 2008)	1.0 (Cexp/CR), (Olmedo et al. 2012)	60–90% (ASHRAE 55: 2007)	15.5 (Karimipanah et al. 2008)
DV	0.55–0.92 (Novoselac and Srebric 2003)	4 (ASHRAE/ ASHE 170, 2008)	0.2–1.4 (2 < DT < 0) (Olesen 2012)	1.2 (ASHRAE 62)	60–70 (Nielsen 1993)	121 (Karimipanah et al. 2008)	12 (Cexp/CR), (Olmedo et al. 2012) (close distance of person, 0.35 m)		15.9 (Karimipanah et al.2008) 2008)
HV, LEV, PiV	1 (PiV) (Novoselac and Srebric 2003)	0.5–4 (HV) (IEA Annex 35)	2 (PiV) (ASHRAE 62)	1.24–1.44 (LEV) (Potter 1988)		123 (HV) (Karimipanah et al. 2008)			15.7–16.1 (HV) (Karimipanah et al. 2008)
PV			1.2–2.2 (ΔT= −6 °C); 1.3–2.3 (ΔT= −3 °C); 1.6–3.5 (ΔT= 0 °C); 1.2–1.6 (Faulkner et al. 1999)	1.3–1.9 (Faulkner et al. 1999)	65–90 (Qian et al. 2006)		8–35% (4 l/s); 50–75% (6 l/s); 80–95% (8 l/s) at 26 °C, (Bolashikov and Melikov 2011)		
SV	1.58–1.98 (Lin et al. 2011)			1.42–1.50 (25.5< design temp. <27 °C)		1.5. (Lin et al. 2011)		>80% (air velocity<0.8 m/s), (Lin et al. 2011)	
POV		3.4–6.0 (Cao et al. 2014a, b)					14–50% (Cao et al. 2014a, b)		

Source Cao et al. 2014a, b

Table 12.2 Recommended air change rate (ACH) in different building facilities

Application	ACH
Assembly rooms	4–8
Bakeries	20–30
Banks/building societies	4–8
Bathrooms	6–10
Boiler rooms	15–30
Canteens	8–12
Cellars	3–10
Cinemas and theatres	10–15
Compressor rooms	10–12
Conference rooms	8–12
Corridors	5–10
Underground vehicle parking	8, Min
Engine rooms/DG rooms	15–30
Entrance halls	3–5
Garages	6–8
Glass houses	25–60
Gymnasium	6, Min
Hospitals sterilizing	15–25
Hospital wards	6–8
Laboratories	6–15
Laundries	10–30
Lecture theatres	5–8
Libraries	3–5
Offices	6–10
Photo and X-ray dark room	10–15
Public house bars	12, Min
Recording studios	10–12
Restaurants	8–12
School rooms	5–7
Shops and supermarkets	8–15

ACH may be increased by 50%, where ETS load is high, or the room is below ground

Ventilation Design and Analysis Tools

The contemporary system designers and architects apply energy simulation approaches to evaluate natural and mechanical ventilation, including HVAC systems and components. For example, AIRPAK, FloVENT, and FLUENT use the principles of CFD in providing a calculation of airflow modelling, contaminant distribution, temperature and humidity distribution, and thermal comfort in and around buildings of all types and sizes. FloVENT is a fast and easy-to-use menu-driven software in the design and optimization of HVAC systems. FLUENT (2006) is used in modelling natural ventilation in buildings. It models airflow under specified conditions, and additional analysis may be required for overall annual energy analysis. STAR-CD is a CFD tool used in understanding heating and ventilation, smoke and pollutant dispersal and fire hazard analysis, and clean room design. The building models incorporate some features of natural ventilation, including calculations of air infiltration as a function of temperature difference, wind speed, and leakage. URBAWIND is modelled to determine the natural airflow rate in the buildings, about the effects of surrounding buildings and the local climatology. ENERGY 10 is an hour-by-hour simulation program of the design process for low-energy buildings.

DOE-2 is a relatively robust program used in predicting the energy use characteristics and cost for all types of buildings (Zhu et al. 2013). The building layout, construction, operating schedules and utility, conditioning systems (lighting, HVAC), weather data are taken as inputs for an hour-to-hour energy simulation. eQUEST is an interactive Windows implementation of the DOE-2 with added wizards and graphic displays for easy use. ENERGY PLUS (version 8.6.0, 2011) is an extensively used building energy simulation program designed for modelling buildings with HVAC, lighting, and other energy flows. Some notable features of ENERGY PLUS are:

(a) Integrated solution of thermal zone conditions and HVAC system;
(b) Heat balance-based solution of radiant and convective effects;
(c) Combined heat and mass transfer model to account for air movement between zones;
(d) Fenestration models including window blinds, glazings, and calculation of solar energy absorbed by window panes;
(e) Illuminance and glare calculations; and
(f) HVAC and lighting control strategies.

Whereas these building simulation packages have different levels of complexity, specificity, and input requirements, there is a great premise on the utility of the approach in whole building energy and ventilation analysis, with reference to airflow modelling, thermal comfort, and other related applications.

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Part V
Building Energy Systems—Standards and Codes

Chapter 13
Lighting Systems

Introduction

The primary purpose of selecting the lighting system is to make the task area illuminated as uniformly as possible. Sizeable spatial variation in illuminance around the task area may lead to visual discomfort. Three types of electric lighting system are shown in the illustration (Fig. 13.1). A general lighting system employs a regular array of luminaires to provide a uniform illuminance across the working plane. A localized lighting system uses luminaires located adjacent to the workstations to provide the task illuminance. A local lighting system employs a lighting scheme to give the ambient illuminance for the central area with additional luminaires, located at the workstations for necessary task illuminance. Local or localized task lighting schemes usually consume less energy than general lighting systems. Integration of daylight with ceiling mounted general lighting can achieve lower energy consumption.

Selecting Light Sources

Wherever there is an absence of options of daylighting, the requirement of interior lighting calls for the design of comprehensive lighting systems. Information on the surface reflectance, the brightness ratio of the interior walls, ceilings, floors décor, and furnishing are examined to make a prudent decision on the requirement of the type and quantity of lighting equipment in office buildings. Apart from the illumination level, the selection of light sources and luminaires depend on the choice for a lighting system, namely general lighting, directional lighting, and localized or local lighting.

Lamp and circuit selection are crucial to the overall requirement of energy efficient design. Lamps with the highest efficacy and circuits with the lowest losses

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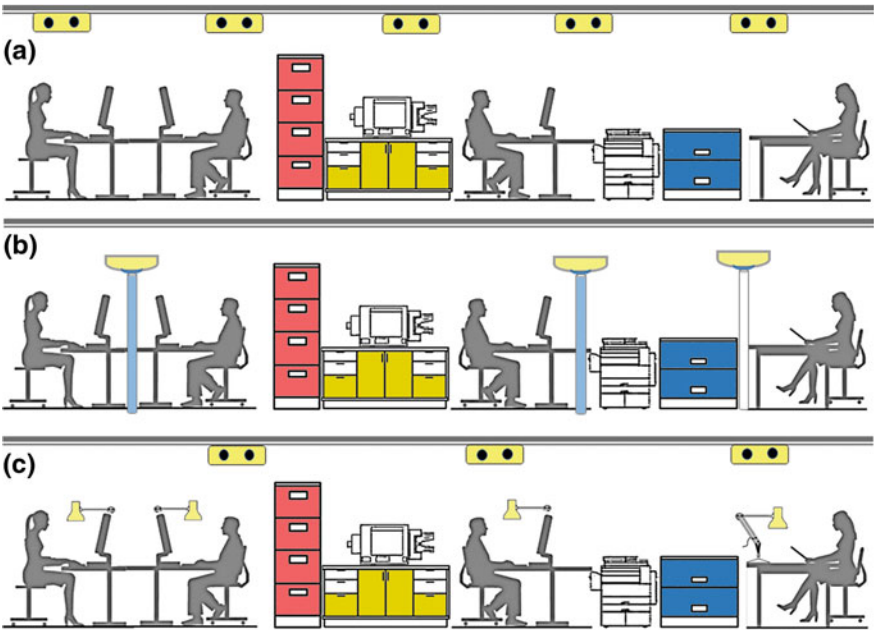

Fig. 13.1 Basic types of electric lighting systems for task illuminance—**a** general lighting system, with a regular array of luminaires, **b** localized lighting system, using luminaires located adjacent to the workstation, and **c** local lighting system, having general lighting scheme and luminaire located at the workstation

should be selected to minimize installed load and running costs. The minimum requirement of the primary efficacy of lighting over the whole building may be >40 lumens per circuit watt. The factors involved in lamp selection are:

- Luminous efficacy (lumen output/watts input)
- Consumption rating (watts)
- Mortality (rated life of the lamp)
- Lumen maintenance (lumen depreciation over life)
- Size (physical properties can affect the optical efficiency of light control)
- Switching or dimming control gears
- Colour appearance and rendering
- Starting, run-up, and restart times
- Minimum starting temperatures.

Artificial electric light sources have undergone transformation through stages, including incandescent lamps, fluorescent/high-intensity discharge (HID) lamps, and light-emitting diodes (LED). Different kinds of bulbs (Fig. 13.2) used in offices and other commercial establishments are described below. Luminous characteristics of different kinds of lamps are summarized in Table 13.1. The EC Regulation 244/2009, for example, sets requirements for lamps, such as incandescent lamps, halogen

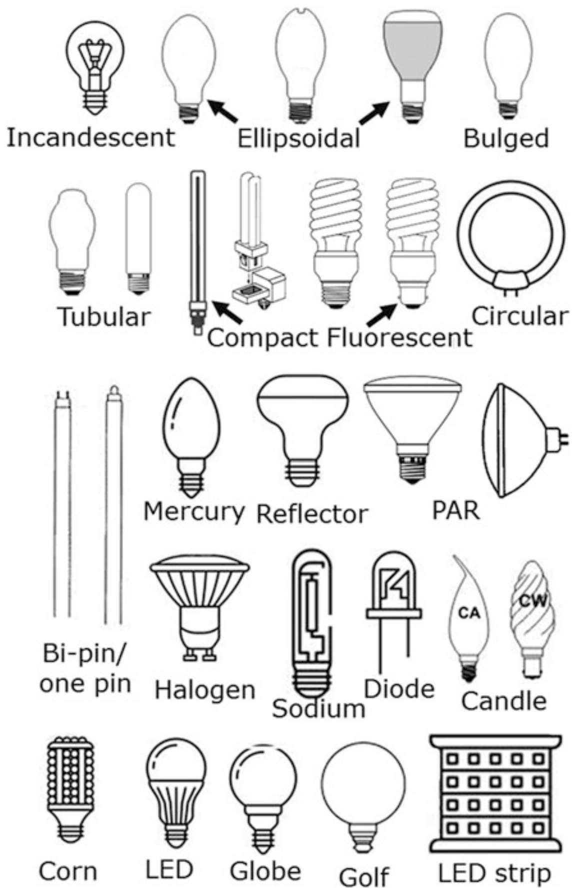

Fig. 13.2 Kinds of lamps used in offices and other commercial establishments. Lamps are identified by series designation, such as ellipsoidal (E or ED), bulbous or ellipsoidal tubular (BT/ET), globe (G), parabolic (PAR), reflector (R), tubular (T)

lamps, and CFLs with integrated ballast. The EC Regulation 245/2009 applies to lamps, ballasts, and luminaires that are used in the tertiary sector, i.e., fluorescent lamps without integrated ballast and HID lamps. All magnetic ballasts are being phased out since they are not able to reach the energy efficiency requirements.

Fluorescent and Compact Fluorescent Lamps

Fluorescent lamps—there is a range of tubular fluorescent lamps, which are differently used in the office interior. Depending on the spatial orientation, the tubular fluorescent lamps are used as surface-mounted and recessed furniture luminaires. Tubular fluorescent lamps have a high luminous efficacy, excellent colour rendering properties, long life, and are relatively low cost. Optimized fluorescent materials, better coating methods, and operation by electronic ballasts (EB) improve the

Table 13.1 Luminous characteristics of different kinds of lamps

Lamp		Type of lamp	Power consumption (Watts)	Luminous flux (lumens)	Luminous efficacy (lumens/Watts)	Light colour	Colour rendering index (R_a)	Base
CFL with integrated ballasts	a	Screw base	5–23	240–1,500	48–65	WW	≥ 90	E27
	b	Screw base	3–11	100–600	33–55			E14
	c	Bulb-shaped	5–15	200–900	40–60			E27
CFL without integrated ballasts	a	2, 4, and 6 tubes	5–42	250–3,200	50–76	WW, DW	80–90	G23, G24, 2G7, GX24
	b	4 tubes flat	18–36	1,100–2,800	61–78		80–90	2G10
	c	2 tubes flat	18–80*	1,200–6,000	67–88		80–90	2G
Fluorescent lamps	a	Three band Ø 26 mm	18–58	1,350–5,200	75–93**	WW, NW, DW	80–90	G13
	b	Three band Ø 16 mm (high luminous efficacy) (EB operation only)	14–35	1,350–3,650	96–104		80–90	G5
	c	Three band Ø 16 mm (high luminous flux) (EB operation only)	24–80	2,000–7,000	83–93		80–90	
	d	Three band Ø 7 mm	6–13	310–1,030	52–79		80–90	W4,3
HVHL with reflector	a	PAR reflector	40–100	–	–	WW	≥ 90	E14, E27
	b	Reflector	50–75	–	–	WW	≥ 90	GU10, GZ10
HVHL without reflector	a	With jacket	60–250	840–4,200	14–17	WW	≥ 90	E27
	b	Candle-shaped	25–60	250–840	10–14	WW	≥ 90	E14
	c	Base at both ends	60–500	840–9,500	14–19	WW	≥ 90	R7s

(continued)

Table 13.1 (continued)

Lamp		Type of lamp	Power consumption (Watts)	Luminous flux (lumens)	Luminous efficacy (lumens/Watts)	Light colour	Colour rendering index (R_a)	Base
		without jacket	25–250	250–4,200	10–17	WW	≥ 90	E15d
LVHL with reflector	a	Reflector lamps	20–65	–	–	WW	≥ 90	GU5,3
	b	Cool-beam reflector	10–35	–	–	WW	≥ 90	GU4
LVHL without reflector	a	Pin-base	5–150	60–3,200	12–21	WW	90	G4, GY6,35
HMHL with reflector	a		35–150	2,000–11,000	57–73	WW	<95	E27
HMHL without reflector	a	Plug-in base	70–1,000	5,000–80,000	68–80	WW, NW	80 < 90 = 90	E27, E40
	b	Screw base	35–150	3,000–12,000	77–80	WW, NW	80 < 90 = 90	PG12, G12
	c	Base at both ends	70–250	5,000–20,000	67–80	WW, NW	80 < 90 = 90	Rx7s, Fc2
HP mercury vapour lamps	a		50–1,000	1,800–58,000	36–58	WW, NW	40–69	E27, E40
Induction lamps	a	HPFL (bulb)	55–165	3,500–12,000	65–73	WW, NW	80–90	Special
	b	HPFL (bulb)	100–150	8,000–12,000	80	WW, NW	80–90	Special

Notes Compact Fluorescent Lamps (CFL); High voltage halogen lamps (HVHL); Low voltage halogen lamps (LVHL); Halogen metal halide lamps (HMHL); High-pressure (HP); High-performance fluorescent lamps (HPFL);
Warm white (WW), daylight white (DW), neutral white (NW);
*40 and 80 W with EB only; **With EB, luminous efficacy increases to 81–100 lm/W; power consumption decreases from 18 to 16 W, from 36 to 32 W, and 58 to 50 W.

luminous flux and life of the fluorescent lamps. Tubular fluorescent lamps are silent and flicker-free and can be dimmed and regulated for daylight-dependent lighting. Fluorescent lamps of 16 mm diameter are all EB-operated and are increasingly considered as an alternative to 26-mm-diameter tubular lamps. Fluorescent lamps of 38 mm diameter are specialized models for work premises, e.g., in low-temperature applications (exterior lighting, refrigerated warehouse). Lamps and *minis* of 7 mm diameter are used in surface-mounted and recessed furniture luminaires.

Compact fluorescent lamps (CFLs)—the CFL family includes models with and without EB integrated into the lamp. These were initially developed as energy efficient replacements for filament lamps with ratings up to $\sim$20 W. Lamps with integrated ballast are high energy efficient lamps, with a useful life of $\sim$8000 h, and available in standard E14 and E27 screw bases. In industrial lighting, short and compact lamps, without integrated ballasts (the ballast mounted in the luminaire), are alternative to tubular fluorescent lamps. The energy balance is better achieved in EB operates lamps rather than in magnetic ballasts. An efficient labelling scheme now covers ballasts for fluorescent and compact fluorescent lamps.

Halogen Lamps

High voltage halogen lamps (HVHL) *with reflector*—the HVHL with reflector is dimmable and about twice the life of an incandescent lamp (about 2,000 h). The tungsten halogen lamps have higher luminous efficacy throughout the operating life. Parabolic aluminized reflector (PAR) lamps are available with a screw base. The HVHL without reflector (clear or matt bulb) also has screw-based designs and can be fitted in place of conventional incandescent lamps. Double-ended HVHL (R7s base) are suitable for floodlighting. In these lamps, tungsten atoms evaporate from the filament and combine with halogen atoms; the gaseous compound then returns to the hot filament, re-deposits atoms, and releases halogens (often referred to as halogen cycle). Thus, no *blackening* of the lamp occurs and no reduction in the luminous flux.

Low voltage halogen lamps (LVHL)—the tiny light sources with brilliant light and dimmable. The LVHL, low-pressure designs, also work on the principle of the halogen cycle. The small dimension lamps can be used for spotlighting or wide-angle lighting. The LVHL encompasses models with metal or silvered glass reflectors for different beam spreads. The lower power consumption of LVHL is achieved by IRC (infrared reflective coating) technology.

Halogen Metal Halide Lamps

Halogen metal halide lamps (HMHL)—with the addition of metal halide compounds, the HMHL are characterized as high luminous efficacy and improved colour quality, and EB prolongs the life of the lamp. These are a further development of the high-pressure (HP) mercury vapour lamps. The lamps with a reflector have ratings up to 150 W (both E27 screw base and plug-in base) and beam spreads of 10°–75°. The *HMHL without reflector* are available with ellipsoid bulb, as tube-shaped models, and in double-ended designs. The high watt lamps are used in high industrial bays, sports facility and floodlighting, and the low-power HMHL with the transparent ceramic burner is used in commercial window displays.

Mercury and Sodium Discharge Lamps

High-pressure (HP) mercury vapour lamps are gradually being phased out, due to poor luminous efficacy and colour quality. High-pressure sodium (SON) and metal halide lamps (MBI) have much greater potencies and colour rendering than HP mercury lamps. The MBI lamps produce nearly white light and lumen output of $\sim$100 lm/W. The application of these lamps includes the indoor lighting of high rise buildings, parking space, and sports facility. The high-pressure SON lamps that produce $\sim$150 lm/W are increasingly used in industrial and commercial applications. However, metal halide and sodium lamps operated on standard control gear have significant run-up and restrike times, and thus, limiting its use with lighting control systems. EBs for lower ratings of MBI lamps have been introduced that provide faster warm-up periods, instant restrike, improved circuit efficacy, and extended lamp life. All discharge lamps require c*ontrol gear (ballast)* to start and control the lamp and, possibly, power factor correction.

Induction Lamps

Induction lamps are available in bulb-shaped and flat designs. These high-performance fluorescent lamps work on the principle of electromagnetic induction and gas discharge and therefore have high promise for interior and exterior lighting, e.g., in tunnels, industrial bays, or exterior lighting systems.

LEDs

LED modules consist of a row of semiconductor crystals or single LEDs housed on a conductor plate. What the light produces in a semiconductor crystal is electrically excited to emit light. It induces electroluminescence. These are available in different shapes and sizes. There are different mounting schemes in its construction, such as modules built with wired LEDs mounted through holes on the PCB, and those using surface-mounted devices or chip-on-board technology. The colour tone of LED light is based on the dominant wavelength (red, orange, yellow, green, and blue).

LEDs have lamp life greater than 50,000 h, and compatible with advanced digital controls. The luminous efficacy of white LEDs is in the range of 250 lm/W. Replacing fluorescent lamps, with the LED technology would markedly reduce power consumption. However, the LED light sources should be well shielded and diffused to avoid glare and optimize extra high light on the work surfaces. LED sources are supposedly flicker-free. However, some lamps may exhibit flicker depending on the driver technology used (Grather 2009).

Energy Conservation in Lighting

The energy consumed by the artificial electric lighting can be substantially optimized with the planning and selecting of lighting devices. Primarily, the clean lamps and luminaires are operated at low power and effectively contribute to energy saving. Incandescent bulbs, having a useful life of only ~1000 h are considerably phased out with the alternatives of more energy efficient lighting. For work area lighting in an office interior, care is needed to use a type of lamps that match CCT of the daylight. The light sources are chosen depending on the mounting height. Fluorescent bulbs and tubes are suitable in high usage areas such as task areas, immediate surroundings of workplaces, provided that the mounting height is less than 7 m. For the same lumen output, nearly half of the energy can be saved where CFL lamps are replaced with induction lamps or LED lamps. Halogen lamps are used in places of the infrequent and short period of use. High-pressure SON lamps having a very high luminous efficacy may be desirable in industrial installations, but are less preferred in office interiors due to its poor CCT and R_a. Solar photovoltaic systems enable direct conversion of sunlight into electricity and is a viable option for a street lighting system in large office complexes.

Lighting Controls

Traditionally, office lighting has been centrally controlled on-all-day schedule, for switching ON luminaires at the beginning of office hours, and switching OFF in the evening. With concerns on energy saving, the lighting controls are primarily intended to maximize the use of daylight and also to control the use of artificial lighting. Besides, controls need to be selected to ensure that perceived changes in lighting levels are not detrimental to safety, visual effectiveness, and comfort of the occupants. Several factors influence the lighting controls, including occupancy pattern, availability of daylight, type of electric lighting, sophistication of controls, and potential capital implications.

In office complexes, energy is wasted where a minimal number of switches control a large area of lighting and that too is in inconvenient locations. Creating more control zones of electric lighting (e.g., zoning of ~3 m depth from the perimeter of the building interior or at the boundary of the window) is an effective way to balance the lighting requirement of daylight and supplementary electric lighting. The methods of lighting control include localized manual switching, time control, reset control, occupancy control, and photoelectric switching and dimming, either operated separately or in combination. Local switching may be manual (rocker switches, push buttons, pull-cords), remote control (infrared, sonic or ultrasonic transmitters), and automatic (sensing presence of occupants), as appropriate. In office buildings, the distance from any switch to the furthest luminaire to control should be less than 8 m, or less than three times the height above the floor of the light fitting.

Localized manual control—localized switching is necessary where the electric lighting is only needed locally of ample space. Controlling such variations of lighting needs results in significant energy savings, as compared to only single switch lighting. The primary limitation is inappropriate labelling of switching arrangements; the multiple rows of luminaires parallel to window walls can be accordingly labelled to control them separately.

Time controls—for a zone of a building that operates for a fixed time each working day, a time-switch for the control of lighting is an obvious priority. However, any occupants, security, and other authorized personnel may be able to override or sequentially control zones, as and when required. The time controls and photoelectric controls are particularly useful in external lighting.

Reset controls (timed OFF, manual ON)—apart from time control systems to switch off lights at a time lapse, the occupants may also be provided with the option to override the locally reset switches (reset control). That may be useful in open-plan offices for localized control. In case of remote switching (e.g., by infrared transmitters), signals are transmitted to luminaires through mains wiring or a dedicated low voltage wiring bus connected to receivers of the luminaires.

Occupancy controls (presence detection)—occupancy detectors use infrared, acoustic, ultrasonic, or microwave sensors to detect movement or noise in the space. These sensors switch the lighting ON when occupancy is detected and OFF if the occupancy detection is failed. A time delay built into the system helps to avoid excessive switching. These controls can be applied to a wide range of lamp types, however, with an account of the run-up and restrike characteristics of the lamps. It is a good practice that the escape/exit or emergency routes are not covered under occupancy control switching.

Movement about a building—illumination in working areas, passages, corridors, stairways, lobbies, and entrances in a building have notable differences. These differences always carry safety risks, when one moves from one area to the other (e.g., passing through less illuminated entrances or stairways from outside the highly illuminated area). There might be a little need for lighting adaptation, or designs should allow entry of adequate natural lighting at the immediate entrance or raise the level of illumination by provisions of supplementary lighting. For a night-time application, the illumination of entrance halls, lobbies, and corridors are so designed that lighting reduces towards the exit and no bright light is in the line of sight of people leaving the building.

Photoelectric switching and dimming controls—office occupants can use the photoelectric switching or dimming control lighting at the individual level to adjust the illuminance according to the needs of tasks and one's individual preferences. There can also be photoelectric daylight linking of externally mounted photocells to the rows of luminaires closer to the windows and provide a coarse control for electric ON/OFF switching or dimming. Since photoelectric switching can cause abrupt changes in lighting and can put occupants to discomfort, such switches may better be suited for daylight areas and in the areas where the switching frequency is low. Switching OFF should occur when the total illuminance is about 3–4 times of the required task illuminance, and it may be ON when the daylight illuminance is about 2–3 times of the necessary task illuminance.

Generally, most standard tubular and compact fluorescent EB lamps and tungsten lamps above 13 W, with suitable control gear, can be dimmed. Dimming control system ensures that the total of daylight and electric lighting always reaches the design illumination. The sensors are designed to adjust the output of the electric light to top-up the sunlight as necessary. Due to this balancing of illumination, the energy saving potential of dimming control is likely to be higher than that of photoelectric switching. Doulos et al. (2008) examined the potential energy savings in daylight sensitive photosensor-based dimming system and 18 pairs of electrical dimming ballasts, using simulation by Daysim. By converting the dimming percentage into the consumed light power, results showed that the energy saving for different pairs of ballasts ranged from 67 to 76%. With the advance in wireless technology and placing of wireless sensors in the luminaire, and smartphone applications, building occupants at the individual level can adjust lighting levels via their smartphones while the lighting grid can be used as a pathway for climatic controls, and other uses (Philips 2014). Overall, controls (switching or dimming, time-based controls, occupancy sensors) are the useful ways to ensure lighting in an area and saving energy. Dimming control provides occupants with more delicate control of light output. Since individuals may have different preferences for illumination levels, providing with personal control over lighting allows them to select their preferred levels for the kind of task performed. From laboratory and field studies, researchers (Boyce et al. 2006a, b; Galasiu et al. 2007) observed that automated lighting controls are energy savings to the extent of 10–25%, in comparison to existing fixed system of timer dependent illumination in a work area. Personal dimming control is also associated with improved comfort and more sustained motivation among the office occupants.

Selection and Arrangement of Luminaires

The light source and luminaire selection are based on the recommended illuminance and quality of light for the office task. A luminaire comprises a casing, a reflector, a lamp and shielding (louvers, lens, or diffusers), and for discharge lamps with a control gear. The photometric efficiency of a luminaire is evaluated from the ratio of the total light output of the luminaire to that of the lamp under a reference condition. Different kinds of luminaires and fixtures have been designed to reflect light off walls, ceilings, and objects. In the typical office interior, semi-direct type of luminaries can enhance the work plane illumination and surrounding luminance. The extent of light reflected off a surface in an office interior, relative to the amount of light that falls on the surface ranges: ceiling (70–80%), walls, window blinds, office equipment (about 50%), and floors, furniture, and accessories (25–45%). It is to be ensured that the placement of light fixtures, the orientation of the workstation, and the objects placed close to the work plane do not cast shadows. For example, a person sitting with one's back to windows, and the light fixtures mounted directly overhead or to the rear, can cast shadows on the work plane.

Usually, luminaires are spaced a meter apart in either direction. For general lighting of an interior, the number of fixtures required is calculated as:

$$\text{No of fixtures} = \frac{\text{desired } E_v(\text{lux}) \times \text{room area (sq.m)}}{\text{MF} \times \text{utilization factor} \times \text{No. of lamps per fixture} \times \text{lumens per lamp} \times \text{absorption factor}}$$

The number of fixtures is subject to some variations depending on the type of interior, decorative fixtures and accessories, and aesthetic balance. The number of lamps is preferred to be more in the rear half of the room than in the vicinity of windows. The need for supplementary lighting is more critical for the innermost parts of the office building, where the daylight component on the working plane falls below 100 lx, and the surrounding luminance drops less than 19 cd/m^2. For corridors and staircases, direct type of luminaries with full spreads light distribution is preferred.

Emergency Lighting

Emergency lighting is the generic term for lighting installations used in commercial buildings as a precaution in the event of failure of the regular mains supply so that people can safely exit the premises (Fig. 13.3). Emergency lighting is also referred to as egress lighting, and therefore, the path of egress and the sensitive, security areas are illuminated by a backup power source. The building facility can also install commercially available battery-backed emergency lighting devices that switch on automatically when the facility faces a power outage. Standby lighting enables people to continue with routine office activities in the event of an abrupt power outage. Escape route lighting is meant for suitable visual conditions and direction of the exit route and to ensure that the locations of firefighting and safety equipment are readily found (e.g., corridors, stairs). The open area (or anti-panic area) lighting reduces the likelihood of panic and to enable occupants to move towards escape routes safely. High-risk task area lighting ensures the safety of people positioned at a hazardous process or dangerous machinery and to allow the concerned to shut down the procedures, and escape to safety appropriately.

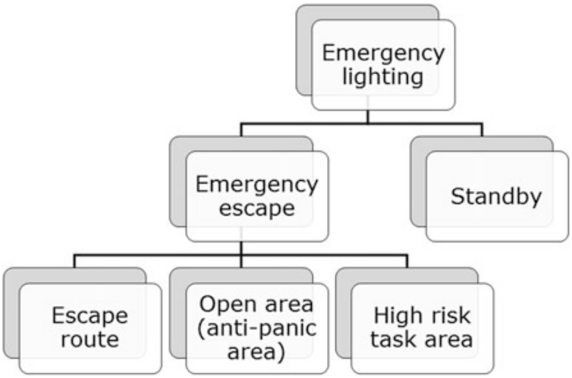

Fig. 13.3 Nature of emergency lighting situations

Some utility areas of emergency lightings (Fig. 13.4a, b) are:

- Illuminating near stairs or any other change of level, to avoid tripping hazards. The luminaires must be located to provide direct light to each tread of stairs. At least two luminaires are needed to provide the 1 lx minimum level on the centre of each tread.
- Providing indicator signs near changes of direction and intersections of corridors for occupants to escape following the route. Appropriate signs and symbols should be located about 2–2.5 m above the floor.
- Positioning luminaires near firefighting equipment and call points (such as extinguishers, hose reels, fire alarm control, fire call points, instructions) for maximum illumination (ICEL 1006: Emergency Lighting Design Guide 2013).
- Illuminating exit and other safety signs, for example, the exit direction, first aid signs, other safety signs of hazardous substances.
- Placing emergency luminaires outside and near to exits for the safety of occupants, away from the influence of the building.

Lighting Standards and Codes

Apart from the human behavioural requirements for visual performance, comfort, and safety, energy saving is perhaps a strong driving motive in formulating lighting and energy-related standards and codes. Many professional agencies and standards organizations, including lighting manufacturers, lighting engineers, building architects, and employers, have interests in influencing lighting system recommendations and establishing illuminance levels, which have implications on optimization of energy use. The Commission Internationale de l'Eclairage (CIE) is the major international body that coordinates the management of standards and recommendations in the related domain. The CIE recommendations of indoor lighting have been adopted by many countries as national standards, with particular

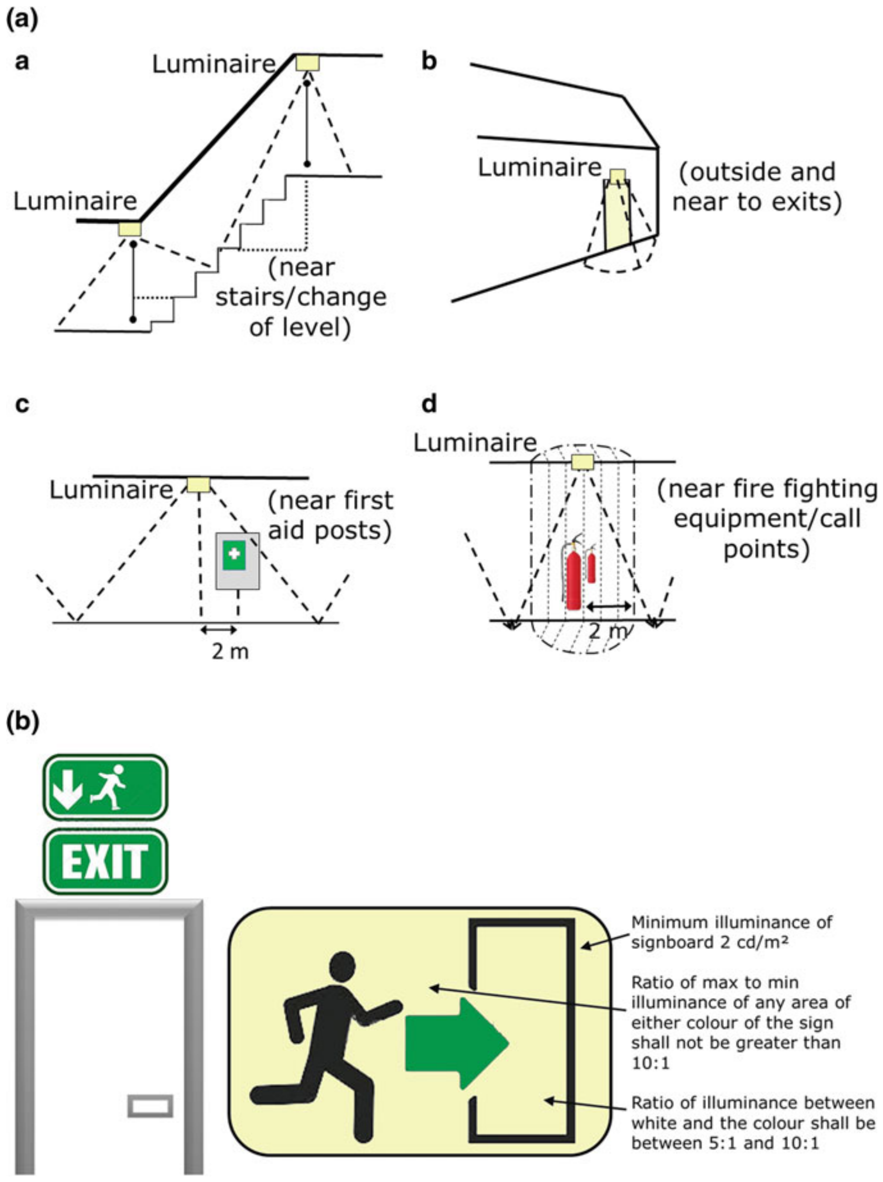

Fig. 13.4 **a** Emergency pathways and display lighting. **b** Exit sign guidance

country-specific interpretation and suitability. Besides, the best known the IES Lighting Handbooks are periodically updated by the Illuminating Engineering Society of North America (IESNA). The lighting professionals would find a multitude of standards that address concerns associated with the design and installation of lighting systems, energy requirements to task situations, allocation of illumination in building types and locations, as well as the efficiency, durability, cost, and maintainability. In all probability, the future anticipates a more sophisticated integration of energy and non-energy considerations in lighting system design.

Categories of Standards

Some of the CIE, ISO, EN, ANSI, IESNA, and country-specific standards and codes related to lighting in buildings are broadly categorized into seven groups and tabulated herewith (Table 13.2). The readers may refer to the most updated standards, which are continually evolving internationally and also as the national lighting codes.

- Lighting Energy Standards (LES) fall under the broad category of energy performance of buildings. These standards describe methods and calculations in the evaluation of building energy performance and efficacy of types of luminaires, aiming at the optimization of energy consumption. The principles for the inspection and testing of lighting practices are included.
- Lighting Design Standards (LDS) integrate illumination requirements into the design principles of luminaires and lamp technologies towards optimizing workplace lighting practices.
- Indoor Lighting Standards (ILS) provide guidance and recommendations on lighting requirements for indoor situations and workplaces. Recommendations include visual comfort and performance in conjunction with artificial and daylighting to specific office settings and VDT operations.
- Workplace-Specific Lighting Standards (WSLS) intend to maximize lighting effectiveness of specific workplace settings, e.g., office lighting, hospital lighting.
- Emergency Lighting Standards (ELS) define suitable illumination requirements to enable people safe and timely evacuation from buildings during emergencies. Guidance on luminaires, exit signs, and egress routes are outlined.
- Outdoor Lighting Standards (OLS) elucidate the implementation of photo controls to manage outdoor lighting fixtures.
- Lighting Standards for Industries (LSI) indicate guidelines for general lighting fixtures, emergency lighting, as well as specific requirements in an industrial setting. Optimizing illumination in the industrial workplace for machinery and other operations, and background working environment is essential to address safety, comfort and productivity concerns in the workplace.

Table 13.2 National and international standards related to lighting in buildings

Category of standards	Standard	Brief details
ELS	AS/NZS 2293.1:1998	Guidance on emergency evacuation lighting for the safe exit of the building's occupants at emergencies
ELS	AS/NZS 2293.2:1995	Standards on emergency evacuation lighting that applies to inspection and maintenance of central and single-point emergency lighting systems, as defined in AS/NZS 2293.1
ELS	AS/NZS 2293.3:1995	Standards on emergency luminaires and exit signs to ensure effective functioning under expected operational and environmental conditions
ELS	CIE S 004/E-2001	Guidance on colours of signal lights used in transport systems (ships, aircraft, motor vehicles, and trains); warning lights on instrument and control panels of industrial processes
ELS	EN 1838-2013	Requirements for emergency escape lighting and standby lighting systems
ELS	EN 50172-2004	Specifies illumination of escape routes, based on the size, type, and usage in workplaces, public premises, and multi-storey dwellings
ELS	IEC 60598-2-22:2014	Requirements for emergency luminaires for use with electrical lamps on emergency power supplies, not exceeding 1000 V
ELS	ISO 30061-2007(E)/CIE S 020/E-2007	Requirements for emergency lighting systems
ELS	BS 5266-1:2016	The code of practice applies to emergency lighting for different categories of premises
ELS	BS 5266-2:1998	Planning, design, installation, and servicing of low-mounted way guidance systems for use within emergency lighting systems
ELS	BS 5266-4:1999	The code of practice for design, installation, and use of optical fibre systems, including escape route lighting, standby lighting

(continued)

Table 13.2 (continued)

Category of standards	Standard	Brief details
ELS	BS 5266-5:1999	Constructional and performance requirements of parts of optical fibre systems
ELS	BS 5266-6:1999	Code of practice for photoluminescent systems; covers emergency lighting, escape lighting, standby lighting, luminaires, fire-escape routes
ILS	AS 1680.2.0-1990	Recommendations for specific tasks and interior lighting
ILS	AS/NZS 1680.0:2009	Visual requirements of publicly accessible areas of buildings to facilitate the safe movement of people
ILS	AS/NZS 1680.1:2006	Principles and recommendations of artificial and daylighting of essential task details of interior workplaces
ILS	AS/NZS 1680.2.1:2008	Lighting recommendation of circulation and other spaces in buildings of various types
ILS	AS/NZS 1680.2.2:2008	Interior lighting recommendations for office and screen-based tasks
ILS	AS/NZS 1680.2.3:2008	Interior lighting recommendations for educational and training facilities to create good seeing conditions and colour treatment
ILS	China: GB 50034-2004	Lighting design of buildings
ILS	CIE 097:2005	Guidance on parameters and procedures of maintenance of indoor electric lighting systems
ILS	CIE S 008/E: 2001/ISO 8995-1:2002	Guidance for illuminance, glare limitation and colour quality of indoor workplaces and task types
ILS	EN 12464-1: 2002/2011	The standard supersedes EN 12464-1:2002; daylight and artificial lighting requirements for all usual visual tasks, including display screen equipment
ILS	IES/NALMCO RP-36-15	Recommendation on the maintenance program, covering typical lighting system behaviour, light loss factors, and approaches to optimize lighting system performance; typical maintenance techniques, equipment, and

(continued)

Table 13.2 (continued)

Category of standards	Standard	Brief details
		operations; disposal of spent components; troubleshooting system problems
ILS	India: IS 3646 (Part 1):1992	General guidance on illumination requirements for working interiors; other sections covered under the standard are (a) method of calculation of the glare indices for interiors, (b) lighting recommendations for industries, offices, hospitals, libraries, educational institutions, and emergency lighting
ILS	India: National Building Code (NBC 2005), Part 8, Sect. 1, Lighting and Ventilation	The code serves as a model for adoption by governmental and other construction agencies, and suitably modification of provisions in accordance with the local requirements; the code covers minimum illuminance (recommended values) required for different areas and cross reference to the accessibility standards; includes requirements for visual contrast, brightness pattern, and lighting for movement about a building
ILS	Japan: JIES-008: 1999	Indoor lighting standard
ILS	Russia: SNiP 23-05-95	Construction standards and rules of Russian Federation, on daylight and artificial lighting requirements in buildings
ILS	South Africa: SANS 10114-1:2005	Code of practice for interior lighting in buildings
ILS	BS 8206-2:2008	A revised code of practice for daylighting in buildings (reference to EN 12464-1 and EN 15193)
ILS	ANSI/IESNA RP-1-12	Office lighting requirements, such as computer-based tasks, new office layouts, the energy efficiency of lighting design, new light sources, and control strategies
LDS	CIE 184:2009	Recommends adoption of ID50 and ID65 indoor daylight illuminants, corresponding to the phases of daylight of about 5000 and 6500 K

(continued)

Table 13.2 (continued)

Category of standards	Standard	Brief details
LDS	CIE 161:2004	Lighting design guidance for obstructed interiors (includes information on the magnitude of light losses in different building interiors and ways to ameliorate the effects of losses)
LDS	EN 40-3-1:2013	Applies to the design of lighting columns of nominal height (<20 m), materials of construction, and performance requirements for horizontal loads due to wind
LDS	EN 40-3-2:2013	Applies to verify the design of steel, aluminium, concrete, and fibre reinforced polymer composite lighting columns by testing
LDS	EN 40-3-3:2013	The standard on design and verification of lighting columns includes performance requirements for horizontal loads due to wind; compares the effects of factored loads against the relative resistance of the structure
LDS	IES DG-10-12	Comprehensive design guide on general and accent lighting luminaires, including high- and low-pressure discharge lamp sources
LDS	IES DG-18-08	A guide to designing quality lighting for people and building covers elucidation of principles of quality lighting, visual performance, energy and economics, and aesthetics for interior and exterior lighting
LDS	IESNA G-1-03	The guideline covers basic security principles, illuminance requirements of different types of building space, a protocol for evaluating lighting levels for security applications
LDS	ISO 11664-2: 2008(E)/CIE S 014-2/E: 2006	Describes the application of CIE standard illuminants, such as CIE standard illuminant A applies to domestic, tungsten-filament lighting, and D65 represents average daylight

(continued)

Table 13.2 (continued)

Category of standards	Standard	Brief details
LES	AS 4934.2:2011	The standard deals with minimum energy performance requirements for tungsten-filament lamps and tungsten halogen lamps used in general lighting services
LES	AS/NZS 4847.1:2010	The standard describes test methods of self-ballasted lamps (CFLs and other gas-discharge lamps) for controlling starting and stable operation
LES	AS/NZS 4783.1:2001 (Rev. 2013)	The standard covers performance evaluation of ballasts lamp circuits
LES	AS/NZS 4783.2:2002 (Rev. 2013)	The standard covers the evaluation of performance requirements for ballasts for linear fluorescent lamps —230 to 250 V ac at 50 Hz supply
LES	EN 15193:2007	The standard describes the methodology to evaluate the amount of energy used in lighting for different building typologies, such as offices, hospitals, manufacturing units; provides Lighting Energy Numeric Indicator (LENI) for lighting energy requirements used for certification purposes
LES	EN 15251:2007	Specifies how to establish the IEQ parameters, such as IAQ, thermal environment, lighting, and acoustics, which impact on the energy performance and building system design
LES	ANSI/IES/ASHRAE 90.1-2016 (I-P)	The revised standard provides the minimum energy efficiency requirements for design and construction of new buildings, addition/alteration of portions of buildings, and new systems and equipment in existing buildings, as well as performance evaluation criteria and compliance guidelines
LSI	AS/NZS 1680.2.4:1997	Recommendation of visual environments to safely and efficiently performing industrial tasks and processes
LSI	NEMA LE 6-2014	Describes the procedure to determine target efficacy ratings for commercial, industrial, and

(continued)

Table 13.2 (continued)

Category of standards	Standard	Brief details
		residential luminaires; describes categories of product used in typical indoor and outdoor lighting applications; updated to include LED technology
LSI	USA: NECA/ANSI 409-2015	The standard for installation and maintenance practices for dry-type, two-winding transformers used in supplying power, heating, and lighting loads for indoor and outdoor applications
LSI	USA: NECA/IESNA 502-2006	The standard for installing lighting systems in industrial and storage buildings
LSI	USA: NECA/IESNA 501-2006	The standard for installing lighting systems for exterior applications near commercial, institutional, industrial, and storage buildings
OLS	AS/NZS 1680.5:2012	Guidelines include general principles and recommendations for the permanent lighting of exterior workplaces
OLS	AS/NZS 4282-1997	The standard recommends limits for the related lighting parameters to contain obtrusive effects within tolerable levels
OLS	EN 12464-2:2014	Lighting requirements for outdoor workplaces to meet the needs for visual comfort and performance
OLS	IES TM-15-11	Luminaire classification system provides information for evaluation of lighting performance for the free zones of interest, concerning luminaire optics, luminaire locations, lumen distribution, lighting quality, and safety and security requirements
OLS	ISO 8995-3:2006(E)/CIE S 016/E: 2005	Lighting requirements according to the visual needs for safety and security in outdoor workplaces
WSLS	ASAE EP344.4:2014	Lighting installations for agricultural facilities, task areas, and also the physiological or biological properties of livestock, birds, fish, and plants
WSLS	IES RP-6-15	Design recommendations of sports lighting systems cover baseball, tennis, basketball, and football

(continued)

Table 13.2 (continued)

Category of standards	Standard	Brief details
WSLS	IES LEM-3-13	IES Guidelines to building owners and facility engineers for any likely upgrade of lighting systems in commercial and institutional spaces
WSLS	SAE ARP 1161A-2004	A guide to design, use, or procurement of crew station lighting systems for commercial and non-military aircraft or aerospace vehicles
WSLS	ANSI/IESNA RP-29-06	Guidelines for lighting in hospitals and healthcare facilities, for patients to have a conducive recovery environment
WSLS	ANSI/IESNA RP-3-13	Lighting requirements at all levels of educational facilities, from preschool to continuing professional development
WSLS	ANSI/IES-RP-28-16	2007 edition of the standard includes recommended visual environment for housing and senior care facilities; 2016 edition covers additional areas, such as offices, hospitality, healthcare, commercial, and places of assembly
	CIE/IEC 62471:2006/CIE S 009:2002	Guidelines specify exposure limits, measurement technique, a classification scheme for evaluation and control of photobiological hazards from electrically powered broadband sources of optical radiation, including LEDs but excluding lasers

Note American Society of Agricultural Engineers (ASAE), Australia (AS); Australia/New Zealand (AS/NZS); Commission Internationale de l'Eclairage (CIE); European Union (EN); Illuminating Engineering Society (IES) of North America (IESNA); International Electrotechnical Commission (IEC); International Standards Organization (ISO), National Electrical Manufacturers Association (NEMA, USA), United Kingdom (BS); USA (ANSI), SAE international (SAE, USA)

Energy and Lighting Software

The planned use of natural light and supplementary artificial lighting in office and non-residential buildings has become an ongoing strategy to minimize lighting, HVAC loads and improve energy efficiency. Detailed field measurement of illuminance level is an empirical requirement to ascertain the extent of the indoor daylight availability in buildings, and overall energy load in the buildings. The early approaches of predicting lighting requirements and performance involve using calculation methods, such as the lumen method, graphics methods (e.g., Waldram diagrams, BRE protractors), and also using physical models under a natural or artificial sky (e.g., Baker et al. 1993). Since the mid-1980s, with the growing of architecture and advances in computational technology in lighting design, several approaches, such as calculation using empirical formulae, numerical derivation algorithms, and software simulation have been emphasized in predicting daylighting and electrical lighting performance or energy simulation in buildings. The architects and designers use lighting software packages to predict the quantity and distribution of daylight or artificial light in an unbuilt design and visualize the human occupied/unoccupied interior spaces. The current software packages are robust in their ability in quantitative prediction of lighting characteristics in a building environment, under varying sky conditions. Early efforts in software packages (e.g., Leso-DIAL) have been on the user-friendly digital translation of the calculation methods, to analytically compute azimuth or altitude angles, sky components, reflectance values, and estimate internally reflected components (IRC) (Paule et al. 1998). Leso-DIAL extends to calculate indices like daylight factor (DF), daylight autonomy (DA) values and optimize the daylighting performance. Both photometry and geometry can be described through graphics and linguistic input. However, the utility of the output often remains limited, since the programming algorithm could not identify many unknown factors of lighting requirements in indoor situations. Subsequent approaches in algorithms, referred to as simulation models, extended to simulating interactions of light and objects, mimicking light being reflected and transmitted, and developing imagery of shadows and highlights.

A review by Ochoa et al. (2012) explored the state-of-the-art lighting simulation tools applied in building science research. This contribution compiles a selected number of lighting design and analysis simulation software (Table 13.3) which have been developed by various lighting agencies. Building energy simulation modelling programs, such as DOE-2, EnergyPlus, DeST (Yan et al. 2008) have been in extensive use to analyse the energy efficiency of building envelopes and HVAC systems, thermal performance of buildings, and depict compliance of building energy codes (Zhu et al. 2013). EnergyPlus (2016) is a next-generation model, based on the load algorithms of BLAST (1991) and the system algorithms of DOE-2, and the model has added features for low-energy building designs and operational controls. However, the informed decision is required in testing and selecting a particular building energy modelling program, concerning the nationally adopted building energy codes and standards (ANSI/ASHRAE 140-2007).

Many of these applications have utility to calculate lighting levels, taking into account daylighting, electric lighting from lamp/luminaire data files, and surface properties of the built environment. For natural daylight, sky models predict the distribution and intensity of direct and diffuse sunlight, based on temporal, geographic and weather data. Besides, the architectural environment can be modelled using the software editor and CAD files of room features. Details of the luminaire and luminous intensity distributions (photometric data) available from the lamp/luminaire manufacturers can be integrated into the software packages. Importable

Table 13.3 Energy and lighting simulation software

Software	Mainly used for	Brief details	Remarks
Radiance (2011, V 4.1) Lawrence Berkeley Laboratory www.radsite.lbl.gov	A comprehensive lighting analysis tool uses a hybrid approach of Monte Carlo (stochastic) and deterministic ray tracing techniques. The tool simulates the direct, specular and diffuse indirect illumination components (Larson and Shakspeare 1998). Radiance uses backward ray tracing technique for the evaluation of visual comfort and light quality from the modelled built environment	Inputs: DXF, IES photometric files, material/object/model libraries available; user options to define shapes and material behaviour, add luminance patterns and sky luminance distributions Outputs: tabulated digital outputs, a mapping of illuminance and luminance values onto a view of the space in contours, and colour-rendered perspectives	Radiance comprises of about 50 constituent programs, including lighting simulation suites, AutoCAD interface (Desktop Radiance). The user-friendly package includes editors for user-defined materials, glazing, furniture, and luminaires
DOE-2.1E	DOE-2, developed at the Lawrence Berkeley National Laboratory, is widely used in the U.S. It has a stand-alone calculation engine and with GUI, such as VisualDOE (2004), EnergyPro (ver. 7.2.2, 2018), eQuest (ver. 3.65, 2016), and EnergyGauge (ver. 6.0.00, 2017)	A building energy consumption simulation program simulates building design features, energy conservation measures and integrates daylight calculation (Li et al. 2005)	On a study in four US cities (hot-dry, hot-humid, cold, and temperate climate), Aldawoud (2013) applied DOE-2 to determine the optimum atrium design in buildings regarding energy consumption. Yang and Nam (2010) evaluated the energy and economic performance of lighting controls in an office building in Seoul. Simulation software 3D Max 8.0 Radiosity was used to calculate the percentage of lights being turned OFF to achieve illuminance (400 and 500 lx) on the working plane for 36 days (10 days interval on each month). The results treated in DOE-2.1 showed annual lighting energy saving of 33, 31 and ∼28% for glazing ratio of 100, 80 and 60%, respectively

(continued)

Table 13.3 (continued)

Software	Mainly used for	Brief details	Remarks
SuperLite Lawrence Berkeley National Laboratory	The updated version, SuperLite IEA 1.0 is a combination of radiosity-based algorithm for reflected sky components with Monte Carlo techniques for the direct components. The program allows multi-zone modelling with radiative transfer, shading/obstruction simulation, and also modelling of internal windows	Inputs: input model is created through ADELINE: The input of sky condition is taken as uniformly overcast, CIE standard overcast, and clear sky (with or without sun): A graphic display allows checking of the inputs and outputs; Outputs: generates tabular data of illumination levels, with options for 3D data plot; outputs to Radiance for creating a rendered image	SuperLite modelling and visualization capabilities are useful in early design stages. Designers can evaluate parameter comparisons of design approaches, aperture designs, reflectance, and glazing transmissions
Superlink	The program calculates hourly energy consumption and an internal load of artificial lighting, according to room properties	The program provides input for thermal analysis software such as DOE2, TRNSYS, and BLAST	Bodart and Herde (2002) used simulated models of facade configurations in Belgium. Results indicated the lighting energy saving due to daylight in the range of 50–80% for a designed illuminance of 500 lx, depending on parameters, such as building orientation, room size, glazing transmittance, and wall reflectance
ADELINE 2.0 (Advanced Day and Electric Light New Environment); http://radsite.lbl.gov/adeline/home.htm	An integrated software, ADELINE 2.0 links to SuperLite IEA, Radiance and SuperLink to predict lighting parameters, thermal and energy performance of a building (Erhorn et al. 1997)	The database contains the material data of about 250 different opaque and transparent materials; CAD program SCRIBE-MODELLER defines surfaces, colour, reflectivity, roughness and the like: The simulation produces illuminance levels, daylight factors, comfort levels and photo-realistic images, and building thermal simulation	ADELINE generates data for annual predictions, such as (a) hourly illuminance distribution on the reference plane under standardized sky models (cloudy or clear skies); (b) hourly energy consumption of general lighting needed for the rated illuminance; and (c) daylighting hours, and switch-ON time of electric lighting

(continued)

Table 13.3 (continued)

Software	Mainly used for	Brief details	Remarks
EnergyPlus	Builds on the strength of BLAST and DOE-2 programs, EnergyPlus (ver. 8.6.0,) is a whole building energy simulation tool Overall, the model calculates energy; consumption for space heating, cooling, ventilation, lighting, process loads and water use in buildings (Li and Wong 2007)	EnergyPlus takes input files from other simulation tools, such as Daysim; Generates hourly schedules of lighting related settings; annual lighting energy consumption assessment includes variables such as a window to wall ratio, the light transmittance of the window and projections	A console-based program assesses thermal zone loads and HVAC system response, heat balance of radiant and convective heat effects, and also illuminance, glare, and visual comfort; Heat and mass transfer model account for air movement between zones. Fenestration model takes into account solar energy absorbed by window panes, heat balance through window blinds and electrochromic glazings; The program incorporates built-in control strategies, dimming controls, and ON/OFF controls concerning the daylight conditions (Chen et al. 2015)
Daysim Advanced Daylight Simulation Software; www.daysim.ning.com	An adapted version of Radiance to simulate lighting energy consumption by modelling a photosensor control system, matching to real space (Reinhart 2006)	Used for energy saving prediction, concerning building features, such as the shading device configuration, treatment of blinds, directional sensitivity, control zones, and daylight aperture geometries	
AGi32 (Jan 2012, V2.3) Lighting Analysts www.agi32.com	Architectural lighting analysis tool provides comprehensive lighting calculations, including rendering for interior and exterior environments and daylighting. AGi32 uses radiosity simulation engine	Outputs: E (lux)—horizontal, vertical, lighting power density (W/m^2), UGR, Luminance (cd/m^2) in rendered pseudo-colour, STV, DF and other related factors	A comprehensive program predicts lighting system performance for multiple applications, from one luminaire to hundreds of luminaires in a facility; Point-by-point lighting, photometrically correct colour-rendered visualizations

(continued)

Table 13.3 (continued)

Software	Mainly used for	Brief details	Remarks
Licaso lighting analysts https://lightinganalysts.com/licaso/	Ultra-fast climate-based annual daylight simulations in AGi32; processing of Licaso expresses its simulation in minutes; Algorithms allow modelling of buildings with several windows and thousands of calculation points, with about 2′ × 2′ spacing	Statistically analyses daylight metrics: daylight autonomy (DA), spatial daylight autonomy (sDA), *Continuous Daylight Autonomy* (DA_{CON}), useful daylight illuminance (UDI), and annual sunlight exposure	Lighting designers and architects use Licaso for daylight modelling. Licaso has in-built rendered and graphical tools
LightScape Lightscape Technologies, Inc., San Jose, California http://www.lightscape.com	LightScape primarily uses radiosity; it has an additional ray-tracing step to add specular effects; The input model looks for identification and correct orientation of surfaces; the system library includes a variety of generic objects, lighting fixtures, and furniture elements	The input model is a DXF or a 3D Studio file; Colour and reflectivity of surface materials and glazing, sky condition, and required parameters are assigned with a menu-driven slider bar; Outputs: the software produces a grid of illuminance and luminance values for a defined surface, and provides rendered images of daylighted and electrically lighted spaces	LightScape has been incorporated in Autodesk VIZ 4
Elum Tools (July 2012, V 2013 R1) Lighting Analysts http://www.elumtools.com	Elum Tools, an interactive radiosity-based add-in for Autodesk Revit, designed to estimate illuminance on work plane or surface, utilizing families of the lighting fixture and surface geometry	Inputs: IES photometric files Outputs: Lux, point-by-point luminance, pseudo-colour, mesh overlay of radiosity	An easy to use tool to aid designers in the calculation process about the interaction of light and surface
Optis www.optis-world.com	OPTIS, integrating with SolidWorks, provide a simulation solution of light and human vision within a Virtual Reality Environment; OptisWorks enables efficiency analysis with active 3D ray tracing; predicts stray light, hot spots, and photometric and colourimetric performance; checks compliance with	Inputs: LDT/IES photometric files, manufacturer plug-in data, CAD files Outputs: Lux, luminance, intensity calculations. Photometry maps, point measurements, colourimetry	OPTIS, a CAD/CAM integrated solution, allows illumination engineers, ergo-designers to simulate and optimize lighting performance, product appearance, and visibility and legibility under man–machine environment

(continued)

Table 13.3 (continued)

Software	Mainly used for	Brief details	Remarks
	legislation and standards, directly within its SolidWorks assemblies		
Relux (2012, V 2) Relux Informatik AG http://www.relux.biz	Relux is a radiosity-based program for artificial lighting and daylight simulation. The tool also uses ray-tracing technology to produce (2D/3D) images, generation of isolines, and pseudo-colours. Relux includes a user-friendly interface for building modelling, and cost-efficiency analysis of luminaires, and daylight influence on isolux diagrams (Bhavani and Khan 2011). Relux contains a luminaire library from the manufacturers	Inputs: DXF, DWG, 3DS, WRL, JPG, PNG, manufacturer lamp data Outputs: luminance, lux isolines, pseudo-colours, 3D light distribution diagrams, lux uniformity; DXF, DWG for scenes; HDR for simulations; XLS for lists; UGR for observers	Relux is an open source; the plug-in for CAD and ray tracing (Radiance) is priced. RELUX (e.g., ReluxEnergy) includes a computational program based on EN 15193-1: 2007. Shailesh and Tuneja (2010) used the ReluxEnergy to evaluate lighting energy characteristics of a commercial building under construction in Mumbai. Estimation under various lighting control schemes yielded that using of the combined occupancy and daylight dimming sensors could save over two-thirds of the lighting energy, as compared to the original lighting design that did not consider daylighting
DIALux (2012, V 4.10) DIAL GmbH www.dial.de	DIALux is a simple to use software to design indoor and outdoor lighting, road lighting, sports complex lighting and emergency lighting DIALux provides the plug-in for CAD and ray tracing POV-RAY option, which is essential to show the customer the results of lighting design. The POV-Ray of DIALux allows generating high-quality images	Inputs: DXF, DWG, 3DS, STF, WRL, manufacturer lamp data Outputs: luminance diagrams, photometric data (intensity), PDF, WMF images, DWG, DXF, STF for architectural elements, UGR for observers, energy evaluation report	DIALux is an open source, free of cost software, including POV-RAY module. Outside Europe, DIALux has partners from 26 countries, such as China, Malaysia, Japan, and Russia and Middle East Saudi Arabia and Dubai
OptiWin (2009, V 2008.3) http://www.	OptiWin is a simple to use software for light calculation	Inputs: DXF, DWG 2D files, DXF, 3DS, for 3D; manufacturer photometric files	OptiWin enables CAD integration for lighting design; imports 3D models from

(continued)

Table 13.3 (continued)

Software	Mainly used for	Brief details	Remarks
glamox-international.com		Outputs: glare calculations UGR, lighting power density (W/m^2), point illuminance calculations (lux), isolux curves, economic calculations	DWG files; integrates calculation of LENI factor with graphical presentation
Visual (2016) Acuity Brands Lighting; http://www.acuitybrandslighting.com	Visual 2016 has several advanced features, over Visual 2012. The software employs calculation and rendering engines, covering multi-threading and vectorization to process calculations. The daylight calculation package takes into account the window openings and sky condition	Inputs: DWG/DXF files, IES/CIE/LDT photometric data files; imports PDF as background images; RealDWG can import drawing files using Autodesk's conversion library Outputs: illuminance point-by-point, isolines-filled contour, pseudo-colour, and greyscale render, economic reports, U_0, Intensity distributions	Visual 2016 includes an IES illuminance database, light loss factor calculator based on the IES guidelines
Lumen Micro V7.5 (1998) Lighting Technologies Inc., Boulder, Colorado http://www.lightingtechnologies.com	Lumen Micro uses radiosity approach; assumes that light energy is conserved in a closed environment, and the light emitted from small patches/discrete surfaces is reflected from or absorbed by other surface elements. From the calculation of the fraction of light, energy leaves each pair of patches and reaches the other, patch intensities are determined (Mitchell 1992; Larson and Shakespeare 1998)	Inputs: imported DXF file used as a dimensional template to build the input model; the model geometry can be from the 3D image Outputs: generates statistical tables of illumination levels, isocontour maps of the plan, elevation and perspective drawings, and also rendered interior perspectives	Lumen Micro produces numerical results reasonably quickly; The software has limitations for advanced simulations; parapets and side bays of the building cannot be modelled

Note Illuminance (as point calculations, isolux contour lines and pseudo-colours); luminance (in rendered pseudo-colour); UGR (Unified Glare Rating); STV (Small Target Visibility, used in street lighting, as a weighted average of the visibility level of an array of targets); DF (Daylight Factor, the ratio of internal to external light level used); U_o—overall luminance uniformity (L_{min}/L_{avg}); UG (uniformity gradient, the highest rate of change of values between adjacent measuring points, E_{max}/E_{min}).

lamp data file formats are IES, CIE, and LDT of which former two file formats were created to transfer photometric data of luminous flux and luminous intensity distribution over the designated angles. In Europe, LDT—Eulumdat is a commonly used an industry standard photometric data file (including CCT and R_a).

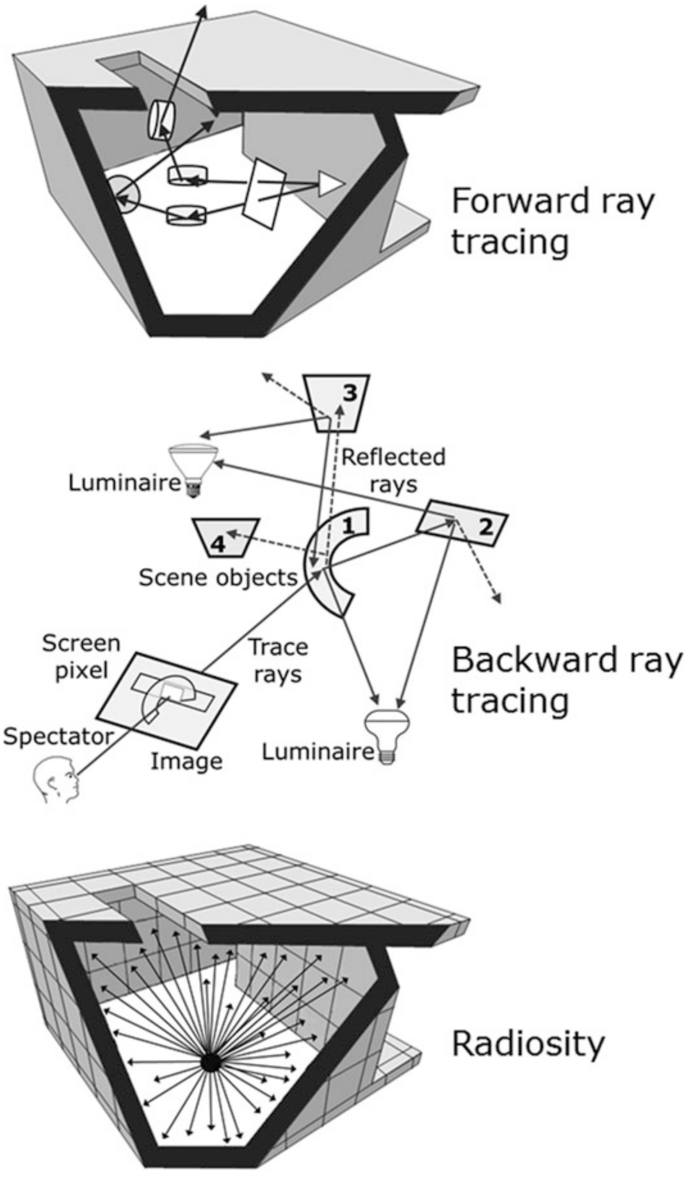

Fig. 13.5 Common illumination algorithms based on ray tracing (view-dependent) and radiosity (scene-dependent) approach

Two most common illumination algorithms are ray-tracing (view-dependent), and radiosity (scene dependent) (Fig. 13.5). In light forwards ray tracing, light follows in the direction of light propagation, i.e., from the light source to the final measurement areas or scene. Backward ray tracing tracks each view ray from the point of measurement to the contributing light sources to creating a realistic image of a geometric scene. That is, in the ray tracing techniques, the scenes that contain specular materials and point light sources are explored, whereas the opposite of ray tracing, the radiosity is a scene-dependent algorithm, in which the scene consists of a limited number of patches and nodes, and the light exchange and colour rendering happen between the nodes (form factors). An average scene may contain thousands of nodes and millions of form factors. The computation involves efficiently approximating form factors, such as using ray casting, grouping nodes, and hierarchically reducing form factors.

Lighting simulation programs mostly use hybrid algorithms, combining both ray-tracing as well as radiosity techniques. However, the software packages differ widely in their modelling basis, quantitative predictions between the simulated and measured results, and output visualization (IESNA 1997). For example, Radiance, developed at Lawrence Berkeley National Laboratory, is a backward ray-tracing daylight simulation package used widely for the evaluation of visual comfort and light quality from the modelled built environment. Undoubtedly, at the design stage of the building, the scaled models and the simulation results are useful (Yi et al. 2009). Ochoa et al. (2012) noted that the estimated reflectivity of indoor wall surface was the most frequent error source in simulation results. The accuracy of prediction tends to increase with the increased complexity of mathematical approach to lighting parameters. The analysis of various software packages amply suggests that the choice of the software would depend on the judicious decision and priority of the architechs and designers. Undoubtedly, the applications of software packages have high utility in the process of selection of lighting systems in buildings.

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Chapter 14
Energy Performance in Buildings: Standards and Codes

The Magnitude of Energy Consumption

The global energy needs are ever expanding with substantial demands arising from China and India (IEA 2015, 2017). Rapid urbanization nearly adds a city of the size of Shanghai to the world's urban population every four months, underpinning the ongoing energy demand. About 30% of the energy demand comes from India, whose share of global energy use might rise over 11% by 2040; however, in comparison the demand is far below to its 18% share in the anticipated global population. Overall, the countries in Asia account for two-thirds of global energy growth. IEA (2017) projection indicates that China needs to add the electricity infrastructure equivalent of today's US power system, by 2040, whereby to meet its rising demand; whereas, India needs to upgrade the power system to the size of today's European Union. Globally, the building sector consumes nearly 40, 25, and 40% of the energy, water, and resources, respectively, and is responsible for emitting one-third of the total greenhouse gas (GHG) emissions (UNEP 2015). The scenario is very much alarming across nations of the developed and the developing world. The US buildings account for about 40% of the primary energy use (equating to 39 quadrillions BTU); lighting consumes about one-fourth of energy demand of the commercial sector (US DOE 2011) and only about 11% in the residential sector. China, the most populous nation, witnesses unprecedented urbanization in the recent decades, with the world's largest market for new construction projecting to the building area of 30 Gm^2 by the year 2020 (Evans et al. 2010). The commercial building space in India has been growing at about 8% annually, and with that estimate, the total commercial building floor area alone might cross 1000 million m^2 by the year 2020. Currently, the buildings account for over one-third of India's total energy consumption (Rawal et al. 2012; Chaturvedi et al. 2014), and the electricity consumption in the building sector is growing at about 7%. On the one hand, India's population growth is poised to supersede China, by the next decade, and on the other, the relentless surge in construction activities

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would be a challenge to reckon regarding India's needs to upgrade the power system (IEA 2017). The energy performance index (EPI) ranges between 200 and 400 kWh/ m^2/year, whereas similar types of buildings in North America, China, and Europe have EPI lower than 150 kWh/m^2/year. Considering the annual energy consumption in commercial buildings and the national power grid emission factor of 0.82 tonne of CO_2/MWh, the annual CO_2 emission due to the existing commercial space, as on 2016, might be about 111 million tonnes (Bureau of Energy Efficiency, India 2008).

The building sector in the EU nations is using 40% of the total EU energy consumption, accounting for over one-third of the CO_2 emissions; the offices represent about 40% regarding the space area covered. In Brazil, nearly half of the total energy consumption is produced by renewable energy, including hydropower. In the public sector, HVAC, light, and office equipment consumes 48, 23, and 15% of the total energy consumption in buildings, respectively. As large as 90% of the energy used in buildings in Australia comes from black coal-fired power generation that produces substantial CO_2 emissions. The energy use by the commercial and institutional buildings in Canada amounts to 1057 PJ, i.e., 12% of Canada's secondary energy use (NRC 2012), and responsible for emitting 11% of the total GHG emission (NRC 2014).

Energy-Related Building Code

The approach in establishing national-level energy-efficient building code and energy certifications for buildings has been emerged as an essential method in improving energy efficiency, minimizing energy consumption and enabling better ways of using energy in buildings (Perez-Lombard et al. 2009). In other words, energy-efficient building code sets national targets for energy performance, promotion of efficient energy practices, energy audits and ratings, benchmarking, labelling and forming building-related performance standards. Much of the energy conservation activities around the world direct towards reducing energy use in buildings, through enforcing building codes for building envelopes, HVAC, SWH, power, and lighting.

European Union: The EU Energy Performance of Buildings Directive (EPBD), 2002/91/EC, requires the member countries to enhance building regulations, introduce energy certification schemes, and improve energy performance. The directive includes:

(a) A uniform methodology to calculate the integrated energy performance in buildings, including HVAC systems and lighting;
(b) Setting minimum standards on the energy performance of new and existing buildings,
(c) The system of energy certification of buildings, and displaying design values of indoor environment and indicators for environmental comfort, and

(d) Periodic inspection of boilers and HVAC systems in buildings, and assessment of heating installations of the boilers of over 15 years old.

The EC Directive 2010/31/EU (EPBD recast, art. 4.1 and 14) introduces a benchmarking mechanism for the member states to compare and set energy performance requirements of buildings and building elements. The directive recommends using the CEN standards to determine the annual primary energy demand, including heating, cooling, ventilation, domestic hot water, and lighting. Whereas, EN 15603:2008 provides a procedure for aggregating the primary energy demands per final use and also that generated on-site from renewable sources. EN ISO 13790:2008 refers to the calculation methods for assessment of the annual energy use for space heating and cooling of different building types. Other associated standards, such as EN 15316:2007, EN 15243:2007, and EN 15193:2007 describe energy performance requirements relating to the heating and DHW systems, renewable energy systems, AC systems and demands for lighting, respectively. The EN ISO 13790:2008 is elaborated later in the chapter about the methods of calculation of heat transfer from multiple building zones and avenues, such as transmission, ventilation, internal and solar heat gains, heating and cooling in maintaining set point temperatures in a building project. Application of these standards brings clear targets of defining high-performance buildings (Maldonado et al. 2007). Other important EU directives are Energy-using Products (EuP) Directive (2005/32/EC), Ballast Directive (EC 2000), Energy Services Directive (ESD) (EC 2006), and Energy Efficiency Label (EEL) (98/11/EC, 1998) .

USA: The Energy Policy Act (EPAct 2005), the Energy Independence and Security Act (EISA 2007), the Energy Conservation and Production Act (ECPA), and American Recovery and Reinvestment Act (ARRA 2009) set the foundation of the Department of Energy (DOE) on energy matters to stipulate building codes and programmes. The residential buildings are those low-rise homes of three stories or less, and all others are referred to as commercial including office, industries, warehouse, school, religious places, and high-rise residential buildings. For commercial buildings, the ANSI/ASHRAE/IES 90.1 (updated 2016) provides the basis for energy code improvements. The International Energy Conservation Code (IECC) primarily applies to the residential facilities, and it has a *commercial* section that allows the use of ANSI/ASHRAE/IES 90.1 for compliance.

The statute of the DOE's Building Energy Codes Program (BECP), established in 1991, outlines directive to develop and periodically improve the model building energy codes, issue determinations of energy and carbon saving, and extend educational and technical assistance to states for energy code adoption. The DOE (2010) guidelines on *Measuring State Energy Code Compliance* indicate the states to apply the evaluation checklists and examine the impacts of energy codes on building energy consumption (http://www.energycodes.gov/arra/compliance_evaluation.stm).

China: The Chinese building energy codes refer to mandatory compliance, covering a prescriptive path of detailed specifications for individual components as well as a performance path relating to the energy consumption of features of the proposed building. It has a multi-step protocol, including third-party involvement for verification and enforcement of building and energy codes (Evans et al. 2010; Shui and Nadel 2012). The Code for Acceptance of Energy-Efficient Building Construction addresses construction quality, testing, and documentation for the building envelope, HVAC systems, lighting, monitoring, and controls. With the adoption of the Acceptance Code, there has been an improvement in compliance rates in large urban areas (IEA 2013). However, the compliance assessment system has only been tested on a limited scale. A comprehensive national-level statistical sampling of building projects is required with appropriate coverage of metropolitan areas, suburban and rural areas, and population density (Shui 2012; Shui and Nadel 2012).

India: The Energy Conservation (EC) Act 2001 promotes energy efficiency in industrial, buildings, and commercial sectors. The EC Act stipulates the legal framework, institutional arrangement, and a regulatory mechanism at the central and state level. The Energy Conservation Building Code (ECBC), launched in 2007, by the Bureau of Energy Efficiency (BEE) sets the energy performance standards for design and construction of commercial and public buildings (on a voluntary basis) (Tulsyan et al. 2013). The state governments may choose to adopt and adapt to ECBC, taking into account the local climatic conditions. India is yet to implement the new building energy code fully and estimated that its compliance would reach about 64% by 2017 (UNDP 2011). The BEE star ratings (Table 14.1) are given to the commercial buildings, targeting three climate zones (composite, hot and dry, warm and humid). The national benchmark of EPI to be ECBC compliant is at the level of 180 kWh/m^2/year. GRIHA (Green Rating for Integrated Habitat Assessment), a green building design evaluation system, jointly developed by the Energy and Resources Institute (TERI, New Delhi) and the Ministry of New and Renewable Energy, applies to all kinds of buildings in different climatic zones of the country.

Table 14.1 BEE energy performance star rating of commercial buildings, in terms of EPI

Star label	Climatic zone—composite		Climatic zone—warm and humid		Climatic zone—hot and dry	
	>50% AC built-up area	<50% AC built-up area	>50% AC built-up area	<50% AC built-up area	>50% AC built-up area	<50% AC built-up area
1 Star	190–165	80–70	200–175	85–75	75–65	180–155
2 Star	165–140	70–60	175–150	75–65	65–55	155–130
3 Star	140–115	60–50	150–125	65–55	55–45	130–105
4 Star	115–90	50–40	125–100	55–45	45–35	105–80
5 Star	Below 90	Below 40	Below 100	Below 45	Below 35	Below 80
	EPI expressed as kWh/sqm of built-up area per year					

In Brazil, the Federal Regulation for energy efficiency and building performance (the Law 9991–2000 and Law 10295–2001) mandated investments in R&D and energy efficiency. The standards ABNT, NBR 15220-3, 2005, and ABNT 15575 elucidate the thermal performance for low-cost houses and the minimum level of performance. The standards provide guidelines on the voluntary labelling of energy efficiency in commercial, public, and service buildings, relating to building's lighting systems, HVAC, and thermal envelope (Carlo and Lamberts 2008). The SANS 0204 (South Africa), incorporated into National Building regulations, includes requirements to improve energy efficiency in all types of new buildings (Milford 2009).

Energy-Efficient Product Development

The EuP directive establishes a framework for setting ecodesign requirements for Energy-using Products (EU directive 2005/32/EC). The performance of the products is evaluated using a methodology that defines the types of products, market potentials, consumer base, technical analysis, the available technology of products, standards, and potentials of future improvement. This EuP directive led to the CE marking of the new products, including the lighting products. This chapter includes different lamp categories that correspond to EuP methodology.

Besides, the ENERGY STAR program (www.energystar.gov) has now global presence, among the manufacturers, retailers, and in governments, in establishing energy efficiency criteria of products (such as washing machines, refrigerators/freezers, room ACs, CFLs, solid-state lighting luminaires). For CFLs, there is a listing of products along with wattage, light output, lamp life, and CCT. For example, for the lamp power <10 W, the lamp efficacy should be at least 50 lm/W. Similarly, for lamp power in the range of 10–15 W and those >15 W, the lumen level should be at least 55 and 65 lm/W, respectively (Energy Star 2008). The Top Runner program was initiated in Japan, for the manufacturers to improve the energy performance of products (such as fluorescent lamps, computers, freezers, refrigerators, TVs, VCRs). The programme sets standard values of products with highest energy efficiency and those for potential technological improvements. Manufacturers are required to ascertain that the weighted average value of the product's energy efficiency meets or exceeds the targeted standard value (Top Runner 2008).

ANSI/ASHRAE/IES 90.1:2016

ANSI/ASHRAE/IES Standard 90.1 is a benchmark of the US commercial building energy code, and many countries have adopted the core components of the standard in developing energy codes. The 2013 version of the standard is the national energy reference standard recognized by the US DoE. The International Energy

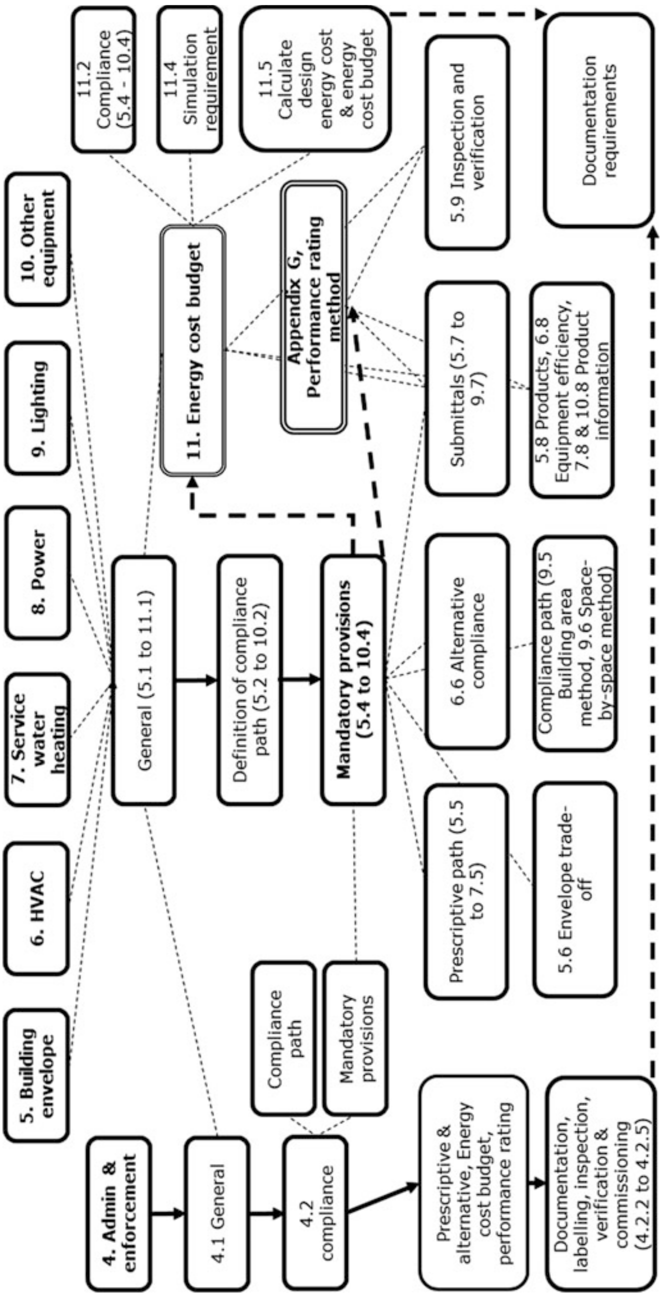

Fig. 14.1 Structure of ASHRAE 90.1:2016

Conservation Code recognizes ANSI/ASHRAE/IES 90.1 as an alternative compliance standard. The Standard 90.1:2016 is the tenth revision since it was first published in 1975. The standard has been placed on continuous emendation and maintenance, due to rapid changes in energy technology and energy prices. The 2016 edition of the standard covers minimum energy efficiency requirements for design and construction of new buildings, renovation of the building, the addition of new systems and equipment in existing buildings. It identifies 16 prototype commercial building models in all US climate zones, representing four-fifths of the entire US building stock, such as offices, educational buildings, hospitals, hotels, apartment buildings, and shopping malls. Perhaps these building models cover a vast majority of the commercial buildings all over the world. The structure of the standard and mandatory provisions for compliance with the energy standard are schematically shown (Fig. 14.1). Apart from the formatting changes to improve usability and readability, the current revision comprises several energy-saving measures and incorporates 125 addenda to that of 2013 revision. While it is not within the scope to elaborate the standard of 387 page long, and other supporting documents, however, the technical changes in the new version briefly cover the following:

Building Envelope

(a) Addition of verification in support of reduced air infiltration and increased requirements for air leakage to overhead coiling doors;
(b) Stringent metal building roofs and walls, fenestration, and opaque doors;
(c) Specification of exterior walls, building orientation, fault assumptions for effective R-value of air spaces, and
(d) Calculation for insulating metal building walls.

Mechanical

(a) Metering of energy use and efficiency for large, electrically driven chilled-water plants;
(b) Outdoor air systems include efficiency and rating requirements for compliance;
(c) Elevator design efficiency covers use category and efficiency class, and
(d) A monitoring system in air-cooled direct-expansion cooling units.

Lighting

(a) Modification of requirement for advanced lighting controls and increased energy savings, and additional lighting controls in some space types, and
(b) Modification in exterior and interior lighting power densities to reflect new lighting levels and efficiency gains from LED technology.

Energy Cost Budget and Modelling

The readers may refer to Appendix G (performance rating method) to be used as a path for compliance with the standard. The scope of the performance rating method covers multiple mandatory provisions, performance calculation, and conformance with the requirements of Sects. 5.4, 6.4, 7.4, 8.4, 9.4, and 10.4 of the standard. It incorporates a metric—the Performance Cost Index (PCI)—as the ratio of the proposed building performance (PBP) to baseline building performance (BBP), and levels showed based on building type and climate zone. All end-use load components within and associated with the building are considered in calculating the PCI. The baseline design performance has been set for different components, such as elevator, motor, and refrigeration baselines and changes to the baseline of existing buildings. Simulation program or compliance software has been suggested for evaluation of the baseline building design and the proposed design. Simulation analysis encompasses the energy use by the components, such as lighting controls, internal equipment loads, service water heating, space heating/cooling, humidification systems, heat rejection, fans, and HVAC equipment. The standard incorporates extensive conformance guidelines, which were not within the scope to reproduce herewith. The lighting requirements are detailed in Chap. 8. Some HVAC requirements are reproduced in Table 14.2.

Compliance with Building Code

Robust enforcement and high compliance rate to building code are critical to achieving energy savings, cost reduction, increased building resale value, and minimal environmental impact (Stellberg 2013; Yu et al. 2014). According to ANSI/ASHRAE/IES 90.1, the compliance checklists are a useful way to support energy code compliance checks and evaluations. Whereas compliance checks are conducted during the building's design and construction, its evaluation is possible from retrospective analysis. In general, compliance check includes reviewing of (a) building plans, (b) products, materials and equipment specifications, (c) tests of installed materials and supporting calculations, (d) inspection during construction and immediately before occupancy and also post-occupancy (DOE 2013). The compliance evaluation covers analysis of data collected from individual buildings and generates an overall compliance rate at the national or regional levels. For example, BEE energy rating scheme requires the primary building energy data (Table 14.3) from building owner(s).

ANSI/ASHRAE/IES 90.1—Compliance Evaluation

The US energy codes include a structured checklist, which can be customized by the prospective users, including the provisions of the applicable standard and regulatory jurisdictions. A format of the checklists, based on ANSI/ASHRAE/IES 90.1-2010, is presented in Table 14.4. The checkpoints are indicative and not exhaustive since 2013, and 2016 editions of the standard have some addenda on the

Table 14.2 HVAC requirements (ASHRAE 91.1:2013)

Class	Size	Heating section	Sub-category	Minimum efficiency	
Air-cooled AC	<65,000 Btu/h	All	Split system	14 SEER, 12 EER (3 phase)	
				14.5 SEER, 12 EER (single phase)	
			Single package	14 SEER, 11 EER (single and 3 phase)	
	>65,000 and <135,000 Btu/h	None/electric resistance	Split system/single package	11.7 EER; 11.8 IEER	
		All other types		11.5 EER; 11.6 IEER	
	>135,000 and <240,000 Btu/h	None/electric resistance		11.7 EER; 11.8 IEER	
		All other types		11.5 EER; 11.6 IEER	
	>240,000 and < 760,000 Btu/h	None/electric resistance		12.4 EER; 13.6 IEER	
		All other types		12.2 EER; 13.4 IEER	
	>760,000	None/electric resistance		12.2 EER; 13.5 IEER	
		All other types		12 EER; 13.3 IEER	
Chillers—air-cooled and water-cooled				*Path A (Full-load optimized)*	*Path B (Part-load optimized)*
Air-cooled chillers	<150 tons		Chillers	≥ 10.4 EER FL; ≥ 12.5 IPLV	≥ 9.56 EER FL; ≥ 15.39 IPLV
	>150 tons			≥ 10.4 EER FL; ≥ 12.75 IPLV	≥ 9.56 EER FL; ≥ 15.07 IPLV
Water-cooled positive displacement	<75 tons			≤ 0.75 kW/ton; ≤ 0.63 IPLV	≤ 0.80 kW/ton; ≤ 0.60 IPLV
	>75 and <150 tons			≤ 0.71 kW/ton; ≤ 0.61 IPLV	≤ 0.79 kW/ton; ≤ 0.51 IPLV
	>150 and <300 tons			≤ 0.68 kW/ton; ≤ 0.58 IPLV	≤ 0.72 kW/ton; ≤ 0.50 IPLV
	>300 and <600 tons			≤ 0.58 kW/ton; ≤ 0.54 IPLV	≤ 0.64 kW/ton; ≤ 0.48 IPLV
	>600 tons			≤ 0.58 kW/ton; ≤ 0.54 IPLV	≤ 0.64 kW/ton; ≤ 0.48 IPLV
Water-cooled, electrically operated centrifugal	<150 tons			≤ 0.62 kW/ton; ≤ 0.60 IPLV	≤ 0.64 kW/ton; ≤ 0.36 IPLV
	≥ 150 tons and <300 tons			≤ 0.59 kW/ton; ≤ 0.60 IPLV	≤ 0.64 kW/ton; ≤ 0.35 IPLV
	≥ 300 tons and <400 tons			≤ 0.56 kW/ton; ≤ 0.55 IPLV	≤ 0.60 kW/ton; ≤ 0.36 IPLV
	≥ 400 tons and <600 tons			≤ 0.56 kW/ton; ≤ 0.55 IPLV	≤ 0.60 kW/ton; ≤ 0.36 IPLV
	>600 tons			≤ 0.55 kW/ton; ≤ 0.40 IPLV	≤ 0.57 KW/ton; ≤ 0.350 IPLV

(continued)

Table 14.2 (continued)

Class	Size	Heating section	Sub-category	Minimum efficiency
Water-cooled AC	<65,000 Btu/h	All	Split system/single package	12.1 EER; 12.3 IEER
	>65,000 and <135,000 Btu/h	None/electric resistance		12.1 EER; 13.9 IEER
		All other types		11.9 EER; 13.7 IEER
	>135,000 and <240,000 Btu/h	None/electric resistance		12.5 EER; 13.9 IEER
		All other types		12.3 EER; 13.7 IEER
	>240,000 and >760,000 Btu/h	None/electric resistance		12.4 EER; 13.6 IEER
		All other types		12.2 EER; 13.4 IEER
	>760,000 Btu/h	None/electric resistance		12.2 EER; 13.5 IEER
		All other types		12.0 EER; 13.3 IEER
Air-cooled air conditioners and heat pumps				
Small commercial split and single package AC and heat pumps (HP, air-cooled)	≥ 65,000 and <135,000 Btu/h	None/electric resistance	AC	12.9 IEER
		All other types		12.7 IEER
		None/electric resistance	HP	12.2 IEER
		All other types		12.0 IEER
Large commercial split and single package AC and HP (Air-cooled)	≥ 135,000 and <240000 Btu/h	None/electric resistance	AC	12.4 IEER
		All other types		12.2 IEER
		None/electric resistance	HP	11.6 IEER
		All other types		11.4 IEER
Very large commercial split and single package AC and HP (Air-cooled)	≥ 240000 and <760000 Btu/h	None/electric resistance	AC	11.6 IEER
		All other types		11.4 IEER
		None/electric resistance	HP	10.6 IEER
		All other types		10.4 IEER

(continued)

Table 14.2 (continued)

Class	Size	Heating section	Sub-category	Minimum efficiency
Air-cooled heat pumps				
Small commercial split and single package HP (Air-cooled)	≥ 65,000 and <135,000 Btu/h	None/electric resistance	HP	3.3 COP
		All other types		3.3 COP
Large commercial split and single package HP (Air-cooled)	≥ 135,000 and <240000 Btu/h	None/electric resistance		3.2 COP
		All other types		3.2 COP
Very large commercial split and single package HP (Air-cooled)	≥ 240,000 and <760,000 Btu/h	None/electric resistance		3.2 COP
		All other types		3.2 COP
Gas- and oil-fired boilers				
Boilers, hot water	<300,000 Btu/h	Gas-fired	Boiler	90%
		Oil-fired		87%
	≥ 300,000 and ≤ 10,000,000 Btu/h	Gas-fired		94% Et
		Oil-fired		85.5% Et
	>10,000,000 Btu/h	Gas-fired		82% Ec
		Oil-fired		84% Ec
Boilers, steam	<300,000 Btu/h	Gas-fired		90%
		Oil-fired		87%
	≥ 300,000 and ≤ 10,000,000 Btu/h	Gas-fired, all including natural draft		80% Et
	>10,000,000 Btu/h	Gas-fired, all excluding natural draft		79% Et
		Gas-fired, natural draft		77% Et

Note COP (coefficient of performance); EER (energy efficiency ratio); Ec (combustion efficiency); Et (thermal efficiency); IEER (integrated energy efficiency ratio), IPLV (integrated part-load value); FL (full-load); SEER (seasonal energy efficiency ratio); AC (air conditioners); HP (heat pumps)

Table 14.3 Standard procedure to arrive at BEE energy rating

Primary building energy data (annual)			
Connected load (kW) or contract demand (kVA)			
Installed capacity: diesel generating (DG)/Gas generating (GG) Sets (kVA or kW)			
Electricity consumption and cost	Purchased from utilities (kWh)	DG/GG set(s) (kWh)	
Building area (excluding parks and roads)	Built-up area (m^2) (excluding basement)	Conditioned area (m^2)	
No. of employees in an office	No. of office occupants at any time during office hours	Daily working hours	Weekly working days
Installed capacity of HVAC system		Installed lighting load (kW)	
Consumption of gas- or oil-fired DG/GG sets (l/m^3)			
Fuel (e.g., FO, LDO, LPG, NG) used in generating steam/water heating (units)			
Energy performance index (EPI, $kWh/m^2/year$) (excluding electricity generated from on-site renewable resources)			

specific requirement and performance guidelines. Therefore, the energy compliance evaluators require to restructure the checklists with minor modifications. The checklists contain the general information and evaluation at stages of construction of the buildings. The steps encompass plan review, footing/foundation inspection, framing/rough-in and plumbing rough-in inspection, mechanical and electrical rough-in inspection, insulation inspection, and final inspection (https://www.energycodes.gov/compliance/evaluation/checklists).

A single evaluation can include multiple buildings, subject to the buildings are of the same type, and the buildings are simultaneously constructed (http://www.energycodes.gov/arra/compliance.evaluation.stm). Evaluation of building compliance can be demonstrated by the prescriptive requirements for compliance, trade-off, or performance approach. That is, the buildings that may not comply with the prescriptive values, but may still be deemed to comply with the code with considerations that some aspects of the building exceed the code. Software simulation and model predictions (COMcheck for energy code of commercial and high-rise residential buildings, and REScheck for energy code of residential complexes) have been advocated to evaluate if the building meets the energy standards. Since human activities and building use behaviours vary greatly, there are uncertainties (Karlsson-Hjorth 2013) in model predictions to the actual energy use. The readers may refer to Chap. 13 that compiled a brief description of different energy and lighting simulation software.

A building project may ascribe to a particular green rating system, and their requirements are differently defined (e.g., the requirements of BREEAM rating system, as elaborated in Chap. 16). For example, a record of values and parameters that are determined by the evaluators during plan review should be noted as the Plans Verified Value, and this is useful if a building complies with an alternative trade-off or performance approach. Field Verified Value includes observed values based on field inspection, and those provided during plan review, such as insulation

Table 14.4 A format for building data collection and compliance evaluation

Building ID/ name, location	Climate zone	Conditioned floor area (sq.ft)	Name of evaluator	
Evaluator qualification	Compliance approach: • Prescriptive •Trade-off • Performance	Compliance software	Above-code program (e.g., LEED, BREEM)	
Building use				
Office	Warehouse/Storage	Education/School	Lodging/Hotel/Motel	Restaurant/ dining/fast food
Retail/ Mercantile	High-rise residential	Health care	Public assembly/ Religious	Other
Foundation type				
Below-grade		Slab	Floor over unconditioned space	
New building		Existing building, addition	Existing building renovation	
The general format of checklist items (refers to sections of ASHRAE 90.1-2010/2016)				
Component	**Plan review**	**Compliance** Y N N/O N/A	**Comments**	
Envelope (plan review)	Plans, specifications, calculations to determine compliance with building envelope		Data and features of the building—calculation, worksheet, compliance form, vendor documents	
Mechanical (plan review)	Plans, specifications, calculations to determine compliance with the mechanical systems		Mechanical system: data and features of building, equipment, and systems	
	Plan document for HVAC systems commissioning >=50,000 sq. ft floor area		HVAC system: data and features of building, equipment, and systems	
	Plans, specifications, calculations for the service water heating systems and equipment		Data and features of service water heating systems, pressure sensors, and flow controls	

(continued)

Table 14.4 (continued)

Project (plan review)	Plans, specifications, calculations for the electrical systems and equipment		Electrical systems: data and features of building, equipment, and systems		
Interior lighting (plan review)	Plans, specifications, calculations for the interior lighting systems and equipment		Interior lighting systems		
Exterior lighting (plan review)	Plans, specifications, calculations for the exterior lighting systems and equipment		Exterior lighting systems		
Checklist items for different stages of inspection are indicative; a full form of the checkpoints may be based on the applicable standard (e.g., ANSI/ASHRAE 90.1:2016)					
Component	**Footing/Foundation Inspection**	**Plans Verified Value**	**Field Verified value**	**Compliance**	**Comments**
Envelope (insulation)	Below-grade wall insulation R-value				
	Slab edge insulation R-value				
	Slab edge insulation depth and length				
	Exterior insulation with protective material against damage by sunlight, moisture, wind				
	Insulation in contact with the ground (below the specified water absorption rate, e.g., <=0.3%)				
	Insulation of piping, ducts, and plenum in or under a slab				
	The bottom surface of the floor is radiant heat insulated to >=R 3.5				
Mechanical (HVAC)	Freeze protection and snow/ice melting system sensors				
Component	**Framing/rough-in inspection**				
Envelope (air leakage)	Air barrier (wrapped, sealed, gasketed), as specified				
	Fenestration and door products meet air leakage and thermal envelope requirements				
	The installed vestibules meet exterior envelope requirements; e.g., building entrance separates conditioned space, and doors are >=7 feet apart				

(continued)

Table 14.4 (continued)

Envelope (fenestration)	Vertical/skylight fenestration, U-factor and SHGC value (as required)				
Component	**Mechanical rough-in inspection**				
Mechanical (HVAC)	HVAC equipment efficiency verification				
	Outdoor air and exhaust systems, with auto-motorized dampers or gravity dampers, to minimize leakage rates				
	Ventilation fans > 0.75 hp with auto-control				
	Parking garage ventilation with automatic contaminant detection and appropriately designed fan capacity				
	Demand control ventilation, based on the size of space and occupant density				
Mechanical (system specification)	Single zone HVAC systems with fan motors >=5 hp having variable airflow controls				
	High cooling capacity AC systems (>=110,000 Btu/h) having variable airflow controls				
Mechanical (HVAC)	Insulation outside of the conditioned space and cooling systems have vapour retardant				
	HVAC piping, ducts, and plenums appropriately insulated				
Mechanical (system specification)	Air economizers meet requirements for design capacity and control				
	Water economizers meet requirements for design capacity, pressure drop, control, and heating system impact				
	Zone controls limit zonal heating and cooling				
	Hydronic heat pumps of water loop meet heat rejection requirements				
Mechanical (HVAC)	Dehumidification controls prevent concurrent heating and cooling of the same air stream				

(continued)

Table 14.4 (continued)

Mechanical (system specification)	VAV fan motors >=10 hp have a vane-axial fan and have controls to limit fan motor demand				
	Multiple zone VAV systems have static pressure set point to individual zones for reset controls				
	Multiple zone HVAC systems provided with supply air temperature reset controls				
	Hydronic heat pumps and water-cooled AC with pump systems > 5 hp have controls to reduce pump motor demand				
Mechanical (HVAC)	Exhaust air energy recovery on systems >=5,000 cfm and 2/3rd of design supply air				
Mechanical (system specification)	Kitchen hoods with an exhaust airflow rate >5,000 cfm meet replacement air, ventilation system, or energy recovery requirements				
Mechanical (HVAC)	Fume hoods exhaust >=15,000 cfm have VAV hood exhaust and supply systems to makeup heat recovery				
	Unenclosed spaces are heated using only radiant heat				
Mechanical (system specification)	Service water heating equipment used for space heating complies with requirements				
Component	**Rough-in electrical inspection**				
Interior lighting (controls)	Auto-control of lighting (ON and OFF) in buildings >5000 sq.ft				
	Occupant accessibility to independent as well as manual lighting controls				
	Parking garage lighting has required lighting controls and daylight transition zone lighting				
	Lighting controls installed in enclosed spaces of daylight areas under skylights and rooftops >900 sq.ft				

(continued)

Table 14.4 (continued)

Exterior lighting (controls)	Auto-controls installed for exterior lighting				
Interior lighting (wattage)	Exit signs do not exceed 5 W; minimum illuminance of signboard 2 cd/m^2				
	Space LPD requirements adjusted based on room cavity ratios and dimensions				
Component	**Insulation inspection**				
Envelope (air leakage)	All likely sources of air leakage are sealed, gasketed to minimize air leakage				
Envelope (insulation)	Roof R-value verification required during framing inspection				
	High-albedo roofs meet solar reflectance >=0.55, or thermal emittance >=0.75, or solar reflectance index >=64				
	Floor and above-grade wall insulation R-value				
	Damage protection of exterior insulation by a protective material verified				
Component	**Final inspection**	**Compliance** Y N N/O N/A		**Comments**	
Mechanical (HVAC)	Heating and cooling of zones are controlled by a thermostat control				
	Temperature controls have set point overlap restrictions				
	HVAC systems equipped with automatic shutdown control (at least one)				
Mechanical (system specification)	Systems having air capacity >10,000 cfm are provided with optimum start controls				

(continued)

Table 14.4 (continued)

Mechanical (HVAC)	Humidification and dehumidification must not operate simultaneously		
	HVAC control systems tested for operation, calibration, and adjustment of controls		
Mechanical (system specification)	Controls (temperature and time switches) are installed in recirculation pump to maintain the temperature of a water storage tank		
Interior lighting (wattage)	Installed lamps and fixtures, interior lighting power are consistent with the approved lighting plans		
Exterior lighting (wattage)	Installed lamps and fixtures, exterior lighting power are consistent with the approved lighting plans		
Mechanical (controls)	Elevators are designed with proper lighting, ventilation power, and standby mode		
Project (controls)	About half of all the electrical receptacles are controlled by auto-control devices		
Mechanical (post construction)	As-built drawings and O&M manuals of HVAC furnished to a designated representative within 90 days of system acceptance		
	As-built drawings and O&M instruction for electrical power systems furnished to the designated representative of the building owner		

Impact: 1 (High impact—Tier 1); 2 (Medium impact—Tier 2); 3 (Low impact—Tier 3)

Compliance: compliant (Y), not compliant (N), not observable (N/O), or not applicable (N/A)

R-value, depth of insulation, fenestration U-factors, SHGC, equipment efficiency, and determination of compliance. The checklist items are indicated for its compliance status, as per the defined code requirements. The prescriptive compliance checklists reflect into multiple tiers of building compliance metric, such as high—Tier 1 with weights of 3 points, medium—Tier 2 with 2 points and low—Tier 3 with weightage of 1 point in the respective tier items. The overall points established by the tier are further graded as good, fair, and poor. In case the checklist item being allocated all available points, a building project is rated "Good". An allocation of two-thirds of the available points is rated as "Fair", and rated "Poor" for allocation of one-third of the available points of the checklist items.

EN 15193—Energy Requirements for Lighting

The EN 15193:2007 includes requirements for direct estimation of the lighting energy used in buildings. The standard considers different aspects of energy consumption, such as:

(a) Installed load (totalling all installed luminaires);
(b) Energy use pattern during the day and night (controlled by occupancy control systems);
(c) Use of constant illuminance (maintenance control);
(d) Standby parasitic power in controlled lighting components; and
(e) Algorithmic lighting and scene setting.

The ratio of total annual energy used for lighting (kWh/year) to the building's total useful floor area (m^2) is expressed as Lighting Energy Numeric Indicator (LENI). The basic formula to calculate the lighting energy usage in a building is tabulated (Table 14.5).

Further to elaboration in Chaps. 7 and 13, the assessment of lighting energy performance may involve different approaches, such as field measurement, empirical numerical derivation, use of different energy and lighting software available today. Conventional field measurement can determine occupant behaviour to lighting control and effectiveness of different lighting control systems. Krarti et al. (2005) proposed a simplified method for the professionals to estimate energy savings of artificial lighting due to daylighting, with the provision of supplying information of window type, areas, transmittance, and building geometry. The numerical equation, as expressed below, includes influencing factors to estimate percentage saving (f_d) in electrical lighting due to daylighting,

$$f_d = b[1 - exp\,(-\alpha\tau_w A_w/A_p)]A_p/A_f$$

where τ_w is the visible transmittance due to window glazing, the A_w, A_p, A_f represent the area of window, daylighted floor area and the total room area, respectively; the constants a and b depend on the location of the building and control strategy, and the annual percentage of time the daylight provides the set illuminance level.

Table 14.5 Formula to calculate the lighting energy usage in a building (EN 15193)

Annual lighting energy for a building —$W_{L,t}$ (kWh)	$= \Sigma[P_n \cdot F_c \cdot \{(t_D \cdot F_o \cdot F_D) + (t_N \cdot F_o)\}] /1000$	P_n (total luminaire power in a zone, W) F_C (constant illuminance factor) t_p (time of parasitic power used, h) t_D (time of daylight usage, h) t_N (time of non-daylight usage, h) t_y (time in a standard year, 8760 h) t_e (emergency lighting charging time, h) F_D (daylight dependency factor) F_o (occupancy factor) P_{pc} (parasitic power or standby losses in a zone, W) P_{em} (total installed charging power for emergency lighting luminaires in a zone, W)
Annual parasitic power for standby power losses and emergency lighting —$W_{P,t}$ (kWh)	$= \Sigma\{[P_{pc} \cdot \{t_y - (t_D + t_N)\}] + (P_{em} \cdot t_e)\} /1000$	
Total annual energy used for lighting—W_{light} (kWh/year)	$= 6\,A + (t_u \cdot \Sigma P_n)/1000$	$t_u = (t_D \cdot F_D \cdot F_o) + (t_n \cdot F_o)$ the effective usage hour; A (total area of the building)

Energy Transfer—Building Envelope

The building facade or envelope is the first line of defence against any untoward external environmental elements. Avoidance of solar radiation in the building is a critical issue in the climatic zones where cooling is the primary concern. The Envelope Thermal Transfer Value (ETTV) for non-residential and Residential Envelope Thermal Transmittance Value (RETV) (Table 14.6) are quantified from the heat conduction through (a) opaque walls (U-value) and (b) transparent elements, i.e., windows (U-value), and (c) solar radiation through transparent elements, i.e., windows (SC value) (BCA 2008). The primary heat inputs are averaged over the whole envelope area to represent the thermal performance of the envelope. The maximum permissible ETTV and RETV have been set at 50 W/m^2 and 25 W/m^2 respectively (BCA 2008). In an air-conditioned building, the ETTV concept applies to its roof, referred to as the Roof Thermal Transfer Value (RTTV), including thermal transmittance through the opaque roof, skylight area, and solar radiation.

There are some basic guidelines that (a) adjust in the window-to-wall ratio influences the amount of heat entering a space, (b) opaque enclosures resist heat transfer better than glass, (c) reduced window size prevents the outside heat from being transferred inside, (d) when the window–wall ratio goes above 50%, it would require high-performance glazing with low shading coefficient, and/or heavy shading, (e) select glass for a project on thermal and visual performance properties, and (f) creative facade design as a function of the orientation influences heat transfer, as required, is only applicable for skylights, and has the same limit of 50 W/m^2. The green building schemes (e.g., HK-BEAM) included checkpoints of overall thermal transfer value for different building types.

Table 14.6 Deriving envelope thermal transfer value and residential envelope transmittance value (BCA 2008)

Transfer values	Equations	Factors
Envelope thermal transfer value, ETTV (W/m^2)	$= 12\ (1 - WW_r)\ U_w + 3.4\ (WW_r)\ U_f + 211(WW_r)\ C_f \cdot S_f$	WW_r (ratio of window area to the gross area of exterior wall) U_w (thermal transmittance of the opaque wall, $W/m^2 \cdot K$) U_f (thermal transmittance of fenestration, $W/m^2 \cdot K$) C_f (correction factor for solar heat gain through fenestration) S_f (shading coefficients of fenestration) SK_r (ratio of roof skylight area to the gross area of the roof) U_r (thermal transmittance of the opaque roof, $W/m^2 \cdot K$) U_s (thermal transmittance of skylight area, $W/m^2 \cdot K$) C_r (solar correction factor for the roof) S_r (shading coefficient of skylight portion of the roof)
Roof thermal transfer value, RTTV (W/m^2)	$= 12.5\ (1 - SK_r)\ U_r + 4.8\ (SK_r)U_s + 485(SK_r)\ C_r \cdot S_r$	
Residential envelope transmittance value, RETV (W/m^2)	$= 3.4\ (1 - WW_r)\ U_w + 1.3\ (WW_r)\ U_f + 58.6\ (WW_r)\ C_f \cdot S_f$	

ISO 50001:2011, Energy Management Systems

The standard specifies requirements to establish, implement, maintain, and improve an energy management system. ISO 50001:2011 includes informative guidance on its use. The documented procedure applies to measurement and reporting of energy use and consumption, design, and procurement of equipment, systems, processes, and personnel practices. Whereas the standard does not include specific energy performance criteria, it can independently be used in an organization to ensure conformance to its stated energy policy. The system conformity ensures from self-evaluation, self-declaration, or certification of the management system by a third party or certifying bodies.

ISO EN 13790:2008—Energy Calculation for Space Heating and Cooling

ISO EN 13790:2008 standard is one of the essential standards in the set of standards to support the EPBD. The standard applies to buildings at the design stage and also to existing buildings. It presents a set of calculation steps (Fig. 14.2) covering annual energy needs to maintain the specified set point temperatures in the building, and also the annual energy use for heating, cooling, and ventilation. A building may be differentiated by zones that have different set point temperatures, and intermittent

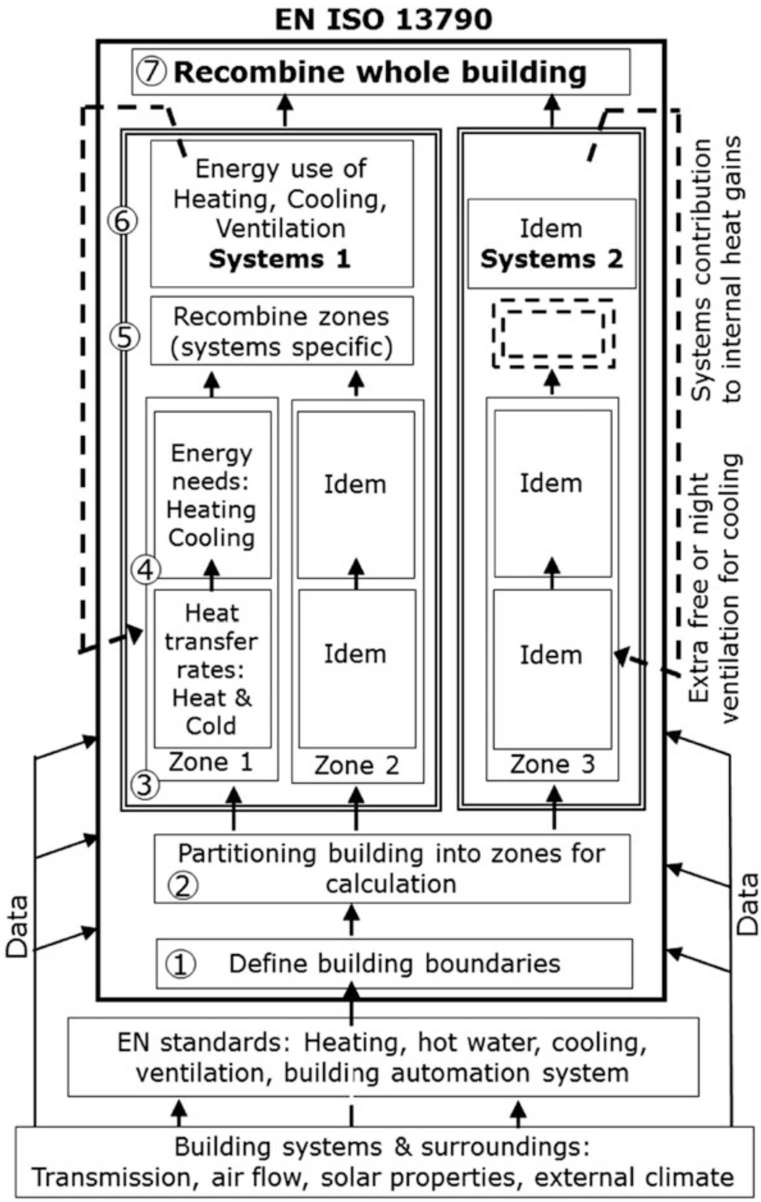

Fig. 14.2 Reference to European EPBD, EN ISO 13790 defined flow chart of main calculation steps of energy use for space heating and cooling

heating and cooling. The calculation may be based on monthly, seasonal, and hourly intervals.

Successive steps of calculation of heating and cooling energy needs, i.e., input from other related standards, and output to other essential standards, such as

EN 15603 determine the building energy performance characteristics. ISO EN 13790:2008 has specific mention of the standards EN 15193-1, EN 15232:2012, EN 15241:2007, EN 15242:2007-09, EN 15243, and EN 15316:2007. EN 15193-1 and EN 15232:2012 about estimation of energy requirements for lighting, building automation, controls, and building management. EN 15241, EN 15242, and EN 15243 describe calculation methods for energy requirements due to ventilation systems, including infiltration, and system load for buildings with room conditioning systems. Whereas EN 15265:2007 provides validation procedures of energy use in space heating and cooling, EN 15316:2007 elucidates method for calculation of energy efficiencies of 11 sub-parts of heating systems in buildings. These cover space heating emission systems, boilers, heat pumps, heating generation—thermal solar systems, performance of CHP, district heating, large volume systems, renewables (heat and electricity), space heating generation and distribution, and domestic hot water systems.

Several other related standards deal with energy performance of buildings. ISO 15099:2003, ISO 10077-1:2006, and ISO 6946:2007 deal with calculating thermal resistance and thermal transmittance of windows, doors and shutters, and other building components. ISO 13370, ISO 13786, and ISO 13789:2007 provide calculation methods for heat transfer via the ground, dynamic thermal characteristics of building components, transmission and ventilation heat transfer coefficients, respectively. EN 410, EN 13363-2, and ISO 9050:2003 deal with glass in buildings and calculating solar and light transmittance, ultraviolet transmittance, and glazing factors for solar protection devices. ISO 15927-4:2006 includes analysis of hourly climatic data to evaluate the annual energy use for heating and cooling and the hygrothermal performance of buildings.

The Structure of the Calculation

The heating and cooling energy loads are calculated from the heat balance of the building, partitioned into multiple zones. The readers may refer to Annex A of the standard for more details of the calculations on the energy use at the system level. The *main inputs* to the system calculation are building project description including building components, systems, use pattern, heat transmission, internal heat sources, solar properties, and climatic set points for comfort requirements. Inputs include data on the heating, cooling, ventilation, hot water supply, and lighting systems, dissipation or recovery of ventilation heat losses in the building, and energy use for de-frosting, pre-heating or pre-cooling.

The building boundaries of the conditioned and the unconditioned spaces, and the boundaries of the calculation zones are defined. Its relative temperature difference governs the transmission heat transfer between the conditioned space and the external environment. Ventilation heat transfer (natural and mechanical ventilation) is governed by the relative gradient of temperature between the conditioned zone and other adjacent space. Estimates of internal heat sources include that heat dissipation or absorption by heating/cooling, ventilation, water, and other systems. Solar heat sources are directly through windows or indirectly via absorption in opaque elements in the building. The calculation yields the amount of energy needed for heating/cooling, per period and building zone, after suitable adjustment of the internal set point temperatures. Recombining zones per system arrive at the energy use for heating, cooling, hot water, and ventilation systems, with due account of the heat dissipation from the systems. Accordingly, it yields the amount of storage or release of heat from the total building mass.

Under ISO EN 13790, there are three basic types of heat balance calculation methods, i.e., (a) a monthly quasi-steady-state method (plus an option of a seasonal method), (b) a simple hourly dynamic method, and (c) calculation procedures of detailed (e.g., hourly) dynamic simulation methods. The quasi-steady-state method of calculation gives an indication of heat balance on an annual basis. There is a likelihood of error in the calculation for heating and cooling the months closer to the beginning and end of the respective seasons. In this method, the introduction of a utilization factor takes into account the dynamic effects. That is, for heating, a utilization factor considers that only parts of the internal and solar heat sources are utilized to compensate the energy need for heating, and the remaining leads to an undesired increase in internal temperature above the set point. For cooling, the utilization factor represents both losses and gains.

The simple hourly dynamic method calculates on hourly user schedules (such as temperature set points, ventilation modes, solar orientation). The variabilities of individual hourly values are always very large. For instance, any surplus of heat during the heating period can effect to raise the internal temperature above the set point and, therefore, require to remove the surplus heat by further transmission, ventilation, or mechanical cooling. A thermostat setback or switch off is not instantaneous due to the thermal inertia of releasing heat from the building mass. A similar situation also applies to cooling.

The *main outputs* of the standard are the monthly and annual basis of energy needs, energy use for heating and cooling, and ventilation systems, and length of a system running hours. Additional outputs are monthly values of primary elements in the energy balance, contribution of renewable energy sources, and recovery of system losses in the building. Overall, the implementation of ISO EN 13790 in a building project provides for an integrated structure and methodology for energy performance evaluation and compliance to minimum energy performance requirements, auditing, and certification, as illustrated in Fig. 14.3. That is, in combination with other energy performance-related standards, ISO EN 13790 has intrinsic potential to assess appropriately:

(a) The energy performance of a building under study, and compare with any outcomes of design alternatives for a planned building, or energy conservation measures on an existing building;
(b) Compliance with energy codes, regarding energy targets; and
(c) Future energy resource needs on a spatial scale (regional, national) based on typical buildings representative of the building stock.

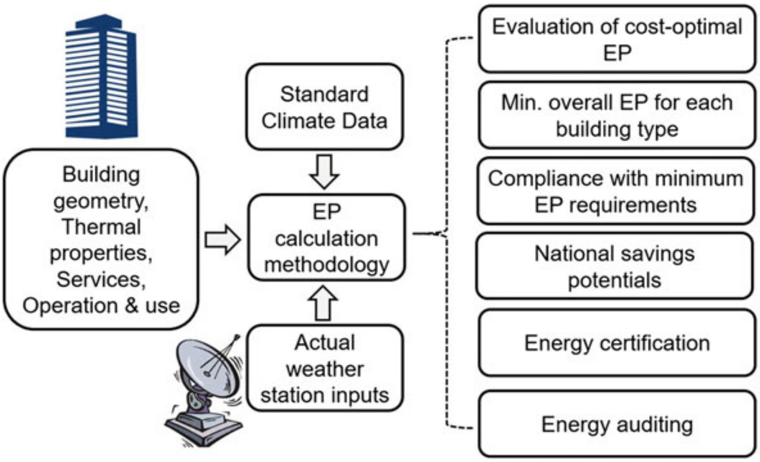

Fig. 14.3 Methodology for energy performance evaluation and compliance

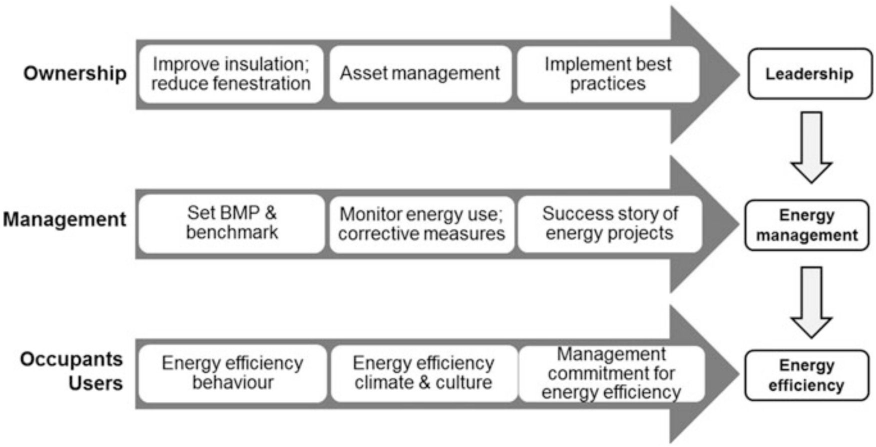

Fig. 14.4 A general framework towards improving building energy operations

From analysing various building energy standards and codes of national and international agencies, it appears imperative that every nation should have a defined road map for improving building energy operations. A general framework is reproduced herewith (Fig. 14.4) to emphasize on improving the building energy operations, for mitigating environmental concerns and enriching health and well-being building occupants.

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Part VI
Green Office Building

Chapter 15
Green Building and Assessment Systems

Introduction

People hardly took cognizance of the early alarm raised about the vastly devastating consequences of climate change on life and living. Anthropogenic activities, business and development, and excessive energy and resource consumptions by different sectors of the society are the added impacts on the climate that the world faces. Today, it is undisputed that the climate change is the most significant threat to sustainability. Globally, the building stock consumes a considerable share of resources, such as energy, electricity, water, and raw materials. A quantum jump in urbanization and infrastructure activity around the world and more so among the countries in the Asia-Pacific regions resulted in unprecedented demand for construction resources and services such as water, transportation, sewage treatment. The sustainability of the built environment is critical in the face of the stark reality of climatic extreme that we might encounter soon. Overall, the buildings contribute to climatic impacts by consuming nearly 40, 25, and 40% of the energy, water, and resources, respectively, and responsible for 1/3rd of the total greenhouse gas emissions (UNEP 2015). The energy consumption of commercial buildings in the future is expected to increase, while the energy demand of residential buildings may tend to decrease (US Department of Energy 2012). If the scenario continues, and hard and soft technologies in construction are not adopted sooner, emissions might reach an alarming level soon in a decade's time. Hardware technologies imply construction material, construction equipment, machinery, construction techniques, whereas software technologies include design and engineering, project planning, control and management, health–safety–environment (HSE) practices, and quality control system.

The World Health Organization indicated that about 36% of the respiratory diseases, 22% of chronic disease, 5% of bronchial catarrh, 5% of cancer, and 5% of leukaemia, totalling nearly 68% of the sufferers had various diseases, caused due to the effects of indoor environmental pollution. The building and decorating materials,

P. K. Nag, *Office Buildings*, Design Science and Innovation,
https://doi.org/10.1007/978-981-13-2577-9_15

paints, and furniture materials, dyes, and glue, textile carpet, use of electrical appliances, heater and the soot from cooking, and other indoor functions are the potential sources of pollution. The chemical pollutants (both inorganic and organic emissions and solid wastes) cause degradation of the environment. The radioactive contamination comes from the release of radioactive elements, called Radon from brick walls, stones, and concrete. Green building initiative is a definitive innovation for sustainable development in construction, with apparent health, environmental, social and economic benefits (Reed et al. 2011; Kibert 2016). Globally, the green building appears to be firmly embedded in the minds of the stakeholders in construction marketplace and continues to increase market share (McGraw Hill Construction 2012). The primary drivers of sustainable green buildings include:

- Population-growth associated unrestrained urbanization, relentless building, and infrastructure activity, for jobs and habitat development;
- Rapid ICT drove enterprise activity across regions, bringing in demands of office infrastructure;
- Need for resource-efficient building practices, in the backdrop of increasing scarcity of natural and building resources;
- Designing energy-efficient buildings and optimizing energy demands through high-performance lighting systems, natural ventilation, HVAC systems, and renewable energy, wherever feasible;
- Growing public sensitization on the issues of indoor and outdoor environmental degradation, and HSE concerns of building occupants and transient users;
- Increasing pressure due to stringent legislation, command, and control in building standards and codes; accrediting building features in structured measures; and
- Quantifying effectiveness of measures towards energy-efficient and environmentally friendly buildings.

Elements of Green Building

All concerned recognize that green building is the concept of creating structures and using optimal natural resources throughout a building's life-cycle and causing a least adverse impact on the environment. The sustainability of the built environment calls for integration and synergism of the building's lifecycle processes to be employed in new construction or renovation of existing structures (UNDP 2011; WBDG 2009). The criticality of green building practice aims at recognizing that the decision to build green begins early in the design process. It maximizes the green potential and assures the economic viability of the green elements. The central focus of green building is to create a healthy, comfortable, and productive indoor environment for building occupants and other transient users. Since the green building practices and technologies are continually evolving, the principles persist on measures and approaches for:

(a) Site and structure design efficiency;
(b) Efficient use of energy, water, and material resources;
(c) Reduction of waste and environmental degradation;
(d) Enhancement of IAQ, ventilation, thermal comfort, daylighting, and acoustical environment; and
(e) Optimization of building operation and maintenance.

In the core, the green building initiative brings together innovative and exemplary practices to minimize impacts of buildings on the environment and human health. The green building endeavour maximizes the applicability of low-impact building materials, renewable resources, and replenishment of groundwater. On aesthetic considerations, the building architecture must be in harmony with the natural features and resources of the locale.

Life cycle assessment (LCA)—The objective of environmentally responsible buildings is to minimize environmental impacts associated with all life cycle phases (Fig. 15.1). For example, the process starts with the extraction of raw materials through processing, manufacture, distribution, use, maintenance, disposal, and recycling (Trusty 2000; Kashkooli and Altan 2010). ISO 14040:2006 includes the detailed LCA methodology to evaluate the environmental impacts of buildings (Finkbeiner et al. 2006; Pryshlakivsky and Searcy 2013). The International Energy Agency directory (IEA 2001) provides useful LCA tools for assessment.

Site and structure design efficiency—Building as a process is not always streamlined since the process varies from one building to the other. The foundation

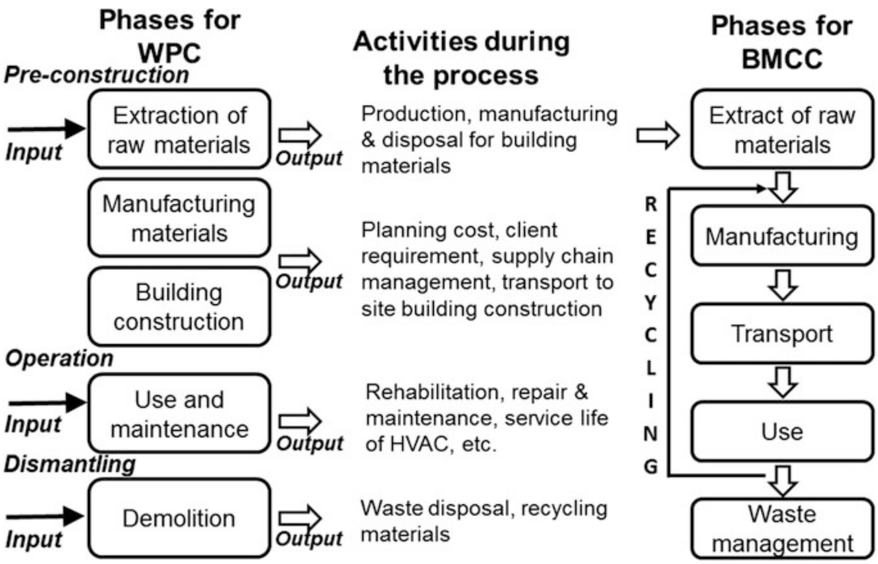

Fig. 15.1 Schematically represented phases of the building lifecycle. (Adapted from Kashkooli and Altan 2010)

is rooted in the planning and design stages of a project. Buildings are composed of a multitude of materials and components, and each is having the potential to affect the environment.

Energy efficiency—Green buildings intend to reduce consumption of both the embodied and operating energy. The embodied energy makes up about 1/3rd of the overall building energy consumption towards extraction, processing, transportation, and installing building materials. The operating energy is necessary for services, such as HVAC, lighting, and other facilities. In reducing operating energy, however, one may look into the tightness of the building envelope, insulation in walls, ceilings, and floors, and effective window placement for more natural ventilation and daylight. Renewable energy generation has been differently deployed in office building complexes for energy efficiency and reduction in the environmental impact of the building.

Water efficiency—The critical issue for the sustainable building is to reduce water consumption and preserve water quality. Given the general scarcity of the supplying aquifer in many geographical regions, the building practices should increase their dependence on water that is collected, treated, and reused on-site.

Materials efficiency—Green building materials typically include logs and timber as approved for construction use, renewable plant materials (e.g., bamboo and straw), recycled stone and metal, and other non-toxic products. Demolition debris, ship dismantling materials, fly ash, foundry sands are often reused in construction projects.

Indoor environmental quality (IEQ)—As described in Chapter 11, IEQ category covers issues of design and construction processes that may affect IAQ, thermal quality, ventilation system, lighting, and acoustics (Lee and Guerin 2009). Building materials, interior finish, and cleaning/maintenance products emit toxic gases, which have detrimental effects on occupants' health. It is important to recognize that many building materials claim to be acceptable products also release harmful gases. Decorating wall painting and ceiling, also known as hard decorating, not only comes from the building materials but also comes from the choice of design and decoration method. Many harmful substances that are persistent (e.g., asbestos fibres) may be slowly released to the indoor environment for even 20 years. By the rule of the wall painting process, the foundation layering is important to prevent the wall surface from shedding skin or tears. Choosing of materials and products with zero or low VOC emissions, and designing a ventilation system that allows adequate entry of clean air from outdoors or recirculating filtered air in different building zones can increase a building's IEQ. The use of composite floorboard as packing below solid wood floor or wall panel may be a potential source of formaldehyde pollution in the indoor environment. Solid wood products are known to be less allergenic; hardwood, vinyl, linoleum tile, granite, or marble flooring are recommended instead of carpet. Briefly, interactions among all the indoor components, including the occupants of the building, determine the IEQ (WBDG 2009). Improving IEQ has a direct bearing on workers' productivity and cost pay-off (Boué 2013).

Operations and maintenance optimization (*O&M*)—The O&M activity is integral to retain green criteria in the building's life (WBDG 2009) that encompasses best practices in energy efficiency, resource conservation, and use of ecologically sensitive products. Awareness among building operators and occupants is crucial to implement sustainable strategies in O&M services.

Waste reduction—During the construction phase and its use, one of the goals is to help minimize waste materials that may go to landfills. For buildings undergoing demolition, deconstruction method is applied to harvest waste and reclaim into useful building material effectively. Extending of the useful life of a structure is also considered as waste reduction; for example, reclaimed wood materials and iron plates may be further used in renovation work. Wastewater from treatment or rainwater storage for non-potable purposes, such as sub-surface irrigation, plant watering, landscape pond, and a toilet flush, are the practical way of waste reduction. Since large wastewater treatment systems are often cost-intensive, an alternative to this process is to convert waste and wastewater into fertilizer, and accordingly reap tangible benefits. Biological wastes are also treated in a biogas plant for useful application as liquid fertilizer and organic nutrients.

Indices of Green Building

In the context of LCA, the readers might have come across different terminologies, referred to as indices of green buildings (Table 15.1), as briefly described below:

Among these indices, the greening index, the water resources index, and the daily energy-saving index have been widely discussed for its substantial impacts in green building. The greening index refers to the greening of roofs, streets, slopes, and ground that (a) improves the appearance of the locale, (b) improves air quality, (c) reduces dazzling sunshine and the urban heat island (UHI) effects, and (d) resists desertification. The water resources index is linked to the water consumption of a building. Improper design of the water use facility and poor water-using habits of people lead to overconsumption of water resources. In an office building, there is always a massive inflow of people, and the installation of water-saving faucets, two-stage toilets, and automatic flushing systems are used to optimize water consumption. The daily energy-saving index is related to the design of energy-saving devices, including the building shell, HVAC, and the lighting system. The design of HVAC system is linked with the architectural space that may be compartmented based on usage and predicted heat load. The lighting energy-saving covers, such as brightness of indoor walls and ceilings, high-efficiency lights, daylighting, and lighting control systems. These green building indices and related standards serve as useful building performance indicators for energy efficiency of office and other non-residential buildings (Fig. 15.2). With these indices in mind, the strategies and technologies that may be useful in a building project are highlighted (Table 15.2),

Table 15.1 Indices of green buildings

Green index	Ecology-greening, wall-greening, water-draining and windproof greening techniques
Water resources index	Referred to as the ratio of total annual withdrawals to available water resources. Plan of water use, the machine of water saving, rainwater reuse, and primary water source
Daily energy-saving index	Energy efficiency in building construction, use, and maintenance; daylighting and passive ventilation referring to the rate of the window opening, a sunshading, glass openings, heat insulation, building materials, roof structure, and curtain
Biodiversity index	Community green net system, earth-saving system, ecology lakes and water bodies, ecology palisade design and porous environment
Carbon dioxide reduction index	Simple construction modelling, indoor decoration, the weight reduction of the structure and the usage of the wood material
Life cycle resource indices	In assessing resource sustainability in buildings, life cycle resource indices evaluate the resource consumption (primary and total material input, after deducting the amount of recycled and reused materials) during the processes of construction and renovation
Lifecycle waste indices	Assess the wastes generated (total waste generation, waste for treatment, taking into account the number of waste materials for recycling, waste for landfill and disposal) during the processes of construction, renovation, and demolition) in the life cycle of a building
Waste reduction index	Use of the reused building material, soil balance, dry partitions
Base water index	Permeable floor, permeable well, artificial structure staying
Sewage and trash improvement index	Rainwater and sewage diversion, improvement in the waste collection, wetlands, wastewater treatment, and waste compost
Interior index	Indoor pollution control, air purification, green paint, and building materials

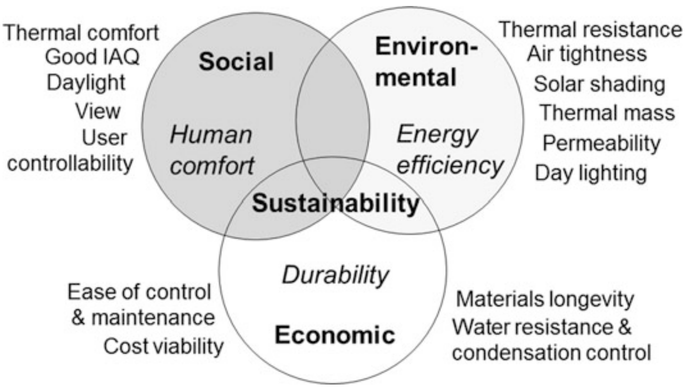

Fig. 15.2 Tangible building performance indicator for energy efficiency in buildings

Table 15.2 Strategies and technologies of a green building project

Sustainable site design	Energy and environment	Water quality and conservation	Materials and resources	IEQ
Make efficient use of space in existing buildings, sites, and other infrastructure; Consider development of brownfield sites; Design/renovation of buildings to maximize future flexibility of use; Ensure minimal disturbance of the local or regional ecosystem; Protection of green fields and wetland sites from building project development; Spread over project development to preserve green space; Efficient use of mass transit systems, and building sites more pedestrian- and bike-friendly; Mitigation of the UHI effect by natural shading, light coloured roofs, porous walkways and paved areas; planting deciduous, shade	Orient building floor plans and window positions to maximize southern exposure, and natural ventilation; window shading to minimize solar gains in summer and maximize solar gains during winter; Maximizing the use of daylighting; building orientation to maximize daylight entry; installing daylight controls, as needed; Use of energy-efficient machinery, office equipment, and water-conserving appliances and plumbing fixtures; Place solar water heater in buildings; Use of high-performance, low-emissivity glazing for energy savings; double/triple glazing or double pane glazing with a suspended low-emissivity film are used;	Strategically locate building site to preserve critical natural hydrological features; Ensure natural stormwater retention, groundwater infiltration, and maintain recharge systems; Minimize excavation and compaction of existing topsoil; Use low-impact rainwater technologies, e.g., bioretention, rain gardens, wetlands, pervious paving, vegetated roofs for on-site retention, groundwater recharge or evapotranspiration; Establish a water budget; harvest, process and recycle rainwater for suitable use in buildings (e.g., toilet flushing, site irrigation, cooling tower); minimize the use of potable water for other purposes;	Minimizing use of non-renewable resources and materials through efficient planning and construction; Maximize the use of recycled materials; use blended concrete of fly ash, slag, concrete aggregate, or other admixtures for recycled content materials; manufacture office furniture and partitions using recycled content; Optimize the use of engineered materials, resource-efficient composite materials, structural systems (concrete/steel), insulated stress skin panels and concrete forms; Deploy waste reduction management plan; adopt a policy to recycle 75% or more of all construction waste; reduce the burden on landfill space for construction debris;	Use construction materials, adhesives, and furnishings that do not emit contaminants, including VOCs; Install ventilation systems that should be capable of exhausting indoor contaminants, and pushing fresh, clean air in; the system should operate independently of the heating and cooling system; install environmental monitoring, integrating with ventilation systems to indicate indoor conditions when it falls outside the optimum range; Create physically isolated smoking areas; ensure that ETS does not get distributed to other building zones; Design building envelope and environmental systems to maintain human thermal comfort, and control the climatic variables, including

(continued)

Table 15.2 (continued)

Sustainable site design	Energy and environment	Water quality and conservation	Materials and resources	IEQ
trees on the east and west ends of the building; Landscape design to encourage the natural habitat; reduce impervious areas by alternative options for parking and roadway design; Optimize the use of on-site stormwater treatment and groundwater recharge; Minimization in compaction of topsoil; provide active sedimentation and silt control during site development and construction; Reduce night-time overillumination of the site and use low cut-off exterior lighting fixtures, directing light downward.	Design window frames and curtain systems for optimum energy performance; Optimize the exterior insulation and thermal performance of the exterior envelope; Use energy-efficient lighting sources; consider indirect lighting to improve light quality and reduce glare; Incorporate sensors and control circuits so that lighting can be switched ON/OFF independently; Use high-efficiency HVAC, chillers, boilers, fire suppression; use variable speed drives on pump motors; use heat recovery ventilators, geothermal heat pump technology for energy savings; Use Energy Star certified devices; Consider on-site small-scale wind, solar, and fuel cell based energy generation, as a substitute.	Preserve the groundwater quality by planting drought resistant and hardy trees and turf that require no fertilizers, pesticides or herbicides.	Implement a waste recycling programme; engage contractors to enforce compliance; label facilities for recycled materials; Explore the use of biobased materials, such as sheathing and insulation board made from agricultural waste and by-products; Use lumbar and wood products from certified forests; Use locally produced materials to support the regional economy and reduce transportation cost.	mean radiant fields of interior surfaces; Prevent the spread of construction dust; maintain the ventilation systems contamination free; avoid construction materials to become damp and mouldy; Use biodegradable and environment-friendly cleaning agents that do not release VOCs or other harmful agents; before occupancy, install new air filters and clean ductwork and ventilation equipment; use fresh outdoor air to naturally or mechanically purge the building of any airborne contaminants.

with respect to the primary areas of assessment, such as site design, energy and environment, water conservation, material and resources optimization, and improving IEQ.

Disability and Accessibility Issues

The International Classification of Functioning, Disability and Health (ICF) (WHO 2001) defines disability as “the outcome or result of a complex relationship between an individual’s health condition and personal factors, and the external factors that represent the circumstances in which the individual lives”. The barriers in architecture and non-accessible built environment significantly hinder persons with disability (Putnam et al. 2003; Darcy and Harris 2003).

Universal design is defined as the design of products and environment for use by all people. Adapting to universal design principles provides accessible technologies that cater to the needs of all range of users (Imrie and Hall 2001). The fundamental principles of universal design, as outlined by the College of Design, North Carolina University (USA), include:

- Equitable use for people with diverse abilities;
- Flexibility in use (accommodating a wide range of people’s preference and abilities);
- Simple and intuitive method (easy to understand, regardless of the user’s experience, knowledge, and skill);
- Perceptible information (unrestrained communication of information to users, irrespective of ambient conditions or the user’s sensory abilities);
- Tolerance for error (minimizes hazards and consequences of an accident or unintended actions);
- Low physical effort (efficient and comfortable use, with minimum fatigue); and
- Appropriate size and space for reach and manipulation, regardless of user’s body size, posture, and mobility.

Green Building Incentives

Implementation of the green building demands collective wisdom of stakeholders, such as designers, constructors, consultants, and project owners. A general misconception prevails that constructing green buildings are not cost-effective. However, Kats (2010) noted that the financial payback might typically exceed the additional cost of greening by a factor of 4–6 times, over a period of 20 years. Logically, the incentive for green building is a worthwhile consideration that can drive sustainable development in the building sector (Queena and Edwin 2008;

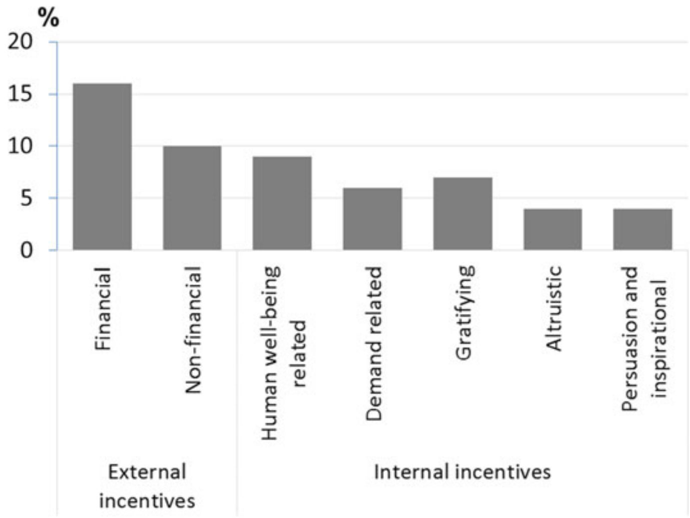

Fig. 15.3 Green building incentives. (Data from Olubunmi et al. 2016)

Choi 2009). Zuo and Zhao's (2014) review includes the various approaches used to deliver green buildings. Effort goes to mandatory or regulatory approaches to meeting green building requirements to benefit from the incentives, which are termed an external incentive (Aliagha et al. 2013; Samari et al. 2013; Abidin and Powmya 2014). In voluntary approach, the stakeholders are incentivized to adopt green building practices (referred to as internal incentive). There is limited comprehensive analysis on the effectiveness of government incentives (Gou et al. 2013; Van der Heijden 2013) and internal incentives (Love et al. 2011; Bond 2010). Olubunmi et al. (2016) reviewed the studies of both external and internal incentives (Fig. 15.3). External incentives, categorized as either financial or non-financial, are extrinsic, specifying the requirements that must be duly fulfilled by the potential stakeholders. The internal incentives (identified as human well-being-related, market demand, altruistic, and inspirational incentives) are intrinsic and manifested as an appeal to all stakeholders to adopt green building projects as goodwill, brand value, and volition. Evidence suggests that the governments across countries are moving towards regulating green building, and this approach has always been critical due to the inadequacy of enforceability mechanism, and lack of a mechanism to determine the optimum level of incentives required. The government and governmental agencies being the largest providers of external incentives, taking cognizance of related administrative requirements and compliance, would encourage the promotion of green building.

Building Environmental Assessment Systems

Decision-making on the environmental performance of buildings has been accomplished all over the world, using various analytical assessment systems and tools, tailored to building typology and functions. There is a recognizable dominance of tools originated from European nations, USA and Canada. It is more of esoteric interest to explore the growth, development, and maturity of the enormous variety of assessment tools that are available today (such as BREEAM, BOMA BESt), LEED, HQE, EcoEffect, EcoProfile, ESCALE, BEAT, LEGEP, BOMA BESt, to name a few). However, researchers have recognized the necessity to classify the systems and tools for specific functions and needs of users. Two well-known classifications are ATHENA assessment tool typology, introduced by Athena Institute (Trusty 2000), and IEA Annex 31 Directory of tools (2001). The ATHENA tool refers to three levels of classification, i.e., (1) product comparison tools and information sources, (2) whole building design or decision support tools, and (3) whole building assessment frameworks or systems. The IEA Annex 31 (2001) identifies the tools into five categories, such as (1) energy modelling software, (2) LCA tools for buildings, (3) assessment frameworks and rating systems, (4) environmental guidelines for design and management of buildings, and (5) environmental product declarations, and certifications. While the ATHENA classification focuses on the assessment tools, the IEA Annex 31 classification has more comprehensive coverage, including energy modelling, environmental assessment frameworks, checklists, product reference information to certifications into the classification system (Haapio and Viitaniemi 2008; Kashkooli and Altan 2010).

With the constant emphasis on the concept of green building, it is visible that most countries have developed or adopted some building assessment tools and methodologies, through voluntary agencies, stakeholder bodies, or government regulations. The maturity of the assessment schemes manifests as acceptance and issuance of certification to different kinds of building typologies. Invariably, some schemes, often referred to as green building rating schemes, such as BREEAM, LEED, Green Star, SBTool, CASBEE, DGNB, have a relatively more significant presence in building accreditation. The first real attempt to establishing comprehensive means of assessing a broad range of environmental considerations in buildings was the Building Research Establishment Environmental Assessment Method (BREEAM), which was commercially launched in 1990 in the UK (Crawley and Aho 1999). Today, it is the most widely used environmental assessment system for buildings. The second global system is LEED (Leadership in Energy and Environmental Design), launched in 1998 by the US Green Building Council (USGBC) as a consensus-based building rating system. Since then, many different standards, rating systems, and tools have been launched, to attract government regulators, building professionals, property appraisers, and consumers to embrace green building.

Fig. 15.4 Brand names and symbols of building assessment systems

The World GBC, established in 2002, is an initiative to creating a single common assessment method for sustainability in construction globally, strengthening strategies to promote green building in the local building policies, and encourage collaboration in the building sector (Myers et al. 2008). This includes (a) optimizing site potential, (b) optimizing energy use, (c) protecting and conserving water, (d) using environmentally preferable products, (e) enhancing IEQ, and (f) optimizing operational and maintenance practices.

Structure, Application, and Criteria

Given a substantial number of assessment systems (Fig. 15.4) are in use, this section is a modest attempt to collating and analysing the structure, application, and criteria embedded in select popular building environmental assessment methodologies.

BREEAM

BREEAM aims at (a) mitigating the lifecycle impacts of buildings on the environment, (b) enabling buildings to be recognized by its environmental benefits, (c) providing a credible, environmental label, and creating value for sustainable buildings, building products, and supply chains. Underlying principles in BREEAM development and operation include:

- Determining environmental quality through holistic, balanced, and quantitative measures of environmental impacts;
- Adopting scientifically sound practices as the basis to quantify and calibrate a cost-effective performance standard in defining environmental quality;
- Providing an international framework of assessment that is tailored to meet the local context including regulation, climate, and sector, and reflect social and economic benefits of meeting environmental objectives;
- Adopting a flexible approach towards integrating building professionals to understand better the building-associated environmental impacts;
- Encouraging stakeholders to adopt third-party certification and to show credibility and consistency of the label;
- Implementing existing industry standards and practices, wherever possible to support developments in policy and technology, and building existing skills with minimal cost implications; and
- Aligning technically and operationally with international standards, in particular, the standards of the European Committee for Standardization Technical Committee CEN/TC 350 on Sustainability of Construction Works.

BREEAM covers building types, such as offices, ecohomes, industrial and retail units, schools, courts, prisons, hospitals, and bespoke. The version of BREEAM International is an adaptation of the existing schemes to assess a building in any region in the world, e.g., BREEAM (Netherlands), BREEAM (Canada). BREEAM is supposedly updated annually; however, the draft version (2014) is described here, which is publicly available. Significant categories of assessment include:

- Management (commissioning, waste recycling, pollution, and materials minimization);
- Health and well-being (ventilation, humidification, lighting, thermal comfort);
- Energy (efficiency and CO_2 impacts);
- Transport (emissions, alternate transport facilities);
- Water (consumption reduction, leak detection);
- Materials (use of crushed aggregate and sustainable timber, reuse of recycled materials, asbestos mitigation);
- Land use (previously used land, remediated contaminated land);
- Ecology (land with low ecological value, maintaining major ecological systems on the land, minimization of biodiversity impacts);
- Pollution (on-site treatment, use of renewable energy sources, avoiding the use of ozone-depleting substances); and
- Innovation.

The methodology for calculating the environmental rating is illustrated in Fig. 15.5. Credits are awarded in meeting the requirements of a stated category and criterion. Description of the credit rating of different criteria is vividly elucidated later in the section, including credit distribution and exemplary level or innovation credits. The environmental categories are weighted according to the perceived importance of the environmental issues, expressed as the percentage score for each issue category. Based on the cumulative points scores achieved, the BREEAM rating is awarded, as Pass—25%, Good—40%, Very Good—55%, or Excellent—70%.

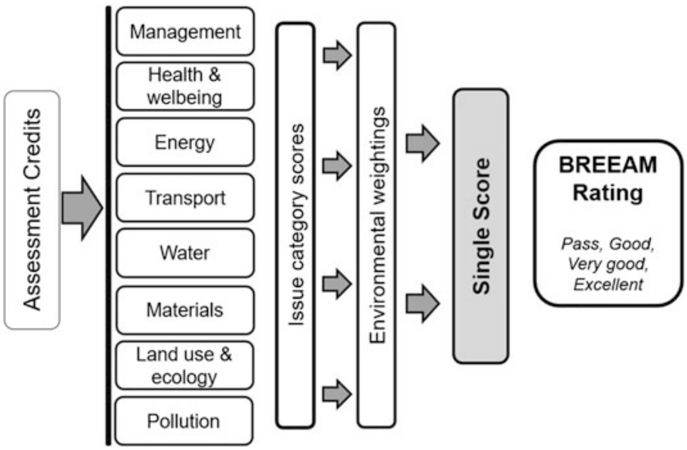

Fig. 15.5 BREEAM scoring and weighting for non-domestic buildings

LEED

LEED is currently the dominant environmental building rating system in the US and has been adopted in many countries, such as LEED Canada, LEED India, LEED Mexico, LEED Brazil, and LEED Emirates (UAE). The LEED undergoes periodic revision and updating on a cycle of 3–5 years, with the option of minor annual changes. Related documentation of the quantifiable sustainable design measures is submitted to the USGBC for third-party verification and certification. There are many versions of the LEED system, depending on the types of buildings, such as new construction and major renovations, core and shell, schools, retail, data centres, warehouse and distribution centres, hospitality, health care. This review used LEED Version 4 (updated 2016). Specific environmental building-related impacts are addressed using a whole building environmental performance approach, in which the prerequisites and credits are spread over essential categories (Fig. 15.6), such as

- Location and transportation (neighbourhood development, priority site, land protection, surrounding density and uses, quality transit, parking, bicycle facilities, green vehicles);
- Sustainable sites (construction activity-related pollution prevention, site master plan, assessment of development impacts, rainwater management, heat island effect, light pollution, guidelines for joint use of facilities, direct exterior access);

Fig. 15.6 Credit categories in LEED

- Water efficiency (landscape and indoor water use reduction, cooling tower and wastewater strategies, water metering);
- Energy and atmosphere (commissioning and verification, energy performance optimization, energy metering, renewable energy use, refrigerant management, green power, and carbon offsets);
- Materials and resources (collection of recyclables locations, building lifecycle impact reduction, construction and demolition waste management, environmental product disclosure, sourcing of raw materials and material ingredients, design for flexibility; special requirements for healthcare facilities, such as persistent bioaccumulative toxic (PBT) source reduction—Pb, Hg, Cd, Cu; furniture and medical furnishings);
- IEQ (enhanced IAQ strategies, ETS control, use of low emitting materials, IAQ management plan, assessment, controllability of thermal and lighting systems, daylighting, acoustic performance);
- Innovation and design process, accredited professional, regional priorities.

A comprehensive picture of LEED prerequisites and credits distribution are tabulated in Chap. 16 for different building typologies. LEED has a simple scoring system in the form of credit points, and the value of each issue is dependent on the number of points available. Based on the final score, four different US GBC certificates and a plaque with the rating are issued—*Certified (26–32 points)*, *Silver (33–38 points)*, *Gold (39–51 points)*, *and Platinum (52–69 points).*

CASBEE

Comprehensive Assessment System for Built Environment Efficiency (CASBEE) was launched in 2004 by the Japan Sustainable Building Consortium. The presently used 2014 edition of CASBEE family has a set of tools, each tailored in accordance with the type of buildings, such as buildings (new construction, existing buildings, renovation, commercial interiors, detached houses). Other purposes of assessment includes market promotion, urban development, and heat island (2010 edition), cities—for global use (2013 and 2015 edition), CASBEE for temporary construction, homes—detached houses (2007), CASBEE checklists for health/community health, and housing renovation. Significant modification of CASBEE assessment methodologies is expected every year.

CASBEE addresses building lifecycle, covering, pre-design, design, and post-design phases for different building typologies (Fig. 15.7). It presents three basic concepts. Firstly, it is designed for assessment of buildings, which corresponds to their lifecycle; secondly, it is based on the concept that distinguishes building environmental loading (L) and quality of building performance (Q) as the major assessment targets, and thirdly, CASBEE applies the concept of ecoefficiency as BEE (Building Environmental Efficiency).

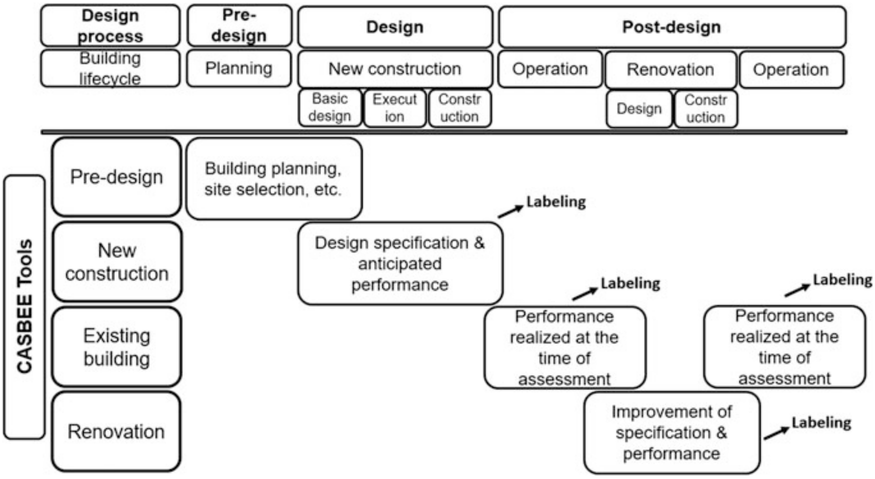

Fig. 15.7 Different phases of building lifecycle covered in CASBEE assessment tools

Environmental quality (Q) and performance—(a) *IEQ* (noise and acoustics, thermal comfort, lighting, IAQ); (b) quality of services (amenities, functionality, durability, flexibility, and adaptability); (c) outdoor environment (creation and preservation of biotope, townscape, landscape). *Quality* (Q) evaluates improvement in living amenity for the building users.

Environmental loadings (L)—(a) Energy (thermal load, natural energy, efficiency of systems and operations); (b) resources and materials (water conservation, sustainably harvested timber, recycled materials, materials with low health risks), (c) reuse and reusability, and avoidance of CFCs and halons; (d) off-site environment (air pollution, light pollution, sunlight, UHI effect, noise and vibration, and local infrastructure). *Loading* (L) evaluates negative aspects of environmental impact.

Each criterion is scored as level 1–5; level 1 referred to as meeting minimum requirements, level 3, as meeting standard technical and social requirements, and level 5 as the high level of achievement at the time of the assessment. Unlike other schemes (e.g., BREEAM, LEED, or Green Star), CASBEE uses a more complicated weighting to address issues with the number of measures available. Weightings are applied to categories, such as indoor and outdoor environment, energy, resources, and materials. Each category has headline issues, such as serviceability, lighting, and illumination, building thermal load. Again there are individual issues, including noise, ventilation, and use of recycled materials. A final layer of weightings applied to the sub-issues (such as ventilation rate, CO_2 monitoring) are grouped under the individual issues. All the issues are split into Q and Load reduction (LR) measures. Most of the sub-issues can be scored between 1 and 5 points, and zero is not available to prevent negative score for Q or L. The final score is calculated as the Building Environmental Efficiency (BEE), as below:

$$BEE = \frac{Building\ Environmental\ Quality\ \&\ Performance(Q)}{Buidling\ EnvironmentalLoadings(L)}$$

$$Q = 25 * (S_Q - 1), where\ S_Q\ is\ score\ of\ Q\ category$$

$$L = 25 * (5 - S_{LR}), where\ S_{LR}\ is\ score\ of\ LR\ category$$

$$S_Q = 0.4\,S_{Q1} + 0.3\,S_{Q2} + 0.3\,S_{Q3}$$

$$S_{LR} = 0.4\,S_{LR1} + S_{LR2} + S_{LR3}$$

Indicating that the best buildings have lowest environmental load and highest quality, the BEE is rated as *0–0.49 (Class C)*, *0.5–0.99 (Class B−)*, *1–1.49 (Class B+)*, *1.5–2.99 (Class A)*, *and 3.0 and above (Class S).*

HQE (Haute Qualité Environnementale)—France

Haute Qualité Environnementale (HQE), the French environmental building assessment system, was launched in 2005, by Centre Scientifique et Technique du Bâtiment (CSTB), and the system has been continuously revised by L'Association HQE. The HQE aimed to enhance the sustainability of buildings over the whole lifecycle, minimize environmental loadings by construction work, and provide healthy and comfortable buildings. HQE schemes are operated through Certivéa, as subsidiary to CSTB for the certification (NF Bâtiments Tertiaires—Démarche HQE) of office, commercial buildings, hotels, health care, hospitals, and logistics centres. The assessment also covers multi-residential or single-family units. Qualigreen (France) is an alternative to HQE, without certification process. Outside of France, the HQE scheme is operated through HQE Référents. AQUA (Brazilian Alta Qualidade Ambientale is a direct translation of HQE) covers ecoconstruction, comfort, ecoconsumption, quality of the indoor environment, and water supply.

The system comprises both management of operation items (Système de Management de l'Opération, SMO) and quality assurance of the building (Qualité Environnementale du Bâtiment, QEB). The SMO supports management during design and construction stages, such as

(a) Engagement—defining design goals, study location, the concept of utilization of the building, and analysis of profitability;
(b) Construction work—determining schedule and responsibilities;
(c) Supervision of different stages; and
(d) Post-occupancy evaluation—customer satisfaction.

The QEB is assessed on 14 unweighted sub-category areas:

1 Managing the impacts on the outdoor environment;
2 Selection of materials/building elements;
3 Sustainable construction site;
4 Energy;
5 Water demand;
6 Waste management;
7 Adaptability and durability of the building;
8 Hygrothermal comfort;
9 Sound insulation;
10 Optimization of natural and artificial light comfort;
11 Reduction in sources of unpleasant odours/air pollutants;
12 Hygienic aspects;
13 Indoor air quality;
14 Drinking water quality.

One sub-category may be assessed as—Base B (basic: regulation level or standard practice), Performant P (good practice, better than basic) and—Très performant TP (best practice, comparable to the best projects in the country). In order to achieve an HQE certificate, a minimum profile is required covering all sub-categories, that is, (a) TP in at least three sub-categories, (b) P in at least four sub-categories, (c) B in 7 sub-categories (at most), and (d) P or TP in sub-category (Energy). Accordingly, the system can be certified with a relative ranking from pass to exceptional.

DGNB

The Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) was developed by German Sustainable Building Council, in collaboration with the German Federal Ministry of Transport, Building, and Urban Affairs, in 2009 (Birgisdottir et al. 2010). The schemes have been developed for the building types, such as new and existing office and administrative buildings, modernized office, retail, industrial, educational, and residential buildings, hotels, city districts. Since the DGNB schemes have been developed on the premise of the European CEN standards and supported by European initiatives for sustainable building, the DGNB certification covers countries, like Denmark, Austria, Bulgaria, Switzerland, Greece, Spain, Turkey, Slovenia, Ukraine, and also Thailand. DGNB communities include Brazil, China, and Russia.

As a structure, DGNB considers six main categories (Fig. 15.8), such as ecological, economic, socio-economic and functional, technical, process, and site qualities. Each of the first four categories takes up 22.5% of the total score, process quality takes up 10%, and site quality does not give any points, but must be

Fig. 15.8 DGNB assessment categories

documented. The categories consist of multiple criteria, which are weighed and prioritized by their significance. An intrinsic feature of DGNB is the fact that no category can be overlooked about quality.

There are 61 criteria (48 active), and under each criterion, multiple indicators are evaluated; for example, IAQ (criterion 20) may be scored based on indoor concentrations of VOC (<500 to >3000 μg/m^3) and formaldehyde (<60 to >120 μg/m^3). All criteria are loaded with a factor from 0 to 3, against 100 percentage points. There is a minimum, which must be reached for each category for the building to get certified, as *bronze* (50%, levelled at 3), *silver* (65%, levelled at 2), or *gold* (levelled 1.5 at 80%). The current DGNB assessment checklist of new construction office and administration includes the following:

Ecological Quality

1 Global warming potential;
2 Ozone depletion potential;
3 Photochemical ozone creation potential;
4 Acidification potential;
5 Eutrophication potential;
6 Local environmental impact;
8 Sustainable use of resources/wood;
10 Non-renewable primary energy demand;
11 Total primary energy demand, and proportion of renewable primary energy;
14 Drinking water demand and wastewater volume;
15 Land use.

Economical Quality

16 Building-related life cycle costs;
17 Suitability for third-party use.

Sociocultural and Functional Quality

(A) Health, comfort, and user well-being

18–19 Thermal comfort in the winter and summer;
20 Indoor air quality;
21 Acoustical comfort;
22 Visual Comfort;
23 User influence on building operation;
24 Quality of outer spaces;
25 Safety and security.

(B) Functionality

26 Handicapped accessibility;
27 Efficiency use of floor area;
28 Suitability for conversion;
29 Public access;
30 Cycling convenience.

(c) Aesthetic quality

31 Design and urban planning quality through competition;
32 Integration of public art.

Technical Quality

33 Fire prevention;
34 Noise protection, emission controls;
35 Building envelope quality;
40 Ease of cleaning and maintenance;
42 Ease of dismantling and recycling.

Process Quality

(A) Quality of Planning

43 Comprehensive project definition;
44 Integrated planning;
45 Comprehensive building design;
46 Sustainable aspects of tender phase;
47 Documentation for facility management.

(B) Quality of Construction

48 Environmental impact of construction site/construction process;
49–50 Pre-qualification of contractors, and construction quality assurance;
51 Systematic commissioning.

Site Quality

56–57 Site location conditions and risks;
58 Public image and social conditions;
59–60 Access to transportation, and specific use facilities;
61 Connection to utilities.

Comparing several building assessment schemes, Birgisdottir et al. (2010) observed that HQE and DGNB were the two most expensive ones for evaluation and forming the necessary documentation for certification. As regards circular economy (totaløkonomi), BREEAM and DGNB were found suitable, since these schemes include the actual lifecycle cost calculations. DGNB pays attention to both the circular economy of the building and the economic side of sustainability along with the social and environmental aspects (DK-GBC 2014). ESUCO (European sustainable construction database), as a part of the DGNB international system, contains (a) environmental data on over 500 construction materials, (b) country-specific data on the use stage of buildings as heating or cooling, electricity, and services in buildings, (c) production technology of core materials, and (d) data on resources, energy, and preliminary products adapted to average conditions.

Green Star

The Green Star was launched in 2003, by the Green Building Council Australia (GBCA), on the framework of BREEAM (UK). Other schemes are Green Star (New Zealand and South Africa). Green Star has different versions according to building types, like offices, retail, industrial, schools, courts, multi-residential, prisons, and bespoke. The framework of the Green Star reflects the differences between Australia and the UK, due to differences in the climate, local environment, and the construction industry practices. The criteria of assessment are grouped as follows:

- *Management*: Adoption of sustainable development principles from project conception through design, construction, commissioning, tuning, and operation;
- *Energy*: Reduction of greenhouse emissions from building maintenance by addressing energy demand reduction, use efficiency, and generation from alternative sources;
- *Water*: Access or use of potable water through efficient design of building services, water reuse, and substitution with other water sources (e.g., rainwater);
- *Land use and ecology*: Projects impact on its immediate ecosystems, by discouraging degradation and encouraging the restoration of flora and fauna;
- *IEQ*: Environmental implications along with occupant well-being and performance by addressing the HVAC, lighting, occupant comfort, and pollutants;
- *Transport*: Reducing the demand for individual cares by both discouraging small car commuting and encouraging the use of alternative transportation;

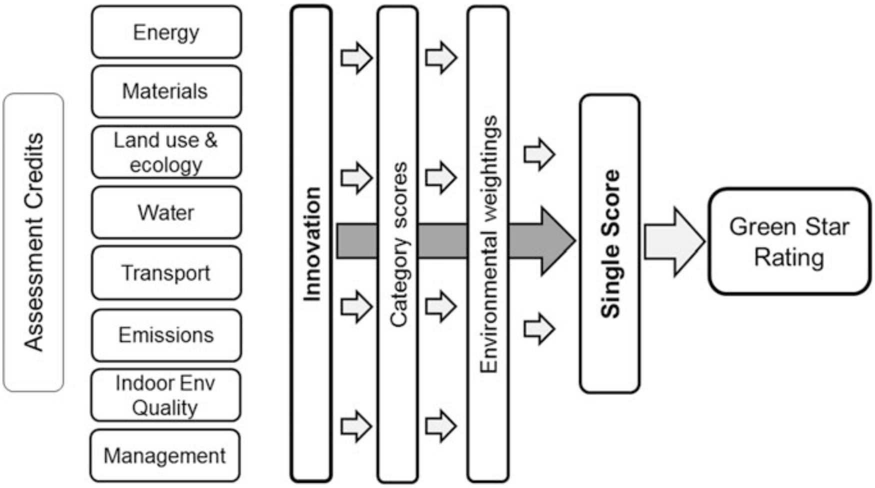

Fig. 15.9 Green Star scoring and weighting

- *Materials*: Resource consumption through material selection, reuse initiates, and efficient management practices;
- *Emissions*: Point source pollution from buildings and building services to the atmosphere, water course, and local ecosystems;
- *Innovation*: Marketplace innovation that fosters the industry's transition to sustainable building.

Compliance with the structured criteria may reflect in reducing a building's impact on the environment. Credits are awarded against with the requirements of each of the criteria, and finally, a percentage score is calculated (Fig. 15.9). Since Green Star applies in large span of climatic zones, the setting of the environmental criteria and weighting factors vary across the states and territories. Green Star includes innovation credits, with a maximum of 5 points, which is added to the weighted score. Like in LEED, Green Star allocates 2 points for the accredited professional status of members of the design team. All self-assessments of a building project are validated through a third-party assessment, and accordingly a Green Star Certification is awarded, based on the rating scores *(10–19), (20–29), and (30–44) as 1, 2, and 3 stars*, *(45–59, 4 Star Best Practice)*, *(score 60–74, 5 Star Australian Excellence)*, *and (score 75–100, 6 Star World Leadership Green Star).*

Green Globes

ECD-Energy and Environment Canada developed Green Globes, an online green building rating, and certification tool in 2002. Similar to many other building rating systems, the genesis of Green Globes was BREEAM (UK). The Green Globes modules cover new construction, existing buildings, major renovation, office fit-ups, operations and maintenance applications, covering different building types, such as offices, hospitals, academic, industrial and sports facilities, hotels, laboratories, and multi-residential buildings. Green Globes is licensed for use in Canada by the brand BOMA BESt (Building Environmental Standards), and the Green Building Initiative, through the American National Standards Institute, ANSI (Reeder 2010). The recent updates to new construction and office fit-ups modules (Green Globes, ANSI/GBI 01–2010) are included herewith. The structure covers several categories of environmental assessment areas, allocating a total of 1000 points.

- Project management (integrated design process, performance goals, environmental management, commissioning) (50 points);
- The site (development area, ecological impacts, rainwater management, landscaping) (115 points);
- Energy (building opaque envelope, lighting, HVAC systems, renewable energy, transportation) (390 points);
- Water (consumption, cooling towers, boilers, water treatment, irrigation, metering) (110 points);
- Materials and resources (building assembly, interior fit-outs, waste, re-use, resource conservation) (125 points);
- Emissions (heating, ozone-depleting and global warming potential) (50 points); and
- Indoor environment (ventilation, source control, and measurement, lighting systems, thermal and acoustic comfort) (160 points).

The Green Globes rating system allows its users to evaluate the systems (self-assessment) based on the applicable available points, with the option of not applicable in some categories. Projects that are third-party verified and have achieved over 35% of the points can earn certification with a rating of 1–4. That is, *1-globe (35–54%); 2-globe (55–69%); 3-globe (70–84%); and 4-globe (85–100%).* BOMA BESt (Canada) certification for existing buildings is rated as *Level 1 (BOMA BESt practice), best practice Level 2 (70–79% score), Level 3 (80–89% score), and Level 4 (90–100% score).*

LEnSE (Label for Environmental, Social and Economic Buildings)

LEnSE, a project abbreviated as Label for Environmental, Social and Economic Buildings, was carried out in 2006/2007 by the Belgian Building Research Institute, aiming at developing a building assessment system for European regions (http://www.lensebuildings.com). The LEnSE methodology was tested in nine European countries, namely, Netherlands, Belgium, UK, Germany, Switzerland, Czech Republic, Greece, Austria, and Italy. The current methodology (residential, office, and mixed-use buildings) includes several sub-issues and categories, grouped under environmental, social, and economic, such as:

Environmental (Total 400 Points)

Building-associated and transport-related depletion of non-renewable energy; Destruction of the stratospheric ozone layer; Use of renewable energy

Climate change (150 points)

Local tropospheric ozone layer;
Minimize point sources of eutrophication;
Land of low ecological value;
Mitigation impact on existing site ecology;
Enhance native plant/animal species.

Biodiversity (100 points)

Habitat management/action plant;
Depletion/use of renewable/non-renewable resources;
Responsible sourcing of materials;
Non-hazardous waste disposal;
Hazardous waste disposal;
Use of freshwater resources;
Re-use of previously developed sites;
Development footprint.

Resource use and waste (100 points)

Contaminated land, bioremediation, and soil reuse;
Certified environmental management system;
Minimizing regional-specific climatological risk.

Environmental management and geophysical risk (50 points)

Minimizing regional-specific geophysical risk.

SOCIAL (240 points)

Lighting comfort (artificial and natural);
Thermal comfort;
Ventilation comfort;

Acoustic comfort;
Occupant satisfaction;
Internal user amenities;
Outdoor space;
Materials/substance exclusion.

Occupants' well-being (75 points)

Indoor air quality;
Avoiding mould from structural work;
Quality of drinking water;
Building safety assessment;
Key amenities—provision and proximity;
Public transport accessibility;
Provision of safe and adequate pedestrian routeways;
Provision of safe and adequate cycle lanes and cyclist facilities.

Accessibility (30 points)

Provision of carpooling facilities;
Site security and spatial arrangement.

Security (65 points)

Building security;
Community impact consultation;
Social cost-benefit analysis;
Socially responsible and ethical procurement of goods/services;
Considerate constructors;
External *neighbourhood* impacts.

Social and cultural value (70 points)

Design quality.

Economic (160 points)

Function analysis.

Financing and management (50 points)

Risk and value management;
Whole life cost (WLC) appraisal—strategic level;
WLC appraisal—component level;
Option appraisal;
Exchange value;
Added value;
Building adaptability.

Whole life value (60 points)

Design for maintainable buildings/ease of maintenance;
Local employment opportunities/use of local services;
Specification/use of locally produced materials.

Externalities (50 points)

Branding and external expression.

Regional Sub-categories—Country-specific (200 points)

The assessment is based on 1000-point (800 points are achievable for the common indicators for all countries, 200 points for country-specific sub-categories). From the total points achieved, the LEnSE labelling of a building project may be presented as A (best possible result) to G scale (worst).

Eu Ecolabel

The European ecolabelling scheme for the building was initiated in 2008, to promote environmental excellence in products and services (http://susproc.jrc.ec.europa.eu/buildings). The EU Ecolabels (Minestrini and Cutaia 2010) may only be awarded to a product having characteristics that contribute significantly to improve vital environmental aspects. The product group *buildings* are considered in its entirety, covering new or existing, public or private, offices and residential, significant refurbishments and renovations (Baldo et al. 2014). The Ecolabel criteria are divided into mandatory (29 items) and optional criteria (25 items), and setting limits on the environmental impacts during different phases of the lifecycle of buildings (project, construction, use and maintenance, refurbishment, end of life). That is, the individual issues covered:

- Energy, water, and materials consumption;
- Waste production and enhance recycling;
- Use of materials with high environmental performances;
- Use of renewable resources and substances that are less hazardous to the environment;
- Indoor health and well-being; and
- Information and education on correct management of the building.

The Green Public Procurement (GPP) criteria for office buildings have been released in December 2016, along with the supporting technical guidance for implementation. The elements of the GPP criteria are listed below:

GPP Criteria

1 Project team competencies;

2 Energy-related criteria

- Performance requirements: minimum energy performance;
- Commissioning of building energy systems; and
- Quality of the completed building fabric.

Lighting

- Performance requirements: lighting control systems and
- Commissioning and handover of lighting control systems.

Building Energy Management System (BEMS)

- Performance requirements: BEMS, and
- Commissioning and handover.

Low or zero carbon energy sources

- Performance requirements for energy supply systems;
- Commissioning and handover of energy supply systems; and
- Heating systems including combined heat and power (CHP).

Facilities energy management

- Reporting on energy use and
- Performance-based energy contracting.

3 Resource-efficient construction

Life cycle performance

- Performance requirements of the main building elements.

Recycled content

- Incorporation of recycling content.

Materials transportation

- Background technical aspects, discussion, and rationale for CO_2 emissions from materials transportation;
- Final criteria proposal following the written consultation.

Timber

- Responsible sourcing of timber construction materials.

Waste management plan

- Demolition waste audit and management plan and
- Site waste management plan.

4 Other environmental criteria

Space/design of facilities

- Recyclable waste storage and
- Waste management system.

Water-saving installations

- Performance requirements for water-saving installations.

5 Office environmental quality criteria

Thermal comfort conditions

- Background technical discussion and rationale;
- Summary of feedback from the stakeholder written consultation; and
- Final criteria proposal.

Daylighting and glare

- Background technical discussion and rationale;
- Summary of feedback from the stakeholder written consultation; and
- Final criteria proposal.

Air quality

- Ventilation and air quality;
- Selection of fit-out materials and finishes; and
- Air quality testing.

At each category of criteria, a uniquely structured check is introduced to identify the *stage of the procurement process at which the criteria are relevant*.

SBTOOL

Green Building Challenge (GBC) is one of the earliest initiatives in promoting awareness on sustainable building and through GBC initiative several major international conferences have been organized (http://www.iisbe.org). International Initiative for a Sustainable Built Environment (IISBE) represents members from about 25 countries. The recently released Sustainable Building Tool (SBTool) is a generic framework, providing logical linkages to a range of issues in different

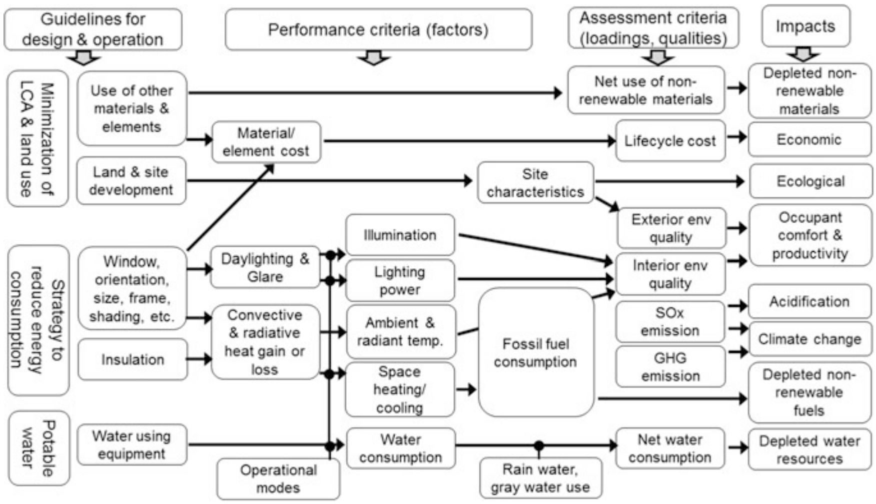

Fig. 15.10 SBTool building assessment framework, showing relationships between design strategies, performance factors, loadings, and impacts

phases of the lifecycle of the building (Larsson 2016). The new version of SBTool is a far deviation in its structure and content to that of the earlier version. Structural principles adopted in the framework of new SBTool (Fig. 15.10) illustrate the relationship between criteria, design strategies or project elements, with performance factors, which are linked to loadings and impacts. The SBTool assumes that, although there may be direct relationships between Performance Factors and Loadings, there may not be any such direct relationship between guidelines and performance factors. As an example, the performance factor daylighting is related to IEQ, under the loadings and quality category, but there are various guidelines and practices to promote good daylighting.

The structure of the SBTool (Larsson 2016) consists of two assessment (site assessment during the pre-design phase, and building assessment during the design, construction or operations phases) (Table 15.3). The site assessment module consists of up to 36 potentially active criteria. Building assessment is subject to weights and benchmarks, including target settings, self-assessed values, and optional third-party verification. Procedurally, one enters target values for scores, in 1/2 point increments up to +5 and then enters self-assessed values based on analysis data available when contract documentation is completed. SBTool includes *integrated design process* guidance, which is not functionally linked to scoring but the parameters are linked for information purposes to score benchmarks appropriately.

It is not within the scope to elaborate the particular construct of the SBTool. However, the issues, categories, criteria, and weightings compiled in Table 15.3 may be useful for the professionals to develop one's variant of assessment (Larsson 2016). For example, energy and resource consumption (category B) is related to resource depletion, while environmental loadings (category C) are related to

Table 15.3 Categories and criteria of SBTool (summated weightings of criteria are taken as the weightings of the sub-categories and categories)

Issues and Categories (S1 to S3), Pre-design Phase Only. (That is, Site Location, Off-site Service availability, and Site Characteristics)	
Issues and Categories (A to G), Design, Construction and Operations phases	
A. Site Regeneration and Development, Urban Design and Infrastructure (weighting: 7.9%)	
A1 Site regeneration and development (weighting: 1.6%, 13 elements)	
	Protection and restoration of wetlands, and coastal environments
	Reforestation for carbon sequestration, soil stability, biodiversity; development of wildlife corridors; remediation of contaminated soil, groundwater or surface water
	Shading of building(s) by deciduous trees; use of vegetation by native plant types; small-scale food production for residential occupants
	Provision of public open space(s), children's play area(s), bicycle pathways and parking, and walkways for pedestrian use
A2 Urban design (weighting: 3.1%, 6 elements)	
	Maximizing the land use efficiency through development density; provision of mixed-use commuting transport
	Building morphology and orientation on the passive solar potential and natural ventilation during the warm and cold season(s)
A3 Project infrastructure and services (weighting: 3.1%, 16 elements)	
	Storage and distribution of surplus thermal energy, photovoltaic energy, hot water, rainwater, and greywater; split grey/potable water services, surface water management system
	Facility to produce energy from solid waste; solid waste collection and sorting services; composting and re-use of organic sludge; On-site treatment of rainwater, grey water, and liquid sanitary waste
	On-site communal transportation system(s), parking facilities, connectivity of roadways for freight or delivery; quality of exterior lighting
B. Energy and Resource Consumption (weighting: 43.1%)	
B1 Total lifecycle non-renewable energy (weighting: 20.5%, 6 elements)	
	Embodied non-renewable energy in construction materials; consumption of renewable and non-renewable energy for building operations, project-related transport, demolition or dismantling process
B2 Electrical peak demand (weighting: 6.2%, 2 elements)	
	Electrical peak demand for building operations; scheduling of operations to reduce peak loads on generating facilities
B3 Use of materials (weighting: 6.6%, 6 elements)	
	The degree of re-use of the existing structure(s); ease of disassembly, re-use or recycling; efficient use of finishing materials; material efficiency of structural and building envelope components
	Use of virgin non-renewable materials
B4 Use of potable water, stormwater, and greywater (weighting: 9.9%, 4 elements)	
	Embodied water in original construction materials; use of water for occupant needs during building operations and irrigation purposes
C. Environmental Loadings (weighting: 28.4%)	
C1 Greenhouse gas emissions (weighting: 12.8%, 4 elements)	

(continued)

Table 15.3 (continued)

	GHG emissions from energy embodied in construction materials, and primary energy used in facility operations, and project-related transport
C2 Other atmospheric emissions (weighting: 0.1%, 3 elements)	
	Emission of ozone-depleting substances, acidifying emissions, photooxidants during facility operations
C3 Solid and liquid wastes (weighting: 4.9%, 5 elements)	
	Solid waste (including non-hazardous waste) from the construction and demolition process; liquid effluents from building operations that are sent off the site; risk of non-radioactive and radioactive wastes
C4 Impacts on project site (weighting: 1.2%, 5 elements)	
	Impact of construction on natural features of the site, soil stability or erosion; changes in biodiversity on the site; adverse wind conditions around tall buildings
	Recharge of groundwater through permeable paving or landscaping
C5 Other local and regional impacts (weighting: 9.4%, 8 elements)	
	Impact of adjacent property on access to daylight or solar energy; UHI effect from roofing, landscaping and paved areas; light pollution from project exterior lighting systems
	Impact of the construction on residents and commercial facility users
	Impact of the public transport system and private vehicles used by building population on peak load capacity of the local road system
	Potential for project operations to contaminate nearby water bodies, cumulative thermal changes to lake water or sub-surface aquifers
D. Indoor Environmental Quality (weighting: 5.0%)	
D1 IAQ and ventilation (weighting: 2.9%, 10 elements)	
	Pollutant migration between occupancies; pollution generated by facility systems, VOCs and CO2 and mould concentrations in indoor air
	The effectiveness of ventilation in naturally ventilated occupancies during cooling, intermediate and heating seasons; air movement in mechanically ventilated occupancies
D2 Air temperature and relative humidity (weighting: 1.2%, 2 elements)	
	Climatic conditions in mechanically cooled occupancies, and naturally ventilated occupancies
D3 Daylighting and illumination (weighting: 0.6%, 3 elements)	
	Daylighting in primary occupancy areas, and control of glare from daylighting; quality of lighting in non-residential occupancies
D4 Noise and acoustics (weighting: 0.2%, 4 elements)	
	Acoustic performance within primary occupancy areas; noise attenuation through the exterior envelope; transmission of facility noise to primary occupancies, and noise attenuation
D5 Control of electromagnetic emissions (weighting: 0%, 1 element)	
	Electromagnetic emissions
E. Service Quality (weighting: 7.3%)	
E1 Safety and security (weighting: 6.5%, 10 elements)	
	Construction safety; security for building users during normal operations
	The risk to occupants from fire, flooding, windstorms, earthquake, incidents of biological or chemical substances, explosion
	Maintenance of core building functions, and occupant egress from tall buildings under emergency conditions

(continued)

Table 15.3 (continued)

E2 Functionality and efficiency (weighting: 0.3%, 8 elements)	
	The functionality of layout, space and fixed equipment, and appropriateness of facility for tenant or occupant needs
	The spatial and volumetric efficiency of buildings; provision of exterior access and unloading facilities for freight or delivery, vertical or horizontal transportation systems in buildings
E3 Controllability (weighting: 0.3%, 4 elements)	
	The effectiveness of facility management control system; Partial operation and personal control of technical facility systems; local control of lighting systems
E4 Flexibility and adaptability (weighting: 0%, 5 elements)	
	The ability for building operator/tenant to modify technical facility systems; adaptability constraints of horizontal or vertical extension of the structure; building envelope, energy supply, and other technical systems
E5 Optimization and maintenance of operating performance (weighting: 0.2%, 9 elements)	
	Operating functionality and efficiency of critical facility systems; adequacy of the building envelope for long-term performance; maintenance management plan, monitoring, and verification of performance; building maintenance log and documentation; skill and knowledge of operating staff; performance incentives in leases or sales agreements
F. Social, Cultural and Perceptual Aspects (weighting: 6.2)	
F1 Social aspects (weighting: 1.8%, 5 elements)	
	Universal access to the site and within the building; access to sunlight, visual privacy in principal areas, private open space
F2 Culture and heritage (weighting: 2.7%, 6 elements)	
	Compatibility of urban design and public open space, with local cultural values; maintenance of the heritage value of an existing facility
	Impact of the design on existing streetscapes; use of traditional local materials and techniques
F3 Perceptual (weighting: 1.6%, 7 elements)	
	Impact of tall structure(s) on view corridors, quality of views; access to exterior views from the interior
	Sway of tall buildings in high wind conditions
	Perceptual quality of site development; aesthetic quality of exterior and interior facility
G. Cost and Economic Aspects (weighting: 1.5%)	
G1 Cost and economics (weighting: 1.5%, 8 elements)	
	Construction cost, operating and maintenance cost, lifecycle cost
	Impact of project on the local economy, land values of adjacent properties; investment risk; the economic viability of commercial occupancies; affordability for rental or cost levels

Source (Larsson 2016), Personal communication—Nils Larsson (2017)

impacts on human health, ecological and climate systems. Generally, like in all other mature rating systems, the weightings are a relative balance between scientific correctness and usability. The weights for individual criteria are required to be structured, making the total of all active weights to 100%. The framework calls for performance benchmarks (minimally acceptable practice, good practice, and best practice) based on comparisons between the characteristics of the object building, and national/international standards or references.

Table 15.4 Green building rating systems in different regions and countries

Rating system and governing body	Building types	Green building design criteria	Certification and rating
TQB (Total Quality Building), Austria, designed in 2002, modified in 2010; http://www.oegnb.net; A Web-based TQB tool is compatible with CEN TC350, and with national systems, such as Klima:aktiv house (http://www.klimaaktiv.at), and IBO ÖKOPASS (http://www.ibo.at/de/oekopass) (Motzl and Fellner 2011)	Non-residential buildings (pre-design, design, and construction stages)	Five criteria (site and facilities, economic and technical performance, energy and water, health and comfort, resource efficiency)	Each criterion allocated up to 200 points (total of 1000 points), against which a project is rated
HK-BEAM Building Environment Assessment Method, 2003, Hong Kong; www.hk-beam.org.hk	New and existing buildings	Site aspects, materials and waste, energy use, water and effluent, IEQ, innovation and performance enhancement	*Overall 40%—Bronze (above average); 55%—Silver (good); 65%—Gold (very good); 75%—Platinum (excellent)*
BCA Green Mark (Singapore Building and Construction Authority, 2005); www.bca.gov.sg	*Buildings*—Non-residential and residential buildings (new and existing), landed houses, existing Schools *Within Buildings*—Office interiors, restaurants, retail, supermarkets, data centres, healthcare facilities *Beyond buildings*—Parks (new and existing), rapid transit system, infrastructure, districts	Energy efficiency, water efficiency, site and project management, IEQ, environment protection and innovation	*50–70 (Certified); 70–80 (Gold); 80–85 (Gold-plus); 85–100 (Platinum);* Prerequisites and additional rating points for each assessment area, for all types of buildings
Green Building Council (Korea) ; www.greenbuilding.or.kr	Multi-unit residential building and office building	Land development, commuting transportation; energy and resource consumption and environment loads; ecological environment; indoor environment quality; supplements	*65 points (excellent); 85 points (best)*

(continued)

Table 15.4 (continued)

Rating system and governing body	Building types	Green building design criteria	Certification and rating
GRIHA, India (Green Rating for Integrated Habitat Assessment), The Energy and Resources Institute, New Delhi, and the Ministry of New and Renewable Energy, Govt of India	Commercial, institutional, and residential buildings (size defined)	Site selection: conservation, and efficient utilization of resources; Building planning and construction: water consumption, energy (operation, embodied and construction, renewable), recycle, and re-use of water, waste management, health and well-being (pollution, ozone depletion, air and water quality); Building operation and maintenance: validation of green performance; Innovation: alternative transportation, life cycle cost analysis	*(1–6 stars)*
TGBRS—Teri Green Building Rating System, India (2003)	New and existing commercial and residential buildings	Site planning, building envelope, building systems, water and waste management and green design practices	*Five-star rating system*
Israel Standard SI—5281: Buildings with reduced environmental impact, 2005	New residential and office buildings	Energy, land use, water use, wastewater, drainage, waste management, air quality, ventilation, radon, and noise	Points system to assess designs; points assigned for provisions of cycle storage, green labelled materials, green roofs, renewables
CEPAS—Comprehensive Environmental Performance Assessment Scheme, the Building Department of the Government of Hong Kong Special Administrative Region (2006)	Pre-design, design, construction, and operation phases of buildings	Human-related factors (IEQ, building amenities, site and neighbourhood amenities); physical factors (resources use, loadings, site and neighbourhood impacts)	*Bronze, silver, gold or platinum awards.* Bonus points awarded for innovation
ENERGY STAR—US EPA; www.energystar.gov	Homes and commercial and industrial buildings, offices, bank branches/financial centres, courthouses, hospitals, K-12 schools, hotels/motels, medical offices, supermarkets, dormitories, and warehouses	Energy efficiency (statement of energy performance)	Obtaining Energy Star rating >75 indicates top performers in energy efficiency; use $\sim$35% less energy than average buildings

(continued)

Table 15.4 (continued)

Rating system and governing body	Building types	Green building design criteria	Certification and rating
EEWH—Ecology, Energy Saving, Waste Reduction and Health, Taiwan; www.taiwangbc.org.tw	Assessed all nine aspects of a building project	Biodiversity, greenery, soil water content, daily energy saving, CO_2 emission reduction, waste reduction, indoor environment, water resource, sewage and garbage improvement	
PromisE—Finnish Environmental Association and Classification system for building, Operated by VTT Technical Research Station	New and existing office, retail and residential buildings	The health of users, consumption of natural resources, environmental loadings, environmental risks. Specific issues include chemical emissions from materials (outgassing), moisture control and ventilation	
Standard 189 (US Standard for the Design of High-Performance Green Buildings), 2007	New commercial buildings and major renovation projects; excludes low-rise residential buildings and existing buildings	Sustainable sites, water use efficiency, energy efficiency, and building's impact on atmosphere, materials and resources, IEQ	Not a rating system; minimum guidelines of green building practices; used in conjunction with ASHRAE standards
GREENSHIP, Indonesia Green Building Council Indonesia (GBCI); www.gbcindonesia.org	New and existing building, interior space, homes, neighbourhood	Appropriate site development, energy efficiency, and conservation, water conservation, material resource and cycle, indoor health and comfort, building environment management	
NABERS—Australia National Australian Building Environmental Rating Scheme (2000), (Mitchell 2010). NABERS replaces Australian Building Greenhouse Rating (ABGR). www.abgr.com.au	New and existing offices, homes, hotels and retail buildings	Energy use, water consumption, waste and indoor environment, with protocols for refrigerants, stormwater run-off, sewage, landscape diversity, transport and occupant satisfaction	*4 stars, 4.5 stars, and 5 stars*

(continued)

Table 15.4 (continued)

Rating system and governing body	Building types	Green building design criteria	Certification and rating
Green Building Index, GBI (Malaysia); www.greenbuildingindex.org	Non-residential and residential new construction and existing buildings	Energy efficiency, IEQ, sustainable site planning and management, materials and resources, water efficiency and innovation	*50–65 (certified), 66–75 (Silver); 76–85 (Gold); > 86 (Platinum)*
Lider A (Portugal)—Sistema de Avaliacao da Sustentabilidade, (2008) (Certification System of Environmentally Sustainable Construction)	Residential, commercial and tourism developments	Local resources, loads, environmental comfort, adaptability, socio-economic issues, environmental management and innovation	
Energy Conservation Building Code (ECBC), 2007, Bureau of Energy Efficiency, India	Air-conditioned and non-air-conditioned office buildings	Energy efficiency standards for design and construction of a building of a minimum conditioned area of 1000 m^2 and a connected demand of power of 500 KW or 600 KVA. A structure having energy performance index (EPI) within 90–200 KWh/m^2/year is termed as *ECBC Compliant Building*	*1–5-star scale.* More stars mean more energy efficiency, rated based on EPI values
Estidama Pearl Rating system, Abu Dhabi, UAE Urban Planning Council (2011)	Office, retail, multi-residential, school, mixed-use, community, vilas	Integrates BREEAM, LEED or Green Star, along with core requirement to adapt to the local climate and culture	*1–5 Pearl*
Perfil de Calidad—Quality Profile (PdC), (Spain); developed by the Instituto Valenciano de la Edificación (IVE); Currently used only in the Valencian Community and Region of Murcia, Spain	New and existing buildings, assessed for all five criteria	Energy saving, environmental protection or sustainability, noise protection, accessibility for disabled people, the functionality of spaces	*High level (Silver, >40); very high level (Gold, >55); minimum requirement—high-level rating in energy saving and environmental protection*

Apart from the assessment schemes described above individually, other schemes that have been applied in non-residential/office building typologies in different regions and countries are compiled in Table 15.4. The list can in no way be considered as the exhaustive; however, the endeavour was taken to review the latest versions of the schemes. There are other building assessment schemes, such as Estidoma (Abu Dhabi), QSAS, Qatar (Sharifi and Murayama 2013), Minergie, Swiss (Beyeler et al. 2009), GB standard (China), GB Label (Taiwan), ESCALE, France (Nibel et al. 2000), Envest2 (BRE), Greenship (Indonesia), PAPOOSE (Programmation et Analyse de Projets d'Ouvrages et d'Opérations Soucieux de l'Environnement), SICES, Mexico (Cole 2012) of related applications. The rating systems, such as BEAT—Danish Building Research Institute (Aalborg University), EcoEffect (1999), and Ecoprofile (1999; Pettersen 2000), are similar schemes for assessment of environmental profiling for buildings, building products, and materials. The author welcomes suggestions from the readers to incorporate newer versions of the schemes in the next edition of this publication.

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Chapter 16
Building Sustainability: Credit Rating Criteria

Introduction

Building sustainability assessment goes far beyond assessing only of building components or products. Since urbanization is vastly expanding, there is an obvious need to explore tools for utility in evaluating neighbourhoods, built environment, transportation, and other allied services, and to support decision-making processes of the stakeholders (Happio 2012; Johansson 2012). The readers from the building and allied environmental professions, urban development planners and property developers who might have only some familiarity with the green building, would be astounded with the enormity and diversity of tools and dimensions incorporated in different global and regional building rating systems. BRE (2004) recorded ~600 tools that evaluated aspects of sustainability, management of rural and natural resources, and the lifecycle phases of buildings from design, construction, operation phase, and post-occupancy monitoring. Apparently, a global set of benchmark parameters would be required in establishing a unified building rating, with due account of national characteristics, regional disparities in climatic and environmental conditions, sociocultural structure, and building stocks of the region (Reed et al. 2011, 2009). Apart from considering all the efforts and goodnesses of green building concept, it is critical that the goal of sustainability of the built environment is well recognized; however, the objective may not be hindered by the absence of a genuinely unified international rating system. The rating systems should correspond to the requirements of the national building codes and regulations, and government regulatory policies, to make the system viable and acceptable to stakeholders. For example, the 2003 EU Energy Performance Directive is compulsory, requiring disclosure of energy performance rather than attaining stringent performance targets.

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Sustainability Construct

Green buildings refer to the structures that aimed at creating energy-efficient, healthy, and productive buildings with minimal adverse impacts on the environment. Under the basic concept of sustainability of buildings, rating and certification have raised awareness of sustainability and sustainable building (Berardi 2012). The building environmental assessment tools illustrate the structural content and parameters for different building typologies and the approaches for evaluation and accreditation of buildings. Apart from the descriptives in the classification of the tools (IEA 2001) and different usage of terminologies, the primary construct (Table 16.1) includes two unique elements, i.e., analytical and valuation aspects in the assessment methodology. The analytical elements cover the characteristics of the buildings referred to as criteria of sustainability with the basic understanding of categories and indicators of assessment. The valuation elements are essentially outcome measures, regarding documented evidence, objectives, and quantifiable dimensions, against which system indicators are weighted and aggregated, indicating the level of system performance.

The readers may refer to, for example, the SBTool checklists to recognize the indicators. That is, in the assessment methodology, attention goes to identifying indicators of assessment, and these indicators are measurable dimensions, as far as possible. Table 16.2 includes an apparent summarization of parameters. Today,

Table 16.1 Basic structure of the assessment methods

Analytical elements	Elements	Description
	Criteria	General characteristics of buildings (such as site selection; public transport accessibility)
	Categories/ subcategories	Criteria summarized to categories and sub-categories (such as health and well-being, IEQ)
	Indicators	Indicators that specify building information into standardized descriptions for comparable evidence (such as a relative reduction in CO_2/VOC emissions; extent of recycled materials used)
Valuation elements	Schedule of evidence	Evidence includes parameters and measuring methods of each criterion (such as estimating daylight, glare factor; energy performance certificate)
	Objectives	Choice of assessment method; objectives are identified for each criterion, using measurable targets. (such as quantitative objectives—primary energy demand, waste reduction; qualitative objectives—conservation of biodiversity, minimization of natural risks)
	Valuation	An extent of achievement for each indicator and objectives; results are reviewed in a rating of the building (for each criterion, a rating scale or benchmarks may be identified)
	Weighting	Defines the criterion and category, using credits, weights, or points (such as the weights and credits may vary in different assessment systems, and the total credits or percentage of total score)
	Aggregation	Weights or credits of multiple indicators are aggregated for an overall assessment of a building project. Accordingly, a green building project may be rated and certified

Table 16.2 Criteria selected for assessment of green building (summarization from different national and international rating systems)

Site/location	Materials	Energy	Water	Process and management	Indoor environment quality	Economic issues	Functionality/ comfort	Innovation
Public transportation	Basic building elements, finishing elements, use of deconstruction materials	Low emission	Reuse/ recycling	Planning	Air quality (pollution)	Costs	Flexibility/ adaptability	Innovation issues considered
Site selection (ecological features, building footprint)	Waste management (non-recyclable and recyclable, composting)	Renewable energy	Water consumption (indoor and outdoor water use)	Construction phase	Daylighting	Life cycle consideration	Access-disabled persons	
Grace/ aesthetics	Robustness	Energy efficiency	Surface water run-off (flood risk)	Commissioning	Acoustics	Value stability	Health, safety, and security	
Bicyclist facilities		Electric demand (internal and external lighting, energy-labelled goods)			Thermal			
		Low carbon			Smell			
		Refrigerant management			Hygiene			

most of the building environmental assessment tools are software-based, structured to the underlying construct. Nguyen and Altan (2011) indicated 382 building software tools are in use for evaluation of energy-efficient building or sustainable design. Needless to mention of the issues raised about the lack of uniformity on the measurable dimensions (Haapio and Viitaniemi 2008; Berardi 2012) that are embedded in different assessment tools.

Refer to Chap. 15, apparently most rating schemes seem to adopt similar approaches and categories of assessment; however, they differ on the framework, weights and scoring methods, and the procedure of performance evaluation. Generally, there are different rating methods in green building evaluation, either on the quantitative and prescriptive basis for the assessment of categories (Srebric and Heidarinejad 2015). For example, the energy and water efficiency are mostly quantitative, whereas the health and safety dimensions, IEQ are primarily prescriptive. Wei et al. (2015) emphasized the strategies of IAQ on green building certifications. From a comparative analysis of five green building rating systems, Wu et al. (2016) highlighted the construction waste management requirement as a fundamental aspect of the process of green building ranking.

One approach is a point-based scoring method, such as in LEED in which each requirement earns points. The sum of all points earned from different elements is the total final score. A second rating method is a weighted approach, e.g., BREEAM. Depending on the perceived importance of the environmental categories, credits are assigned to achieve the required criteria. The aggregated score of the issue categories represents as a percentage score. In some assessment tools (e.g., SBTool), different weighting values are employed for the categories in calculating the total final score. Based on the scoring, buildings are certified as the green building at different levels of accomplishment (four levels in LEED certification, i.e., certified, silver, gold, and platinum; six levels in BREEAM certification, i.e., unclassified, pass, good, very good, excellent, and outstanding), whereas CASBEE has another rating method with complicated ways of evaluation.

CEN/TC 350—Sustainability of Construction Works

Many popular assessment systems, e.g., BREEAM, HQE, DGNB, TQB, conform to guidelines of the CEN/TC 350. Therefore, before describing valuation elements, and credits attached to different indicators of the assessment schemes, the CEN/TC 350 guidelines are briefly elaborated herewith. The CEN (Comité Européen de Normalisation) technical committee, CEN/TC 350, was responsible for developing voluntary horizontally standard methods for (i) assessing the sustainability of new and existing construction works and (ii) environmental product declaration of construction products. The standard, EN 15643-1:2010 is a general framework for assessing the environmental, social, and economic performance of both new and existing buildings, and EN 15643-2:2011 describes the assessment of environmental performance. The environmental dimensions of sustainability centred on assessing environmental aspects and impacts of a building, based on LCA and selected quantifiable indicators, however, with the exclusion of environmental risk assessment. EN 15643-3:2012 and EN 16309+A1:2014 describe the principles, methods, and requirements in assessing the social performance of buildings. The measures of social performance are represented through indicators, such as accessibility, adaptability, health and comfort, loadings on the neighbourhood, safety/ security, materials, and services. EN 15643-4:2012 includes economic aspects within the area of the building site. EN 15978:2011 specifies the calculation method to assess the environmental performance, covering related construction processes, products, and services. The standard describes:

(a) the object of assessment;
(b) the system boundary that applies to the building level;
(c) the procedure used for inventory analysis;
(d) the list of indicators, data, and methods for calculation; and
(e) the presentation of results.

Besides, the ISO has also been active on the environmental assessment of buildings and released a series of standards on sustainability in building construction by the ISO Technical Committee (TC) 59, and its Subcommittee (SC) 17. The standards on sustainability in building construction include general principles and its guidelines on the application (ISO 15392:2008; ISO/TS 12720:2014), sustainability indicators (ISO 21929-1:2011; ISO/TS 21929-2:2015), environmental product declaration (ISO 21930:2017), methods of assessment of the environmental performance (ISO 21931-1:2010; ISO/DIS 21931-2), carbon metric of a building (ISO 16745-1:2017), and the like.

Environmental Indicators (CEN/TC 350)

Reference to the standards cited above, the environmental indicators categorized under environmental impacts, resource use, and other information on waste categories and outputs, are as follows:

Environmental impacts:

Global warming potential (CO_2 equivalent);
Ozone-depleting potential at the stratospheric layer (CFC 11 equivalent);
Acidification potential of soil and water (SO_2 equivalent);
Eutrophication potential ($(PO_4)_3$ equivalent);
Formation potential of tropospheric ozone (Ethene equivalent);
Abiotic depletion potential for non-fossil resources (Sb equivalent); and
Abiotic depletion potential for fossil resources (net calorific value).

Resource use:

Renewable primary energy, and raw material resources (net calorific value);
Non-renewable primary energy, and raw material resources (net calorific value);
Renewable and non-renewable secondary fuels (net calorific value); and
Use of net freshwater.

Table 16.3 Social indicators

Building-related data, during use stage—maintenance, repair, refurbishment, and replacement:	User- and control system-related data for the operation of buildings and its elements during use stage:
(a) Health and comfort: thermal performance, humidity, quality of water in buildings, IAQ, acoustic performance, visual comfort;	(a) Health and comfort: thermal performance, humidity, IAQ, visual comfort;
(b) Safety and security: resistance to climate change, fire safety, security against intruders and vandalism, security against interruptions of utility supply (e.g., electricity, water, heating);	(b) Safety and security: security against intruders and vandalism;
(c) Accessibility: for people with specific needs;	
(d) Maintenance requirement;	(c) Maintenance requirement;
(e) Loadings on the neighbourhood: noise, emissions, glare, shocks/vibrations	(d) Loadings on the neighbourhood: noise, emissions

Note CEN/TC 350—Sustainability of Construction Works

Waste categories:

Hazardous and non-hazardous waste disposed, and
Radioactive waste disposed of.

Output flows:

Materials and components for recycling and reuse;
Materials for energy recovery; and
Exported energy (MJ per energy carrier).

Social Indicators (CEN/TC 350)

Social dimensions of sustainability include the following (Table 16.3).

BREEAM—Quantitative Valuation

For the quantitative valuation of the assessment schemes, the publicly available 2014 version of the BREEAM is reviewed herewith, for credit allocation to different criteria and section categories. The assessment and certification of BREEAM involve deriving credits and weights under environmental issue categories. Each of the issue categories is weighted, as the perceived importance of the environmental issue. Innovation category especially covers the exemplary level of performance in any of the identified categories (Table 16.4). From the aggregated score (expressed as a percentage), the BREEAM rating to a building is awarded.

The criteria description may be transformed into particular variants of checklists for assessment. For reference, the LEED credit points allocated to categories and criteria to different building types are summarized in Table 16.5. There are both prerequisites and credits in LEED, and out of the total of 110 credits, the buildings are rated for certification.

Table 16.4 BREEAM (2014) New Construction environmental sections and assessment issues

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
Management				
Man 01	Project brief and design	4 (min. standard)	1 credit each—stakeholder consultation, and a third party; sustainability champion for design and monitoring in project delivery;	
Man 02	Life cycle cost and service life planning	4	2 credit—elemental lifecycle cost (LCC); 1 credit each—component level LCC plan, capital cost reporting	
Man 03	Responsible construction practices	6 (min. standard)	1 credit each—environmental management, sustainability leadership, utility consumption (energy and water), transport of materials and waste; Max. two credits each—considerate construction, and monitoring of site impacts	1 innovation credit—principal contractor achieves compliance with the criteria in applicable considerate construction scheme (CCS) at an exemplary level of practice (i.e., CCS score >40)
Man 04	Commissioning and handover	4 (min. standard)	1 credit each—commissioning schedule and responsibilities, building services, building fabric, and handover	
Man 05	Aftercare	3 (min. standard)	1 credit each—aftercare support, seasonal commissioning, post-occupancy evaluation	1 innovation credit—operational infrastructure to gather quarterly data for 3 years (occupant satisfaction, energy, and water consumption; analyze building performance and user behaviour; targets and progress in reducing water and energy consumption; feedback on lessons learned)
Health and well-being				
Hea 01	Visual Comfort	5, BTD	1 credit each—Glare control, window viewing, internal and external lighting, zoning and control; Max. 2 credit—daylighting	1 innovation credit for daylighting, such as strategy achieved in controlling disabling glare; Daylighting: uniformity ratio, skyview, room depth criterion met; or at least, 80% of building areas meet 300 lx; min 90 lx daylight illuminance for >2650 h per year

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
Hea 02	IAQ	5, BTD	1 credit each—IAQ plan, ventilation, potential natural ventilation, VOC emission levels (products and post-construction)	3 innovation credits— 1 credit—design of ventilation to minimize the build-up of air pollutants; formaldehyde emission ≤ 0.06 mg/m^3 air; 2 credits—achieving fresh air ventilation, the design of ventilation pathways, formaldehyde emission ≤ 0.01 mg/m^3 air
Hea 03	Safe containment in laboratory	2, BTD	1 credit each—laboratory containment devices; building with containment level 2 and 3 laboratory facilities	
Hea 04	Thermal comfort	3	1 credit each—thermal modelling, adaptability to climate change scenario, thermal zoning, and controls	
Hea 05	Acoustic performance	3, BTD	Max. 3 credits—sound insulation, indoor noise levels, and reverberation times	
Hea 06	Safety and security	2	1 credit each—safe access, security of building site	
Energy				
Ene 01	Reduction of energy use and carbon emissions	12 (min. standard)	Max. 12 credits— Energy performance ratio (EPR) of new construction, against a benchmark; EPR of 0.075 (1 credit), 0.15 (2 credits) and so on. EPR of 0.375 (5 credits—excellent), 0.6 (8 credits—outstanding), and 0.9 (12 credits—zero net regulated CO_2 emissions)	5 innovation credits—Max. 4 credits—building achieves EPR ≥ 0.9; 5 credits—negative carbon building regarding modelled operational energy consumption (regulated and unregulated energy)
Ene 02	Energy monitoring	2, BTD (min. standard)	1 credit each—sub-metering of primary energy consuming systems, high energy load and tenancy areas	

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
Ene 03	External lighting	1	No external lighting, or luminous efficacy of luminaire (>60 lumens per circuit Watt), auto-control of daylight and occupant presence detection	
Ene 04	Low carbon design	3	1 credit each—passive design analysis, free cooling, low carbon technology	
Ene 05	Energy-efficient cold storage	2	1 credit each—energy load in refrigeration, greenhouse gas emissions	
Ene 06	Energy-efficient transportation systems	3	1 credit each—energy demand, energy-efficient features, and regeneration	
Ene 07	Energy-efficient laboratory systems	5, BTD	Prerequisite: risk assessment—health and well-being, safe containment in laboratories; 1 credit—design specification (laboratory containment devices/containment areas); Max. 4 credits—best practice energy-efficient measures	
Ene 08	Energy-efficient equipment	2	1 credit each—identify unregulated energy consuming loads, and demonstrate its reduction through good practice design/specification	
Ene 09	Drying space	1	(Applicable in case of self-contained dwellings)	
Transport				
Tra 01	Public transport accessibility	5, BTD	Max. 5 credits—accessibility Index (proximity and diversity of public transport; frequency of services); or 1 credit—dedicated bus service	
Tra 02	Proximity to amenities	2, BTD	Max. 2 credits—proximity to local amenities	
Tra 03	Cyclist facilities	2, BTD	1 credit each—cycle storage and cyclist facilities, as a ratio to the user population	

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
Tra 04	Maximum car parking capacity	2, BTD	Max. 2 credits—car parking, as a ratio to the estimated user population	
Tra 05	Travel plan	1	1 credit—manage travel and transport for all, including disabled; physical and behavioural measures to increase travel choices	
Water				
Wat 01	Water consumption	5 (min. standard)	Max. 5 credits—potable and non-potable water consumption, the efficiency of water-consuming components; installing greywater/rainwater system; water use in different functional areas	
Wat 02	Water monitoring	1 (min. standard)	1 credit—water monitoring equipment; sub-meters for water demand >10% of total demand; each meter connected to the building management system	
Wat 03	Water leak detection	2	1 credit each—leak detection system, flow control devices	
Wat 04	Water efficient equipment	1	1 credit—identify unregulated water demands, and demonstrate its reduction with good practice design or specification	
Materials				
Mat 01	Life cycle impacts	6, BTD	Max. 6 credits—based on quantified lifecycle impact: assessing building elements—external/internal walls, windows, roof, upper floor slab, floor finishes/coverings	3 innovation credits—refer to Green Guide: elemental approach; (www.thegreenguide.org.uk). 1 credit— >4 more building elements to achieve at least 2 points; or <4 building elements to achieve 1 point. 2 credits—(use of compliant LCA software: whole building approach); demonstrate IMPACT compliant software (or equiv.) benefits to assess and reduce environmental impact

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
Mat 02	Hard landscaping and boundary protection	1	1 credit—$\sim$80% of all external hard landscaping and boundary protection of construction zones achieve A or A+ rating (ref: Green Guide);	
Mat 03	Responsible sourcing of materials (RSM)	4 (min. standard)	Prerequisite: all timber is legally harvested and traded; 1 credit—sustainable procurement plan; Max. 3 credits—RSM	1 innovation credit—TBC% of the available RSM points achieved
Mat 04	Insulation (refer to Green Guide)	1	1 credit—embodied impact. Insulation specified for external wall, ground floor, roof, building services; Example: volume weighted thermal resistance (area of insulation, m^2 $\times$ thickness, m/thermal conductivity, W/m K); or (total amount of insulation used, m^3/thermal conductivity, W/m K) and then multiplied by the Green Guide rating points. Insulation Index: Sum of the rated values for all insulating elements, divided by the volume weighted thermal resistance values	
Mat 05	Designing for durability and resilience	1	1 credit—protect vulnerable parts from damage/exposed parts from environmental effects and material degradation	
Mat 06	Material efficiency	1	1 credit—optimize the use of materials and components (e.g., minimal use of materials, reuse of demolition materials, and use of materials with high levels of recycled content)	

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
Waste				
Wst 01	Construction waste management	4 (min. standard)	Max. 3 credits—construction resource efficiency (for example, 1 credit for ≤ 13 m^3 or ≤ 11 tons waste generated/100 m^2 internal floor area, and every halving of waste generation, additional credit is achieved); 1 credit—diversion of resources from landfill (non-demolition and demolition—70 to 80% volume; 80 to 90% tonnage)	1 innovation credit each— ≤ 1.6 m or ≤ 1.9 tons waste generated/100 m^2 internal floor area; Diversion of resources (non-demolition, demolition and excavation—85–95% volume; 90–95% tonnage).
Wst 02	Recycled aggregates	1	1 credit—recycled and secondary aggregate meet the minimum level; structural frame and concrete road surface (15%), building foundation (20%); bitumen (30%)	1 innovation credit—structural frame (30%), building foundation (35%), concrete road surface (45%), bitumen (75%)
Wst 03	Operational waste	1 (min. standard)	1 credit—dedicated space(s) for segregation of recyclable wastes; accessible to occupants and others for waste deposition and collection; segregating food and organic wastes for delivery to composting facility; predicted daily/weekly volume of waste; water outlet close to the facility for cleaning purposes; compliant operational waste facilities for healthcare buildings	
Wst 04	Speculative floor and ceiling finishes	1	1 credit—speculative floor and ceiling finish for tenanted areas; carpets, floor/ceiling finishes installed for occupants' approval	
Wst 05	Adaptation to climate change	1	1 credit—structural and building fabric resilience;	1 innovation credit—respond to adaptation to climate change;

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
			Appraisal of climate change adaptation strategy over the building's projected lifecycle; risk analysis to identify and mitigate the impact of extreme weather	Hea 04 (prevent increased risks of overheating); Ene 01 (reduce CO_2 emissions, maximize energy efficiency contributing to low carbon emissions); Ene 04 (maximize alternatives for low carbon design); Wat 01 (minimize water demands in periods of drought; at least 3 credits achieved); Mat 05 (design for resilience and robustness; avoid risks of deterioration and high maintenance demands; material degradation credit achieved); Pol 03 (minimize risks of increased flood risk and surface water run-off); flood risk—1 credit achieved; surface water run-off—at least 2 credits achieved.
Wst 06	Functional adaptability	1	1 credit—cost-effective, functional adaptation measures; For example, easy replacement of panels, floors/walls, without affecting the structure; local services accessibility; the ability for refurbishment (replacing façade)	
Land use and ecology				
LE 01	Site selection	2	1 credit—previously occupied land (about 75% of the proposed land area occupied for infrastructure requirement); 1 credit—contaminated land (risk assessment of contaminated site; remediation of pollution)	
LE 02	The ecological value of site and protection of ecological features	2	1 credit—the low ecological value of site; 1 credit—protection of ecological features (site preparation and construction activities)	

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
LE 03	Minimizing impact on existing site ecology	2 (min. standard)	2 credits—change in ecological value 1; the site is equal to or greater than zero plant species; analysis of habitat types, including richness of taxon (plant species); 1 credit—change in ecological value 2; change in the ecological value of the site is less than zero but equal to or higher than minus nine plant species, i.e., a minimal change, as stated above	
LE 04	Enhancing site ecology	BTD	1 credit—ecologist's recommendations in the final design for enhancing site ecology (2 credits in case of prison buildings sites only); 2 credits—increase in ecological value (criteria of the first credit met, and the ecologist confirms implementation of recommendations, to increase the ecological value of the site, with a rise of six plant species or greater; 1 credit—measures include (a) planting of native species, or those benefit local wildlife, (b) adoption of good horticultural practice (e.g., low use of pesticides), (c) installation of bird, bat, and insect boxes at appropriate locations	
LE 05	Long-term impact on biodiversity	2	Max. 2 credits—ecologist confirms that legislation relevant to protection and enhancement of ecology has been compiled. A 5-year plan for landscape and habitat management available with the building owner/occupants; adoption of measures to improve the biodiversity of the sites	

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
Pollution				
Pol 01	Impact of refrigerants	3	3 credits—no use of refrigerant within installed plant/systems of the building; For a building that uses refrigerants: Impact of refrigerant (2 credits) • systems using refrigerants, direct effect lifecycle CO_2 equivalent emissions of ≤ 100 kg CO_2/kW cooling/heating capacity; or • air-conditioning or refrigeration systems installed, and refrigerants have GWP ≤ 10; Impact of refrigerant (1 credit) • systems using refrigerants have direct effect lifecycle CO_2 equivalent emissions of ≤ 1000 kg CO_2/kW cooling/heating capacity; Leak detection (1 credit) • a robust refrigerant leak detection system installed; • the system is capable of isolating the refrigerant(s) charge at the incident of leak detection	
Pol 02	NO_x emissions	3, BTD	Max. 3 credits—(all building types except industrial); where a plant installed for heating and hot water demand: 1 credit— ≤ 100 mg/kWh NO_x emission; 2 credits— ≤ 70 mg/kWh; 3 credits— ≤ 40 mg/kWh	

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
Pol 03	Surface water run-off	5	Max. 2 credits—flood resilience; 2 credits—Low flood risk (risk assessment confirms low annual probability of flooding; 1 credit—medium/high flood annual probability of flooding; Both the building and the site must be ~60 cm above the design flood level of the flood zone; Max. 2 credits—Surface water run-off; Prerequisite is to appoint a consultant to confirm the development's compliance; 1 credit—drainage measure for the peak rate of run-off to a watercourse is not significantly higher for the developed site than it was for the pre-development site. 1 credit—no flooding of property due to the failure of the local drainage system; additional run-off prevented by using infiltration or other sustainable drainage systems; 1 credit—minimizing watercourse pollution; for a low-risk source of watercourse pollution (e.g., car washing), pollution prevention provided. For possible spillage of substances such as petrol and oil, separators or other system are installed in surface water drainage systems. Containment shut-off valves in the drainage systems prevent accidental escape of chemicals from storage devices to natural watercourses	

(continued)

Table 16.4 (continued)

Category	Sections and criteria	Credits	Details of criteria	Exemplary credits
Pol 04	Reduction of night-time light pollution	1	1 credit—external lighting pollution, glowing lighting advertisements are eliminated by effective lighting design, with no compromise to safety and security of the occupants	
Pol 05	Reduction of noise pollution	1	1 credit—noise impacts assessed with reference to existing background noise levels, and any new noise source; noise level from the proposed site/building is no greater than a difference of +5 dB (7 AM to 11 PM), and +3 dB (11 PM to 7 AM), as compared to the background noise level; In places where the noise levels are higher, preventive measures installed to attenuate the noise at its source	
Innovation				
Inn 01	Innovation	10		1 innovation credit for each approved innovation application; Man 03 Responsible construction practices; Man 05 Aftercare; Hea 01 Visual comfort; Hea 02 IAQ; Ene 01 Reduction of energy use and carbon emissions; Wat 01 Water consumption; Mat 01 Lifecycle impacts; Mat 03 Responsible sourcing of materials; Wst 01 Construction site waste management; Wst 02 Recycled aggregates; Wst 05 Adaptation to climate change.

BTD (building-type dependent)

Table 16.5 LEED credit points allocated to categories and criteria to different building types

	Building types							
Category	New construction and major Renovation	Core and Shell	Schools	Retail	Data Centers	Warehouse and distribution Center	Hospitality	Healthcare
Integrative process	1	1	1	1	1	1	1	1
Location and Transportation (LT)	16	20	15	16	16	16	16	9
Neighbourhood development location								
Sensitive land protection	1	2	1	1	1	1	1	1
High priority site	2	3	2	2	2	2	2	2
Surrounding density and diverse uses	5	6	5	5	5	5	5	1
Access to quality transit	5	6	4	5	5	5	5	2
Bicycle facilities	1	1	1	1	1	1	1	1
Reduced parking footprint	1	1	1	1	1	1	1	1
Green vehicles	1	1	1	1	1	1	1	1
Sustainable Sites (SS)	10	11	12	10	10	10	10	9
Construction activity pollution prevention	Pre-Req							
Site assessment	1	1	1	1	1	1	1	Pre-Req
Site development—protect or restore habitat	2	2	2	2	2	2	2	1
Open space	1	1	1	1	1	1	1	1
Rainwater management	3	3	3	3	3	3	3	1
UHI reduction	2	2	2	2	2	2	2	2
Light pollution reduction	1	1	1	1	1	1	1	1
Tenant design and construction guidelines		1						1

(continued)

Table 16.5 (continued)

	Building types							
Category	New construction and major Renovation	Core and Shell	Schools	Retail	Data Centers	Warehouse and distribution Center	Hospitality	Healthcare
Site master plan			1					
Joint use of facilities			1					
Environmental site assessment			Pre-Req					
Places of respite								1
Direct exterior access								1
Water Efficiency (WE)	11	11	12	12	11	11	11	11
Outdoor and indoor water use reduction	(Pre-Req)							
Water metering	(Pre-Req)							
Outdoor water use reduction	2	2	2	2	2	2	2	1
Indoor water use reduction	6	6	7	7	6	6	6	7
Cooling tower water use	2	2	2	2	2	2	2	2
Water metering	1	1	1	1	1	1	1	1
Energy and Atmosphere (EA)	33	33	31	33	33	33	33	35
Fundamental Commissioning and Verification	(Pre-Req)							
Minimum energy performance	(Pre-Req)							
Energy metering	(Pre-Req)							
Fundamental refrigerant management	(Pre-Req)							
Enhanced commissioning	6	6	6	6	6	6	6	6
Optimize energy performance	18	18	16	18	18	18	18	20
Energy metering	1	1	1	1	1	1	1	1

(continued)

Table 16.5 (continued)

	Building types							
Category	New construction and major Renovation	Core and Shell	Schools	Retail	Data Centers	Warehouse and distribution Center	Hospitality	Healthcare
Demand response	2	2	2	2	2	2	2	2
Renewable energy production	3	3	3	3	3	3	3	3
Refrigerant management	1	1	1	1	1	1	1	1
Green power and carbon offsets	2	2	2	2	2	2	2	2
Materials and resources (MR)	13	14	13	13	13	13	13	19
Storage and collection of recyclables	(Pre-Req)							
Construction/demolition waste management planning	(Pre-Req)							
Building life cycle impact reduction	5	6	5	5	5	5	5	5
Product disclosure—environmental product declarations	2	2	2	2	2	2	2	2
Product disclosure—sourcing of raw materials	2	2	2	2	2	2	2	2
Construction/demolition waste management	2	2	2	2	2	2	2	2
Product disclosure and optimization—material ingredients	2	2	2	2	2	2	2	2
PBT source reduction—Hg (Pre-Req)								1
PBT source reduction—Pb, Cd, and Cu								2
Furniture and medical furnishings								2
Design for flexibility				2	2	2	2	1
Indoor Environmental Quality (IEQ)	16	10	16	15	16	16	16	16
Minimum IAQ performance	(Pre-Req)							
ETS control	(Pre-Req)							

(continued)

Table 16.5 (continued)

Category	Building types							
	New construction and major Renovation	Core and Shell	Schools	Retail	Data Centers	Warehouse and distribution Center	Hospitality	Healthcare
Enhanced IAQ strategies	2	2	2	2	2	2	2	2
Low-emitting materials	3	3	3	3	3	3	3	3
Construction IAQ management plan	1	1	1	1	1	1	1	1
IAQ assessment	2		2	2	2	2	2	2
Thermal comfort	1		1	1	1	1	1	1
Interior lighting	2		2	2	2	2	2	1
Daylighting	3	3	3	3	3	3	3	2
Quality views	1	1	1	1	1	1	1	2
Acoustic performance	1		1		1	1	1	2
Minimum acoustic performance			(Pre-Req)					
Innovation (I)	6	6	6	6	6	6	6	6
Innovation	5	5	5	5	5	5	5	5
Accredited professional	1	1	1	1	1	1	1	1
Regional priority: specific credit	4	4	4	4	4	4	4	4
Total credits	110	110	110	110	110	110	110	110

Note Pre-Req prerequisite; PBT persistent bioaccumulative and toxic

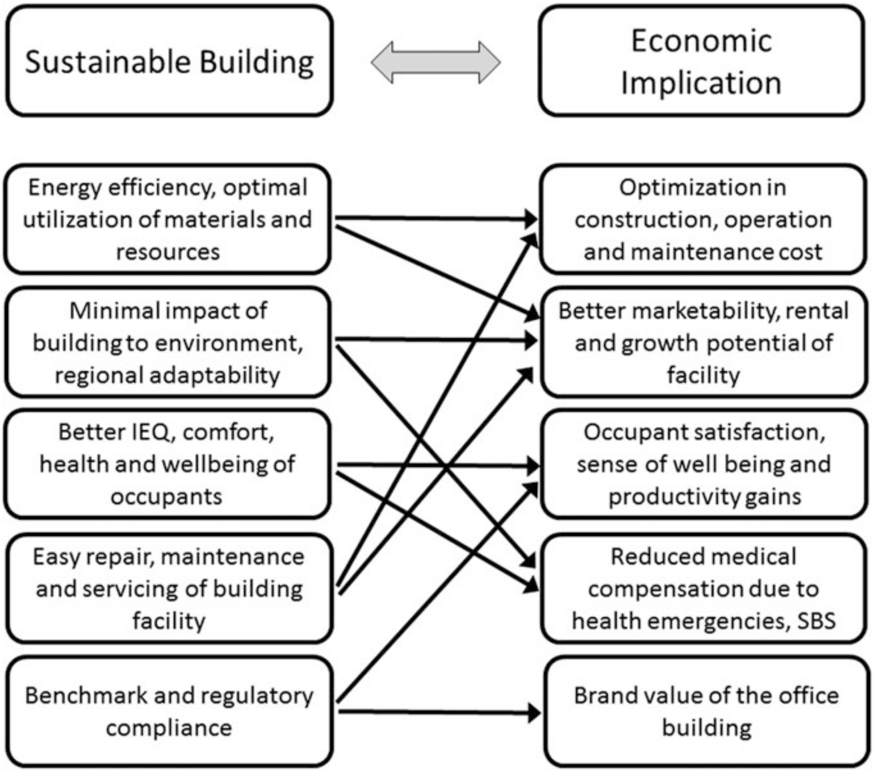

Fig. 16.1 Potential linkages between the sustainable building and its positive economic implications

Prospects and Challenges of Building Rating Systems

Building environmental assessment systems referred to as green building or sustainable building rating systems have come to stay to confirm the environmental credentials of different building typologies. All concerned recognizes the potential implications in adopting the principles of green building, which might go a long way to cope up with the imminent threat of climate change impacts on life, living, and property, and brings substantial benefit to construction activities (Fig. 16.1). Millions of buildings have been officially rated as green building or sustainable building, and the avenue is wide open to bring in fold a much larger sector that falls under the small- and medium-sized building stock both in the developed and in the developing world. The green building schemes have been developed by regional and national building agencies and regulatory authorities, either as a voluntary system, labelling, benchmark, and regulatory guidelines. With the earnest endeavour of the green building councils, there is a recognizable dominance of tools originated from European nations and North America. Revolving around the development of the schemes, one may recognize some visible differences in the system frameworks, influenced by the conceptual differentiation of understanding, region-specific issues, geographical conditions, such as soil conservation and erosion, rainfall, earthquake proneness of a region, hotter or cooler climates, building technology adoption, and environmental performance yardsticks.

International Consensus—Since long, there has been an endeavour in defining and characterizing the concept of green building. It is aptly understood that a technical or scientific definition, to be useful, must be directed towards for whom it is intended so that the broad meaning of the description and its characterization is interpretable. The system frameworks of available schemes bring considerable shades of difference to get a unified understanding. An assessment or rating system is a planned, documented and verifiable process of managing environmental aspects and impacts, with the deliberate linking of the indicators that govern the way for a quantifiable expression of environmental effects in a building or a building site. Therefore, the rating systems that are sufficiently universal are required to carry potentials to obviate adjustments of regional and territorial effects and building types. Currently, there is complete neglect of attention required for the human settlements and economic activities in the congested urban and suburban locale of small cities and town all over the populous countries.

International standardization and uniform conditions in environmental and energy performance certification intended to enhance the comparability, transparency, coherence, reliability, and accuracy of assessment of buildings, across countries. The CEN/TC 350 and allied EN and ISO standards on sustainable construction works are the acceptable foundation to harmonize and unify the rating schemes. The Energy Performance of Buildings Directive (EPBD) of the European Commission (2002, 2010) is an effort to adopt a common scheme to achieve energy performance in non-residential buildings. Sustainable Building Alliance (http://www.sballiance.org), member grouping from BRE, USGBC, DGNB, HQE, Effinergie, and others, addresses to setting common metrics, indicators and minimum standards for performance of buildings, and developing more commonality among the voluntary rating systems. A unified understanding of the compatibility and utility of different schemes can be an avenue for trans-national building agencies to adopt dual or multiple certifications, following guidelines of regulatory provisions and local requirements in the respective countries (BRE 2008). Sharing the best practice of one country to another and one rating scheme to another would perhaps the first step towards achieving international consensus in building sustainability.

Regional Priority—Regional or country-specific variations in building rating systems are distinct, due to widely different climatic and geographical conditions in the regions. BREEAM in the UK has a higher emphasis on land use and ecology, and population density. The northern UK has abundant rainfall, and thus, water economy is not a challenging issue in contrast to those in arid countries. The water conservation in Green Star (Australia) is a priority measure, because of the drought considerations in the region. Soil conservation and erosion are concerns in Taiwan and regions of India. The North American and many areas of Europe emphasize

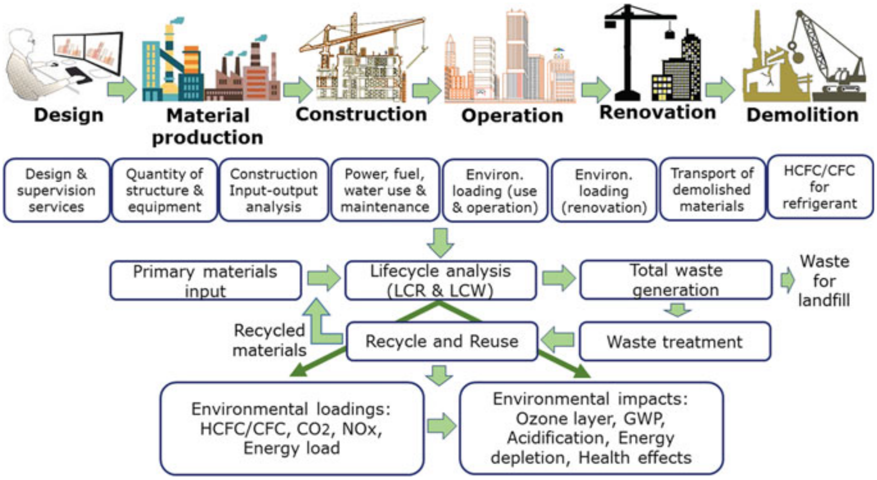

Fig. 16.2 Life cycle phases in a building project

requirements for energy-efficient heating systems, because of the extreme cold climate in regions. These considerations are not very relevant in the tropical areas of Asia for most of the year. Both LEED and BREEAM have similar scores for energy and transport, while the BREEAM emphasizes reducing CO_2 emissions that caused by energy consumption in buildings, and LEED focuses on lowering expenses on energy in buildings. The DGNB system has a balanced approach to both financial concerns and environmental issues. The regional disparities are partly obviated in BREEAM, LEED, for example, that establishes building-type-dependent minimum standards (BREEAM) or prerequisites (LEED).

Life cycle analysis (LCA)—A building may comprise about 60 primary materials and about 2000 separate products, and all of them having different predicted service lives. Therefore, the impact of building materials is very decisive for sustainable building management in the overall life cycle of buildings. Further to the description given in Chap. 15, the environmental loading and impacts in the entire life cycle of the building are schematically depicted in Fig. 16.2. Among the assessment schemes elaborated in Chap. 15, both BREEAM and LEED use LCA for its evaluation, wherein LEED uses a checklist approach to assess the embodied impact of the materials. LCA is optional in the CASBEE rating system since it does not impact the Building Environmental Efficiency (BEE) assessment. CASBEE applies the concept of eco-efficiency as BEE distinguishing between the quality of building performance and the building environmental loadings.

The SBTool incorporates materials credits based on attributes. The Green Building Initiative and Green Globes in its resources section include LCA. Giama and Papadopoulos (2016) evaluated building rating schemes through an LCA methodology. The study focused on the role of environmental evaluation of construction materials. About the Malaysian Green Building Index, Dodo et al. (2015)

examined the impact of three green products of Nippon Paint. As described in Chap. 15, life cycle resource (LCR) and life cycle waste (LCW) indices (Sato et al. 2005, 2006) were used for assessing resource sustainability in buildings, with reference to both upstream (construction and renovation), and downstream (construction, renovation, and demolition) processes in the life cycle of a building. However, given constraints in obtaining LCA data of materials and energy criteria, all critical requirements of LCA are not included in many of the matured green building rating systems and codes.

Categorizing and comparing the rating systems—The present discussion is limited to assessment frameworks, contents and characteristics, and credit rating criteria of different schemes. These schemes have been developed for different purposes, for example, research, consulting, decision-making, and maintenance. The user groups also vary to a great extent, such as designers, architects, researchers, consultants, public and private sector owners, tenants, and regulatory authorities. By categorizing the tools, any similarities and the differences in the content and characteristic of the schemes can be utilized for its emendation. Many of the proprietary tools have modules matching to the requirement of certain types of buildings (residential or non-residential, new or existing); for example, BREEAM, LEED, and CASBEE, DGNB have modules for different building types. BREEAM does not cover demolition, but they do cover disposal.

Comparison of the criteria and indicators are often tricky across the schemes (Haapio and Viitaniemi 2008), and also the corresponding database influence the values of the indicators that a particular scheme subscribes for its rating. Since there is a gross lack of uniformity in data and analysis, the comparison of schemes, claims, and counterclaims of relative superiority are parochial or at best, matters of esoteric interest. For example, with regard to an emphasis on IEQ of buildings, a primary premise is that building performance depends to a great extent on the health and well-being of the occupants. BREEAM has health and well-being category covering IEQ issues, whereas LEED has IEQ category.Apart from some variations in the methods of analysis and scoring, the green building schemes generally focus on IAQ, thermal comfort, visual comfort, including daylighting, acoustic performance, private space (Lee 2010).

That is, by choosing a scheme, the subscriber has been forced to a set of guidelines, like definitions, weighting or scoring systems, and databases. There are apparent discrepancies in the descriptions regarding criteria and categories, and calculations. Confusion or uncertainty prevails in the meaning and interpretation that may finally affect the environmental performance on equivalent scale (e.g., recommended illumination levels for office environment vary widely in different national standards). That is, the basis of ratings or credits may not be straightforward, because of its dependence on different databases and guidelines (Dixon et al. 2008). In BREEAM, each category allocated credits, which can be awarded all or none. CASBEE uses a more complicated weighting, and some indicators weighted according to benchmarks set by the prevailing regulatory provisions, guidelines, and expected practice. In CASBEE, LCA is included in the first phase of the building project. However, it places no role to arrive at BEE assessment. For Green Star and DGNB, a third party establishes a benchmark for different criteria. Green Globes uses the EPA Target Finder for energy benchmark. The US Green Building Initiative suggests a third party to train and authorize evaluators. Also, the ranges of indicators included in the assessment are very different in most of the assessment schemes.

BRE (2008) compared different assessment schemes (BREEAM, LEED, Green Star, and CASBEE) about the launch date, governance, assessment rating scales, credit interpretation, qualification of assessors, third-party validation, certification fees, and maturity of the scheme. Observations suggest inconsistencies on the levels of equivalence in different schemes; for example, a Green Star (six-star level, world leadership) is less sustainable than a LEED (platinum rated), which are again not equivalent to BREEAM (excellent rated). The readers may note that the process of certification varies in different systems. Whereas BREEAM and CASBEE has a six-stage process to certification, LEED has eight, and Green Star has nine steps (BRE 2008). Limitation remains in most of the current rating systems, as regard to its less emphasis on the design of interiors spaces, and complete neglect to workplace design and layout, and building ergonomics. Several studies on LEED-rated buildings (Fuerst and McAllister 2011; Dermisi 2009; Kok et al. 2012) emphasize that a high-performance building reduces absenteeism, increases occupant productivity, satisfaction and well-being, and also raises brand and market property value. Generally, occupancy rates and personal satisfaction were found to be higher and more stable in certified green buildings than those occupants in non-accredited office buildings (Preston 2008). Greater satisfaction of occupants was associated with office furnishings, IAQ, and job performance in personal workplaces (Lee and Kim 2008; Lee and Guerin 2009).

In general, the apparent distinctions are vivid in different building rating systems, since there are regional disparities in construction practices, challenges to bring compatibility in national building codes, possible regulatory issues, limitations of uniform auditability and international credibility of the schemes and models. Many comparative studies indicate the above-stated limitations, which remain at the core to arrive at a globally harmonized strategy on building performance. The future of building sustainability draws upon the fundamental concern to obviate multiplicity of the system frameworks. The obvious imperative is to evolve a system framework that is mutually compatible and aligned to regional requirements and building typologies. The system framework is embedded with a mechanism to manage continual improvement in building performance seamlessly, minimize environmental impact, and set credible standards and objective measures to judge a building's effect on the environment. A potential approach is to harmonize the building rating systems and apply simulation-based tools for compliance, with the active support of the predominant market players across sectors. Anticipation is alive that the green building initiative receives more extensive visibility and acceptance among the stakeholders for synergized application in the building sector in the developed as well as in the developing countries.

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