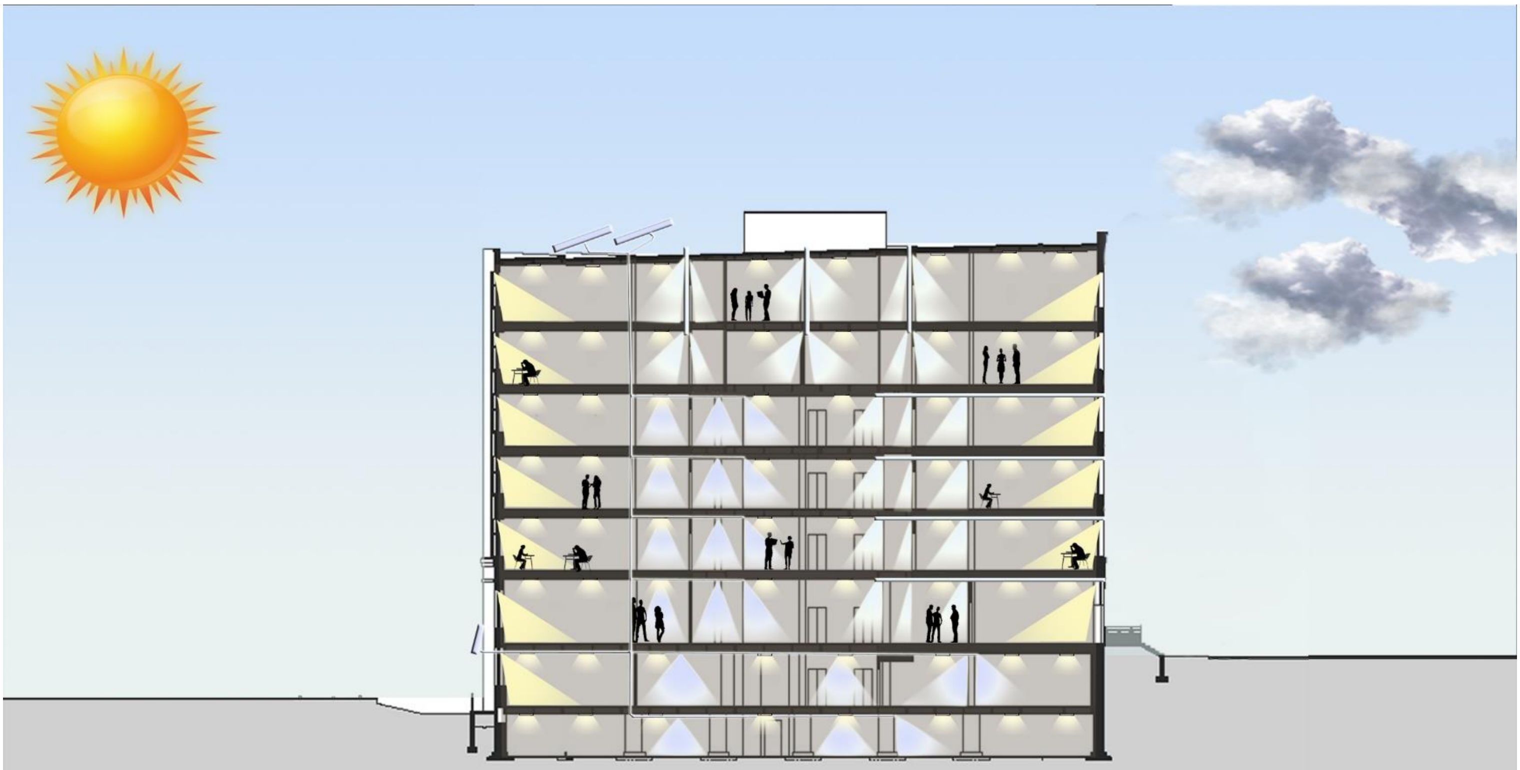
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Literature review-Energy saving potential of user-centered integrated lighting solutions



IEA SHC Task 61 / EBC Annex 77: Integrated Solutions for Daylighting and Electric Lighting

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- Solar District Heating (Tasks 7, 45, 55)
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- Solar Thermal & PV (Tasks 16, 35, 60)
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Literature review - Energy saving potential of user-centred integrated lighting solutions

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PREFACE

Lighting accounts for approximately 15 % of the global electric energy consumption and 5 % of greenhouse gas emissions. Growing economies, higher user demands for quality lighting and rebound effects as a result of low priced and more versatile electric lighting continuously still lead to an absolute increase of lighting energy consumption. More light is used, often less consciously.

Especially the electric lighting market but as well the façade, daylighting und building automation sectors have seen significant technological developments in the past decade. However these sectors still act mainly independent of each other, leaving out big potentials lying in a better technology and market integration. This integration is on the one hand beneficial to providing better user-centred lighting of indoor spaces. On the other hand it can contribute significantly to the reduction of worldwide electricity consumptions and C02-emissions, which is in line with several different governmental energy efficiency and sustainability targets.

IEA SHC Task 61 / EBC Annex 77 "Integrated Solutions for daylighting and electric lighting – From Component to system efficiency" therefore pursues the goal to support and foster the better integration of electric lighting and daylighting systems including lighting controls with a main focus on the non-residential sector. This includes the following activities:

- Review relation between user perspective (needs/acceptance) and energy in the emerging age of "smart and connected lighting" for a relevant repertory of buildings.
- Consolidate findings in use cases and "personas" reflecting the behaviour of typical users.
- Based on a review of specifications concerning lighting quality, non-visual effects as well as ease of design, installation and use, provision of recommendations for energy regulations and building performance certificates.
- Assess and increase robustness of integrated daylight and electric lighting approaches technically, ecologically and economically.
- Demonstrate and verify or reject concepts in lab studies and real use cases based on performance validation protocols.
- Develop integral photometric, user comfort and energy rating models (spectral, hourly) as pre-normative work linked to relevant bodies: CIE, CEN, ISO. Initialize standardization.
- Provide decision and design guidelines incorporating virtual reality sessions. Integrate approaches into wide spread lighting design software.
- Combine competencies: Bring companies from electric lighting and façade together in workshops and specific projects. Hereby support allocation of added value of integrated solutions in the market.

To achieve this goal, the work plan of IEA SHC Task 61 / EBC Annex 77 is organized according to the following four main subtasks, which are interconnected by a joint working group:

- Subtask A: User perspective and requirements
- Subtask B: Integration and optimization of daylight and electric lighting
- Subtask C: Design support for practitioners (Tools, Standards, Guidelines)
- Subtask D: Lab and field study performance tracking
- Joint Working Group: Evaluation tool & VR Decision Guide

Subtask D demonstrates and assesses, and either verify or reject, currently available and typically applied concepts for daylighting and electric lighting design and their integration to better understand how various integrated lighting systems and their control mechanisms behave with respect to several important parameters (e.g., energy use, thermal and visual environment, maintenance, adaptability to new requirements, etc.) and how building users respond to them. Work includes a comprehensive literature review of relevant research materials (in close collaboration with Subtask A.1), targeted medium-term experiments in several living laboratories, supplemented by short-term investigations of specific concepts or ideas in controlled research laboratory environments, as well as performance tracking through "real" field studies in recently completed or retrofitted buildings across selected building types in several of the participating countries. Case studies were selected in close collaboration with other Subtasks.

Subtask D project areas:

- D.1. Literature Survey: Quantifying Potential Energy Savings
- D.2. Monitoring Protocol
- D.3. Case Studies: Living Laboratories and Real Buildings
- D.4. Lessons Learned – Guidance to Decision Makers

EXECUTIVE SUMMARY

Measures for the reduction of electric energy loads for lighting have predominantly focussed on increasing the efficiency of lighting systems. This efficiency has now reached levels unthinkable a few decades ago. However, a focus on mere efficiency is physically limiting, and does not necessarily ensure that the anticipated energy savings actually materialize. There are technical and non-technical reasons because of which effective integration of lighting solutions and their controls, and thus a reduction in energy use, does not happen.

This literature review aims to assess the energy saving potential of integrated daylight and electric lighting design and controls, especially with respect to user preferences and behaviour. It does so by collecting available scientific knowledge and experience on daylighting, electric lighting, and related control systems, as well as on effective strategies for their integration.

Based on this knowledge, the review suggests design processes, innovative design strategies and design solutions which – if implemented appropriately – could improve user comfort, health, well-being and productivity, while saving energy as well as the operation and maintenance of lighting systems. The review highlights also regulatory, technical, and design challenges hindering energy savings.

Potential energy savings are reported from the retrieved studies. However, these savings derived from separate studies are dependent on their specific contexts, which lowers the ecological validity of the findings. Studies on strategies based on behavioural interventions, like information, feedback, and social norms, did not report energy saving performance. This is an interesting conclusion, since the papers indicate high potentials that deserve further exploration. Quantifying potential savings is fundamental to fostering large scale adoption of user-driven strategies, since this would allow at least a rough estimation of returns for the investors. However, such quantification requires that studies are designed with an inter-disciplinary approach.

The literature also shows that strategies, where there is more communication between façade and lighting designers, are more successful in integrated design, which calls for more communication between stakeholders in future building processes.

Contents

1 Introduction

1.1 Energy Use Associated with Lighting in Buildings

Measures for the reduction of electric energy loads for lighting have predominantly focussed on increasing the efficiency of lighting systems. This efficiency has now reached levels unthinkable a few decades ago. However, a focus on mere efficiency is physically limiting, and does not necessarily ensure that the anticipated energy savings actually materialize. There are technical and non-technical reasons because of which effective integration of lighting solutions and their controls, and thus a reduction in energy use, does not happen.

On the non-technical side, design of daylighting and of electric lighting occur at different phases of the overall building design process; and are usually completed by different building professionals. The design of daylight openings and selection of glazing products typically falls in the architect's domain, and is part of the earlier design phases; whereas electric lighting design is most often performed by electrical engineers and happens much later in the design process.

At times, especially – but not solely – for speculative buildings for which the future owners are not known during the design phase, a clear understanding of occupancy type and profile can be missing – which makes it difficult to select appropriate technologies and strategies for lighting systems and lighting controls. In addition, calibration and commissioning procedures are often not implemented or not implemented effectively, especially when delays in construction lead to difficulties in completing a building on time. It can also be observed that originally specified electric lighting and control systems are downgraded in later phases of the construction process, in order to make up for cost overruns associated with construction of other building elements. High-quality lighting systems might then be substituted with similar looking, but not necessarily similarly performing ones at lower cost. Such substitution can undoubtedly lead to decreased user satisfaction and increased energy use.

On the technical side, the lack of integration is often due to the very limited availability of shared communication protocols between controls for daylighting and electric lighting, or the lack of compatibility between the various available technologies. Here, action is needed to enhance opportunities.

Commercially available technologies for daylighting and electric lighting are currently undergoing rapid changes, increasing the need for newer approaches towards design and implementation of integrated lighting and control systems in buildings. While the IEA SHC Task 61 Subtask A.1 focused mostly on the requirements for user-centred integrated lighting solutions, this Subtask D.1 paid particular attention to how these various systems and user interactions with them affect energy use related to lighting in both new and existing buildings. It identifies key aspects for lighting control decisions with respect to daylight use, control strategies, control interfaces, feedback systems, rebound effects and social norms regarding user behaviour and makes recommendations for further research.

Special attention, for example, might be paid to the calibration and commissioning procedures to ensure proper operation of lighting control systems, as well as to achieve the expected energy savings. Unsatisfactory (e.g., too complex) or unexpected operation (e.g., at undesired times or too often/seldom) of lighting and shading control systems can lead to undesirable interventions by building users; and could thus significantly increase the building's energy use for lighting and other processes (e.g., heating and/or cooling loads), and may also affect longer-term comfort. Conversely, an intuitive feedback to the user by a control system, can incentivise the user to take potential energy savings seriously.

The available literature was thus reviewed to:

- pinpoint the actual potential for energy savings associated with the implementation of smart and innovative lighting control systems that integrate daylight and electric lighting, and to
- identify appropriate design and implementation strategies in recently published research and case study reports.

In addition, solutions particularly suitable for achieving high amounts of user comfort and satisfaction, as well as significant energy savings, were identified. Whenever possible, the strategies and behaviours discussed are supported by quantitative data. For all these activities, close collaboration and discussion with relevant industry representatives was sought, including with architects, building engineers, designers and building managers.

1.2 Objectives of the Literature Review

The document presented here is primarily intended for designers of user-focussed integrated daylighting and electric lighting systems.

It aims to provide architects, building engineers, lighting designers and other building professionals; an overview of the latest advanced concepts coupled with supporting findings from research (Section 2), and the inferred guidance (Section 3) – for successful inclusion of appropriately integrated daylighting and electric lighting (including control systems). This intention from this inclusion is towards meeting desired quality criteria for health, comfort, performance and well-being of building occupants, as well as leading to significant savings for lighting and related building energy use.

In addition, the document can be used by:

- future building owners, managers or occupants intending to engage building professionals in designing a new building, while preparing themselves to provide specific instructions to the designer(s) and asking the right questions, and
- users already occupying a building who wish to suggest improvements for integrating the daylighting and electric lighting systems already in place in their building or space.

The literature review has the following purposes:

- To assess the energy saving potential of integrated daylight and electric lighting design and controls, especially with respect to user preferences and behaviour,
- To collect available scientific knowledge and experience on
  - Daylighting, electric lighting, and related control systems
  - Effective strategies for their integration

Based on this knowledge, the review suggests:

- Design processes, innovative design strategies and design solutions which – if implemented appropriately – could improve:
  - User comfort, health, well-being and productivity
  - Energy savings
  - Operation and maintenance of lighting systems

In this literature survey, peer-reviewed studies, mainly published in the last decade, were collected and critically evaluated. The search keywords were gathered from an appraisal based on the contributions of 30 lighting experts with different competences and areas of expertise. The keywords were entered into relevant databases - e.g. Scopus, Web of Science and IEEE Xplore - in order to retrieve a first set of fundamental papers. Other papers were gathered via cross-referencing from the first set of publications. The papers were grouped by topics according to the strategies they described. Based on the findings, a reasoned estimate of potential energy savings was established for each group of topics/strategies. Topics and strategies included both electric lighting and daylighting, with emphasis on integrated systems and solutions.

2 Daylighting and Electric Lighting Systems

2.1 Daylighting

This section is intended as a general introduction to some of the issues associated with the selection of appropriate systems for daylighting and lighting, and strategies for their integration in a building. For this reason, we attempt to connect daylighting design decisions with other considerations affecting user comfort and building energy use in a generic manner before getting into details.

Various authors (Moore, 1985; Meek and Wymelenberg, 2014; Lechner, 2015; Dubois, Gentile, Laike, Bournas and Alenius, 2019) have published well-written books or chapters on the subject of daylighting design, and the readers of this review are encouraged to delve deeper into these and other related works. Similar publications can be found in many regions and in other languages than English, often with a particular view of addressing the specific requirements of the prevalent climate and vernacular building traditions. Many of the considerations for daylighting design echo human preferences and desires; and should not come as a surprise to well-educated and thoughtful designers. Good daylighting design is an essential prerequisite for integrated design of lighting and lighting control systems. Daylighting should therefore be addressed very early in the design process, but alongside all other aspects of lighting design. Electric lighting and lighting controls need to be evaluated and planned in unison with daylighting strategies to allow for effective integration.

Daylighting is a technique used to provide daylight to the building interiors. There are numerous ways of providing daylight inside a building using architectural design elements (Baker, Fanchiotti and Steemers, 2013) and daylighting systems (Arnesen, 2003). Those daylighting elements and systems have the role of either providing daylight into the building, or of shading from direct sunlight, and in many cases both. Vertical windows in the façade are the most frequent strategy used for daylight delivery, and Venetian blinds are a simple and frequently applied strategy for shading and daylight redirection (Kolås, 2013). Daylight openings in roof surfaces can also be employed, and shading devices can take many forms – from adjustable roller blinds to fixed architectural elements such as overhangs or light shelves.

The daylighting strategy employed in a particular building depends on the building's construction and functionality, as well as orientation, location (latitude), site and physical outdoor conditions. Many authors have discussed suitable methodologies for assessing this issue, both theoretically and through computer simulations (Littlefair, 1991, 2001; Compagnon, 2004; Dekay, 2010; Strømann-Andersen and Sattrup, 2011; Mardaljevic and Janes, 2013; Sattrup and Strømann-Andersen, 2013).

Human preferences for daylight and view are essentially associated with windows placed in such a way, that a view to the exterior is possible and attractive. It is a recurrent discussion in the building industry whether proximity to windows and view availability could yield higher profitability to building developers. Studies have confirmed (Boyce, Hunter and Howlett, 2003; Veitch and Galasiu, 2011), that people's desire for and appreciation of daylight, is much higher than that associated with the best designed electric lighting. The variation of daylight intensity, colour, and direction are the main reasons for people's preference for daylight, along with its ability to create a pleasant atmosphere in any interior space. Daylight is the preferred light source for psychological and visual comfort, general health and wellbeing. In many studies in the last decade, majority of the participants agree that daylight provides better office appearance and pleasantness, and better colour appearance of interior furnishings. Additionally, it leads to better work performance, particularly for jobs that require fine observation.

In past decades, daylight has been studied for its visual effects on humans, but lately there has been increased focus on its non-visual effects. The reason for this, is that research has demonstrated (Brainard, Hanifin, Greeson, Byrne, Glickman, Gerner and Rollag, 2001; Thapan, Arendt and Skene, 2001; Rea, Bullough and Figueiro, 2002; al Enezi, Revell, Brown, Wynne, Schlangen and Lucas, 2011; Lucas, Peirson, Berson, Brown, Cooper, Czeisler, Figueiro, Gamlin, *et al.*, 2014) the existence of photoreceptors in the human eye that are sensitive to a particular part of the light spectrum and affect the human biological clock or circadian rhythm. The human circadian rhythm, which is controlled by the production of melatonin and cortisol hormones in the body, is responsible for many physiological processes in the human body. As people spend up to 90% of their time indoors, daylight harvesting in buildings and the provision of daylight exposure for building occupants has become an important component in the design of healthy buildings. Due to this, there has also been a focus in the lighting industry to develop more comprehensive lighting systems that better respond to the occupants' circadian needs. Such lighting systems are termed human centric lighting, and have been designed to imitate those non-visual features of daylighting that have a direct impact on the human circadian rhythm (Perez, Strother, Vincent, Rabin and Kaplan, 2019).

Daylight has many effects on wellbeing, which undoubtedly increases human performance and productivity (Juslén and Tenner, 2005). Since presence of daylight positively influences the visual effect of a workspace, work performance can be directly connected to daylight; and this raises the issue of profitability of investment in daylighting systems, through improved organizational productivity. Some studies (Fontoynont, 2002) have addressed this issue, and have shown that the gain in productivity through investment in daylighting systems is much higher as compared to the capital costs.

Daylight harvesting in buildings has also been used as a strategy for energy savings. Many studies: both, theoretical (through simulations), and practical (using full-scale experiments), have demonstrated that daylighting delivered through windows and skylights can save energy by reducing the need for electric lighting. Studies have shown that savings of up to 20-40% in electric lighting can be expected, if a daylight responsive dimming control is used in offices (Opdal and Brekke, 1995; Galasiu, Atif and MacDonald, 2004; Li, Lam and Wong, 2006; Galasiu, Newsham, Suvagau and Sander, 2007). There can be additional savings of at least 50% if the building has automated shading solutions, in combination with the daylight responsive lighting controls (Galasiu, Atif and MacDonald, 2004; Lee and Selkowitz, 2006; Bülow-Hübe, 2007; Galasiu, Newsham, Suvagau and Sander, 2007) . Even higher savings can be expected for daylight systems that are customized for a particular building, taking into consideration its site and solar conditions. Some studies (Fontoynont, 2008) have shown a lower investment and maintenance cost for daylighting systems, as compared to electric lighting, which is a good argument for policy makers.

2.1.1 Daylight Openings

Climate conditions coupled with our work and living practices, require us to spend major portions of a typical day inside buildings, which are more-or-less enclosed. Openings in the building skin are regarded as essential elements of an architecture that responds to human needs. With these openings, we associate daylight for illuminating our work and living quarters, connecting views with our immediate surroundings; and ventilation with air to breathe. But the utilization of window or skylight elements is not without problems, as discomfort from too much or too bright light, unwanted solar heat gains, or winter heat losses, can become critical factors in a building's performance.

The visual character of a building's interior is primarily dependent on the means by which daylight is brought into the building, and also on the way in which the interplay of light and shade is used to reveal form, surface and space. The daylighting methods and the distribution of windows and skylights have far-reaching consequences on a building's layout and form, both in plan and section.

The view-out of differently sized openings – from small windows to large fully glazed façade, has its place in daylighting design, and each helps set the tone of architectural expression, both internal and external. Conversely, the proportions of direct and indirect daylight has a strong impact on a design's character. A high proportion of direct light renders strong modelling with heavily dramatic character, whereas high proportion of indirect light provides lower contrasts, along with a softer, restful character.

The view-out through windows also helps determine the character of a room. Windows are normally spaced to support an easy view from all positions in the room, but windows should, where possible, provide a natural view of an interesting scene outside. Exaggerated vertical or horizontal window strips normally restrict the view in an unnatural way, but this may occasionally be desirable in framing certain specific views. Occupants seem to prefer windows that are slightly wider than their height: this may be since eye movements tend to occur more frequently when horizontal as compared to along the vertical. Window bars that break up a view may be perceived as annoying and distracting, and more so since they result in a high contrast. A horizontal bar at- or just below the eye level is particularly distracting.

The size of daylight openings has historically been determined by locally prevailing climatic conditions. Windows in hot, arid climates used to be small and set into deep wall reveals, to prevent direct sunlight entering the interior. In hot and humid climates, such openings were protected by large overhangs or screens for the same reason, but windows were larger to allow for increased natural ventilation. At times, settlers moving across climatic regions would introduce their construction methods to their new locations, only to find that their old methods weren't suitable anymore. This is true even for much of today's architecture, where designs aren't climate responsive; the construction of large buildings with glazed facades in desert environments is one such example, where enormous amounts of energy is wasted just to keep such buildings cool. The awareness of a location's climatic conditions is therefore essential, if a well-integrated design project is to be undertaken.

Cultural aspects also play a role in governing daylight exposure through windows and other openings. In many Islamic countries, the requirement for women to be veiled in front of male members of the public, resulted in screened daylight openings; where small hole-like openings allowed women to look outwards, but simultaneously restricted a view-in from the outside.

Similar to opening size, the surface colour in buildings can also be influenced by cultural and climate conditions. Regions with a prevailing clear sky conditions favour bright and saturated colour schemes, whereas regions with predominantly overcast skies tend to favour more subdued colour schemes with higher reflectance. In Australia and New Zealand, for example, many buildings are painted with bright colours both inside and outside; and he cultures of Aborigines and Maori appear to have contributed to such developments.

Classical daylighting strategies include sidelighting and toplighting. Sidelighting is mostly found in offices, homes, apartment buildings, and multistorey buildings. Toplighting is predominant in warehouses, factories, markets and other public or single-story buildings, primarily because the buildings are usually deep. Residential buildings frequently employ top-lighting strategies in spaces located under the roof. An atrium or courtyard combines both forms, as it initially admits daylight through a horizontal or near-horizontal opening, and later allows the light penetration through vertical openings into spaces surrounding the atrium.

2.1.1.1 Sidelighting

Fenestration in vertical or near-vertical surfaces is the most common form of daylight provision in buildings. For small-scale buildings, solar heat gain and heat loss through fenestration must be well-balanced for ensuring a sustainable energy use. For larger buildings with greater internal heat gains from people and equipment, the freedom to design daylight openings is somewhat greater.

The façade facing the midday sun, like the southern exposure in the northern hemisphere, is typically the most desirable façade, since daylight is most prominent and fairly uniform in that part of the sky. During summer, when excessive heat gains are undesired, horizontal overhangs can partially control direct irradiation from the high-altitude midday sun, but for other seasons, additional intervention is needed for sun shading as well as for glare control. The façade facing away from the midday sun, such as the northern exposure in the northern hemisphere, is the second most effective façade; since the received daylight is predominantly diffuse in nature – except for early mornings and late evenings, which also occurs only during the peak summer. However, these façades have undesired heat loss issues in winters.

East- and west-facing facades are exposed to direct sunlight for half the day, while the sun is at lower altitude angles. This makes effective fenestration design somewhat difficult for these facades. In particular, a west-facing facade can experience large undesirable heat gains during summers, in addition to glare issue associated with low solar altitude angle.

Daylight openings placed high in the façade typically yield higher, deeper, and more uniform illumination levels than similarly-sized lower windows. This is also because high-placed openings are exposed to brighter portions of the sky under overcast conditions. The preferred placement as seen from the interiors, is at approximately 45 degrees with the horizon. Such openings minimize veiling reflections, while also benefiting from brighter sky-portions, for providing better illumination indoors.

In addition to thermal and daylighting considerations, placement of fenestration openings should also consider the occupants' desire for pleasant and interesting views to the surroundings. Not all view directions coincide with a desirable daylight exposure, and trade-offs have to be made to balance view quality with daylight and control of solar gains or glare. Since windows for view are placed at sitting- or standing-eye levels, they present a potential for the undesired high-brightness contrast between the visible sky and the surrounding wall. To address this, one suitable solution is to divide the fenestration into daylighting and view windows, combined with a deeper wall section.

Strip windows typically provide a uniform daylight illumination with minimum glare, as compared to individual punched windows. Walls in which windows are placed should be as light as possible, in order to reduce contrast between a wall and a bright window. Window reveals might be splayed for further reducing this contrast, by providing an additional surface with intermediate brightness.

Alternatively, windows might be placed directly next to a perpendicular wall or in two adjacent walls, or in ceiling and wall, thus allowing daylight to illuminate alternating surfaces respectively, thereby reducing the brightness contrast between window and surrounding walls.

In many early buildings, particularly churches and other buildings with tall rooms, clerestories were used. Clerestories are side-lighting openings placed higher in the wall, and parallel to the primary axis of a space. Combined with the structural order in a building (such as columns in a Gothic cathedral), these can produce dramatic lighting effects.

An innovative light distribution strategy is a horizontal fin placed above eye level but below the ceiling, often protruding both on the inner and/or the outer portions of the glazing. Such fins are referred to as light shelves, and they may have different glazing and shading systems above and below the shelf. Their effectiveness depends on orientation and climate conditions, generally performing better in sunny climates and on facades facing the sun. If properly designed, they can create an even light distribution; by decreasing the illumination level at the front without decreasing the level at the rear of the room.

2.1.1.2 Toplighting

Toplighting strategies include sawtooth roofs, roof monitors and skylights. A sawtooth roof uses a series of single exposure clerestories, a design typical with industrial buildings of all sizes in Europe and elsewhere, dating from the 1900s. The openings usually face away from the sun to utilize the diffused skylight, rather than direct sunlight for illuminating the building interior. If facing the sun, sawtooth roof openings require effective shading devices to prevent glare issue.

Roof monitors are a version of a stepped roof, which may allow light to enter simultaneously from two or more directions. With a proper overhang on the façade facing the sun, the light distribution in the interiors can be very uniform.

Skylights are the horizontal or near-horizontal openings in the ceiling or roof surface, which bring in a large amount of light with minimum glazing area. Almost all other roof construction methods provide better insulators, as compared to even the best skylights, however, these are particularly suited for large-area factory and warehouse buildings, which have a high volume-to-perimeter-wall ratio. To minimize summer heat gains in sunny climates, it may be necessary to provide external shading devices above skylights or deeper light wells.

2.1.1.3 Light-Guiding Systems

Prismatic or holographic glazing panels, mirror panels and core daylighting systems (such as light guides, light pipes, or Fresnel lenses combined with fibre-optics) are the technically advanced systems aimed at improving daylighting access and connection to the outdoors; and communicate the temporal changes in daylight intensity for spaces placed deeper inside a building, or even those situated below ground levels (Ruck, Aschehoug, Aydinli, Christoffersen, Courret, Edmonds, Jakobiak, Kischkoweit-Lopin, *et al.*, 2000). A major disadvantage for large-scale core daylighting systems, is the higher requirements of cost and space. For this reason, they are most suitable for new buildings, as well as retrofit applications in limited cases, where sufficient daylighting cannot be achieved with the strategies described earlier. Coplanar window films, shades, and between-pane daylight-redirecting systems have been developed too, as lower cost alternatives. These systems redirect direct sunlight and/or diffuse skylight from the sidelit windows; and help illuminate the core areas of a building.

2.1.1.4 Heat Loss through Fenestration

Windows are often a weak point in a building's insulation; and can lead to heat loss and condensation on glazing surfaces. Researchers globally have spent considerable effort on advancing window components, to improve overall insulation values of windows to match those of wall elements. Other components commonly used across Europe, are rolling shutters; which are lowered at night to increase the window's insulating value while also providing privacy and added security to occupants. These shutters are usually opaque, and need to be opened during daytime, to allow sufficient daylight in the room.

2.1.1.5 Solar Heat Gains through Fenestration

It is generally recommended that undesirable direct solar radiation be prevented from entering a building, as it can lead to overheating in workspaces during much of the year, especially in summer and early fall. In a phenomenon commonly referred to as the greenhouse effect, short-wave solar radiation is converted to long-wave heat radiation once it passes through window glass and strikes an interior surface. Glazing materials are opaque to long-wave heat radiation, and do not let the heat escape from the interiors. Excess heat in a building can lead to thermal discomfort, and is referred to as a cooling load that needs to be removed, either by natural ventilation, or by active equipment for air-conditioning and refrigeration. Active systems are used especially in larger offices and in institutional buildings, where windows often cannot be opened to support natural ventilation.

2.1.1.6 Glazing Selection

Among all the components of the building envelope, windows typically represent the element through which the greatest heat transfer occurs. Indeed, about 4% of the total energy consumption in Europe (European Commission, 2015) can be ascribed to heat loss and gain through windows. Windows therefore represent a critical component in the building envelope, and managing solar gain is an important strategy for controlling indoor thermal and visual environment, as well as for reducing energy consumption for electric lighting and cooling. For these reasons, selecting the right glazing is critical for ensuring user comfort.

Depending on the operative mode, glazing is classified into two categories: static and dynamic. The first group includes all glazing whose characteristics remain unchanged across various conditions. The second group, the innovative dynamic glazing, is capable of reversibly altering its optical characteristics.

The market offers different typologies of static transparent glazing: clear, heat absorbing, tinted, reflective, and spectrally selective. In general, heat-absorbing tinted glazing and reflective glazing are not adequate for daylight applications, since they reduce the daylight transmittance or modify the daylight's colour. Instead, spectrally selective low-e glazing should be used when little or no heat is desired; whereas low-e glazing is recommended when winter solar heat gains are desired, since these transmit both the visible and the infrared solar radiation.

Spectrally selective window coatings can filter out selected wavelengths, such as the infrared portion of the solar spectrum, in order to contribute to a more controlled heat transmission through the glass. It is important to find the right balance between a glazing's visible transmittance (T_{vis}), and its total energy transmittance (g-value or SHGC). The excessive reduction of the visible transmittance may result in gloomy indoors under daylight-only conditions, and could lead to increased internal heat gain and energy consumption from the supplementary electric lighting used.

Another typology of glazing is represented by translucent glazing. It modifies the way by which the daylight is transmitted into a room, diffusing light in all directions and obscuring view. The diffusing characteristic makes it a potential glare source, when it is characterized by a very high light transmittance. If a translucent glazing has relatively low visible transmittance, it can be useful in large fenestration for controlling solar ingress.

Unlike static glazing, where T_{vis} and SHCG determined in assembly stages are not adjustable; dynamic glazing systems enables these values to modulate through application of an external stimulus.

With static glazing, a low SHGC would be desirable for buildings with high cooling loads (e.g. in tropical and hot climates), whereas a high SHGC would be beneficial for buildings with high passive heating requirements (e.g. in cold climate conditions). Moreover, a glazing unit with a high visible transmittance can reduce the electric lighting load and its associated cooling load. However, many design problems are not that simple, and climatic conditions or interior space-use could require different strategies at different times. Dynamic glazing, by allowing temporal variation in T_{vis} and SHGC, could help regulate internal environment in spaces that experience high direct solar gains during certain portions of the day (or year), but could also benefit from added solar gains during the winter months. The T_{vis} may also be adjusted to control glare from direct sunlight.

Dynamic or switchable glazing solutions are capable of enhancing a building's environmental performance, by modulating the thermal energy gain and incident light transmission, and controlling incoming solar radiation, to ensure maximum visual comfort while managing solar gain strategies in both hot and cold season (Casini, 2014; Rezaei, Shannigrahi and Ramakrishna, 2017). These performance enhancements are achieved by inserting adaptive functional layers between two layers of glass. The adaptive functional layers are capable of modulating their transmission and/or absorption coefficients. Dynamic glazing can be distinguished as passive or active, depending upon their operative mode. Passive glazing are self-regulating and respond to a change in conditions of light (photochromic glazing) or heat (thermochromic glazing and phase-changing materials); whereas active glazing respond to stimulus from a user-generated signal.

Photochromic (PC) glazing changes its colour reversibly when sunlight radiation increases. When this stimulus ceases, the system returns to the initial state. Photochromatism characterizes several chemical compounds, which generally are organic, and it is triggered by the photolysis of the crystals suspended in the inert glass. When incident light has a low energy content, the crystalline structure does not appreciably disperse light, and the system appears as transparent. However, when the energy level of light rises above the defined threshold, the crystalline structure changes, reducing the transmission coefficient (Wu, Zhao, Huang and Lim, 2017).

Unlike photochromic glazing, thermochromic (TC) glazing change their colour and optical properties, as a response to temperature variations. When temperature reaches a threshold, a transition occurs from the semiconductor layer to the metallic layer in a TC, and the reflection of infrared radiation is obtained. The adaptive layer in TC glazing is usually made of vanadium oxide (VO_2) (Granqvist, 2014) but polymers are also applied (Lv, Hu, Yang, Li, Huang and Liu, 2015) . Field measurements of a polymer TC window were conducted in an outdoor testbed: lighting energy savings were limited due to the narrow switching range of T_{vis}=0.28-0.03 over a glass temperature range of 24-75°C (Lee, Pang, Hoffmann, Goudey and Thanachareonkit, 2013). In a separate study, occupants indicated dissatisfaction with the resultant gloomy appearance of the workspace, partly because the window switched to dark tinted state, even during cold winter season on sunny days (Lee, Fernandes, Goudey, Jonsson, Curcija, Pang, DiBartolomeo and Hoffmann, 2014). Near-infrared switching thermochromics have the potential to solve this problem, by raising the switching range to e.g., T_{vis}=0.60-0.30 (Hoffmann, Lee and Clavero, 2014), but the lowest total energy use for heating, cooling, and lighting, depends highly on the solar-optical and temperature switching range of the thermochromic window, and on the application conditions (i.e., orientation, climate, solar exposure at the window, etc).

Phase changing materials (PCMs) are another category of devices capable of modifying daylight transmission, as a response to variation in temperature. PCMs are capable of switching from solid to a liquid state and vice-versa. In these systems, the outer glazing unit contains a prismatic filter that reflects the higher-angled sunlight (summer) to the outside and transmits the low-angled sunlight (winter) into the inner layers which encapsulate PCM in polycarbonate cells. During its melting process, a large quantity of energy is absorbed which increases the specific heat of PCMs, while, when the external temperature decreases below the melting point, the PCM solidifies and releases the stored energy into the building. The main effects of these processes are the reduction of heat flow from the outdoor to the indoor space during the daytime and the decrease of the building energy load in peak hours. A comparison between main properties of passive glazing systems shows that PC and TC are capable of reducing SHGC, and are suitable for application in a hot climate, whereas the ability to absorb and release heat makes PCMs suitable in a cold climate.

Unlike passive devices which respond to natural stimuli in changing their characteristic attributes, active glazing is user adjustable, and responds to an external electrical stimulus when changing its optical characteristics. The main electrically controlled active systems on the market include electrochromic

(EC) glazing, suspended particle devices (SPDs), and liquid crystal devices (LCDs) such as polymer dispersed liquid crystals (PDLCs).

The EC glazing varies its optical and thermal characteristics when a small electric field (usually between 1 and 5 V) is applied to the EC device. Generally, an EC device is realized with five superimposed coatings – each about a nanometer-thick – on a glass substrate and can be considered as an electrical battery (Granqvist, 2014). Two oxide films, one cathodic and anodic each, are electrically connected through an electrolyte, and then the obtained system is enclosed between two transparent electrical conductors. While, this type of glazing has advantages, such as the possibility to (i) vary its thermal and visual characteristics, (ii) be user-controlled, and (iii) be supplied by a low voltage; there are certain disadvantages that prevent their wide-spread use in building application. The first major disadvantage is the longer switching time as compared to quick and dynamic fluctuations of sunlight conditions under partially cloudy skies, which prevents it from dynamically modulating internal conditions for prevention of glare. The second major disadvantage is that its T_{vis} drops below 10% in tinted stage, which results in the reduction of colour rendering index (CRI) value to under 80. Field demonstrations in occupied buildings indicated that 63-92% of the occupants preferred EC windows over the existing low-emittance windows; however, control implementations that satisfy occupants and meet performance requirements are challenging and take time to fine-tune (Fernandes, Lee, Dickerhoff, Thanachareonkit., Wang and Gehbauer, 2016; Lee, Fernandes, Touzani, Thanachareonkit, Pang and Dickerhoff, 2016).

The efforts of researchers and manufacturers have resulted in a continuous improvement of the EC devices' performance. The products currently available on the market try to overcome the limits of older products, reducing the switching time as well as improving the transparency and neutrality to visible spectrum (high colour rendering index values), as presented in Table 1. Near-infrared switching EC devices provide greater daylight per unit of solar control, as compared to broadband switching EC devices which are currently under development (DeForest, Shehabi, Garcia, Greenblatt, Masanet, Lee, Selkowitz and Milliron, 2013; DeForest, Shehabi, O'Donnell, Garcia, Greenblatt, Lee, Selkowitz and Milliron, 2015). At the same time, more effective controllers (Halio Inc, 2021) capable of benefiting from these new EC devices have been developed. These new controllers use a sensor system to evaluate the real sky condition: measuring the global, direct and diffuse solar radiation on a building's roof. Complex control algorithms account for various parameters, such as the real local weather conditions, location, building orientation and function, to adapt the state of the EC windows' towards achieving specific room requirements (Wu, Wang, Lee, Kämpf and Scartezzini, 2019); facilitating large-scale goals for minimising energy cost, as we move toward zero-energy buildings (Gehbauer, Blum, Wang and Lee, 2020).

Table 1: Main characteristics of EC windows in insulated glass unit sold by Halio Inc (Halio Inc, 2021)

	T_{vis} (%)		**Solar factor (%)**		**Thermal transmittance (W/m^2K)**	**Colour Rendering Index (-)**	**Switch Time (min)**	**Operating voltage (V)**	**Power consumption in transition (W)**	**Power consumption at rest (W)**
	Clear	Tinted	Clear	Tinted						
Halio	66	3	45	5	1.1	97	< 3	48	14	1
Halio Black	52	0.1	35	4	1.1	94	< 3	48	14	1

An SPD consists of a polymer layer, which contains numerous light-absorbing and polarizable particles, comprised between two sheets of glass or plastic coated with transparent and electrically conducting thin films facing the polymer layer. They consist of polyiodides or, more generally, polyhalides, and show a large optical anisotropy. The most well-known compound of this class is the herapathite (quinine bisulfate polyiodide), which was extensively used in early stages on polarizers and other optical devices. Its optical anisotropy was recently theoretically described in considerable detail (Liang, Rulis, Kahr and Ching, 2009). A number of related compounds were used in later work in SPDs (Takeuchi, Usuki, Tatsuda, Tanaka, Okada and Tojima, 1996). In the absence of an applied electrical field, the particles move randomly in a liquid suspension due to the Brownian movement. In this state, the light passing into the cell is rejected, transmitted or absorbed, depending on the cell structure, the nature and the concentration of the particles and the energy content of the light. The presence of an electric field causes the particles to align, allowing most of the light to pass through the cell. For glazing applications, plastic films are used rather than a liquid suspension, since these avoid the bulging effect in liquids, where hydrostatic pressure may cause leakage from the device. Also, the number of particles is lower in the plastic film, so that they do not noticeably agglomerate when the film is repeatedly activated.

PDLCs are composed of a polymer matrix containing droplets of liquid crystal, with a size range of the LC droplet between 1 and 20 μm. In the droplets, the liquid crystal (LC) molecules are randomly oriented in the polymer, and due to their anisotropic orientation, the PDLC scatters incident beam and appears opaque, which is the so-called 'OFF-state'. When a uniform electric field is applied to the PDLC, the LC molecules align along the electric field line, and in this state, the PDLC appears as transparent – the so-called 'ON-state'. Figure 1 shows a window equipped with LC glazing in the clear (left pane) and milky (right pane) states (Sibilio, Rosato and Iuliano, 2017; Sibilio, Scorpio, Ciampi, Iuliano, Rosato, Maffei and Almeida, 2018). As seen in the figure, the glazing in its milky state modifies the transmitted light in a way that it acts as a diffuser, and differs markedly from a conventional clear glass.

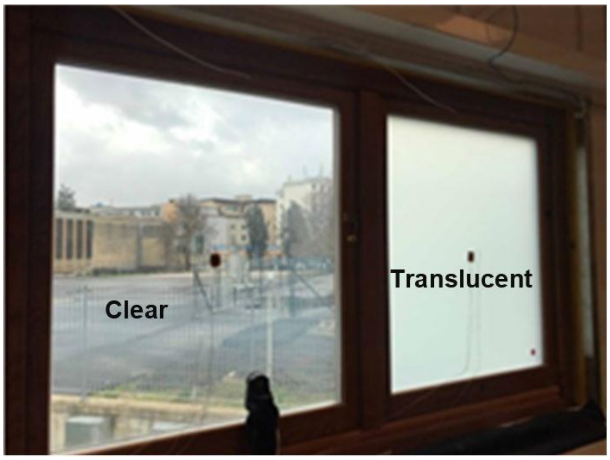

Figure 1: LC glazing in the clear and translucent states (Sibilio, Scorpio, Ciampi, Iuliano, Rosato, Maffei and Almeida, 2018).

Both SPD and PDLC have limitations, such as: (i) requirement of high driving voltage, usually between 60V and 120V; and (ii) a milky haziness even in the 'ON-state', which is a serious impediment towards satisfying commercial demands. The haziness of SPD and PDLC is related to the large scattering angle, which is a result of the large size of LC droplets.

However, SPD and PDLC glazing have certain advantages over EC glazing, which are:

- They can be directly connected to a main alternating current (AC) power supply with no external conversion devices required, as against the EC glazing which works on Direct Current supply, and needs an inverter to connect with the AC main supply (Vergaz, Sánchez-Pena, Barrios, Vázquez and Contreras-Lallana, 2008);
- No power is required to maintain the "milky" state (Vergaz, Sánchez-Pena, Barrios, Vázquez and Contreras-Lallana, 2008; Barrios, Vergaz, Sánchez-Pena, García-Cámara, Granqvist and Niklasson, 2015);
- They have fast switching speed (Ghosh, Norton and Duffy, 2015).

The literature review highlights the significant potential of dynamic windows for improving indoor conditions. It also underlines several crucial problems that prevent widespread application of this kind of windows in residential and commercial fields, such as (i) the need to connect each glazing to electrical system; and (ii) the high cost of these systems. Innovative production lines and low-cost manufacturing processes are extremely important to reduce the capital costs, as well as to allow the scalability of new and more efficient materials, from the laboratory stage to becoming marketable products.

2.2 Electric Lighting

2.2.1 Incandescent and Fluorescent Electric Lighting

Traditional lighting technologies include incandescent and fluorescent lamps. Despite their status of being "traditional", they covered about 60% of the global lighting market in 2018 (IEA, 2018) and, therefore, they are still current in many buildings.

However, incandescent light sources, like tungsten filament and halogen lamps, are rapidly disappearing from the global lighting market as a result of energy efficiency regulations. For example, in Europe, the Ecodesign Directive banned tungsten filament lamps since 2009, and most halogen lamp types were phased out by 2018. In other countries, like Brazil, China and India, the phase-out started more recently or it is about to start (IEA, 2017). The incandescent technologies have a luminous efficacy varying between ≈10 lm/W and ≈18 lm/W for tungsten filament and halogen lamps, respectively. They also have a short lifetime of between 2,000 and 3,000 hours. Bulbs and spotlights with higher power loads are more effective, but they have an even shorter lifetime.

The phase-out of incandescent light sources has been somewhat opposed. For the residential sector, one argument is that switching to new technologies may not be economically viable for end-users, due to the low production costs of incandescent technologies and considering that the use is limited to few hours per day (Frondel and Lohmann, 2011). Other arguments focus on the quality aspects of lighting. Similar to the solar spectrum, incandescent technologies offer a continuous spectral emission across the whole visible range of wavelengths. This is a much appreciated feature which has interesting implications: they offer excellent colour rendering; they are likely to support circadian entrainment (assuming appropriate illuminance levels), and, arguably, they can psychological functions thanks to their infrared (heat) component (Veto, 2019). Some argue that incandescent sources are preferred by users, but recent research shows that modern light-emitting diodes (LEDs) are increasingly accepted even in dwellings (Gerhardsson, Laike and Johansson, 2019). Simplicity is another feature characterizing incandescent technology. Incandescent sources exhibit technological simplicity, as they do not require any additional driving gear to switch on or dim. Additionally, they offer simplicity on the end-consumer side, since there is a nearly linear relationship between power load, luminous intensity, and CCT.

Another traditional lighting technology: the fluorescent lighting, raises the efficiency bar to ≈100 lm/W; extends the lifetime of lamps to more than 10 000 hours, and achieves reasonably high CRIs of over 80 or 90. However, it provides a discontinuous spectrum of lighting across the visible range. Fluorescent lighting is still the main light source in the non-residential sector in many countries, and it keeps a good market penetration in the residential sector, mainly with its compact-fluorescent version. Sales for this technology were about 40% of the global lighting market in 2018 (IEA, 2018) . Fluorescent lighting is produced with a different range of CCT, typically in the range 2,700 – 6,500 K, allowing more lighting design solutions in comparison with incandescent sources. Fluorescent lamps require additional control gear to run, such as a starters and ballasts. This represents both: a positive side from enhanced quality as well as the flip side of energy concern. On the quality side is the transition from magnetic to electronic ballasts, and the enhanced frequency: the obsolete magnetic ballasts were known to generate low frequency flicker - around 100 to 120 Hz - which causes eye fatigue, eye strain and headache; but the current electronic ballasts flicker at about 20,000 Hz, which does not represent a concern at the best of today's knowledge. Still on quality, in the dimmable version of fluorescent lamps, there is a unique relation between power load to the ballast and luminous power emitted by the lamp. In other words, changing lamp or ballast will change the power-to-dimming curve, which makes replacements quite difficult. In addition, fluorescent lamps cannot be dimmed down to no light output. Finally, the luminous power is affected by ambient temperature, where a colder environment reduces the output. On the energy side, the ballast itself requires some energy to run, although this is usually negligible for modern electronic ballasts. On other sustainability aspects, fluorescent lighting requires the use of small quantities of mercury, while rare earth metals are needed to produce the phosphor coatings.

2.2.2 Solid-State Lighting

Recent statistics from the International Energy Agency (IEA) show that sales of solid-state lighting (SSL) or light-emitting diodes (LEDs) in 2017 covered 30% of the lighting market in developed countries, and that they will likely cover more than 80% of the lighting stock by 2040 (IEA, 2017). The cost of LEDs is expected to decrease by 47-55% in the next two decades (IEA, 2015), while the luminous efficacy of commercial lamps is projected to increase from the current 120 lm/W to more than 200 lm/W (US DOE, 2016). In addition to low cost and higher efficiency, LED lighting offers some interesting aspects in terms of integration possibilities with daylight, namely:

- design flexibility
- colour tunability

- intrinsic connectivity via Light Fidelity (Li-Fi)

Design flexibility is the opportunity of designing luminaires with countless light distributions, combining more LED chips, which are small point light sources, with appropriate optics and luminaire shapes. Design flexibility is more limited in traditional technologies, for example with linear (fluorescent tubes) or diffuse point light sources (compact fluorescent or incandescent lamps).

Colour tunability is the possibility of changing the spectrum correlated colour temperature (CCT) of the light source. In an integration perspective, colour tunability can be used, for example, to constantly match the daylight CCT, generating a theoretically seamless luminous colour stimulus. Colour tunability is very limited with traditional light sources as this would usually require rotatable filters in front of the light sources or switching between light sources with different spectral properties.

LEDs are also suitable for implementing Li-Fi, a wireless communication technology that is based on high frequency fluctuations of visible and infrared light output. The fluctuations are controlled by an LED driver and received by micro detectors integrated in the LED luminaire (Haas, Yin, Wang and Chen, 2016). Mobile devices, such as laptops or smartphone, are also suitable for Li-Fi. Therefore, LED lighting can be an active transmitter and receiver in a control network (Haas, Chen and O'Brien, 2017). This appears to be a game changing, as, for the first time in the field of lighting controls, the same apparatus works as luminous source, signal transmitter and sensing device. Such characteristic can deploy ubiquitous distribution of sensors and signal emitters in the space, supporting e.g. self-detection of failures or users feedback at individual level.

Nominally white LEDs, which are used for illumination, are actually blue LED chips covered by a phosphor coating which re-emits part of the radiation at longer wavelengths, especially in the yellow area of the spectrum (Nakamura, Mukai and Senoh, 1994). As a consequence, the spectral power distribution of LEDs is characterised by a continuous emission over the visible spectrum, with two peaks: one in the blue, the other in the yellow region. Low CCTs show higher peaks in the yellow, while high CCTs show that in the blue region. In term of non-visual effects of lighting, some researchers addressed the potential risks associated with the blue peak, but such claims are currently not supported by peer-reviewed research (CIE, 2019).

Some recent developments resulted in LED chips with less marked differences between the blue and yellow peaks. These new sources are slightly less energy efficient, but they provide a full spectrum emission which is closer to that of daylight, as shown in Figure 2. With respect to traditional LED sources, a recent laboratory study found that this technology could improve visual comfort, mood, alertness and intensity of sleep, although it did not significantly impact melatonin profiles (Cajochen, Freyburger, Basishvili, Garbazza, Rudzik, Renz, Kobayashi, Shirakawa, Stefani and Weibel, 2019).

LEDs work with direct current (DC), therefore, like fluorescent lamps, LEDs need a driver to run on alternating current. The driver uses some energy, and cheaper drivers may exhibit quality issues – such as dimming via pulse-modulation width (PMW), which makes the source appear as flickering, despite LEDs being potentially flicker-free. LEDs are inherently dimmable, with incremental driver costs that are nominal compared to continuous dimming electronic ballasts. LED driver power dimming curve, minimum power, and standby power are significantly more efficient as compared to fluorescent lighting, which opens opportunities of tuning the light intensity and spectrum on a per-luminaire basis. LED lamp life is also minimally affected with continuous dimming.

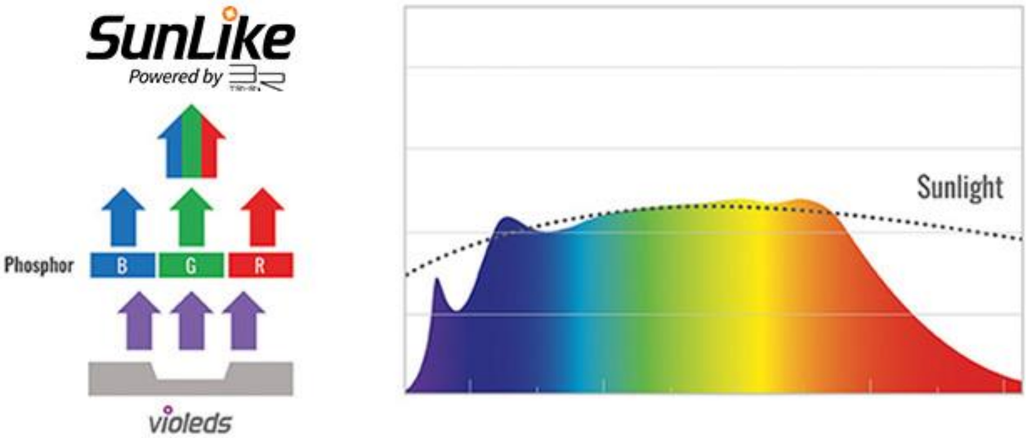

Figure 2: SPD of the 'SunLike' LED chip (Seoul Semiconductor).

2.3 Control Systems

In lighting technology, the definition of a "control system" includes:

- sensors or the like that detect environmental information
- controllers that elaborate the signal from sensors
- actuators that act on lighting or shading devices, according to the controller's instruction
- the light source, here described in its broader definition of electric light or daylight source

Although the terminology may suggest that controls are based on highly evolved technology, simple systems like manual switches are also controls and they include the four listed components; in such case, the human eye is the sensor, the brain is the controller, and hand and switch are the actuators (Gentile, 2017): as presented in Figure 3. Similarly, any network of controls shows the same components, but in higher number or with higher complexity. In case of networks, a gateway allowing data flow among networks – possibly using different communication protocols - may also be present.

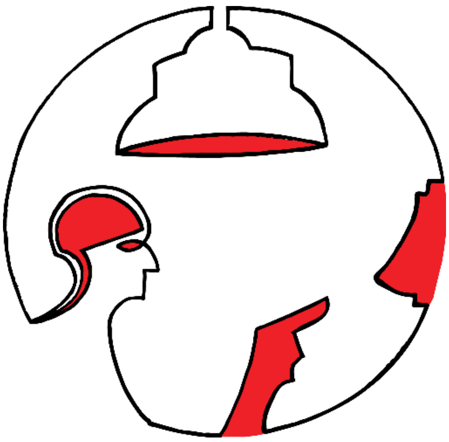

Figure 3: Manual switch is a lighting control system in full. Artwork 'Light Man' by K. Zanni, commissioned.

Lighting and shading control systems are primarily used to ensure visual comfort, and to save energy. Other reasons for using controls are towards supporting building appearance, and in increasing safety (CIE, 2017). Their combined performance depends on individual performances of the components (sensors, controllers, actuators, lighting/shading), the interoperability of such components, and on their correct installation, calibration, maintenance and verification.

2.3.1 Control Strategies

With growing penetration of building automation, the strategies for controlling daylight and electric light seem endless. A control strategy defines how daylight and electric lighting is provided in space by a system, and it can be as simple as a manual on/off switch and manually operated blinds or as complex as an integrated building management system including several sensors and control actions. This chapter investigates only a few examples of strategies, but many more exist and are continuously being developed.

2.3.1.1 Personal Control

Personal control in its simplest form includes a manual switch and/or a dimmer, but more elaborate methods are available, such as remote manual controllers or scene selection through buttons or graphical user interfaces. This strategy allows the user to be in full control of their environment, which has a positive effect on user satisfaction (Moore, Carter and Slater, 2004). Research shows that illuminance preferences vary based on the illuminance range available (Logadóttir, Christoffersen and Fotios, 2011), and there is no general agreement on the preferred illuminance levels (Nagy, Yong, Frei and Schlueter, 2015; Nagy, Yong and Schlueter, 2016) . Furthermore, it is reported that users might accept illuminance levels lower than standard recommendations, which indicates that individual control has a potential to create energy savings by using lower light levels without negatively affecting occupants' visual comfort (t. Moore, Carter and Slater, 2002).

Personal daylight control includes manual adjustment of dynamic blinds or shades. A literature review (O'Brien, Kapsis and Athienitis, 2013) identified visual comfort, thermal comfort, privacy and view as the main parameters affecting blind adjustment. One of their major conclusions was that occupants tend to operate shading devices based on current weather conditions, and not in anticipation of future unwanted conditions, motivated mostly by glare. They also concluded that most of the occupants are relatively inactive, and while they tend to react to annoying visual conditions by closing blinds, they are not as quick to open them again when they are not needed.

2.3.1.2 Daylight-Responsive Control

Daylight-responsive control strategies utilize light-detecting sensors to adjust output from electric light systems, based on the available daylight. The control output can be a binary off /on, stepped control, or continuous dimming in order to maintain light levels within predefined illuminance thresholds. The available daylight depends on geographical location, season of the year, and weather conditions. The effectiveness of the system depends on several parameters, such as shape of room, placement of windows, shading from obstructions/vegetation, orientation, optical properties of materials, visual task requirements, glare, work time, location of work places and maintenance (CIE, 2017).

Significant energy savings have been reported from daylight linked control used in fluorescent lighting (CIE, 2017). LEDs obtain less absolute energy savings due to their lower installed lighting power density, but incremental hardware cost for continuous dimming is negligible in their case, as compared to fluorescent ballasts; and can be justified by other qualitative arguments. Widespread implementation has been slow due to cost, difficulties linked with their design and installation, objections of users who prefer to have full control, and limited modeling software to quantify the potential energy savings (Bellia, Fragliasso and Stefanizzi, 2016). As of 2017, daylight control is required in prescriptive building energy codes in the U.S. To step beyond mere energy savings, a series of metrics was defined in another study (Bellia and Fragliasso, 2017), for evaluating the performance of daylight-responsive controls; metrics focusing on quantifying light deficit or excess, which describe the incidence of different control operating conditions.

Daylight-responsive control can also include automatic adjustment of shading devices, in order to avoid negative effects of direct sunlight and glare, while also maximizing the benefits of daylight. The automatic opening of blinds might be more acceptable than automatic closing. A case study (Reinhart and Voss, 2003) recorded a strong occupant tendency to open blinds, after they have been lowered by a control system. However, lowering the blinds can have a significant decrease in cooling loads and help reduce overheating (Tzempelikos and Athienitis, 2007; Foldbjerg, P., Asmussen, 2013; Knudsen and Petersen, 2020) as well as avoid glare (Osterhaus, 2009).

2.3.1.3 Occupancy Scheduling and Detection

Occupancy scheduling or sensor-based detection ensures that lights are turned off when a space is empty, and turns them back on when occupied. Scheduled lighting is performed at whole- building level, and is defined by a business' hours of operation. Occupancy detection requires a time delay after vacancy is detected before the electric lights are switched off. Typical values of time delay range from 15 to 30 minutes (Guo, Tiller, Henze and Waters, 2010; Nagy, Yong, Frei and Schlueter, 2015). Decreasing the time delay has potential to increase energy savings, but it can also cause lights to turn off while occupants are still in the space; which decreases occupants' acceptance of the system (Guo, Tiller, Henze and Waters, 2010).

It has been reported (Von Neida, Manicria and Tweed, 2001) that occupants can be neglectful in switching off the lights when they exit a room, both in common areas as well as in private areas. Occupancy sensing can therefore be useful for reducing electric lighting energy use. The estimated decrease in energy use varies from study to study and between manufacturers' claims and observed savings (Guo, Tiller, Henze and Waters, 2010).

Increased digitalization of lighting has now made it possible to sensing and control lighting at fixture resolution. Such control enables additional opportunities to finetune lighting control, and reduce energy use in open plan offices and other large-area work places. In a Living Laboratory demonstration of high-resolution lighting controls, individually controlled LED indirect-direct fixtures were evaluated in an open plan office setting. Depending on the system (four sets of technologies were evaluated in the 3716 m^2 test area), scheduling, occupancy, setpoint tuning, and daylight control occurred at a 9-61 m^2 resolution with a sensor-to-fixture ratio ranging from 1:1 to 1:6. Annual lighting energy savings ranged from 73% to 87% compared to the existing conditions: T5 pendant lighting with scheduling and daylight control at a 425-637 m^2 resolution (Lee, Fernandes, Wang, Selkowitz, Mesh, Frank and Yancey, 2017).

2.3.1.4 Occupant-Centered Control

An occupant-centered control (OCC) adapts its settings automatically, based on user preference and behaviour. Several studies have associated this feature with higher user satisfaction and increased energy savings.

An adaptive lighting control strategy was designed and tested in offices (Nagy, Yong, Frei and Schlueter, 2015), with the assumption that although each occupant is unique, they remain consistent in their actions; and statistical analysis could be used to derive the appropriate set-points for turning electric lighting on and off. For this analysis, the data used was that recorded by the building management system from various sensors, including occupancy sensors, data regarding manual interaction of occupants with lighting system via switches, illuminance levels in the room, and on/off status of the electric lights. A suitable algorithm was implemented in the controller, and through statistical analysis of recorded data in individual offices, various values were identified, such as suitable set-points for the time delay (for turning off electric lights), minimum illuminance threshold (below which the system turns the electric lights on) and maximum illuminance threshold (above which the system turns the electric lights off). Over a period of six weeks, along with associated system-learning; unique set-points for time delay and illuminance were achieved for each of the eight studied office spaces. Energy savings over the period was 37.9%, as compared to the standard setting control baseline. The results of this study highlight the variation of individual user preference, since the final set-points for time delay and illuminance were different in all the investigated test rooms. They also point out the dynamic nature of illuminance adaptation, as the illuminance thresholds kept changing over the six-week duration. The writers claim that occupant adaptive control can have significant energy savings in rooms used on a regular basis, such as offices; but is probably unsuitable for common rooms like kitchens and printer rooms.

The same research group performed a follow-up study in six offices for a period of twelve weeks, this time focusing on user satisfaction (Nagy, Yong and Schlueter, 2016). A similar algorithm was implemented to define personalized time delay and illuminance thresholds. In this study, a web-based interface was additionally provided to occupants, allowing them to see and override the control settings if necessary. The reason for the interface was to address common complaints, such as the lack of absolute user control and inability to understand the system. Nevertheless, the occupants' responses showed a preference for standard light switches, as compared to web interface, supporting the claim of other studies that users prefer what is ''traditional'' or ''familiar'' (Maleetipwan-Mattsson, Laike and Johansson, 2017). Overall, this control system reduced the energy use by 13.4% as compared to a manual control scenario, without significantly affecting users' comfort. The control actions were mostly accepted, with users never overriding the 'Control-On' action; and accepting the 'Control-Off' action almost 75% of the time.

In another study, a low-cost occupant-centred controller was developed for lighting (Park, Dougherty, Fritz and Nagy, 2019), based on reinforced learning (RL) – a machine learning technique that uses environmental feedback to decide the best possible action given a current state. Their controller consisted of a Raspberry Pi microcomputer, paired with an illuminance sensor, and a Bluetooth functionality was used to detect occupancy by pairing with user's mobile phones. Based on this data which included occupancy, switch position, and available daylight; the device evaluated the action needed (turn lights on/off or do nothing) every minute, in order to maximize an associated ''reward'', which was defined by energy savings or occupant satisfaction. The lighting thresholds in this study were adapted daily, based on user preferences. Their results showed a reduction in energy use, as compared to a schedule-based and an occupancy-based control scenario; and showed slight increase in user satisfaction.

A control algorithm was developed (Seyedolhosseini, Masoumi, Modarressi and Karimian, 2020) for calculating dimming levels of individual dimmable LEDs, in a complex indoor environment with multiple lighting zones, luminaires and photosensors; in order to maintain a desired illuminance and uniformity level. Their methodology combines artificial neural networks with linear optimization process, for continuously deciding the amount of dimming for luminaires. Each lighting zone was given a user-defined priority based on factors, such as presence, duration of stay, zone type etc. Their algorithm consisted of three main blocks, which were: 1) an initiator for collecting input conditions (occupancy, priority, measured and desired zone illuminance and uniformity), 2) a pre-processor for performing linear optimization and calculating target illuminance at each photosensor, and 3) a decision maker using neural network trained with appropriate data, for defining dimming level. Their method focused on accurately providing the illuminance levels required, and achieved an approximate accuracy range of 13 to 29.9%, depending on priority factor. The priority factor also affected the system's energy consumption, but a comparison with energy use of a conventional control system was not reported.

2.3.1.5 Integrative Lighting

The human circadian system may be defined as an internal biological clock, which has evolutionarily been regulated and synchronised by the temporally varying light/dark patterns caused by the 24-hour rotation of the earth around its axis (Rea, Figueiro, Bierman and Bullough, 2010).To support the human circadian system using electric lighting, a predefined schedule that dynamically changes lighting settings based on time of day can be used. Various labels have been attributed to such control systems, such as: dynamic lighting, biological lighting, human centric lighting (HCL), circadian lighting or integrative lighting. Since 2019, "integrative lighting" is the official name for this control strategy (CIE DIS 017/E:2016, 2017), which focuses on supporting the human circadian rhythm . Electric light may also influence our biological clock, depending on colour spectrum, intensity, time of the day, and previous lighting intake.

Integrative Lighting is important for health, productivity and well-being, and has uses not only in hospitals, health care facilities, and elderly homes that focus on healing, but also in offices and residential buildings. Typically, these systems dynamic modulate intensity and CCT of light, since these are the parameters associated with healthy lighting in most research in this domain (van Duijnhoven, Aarts, Aries, Rosemann and Kort, 2019). Circadian-effective lighting systems has been reported to increase alertness and sleep quality of office workers (Figueiro, Kalsher, Steverson, Heerwagen, Kampschroer and Rea, 2019). Although there are a few companies that provide dynamic lighting solutions, this domain is still in its nascent stages; and research evidence may still be biased by methodological gaps (van Duijnhoven, Aarts, Aries, Rosemann and Kort, 2019). Most knowledge regarding health effects is based on experiment in highly controlled testbeds (Figueiro, Kalsher, Steverson, Heerwagen, Kampschroer and Rea, 2019), and more case studies are needed to demonstrate the effect of these systems. Such control, however, is known to increase lighting energy use due to the higher required light intensities. A monitored study of high efficacy LED luminaires (Shackelford, 2021) found that annual lighting energy use increased by 31 to 42% -- from 6.99 kWh/m^2-yr to 9.90 kWh/m^2-yr at a 300 lux setpoint, when controlled to provide a 4 hour CCT and intensity increase in the morning in an open plan office testbed. In the daylit zone, however, circadian criteria were met without any additional electric lighting power.

2.3.1.6 Demand-Responsive Controls

Demand-responsive controls are used to dim or turn off lighting, or to increase the HVAC thermostat setpoint range, when electric loads on the utility grid are high. Such controls help avoid use of on-peak generators for utilities, since these generators are typically inefficient and use non-renewable sources; and can improve the project's energy security and resiliency.

Peak lighting loads are usually predictable, so building owners or facility managers may agree to reduce lighting loads and avoid paying demand charges – which are significantly higher than base load energy costs. This could lead to significant cost savings, since lighting represents a large share of total power demand during peak periods (Dortans, Jack, Anderson and Stephenson, 2020). When electric lighting is dimmed to a lower setpoint via slow and moderate dimming, this change was reported to be imperceptible to occupants, even when it occurred without explanation during, for instance, a peak load event (Akashi and Neches, 2005; Newsham, Mancini and Marchand, 2008).

Integrated control of solar gains, daylight, and lighting can yield further demand reductions. When using demand-responsive illuminance setpoints, trade-offs between admitting daylight for offsetting electric lighting loads, and excluding solar gains for minimizing thermal loads yield lowest electric demand; especially when the window-controls are automated (motorized shading or switchable glazing), along with controls for dimmable lighting and thermostats. The constrains in these automated controls are: occupant comfort, indoor environmental quality requirements of view, daylight, etc.; and technology limits such as switching speed, and limits on actuation, among others. Model predictive controls are applied in cases, where optimization includes forecasted lag effect of thermal mass on various loads (Lee, Gehbauer, Coffey, McNeil, Stadler and Marnay, 2015; Gehbauer, Blum, Wang and Lee, 2020). Reinforcement learning can provide low cost alternatives, capable of adapting to building operations, over the life of its installation (Gehbauer, Rippl and Lee, 2021). Such control has been demonstrated to flatten the load profiles, in accordance with time-of-use utility rate schedules.

From a technological standpoint, the implementation of demand responsive controls require high automation and communication between buildings and city grid, therefore, the transition towards smarter cities requires inclusion of demand responsive controls.

2.3.2 Sensor Types, Positioning, and Calibration

The selection of appropriate sensors is essential for the implementation of an effective control strategy. In this chapter, the term 'sensor' refers to any device that measures environmental conditions – such as occupancy, presence of people, or the levels of available light.

2.3.2.1 Sensors Detecting Occupancy

The most common occupancy sensors are Passive Infrared (PIR) sensors, which detect motion by spotting temperature changes across their field of view. Ultrasonic occupancy sensors are also often used in commercial buildings. Their functionality is based on emitting sound waves to determine motion, using reflected signal from the surrounding environment. Ultrasonic sensors are better suited for partitioned or irregularly shaped spaces, as compared to PIR, but are more sensitive to false triggering (Guo, Tiller, Henze and Waters, 2010). Other sensors include passive acoustic detectors, microwave sensors, light barriers, video cameras, biometric systems and pressure sensors (Guo, Tiller, Henze and Waters, 2010). Some of the later sensors are rarely used in building control, but owing to their special functionalities, such as security; these may be used in combination with other sensors.

2.3.2.2 Sensors Detecting Light Levels

Photosensors are a class of sensors that detect light levels, and are used for integrating electric light with daylight. Their purpose is to adjust (turn on/off or dim) the electric light output, based on the detected daylight availability.

Light detecting sensors are usually placed over- or near the ceiling for closed-loop control, or near the window for open-loop control; and need to be specifically calibrated for evaluating workplane illuminance from the captured sensor data. Light sensors mounted on ceilings measure incident radiation and convert it to proportional control signal, however, the ratio of ceiling to workplane illuminance is not constant; and depends on various factors, such as: sensor's field of view, the daylight distribution in the room affected by shade position (Lee, DiBartolomeo and Selkowitz, 1998), and placement of the desk (Doulos, Tsangrassoulis and Topalis, 2014). With recessed and pendant LED fixtures, it is becoming common to place sensors within each fixture's housing, and the on-site labour costs are reduced by installing control hardware during the manufacturing itself.

It is useful to know a photosensor's spatial response or field of view. Photosensors with narrow spatial response might be appropriate for tracking illuminance over a desk, but sensors with wider spatial sensitivity might be more suitable for larger control areas (NLPIP, 2007). Figure 4 presents example spatial response curves for two photosensors, with wide and narrow sensitivity, respectively.

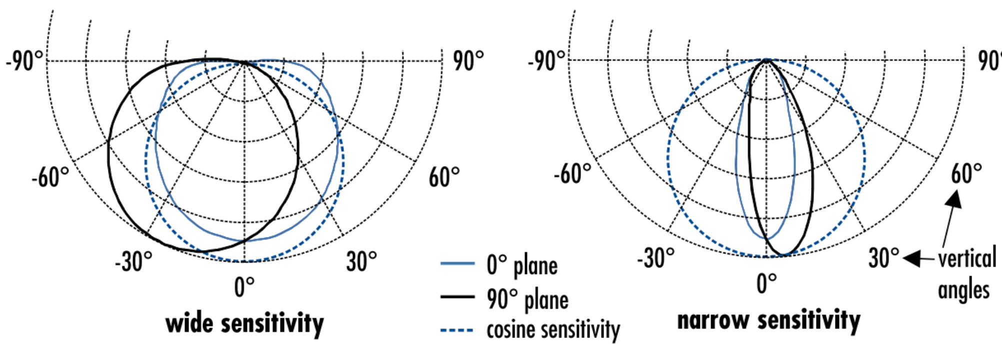

Figure 4: Example spatial response curves of photosensors with wide and narrow sensitivity (NLPIP, 2007).

The spectral response of a photosensor is its sensitivity for different wavelengths of light, and it is expected that the sensor's spectral response should approximate the sensitivity curve of the human eye. Commercial photosensors may not correctly match the human photopic luminous efficacy function V(λ) and may detect wavelengths beyond the visible spectrum, as presented in Figure 5. Doulos et al. (Doulos, Tsangrassoulis and Topalis, 2008) tested five different photosensors while filtering light by using different glazing samples, and reported that the measured illuminance varied between 36% and 118% of the actual illuminance for the different photosensors.

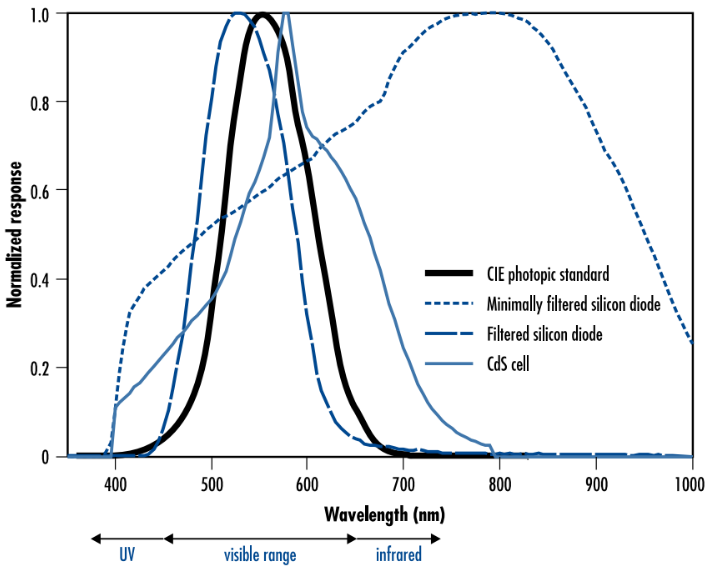

Figure 5: Spectral response curves of different photosensors compared with V(λ) (NLPIP, 2007).

It is important that an appropriate location for mounting is identified, although ceiling is a preferred location; hence a study by Doulos et al. (Doulos, Tsangrassoulis and Topalis, 2014) proposed a decision making method for determining the appropriate position and field of view of the photosensor. This was done based on three criteria, which were: 1) correlation between ceiling and workplane illuminance, 2) energy savings, and 3) light adequacy defined as percentage of time with illuminance exceeding a threshold. Their method used simulations to generate illuminance data for various possibilities of mounting locations and spatial responses; and an optimization algorithm was used to determine the best option. Beyond their recommendation for the specific case, the authors recommended that their approach could be used for identifying best sensor location, during the commissioning phase of any daylight responsive system, to help it operate efficiently and economically.

Another study compared the illuminance measured by ceiling-mounted sensors with illuminance meters placed on desks, and found a difference of up to 350 lux and 1000 lux on a typical spring and summer day respectively (Chiogna, Albatici and Frattari, 2013). They concluded that by adjusting the ceiling sensor value with correction functions, can yield an energy savings of up to 10%, by reducing the unnecessary use times for electric lighting.

2.3.2.3 Sensors Detecting Light Colour

Chromaticity sensors convert the incident light into RGB or XYZ tri-stimulus values. These consist of photodiodes with connected filters, that exclude infrared radiation and provide high accuracy in the visible spectrum (Rossi, 2019). They have applications in digital photography; and can be used to measure and control correlated colour temperature of tuneable LED sources.

2.3.2.4 Sensors Detecting Irradiance

A pyranometer is a device that measures global solar irradiance in a hemispherical field of view, which has other common applications in climate data collection, and in monitoring of PV technologies. Pyranometers or irradiance meters have been used for controlling shading devices (Jain and Garg, 2018; Motamed, Bueno, Deschamps, Kuhn and Scartezzini, 2020). Additionally, solar trackers that accurately locate the position of the sun, and measure direct normal irradiance data, can also be used for shading control (Jain and Garg, 2018).

2.3.2.5 Sensors Generating Luminance Maps

The inadequacy of horizontal illuminance as target metric may partially explain why photosensor-based systems, like those used for daylight harvesting, are generally not very appreciated by users (Gentile, Dubois and Laike, 2015). Luminance measurements are better predictors of lighting quality, as compared to horizontal illuminance on task space (Van Den Wymelenberg and Inanici, 2016; Kruisselbrink, Dangol and Rosemann, 2018).

Earlier technologies of luminance camera required long and complex calibration procedure (Bellia, Cesarano, Minichiello and Sibilio, 2002), but the use of High Dynamic Range (HDR) photography with commercially available digital cameras helps generate reliable luminance maps in a relatively simpler process (Inanici, 2006). Early research on HDR imaging suggested that luminance maps can effectively replace many sensors and, at the same time, provide information on occupants' activity, lighting energy and shading use. In other words, a single HDR camera can provide data on occupancy and support sensing and control of integrated lighting (Newsham and Arsenault, 2009). The issue of privacy has been raised, when cameras are used in workplaces (Newsham and Arsenault, 2009), although automated post-processing techniques can address such issues. Such or similar techniques are already demonstrated, for example those aiming at removing "ghosts" created by moving people (Mardaljevic, Cannon-Brookes, Lithgow and Blades, 2016). Today, highly accurate luminance maps can be created with inexpensive, miniaturized, and reliable cameras, with luminance ranges between 10 to 50 000 cd/m^2 (Mead and Mosalam, 2017). Cameras based on programmable controllers, like Raspberry Pi, may also be provided with automated on-the-fly post-processing, as well as real time transfer of processed images to some external memory (Kruisselbrink, Aries and Rosemann, 2017).

There are also recommendations for camera placement in office settings (Kruisselbrink, Dangol and van Loenen, 2020), such as:

- Cameras mounted on the ceiling, generating top-down images. This approach does not interfere with users' activities, and can be used to measure illumination on task position and surrounding; by using luminance map as proxy to measure illuminance on surfaces (Sarkar and Mistrick, 2006; Mardaljevic, Painter and Andersen, 2009).
- Cameras placed in line with a user's view direction, but translated on a monitor or on a partition. This approach also does not interfere much with the users' activities, but may annoy other occupants. In this position, the camera can be possibly used for predicting glare (Motamed, Deschamps and Scartezzini, 2015), but as a proxy; since the task area is not in the field of view of a camera placed at some distance.

- Camera placed next to a user’s eye. This approach is invasive, but can effectively be used for glare sensing and control (Motamed, Deschamps and Scartezzini, 2017).

For ceiling-mounted cameras in open-plan offices, positioning on aisle at 20 degrees inclination has been reported ideal, as it can be used to predict multiple luminance based metrics (Kruisselbrink, Dangol and van Loenen, 2020). However, recommendations are based on a single case study and more research is needed. In case of vertically-mounted cameras at eye position, the spatial resolution and accuracy of the camera is critical, as it directly affects the prediction of glare indices (Motamed, Deschamps and Scartezzini, 2017). In both cases, commissioning can be a critical part, since a careful calibration process is required for every individual space. A recent paper (Motamed, Bueno, Deschamps, Kuhn and Scartezzini, 2020) reports successful testing of a self-commissioned approach, aimed at simplifying the commissioning phase, however, there is still a need for more validation of the approach.

In addition to the above, an attempt to retrieve spectral information has been reported, using luminous maps generated via HDR imaging, aimed at low-cost, long-term monitoring of circadian potential of spaces (Jung and Inanici, 2019). The reliability of the method needs to be improved since the measurement is affected by various factor, for example, the illuminant (Kruisselbrink, Dangol, Rosemann and van Loenen, 2019). Addition, it is reported that camera specific calibration can lead to robust results (Cauwerts, Jost and Deroisy, 2019) .

2.3.3 Control Algorithms

Control algorithms can be open- or closed-loop. Open-loop controls are those that have no feedback loop, and the system does not ‘’see’’ the light that it controls. An example of this may be a light sensor located on a building façade that controls electric light inside the building, but only measures daylight at the exterior. An obvious drawback of this type of control is that the system cannot respond to any changes that affect the relationship of indoor and outdoor conditions, such as the use of blinds. Calibrating an open-loop control signal consists of adjusting the ratio between sensor signal and control voltage (Lighting Research Centre, 2004).

A closed-loop controls, however, receives feedback from the actuators and responds to it. An example of this would be a light sensor in the room. A close-loop control is however less reliable for measuring daylight, as compared to an open-loop, since there is a possibility of occupant interference. The calibration of a closed-loop control signal includes adjusting the proportion between the sensor signal and the control voltage (similarly to open-loop) but also includes calculating an offset, to prevent dimming until a desired light level is reached (Lighting Research Centre, 2004). A dual-loop algorithm maximises individual benefits of both the strategies, by combining open-loop controls with closed-loop controls.

3 Integration strategies

3.1 Design process

An architectural or building design process usually includes non-linear sequence of activities, aimed at creating forms and spaces capable of providing working and living conditions, which are aesthetically pleasing and appropriate for their occupants. A non-linear sequence implies that the design needs to be revisited multiple times, based on feedback loops with various stakeholders in the design process, and this can happen at any time if any desired design criteria is not met for any reason. This could involve revisiting previous design decisions, and possibly changing the assumptions or actions. An integrated design of daylighting and electric lighting, is particularly important in order to achieve pleasing and appropriate working and living conditions, while at the same time creating a sustainable solution with respect to energy, materials use and longevity of the building.

The stakeholders involved in the design process can vary, depending on the size and complexity of the design task. It is possible that a lighting designer is be hired by – and works directly with – the building owners and/or their representatives, while it is also possible that the lighting designer is also the architect; or is hired by the architect. Similarly, their affiliation could be with any of the other design team members, such as interior designers, electrical or mechanical engineers, or energy consultants. In any case, good communication among all parties is key to a successful design.

3.1.1 Planning Concerns for Daylight Utilization

Researchers and designers attempt to coordinate all relevant building systems – such as site layout and design, structural system, building envelope, interior design elements, and environmental control systems – in a manner that helps all components to work in unison; to create thermal, acoustic and visual comfort in an economical and energy-efficient way, while also providing good air quality and safety for the user. Advanced computer systems can be utilized during the building's design and construction phases, and for monitoring performance in the post-occupancy phase, to assure that problems are detected and remedied at the earliest.

The integrative daylighting design process requires particular care, because the potential for daylight utilization depends largely on the earliest design decisions; such as site layout, building orientation, building shape and volume, as well as on the placement of openings in façade. It is challenging to illuminate the interiors only with daylight, if the exterior surface area is minimal as compared to the building's volume. Similarly, if a building is placed in the shadow of a high-rise structure, daylight and sunlight access will be limited.

To make specific design recommendations for illuminating a particular building with daylight, the designer needs to take several steps. It is important to conduct a detailed site and climate analysis to gather data for solar radiation and daylight levels. Daylight availability varies throughout the day and across the seasons, in terms of intensity, duration or consistency: some days are cloudy, others bright and sunny, while some are intermediate. Days in the winter are shorter, while those in the summer are much longer. On a bright sunny day, daylight levels of 100,000 lx or more are achievable, but this may drop to only a few hundred lux on an extremely dark and rainy day, or during dusk and dawn periods. Local data may be available from a nearby weather station at an airport, but this will probably need adjustment, when differences in terrain between the measured and actual site need to be accounted for; in addition to the effects of surrounding buildings and varying topographical features. Reliable information on average daylight levels is required to accurately predict the illuminance values on exterior and interior surfaces for a given day. The lighting designer also needs to know the time periods when daylight alone is insufficient to meet recommended lighting levels – and typical frequency of such occurrences of insufficiency – to size the supplementary electric lighting.

3.1.2 Programming and Project Brief

A good design requires both functionality and aesthetics. A building design that is visually pleasing, but fails to comply with the users' requirements, will probably be rejected. A daylight designer needs to gather information about user and client needs, preferences and constraints, in the initial phases of the project. It is essential that the kinds of tasks to be performed in the building, as well as the various requirements associated with these tasks, are carefully assessed. A participatory process involving various user groups is one way of determining what is needed and desired. Assessing the future occupants' current facility, as well as its strengths and weaknesses, will also add valuable information and sources of inspiration to the process. Lighting design, and particularly daylighting design, must reference many factors in order to provide the proper quality and quantity of light in an architecturally appealing way. A site visit gives the designer a chance to experience the context in which a building will be placed.

The daylighting designer seeks from the client and the whole design team, the various design objectives such as:

- space functions and layout requirements,
- comfort level and satisfaction of occupants, workers, users or visitors,
- visual and perceptual needs, depending on age of occupants and tasks to be performed
- architectural opportunities and constraints, including context, potential obstructions, building materials, room finishes and architectural styles,
- incorporation of specific views and view directions from the building,
- desired impressions and the intended image,
- performance targets for daylighting, lighting, heating, cooling, ventilation and energy use,
- special requirement for the flexibility in the future arrangement of spaces and workstations,
- safety and security concerns,
- maintenance considerations, and
- budget indications and constraints.

Based on these, and perhaps other considerations, a project brief or program is established. The daylighting designer should also establish a framework to judge how a daylit space will feel to the user. This provides a reference against which the final design can be judged.

3.1.3 The "Big Picture" or Conceptual Design

In the design and construction of a new building, once the project brief is established, the designers typically engage in schematic design activities, during which the "big picture" or overall concept is defined. For interior spaces where sunlight (direct-beam light from the sun) and daylight (diffuse light from the sky) are essential parts of the luminous environment, this early design process must ensure proper placement of the building, in relation to its site and the surrounding environment, proper orientation, massing, space planning, and sizing and shaping of openings. This is because the early design decisions have a greater effect on the overall building performance – both with respect to user satisfaction and also to the sustainability aspects, such as energy use, material selection, HVAC system sizing, etc.

3.1.4 Daylight and Climate

To establish detailed performance targets for daylighting, the designer needs to understand the site's macro- and micro-climate conditions. While climate data from the closest available weather station might provide a general picture of the regional climate, conditions at the building site might be significantly affected by localized weather patterns dictated by terrain or water bodies. These local weather patterns might affect temperature, humidity, fog and cloud cover, but also wind conditions which might require a different design response as compared to what the data from closest weather station might suggest.

3.1.5 Site Layout and Context

Because of its potentially large contribution to various aspects, including but not limited to building illumination, the solar position is very important for a designer. Understanding a site's surroundings, and assessing the site's exposure to direct sunlight is necessary, for which a horizon obstruction diagram is used; which helps predict the instances over the year, when direct sunlight is blocked from reaching any point on the site. With the aid of a transit or theodolite, it is possible to plot the "skyline" directly onto a sun path diagram, for any site depending on its latitude. However, it is important to consider the other buildings and landforms (topography) surrounding the building site, including trees and other vegetation.

It is also advisable to assess how the topography and context of the site influence other environmental control parameters of the building, such as heating and cooling, as well as wind and moisture. A hill-top location exposed to strong winds makes deployment of certain exterior shading devices difficult; whereas lower altitude locations such as those in a valley would need higher requirements of thermal resistance for walls and fenestration systems. Locations on slopes facing the sun tend to be warmer and receive more daylight than those on slopes facing away from the sun. Prevailing winds, however, need to be taken into consideration as they can alter thermal conditions substantially.

3.1.6 Building Massing and Orientation

In the early design stages, consideration of the exterior form, geometry and orientation of a building are of utmost importance, since good daylighting very much relies on the sky-exposure of the building interiors. Single-story buildings or top-floors of multi-story structures can utilize both strategies of top- and side-lighting. Overhead daylight openings are especially effective for illuminating horizontal tasks, as the cosine reduction due to the earth's atmosphere is less towards the zenith as compared to near the horizon.

A room's depth from a window is limited by the daylight requirements; hence the dimensions such as height of the window-sill; and overall height and width of the window, are all critical in the daylight performance. Similarly, the overall width of a building is limited by the depth of daylight penetration, thus, well-daylit buildings tend to have typical footprints.

To effectively utilize daylight in a multistorey building, narrow plans are better since they allow daylight penetration into all floor areas. In many buildings, the shorter cross-section is therefore limited to approximately 14 meters in depth, with an up to 2m wide central corridor surrounded by up to 6m deep rooms on either side. Finger plans, which include wings attached to the main body of a building, can be used when elongated floor plans cannot be accommodated, or are undesirable for other reasons. A variety of floor plans can commonly be found, roughly resembling the letters I, L, F, E, H, U and O.

In some spaces, it may be possible to have sidelighting from more than one side of the building. However, one needs to consider that differences in orientation will affect the amount of available daylight entering the space. The reflectivity of room surfaces is another important factor: the higher the reflectivity, the more is the possibility of light to be evenly distributed; and directed towards the rear of the room.

With higher buildings, however, the obstructions of fingers onto other parts of the building needs to be considered. An example of this can be referred in Fig. 7-5, p. 65 in (Moore, 1985).

Building geometries that include courtyards or atria -- which are basically courtyards covered by glazing – are other options that support daylight inclusion into most spaces. Since locations facing the interior often have little or no direct exposure to the sky dome; the surfaces surrounding the courtyard or atrium should be as light as possible for enhanced reflections. On the other hand, courtyards and atria reduce the need for solar shading and glare control, since they shield the courtyard-facing facades from low-angle direct sunlight. It is essential that the courtyards or atria are large enough to allow sufficient exposure to the sky, for the rooms at lower floors.

Simple design tools can be used to ensure the fulfilment of essential criteria for daylight exposure. It is advisable to perform initial energy performance calculations at this stage; and correct the conceptual design decisions if necessary.

3.1.7 Daylighting Design Development

Depending on the overall form and orientation of a building, the development of window designs should take several factors into account. If a building is characterized by narrow footprints and shallow rooms, it is normally sufficient to provide windows along its perimeter. Amount of daylight illuminance in a room is determined by the inverse relationship between visible transmittance and window dimensions: the lower the visible transmittance is, the larger is the glazing area requirements for allowing certain amount of daylight. Thus, a designer needs to be aware of selecting appropriately sized windows, with reference to desired thermal and visible transmittance requirements.

When a building has a large footprint and deep spaces, vertical openings can effectively illuminate only the perimeter areas. The top floor can usually be lit by skylights or other openings in the roof surface. To illuminate sections in the interior parts of the building, courtyards or atria can be considered. Detailed simulations should be conducted to ensure that the design achieves the desired criteria.

During the design development process, further decisions are made regarding the exact location and sizing of fenestration openings, the appropriate shading devices and glazing technologies; and also the interaction between the daylighting and electric lighting systems. This includes zoning the building for daylight-responsive lighting control operation, as well as coordination of light sources in terms of appearance and operational principles. Here, the parameters of appearance include colour rendering, correlated colour temperature, light distribution patterns, etc., whereas the operational principles could include their dimming or switching capabilities. Visual comfort criteria also need to be checked at this stage, and a detailed analysis needs to be performed, to eliminate potential problems of glare and visual distractions.

It is also important to coordinate the daylighting and electric lighting systems, along with the selection and operation of heating, cooling and ventilation systems for the building. Since the linkage between energy requirements for space conditioning, and solar heat gains/losses through daylight openings, is clear; this coordination should not be left to chance. Suitable building energy performance tools should be used to select and configure such systems. If multiple issues arise in achieving energy-efficient and comfortable overall operation of the combined systems, which are connected with improper daylight design; design decisions will have to be revised.

3.1.8 Optimizing Daylighting Design

Even with highly structured and well-conceived design processes, there is often a significant scope of optimizing the final outcome. It is advisable to set ambitious yet appropriate performance targets, which are revisited throughout the design process, in order to ensure that they are met – and perhaps even enhanced further. The amount of improvements achieved, usually depends on the available time and budget, but also on the designers' experience. Highly experienced designers have much better insights into the scope of improving daylighting design, and also its integration with electric lighting and other aspects. It should then be obvious, that optimizing daylighting performance alone is rarely the best overall design solution, and there are definite relationships between the various involved factors, such as: building form, design of daylight openings and electric lighting, energy performance, and indoor environment characteristics. To deliver a successful design requires careful and deliberate thoughts on the various aspects of integration.

3.1.9 Daylighting Integration

Design for daylight must be modified according to, and integrated with, other environmental concerns. Views, thermal comfort, natural air movement, acoustics, and electric lighting are all elements to be considered. A change in building or component design in response to one element of the environment, is likely to affect the response to other elements – for example, an operable window intended to allow daylight and natural airflow, will also allow noise to enter the space. This means that all environmental factors must be simultaneously considered in a design. Proper integration of daylight with building systems is required with respect to electric lighting control and mechanical coordination. This integration can only be achieved through a carefully coordinated design, with a calibrated daylight and electric lighting system. Computer software tools can enable designers to quantify the impact of daylighting decisions, in terms of lighting levels and energy savings.

3.1.10 Mechanical System Coordination

Besides its influence on perception and visual comfort, the effect of daylighting design on building energy performance and the selection of environmental control or building services systems has gained renewed interest in the building industry. Excess heat in a building is referred to as a cooling load, which needs to be removed via systems for refrigeration, air-conditioning or ventilation. This is especially true for larger office buildings, where windows often cannot be opened for natural ventilation purposes, since this might disturb the operation of mechanical cooling equipment. Likewise, large window areas in winters, might allow for too much heat loss through the glazing. It is therefore essential that designers consider the interactions of daylighting and solar shading systems with the mechanical systems used for heating, cooling and ventilation. The earlier this is investigated in a design process, the better is the chance for achieving a good balance. Ideally, the control strategies for lighting and HVAC (heating, ventilating, air-conditioning) technologies are discussed early in a design process, to allow for an integrated building system that fulfils user and energy conservation needs. Such a holistic approach to architectural technology is in the centre of the discussion about “intelligent and sustainable buildings.”

3.1.11 Electric Lighting Coordination

The goal is to utilize daylight energy in such a way, that energy consumption for electric lighting is partially or completely eliminated; and cooling loads associated with the electric lighting system are reduced. When electric lighting systems are selected for integration with daylighting design, it is also important to choose luminaires which exhibit appropriate colour rendering qualities, are energy-efficient, and which might be suitable for operation with daylight-responsive lighting controls. Appropriate spatial distribution of light from luminaires, while avoiding undesirable side-effects like glare, is also critical. Indirect luminaires typically produce fewer glare problems, but might not be as energy-efficient as direct luminaires; or might create less interesting luminous environments due to higher proportion of reflected light.

3.1.12 Daylighting Design Tools

The importance of architectural design decisions, and the detailing of building systems and components, is well known – from the aspects of building energy performance, and the well-being of its occupants. Nevertheless, the formal and aesthetic aspects are still the focal point of attention for many architects and designers; and building energy conservation is considered only when building codes or the client specifically require it. In most cases, energy awareness is not an integral part of the design process, but rather an add-on; an approach that is unable to provide benefits achievable with the currently available technology. Globally, multiple Building energy research institutes are working on developing design tools that are user-friendly yet effective and comprehensive, meant to allow designers get a quick feedback of their design decisions – the impact on energy performance and occupant comfort at any point in the process. That is also the case for daylighting design.

3.1.13 Graphic Daylighting Tools

Simple graphic assessment can be a first step in the right direction. One such tool: the Daylight Factor, is described further, while another – the ‘no-skyline diagram’ is presented in Figure 6.

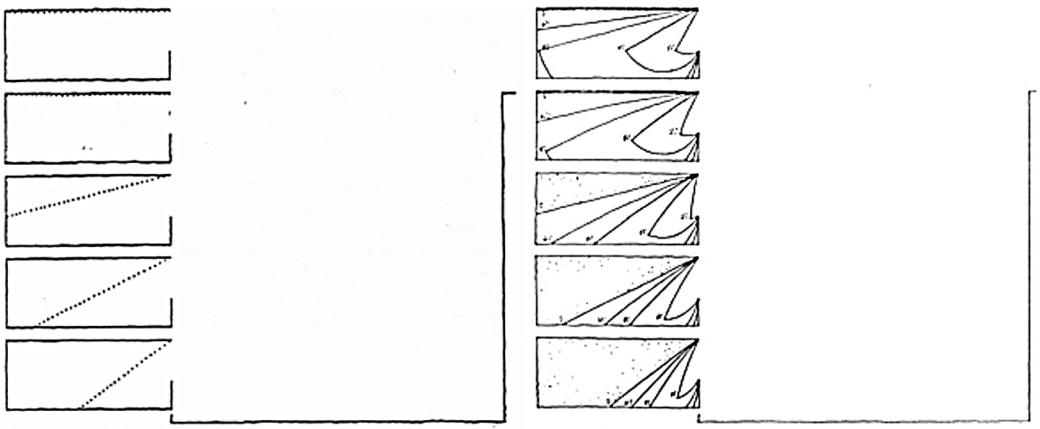

Figure 6: No sky-line diagram to graphically assess the depth of daylight penetration from the diffuse sky. The higher the room and the lower the surrounding buildings obstructing the horizon, the deeper can daylight penetrate the room (Madsen, 2004)

3.1.13.1 Daylight Factor

The concept of the Daylight Factor (DF) was developed in the United Kingdom in the early 20th century. This factor is a ratio that represents the amount of illumination available indoors, relative to the horizontal illumination present outdoors at the same time under overcast skies; and hence is applicable under overcast sky conditions only. The DF is the most common metric used when studying physical models to test daylighting designs in overcast-sky simulators. It is reasonably easy to calculate this metric in real buildings or physical models with illumination meters.

Unlike the simplicity of the DF metric, there are other dynamic parameters for evaluating daylight performance, which depend on actual conditions – and are based on simulated daylight conditions over an entire year based on local weather data. The approach is much more complex as compared to the DF calculation, which is based on a "snapshot" situation of the daylighting of a space. Since the DF approach works under a uniformly overcast sky, it is independent of the location or orientation of the building, which limits its accuracy. Unlike Daylight factor calculations, various factors are considered in evaluating the dynamic daylight performance parameters, such as:

- Orientation of windows and skylights in relation to the world's corners
- The latitude of the place, and thus the variation in the sun's time in the sky throughout the year
- The local climate, and, for example, how many hours of sunshine there is in a year
- Building life and user or automation control of daylight control systems.

3.1.14 Physical Models

Scale models are usually constructed during design processes, for studying as well as for demonstration during meetings with clients and building officials. These models can be adapted in a way, that they can be purposed for predicting interior daylight levels and their spatial distribution with acceptable accuracy. This is possible because the behavior of light does not change with the scale of the environment. The DF metric described earlier evaluates the measured illuminance values for various points inside the room, as a percentage of the available daylight outside. DF evaluation can easily be performed on an unobstructed horizontal outdoor surface under stable overcast sky conditions. An array of small light sensors connected to a readout instrument, or a data logger is all that is needed. As the daylight factor is independent of absolute lighting levels and depends only on the geometry of the space and its components, it is a very convenient measure for evaluating daylighting performance. The same scale models can also be used to study sunlight penetration and effectiveness of shading devices, using a heliodon sun simulator: a simple table that can be rotated and tilted to simulate the effects of different latitudes and seasonal, or diurnal changes on the sun position and its subsequent impact on building performance.

To be able to simulate various sun positions and sky distributions at any given time of the year, research institutes, architecture and engineering schools, as well as some lighting design practitioners, have built sky simulators that allow researchers and designers to test building projects with a larger degree of accuracy and without having to tilt the model. That permits architects to build more flexible models that could incorporate removable parts for testing alternative design schemes. Fairly elaborate sky simulators are available in some institutions.

Simpler devices called as mirror-box sky simulators, which emulate daylight levels for overcast sky conditions, are also available in many architecture- or engineering schools across the world. Figures 7 and 8 present mirror box and sun simulator / single-patch sky simulator setups. Some schools also provide more sophisticated sun simulators to test solar shading devices; and evaluate solar obstructions resulting from surrounding buildings.

Figure 7: Mirror-box sky and sun simulator at the Royal Academy of Fine Arts School of Architecture in Copenhagen (Photography: Werner Osterhaus).

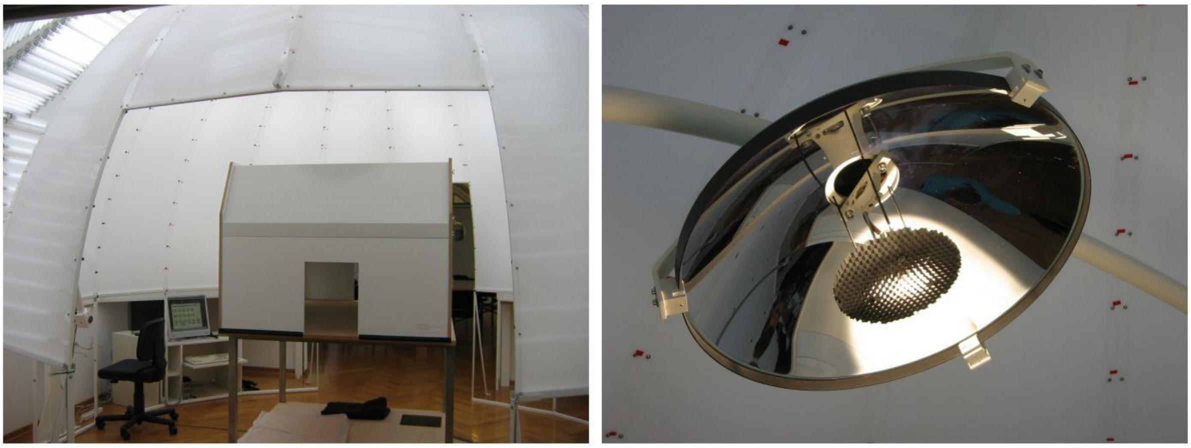

Figure 8: Sky and sun simulator at the office of lighting designer Peter Andres in Hamburg (Photography: Werner Osterhaus).

By integrating advanced technical equipment into daylight simulators or actual buildings – such as a digital camera calibrated for luminance measurements – building scientists and architects are able to analyze fundamental questions of visual comfort, and particularly glare. These issues have so far been treated rather intuitively, since their calculation procedures have been very time consuming and complex for many designers.

3.1.15 Full-Scale Test Rooms and Mock-Ups

For certain projects, it can be advisable to test full-scale test rooms or mock-ups, to assess daylighting performance as accurately as possible. This is especially recommended when other simulation tools cannot handle the complexities of the technology which the designers intend to employ, or when spaces are to be equipped with a particular design solution that has not been extensively tested. This is particularly true for assessing qualitative requirements, such as the perception of space and visual comfort in complex daylighting design schemes incorporating advanced fenestration and shading systems.

Some of the qualitative requirements can be formally investigated using structured scientific methods, including:

- perception and visual adaptation (ergo-ophthalmology)
- visual comfort and performance (visual ergonomics)
- light propagation, transmission and reflection (photometry)

Full-scale mock-ups can avoid costly mistakes, particularly when many spaces of the same type are to be built. A prominent example is the New York Times office building, for which such mock-ups have been extensively tested (LBNL, 2021), as presented in Figures 9 and 10.

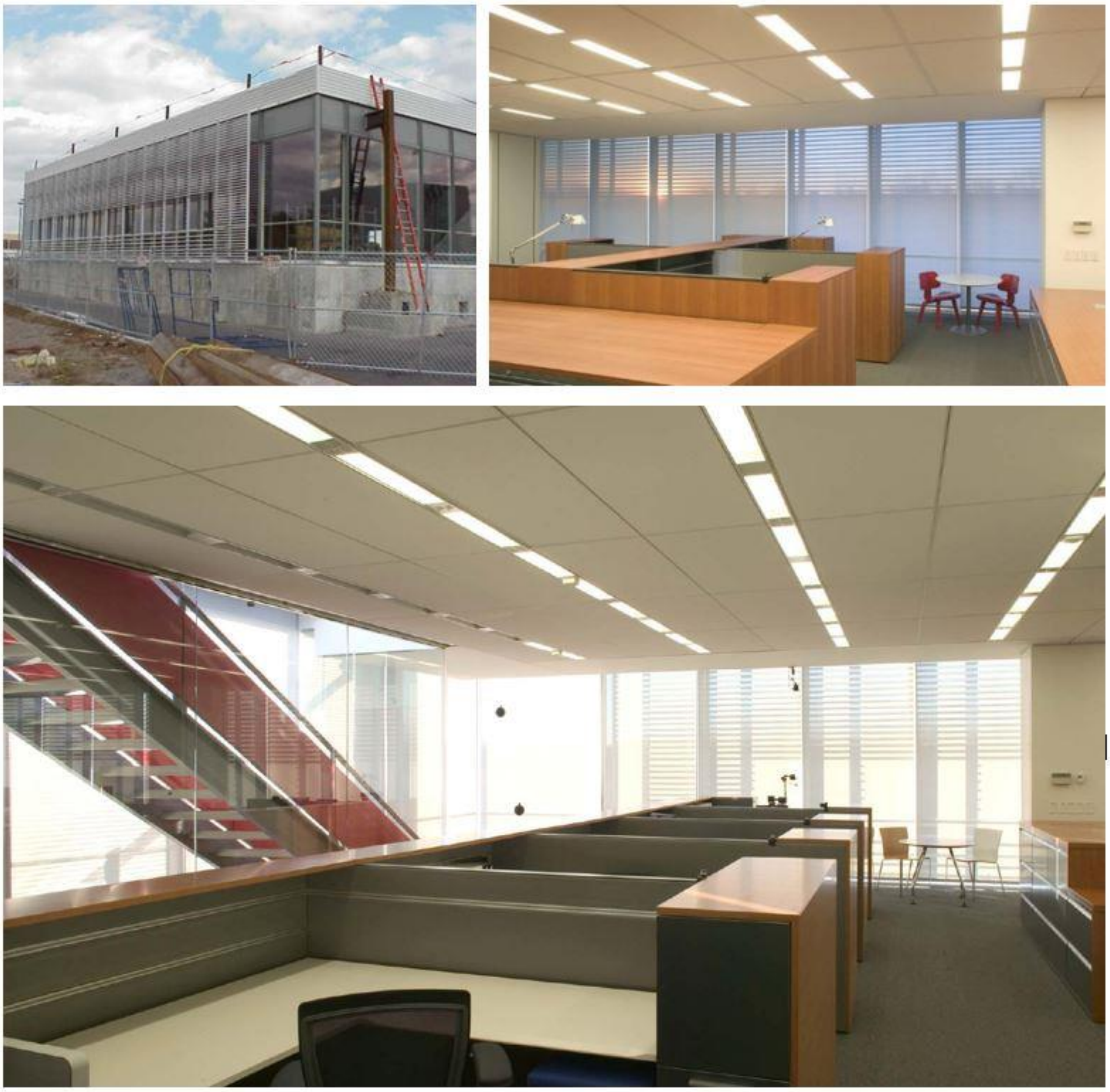

Figure 9: Full-scale mock-up construction for testing of lighting systems for the New York Times building. Note the hanging globe thermometers for measurement of mean radiant temperature and the illuminance sensors at the top of the low partition walls and at the façade in the bottom image. (Lee, Selkowitz, Hughes, Clear, Ward, Mardaljevic, Lai, Inanici and Inkarojrit, 2005)

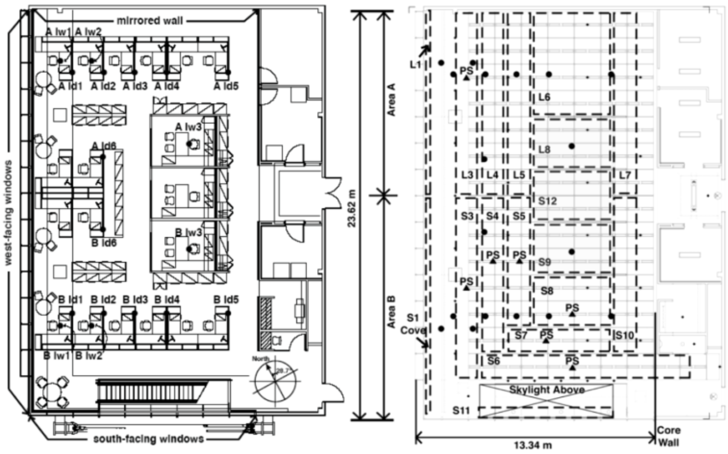

Figure 10: Floor plan of New York Times Mock-Up (Lee and Selkowitz, 2006)

3.1.16 Virtual Models and Computer-Based Simulation

Computer programs permit the simulation and analysis of daylighting and/or electric lighting systems, for simple and complex room geometries, and evaluate metrics ranging from daylight factor to others based on absolute illuminance and luminance values. Some programs are useful in the early phases of a design project, since a graphic input interface often allows for the assessment of simple room geometries. With appropriate import features, they can also handle reasonably complex building geometries, but this requires building the simulation model in an external Computer-Aided Design (CAD) program. They also have reasonably intuitive interface designs and allow for both daylighting and electric lighting assessment. Many of these programs also allow for the assessment of glare associated with electric lighting. Ray-tracing lighting simulation programs like RADIANCE (Fuller and Mcneil, 2017) allow users to simulate almost any lighting situation with extraordinary accuracy and photographic image quality. To allow easier input and output interfaces, the RADIANCE simulation engine has been incorporated into various other lighting design tools (e.g., DaySim, Ladybug/Honeybee, Groundhog, DIALux, Fener, IES-VE, DIVA-for-Rhino, LightStanza, OpenStudio, etc.). RADIANCE also supports evaluation of various glare indices for both daylight and electric lighting; and thus is employed by many lighting-related research institutions and designers over the world.

There are many simulation tools for evaluating the Daylight Factor metric, which itself is inherently disadvantageous due to the static nature of its analysis, unsuitable for any specific date and time. To overcome this limitation and support dynamic assessment of daylighting performance over a whole year or in parts, further simulation tools have been developed, which support the evaluation of climate-based daylight metrics (CBDM), while also evaluating the thermal behaviour of fenestration elements; thus performing a holistic evaluation of visual conditions, thermal comfort and energy performance. Combined use of raytracing and matrix algebraic algorithms has increased the speed of annual daylight simulations by several orders of magnitude with near comparable levels of accuracy to conventional raytracing-based simulations (McNeil and Lee, 2012; Lee, Geisler-Moroder and Ward, 2018; Wang, Ward and Lee, 2018).

The complex light-scattering properties of shading and daylighting systems are represented by bidirectional scattering distribution functions (BSDF) and are required for daylight simulations. Industry organizations and laboratories are working to develop methods of characterization and BSDF product databases to support simulations of energy use, comfort, and qualitative performance (Geisler-Moroder, Lee, Ward, Bueno, Grobe, Wang, Deroisy and Wilson, 2021; Ward, Wang, Geisler-Moroder, Lee, Grobe, Wienold and Jonsson, 2021). In several instances, graphic interface programs allowing extensive parametric and optimization studies, via genetic algorithms, have added considerable usability to lighting simulation programs.

Many architecture and engineering schools now offer courses which include simulation assignments, for the evaluation of lighting design decisions, to assist future designers in their decision making. Additionally, the development of climate-based daylight simulations has paved way to multiple advanced daylight performance metrics, which are now becoming common to daylighting design. Some of these advanced metrics and briefly described here.

3.1.16.1 Daylight Autonomy (DA)

Daylight autonomy is simply the total number of occupied hours for a space, when a daylight illuminance above a minimum threshold is achieved. Continuous Daylight Autonomy (DA_{con}) is another metric that also does the same, but also includes values below the reference level with a linear weighting factor applied. Maximum Daylight Autonomy (DA_{max}) counts the number of hours above an upper threshold reference level, which is typically 10 times the DA_{con} reference level; and typically reference levels for DA_{con} and DA_{max}, are 300lx and 3000 lx, respectively.

3.1.16.2 Useful Daylight Illuminance *(UDI)*

Useful Daylight Illuminance is another dynamic daylight performance parameter, that results from the simulation of daylight in a room (with no operable shades) using weather data over an entire year. UDI is divided into three categories according to the desired illuminance required by the occupants:

- Too low daylight intensity (i.e. not meeting the minimum lighting standard requirements)
- Acceptable daylight illuminance (i.e. within the acceptable range of illuminance)
- Too high daylight illumination (i.e. above the upper threshold and consequently glare and / or overheating problems in the room)

3.1.16.3 Spatial Daylight Autonomy (sDA)

Spatial Daylight Autonomy (sDA) describes how much of a space receives sufficient daylight. Specifically, it describes the percentage of floor area that receives at least a specified illuminance level, such as 300 lx, for at least 50% of the annual occupied hours.

3.1.16.4 Annual Sun Exposure (ASE)

Annual Sun Exposure (ASE) describes how much of space receives too much direct sunlight, which can cause visual discomfort (glare) or increase cooling loads. Specifically, ASE measures the percentage of floor area that receives at least 1,000 lx for at least 250 occupied hours per year.

3.1.16.5 Sunlight Exposure

Sunlight exposure duration is estimated by the time period between the first and last moments in time when sunlight insolates a set reference point, while considering external obstructions, such as overhangs and other shading features, neighbouring buildings, trees etc. Sunlight exposure at solar altitude angles below a defined minimum solar altitude is not considered; and this minimum angle depends on the geographical latitude and is, for example, listed with 10° for Denmark (55.63° N average latitude). The assessment can be completed using software or manual geometric constructions.

According to the new European Daylighting Standard EN 17037 (MITÉ EUROPÉEN DENORMALISATION, 2018), a space should receive possible sunlight for a specified duration on a date between 1 February and 21 March at a reference point located as specified in the standard, assuming that the day would be cloudless. The standard proposes three levels for sunlight exposure, as presented in Table 2; and at least one room of a dwelling should have at the respective level of sunlight exposure.

Table 2: Recommendations for daily sunlight exposure according to Table A.6 in EN 17037 - Daylight in Buildings.

LEVEL OF RECOMMENDATION FOR EXPOSURE TO SUNLIGHT	**SUNLIGHT EXPOSURE**
Minimum	**1.5 hours**
Medium	**3 hours**
High	**4 hours**

3.1.17 Solar Shading and Glare Control Devices

Strategies for shading and glare control through vertical window openings, include various internal and external devices -- as components of the fenestration system. For architectural applications, solar shading devices are classified in two categories: fixed and movable. Fixed shading devices include overhangs, fins, egg-crates, horizontal and vertical louvers, and light shelves, whereas movable devices include adjustable awnings, Venetian blinds, shutters, and curtains. Both these categories are capable of controlling the direct sun penetration, while also allowing diffuse or scattered daylight to enter the building. Fixed devices require compromises to balance various needs of daylight utilization, solar shading, glare protection, and view; since these cannot be adjusted or completely removed when weather conditions and sun positions change. Exterior shading devices are more effective in reducing the impact of solar radiation on unwanted heat gain in buildings, as they prevent the greenhouse effect (Lee, Selkowitz, DiBartolomeo, Klems, Clear, Konis, Hitchcock, Yazdanian, Mitchell and Konstantoglou, 2009; Hoffmann, Lee, McNeil, Fernandes, Vidanovic and Thanachareonkit, 2016). To increase performance, consideration of separate systems for solar shading and glare control might be a better choice. Architectural aesthetics or maintenance concerns, due to exposure to high winds or environmental pollution, may however preclude the use of exterior sun control; and may suggest the use of shading devices between two glazing elements or on the interior side of the window.

Adjustable Venetian blinds that are placed between two or more glass panes, are particularly not exposed to dust and other dirt particles; but can effectively control solar radiation while allowing daylight to enter a space. Similar devices include fixed reflector elements, honeycomb, and tubular or aerogel sheets between glass panes (Fernandes, Lee, McNeil, Jonsson, Nouidui, Pang and Hoffmann, 2015). Aerogel, despite its excellent insulating capabilities, is a translucent material; and its lack of transparency limits its application to windows or skylights that do not require outdoor view connections. While transparent honeycomb or tubular insulation materials allow for some view out, they are best suited for window sections above line of sight, or for clerestory windows.

In recent years, other technologies have been developed for better daylight utilization, and for improving thermal and visual comfort. Recent developments aimed at improving daylighting access for spaces located deep within a building, includes prismatic or holographic glazing panels, mirror panels, and core daylighting systems such as light guides, light pipes and Fresnel lenses, sometimes combined with fibre-optics. These are also described earlier, in Section 2.1.1.3.

Reducing visible transmittance of glazing in conjunction with solar radiation control is typically not advisable, since this also reduces daylight penetration; and might lead to a gloomy appearance of the space.

3.1.18 Control Systems for Daylighting, Daylight-Dependent Electric Lighting and Shading Systems

When designing control systems for regulating the amount of daylight, sunlight or electric lighting, the fact that daylight is a highly dynamic source of lighting, must be thoroughly considered. Daylight availability is strongly influenced by seasonal and diurnal variations, as well as sky conditions present at the location. Daylight and electric lighting control systems thus need to adapt to those changing conditions -- and regulate shading systems and electric lighting to meet both visual requirements for the space as well as energy performance targets.

There are at least two dimensions to daylight-responsive controls: the control of the daylight input into the space, and the control of the electric lighting output. The first is critical for providing adequate quantity and quality of daylight in the interior spaces, whereas the second saves energy and improves the overall distribution of light when daylight is insufficient to illuminate the room. For both these systems, user satisfaction and acceptance is extremely important. Annoyances caused by the system, such as glare, temporary reductions or sudden changes in brightness, or irritating noise from motors while adjusting the windows or shading devices, will reduce the system’s overall effectiveness and acceptance.

In order to avoid rejection by users, a control system should progressively adapt its parameters to match user preferences. Building services and control systems that do not fulfil this condition, are primary causes of the well-known "Sick Building Syndrome". Setting proper operational conditions for a control system is, unfortunately, complicated by the fact, that such preferences may drastically vary between individual users.

Maintaining constant illumination at the reference plane, through a daylight-responsive control system, is not always desirable – and is often impossible to achieve. The daylight illuminance is highly variable, as compared to the illuminance provided by electric lighting; where factors such as density and movement of clouds can lead to random variations in sky luminance. While this may be a potential nuisance while setting up the control algorithms, the continuous variation of the daylight levels is also seen as one of daylight's desirable qualities.

In side-lit rooms, the illuminance at points near the window is rarely more than one-tenth of that outdoors; and is often considerably less at points far from the window. The daylight in an interior space is nevertheless sufficient in magnitude, to be considered a useful contributor to indoor lighting for most parts of the year. Daylighting and daylighting systems should therefore not be considered isolated elements in a building's design.

Electric lighting is a major energy end use in commercial buildings; and can affect the cooling and heating loads. Internal heat generation from electric lighting, equipment, and occupants will often result in increased cooling load for most of the year, especially during the daytime occupancy hours. Some of the electric lighting and associated equipment energy may be reduced, by increasing the use of daylight and through daylight-responsive electric lighting controls, as long as solar heat gain is also controlled by appropriate shading devices – preferably on the exterior side of the glazing.

To achieve the best possible results, an interior space needs to be zoned for optimal placement of luminaires and sensors, with the longer axis of luminaires arranged parallel to the window. A further critical consideration is how lighting is positioned relative to workstations. Both task and ambient lighting need to be assessed in this respect.

Certain types of electric light sources, such as most high intensity discharge (HID) lamps, cannot be dimmed or frequently switched on and off. This is not an issue for few other sources, hence fluorescent or, more recently, LED lighting has generally been coupled with electric lighting controls. Careful consideration should be given to the colour rendering properties, and the colour appearance of these selected light sources, if they are to be used in conjunction with daylight. Although daylight might reach lower or higher correlated colour temperatures (CCT) than available electric lighting sources; lamps between 3,000K and 4,500K are most likely to match daylight's CCT at various times of the day. Daylight conditions, climate and individual preferences must, however, be considered: High-latitude countries, which are predominantly cloudy, appear to prefer warm-white lamps (ca. 3,000K), whereas sunny low-latitude countries seem to prefer the cool-white sources (ca. 4,000-5,000K). The latter CCTs may, however, be seen as too cold for prolonged night-time use.

When both daylight and electric lighting are used simultaneously, care should be taken to minimize luminance differences between the window area and its surroundings, in order to ensure visual comfort. For both visual comfort and lighting energy savings, interior surfaces need to be light in colour, to maximize internal reflection. Additionally, particular consideration should be given to specular reflection from shiny or mirrored surfaces, which often arises from components used in daylighting systems and/or shading devices.

3.1.19 Daylight-Responsive Electric Lighting Control Systems

Photoelectric controls can be very effective in reducing lighting, heating, and cooling loads in certain space types, such as offices, restaurants, shops, industrial buildings, and schools. Control by switching or dimming has become a standard in controlling lighting devices; and is helping realize the energy-saving potential of daylight. Prediction methods have also been developed to assess the potential energy benefits of these controls.

Lighting control strategies include automatically dimming lights as a response to available daylight; dimming and switching luminaires based on occupancy, and performing lumen maintenance, i.e., automatically compensating for long-term lumen losses. Various strategies for lighting control, and recommendation on their appropriateness for deployment in various cases, is presented in Table 3 below. Available lighting controls also help with light energy monitoring and diagnostics, have accessible dimming capabilities, and offer the ability to respond to real-time utility pricing signals. Research has found that daylight-linked control systems can result in sustainable reductions, of 30–41% in electrical energy for the outermost row of fluorescent lights in a perimeter zone, and 16–22% for the second row of fluorescent lights in open-plan office spaces (Rubinstein, Jennings, Avery and Blanc, 1999).

Table 3: *Lighting control recommendations (red) and options to consider (black) for different types of office building spaces.* (Simpson, 2003)

Space Characteristics	Daylit spaces with high occupancy	Daylit spaces with low occupancy	Non daylit spaces with high occupancy	Non daylit spaces with low occupancy
Sole or Double occupancy (Private offices)	Manual control at door Flexible manual control Timed off/manual on Light sensor dimming	Manual control at door Flexible manual control Timed off/manual on Presence detection	Manual control at door Flexible manual control	Manual control at door Flexible manual control Presence detection
Shared occupancy (Open plan office, workshop, laboratory)	Flexible manual control Timed off/manual on Light sensor dimming	Flexible manual control Timed off/manual on Light sensor dimming Presence detection	Flexible manual control Time switching	Flexible manual control Presence detection
Temporary occupancy (Meeting room)	Local manual control Flexible manual control Presence detection Timed off/manual on Light sensor dimming	Local manual control Presence detection Flexible manual control Timed off/manual on Key control	Local manual control Presence detection	Local manual control Presence detection Flexible manual control Timed off/manual on Key control
Occasionally visited (Toilet, storage, copy room)	Not applicable	Presence detection Full occupancy link Local manual control Timed off/manual on Key control	Not applicable	Presence detection Full occupancy link Local manual control Timed off/manual on Key control
Unowned (Corridor, elevator lobby)	Light sensor dimming Light sensor switching	Full occupancy link Presence detection Timed off/manual on Light sensor dimming Light sensor switching	Time switching Presence detection	Full occupancy link Presence detection Timed off/manual on
Managed (Entrance hall, atrium, cafeteria)	Light sensor dimming Time switching Centralised manual control Light sensor switching Programmed scene setting	Light sensor dimming Time switching Centralised manual control Light sensor switching Programmed scene setting Full occupancy link	Time switching Centralised manual control Programmed scene setting	Time switching Centralised manual control Programmed scene setting Full occupancy link

Inexpensive handheld remote controls have now made occupant-controlled dimming an affordable option, and are now resulting in high occupant satisfaction rating (Maniccia, Rutledge, Rea and Morrow, 1999). A study conducted by LBNL compared the energy savings and effectiveness of various control techniques in offices, during a seven-month period in a San Francisco building; and reported that controls helped achieve savings of 23% for bi-level switching, 45% for occupant sensing with task tuning, 40% with occupant sensing and manual dimming, and 44% for occupant sensing and automatic dimming. The last figure for savings could have been higher, but for the high illuminance requirement by the occupants (Jennings, Rubinstein, DiBartolomeo and Blanc, 2000).

Energy savings from occupant sensing versus dimming depend to a large extent on the occupants' behaviour. In offices where occupants remain at desks during the day, there is a higher energy saving potential in dimming controls. Occupants' immediate lighting requirements will also vary with the type of work being undertaken and the working space arrangements. Designers must therefore also remember that highly occupied large open-floor areas will likely require different control systems or strategies, as compared to smaller spaces with a single occupant or just a few occupants. In case of the energy saving potential of switching vs dimming, the selection of appropriate strategy depends on the location of deployment; and switching systems tend to have a quicker payback at locations closer to a window, as compared to dimming systems, as seen in Figure 11.

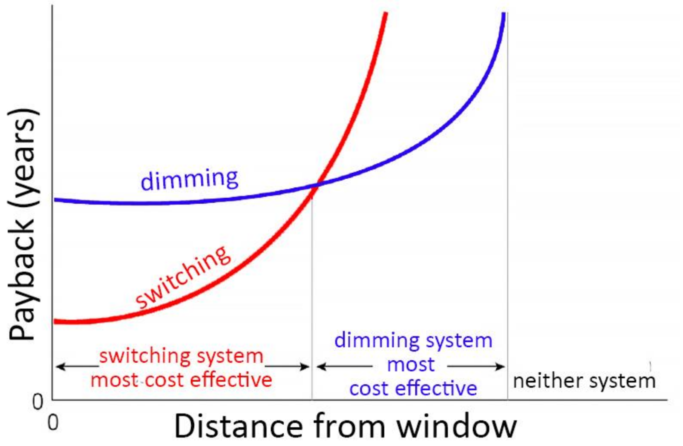

Figure 11: A system's payback with its specific distance from the window (Schumann, Lee, Rubinstein, Selkowitz, Curcija, Donn, Greenberg, Mcneil and Regnier, 2013)

A lighting control system can be made up of various building blocks, which can be installed in different configurations and combinations. In general terms, lighting can be regulated by the following methods:

- programmed lighting scenes (switching and/or dimming) for different activities,
- presence-dependent activation/deactivation (switching) by motion detectors,
- daylight-dependent regulation (dimming) of lighting level via:
    - light sensors on task luminaires,
    - light sensors in the room,
    - outdoor light sensors.

Daylight, electric lighting, and shading systems cannot be treated independently, since daylight influences electric lighting needs -- and potentially introduces direct sunlight and glare, which may make building occupants uncomfortable. Daylighting design is therefore essentially a challenge of systems integration.

Integrated and dynamic envelope and lighting control systems, such as Venetian blinds and electric lighting, are characterized by:

- their capacity to optimize the use of daylighting under varying sky conditions,
- their ability to regulate solar gain and avoid visual discomfort,
- their continuous adaptation to user preferences via override functions granted to the user.

Often, daylight-responsive dimming of fluorescent lamps or LEDs is coupled with automatically controlled Venetian blinds, which excludes direct sunlight by automatically changing the slat angle. Such a system is designed to balance thermal gains (cooling loads) and manage daylight and electric lighting levels to provide illuminance levels at a workstation, that are maintained within a specified range. The angles of the blind slats are regularly checked by the system and activated to block direct sun and maintain target daylight illuminance if daylight is available. If daylight alone is insufficient to maintain the target illuminance, electric lighting is added accordingly.

Such automated lighting control systems are a response to occupant behavior, which indicates that manual lighting controls are often not used effectively. Many occupants leave electric lighting on, even if the daylight levels are considered adequate. Blinds, once closed because of unwanted sun penetration, are often left closed even when the sun has long disappeared behind a thick layer of clouds.

Energy savings cannot be realized in daylit buildings, unless the electric light sources are dimmed or switched in response to the available daylight. The magnitude of potential energy savings achievable with daylight-responsive lighting controls depends on various factors, such as daylight climate, the sophistication of the selected control system, and the size of the control zones.

It is advisable to create control zones: which means deploying specific controls for different zones by clubbing areas of similar daylight availability and space function. In open plan areas with a uniform window façade, a control zone could include luminaire groups in rows parallel to the window with separate control for each row in from the window (for strip windows); or it could be in groups associated with each window (for punched windows).

Lighting control zones should also be designed to correspond to window shading device zones. For example, if an individual office contains manually operable blinds, the entire office will generally form, at least, one control zone. Where possible, the number of zones should be limited by making them as large as possible, since the cost of controls increases with the number of control zones. Making the zones too large, however, might lead to potentially underlit areas, or some occupants being dissatisfied with the lighting conditions.

Although most case studies of lighting controls have focused on energy savings, a major factor in selecting lighting controls should be the improvement of visual comfort and user satisfaction with a system. It is now well understood that user interactions with lighting control systems can have huge impacts on the achievable reduction in energy use.

For this reason, user participation in affecting lighting conditions should always be considered. Investigators have found that physical and perceived performance of daylight control systems can differ significantly. If a building occupant finds the situation created by the system uncomfortable in any way, such as abrupt switching in lighting or excessive noise from motors adjusting the blinds, the occupant will likely reject the system or may attempt to compromise it, for example, by placing tapes over the sensor or by cutting the connecting wires.

Researchers have also found that satisfaction with lighting controls increases, when users are able to change settings via remote-control devices, or via switches at their workstation. This suggests that building occupants expect to be in control of their environment. User-controlled systems enable occupants to set workplace conditions according to performance, activity and location. While wall-mounted controllers communicate with blinds and lighting systems via hard-wire, hand-held units use infrared signals.

A combination of automated and individual controls could thus be exploited – to enhance the advantages of both these systems. Empirical studies have demonstrated that occupants in relatively glare-free spaces are often satisfied with lower levels of work plane illuminance than values typically set for automatic control systems. Rather than maintaining a set work plane illuminance, electric lighting could therefore be turned off once the set level for daylight illuminance is reached and stay off, even when daylight drops below the set level, until the user responds by switching the electric lighting back on. Blinds could continue to be automatically operated to improve the combination of daylight admission and glare control.

3.1.20 Location and Calibration of Sensors

The installation of luminaires with factory-installed sensors does not differ greatly from the installation of conventional luminaires. At the installation site, installers only need to measure illuminance on the work surface under each luminaire at day and night, and to adjust the sensor until the desired lighting level is achieved. If a single daylight sensor is controlling multiple luminaires in a single zone or room, the placement of this sensor is critical. Generally, such sensor should view a representative luminance on a work surface; should not be able to “look outside” for minimizing interference; and should be located where it will not receive light from upward-directed lamps when indirect lighting is used.

The most appropriate location for a sensor in small spaces, such as private offices, is usually on the ceiling near the primary work area. Calibrating an occupant sensor means setting the sensitivity and time delay for appropriate operations, in the space where a unit is installed. Advanced control systems can often be calibrated using appropriate software.

The installers generally follow the calibration instructions given by the manufacturers, or request that calibration be provided during installation by the local representatives. Calibration and commissioning of controls generally requires specialized knowledge and skills. Here, commissioning is an important part where all buildings systems are checked to perform according to the owner needs and what the designer intended. Lighting controls are part of the building systems and therefore they also fall under the commissioning process.

The steps required for a proper commissioning might be different for each type of control system, building and user. However, calibration is very likely to be part of the commissioning process because any sensor used in the project must be properly calibrated for optimal performance. Calibration of electrical and mechanical sensors consists on the adjustment of the sensor to obtain the desired output given the actual range of a specific input, for example a physical parameter such as light (Rubinstein, Avery, Jennings and Blanc, 1997). The calibration activities change according to the control type. For instance, daylight-linked control has a different verification process than occupant sensors or manual dimming. Table 4 below lists the various calibration and commissioning activities typical for different control types.

Table 4: Typical calibration/commissioning activities for controls (Rubinstein, Avery, Jennings and Blanc, 1997)

Control type	Calibration and commissioning activities
Daylight linked	Verify sensor placement and orientation for optimum operation. Adjust if required. Make adjustment at the light sensor or controller to obtain the desired light level at the work surface.
Lumen maintenance	Verify sensor placement for optimum operation. Adjust if required. Make adjustment at the light sensor or controller to obtain the desired light level at the work surface.
Occupant sensors	Verify placement and field of view for optimum operation. If unanticipated obstructions are present, adjust sensor location. Adjust the sensitivity and time delay of the occupant sensor.
Sweep-off	Input start/stop time and override processing
Manual dimming	Set upper/lower limits of dimming range

It is necessary to adjust placement and orientation of the sensors according to the geometry and layout of the room, as well as defining the set-point at the light sensor if applicable.

Light sensors that monitor illumination levels across the space, are generally placed at the ceiling where they may be powered easily. In some configurations, the light sensors may be located at the luminaires, which makes installation and commissioning simpler. However, this means that direct measurements at the workplace are not available, and therefore, an initial night-time calibration (in the absence of daylight) with light meters is necessary to establish a relationship between the illuminance at the working area and the illuminance at the ceiling; as mentioned earlier. Even if the set-point is defined and calibration is done, under/over-illumination issues may occur when light sensors read the luminance outside their field of view , or if there are changes in the workspace environment that modify reflectance, such as objects on the working space or a new furniture layout, which adversely changes the outcome (Caicedo, Pandharipande and Willems, 2014).

Automated commissioning algorithms can enable a reliable performance from daylight dimming control systems, by predetermining the correlations between electric lighting output with photosensor signal and the work-plane illuminance. The remaining correlation between photosensor signal and daylight illuminance is determined based on data collected under representative sky conditions. In a field study in an outdoor testbed, daylight control of individual indirect-direct pendant LED fixtures was shown to be significantly more reliable, when this approach was used, as compared to conventional commissioning practices (McNeil, Kohler, Lee and Selkowitz, 2014). Correlation coefficients derived in the testbed are then used for guidance during the commissioning and burn-in period in real buildings (McNeil and Lee, 2015).

Alternative locations are possible for placing sensors; such as at the workspaces, and even carried by occupants; however, these options present power constrains and potentially short-term sensor-blocking by the user's movement. Nevertheless, the approach of alternative placement has been studied, and sensors at the workplace have been used to re-calibrate the ceiling sensor: which means that sensors are installed at the workspace and at the ceiling; and the one at workspace height is used as "verification" (Caicedo, Li and Pandharipande, 2016). This study reported an improvement in relation to under/over-illumination issues, when information from both locations of desk and ceiling are combined into the controller's algorithm. While no significant reduction was observed in the energy use, but the under-illumination issues from the ceiling-setup alone were addressed. User behaviour was not part of the study, although it might be interesting to assess aspects such as whether a user appreciates the improvement in light conditions, or whether the user is aware of sensors at the desk area.

To ensure proper functioning of sensors, a method was developed and tested (Caicedo, Pandharipande and Willems, 2014) where the sensors' set-point-calibration was monitored, meaning that the system recalibrates sensor set-point if changes occur in the reflectance. A lighting controller algorithm was developed, with the capability of tracking changes in reflectance; and performing self-corrections for maintaining the illuminance setpoint. The algorithm was tested through simulations in an office model, and the results showed that systems with calibration-tracking maintained their target setpoint for average illumination, even when light-coloured objects were introduced on the table, or when the tables' layout was varied. Without a calibration tacking system, higher reflectance objects in a sensor's field of view usually raise the actual set-point, which is an 'over-illumination' situation that could lead to increased energy consumption. Conversely, when the ceiling mounted sensor sees the floor -- which has lower reflectance than the table – as a result of furniture rearrangement, the set-point drops below the initially defined value and may lead to under-illumination issues. Calibration-tracking was reported to address these issues while maintaining the illuminance setpoint.

3.2 Integration process

3.2.1 Occupant behaviour

The electricity demand for lighting can be lowered by at least 50%, only by switching to the available efficient technologies (Dubois, Bisegna, Gentile, Knoop, Matusiak, Osterhaus and Tetri, 2015). Additionally, integration schemes with daylighting can save up to 60% compared to traditional installations (Ihm, Nemri and Krarti, 2009). These saving margins present an enormous potential, considering that lighting retrofit is one of the most cost-efficient energy conservation measure in buildings (Enkvist, Dinkel and Lin, 2010). However, the actual energy performance of building services, including lighting, is highly impacted by the human behaviour (Menezes, Cripps, Bouchlaghem and Buswell, 2012). In this context, a differentiation between energy efficiency and energy saving has been presented (Oikonomou, Becchis, Steg and Russolillo, 2009); where energy efficiency – the ratio between the energy entering and leaving a system – is designated purely a technological matter; whereas energy saving or energy conservation is affected by a complex energy-related behaviour from various stakeholders: technology investors, consumers and end-users; and is triggered by economical and psychological considerations. The energy saving potential of the human behavioural component, is estimated between 5-30% in non-residential buildings (Zhang, Bai, Mills and Pezzey, 2018), and this could lead to little savings even with efficient technologies. Therefore, energy policies and regulations should focus on rewarding energy saving, rather than efficiency (Bertoldi, Rezessy and Oikonomou, 2013). Figure 12 presents a schematic of energy efficiency vs energy saving, and how policies and regulations focussed on rewarding stimuli can help drive energy saving via energy efficiency.

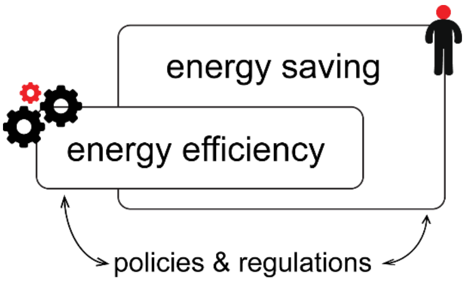

Figure 12: Energy efficiency is one of the drivers of energy saving

To capitalise on this factor, there is a need of further studies on occupant behaviour, which may seek to:

> **Understand occupancy profiles**. The occupant will adapt (day)lighting based on physiological needs, such as, when they face glare, under-illumination, or thermal discomfort. Energy is typically saved by mining occupancy profiles and designing systems capable of accommodating them. Although the conventional approaches like probabilistic modelling can be used to model behaviour, further individual consideration may be added by using agent-based models (Gaetani, Hoes and Hensen, 2016) .

Trigger behavioural change. The occupant may take different, and even contrasting decisions, when facing the same luminous stimuli. These actions are driven by a set of evaluations, such as the antecedent lighting conditions, psychological processes and social norms. Energy can be saved by understanding the psychological processes, which could be trigger towards eliciting energy saving behaviours.

In the following subchapters, we have primarily reviewed the currently available literature on aspects of occupant behaviour in relation to lighting, which have been – or can possibly be – modelled via conventional modelling approaches. Further, multiple solutions are reviewed, which may elicit energy saving behaviours in lighting. These solutions may be implemented in future agent-based models.

3.2.1.1 Understanding Occupancy Profiles and Actions

This aspect is implicitly discussed in several sections of this report, for example when occupancy sensors are introduced. Sometimes, more than half the energy use in offices is consumed during the occupied hours, largely as a result of occupants leaving lights and equipment on (Masoso and Grobler, 2010). Implementing occupancy-driven control strategies, therefore, have a great potential towards reducing the building energy consumption (ABB Inc, 2010). Energy simulation research has been reported to have substantial error, when compared to actual building performance (Newsham, Mancini and Birt, 2009; Scofield, 2009); and the most important factor leading to this discrepancy, is how occupancy profiles are defined -- the singular most important factor that leads to substantial differences between intended design and the real building energy performance. This issue is often referred to as the energy performance gap.

It is difficult to accurately define the number of occupants of a particular space for any given duration, since human behaviour is considered stochastic in nature (Virote and Neves-Silva, 2012); and there are limitations with accessing the existing occupancy datasets. Hence, building occupancy schedules are based on generalized assumptions; and the common method for considering occupancy is to use fixed design profiles (Davis and Nutter, 2010) defined by organizations such as ASHRAE (ASHRAE, 2004). However, there are limitations to this, since the ASHRAE 2004 occupancy profiles do not differentiate between private or open floor plan offices; and the standard profiles for workdays and weekends are set with no change in occupancy schedules throughout the year. To accurately model the complex occupancy patterns, no week is the same as another, and simple assumptions are not realistic enough to represent how occupants interact within building rooms. It would be beneficial to work with realistic occupancy patterns, since the impact of human interaction with built environment on the net energy consumption of buildings is well recognized (Hoes, Hensen, Loomans, de Vries and Bourgeois, 2009; Geun Young Yun, Hyo Joo Kong and Jeong Tai Kim, 2011) .

In case of private offices, field data suggests that occupancy tends to be rather low. Average occupancy of slightly more than four hours per working day has been reported (Maniccia, Rutledge, Rea and Morrow, 1999), and may even be lower if employees -- like academic staff – are frequently involved in meetings or activities outside their offices (Gentile and Dubois, 2017).

Understanding occupancy schedules is an important first step in the integration process. For example, private spaces with intermittent occupancy schedules may benefit from absence sensors, which could address the issue of occupants forgetting to turn their lights off. Common areas, with continuous occupancy, may rather be integrated with switch-off at set time, such as at the end of the working day. Yet, occupancy profiles do not account for the actual occupant behaviour towards the shading and lighting systems.

As an overview of all building energy services, the IEA EBC Annex 66, which concluded in 2018 – provides a comprehensive definition of occupancy behaviour in buildings, including simulation models for occupancy profiles (Yan, Hong, Dong, Mahdavi, D’Oca, Gaetani and Feng, 2017; IEA-EBC, 2018). In this large international project, three types of occupant models were identified:

- the above-discussed occupancy models, concerning the time and frequency of arrival and departure;
- adaptive behaviour models, concerning the likelihood of acting on the building system;
- non-adaptive behaviour models, linking behaviour from similar buildings.

IEA EBC Annex 66 developed literature-based quantitative description of occupant behaviour, resulting in a library of 52 typical energy-related occupant behaviours. The library is formed by 52 obXML files, which can be used in multiple energy simulation software (Yan, Hong, Dong, Mahdavi, D'Oca, Gaetani and Feng, 2017).

Extensive research has been carried out to understand occupant behaviour in relation to lighting and shading systems. Early works on occupants' switch-on/switch-off events found that switch-on events correlate well with daylight levels, but not the switch-off events (Hunt, 1979), and suggested that a forced switch-off at midday could be a useful energy conservation strategy (Hunt, 1980) . Most of interactions with shading/lighting controls occurs during arrival, departure, or surrounding long absence from offices, and although less than a quarter of all interactions occur during occupancy time (Lindelöf and Morel, 2006); shading devices are likely to be adjusted even during these hours (Mahdavi, 2009; Correia da Silva, Leal and Andersen, 2013). A review of environmental and time-related factors that drive adjustment-related actions for lighting and shading (Stazi, Naspi and D'Orazio, 2017) suggests that while work-plane illuminance is one acceptable predictor of 'switch-on' action, it is nearly impossible to define a single illuminance threshold that triggers this action. A probabilistic description for different illuminance ranges has been recommended as a more appropriate approach (Lindelöf and Morel, 2006).

Occupant behaviour is also affected by social norms (Despenic, Chraibi, Lashina and Rosemann, 2017; Lashina, Chraibi, Despenic, Shrubsole, Rosemann and van Loenen, 2019); and the same model of occupant behaviour is not applicable to both private and open-plan offices. Therefore, it is understood that conventional occupancy models adopting a non-probabilistic approach are overly simplified in their description of occupants' interactions with shading and lighting controls.

Stochastic methods can be used to model randomness in occupant behaviour. *Lightswitch* (Newsham, Mahdavi and Beausoleil-Morrison, 1995) was the first stochastic approach developed using field data, which produced an average-day profile including occupancy and switch-on/switch-off events in single occupant offices. The model was refined in *Lightswitch-2002* (Reinhart, 2004), where the use of shadings was included and "dynamicity" was added to the stochastic process. This approach included four types of users with two overarching categories: active and passive occupants; and could generate schedules through the year with a step-size of 5 minutes. This model used experimental data and was built for single or two-occupant offices only.

For open-plan offices, it was suggested that occupants be classified based on their activeness, while also accounting for individual and social factors like tolerance and dominance, which tend to determine settings in open-plan offices (Despenic, Chraibi, Lashina and Rosemann, 2017). For such offices, stochastic modelling was applied to estimate occupancy patterns (de Bakker, Aries, Kort and Rosemann, 2017), and to evaluate the influence of their variance on energy savings for different sizes of lighting control zones, as presented in the reproduced Figure 13.

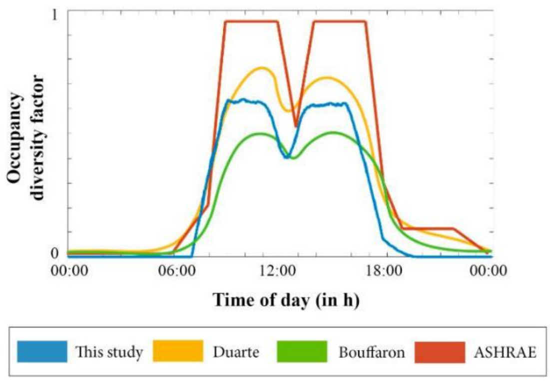

Figure 13: Graph from (de Bakker, Aries, Kort and Rosemann, 2017) *showing occupancy diversity factors of the validation case simulated in their study and occupancy diversity factor of earlier studies.*

Occupancy-based lighting controls are typically used at room level, but recent advances include implementation of fine-grained controls, which allow for lighting control at desk level. Such individual controls have a significantly higher potential for energy savings, as compared to strategies with larger control zones. For all office cases, individual lighting control at desk area showed energy potential up to 40% (Galasiu, Newsham, Suvagau and Sander, 2007; Enscoe, Rubinstein, Berkeley, Laboratory, Levi and Powell, 2010); although the actual savings have reduced in recent years (de Bakker, Aries, Kort and Rosemann, 2017), probably due to the increase in efficiency of lighting sources. Considering this, although individual controls have the potential of increasing users' comfort, their return of investment may be longer than five years due to reduction in savings.

While individual manual controls are actively triggered by users, recent advances in technology has enabled control systems to adapt to the individual preferences and behaviours. Nagy et al. (Nagy, Yong, Frei and Schlueter, 2015) proposed an adaptive control strategy which takes into consideration the light level, occupancy sensor, action on the manual light switch, and the on-off status of electric lighting. The strategy determines two customized set-points: one for time-delay before switch-off, and the other for preferred illuminance – for a set of rooms including private offices, multi-occupant offices, and also printer rooms. The application of this strategy resulted in a convergence of results for time delay set point within a week of use, while the preferred illuminance took much longer to converge. In any case, the authors could achieve 37.9% energy saving compared to a standard occupancy system (Nagy, Yong, Frei and Schlueter, 2015) .

Another example of machine learning in lighting controls is 'LightLearn'*:* a reinforcement learning (RL) based controller designed to understand occupant preference (Park, Dougherty, Fritz and Nagy, 2019). This system recognizes occupant via Bluetooth pairing, and records and elaborates illuminance and switch on-off events. It then adapts the operation of lighting systems based on the occupant's recorded behaviours; balancing comfort with energy use. The system was successfully tested in five private offices in Austin, TX, and was reported to achieve high energy performance, without decreasing occupant appreciation of the lighting system. While the current version of *LightLearn* has a limited set of acquired variables -- such as occupancy, switch event, and illuminance; the *LightLearn* model can be adapted to a bigger set of significant variables. For example, the authors reported that automatic switch-off events were reported among the most inconvenient for occupants; the performance and acceptability of the system could be improved by including dimming in *LightLearn* (Park, Dougherty, Fritz and Nagy, 2019). Additionally, since the controller acquires occupancy via pairing with personal devices -- like smartphones, the controller has potential for use in open plan offices, in detecting occupancy at the individual level (Park, Dougherty, Fritz and Nagy, 2019).

3.2.1.2 Triggering Behavioural Change

The concept of "active" and "passive" occupants (Reinhart, 2004) has been previously introduced (§3.2.1.1). Triggering a behavioural change may be seen as transforming passive users into active users, for example, by providing easily accessible and intuitive controls. Considering the advances in technical efficiency of lighting systems, the margins for efficiency gains is likely reduce; and strategies beyond technology enhancement – such as triggering behavioural changes -- are gaining importance. For this, some of the behavioural elements emerging from literature are reviewed; elements which have - or may have - an impact on the energy use in an integrated lighting scheme.

3.2.1.2.1 Design of the Interface

It is assumed that a well-designed control interface has high chances of being used in the way it was intended, and hence reducing the energy use. The terms "affordance" and "tangibility" have been respectively used in literature to describe intrinsic design features of the interface and its interaction with end-user (Dugar, Donn and Osterhaus, 2011; Maleetipwan-Mattsson, Laike and Johansson, 2017). Affordance and/or tangibility of lighting and daylighting controls have been explored by some studies in the recent past, and theoretical frameworks have been designed to evaluate their affordance, as seen in Figure 14.

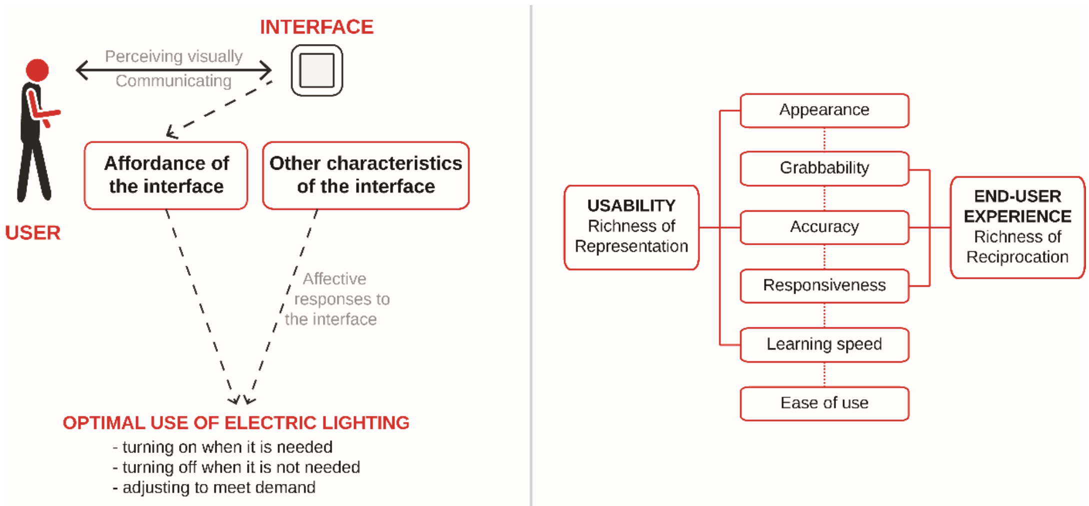

Figure 14: Theoretical frameworks to evaluate the affordance of lighting interface: [Left] the framework proposed by (Maleetipwan-Mattsson, Laike and Johansson, 2017)*; [Right] the framework proposed by* (Dugar, Donn and Osterhaus, 2011) *(adapted).*

It was observed that interfaces with a rich representation of the functioning helps users learn lighting control better – for example by using indicators for the level of dimming. Additionally, providing feedback on the use and giving a multisensory interactive experience from the interface – for example, by merging tactile and graphical information, helps use the controls better (Dugar, Donn and Osterhaus, 2011). By designing a “tangible” interface, which consisted of touchscreen-based scene controller coupled with graphical information – such as a preview of the light scene change; the authors compared this with a text-only touchscreen interface; and reported that use of tangibility resulted in significant improvement in the learning speed and overall appreciation (Dugar, Donn and Marshall, 2012) . Further identification reported (Maleetipwan-Mattsson, Laike and Johansson, 2017) that a good switch interface should: 1) be simple and easy to use (affordances), 2) be perceived has safe for use (e.g. no red warning lights), 3) be able to trigger energy saving, 4) be visible, 5) be suitable for the context, and 6) be hygienic – which is particularly relevant for public buildings. The same research group conducted a study in two patient wards in Sweden, where it was observed that patients interacted differently with push-button switches for coloured interfaces, as compared to the traditional white ones. The study estimated a projected energy saving between 31 and 61% when different interfaces were used in the dining and in the dayroom respectively: the traditional white push-on buttons were reported to promote interaction in dining rooms, whereas similar but coloured switches were reported to promote interaction in the dayroom. Although the ecological validity of these findings is limited because of inferences drawn from short-term observations, the effect of the interface design on the switch on-off patterns is indisputable (Maleetipwan-Mattsson, Laike and Johansson, 2016).

Yılmaz et al. (Yılmaz, Ticleanu, Howlett, King and Littlefair, 2016) tested different traditional and touch-screen interfaces for switches, dimmers and CCT tuners to evaluate their “people-friendliness”, a concept which closely resembles the definitions of “affordance” and “tangibility” of the control interface. Users appreciated most traditional interfaces and they were highly favourable towards any simple, immediately understandable and responsive interface which could provide clear feedback, e.g. the toggle being on the on or off position. More complex interface generated confusions, especially among users with no knowledge in lighting. For example, some users could not understand what a “light scene” meant, or when the unit of CCT “K” in colour tuners was often confused with energy units kWh (Yılmaz, Ticleanu, Howlett, King and Littlefair, 2016). Social aspects also drive the interaction with controls, for example, interactions visible to other users in a shared environment would help avoid conflicts. In a study involving 14 open-plan offices, larger groups of luminaires were associated with lower number of switch events (T. Moore, Carter and Slater, 2002) , suggesting that granular lighting with local lighting control interfaces should be preferred.

In integrated design of daylighting and electric lighting, it was reported that users operate shadings and electric lighting interdependently; when both interfaces are co-located. In such cases, it was identified that manually controlled shading and lighting systems operated in near optimal conditions, while providing a much higher level of comfort, satisfaction, and productivity as compared to an automated systems (Sadeghi, Karava, Konstantzos and Tzempelikos, 2016) .

Recent developments in IT and lighting technologies have helped spawn numerous possible interactions with lighting, which goes way beyond the simple 'switch-and-dimming' controls (van de Werff, Niemantsverdriet, van Essen and Eggen, 2017). With lighting and shading manufacturers designing custom control interfaces, a variety of solutions have come into being; however, different interface designs and locations tend to discourage and bewilder the users (van Someren, Beaman and Shao, 2018), which calls for standardisation in design. For the purpose, a first proposal of standard lighting control interfaces was issued in 2012 (Nordman, Granderson and Cunningham, 2012); followed-up by a survey in 2017 (Nordman, Dulla and Kloss, 2017), and an initial standard proposal was reported (Nordman, 2017). Work in this domain is currently being pursued (Nordman, 2019) .

3.2.1.2.2 Anchor Point, Illuminance Ranges, Illuminance Fade-Out

In traditional office settings, the target horizontal illuminance on working spaces is set at 500lx in several standards and regulations, as is thought as a balance between user preference, visibility, and energy use. However, it has been claimed that preferred illuminance is dynamic definition, which depends on various factors, such as individuals (Boyce, Eklund and Simpson, 2000), previous lighting conditions, as well as the lighting source (Escuyer and Fontoynont, 2001) -- whereby lower illuminance is preferred when provided by daylight.

When manual dimming is provided, it was demonstrated (Logadóttir, Christoffersen and Fotios, 2011) that individuals tend to choose lower illuminance when the anchor point is lower and the stimulus range is narrower. For example, individuals provided with anchor points 0 lx and 500 lx are likely to choose 193 lx and 455 lx as preferred illuminance, respectively; which corresponds to about 50% difference in energy use among the two settings (Logadóttir, 2015) . Additionally, individuals are likely to retain default lighting settings, if provided enough daylight (Heydarian, Pantazis, Carneiro, Gerber and Becerik-Gerber, 2016). As an implication, providing abundant daylight as default setting, for example, by maintaining shading in open position at the beginning of the day, would significantly reduce the chances of occupants turning-on electric lighting during the day.

The dimming speeds may also affect lighting preferences. It has been reported that up to 20% reduction in illuminance usually goes unnoticed, or is accepted by more than half of the users (Chraibi, Creemers, Rosenkötter, van Loenen, Aries and Rosemann, 2018). It has also been reported that if fading-out is slower than 1 lx/s, illuminance reduction even above 20% may not be detected (Akashi and Neches, 2005) . Slow and limited dimming remains unnoticed, in both--individual and open plan office settings (Chraibi, Creemers, Rosenkötter, van Loenen, Aries and Rosemann, 2018) . In integrated designs, daylight works as a mediating factor in the perception of light fading. A study (Newsham, Aries, Mancini and Faye, 2008) confirmed that a reduction of 20% illuminance – provided, in this case, by a mix of daylight and electric lighting – is unlikely to be noticed. However, with high daylight provision, this 20% actually corresponds to up to 60% of dimming down of electric lighting (Newsham, Mancini and Marchand, 2008). Findings from this study have interesting implications on load shedding in view of smart cities, and implies that daytime loads from electric lighting may be reduced with no impact on lighting users.

Finally, electric lighting should be switched off when not needed, for example, when daylight can provide necessary illumination, or when occupants leave the room. Unwanted switch-offs generate aversion and sabotage to the lighting system; and for daylight-linked systems, the previous knowledge on dimming speed suggests that a smooth and slow fade out of electric lighting is unlikely to be noticed (de Bakker, van de Voort, van Duijhoven and Rosemann, 2017).

3.2.1.2.3 Information Strategies and Feedback Systems

Providing information to the users about the impact of lighting use – on energy use or on the utility bills – helps raise awareness. Information strategies based on energy monitors or similar devices are advisable as feedback systems.

A mixed information-feedback strategy has been reported (Orland, Ram, Lang, Houser, Kling and Coccia, 2014), where a feedback information was provided to 41 employees over a 6-month period. This was in the form of a web-based game, where 'chickens' had to be kept 'alive and healthy', by saving energy from office appliances with respect to a baseline, and thus feedback was shared with the occupants towards driving actionable behaviour. This resulted in a 23% energy saving with respect to the baseline, while the employees played this feedback game; however, the persistency of their energy-saving behaviour dropped once the game was over. These conclusions may be extended to lighting as well, although lighting was not included in this study. A remote team competition was conducted for households (Gustafsson, Katzeff and Bang, 2009) where energy saving was measured, and to incentivize their actions; some participants went as far as lighting candles to save energy for lighting.

Although feedback is reported to drive user behaviour, information alone also plays a very important role. It was reported (Akashi and Neches, 2005) that just informing users the importance of reducing lighting loads, help them accept a reduction in target illuminance by 80lux, as compared to uninformed users, without adverse effects on their performance. The benefits of feedback alone are also proven, although potential savings are debated (Karlin, Zinger and Ford, 2015); and interventions seem to lack in persistency of behaviour (Murtagh, Nati, Headley, Gatersleben, Gluhak, Imran and Uzzell, 2013).

Prompts, such as wall stickers inviting users to switch-off lighting, help significantly increase the frequency of switch-offs when occupants leave the room (Tetlow, Beaman, Elmualim and Couling, 2014) . However, the effect is lower in rooms with PIR absence sensor (Tetlow, Beaman, Elmualim and Couling, 2014); which may suggest that users tend to rely more on technology themselves (Pigg, Eilers and Reed, 1996).

Using feedback messages can also re-assure users, that automatic systems are working as intended. A custom interface designed on top of a virtual window was used to display intensity of solar radiation, while up/down arrows could take user feedback, if there was a need to lower or open the shading. It was found that users were less likely to correct automatic adjustment, when provided with a feedback (Meerbeek, de Bakker, de Kort, van Loenen and Bergman, 2016) .

3.2.1.2.4 Social Norms

There is enormous literature on social norms and group dynamics; and lighting studies mostly focus on dynamics between occupants in open plan offices. A study involving 14 open-plan offices showed that locally controlled luminaires are toggled more frequently, possibly because this would not affect others (t. Moore, Carter and Slater, 2002). A more recent study confirmed this finding, that lighting is adjusted only if it does not lead to conflict in a shared environment (van de Werff, Niemantsverdriet, van Essen and Eggen, 2017). Although conflicts are usually avoided, another study (Lashina, Chraibi, Despenic, Shrubsole, Rosemann and van Loenen, 2019) found that some users displaying dominant behaviour tend to change lighting anyway, while some others would act submissively in accepting the change, even if the new lighting conditions are not satisfactory. Some other users also accept the change, but not because of submissive tendencies, but rather because they have high tolerances to lighting variations (Despenic, Chraibi, Lashina and Rosemann, 2017).

3.2.1.2.5 Lighting and thermal sensations

The 'hue-heat' hypothesis speculates that 'warmer' illumination associates to higher perceived ambient temperature. If the hypothesis holds true, energy for heating can be saved by using luminaires with low CCT. This hypothesis has been investigated for many decades, but studies have reported contrasting results; and the inconsistency may be linked to different study designs (Toftum, Thorseth, Markvart and Logadóttir, 2018) . In a Danish study, 8% of the total energy use in an office building, could theoretically be saved simply by decreasing the heat set point from 22 °C to 21.2 °C, and by tuning light from 4000 K to 2700 K without any changes in the thermal comfort (Toftum, Thorseth, Markvart and Logadóttir, 2018). However, a similar study rejected the hue-heat hypothesis and found positive association only for thermal sensation between 2700 K and 4000 K at 25 °C, but not for thermal comfort (Baniya, Tetri, Virtanen and Halonen, 2018).

In a 'hue-heat' study using daylight as light source, the spectral composition of daylight could be modulated in a semi-controlled daylight office mock-up, by using three types of tinted glazing (blue, neutral, and orange), and three operative temperatures could be maintained (19 °C – 22 °C – 26 °C). At 19 °C and 22 °C, it was reported that subjects preferred warmer temperatures when exposed to blue glazing (Chinazzo, Wienold and Andersen, 2018) . It is however worth mentioning, that only subjective thermal sensations were considered, while a tinted glazing itself did not play any major role in physiological responses. The effect of confounding variables was stressed on in this study, when the 'hue-heat' hypothesis was subjected to verification. Another study (te Kulve, Schlangen and van Marken

Lichtenbelt, 2018) suggested a mutual influence between visual and thermal perceptions, and that exposure to light (intensity and CCT) may tune thermal perception via visual perception.

Irrespective of the verification of 'hue-heat' hypothesis, it remains unclear if changes in thermal sensation; such as active changes in room temperature, do trigger a behaviour. This aspect has partially been investigated in a laboratory experiment (Lu, Ham and Midden, 2015); where the intentional behaviour – rather than actual behaviour – was tested. The 'hue-heat' hypothesis was accepted in this case, but it was found that subjects were not willing to actively change the room temperature (Lu, Ham and Midden, 2015) .

3.2.2 Commissioning, Monitoring, Maintenance, Verification

3.2.2.1 Commissioning

The process of commissioning lighting systems, ensures that all parts of it -- including systems for daylighting and electric lighting, function as close to design intent as possible; and is done after their installation but before the building or space is occupied. A successful commissioning process eliminates many operational problems that exist from start-up, and gets the building on right track before the occupants arrive. Special areas of concern should be identified during the programming and design phase; and all equipment along with their mutual interactions be checked for confirming proper operations during the commissioning process. An accurate baseline performance can be established to guide operations, while performing maintenance procedure throughout a building's lifetime.

Providing training to maintenance personnel and building occupants; and enabling them to operate the daylighting and electric lighting system components and their respective control systems; is an important but often overlooked aspect of control installations. Although most manufacturers provide technical support for a period following the installation, it is easier and more economical if the occupants and facility managers are able to address most problems without external intervention. This training should occur during commissioning phase, and these stakeholders need to be trained towards operating and adjusting the system. A perennial key problem in this domain is the trade-off between energy savings (with additional consideration for demand-based electricity rates) and other aspects, such as visual comfort, lighting quality and view-out. These trade-offs are rarely quantified with control options; and reducing control options towards developing a usable common metric would help facility managers in taking appropriate decisions between operational savings vs. occupant complaints. The facility managers also need to understand their system's performance, and be able to conduct appropriate emergency procedures if anything goes wrong; which means that their training must be complemented with detailed and well-indexed manuals for operations and maintenance – including plans, schedules and responsibilities, equipment specifications, line diagrams, manufacturer's warranties and contact information. Occasional re-training might also be appropriate, and the training should be repeated for every new employee; not just those at the time of the building's first occupancy. Building occupants should also receive information in a user-friendly language, about the purpose of a system and its operations.

3.2.2.2 Maintenance

The maintenance process ensures effective lifetime performance in energy efficiency and occupant comfort, by allowing the building systems to operate according to design specifications. Budget constraints along with understaffing of operations and maintenance teams, becomes a major cause for the poor operations of many buildings, which leads to high energy cost over the long run, in addition to equipment penalties. A dedicated budget should be established for timely repair and dedicated preventative maintenance. Problems identified by building users should be addressed as soon as possible, and users must be informed about the action taken. Occupants can be good team players towards the common goal of increased energy efficiency; if they are made aware of energy penalties due to individual behaviour patterns – and encouraged to participate in reducing overall building energy use.

The need for maintenance depends on many factors; the most obvious of which in this domain are the lifetime of windows, and various components of fixed and moveable shading devices, as well as the life of electric lamps – which is the number of hours a lamp is expected to provide light. Ageing of sensors can also influence the system performance, and systems may require recalibration when sensors experience degradation over time. Although photodiodes are known for their stable performance, the diffuse plastic covering of these photosensors is known to degrade. While replacing or cleaning lamps as part of the normal maintenance procedure, sensors should also be checked and cleaned. Whenever extensive re-lamping takes place, or when changes such as replacing luminaire types or relocating partition walls are introduced, sensors must be recalibrated based on measured luminance and illuminance data, so as to warrant continuous operation according to design specifications.

It is important to consider the daily control, management, and behaviour of automated shading devices in case of failure, such as the short-circuiting of sensors. Manually operated blinds and other shading devices should also be checked for proper operation and general condition. When major components fail, or when replacement is needed for major parts of a system, it creates an opportunity to review more advanced technologies, which may not have been available or affordable when the building was first constructed. It is also worthwhile to check with local governments and energy suppliers, if there are any incentives for replacing equipment with more energy-efficient technology. Potential savings towards energy and maintenance, as well as improvements in occupant comfort, should be assessed against installation costs of such new equipment. If updates are made, operation and maintenance procedures, as well as occupant information, needs to be changed accordingly.

The luminous flux of any luminaire reduces over its lifetime; however, the light levels should not be allowed to depreciate, which is why lighting designs must include a maintenance factor. This factor ensures that the design fulfils its illuminance requirements not only at installation, but also at the end of its scheduled operational period. This factor for a luminaire is calculated as the ratio of average workplane illuminance after a certain period of use, over the initial average illuminance obtained under same conditions.

Many factors contribute to the decay of illuminance levels, such as soiling of room surfaces, soiling of luminaires, lumen depreciation of light source, and lamp-failure. The Room Surface Maintenance Factor (RSMF) accounts for the effect of accumulated dirt and dust, which degrades the reflectivity of room surfaces. This factor depends highly on the order of cleanliness in a room; and the dirtier a room is, the lower is its maintenance factor. The Luminaire Maintenance Factor (LMF) accounts for the effect of dust and dirt accumulated on a luminaire itself; and depends on the construction and design of a luminaire as well as on other environmental conditions. The higher the luminaire's protection is from dust, and the cleaner the room is; the higher is its maintenance factor. The Lamp Lumen Maintenance Factor (LLMF) describes the reduction in light intensity over time; and is the ratio of luminous flux at a specific time, compared to the manufacturer's data sheet on luminous flux for the lamps. The Lamp Survival Factor (LSF) considers the effect of the failure of the light source during the maintenance period; and a table of LSF is provided by lamp manufacturers. In cases where the lamp fails and needs replacement right after installation, its LSF can be set at 1.

Considering these factors, since lighting systems are designed to overcome the aging and increasing dirtiness over their lifetime; this oversizing leads to an increase in energy demand. There are cases where dimming strategies are implemented to minimise luminaire output, so as to reduce excessive energy use and minimise over-lit spaces. This dimming strategy is meant to mainly offset the dirt accumulation on the luminaires; and luminaires are dimmed at the beginning of their maintenance period (and after they are cleaned) to ensure that minimum level requirements are met, but upper limits are not exceeded. This approach becomes very effective with low maintenance installations and dirt environments, such as metro stations, where energy saving can be up to 33% of the stations' baseline lighting consumption (Casals, Gangolells, Forcada and Macarulla, 2016) . Moreover, this strategy needs minimum investment, since the only extra equipment needed is a digital addressable lighting interface (DALI) controller.

Estimates for reduction in light output as a result of dirt and lamp aging, varies in the literature. The IES lighting handbook recommends a light loss factor (LLF) not greater than 0.70, which includes lamp lumen depreciation, luminaire dirt depreciation and lamp burnout (DiLaura DL, Houser KW, Mistrick RG, 2011). This IES reference has created a rule-of-thumb LLF of 0.70 for all conventional luminaires and LEDs, despite well-documented variation in product performance. Some studies on outdoor lighting installations, observed an average luminaire dirt depreciation of 12%, and LED lumen depreciation of 10% -- both after 20,300 hours of operation (Kinzey and Davis, 2014) . In terms of dirt depreciation, other studies have reported an overall reduction of 8% in light output after 20 months of operation, which goes in line with IES' estimates for LDD, which assumes 8.6% reduction in clean environments (Wilkerson, Sullivan and Davis, 2016) .

Light loss factor for LED might not be as low as the 0.70 assumed in IES; and therefore installations tend to use excessive electricity while keeping spaces over-lit, since a lower LLF is used. By changing lamp lumen depreciation (LLD) from 0.70 to 0.80, the initial light level is reduced from 143% to 125% of the target, respectively; which results in an energy reduction of about 13% over the life of the system (Royer, 2014) .

Thus, the estimation of maintenance factors deserves more attention. These factors need to be defined carefully, and those that best represent the expected performance of the installation, must be used. Conversely, it is important to define an optimal maintenance plan for the installation's efficient functioning, and towards extending the system's life. Maintenance actions can be classified as preventive and corrective, and include lamp replacement, cleaning and systematic inspections. A reasonable time needs to be found between maintenance and operating hours, since maintenance cycles are related to costs. Neither among "no maintenance" or "full maintenance" is preferable; and the maintenance plan should not be defined with reasonable simplicity, else the implementation would be complicated and expensive. The longer the operation time without maintenance, the more luminaires need to be installed to guarantee the required levels; and the more frequent the maintenance cycles, the higher the cost for the facility service. Hence, designers must think carefully when setting up a lighting installation maintenance plan (Ye, Xia, Zhang and Zhu, 2015).

3.2.2.3 Post-Occupancy Evaluations (POE)

Another way of enhancing performance of integrated daylighting and electric lighting systems, is through learning from successes and failures of existing projects. Post-occupancy evaluation is an excellent tool that assists designers in this process; and participatory processes for building evaluation offers much more than a record of a design's actual performance. Post-occupancy evaluations typically have the following objectives:

- To identify the extent to which a building matches the design brief
- To determine how well a building meets the user's requirements
- To suggest potential modifications for improving areas, which are identified as not meeting user needs
- To identify positive traits and knowledge, which might be incorporated into future building projects.

In addition to the building programme's or design brief's review, post-occupancy evaluation procedure often also includes the construction documents, drawings and associated documents which describe the technical installations and maintenance procedures; as well as data of interviews conducted for various building user or interest groups, relevant information collected through written surveys, and recorded physical measurements of building performance.

In case of evaluating lighting performance, the recorded measurements might include a detailed assessment of the luminous environment in representative spaces, and in areas that have been identified as presenting some problems. The visual quality of building spaces depends on factors such as colours, surface reflectance, position of visual tasks (e.g. work stations), glare perception, as well as levels of daylight and electric lighting. Some of these can be evaluated by simple visual observations, while others may need a trained eye or require the use of technical equipment or methods coupled with knowledge of lighting and control technology.

In the simplest case, the evaluators might conduct measurements of illuminance and its uniformity at critical points, along with luminance measurements with spot-luminance meters or luminance-mapping CCD cameras, and assess the potential glare problems while checking proper operation of lighting systems and their controls.

A systematic survey of the users' attitudes to the indoor environment can help understand the various performance aspects of daylighting and electric lighting systems and controls, which have adapted to specific building conditions. Dissatisfaction expressed should be used for enquiring about the origin and reasons for the underlying problems; which provides opportunity for potential changes towards improving the indoor environment.

A system that is accepted by all users at all times, simply does not exist; and this fact must be remembered when designing and conducting surveys. Since there are various factors that affect daylight conditions to dynamically change, such as cloud cover or the time of day and the year; any spot test or study cannot be regarded as representative of daylight quality for the building and its systems across the whole time period. Similarly, a user's reactions to different outdoor conditions must be considered over an extended period – which implies that a study must be repeated or at least designed purposefully, to get a response covering an extended use-period. The POEs can be supplemented by other indicators of the work environment's quality, such as: sick leave, records of spontaneous complaints about work conditions, complaints of tiredness, eye problems related to visual environment, draughts, temperatures perceived too cold or too hot, noise problems, etc.

3.2.3 Lighting Energy

3.2.3.1 Overview of research studies conducted on lighting controls and electric lighting energy use

3.2.3.1.1 Considerations on parasitic energy use

There have been reports about parasitic energy use in lighting systems. Lighting energy use includes energy for functional illumination, as well as for standby during non-lighting periods (CEN, 2017) . In traditional installations, the standby energy use factor is about an order of magnitude lower than that required for functional lighting; but the increasing luminaire efficiency is greatly reducing the functional factor; and if energy for standby remains constant, its share on total lighting energy use would get higher. Therefore, a focus on reducing standby energy use is gaining interest. Additionally, the ubiquitous use of lighting controls calls for more non-illuminating devices – and with controls themselves aimed towards reducing energy for illumination; it is important to check their impact when in standby.

Traditional sensors and controllers may require as little as 0.5W. In efficient LED luminaires running on 28W with an integrated control, the power requirement for standby are 56 times lower than that for functional illumination. Yet, in spaces with very low occupancy and good daylight provision, electric illumination may be required for very short periods, and the energy for standby may be of the same order of magnitude as that for illumination (Gentile and Dubois, 2017) .

3.2.3.1.2 Considerations on thermal gains

Convection and thermal radiation are the major contributors to the heat gain associated with lighting, while contributions related to conduction may be ignored. During operations, the heat produced by LED junctions is transmitted to a heat sink through conductive means; which is then dissipated to the surroundings through radiation and convection. Radiatively, this includes visible light, ultraviolet (UV), and infrared radiant (IR) heat; and the emitted radiation is absorbed by surrounding surfaces which further re-emitted them to the surroundings. Among the radiation emitted by LED, IR radiation represents the greatest radiative heat contribution to a building's cooling loads.

The convective heat transfer is an instantaneous gain in the conditioned space, and therefore represents an immediate cooling load. Radiative heat is absorbed by the surfaces over time, and therefore have a time-lag effect on the cooling load. It is important to determine the split between convective heat and radiative heat to effectively calculate the space cooling load, the identification of which is another key factor for calculating lighting heat gains. Although 100% of the lighting energy is converted into the heat gain of the surroundings, only the heat transferred to the conditioned space is considered as space-cooling load. The fractions of radiative heat and convective heat generated by LEDs are much different from the conventional lighting technologies. Table 5 lists the reference values of the heat gain distributions for different lighting technologies. The table highlights that the radiative heat from the LED package is mainly related to visible light, with low levels of longwave radiation. As a result, the LED lighting fixtures contribute less to the conditioned spaces cooling load than traditional lighting systems (Liu, Zhou, Lochhead, Zhong, Huynh and Maxwell, 2017) .

Table 5: Heat gain distributions for different lighting technologies (Liu, Zhou, Lochhead, Zhong, Huynh and Maxwell, 2017)

Lighting technology	Visible light (%)	UV and IR radiative heat (%)	Convective heat (%)
Incandescent	8 - 10	73	19
Fluorescent	21	37	42
LED	15 - 32	≈ 0	68 - 85

A detailed determination of heat gain distributions from 14 commercially available LED luminaires is available (Liu, Zhou, Lochhead, Zhong, Huynh and Maxwell, 2017), where heat gains are split between their convective and the radiative components, as well as into heat gain in conditioned spaces and in the ceiling plenum. This was done using a test chamber assembled inside a temperature-controller test room, and the heat gain distributions of 7 different types of LED luminaires was examined. This study reported that the entire lighting fixture is exposed to conditioned space for suspended luminaires, and consequently, all forms of heat transfer from the LED fixture contribute to the conditioned spaces cooling load. Although majority of this heat is expected to be convective, the heat sink can also emit radiation and should be counted as radiative heat; in addition to the visible light emitted by LED packages.

In case of recessed luminaires, the majority of convective heat from LEDs is dissipated into the ceiling plenum instead of in the conditioned space. By varying the conditioned space temperature and return-airflow rate, a temperature gradient may exist between the conditioned space and ceiling plenum, leading to heat transfer through the ceiling in either direction.

For each analysed LED luminaire type, Table 6 presents how lighting heat was transferred to: (i) the conditioned and plenum space heat fraction over the total lighting power, (ii) the radiative/convective heat fraction over the total lighting power; and (iii) the radiative/convective heat gains as fractions of conditioned space heat gain. The table also lists the lighting power converted to short-wave radiant heat, including the visible light.

Table 6: Results summary for the analysed LED luminaires (Liu, Zhou, Lochhead, Zhong, Huynh and Maxwell, 2017)

Group	LED fixture	High-bay (min/max)	Linear pendant (min/max)	Recessed troffers (min/max)	Recessed Downlight	Recessed High-efficacy troffer	Recessed Colour tuning troffer (cool/warm)	Recessed Retrofit kit
	Rated efficacy, (lumen/W)	101-113	86	88-120	52	150	89	95
	Conditioned space fraction (%)	100	100	42.5–52.5	46.6	58.9	56.2/53.0	42.5
	Plenum space fraction (%)			47.5-57.5	53.4	41.1	43.8/47.0	57.5
Radiative heat fraction over lighting power	Long wave radiative heat fraction (%)	11.5-11.8	31.5-35.4	8.6-12.1	0.5	10.4	10.9/11.7	10.5
Radiative heat fraction over lighting power	Short wave radiative heat fraction (%)	29.9-39.1	19.3-29.0	21.7-31.9	15.4	40.5	31.2/28.7	25.1
Radiative heat fraction over lighting power	Total radiative heat fraction (%)	41.6-50.6	54.7-60.5	30.3-41.3	15.9	50.9	42.1/40.5	35.6
Radiative heat fraction over lighting power	Total convective heat fraction (%)	58.4–49.4	39.5-45.3	58.7–69.7	84.1	49.1	57.9/59.5	64.4
Radiative heat fraction over conditioned space heat gain	Long wave radiative heat fraction (%)			14.0-24.5	1.0	17.7	19.5/22.1	24.8
Radiative heat fraction over conditioned space heat gain	Short wave radiative heat fraction (%)			50.9–62.1	33.1	68.8	55.4/54.2	59.1
Radiative heat fraction over conditioned space heat gain	Total radiative heat fraction (%)			70.4–84.0	34.1	86.5	74.9/76.3	83.9
Radiative heat fraction over conditioned space heat gain	Total convective heat fraction (%)			16.0–29.6	65.9	13.5	25.1/23.7	16.1

3.2.3.2 Impact of Window Blind Use on Energy Consumption

Interactions have been analysed between user behaviour, shading devices properties, and their effects on building's luminous and thermal environments (Garcia and Pereira, 2019); with the aim of correlating reduction in daylight glare probability (DGP) arising from internal shading devices, when used for minimising window's solar heat gains and thus the overall cooling energy demand. The model was simulated in East, West, North and South orientations, in Florianópolis – a subtropical Brazilian city. Starting from 'without solar control' cases, 8 controls were applied to 4 internal shading devices: with blinds at 50°, blinds at 0°, with curtains and with roller shades. Two colours were considered: one clear and one dark. With two fixed obstruction modes at 100% and 50% respectively, the setpoints of $DGP_{intolerable}$ >45% and direct solar radiation >50W/m² were applied, to proposed controls on monthly, daily and automatic basis. The hourly DGP values were generated using Rhinoceros 3D 5.0 using Grasshopper+DIVA plugins, for an occupant seated 1.5 m away from the window at a side lit-room; for an open-access model of a typical private office in a multi-floor building. The solar heat gains and energy cooling demands were calculated using EnergyPlus 8.4 software; and the electric lighting system was manually operated following the "Lightswitch-2002" model with installed power density of 10.76 W/m² and target illuminance of 300 lx (Reinhart, 2004). The internal shading devices utilization followed eight control modes: always 100% closed, always 50% closed, two daily users, two monthly users and two automatic systems. Two triggers were implemented for these controls: with $DGP_{intolerable}$ and direct sunlight limited to set values at the task plane (0.8 m). The results highlighted that combinations which implemented clear roller shades as shading devices, achieved greatest reduction in terms of cooling energy demand. By deploying on the West façade, the two monthly users and 'always 100% closed mode' achieved 11.4% energy reduction. Also on the West façade, daily user and automatic system guided by $DGP_{intolerable}$ achieved a 7% reduction, while 'always closed 50%' mode reduced the energy demand related to the cooling system by a 6%. On the East façade, with these controls and with a daily user, $DGP_{intolerable}$ control strategy obtained a 6% energy demand reduction. On the contrary, dark roller shades did not achieve energy cooling demand reduction through any combinations; and Dark curtains set at 'always 50% closed' mode managed to reduce the energy demand only by 2%.

The energy performance of automated controls is relatively straightforward to model, as it is based on deterministic correlations between physical quantities, like illuminance at a photocell and the status of an electric lighting system. Investigations performed for a private or a two-person office, highlight that with regards to blind control, occupants avoid the presence of direct sunlight on their workplace by activating their shading device, i.e. by lowering their blinds to block direct sunlight. While these closing criteria for blinds are well-established, it remains unclear whether occupants re-open their blinds on a daily, weekly or even seasonal basis. As for electric lighting, there is a widespread individual habit, such as: i) blinds were left untouched in single offices for weeks and months or ii) some occupants tended to retract their blinds daily at departure or in the morning upon arrival (Reinhart, 2004).

In another study, a virtual 4-story office building was simulated (Shishegar and Boubekri, 2017), where the office was a rectangular-shaped building measuring 18 m wide x 36 m long x 15 m high, oriented along the east-west axis. Window-to-wall ratios (WWR) of 20, 40, 60, and 90 percent were evaluated, and windows consisted of 0.6m horizontal shading in all façades for optimizing simulation results; clubbed with light-coloured vertical blinds on East/West faces for glare reduction. Different vertical blinds schedules were used, depending on façade orientation, seasons and occupancy. Simulations were performed in E-Quest for office buildings located in the US cities of Miami, Houston, and Phoenix. The results of this study underline that all daylight control systems decrease cooling energy consumption, regardless of their type. In office buildings situated in hot climates, installing daylight control systems offers a saving potential of 8-16% in annual cooling energy use. Moreover, different controllers were identified to have similar impacts on cooling energy consumptions, and negligible difference was found among their efficiency, in terms of cooling energy savings. Additionally, results demonstrated that use of daylight controllers in virtual office buildings can reduce annual electrical energy consumption and provide up to 30% of total electrical energy savings. The actual amount however varies depending on control types. Among examined daylight controllers, On/Off, Full-1/2-Off and Full-2/3-1/3-Off daylight sensors provide the most annual electrical energy savings (27-30%).

Similar results were obtained by another study (Tzempelikos and Athienitis, 2007), where a typical private perimeter office space in Montreal – with dimensions of 4m wide x 4m long x 3m high – was used as a base case. Exterior roller shades commonly used as shading layers, were deployed on the south-facing façade, with a 30% window-to-wall ratio. Simulations were performed using TRNSYS, while varying the shade transmittance. Two types of shading controls were considered, which were: (i) a passive control in the form of roller shade, which remains closed during working hours to ensure privacy while reducing glare and (ii) an active automatic control in the form of an open roller shade, at times when beam illuminance on windows is negligible, and beam solar radiation incident on the window is less than 20 W/m^2. For each annual working hour with these conditions satisfied, the roller shades opened automatically for maximizing daylight and view-out. There was no glare issue, since there is no direct sunlight. Lighting energy demand reduction was not found significant, when the shade transmittance was increased beyond 20% -- where the annual electric lighting energy demand already reduced by 40% for passive shading control, and by 60% for active automatic shading control, as compared to passive lighting control. Shading operations resulted in increased heating demand – which accounted for 51% of the total load – while cooling demand reduced to 36% of the total annual energy demand. Shading control has the highest impact on cooling energy demand, which drastically reduced by almost 50%, as compared to active lighting control without shading. Lighting energy demand is mostly affected by lighting control; and was identified to increase by 38% if automated shading is used, because this leads to relative decrease in daylight availability; although shading control already accounts for maximising daylight. However, using an exterior shade having 20% transmittance with active automatic controls, results in a 12% reduction of the total annual energy demand.

3.2.3.3 Impact of Different Control Strategies on Electric Lighting Energy Use

Among the numerous motivations for adopting a lighting control system in a building, the following were reported (Sansoni, Mercatelli and Farini, 2015) to be the most common:

- to ensure visual comfort,
- to achieve energy savings,
- to increase building functionality; and
- to enhance environmental visual appearance.

Energy savings can be achieved by avoiding unnecessary use of electric lighting: when a space is not occupied, or when daylight alone is sufficient for supporting the occupants' visual needs. In recent years, lighting control systems are also being used to enhance the visual appearance of a space, by dynamically varying the colour and intensity of lights. Centralized lighting control systems, when integrated into building management systems, offer the additional advantage of increasing a building's functionality. This helps achieve a higher flexibility in reorganizing the space layouts, or lowering the maintenance costs (Pellegrino, 2010).

The control of lighting can be realized through several strategies (Sansoni, Mercatelli and Farini, 2015), such as :

- Manual switching/dimming,
- Time-based switching,
- Presence detection,
- Daylight harvesting,
- Constant illuminance, and
- Scene setting.

Lighting controls should be designed with the ability to create required lighting conditions, at the right times and for the right purposes. All these strategies influence overall energy consumption, and savings may vary over a wide range depending on the contexts; such as architectural features of the building, geographical site location, building use, and a combination of controls and users' behaviour. When energy saving is the main aim driving lighting controls, the following are the most recurrent control strategies: time switching, occupancy control, daylight harvesting; and sometimes any combination of all these. Manual and automatic controls are often combined, in order to offer users, the possibility of automatic overriding control, in case their requirements are not met.

3.2.3.3.1 Manual Switching/Dimming

Manual switching is the most widespread (and the most traditional) way of controlling electric lighting. The occupants decide when to turn a light on-or-off; and the resulting environmental lighting conditions and energy consumption therefore depends on their preferences and aptitudes for interacting with these controls. Nowadays, the manual on/off controls can be enhanced by adding dimming functions, which can increase the possibility of obtaining an optimal lighting condition, while reducing the energy consumption. The derived savings through manual control, however, are mainly influenced by the users' behaviour.

3.2.3.3.2 Time-Based Switching

Time-based switching is a strategy that enables automatic modification of the lighting fittings' status, based on predetermined schedules. Luminaires are usually turned on-and-off by schedules, to avoid energy waste from lighting outside working hours. This strategy is particularly effective in large buildings, or in public spaces where the users are not allowed or expected to operate lighting; and pre-programmed switching can avoid unnecessary overnight lighting.

3.2.3.3.3 Presence Detection

Presence detection is a control strategy that enables luminaires to be automatically turned on-and-off, when the presence or absence of people in a space is detected using an active device – the occupancy sensor – in the control system. This automatic control avoids energy waste from lights in unoccupied spaces. A control system could be set either to switch lights on-and-off – or just off, which allows users the possibility to turn them on, when necessary.

3.2.3.3.4 Daylight Harvesting

Daylight harvesting is a control strategy, which enables the adjustment of light output from luminaires; by switching them on-or-off, or by dimming them in order to maintain predefined illuminance in a room, while taking the contribution of daylight into account. This lighting control strategy aims to ensure adequate lighting condition throughout working hours, and particularly to save energy by reducing lighting load as a function of daylight supply. Different types of photosensor can be used to obtain proper integration of electric lighting and daylight: such as closed-loop sensors or open loop sensors. The closed-loop sensors are usually installed inside controlled spaces, for measuring the global internal light availability (daylight plus electric light), whereas the open-loop sensors are installed on an external façade, for measuring the natural light entering a space (daylight available outside a building). Daylight harvesting strategy is especially useful for energy savings, in rooms or buildings characterized by a high daylight availability, which are mainly occupied during daytime.

3.2.3.3.5 Constant Illuminance

This control strategy is aimed at controlling the light output from luminaire, in order to provide a constant illuminance on the working plane, and compensate for the lumen depreciation effects. A constant illuminance control strategy can save energy by limiting input power, even though no daylight is available when the lamps and fixtures are new, and provide a higher light flux output than required.

3.2.3.3.6 Scene Setting

Scene setting is a control strategy aimed at increasing a building's functionality and flexibility. There are several spaces in a building that require different lighting quantities, distributions, and even colour – for carrying out a variety of activities that the space serves; such as meeting rooms, conference rooms, theatres, classrooms, showrooms, museums, restaurants, bars, etc. Scene setting is a strategy that supports predefined lighting conditions, by switching on/off or dimming each luminaire circuit of a room differently. Change in the lighting scene is usually introduced manually, but automatic sequences of lighting scenes can be programmed and automatically activated. In such cases, the efficacy and the possible energy saving of each lighting strategy are affected by the two main factors: which are: user behaviour, and the building/room type and number of occupants.

3.2.3.3.7 Building/room type and number of occupants

The type of building or room, along with the type of activity performed, plays a strong role in affecting energy savings achievable with lighting controls. The length of absence from workplace strongly correlates with the probability, that the electric lighting is manually switched off. It has been found that the presence of automated lighting controls influences the behaviour of some people (Reinhart, 2004).

In intermittently occupied spaces, such as classrooms, people switch lights on-and-off throughout the day; and the probability of switching-on is closely related to the daylight level. Electric lighting is reported to be used for less than 50% of the occupied time, when internal daylight level over the working plane exceeded 300 lux; and not at all when it exceeded 1200 lux. In contrast, these were often found in use even when internal daylight level exceeded 1000 lux in continuously occupied spaces, such as multi-person offices, because people rarely switched lights off during the day (Hunt, 1979). In such offices, lights were generally switched-off only when these became completely empty. A summary of the research outcomes on energy savings, obtained when occupancy sensors were used for controlling lights, is presented in Table 7 (Guo, Tiller, Henze and Waters, 2010) .

3.2.3.3.8 User behaviour

Studies have highlighted that the energy saving is strongly affected by occupant behaviour (Hunt, 1979; Reinhart, 2004), especially in case of manual switching/dimming of lighting systems. Manual lighting control mainly coincides with the occupant's arrival, or departure from the workplace. Some individuals keep lights on throughout the working day, irrespective of prevailing daylight levels: and their behaviour 'does not consider' daylight. Others only switch on their electric lighting when indoor daylight illuminance levels are low: for such users who 'consider daylight', the switch-on probability for electric lighting tends to be correlated with minimum indoor illuminance levels at the work plane, and happens upon arrival. People occasionally switch the lights on during the occupation period.

In line with this, experimental tests have been carried out in a university building, where laboratories and other rooms were equipped with the KNX building automation system (Kaminska and Ozadowicz, 2018). A dimmable control strategy was investigated, which depended on daylight illuminance. The window-size was the same in all rooms (0.63 m^2); and the windows are placed 0.3m from the exterior surface of the building. The facility included two laboratory rooms, two offices, and a corridor; and the occupancy of each room was monitored using a sensor. Lights were turned off as a response to inactivity for a sufficiently long period of time; and turned on instantly when activity was detected. The savings in lighting energy was similar to that expected in non-residential buildings: 28% for offices and 24% for educational buildings, respectively.

Table 7: Summary of energy savings, when occupancy sensors are used for lighting control (Guo, Tiller, Henze and Waters, 2010) .

Source	Energy savings		Time delay (min)	Space type	Baseline for energy saving calculation
	Regularly occupied spaces	Irregularly occupied spaces			
(Richman, Dittmer and Keller, 1996)	3–50%	46–86%	5-20	Office and restroom	Total lighted unoccupied time (savings equal to 100% if no time-delay applied)
(Floyd, Parker and Sherwin, 2002)	10–19%[a]	-	7-15	Office and educational buildings	Pre-retrofit lighting energy consumption
(Maniccia, Rutledge, Rea and Morrow, 1999)	43%	-	30	Private offices	10-hour lights continuously on scenario
(Maniccia, Tweed, Bierman and Von Neida, 2001)	28–38%	17–60%	5–20	Commercial buildings	Lighting usage measured by photosensor
(Jennings, Rubinstein, DiBartolomeo and Blanc, 2000)	20–26%	-	15–20	Offices	Lighting usage if lights were controlled by manual switch
(Chung and Burnett, 2001)	26.1–33.3% 6.9–15.2%		5–20 5–20	Office building	All lights on from 7 AM to 9 PM Following a simulated occupancy
(Pacific Gas and Electric Company, 1997)	25–50%	30–75%	NA	1-2 Person Offices	NA

[a] (Floyd, Parker and Sherwin, 2002) studied both commercial and school buildings, and found 10–19% energy savings in the commercial building and 11% in one school. However, energy use increased in the other school building.

Another study (Laidi, Djenouri and Ringel, 2019) investigated the economic, social, and environmental impacts of adopting different smart-lighting architectures, for home automation in two geographical and regulatory regions. Simulations were conducted for Algiers (Algeria), and Stuttgart (Germany), and the impact of dimming, daylight harvesting, scheduling, and motion detection was evaluated. In the simulation scenario, the family house was occupied by a family of four members, and two occupancy profiles were used for model patterns common to both Central Europe and Northern Africa. These stylized profiles were:

- Profile 1: Continuous random occupancy along the day, while weekdays and weekends are similar. For instance, this profile may correspond to families with retired elderly persons, under school-age children, or a home staying adult.
- Profile 2: Predictable long periods of non-occupancy in the middle of weekdays that correspond to regular working hours. Weekends are similar to Profile 1. This profile reflects families with working adults in regular working hours, and school enrolled children.

Three lighting control models were simulated, which were: no-daylight harvesting with on/off; daylight harvesting with on/off ('DH'); and daylight harvesting with dimming ('DH + dim'). Two methods were used to measure the time of operation for both profiles: which were Scheduling (Sched), and Motion Detection (MD). The simulation results for energy consumption for each scenario are presented in Figure 15.

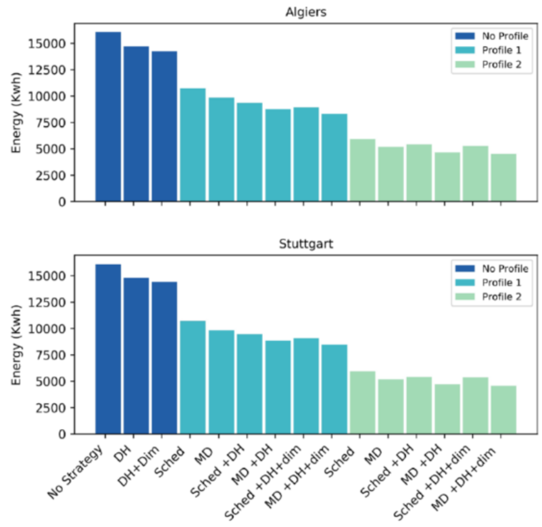

Figure 15: Total energy consumption for lighting control strategies.

'DH' and 'DH + dim' were identified to reduce energy consumption by almost 11%, with slight decrease in energy consumption for Algiers; due to its exposure to longer sunshine hours. The results show that the occupancy pattern is a leading factor in designing smart lighting architecture. The inclusion of motion detection sensors is more profitable for families with dynamic occupancy habits during daylight hours. The estimates of potential energy savings for different lighting control strategies compared to manual, or non-automated controls, in today's commercial buildings are shown in Table 8 (LUTRON, 2020).

Table 8: Estimates of potential energy savings in commercial buildings for different lighting control strategies (LUTRON, 2020).

	Strategy	Potential Savings in Lighting energy use
	Scheduling provides pre-programmed changes in light levels based on time of day	10-20%
	Occupancy/vacancy sensing turns lights on, when occupants are in space, and off when they vacate the space	20-60%
	High end trim/tuning sets the maximum light level based on customer requirements in each space	10-30%
	Daylight harvesting dims electric lights when daylight is available to light the space	25-60%
	Personal dimming control gives occupants the ability to set the light level	10-20%

3.2.3.4 Impact of complex glazing and fenestration systems on electric lighting energy use

Building energy efficiency is a global goal in policy and strategy. Several studies have shown that correct use of daylighting supports a reduction in lighting energy use, as well as improves visual comfort. Complex systems for glazing and fenestration, especially the automated ones, play an important role in regulating the visual and thermal conditions inside a room. The use of shading systems -- such as venetian blinds, rollers and louvers, etc; along with sunlight redirection system or electrochromic windows, makes it possible to either control the incoming solar radiation, to modify the solar gains and potential glare, or to improve the daylight distribution by redirecting a significant part of the incoming light flux towards the ceiling.

Another important aspect to be considered while reducing lighting energy use, is the selection of luminaire typology and appropriate lighting control systems. The benefits of using an efficient combination of these, include reduced cost for lighting and cooling. For lighting, savings are achieved mostly by reducing the time-of-operation for luminaires, while savings in cooling energy are mainly driven by reducing heat generation from lighting system (Doulos, Tsangrassoulis and Topalis, 2008) .

3.2.3.4.1 *Sunlight redirection system*

Over the years, many passive and static shading systems have been developed for enhancing and balancing daylight in spaces. The static nature limits their performance potential (Raphael, 2011), especially in climates with predominantly clear sky conditions; where dynamic systems for daylight redirection could be significantly more effective. A study conducted in Singapore used a mirrored shelf where the external part could be rotated; and showed net energy savings of 12% as compared with a static light-shelf. This research spawned many innovative redirecting systems, which have since been developed and analysed. Another study analysed the potential of a dynamic dual-axis daylight redirection prototype (Dogan and Stec, 2018), in order to improve the daylight availability and reduce lighting energy consumption. The prototype was analysed theoretically and experimentally; and it was reported that the new system supports lighting energy savings between 35% and 22%, when compared to a façade without a redirection system, or one with a static light shelf. Similar results were reported in another study (Kontadakis, Tsangrassoulis, Doulos and Topalis, 2017), which analysed an active sunlight redirection system for its daylighting and energy consumption perspectives. The system comprises of three mirrors placed in an array, mounted at about mid-window height: where each mirror is installed on a solar tracker. This system was simulated with Radiance and EnergyPlus, where the proposed system was compared with four other fenestration configurations, which were: (i) unshaded and unobstructed, (ii) with exterior blinds, (iii) with an external light shelf and (iv) with the Active Sunlight Redirection System (ASRS) and exterior blinds. The results showed that the proposed system could reduce lighting energy consumption by over 30%. In general, the possibility of obtaining a lighting energy reduction is strongly related to the fenestration configuration and to the considered time-of-year.

In another study, Solstice-to-solstice field tests were conducted in an office testbed – which comprised of prismatic blinds, dual-zone mirrored blinds, translucent diffusing panels, and automated motorized blinds. The outcome of this study showed that annual lighting energy savings of 62-69% could be achieved, at a depth of 3.8m from a south-facing, large-area window; as compared to a reference case with no lighting controls (Lee, Selkowitz, DiBartolomeo, Klems, Clear, Konis, Hitchcock, Yazdanian, Mitchell and Konstantoglou, 2009) . Micro-prismatic window films produced using low-cost roll-to-roll fabrication methods, were shown to provide significant redirection of direct sunlight, which extended the daylit zone to at least 7.3m while significantly raising daylight levels (Perry, Heschong and Baccei, 2012; Padiyath, 2013; Thanachareonkit, Lee and McNeil, 2013; Lee, Fernandes, Touzani, Thanachareonkit, Pang and Dickerhoff, 2016; McNeil, Lee and Jonsson, 2017). Lab-scale investigations were reported using electro-actuated metamaterial coatings, and evaluate the feasibility of developing inexpensive, scalable coatings from redox active organometallic polymers and self-assembled colloidal crystals. If deployed, this was reported to offer a potential annual lighting energy savings, of about 930 TBtu per year in the US alone, over a perimeter zone depth of 12.2m – which is approximately 85% higher, than energy savings estimated solely from implementing conventional vertical daylight strategies (Shehabi, Deforest, McNeil, Masanet, Greenblatt, Lee, Masson, Helms and Milliron, 2013) .

3.2.3.4.2 *Venetian Blinds*

Venetian blinds can be effective in controlling sunlight, reducing sky glare, and in redirecting light to the ceiling; and can provide shading effects equivalent to a very substantial overhang. Manual venetian blinds are widely used in commercial buildings, thanks to their potentiality to provide daylight, view-out, and privacy. Nonetheless, studies have shown that occupants often do not adjust blind positions, which could lead to visual and thermal discomfort, along with undesired energy wastage. Automated blinds try to overcome limitation of manual blinds, giving the possibility to adjust the blinds opening according to the existing outdoor solar conditions. To further improve energy saving, automated blinds are often coupled with automated lighting control systems. The use of automated blinds, when used to maintain daylight levels in the 540-700 lux range, was reported (Lee, DiBartolomeo and Selkowitz, 1998) to help reduce lighting energy by 19% to 52%, as compared to static blinds. The savings in lighting energy achievable with the use of motorized blinds, when coupled with daylight-controlled office luminaires, has been analysed in comparison with a reference system (Bülow-Hübe, 2007). The tilt angle of motorised venetian blinds was controlled, using illuminance data acquired by sensors installed on the façade. Blinds were closed when sensor-read illuminance values increased beyond 20 Klux for over a minute. The research showed that the proposed system supported lighting electricity savings, of about 77% in May and 5% in November. The annual saving was calculated at about 50%. An automated blind with adjustable mirrored slat spacing and tilt angle, was estimated to provide 14%-42% annual lighting energy use savings compared with conventional automated reflective blinds, and 9%-54% savings compared with conventional matte white venetian blinds – while maintaining acceptable or better visual comfort conditions (Fernandes, Lee, Thanachareonkit and Selkowitz, 2021; Thanachareonkit, Fernandes, Mouledoux and Lee, 2021) .

Photovoltaic blinds represent an evolution in dynamic venetian-blind-based shading systems. In such devices, PV modules are attached to the external side of blinds, to transform some portion of the potentially harmful solar energy – into useful electric power. Photovoltaic-blinds allow to offset the energy use for motorised blinds by routing the power generated by PV modules, and thus increase the benefits in lighting energy savings (Kim, Kim, Choi and Sung, 2014; Luo, Zhang, Liu, Su, Lian and Luo, 2018) .

3.2.3.4.3 Electrochromic Windows

Electrochromic (EC) windows can play an important role in controlling visual and thermal conditions inside a room, as well as reduce energy consumption for lighting; thanks to their ability of varying visible solar transmission and solar factor values through application of small electric field (Sibilio, Rosato, Scorpio, Iuliano, Ciampi, Vanoli and Rossi, 2016). Several experimental and theoretical studies have been performed in this domain, to assess the impact of these devices on lighting energy use (Clear, Inkarojrit and Lee, 2006; Lee, DiBartolomeo and Selkowitz, 2006) – where full-scale office test-beds were used during equinox periods to evaluate performance of EC window prototypes. These were compared with two conventional glazing; with visible transmittance values of 50% and 15%, respectively. It was highlighted in the experimental measurements, that coupling EC windows with a lighting control system allowed maintaining illuminance levels in range of 510-700lx inside office spaces. The EC window, when compared with reference windows of T_{vis} 15% and 50%, demonstrated lighting energy reduction of 44-59%, and 8%-23%, respectively. The reduction was even higher, in the range of 50-76%, when compared with either reference windows with no dimming lighting control.

A west-oriented conference room equipped with an automatically driven EC window – along with an efficient dimmable lighting system, was used to analyse interaction between EC windows and occupants (Lee, Claybaugh and LaFrance, 2012) ; and was simulated in EnergyPlus tool to assess annual energy use for HVAC and lighting. The research highlighted an energy saving of 49%, when the EC window was coupled with an occupancy-based control. Another study used Radiance to evaluate lighting energy savings, when an EC window was used (L L Fernandes, Lee and Ward, 2013); where an optimised control algorithm was defined to modulate the EC window-lighting controller, in order to guarantee a target illuminance on the work-plane. The research results highlight a remarkable energy-saving potential of south-facing EC windows: when compared with clear glass, the EC windows allowed energy saving of about 48%.

3.2.3.4.4 Liquid Crystal Windows

A recent study evaluated the impact of window refurbishment on energy consumption (Scorpio, Ciampi, Rosato, Maffei, Masullo, Almeida and Sibilio, 2020), as well as on internal daylight availability during the summer period (June 1st to August 31st) for a south-oriented office in Aversa, South Italy. The study was conducted for the Abbey of San Lorenzo ad Septimum, where the dynamic simulation software TRNSYS was coupled with Radiance for the simulations. The study explored a liquid crystal based Electrical-Driven (ED) window, rather than a conventional double-glazing Low-E window. The numerical models of the ED glazing were developed using OPTICS 6 and WINDOW 7.5. Validated “in-situ” measurements previously taken by the authors, were used to define parameters, such as: the LC glass of the ED glazing becomes transparent when a voltage of 115 V is applied (clear state); but returns to being opaque when the applied voltage is removed (milky state). Two different ED were investigated from the thermal and visual standpoints; where the first (provided by Gesimat GmbH) was characterised by solar- and visual-transmittance of 0.651 and 0.725 in the clear state, and 0.554 and 0.607 in the milky state; while the second hypothetical ED glazing (ED-LT) was characterised with 20% reduced values in milky state. The electric lighting system was considered ON, if the indoor value of the average daylight illuminance was lower than 300 lux.

For carrying out the thermal and lighting simulations, variations in the following parameters was conducted: (i) the deployed control strategy, from among Thermal, Daylight, and Solar strategies, (ii) the outside vertical solar radiation values for solar strategy, from among 100, 200 and 300 W/m^2, (iii) the window typology, and (iv) the switching time from among 1 h and 15 min. The simulation results highlight that:

- The maximum values of PES and Δm_{CO2} were achieved when ED windows were controlled with a solar strategy, with target vertical solar radiation at 100 W/m^2; whereas these were the minimum when ED windows were controlled with a thermal strategy,
- For either of the dynamic window typologies, the highest $sDA_{300/50\%}$ values was obtained following the solar strategy, when the target value was set at 300 W/m^2, and
- When equal control strategy is used on ED glazing with Lower Transmission, no points in the office receive an illuminance exceeding the upper limit of 2000 lux.

Concerning electric energy consumptions associated with electric lighting systems, the investigation underlines that:

- The energy consumption for electric lighting is strongly affected by the control strategy for LC glazing,
- The daylight strategy supports the lowest lighting energy consumption,
- The lighting energy consumption in ED windows, when equal control strategy is used, is always lower than the amount associated with ED-LT window. This is because the daylight availability is reduced in ED-LT windows, and
- The lighting energy consumption reduces when a lower switching time is defined (15 min instead of 1 h).

3.2.4 Integration in Existing Certification Systems

The following paragraphs illustrate the main principles and criteria on which the integration of daylight and electric lighting is featured, in some of the commonly adopted green building certification systems and rating tools, specifically: LEED *(Leadership in Energy and Environmental Design, USA)*; BREEAM (*Building Research Establishment Environmental Assessment Method, UK)*; BCA Green Mark *(Singapore)*; Green Star *(Australia)*, and the International WELL Building Standard.

Although this is not an exhaustive list, and many other certification systems exist; the aim of this section is towards providing an overview: of integrating lighting-related credits within design and operation criteria, that are meant primarily at reducing the environmental impact of buildings, and for improving the indoor environment quality for occupants. For this, a further selection has been made in this section where only the newly constructed commercial buildings are considered. In all the following certification systems, different requirements might apply to other building types (e.g., residential) or to buildings at different stages of their life cycle (e.g., for renovations).

3.2.4.1 LEED – Leadership in Energy and Environmental Design

LEED v4.1 is the latest release of this rating system, that was originally launched by USGBC (Unites States Green Building Council) in 1998. This rating system can be applied to commercial buildings of new construction (BD+C), existing buildings aiming to certify their operation and maintenance (O+M), buildings having been already certified (Recertification), interior spaces (ID+C), residential buildings (Residential) and planned and existing cities and communities (Cities and Communities) (USGBC, 2020).

Under LEED v4.1 BD+C: New Construction, credits related to the natural and electric lighting of interior spaces are featured in the category Indoor Environmental Quality (USGBC, 2020). Specifically, up to 3 points are available for the credit “Daylight”, up to 2 points can be achieved by satisfying criteria related to “Interior Lighting”, and up to 2 points can be scored for meeting requirements for “Quality views”.

Daylight

The aim of this credit is to “*connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space*” (USGBC, 2020). Meeting this credit requires the provision of manual or automatic (with manual override) glare-control devices for all regularly occupied spaces and, in addition, meeting one of three options:

Option 1: Perform annual computer simulations for spatial daylight autonomy ($sDA_{300,\ 50\%}$) and annual sunlight exposure ($ASE_{1000,\ 250}$) for each regularly occupied space. Depending on the results obtained for the average sDA for the total regularly occupied floor area (at least 40%, 55% or 75%), 1 to 3 points can be achieved. If each occupied space achieves $sDA_{300,50\%}$ of at least 55%, then 1 additional point can be obtained if only 1 or 2 points were achieved by consideration of average sDA. Healthcare projects have different benchmarks than other buildings (and only 1 to 2 points available). For ASE, regularly occupied spaces need to demonstrate an $ASE_{1000,\ 250}$ lower than 10%. For an ASE greater than 10%, the strategies used to address glare can be identified. Specific details are provided for the size of the grid (not larger than 600 mm^2), the work plane height (76 mm), the data to be used (TMY) and the inclusion of any permanent interior obstructions, with the exclusion of moveable furniture (USGBC, 2020).

Option 2: Perform illuminance simulation, demonstrating levels between 300 and 3000 lux at both 9am and 3pm on a clear sky day at the equinox for each regularly occupied space. Depending on the percentage of floor area (55%, 75% or 90%) meeting these requirements, 1 to 3 points can be achieved (1 to 2 for healthcare). Sun (direct) and sky (diffuse) components can be simulated using typical meteorological year data, selecting one day within 15 days of September and March 21 representing the clearest sky condition, and using the average of the hourly values for the two days. Blinds, shades and movable furniture should be excluded from the model, while permanent interior obstructions need to be considered. Spaces with view-preserving automatic (with manual override) glare-control devices can demonstrate compliance for only the minimum 300 lux illuminance level (USGBC, 2020).

Option 3: Perform illuminance measurements, demonstrating to achieve levels between 300 and 3000 lux for 55%, 75% or 90% of regularly occupied floor area, achieved at one or two times of the year, in order to obtain between 1 to 3 points (1 to 2 points for healthcare buildings). Spaces with view-preserving automatic (with manual override) glare-control devices may demonstrate compliance for only the minimum 300 lux illuminance level. Measurements need to be taken with furniture, fixtures and equipment in places, at appropriate work plane height, at any hour between 9am and 3pm, and – if pursuing more than 1 point – have to be taken at months suitably spaced apart (USGBC, 2020).

Interior Lighting

This credit aims to "*promote occupants' productivity, comfort, and well-being by providing high-quality lighting*" (USGBC, 2020). One point can be achieved by meeting one or both of the following options:

Option 1. For at least 90% of individual occupant spaces, individual lighting controls need to be provided so as to allow adjusting the lighting with at least three levels or scenes (on, off, midlevel, whereas the latter is 30% to 70% of the maximum illumination level, not including daylight contributions). In addition, all shared spaces need to have in place: multizone control systems that enable occupants to adjust the lighting to meet group needs with at least three lighting levels; separately-controlled lighting for presentation or projection lighting; and, switches or manual controls located in the same space and in direct line of sight of the controlled luminaires (USGBC, 2020).

Option 2. Four of the following strategies must be chosen and met: A) For all regularly occupied spaces, light fixtures with a luminance of less than 2,500 cd/m^2 between 45 and 90 degrees from nadir; B) For the entire project, light sources with a CRI of 80 or higher; C) For at least 75% of the total lighting load, light sources with a rated life of at least 24,000 hours; D) Direct-only overhead lighting for 25% or less of the total connected lighting load for all regularly occupied spaces; E) For at least 90% of the regularly occupied floor area, thresholds for area-weighted average surface reflectance meeting or exceeding: 85% for ceilings, 60% for walls, and 25% for floors; F) Furniture finishes meeting or exceeding the following thresholds for area-weighted average surface reflectance: 45% for work surfaces, and 50% for movable partitions; G) For at least 75% of the regularly occupied floor area, a ratio of average wall surface to average work plane illuminance not exceeding 1:10. Must also meet strategy E, strategy F, or demonstrate area-weighted surface reflectance of at least 60% for walls; H) For at least 75% of the regularly occupied floor area, a ratio of average ceiling to work surface illuminance not exceeding 1:10. Must also meet strategy E, strategy F, or demonstrate area-weighted surface reflectance of at least 85% for ceilings. For each strategy, exceptions are provided (USGBC, 2020).

Quality Views

The aim of this credit is "*to give building occupants a connection to the natural outdoor environment by providing quality views*" (USGBC, 2020). For this criterion to be met, a direct line of sight to the outdoors must be provided via vision glazing for 75% of all regularly occupied floor area. View glazing does not have to be obstructed by frits, fibres, patterned glazing, or added tints that distort colour balance. In addition, 75% of all regularly occupied floor area must have at least two of the following:

A. multiple lines of sight to vision glazing in different directions at least 90 degrees apart;
B. views that include at least two of the following:

1 flora, fauna, or sky;
2 movement; and
3 objects at least 7.5 meters from the exterior of the glazing;

C. unobstructed views within the distance of 3 times the head height of the vision glazing; and,
D. views with a view factor of 3 or greater.

Views into interior atria can be used to meet up to 30% of the required area. For Healthcare buildings, the Quality Views credit can award up to 2 points (USGBC, 2020).

3.2.4.2 BREEAM – Building Research Establishment Environmental Assessment Method

Under BREEAM UK for New Construction – Non-domestic buildings (BRE, 2021), criteria related to daylighting and electric lighting are featured under the Health and Wellbeing section, and the "HEA 01 Visual Comfort" assessment issue. Up to 6 credits are available, with the aim of "*providing occupants with the conditions that facilitate good visual comfort by designing out the potential for glare, achieving good practice daylight factors and having an adequate view out; and, designing internal and external lighting systems to provide appropriate illuminance (lux) levels, thereby giving a more comfortable environment for occupants*" (BRE, 2021).

The "HEA 01 Visual Comfort" issue is split into four parts:

1. Control of glare from sunlight (1 credit)
2. Daylighting (up to 2 credits, depending on building type)
3. View out (1 credit for all buildings, 2 credits for healthcare buildings)
4. Internal and external lighting levels, zoning and control (1 credit)

Control of glare from sunlight

This credit requires to identify areas at risk of glare using a glare control assessment methodology (e.g., survey or modelling of the relationship between sunlight and the building). Where risk has been identified, a glare control strategy that does not increase energy consumption for lighting needs to be defined to design out the potential for glare. The strategy can maximise daylight and ensure that the use or location of shading does not conflict with the operation of lighting control systems (BRE, 2021).

Daylighting

Daylighting criteria need to include good practice daylight factors and other criteria defined according to building or area type (these are provided and described in tables). Average daylight factors values required generally range between 1.5% and 3%, applicable to different values of minimum building areas for compliance, and need to be considered alongside daylight uniformity criteria. Alternatively, building or their areas need to meet specific good practice average and minimum point daylight illuminance criteria (e.g., 300 lux) for a certain number of hours per year (e.g., 2000 hours). For healthcare buildings, consideration can also be given to median and minimum daylight factors. Criteria for reflectance are also provided for maximum room depths and window head heights (BRE, 2021).

View out

This credit requires that 95% of the floor area in 95% of spaces for each relevant building area provides an adequate view out, defined according to specific criteria linked to room and window size and content of the view. Building type criteria also need to be considered for specific needs (BRE, 2021).

Internal and external lighting levels, zoning and control

Internal lighting in all relevant areas of the building needs to provide illuminance (lux) levels and a colouring rendering index in accordance with the "SLL Code for Lighting 2012" (CIBSE, 2012) and/or any other relevant industry standard. Internal lighting should be appropriate to the tasks undertaken, accounting for building user concentration and comfort levels. If computer screens are regularly used, compliance is needed with industry recommendations related to screen reflections, areas where a surface is used to reflect light into a space (e.g., uplighting), direct lighting, ceiling illuminance, and average wall illuminance.

For external lighting, all fittings located within the construction zone need to be specified in accordance with current codes for practice and regulations (e.g. (CEN, 2011))

For zoning and occupant control, the standard defines zoning criteria based on the type of areas or activity present in the building (BRE, 2021).

3.2.4.3 BCA Green Mark

In the Singaporean Green Mark for non-residential buildings scheme (BCA, 2016), lighting criteria are included both within issues related to Building Energy Performance ("P.5 Lighting efficiency and control" and "2.1b Lighting System Efficiency") and under the category of Smart and Healthy Buildings ("4.2 Spatial quality – 4.2.a Lighting" and "4.3 Smart Building Operations – 4.3b Demand Control").

P.5 **Lighting Efficiency and Controls** (pre-requisite)

This credit requires compliance with the Singaporean "SS 530 : 2014 – Code of Practice for Energy Efficiency Standard for Building Services and Equipment".

2.1b **Lighting System Efficiency** (up to 3 points)

The points scored under this credit are calculated based on the formula: Points scored = 0.1 x % improvement from baseline. The baseline is the "SS 530: 2014 - Code of Practice for Energy Efficiency Standard for Building Services and Equipment". The design needs to comply with "SS 531 – 1: 2006 (2013)– Code of Practice for Lighting of Workplaces".

4.2a **Lighting** (up to 6 points)

Considering that the BCA scheme is designed for building in the tropics, special care is given to maximise effective daylight while minimising visual discomfort and maintaining the façade's thermal efficiency. This credit is organised in 3 different parts:

(i) *Effective daylighting for common areas* (up to 2 points)

This criterion prorates the number of daylit transient common spaces with effective automatic lighting controls against the total number of applicable spaces. The points are scored based on the following formula = 1.5 x (% count with daylighting for toilets, staircases, corridors, lift lobbies and atriums) + 0.5 x (% areas of carpark with daylighting or having no carpark).

(ii) *Effective daylighting for occupied spaces* (up to 4 points)

- *Percentage of occupied spaces with access to effective daylighting* (up to 3 points)

  Points are calculated based on the percentage of total occupied areas achieving the specific Daylight Autonomy (DA) requirement outlined in the "Green Mark NRB: 2015 Technical Guide and Requirements Annex B: Effective Daylighting Simulation and Pre-Simulated Daylight Availability Tables Methodology and Requirements". Effectively daylit areas need to be integrated with automated lighting controls.

- *Effective Mitigation of Overlit Areas* (up to 1 point)

  Adoption of suitable mitigation strategies for overlit spaces need to be verified via pre-simulation daylight availability tables or daylight simulation.

(iii) *Quality of Electric Lighting* (up to 1 point)

A "low impact" item for this criterion includes consideration of: good light-output over life with a minimum lifespan rating of L70 ≥ 50,000 life hours; lighting designed to avoid flicker and stroboscopic effects, by using high frequency ballasts for fluorescent luminaries and LED lighting with ≤ 30% flicker; meeting the minimum colour rendering index in "SS 531 – 1 : 2006 (2013) – Code of Practice for Lighting of Workplaces".

A "high impact" item for this credit requires LED Luminaires certified under the SGBP scheme.

4.3b **Demand Control** (up to 3 points)

This credit requires occupancy-based controls to monitor the usage of spaces and vary temperature, ventilation and lighting demand while maintaining room temperature effectiveness, good indoor environmental quality and lighting quality. For lighting:

(ii) *Lighting Demand Control* (up to 1 point)

The credit requires the use of occupancy/vacancy sensors to moderate brightness of the luminaries for ≥ 80% of all transient (0.5 points) and occupied (0.5 points) areas (BCA, 2016).

3.2.4.4 Green Star

Under the Australia Green Star Design & As Build v1.3 scheme (GBCA, 2019), requirements pertaining daylighting and electric lighting are featured within the Indoor Environmental Quality category, and more specifically under the "Lighting Comfort" and "Visual Comfort" credits.

Lighting Comfort

Points for lighting comfort aim at encouraging and recognising well-lit spaces that provide a high degree of comfort to users. Points available are awarded for:

- Minimum lighting comfort (minimum requirement)
- General illuminance and glare reduction (1 point)
- Surface illuminance (1 point)
- Localised lighting control (1 point)

Visual Comfort

The visual comfort credit recognises the delivery of well-lit spaces that provide high levels of visual comfort to building occupants. Points are achieved by compliance for:

- Glare reduction (minimum requirement)
- Daylight (2 points)
- Views (1 points)

Specific documentation is provided to detail the methodologies required for calculation of compliance for all criteria, including for example methods for defining overshadowing requirements, visual light transmittance of glazing, lines of sight, daylight atrium views, etc (GBCA, 2019).

3.2.4.5 International WELL Building Standard

Under the WELL v2 pilot Q3 2021 standard (IWBI, 2021), an entire Concept is dedicated to Light, structured in 2 preconditions and 6 optimization features, as summarized below:

L01: Light Exposure (precondition)

This feature requires projects to ensure appropriate light exposure in indoor environments by using daylighting or electric lighting strategies. To encourage users to seek light exposure on their own, projects are required to provide users with education about the importance of light for health (IWBI, 2021). The feature is structured in the following part:

Part 1: Ensure Indoor Light Exposure. Includes criteria of daylight simulation, interior layout and building design. These criteria must be verified by architectural drawings and modeling reports.

Part 2: Promote Lighting Education. This part requires projects to provide educational resources on circadian rhythm, sleep hygiene, age-related increases in light requirements and/or importance of daylight exposure on circadian and mental health.

L02: Visual Lighting Design (precondition)

This feature requires projects to provide appropriate illuminances on work planes for regular users of all age groups while considering light levels required for the tasks performed in the space (IWBI, 2021).

Part 1: Light Levels for Visual Acuity. Requires all indoor and outdoor spaces (including transition areas) to comply with illuminance recommendations specified in international standards (e.g (CEN, 2011)) and that a lighting plan details the tasks or activities considered for visual lighting design in the project, the height or work planes or other target of illumination, and the age ranges for the majority of occupants (IWBI, 2021).

L03: Circadian Lighting Design (optimization, 3 points)

This feature requires projects to provide users with appropriate exposure to light for maintaining circadian health and aligning the circadian rhythm with the day-night cycle (IWBI, 2021).

Part 1: Lighting for the Circadian System (Max: 3 points).

For all spaces:

Electric lighting is used to achieve specific light levels as measured vertically at the eye level of the occupant. The light levels are achieved at least between the hours of 9 a.m. and 1 p.m. and may be lowered after 8 p.m. at night:

a. The project meets the following requirements in regularly occupied spaces:
   1 point
   - At least 150 EML [136 melanopic equivalent daylight D65]

   OR

   - The project achieves at least 120 EML [109 melanopic equivalent daylight D65] with electric light and at least 2 points in Feature L05: Enhanced Daylight Access.

   3 Points
   - At least 240 EML [218 melanopic equivalent daylight D65]

   OR

   - The project achieves at least 180 EML [163 melanopic equivalent daylight D65] with electric light and at least 2 points in Feature L05: Enhanced Daylight Access.

L04: Glare Control (optimization, 2 points)

This feature requires projects to manage glare by using a combination of strategies such as glare calculations, choosing suitable light fixtures for the space and using shading techniques (IWBI, 2021).

Part 1: Control Solar Glare (2 points).

For all spaces, a choice is provided between:

Window shading:

The following requirements are met in regularly occupied spaces:

- All exterior envelope glazing has shading. Atria or lobbies may be excluded.
- The shading is controllable by the occupants or set to automatically prevent glare. If shading is controlled by occupants, all shades are raised or retracted either manually or automatically at least twice per week.

Glare calculation:

The following requirement is met:

- Annual sunlight exposure of ASE1000,250 is achieved for no more than 10% of regularly occupied space.

Part 2: Manage Glare from Electric Lighting (2 points).

Each luminaire (excluding wall wash fixtures and task lamps positioned as specified by manufacturer's data, and decorative fixtures) meets one of the following requirements for regularly occupied spaces:

a) Shielding angles between 0 and 30º depending on source luminance
b) Fixture luminance not exceeding specified thresholds
c) 100% of light is emitted above the horizontal plane.
d) Unified Glare Rating (UGR) values defined based on the height of installation

L05: Enhanced Daylight Access (optimization, 3 points)

This feature requires projects to design spaces to integrate daylight into indoor environments so that daylight may be used for visual tasks along with electric lighting. It also provides individuals with a connection to outdoor spaces through windows (IWBI, 2021). Requirements are as follows:

Part 1: Implement Enhanced Daylight Plan (1 point). For all spaces except dwelling units, projects need to meet at least one of the following requirements on each floor:

- 70% of all workstations are within 7.5 m [25 ft] of transparent envelope glazing or atria. Visible light transmittance (VLT) of transparent glazing is greater than 40%.
- Window area is no less than 10% of the floor area. Visible light transmittance (VLT) of transparent glazing is greater than 40%

Different criteria apply to dwelling units.

Part 2: Implement Enhanced Daylight Simulation (Max: 2 points). For all spaces except dwelling units, projects demonstrate through computer simulations that sDA300,50% is achieved for the area on each floor as follows:

- sDA300,50% achieved for > 55% of regularly occupied floor area (1 point)
- sDA300,50% achieved for > 75% of regularly occupied floor area (2 points)

Different criteria apply to dwelling units.

Part 3: Ensure Views (1 point). For all spaces:
Transparent envelope glazing provides access to views for at least 50% of regular occupants.
Views meet at least two of the following requirements:

- If at ground floor, distance from fenestration to roadway and parking lots is at least 7.5 m [25 ft] from the exterior of the glazing.
- View factor of 3 or greater.
- Views with a vertical view angle of at least 30 degrees from occupant facing forward or sideways provide a direct line of sight to the ground or sky.

L06: Visual Balance (optimization, 1 point)

This feature requires projects to develop and implement strategies that take into account the light sources used in a space and create a visually comfortable lighting environment (IWBI, 2021).

Part 1: Manage Brightness (1 point). For all regularly occupied spaces, at least four of the following requirements are met:

- Main rooms do not exhibit 10 times greater or lesser luminance than an ancillary space.
- Surfaces do not exhibit 3 times greater or lesser luminance than an adjacent surface.
- Surfaces do not exhibit 10 times greater or lesser luminance than another remote surface in the same room.
- Changes in light levels to 1.5 times higher or lower than initial light levels are carried out over the span of at least 30 minutes in steps or with a smooth transition.
- Uniformity of at least 0.4 is achieved on work planes. Exclude supplemental lighting from calculations.
- One section of the ceiling does not exhibit 10 times greater or lesser luminance than another section of the ceiling in the same room.

L07: Electric Light Quality (optimization, 2 points)

This feature requires projects to consider characteristics of electric light used in the space, such as colour rendering and flicker (IWBI, 2021).

Part 1. Ensure Colour Rendering Quality (1 point). For all spaces (except circulation areas), all luminaires (except decorative fixtures, emergency lights and other special-purpose lighting) meet at least one of the following colour-rendering requirements.

a. CRI ≥90.
b. CRI ≥ 80 with R9 ≥ 50.
c. IES Rf ≥ 78, IES Rg ≥ 100, -1% ≤ IES Rcs,h1 ≤ 15%.

Circulation areas have different requirements

Part 2: Manage Flicker (2 points). For all spaces, all luminaires (except decorative lights, emergency lights and other special-purpose lighting), used in regularly occupied spaces meet at least one of the following requirements for flicker:

a. A minimum frequency of 90 Hz at all 10% light output intervals from 10% to 100% light output.
b. LED products with a "low risk" level of flicker (light modulation) of less than 5%, especially below 90 Hz operation as defined by IEEE standard 1789-2015 LED.

L08: Occupant Control of Lighting Environment (optimization, 2 points)

This WELL feature requires projects to implement innovative lighting strategies that take into account personal preferences of users, as well as their interaction with the physical space (IWBI, 2021).

Part 1: Enhance Occupant Controllability (Max 2 points). For all spaces, Ambient lighting systems in regularly occupied spaces meet the following requirements:

- Light systems are tunable and automated to meet the circadian and visual requirements of the occupants.
- Occupants have control of light levels, color temperature and color of electric light in their immediate environment and can override automated settings for at least 30% of operating hours

Part 2: Provide Supplemental Lighting (1 point). For all spaces except dwelling units, the following requirements are met:

a) Supplemental light fixtures meet the following requirements:
1. Can increase the light level on the task surface to at least twice the recommended light levels based on the reference used to meet Part 1: Light Levels for Visual Acuity in Feature L02: Visual Lighting Design.
2. Are provided at no cost upon request.

b) Requests for supplemental light fixtures are met within eight weeks of request.

3.2.5 Increase Savings through Business: Light as a Service

A circular or closed-loop economy, is a regenerative economical system that follows the cradle-to-cradle model, where resource input and waste are minimized by producing efficient, long-lasting, repairable, reusable, refurbishable and upgradable products. A circular economy is different from the current traditional linear economy, which is based on a take-make-and-dispose (or a cradle-to-grave) business model. Circular economy principles do not reject the development and growth paradigm; yet reshape it in a world of finite resources.

As our current economic system largely bears a linear economy approach, the transition to circular economy business models is still quite slow. However, considering the increasing demand of resources and energy, there seem limited choices for the future. Circular economy is already on the political agenda: in 2012, the European Commission released a first position paper termed "*Manifesto for a Resource-Efficient Europe*", which was followed by a policy and regulatory framework for circular economy issued in December 2015. Europe has already invested considerable resources for its practical implementation; and a number of these efforts are available on the European Circular Economy Stakeholder Platform.

Principles of Circular economy can successfully be applied to lighting, which can lead to innovation as well as energy saving. An example of this would be to design lighting products for serviceability – which is the ability to prolong a product's lifetime. While this certainly includes the use of more reliable hardware, it also needs to have individually replaceable components. A sealed LED desk lamp, for example, is a non-serviceable product, and when any component such as the LED driver fails, the whole luminaire needs to be replaced. Serviceability also includes modularity, connectivity and programmability, as they enable future upgrades of the lighting product.

Another example of circular economy is the application of the so-called Product-Service-System (PSS) business model to lighting domain. In PSS, a lighting producer can sell "photons" rather than lighting systems, i.e., lighting can be sold as a service rather than as a product. In such a model, the lighting producers own the lighting system, while the costumers pay a fee for the service and warranty, as well as for the electricity costs. Such approach has several advantages. For the lighting producer, it leads to a decrease in production costs and increase of profits due to optimization of the production chain. For the customer, it guarantees better lighting design, lower costs and a safer return of investments. On a global scale, the producers are encouraged to produce more long-lasting, repairable and upgradable lighting products, while the energy performance is secured by contractual provisions.

3.2.6 Risks associated with Efficient Lighting Technologies: The Rebound Effect

Globally between 2012 and 2016, the electrically lit outdoor area grew by 2.2% each year, with an annual increase rate of radiance of 1.8% (Kyba, Kuester, Sánchez de Miguel, Baugh, Jechow, Hölker, Bennie, Elvidge, Gaston and Guanter, 2017) . It can be inferred that the transition to efficient and inexpensive LED lighting, while contributing to a reduction in energy use for the areas that were already brightly lit; it can also increase the use of lighting in areas that were previously dark (Kyba, Kuester, Sánchez de Miguel, Baugh, Jechow, Hölker, Bennie, Elvidge, Gaston and Guanter, 2017) . In economics, such phenomena is termed as the rebound effect. This effect suggests that users are prone to increase the use of a service, when it becomes more efficient and affordable (Khazzoom, 1980); for example, a car using less fuel per kilometre might invite someone to drive longer. In extreme cases, the rebound effect can be so strong that it completely offsets the gains in efficiency. Such cases are termed as backfire, or as Jevons' Paradox (Jevons, 1866; Alcott, 2005).

In the last three centuries – irrespective of continents or lighting technology; the expenditure for electric lighting steadily accounted for 0.72% of the gross domestic product. This implies that the per-capita consumption of electric lighting grew constantly, leading to a 100% rebound effect, and reached 1.30 x 10^{17} lumen-hours in 2005 (Tsao and Waide, 2010).It was expected that this trend would continue even with transition to LED lighting, although the authors identified three instances of uncertainty in the forecast: 1) rebound may reduce as global lighting demand approaches saturations, 2) rebound may increase because LEDs offer ground-breaking features, and 3) rebound may increase/decrease in relation to policies. The overall global electric lighting demand was also investigated, but it was identified that indoor lighting is not immune to rebound. In 2014, a simple model was proposed (Borenstein, 2014) to estimate energy rebound effects, by accounting for a number of income-based constraints and assumptions. This model was applied to the hypothetical case of lighting in the U.S., and 43% of total rebound was calculated when substituting incandescent sources with LED bulbs. In another study (Hicks and Theis, 2014), an agent based modelling approach was used, based on U.S. survey on lighting consumers. The model created five different scenarios between 2012-2030, spacing from an unlikely "light saturation" scenario where the agent cannot use light for more hours, independently of the technology, to other scenarios which considered monetary incentives for purchase of LEDs, premature failure of LEDs, etc. The model resulted in high energy savings when light saturation was considered, but also the increased energy use when the cost of LEDs was dropped, leaving the agent with the possibility of unlimited burning time. The authors later refined the agent-based model, by adding more options, such as the possibility of increasing number of bulbs – rather than only the burning time – but this also led to very similar scenarios (Hicks, Theis and Zellner, 2015) .

Fortunately, real data showed that such figures were a bit pessimistic. In the same year, a survey of 6409 German households was published (Schleich, Mills and Dütschke, 2014), and it was identified that the total energy rebound from incandescent bulbs to LEDs was about 6%; and this seems to be a more reliable estimate at present. Interestingly in this study, while the efficient bulbs were kept on for longer then the less efficient ones – in a burning-time-rebound strategy – a large part of the rebound (60%) was due to luminosity rebound, where the LED replacement bulbs delivered an average of 24% more lumens then the previous bulbs. It can be argued that part of the rebound in the Luminosity-rebound is not caused by an active choice of the consumer, but rather by a market "pitfall" that only provides LED replacement bulbs with higher luminous power. In any case, only 6% rebound was associated with change in technology, while more than 500% increase in energy efficiency was assured -- from ~15 lm/W to ~100 lm/W.

It should be noted that the mentioned study merely focussed on simple one-on-one substitution of bulbs. Another study (Porritt, Tulej and Mucklejohn, 2013) hypothesized that the required lumens per-capita may increase in the future, because the visual acuity reduces in the ageing population, whereas the floor area per person is grows when wealthier population lives in bigger houses. An unknown - and probably unknowable - risk is that cheaper and versatile light sources may affect lighting design, possibly resulting in much higher rebounds. For example, strip lighting, full colour lighting, and an array of other creative lighting solutions presently available to designers; while certainly creating an aesthetically pleasant design, will also most likely increase the number of delivered lumens. This topic needs further exploration.

The rebound effect is a clear risk in terms of energy savings, yet it was highlighted that the existence of the rebound effect should not hinder efficiency gains (Hanley, McGregor, Swales and Turner, 2009); rather it should further encourage policies oriented towards energy savings. Moreover, moving from the energy issue and having a wider sight on the topic, some rebound effects may even have positive outcomes. A review of the most relevant studies on rebound and its associated effects (Gillingham, Rapson and Wagner, 2016), concluded that restrained rebounds without severe external costs are associated with induced innovation and productivity, and consequently with welfare gains; which should also be included in the benefit-analysis of energy policies. For example, increased access to lighting has historically triggered essential societal changes, which has been recognized by the United Nations (2013). Hence, in case when access to electric lighting in developing countries increases energy consumption, greater weight should probably be given to the resultant welfare gains, rather than the energy issues (Saunders and Tsao, 2012). It should also not be forgotten, that electric lighting would substitute more dangerous and pollutant electric light sources in developing countries, which makes “lightification” a matter of equality, of democracy, and of justice.

4 Discussion

An early Edison Electric Light sign, dating from the 1920s, is allegedly known to have been used to guide the transition from match-lit indoor gas lights to switch-operated electric bulbs. The sign recites: “This room is equipped with Edison Electric Light. Do not attempt to light with match. Simply turn key on wall by the door”. A note then explains: “The use of Electricity for lighting is in no way harmful to health, nor does it affect the soundness of sleep” (Figure 16)

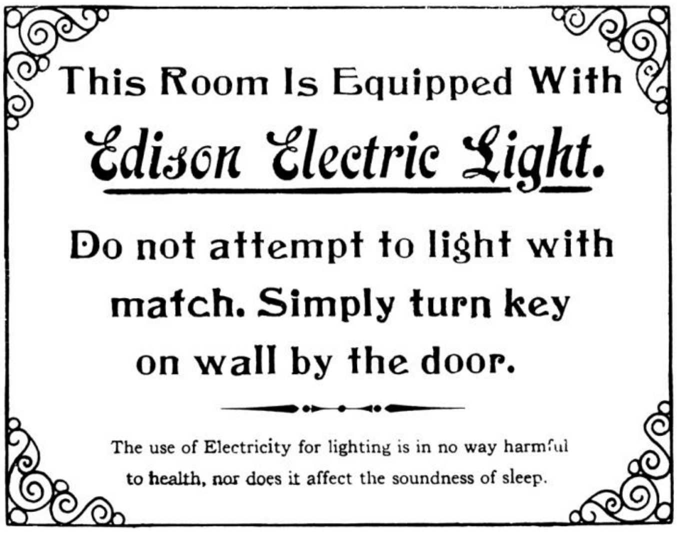

Figure 16: Edison Electric Light sign (modified from Commons.Wikimedia.org)

From these bases, over the last century our knowledge and appreciation of the various intricate influences of light and lighting on visual comfort, task performance, health and well-being, and on building’s energy balance for lighting and thermal needs, have made some remarkable steps. Nonetheless, the definition of adequate and integrated solutions for user-focused and energy efficient daylighting and electric lighting still brings substantial design and technical challenges.

Cognisant of the rapid changes that today characterise commercially available technologies for daylighting and electric lighting – and of the demand towards new approaches for the design and implementation of integrated systems and solutions in buildings – this technical report sought to offer a wide review of recent literature studies focusing on: daylighting (e.g., fenestration systems), electric lighting (including both traditional technologies and the most recent solid-state lighting) and their relative control systems (e.g., sensors, control strategies and algorithms); integration strategies and processes (featuring consideration of siting, massing, orientation, design tools, computer-based simulations, shading, daylight-responsive control, occupant behaviour, commissioning, monitoring, maintenance, etc.). Coherent with the overall objectives of the IEA SHC Task 61 / EBC Annex 77, other than offering to designers a body of scientific knowledge necessary to support best practice in design implementation, this report has given particular emphasis to the effective energy savings that could be associated to the integration of daylight and electric lighting systems and strategies, while identifying solutions that could allow the achievement of user comfort, well-being and satisfaction, and providing examples of design and implementation strategies as published in recent research.

The luminous environment comprises the band of electromagnetic spectrum between 380 and 780nm that is detected by the human eye and interpreted as vision (CIE, 2017). As emphasised in Sections 2 and 3 of this report, however, there is much more to lighting than merely enabling task illumination.

The use of daylighting and electric lighting, in fact, has to respond at once to the needs of the building and to the demands of the users, continuously seeking to reconcile requirements of light transmission, protection, and distribution. Specifying lighting solutions can be a very complex task – dependent on climate, orientation, functions, etc. – where many variables can diverge from each other, making design selection and optimization rather challenging. An integrated design should, however, first and foremost take into consideration the challenges and opportunities that are summarised here below.

Daylighting from windows, with its continuous dynamic variations in intensity, directionality, and spectral composition, can define the visual comfort and satisfaction of building users to support their personal and professional tasks but can also greatly influence buildings' energy demands, dictating the needs for electric lighting and regulating the amounts of thermal gains (solar and internal) (Boyce, 2014). In terms of daylight distribution, a combination of diffuse and direct natural lighting can enhance the three-dimensional recognition of objects and animate the internal environment. Spatial contrast, directionality of lighting, and variations, in fact, are fundamental to the appearance of a space. However, luminous ratios should be contained within specific boundaries: too large, and it will be difficult for the eyes to adapt; too small, and it might be hard to estimate depths and distances (Altomonte, Rutherford and Wilson, 2017). And yet, the use of daylight in buildings is often still a rather underexploited resource, mostly due to its mutable nature but also to the requirement of shading or re-directing systems that can help to moderate the incoming direct or diffuse radiation or provide visual privacy. The palette of shading devices currently available is very broad and new products are constantly being introduced in the market. Shading systems can range from simple static – e.g., louvers, overhangs, fins, etc. – to adaptable and dynamic elements – e.g., roller or venetian blinds, switchable glazing, etc. (L. L. Fernandes, Lee and Ward, 2013) – and/or their combinations. These systems can help to reduce the occurrence and magnitude of visual discomfort and, when mounted externally to the glazing, might also reduce the risks of solar overheating. However, many daylighting systems offer limited flexibility when it comes to controlling solar ingress. Several of them can only be operated to be in an either fully open or closed position, or might introduce high contrast between the shaded and unshaded part of the window. External systems provide the best solar protection, but can be constrained by weather (e.g., wind, rain, frost), costs (e.g., added structure, maintenance, motorisation), and user acceptance (e.g., noise, parts in motion) (Meerbeek, de Bakker, de Kort, van Loenen and Bergman, 2016). Internal devices offer limited solar overheating protection but they usually can be manually-operated for glare control (Garcia and Pereira, 2019), although this might result in blinds that are often left closed after the external condition (or internal requirements) have changed (Konis and Selkowitz, 2017). And protection might come at the cost of the external view. Conversely, a daylight strategy including unobstructed access to a view out is often favoured by building occupants. A pleasurable view can offer relief from visual muscle strain, relaxation, and spatio-temporal orientation. A connection to the outside has also been found to significantly benefit the mental health of building users (Ulrich, 1984). In this context, the window-to-wall ratio and the geometry of openings are particularly important. Wide windows placed high in the wall can be more efficient for lighting and solar energy penetration. However, floor-to-ceiling openings offering access to many layers of the external environment are more conducive to good view quality.

To enhance the lighting of buildings, daylighting needs to be complemented – and, when required, supplemented – by adequate electric lighting that allow proper illumination of spaces and perception of colours. Daylight and electric lighting are, however, intrinsically different primarily in terms of their spectral distributions. Daylight typically shows a smooth curve spectrum with energy content that is distributed across all frequencies. Electric lighting devices, instead, normally produce discontinuous spectra that peak at different wavelengths based on the type of luminous system. In lighting design, the installation of multiple fixtures, direct or indirect, should be preferred to evenly-distributed ceiling luminaries, particularly if lighting systems can be grouped based on areas of similar daylight availability. As of colour temperature, the selection should be based upon programmatic requirements (e.g., offices, shops, etc.) and issues of luminous perception, including the impression of warmth, relaxation, clarity, etc. In terms of lamp types, as presented in Section 2, these can be divided based on the physical process by which electricity is converted into radiant energy: heating a metal filament; passing current through a gas; or using a semi-conductor device. In addition, some lamp types can use the principle of fluorescence, by which radiant energy is absorbed by a material and re-radiated at different frequencies. Finally, light-emitting diodes (LEDs) use the principle of electroluminescence occurring when electrons are repositioned in a junction between two semiconductors (Tregenza and Loe, 2013).

As this report has clearly emphasised, effective integration of daylighting and electric lighting can allow to gradually reduce the amount of energy required for illumination when natural lighting is sufficient to support occupants' needs in terms of visual tasks and internal requirements, or after occupancy (Dubois, Gentile, Amorim, Osterhaus, Stoffer, Jakobiak, Geisler-Moroder, Matusiak, Onarheim and Tetri, 2016). To this aim, since the intensity and spectral composition of daylight can show significant variations during the day, and from season to season, a dynamically-optimised control system can guarantee variation in both colour and lighting levels, dimming, tuning and/or turning off electric lighting to enhance energy savings (Gentile, 2017). Dimming control is generally accepted by users since changes in light levels are less abrupt (Escuyer and Fontoynont, 2001), although automated systems without local over-ride should be avoided (de Bakker, Aries, Kort and Rosemann, 2017). To enable effective dimming strategies, monitoring or modelling of actual or predicted lighting levels is required (Chraibi, Creemers, Rosenkötter, van Loenen, Aries and Rosemann, 2018). This can be done by various sensors and monitoring equipment available on the market (Chung and Burnett, 2001), allowing to characterise lighting distribution either at a specific point-in-time or based on annual projections. Monitoring data can be translated under various metrics to assess buildings' light performance and continuously evaluate, and eventually adjust, the effectiveness of a chosen strategy. Some of these metrics are static measures or indicators (e.g., the 'traditional' daylight factor), other include dynamic indexes allowing consideration of spatial daylight autonomy (e.g., minimum daylight in a specified time period from climate data), annual solar exposure, glare occurrence, quality of view out, etc. (Gentile and Dubois, 2017).

In the definition of user-centred integrated lighting solutions, other than measuring the efficiency of lighting strategies based on conventional measures and indicators to ensure buildings' luminous and energy balance (Van Den Wymelenberg and Inanici, 2016), proper consideration has also to be given to the fact that the presence and distribution of light also strongly affects occupant's physiology, psychology, and behaviour. Recent advances in neurosciences and photobiology, in fact, have highlighted that light exposure, other than enabling visual comfort and task performance, presents a potent cue (zeitgeber) for entraining several neuro-physiological, endocrine, and behavioural processes via the non-image forming (NIF) action of a distinct photoreceptor in the eye, the melanopsin-containing intrinsically photosensitive retinal ganglion cells (iPRGCs). NIF responses to retinal illumination are also often referred to as non-visual, since they originate in the eye but are separate from other aspects of vision (Rea, Figueiro, Bierman and Bullough, 2010). These processes seem to be associated to specific patterns of spectrum, intensity, duration, timing, and history of light exposure that radically differ from the characteristics of the known photoreceptors in the eye, the cones and the rods. This implies a basic reconsideration of lighting strategies beyond the conventional photopic luminous efficiency function V(λ), which is solely based on the sensitivities of M- and L- cones (Rossi, 2019). In fact, the peak sensitivity of ipRGCs has been found to be shifted towards shorter wavelengths (~480 nm) with respect to the cones that drive photopic vision (peaking at ~555nm). NIF effects can be measured in both the long and the short term (Figueiro, Kalsher, Steverson, Heerwagen, Kampschroer and Rea, 2019). In the long term, exposure to a natural cycle of light/dark entrains the endogenous circadian (circa-dian, about a day) clock to an approximate 24-hour schedule, orchestrating several metabolic processes and neuro-behavioural functions, the sleep/wake cycle, etc. Lack of synchronisation to the day/night rhythm has been linked to increasing risks of sleep disorders, fatigue, metabolic disfunctions, mood disorder, etc. (Cajochen, Freyburger, Basishvili, Garbazza, Rudzik, Renz, Kobayashi, Shirakawa, Stefani and Weibel, 2019). In the short term, retinal illumination has been associated to several acute effects, contributing to suppress the pineal hormone melatonin (whose secretion is associated with the body preparing for sleep at night), stimulating the production of cortisol, regulating heart rate, core body temperature, and neuro-physiological processes related to alertness, arousal, cognitive performance, etc. The importance of considering the NIF effects of light in the design and operation of buildings has been reinforced by recent recommendations published by the CIE and by its inclusion in several new certification schemes (CIE, 2019). This is a clear demonstration of the importance that daylighting and electric lighting has towards ensuring the quality and sustainability of our built environment, not only from a perspective of energy savings, but also in terms of ensuring the comfort, satisfaction, and well-being of occupants.

5 Conclusions

This technical report has offered a comprehensive and documented review of the latest systems integrating daylighting and electric lighting, which includes detailed description of their control operations, while also presenting solutions that – if properly implemented, can support better experience for occupants as well as energy savings. The adoption of user-focused and integrated lighting solutions needs to be a consistent priority towards a more sustainable design of our built environment.

For example, in *homes*, the effective use of daylight; with its intensity, spectral variations, views, and an adequate integration with electric lighting, can emphasise spatial characteristics, foster metabolic processes at times of day that correspond to key circadian phases (e.g., morning, night, etc.), and efficiently offset energy demands for luminous and thermal needs. In *healthcare* and *educational* facilities, design solutions informed by the multi-faceted effects of light, and the presence of restorative visual scenes, can reduce recovery times, enhance attention, and encourage concentration, learning, etc. In *tertiary buildings* (e.g., offices, commerce), a comprehensive characterisation of programmatic requirements and energy demands, and proper consideration of users' visual and nonvisual needs, could enable the definition of tailored lighting and shading strategies to improve task performance, alertness and mood, while contributing to energy savings.

However, many challenges are yet to be fully addressed, including the following:

Regulatory:

- International lighting standards specify several design recommendations for a wide range of activities based on energy performance and visual comfort criteria. However, most requirements are very often still limited to horizontal light distribution, glare from small lighting sources and colour properties, without requiring effective integration between daylighting and electric lighting solutions;
- Lighting standards are still often focused on buildings' energy efficiency criteria, without effective consideration of user demands, including the combination of visual and non-visual requirements.

Technical:

- Proper integration of daylighting and electric lighting solutions are often non implemented in practice since they are the responsibility of different actors of the building design process;
- The lack of shared communication protocols between daylighting and electric lighting control systems often hinders the attainment of predicted energy saving and occupant experience;
- The control logics adopted for designing and operating daylighting systems and strategies need to be informed by proper continuous monitoring of relevant lighting and energy data.

Design:

- Effective integration of daylighting and electric lighting solutions requires comprehensive characterisation of the inter- and intra-individual differences of buildings' occupancy, including user characteristics (e.g., age) and needs (e.g., tasks and activities over time);
- Attainment of anticipated energy savings from properly integrated lighting solutions requires a proper modelling and prediction of users' perceptions and behaviours.

The following insights may be drawn:

Daylighting remains the preferred light source for most users, and better daylighting provision – in combination with appropriate supplementary electric lighting – can lead to substantial energy savings. Building occupants typically accept lower illuminance levels when the essential illumination is provided -- or is perceived to be provided -- by daylight, as compared to when electric lighting is used. It is somewhat difficult to design a good daylighting solution which can effectively be integrated with electric lighting (via appropriate control systems) since there are many conflicting aspects that need to be considered. Among these are the trade-offs between user comfort (visual and thermal), view out and privacy, as well as the conflicting aspects of visual performance/productivity clubbed with spatial perception, and energy savings clubbed with overall building performance. Increased daylight levels might lead to unwanted solar gains and discomfort glare, which in turn might require blinds to be closed, which may further lead to increased electric lighting loads.

Potential energy savings have been reported from the retrieved studies. However, these savings derived from separate studies are dependent on their specific contexts, which lowers the ecological validity of the findings. Studies on strategies, like information, feedback, and social norms, did not report energy saving performance. This is an interesting conclusion, since the papers indicate high potentials that deserve further exploration. Quantifying potential savings is fundamental to fostering large scale adoption of user-driven strategies, since this would allow at least a rough estimation of returns for the investors. However, such quantification requires that studies are designed with an inter-disciplinary approach. For example, during the review process, it was noticed that social science studies tend to provide comprehensive but only qualitative results, while engineering studies tend to measure energy effects of the intervention, but their experimental designs lack solid theoretical frameworks; and their results cannot be transferred easily to other contexts. A study design which involves expertise from different disciplines, would eventually overcome these limitations. Encouraging users to be more conscious of their lighting-use behaviour, can likely achieve sizeable energy savings. However, the saving potential is purely hypothetical at this point; and is greatly affected by many aspects that are highly situation specific. It therefore seems necessary to conduct purposeful studies on integrated lighting design solutions – capable of addressing lighting and lighting-related energy aspects from daylight, electric lighting, and shading systems; before specific recommendations can be made.

The following design recommendations can be made:

- Manual or partially-automated shading devices provide higher satisfaction, and encourage appropriate use, while fully-automated systems are more likely to be overridden (Meerbeek, de Bakker, de Kort, van Loenen and Bergman, 2016). The use of manual and partially-automated shading devices benefits from feedback systems, and users tend to act simultaneously on lighting and shading when the control interface is unique and conveniently located (Sadeghi, Karava, Konstantzos and Tzempelikos, 2016) .

- Energy savings can be fostered by dimming electric light, provided that the speed and range of variation is appropriately regulated (Newsham, Mancini and Marchand, 2008). For maximising daylight, shading automation may be limited to opening shading devices near the end of the day, since users usually maintain default settings.

- Fully automated controls with occupancy sensor and on/off switching should be avoided, as they increase the energy use in most cases; even when compared to manual switching. In some settings, it might even be better to use only manual lighting controls. Energy code requirements might require revisions to permit this. Lighting controls offering appropriate, gradual, and unnoticeable changes in illuminance levels are less likely to annoy occupants; and those with built-in system-learning capabilities for gradually adapting to user preferences are promising. However, additional research is needed for identifying the best implementation of such systems in a variety of settings, especially for larger spaces with multiple occupants. Intuitive and tangible lighting controls constitute another topic, which deserves increased attention. Standards for lighting control devices can perhaps address this, through interdisciplinary scientific studies with different user groups.

Social norms play an increasing role in affecting energy-use behaviours. These can likely be reinforced by feedback from lighting and shading control systems via clearly articulated, intuitive, and graphical prompts. If some users are seen making an effort for energy conservation, their colleagues might be persuaded to do the same.

Rebound effects have been reported, where the lighting energy use was found to increase despite higher luminous efficacy of luminaires. This appears to be related to the perception, that more efficient light sources can be used more frequently and perhaps in more places than those with lower efficacy. However, these effects might also be due to increased lighting needs of an aging population, and a higher area-per-person ratio in many building types, especially residences. More detailed studies addressing energy use, such as pre-and post- retrofit evaluation in various sectors of the lighting market, would be useful to identify areas where rebound effects pose particular threats to energy conservation targets.

This review has explored some “user-driven strategies” to save energy in the field of integrated lighting design. The strategies listed above suggest that sizeable energy savings can be achieved, by encouraging users to be more conscious of their behaviour with respect to lighting energy use. However, the saving potential is purely hypothetical, and is greatly affected by a number of aspects that are situation specific.

It is also identified through literature survey, that further exploration in lighting research is needed for several topics relevant to energy efficiency and user behaviour. This is needed for further enhancing the limited available knowledge in this domain, as compared to other areas of building energy services. Topics for research that needs to be urgently focussed on, includes feedback systems and social norms in integrated lighting design. Some topics, such as the rebound effect, represent risks rather than opportunities; but reinforce the need for deeper understanding of energy-related behavioural patterns and decision-making processes, for various stakeholders such as building owners, designers, lighting suppliers, installers and end-users. The literature also showed that strategies, where there is more communication between façade and lighting designers, are more successful in integrated design, which calls for more communication between stakeholders in future building processes. Finally, it can be argued, that research on user-driven strategies is needed today more than ever; since the increasing level of lighting efficiency, may render further gains marginal.

Thankfully, our knowledge is swiftly making significant steps ahead to address these challenges. In this direction, this technical report – together with all other outputs from Subtask D of IEA SHC Task 61 / EBC Annex 77 – has intended to offer a contribution for such knowledge to be more effectively translated in the practice of building lighting design.

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