# POLITECNICO DI TORINO

**Corso di Laurea Magistrale**
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# Daylight in Zero Energy Office Buildings


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Ai miei genitori,
luce che guida e ombra che segue.

When strong environmental targets become good business,
the world is better equipped to face the challenge of climate change.

[cit. Marius Holm, Managing Director Zero]

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# 0 Sommario in Italiano

Il presente documento è una Tesi di Laurea Magistrale in Ingegneria dei Sistemi edilizi della studentessa Serena De Simone, iscritta presso il Politecnico di Torino.

I contenuti dell'elaborato sono riassunti in lingua italiana nel capitolo corrente in quanto l'intero lavoro di tesi è stato svolto in lingua inglese presso la Norwegian University of Science and Technology a Trondheim, Norvegia.

Con il presente elaborato si rimarca l'importanza di ottimizzare l'uso della luce naturale per l'illuminazione di ambienti interni ed in particolare in edifici ad energia zero (ZEB) ad uso ufficio. Dopo la presentazione dello stato dell'arte in ambito di strategie bioclimatiche alla base del concetto di ZEB, e delle cause che hanno portato a modificare le tecniche costruttive nel campo dell'edilizia, sarà evidenziata l'influenza positiva della luce naturale sull'organismo umano, come incoraggiamento ad una progettazione più accorta verso il benessere dell'utente. Unitamente a ragioni fisiologiche e psicologiche verrà presentato il grande peso occupato dall'illuminazione artificiale di interni nel bilancio energetico, e quindi economico, di un edificio. In tale ottica si ripercorreranno brevemente i momenti più significativi in termini di accordi internazionali e norme elaborate circa il controllo di consumi energetici ed emissioni di gas serra, che hanno portato alla necessità di avere edifici sempre più virtuosi e sistemi di certificazione che ne attestino la prestazioni.

Infine verrà presentato lo studio di un edificio ad energia zero ad uso ufficio, sito in Norvegia ed oggetto di monitoraggio dal punto di vista della condizione di illuminazione naturale. L'esperienza rientra nel programma dell'Agenzia Internazionale dell'Energia (IEA) che ha messo a punto 39 temi di ricerca, detti Tasks, riguardanti diversi aspetti del controllo del fabbisogno energetico di un edificio. In particolare la Task 50 Subtask D prevede l'elaborazione di un protocollo di monitoraggio per edifici aventi soluzioni di illuminazione avanzate ed l'edificio analizzato durante l'esperienza di tesi verrà inserito come caso studio in sede di pubblicazione. Le misurazioni ottenute secondo il protocollo di monitoraggio verranno confrontate con simulazioni di tipo illuminotecnico ottenute tramite software specifici. Poiché precedentemente soggetto a ristrutturazione, l'edificio oggetto di studio verrà analizzato anche con riferimento alla situazione di illuminazione prima e dopo il rifacimento che lo ha portato ad ottenere la certificazione di livello eccezionale.

## *0.1 Introduzione*

La luce naturale è da sempre uno degli elementi più importanti del quotidiano di ogni essere vivente, la vita sulla terra è basata sul ritmo sonno-veglia influenzato dal percorso solare nel cielo e prima dell'invenzione e diffusione di sorgenti di luce artificiali, l'uomo iniziava la sua giornata al sorgere del sole e la concludeva al tramonto. Alcune ragioni per le quali la luce naturale sia importantissima per la vita sono note ai più e facili da comprendere, altre riguardano la sfera sensoriale e sono ancora oggi oggetto d'indagine da parte di ricercatori.

Inizialmente l'invenzione della lampadina ha fatto sì che l'uomo passasse da uno stile di vita basato sulla luce naturale a svincolare le sue abitudini giornaliere dal numero di ora di luce in un giorno, causando un uso incontrollato e molto spesso superfluo di fonti di luce artificiale. A partire dalla fine del XX secolo si sta cercando di invertire tale tendenza grazie ad accordi internazionali e leggi locali, all'interno di un più ampio progetto che mira alla riduzione delle emissioni di anidride carbonica, responsabili del surriscaldamento globale.

Con l'evoluzione umana e la conseguente crescita tecnologica infatti, il nostro pianeta è sempre più antropizzato, gli spazi dapprima occupati da vegetazione sono stati progressivamente sostituiti da costruzioni, riducendo la possibilità di conversione di $CO_2$ in ossigeno ed incrementando le sorgenti di produzione di gas serra. L'emissione di tali gas è dovuta alla produzione di energia e più di un terzo dell'energia primaria mondiale è legata al mondo delle costruzioni, dal cantiere alla fase d'uso (riscaldamento di spazi ed acqua sanitaria, ventilazione, illuminazione, raffrescamento), affiancato dal settore industriale e dei trasporti. La riduzione di tali emissioni si può ottenere tramite l'uso di fonti di energia rinnovabili e un notevole contenimento nei consumi; negli Stati Uniti il maggior consumo di energia si ha per l'illuminazione di edifici commerciali, mentre in Europa è secondo all'energia necessaria per il riscaldamento(IEA, 2014a), come mostrato in figura 1.1 e 1.2.

Data l'importanza del settore delle costruzioni nel controllo del surriscaldamento globale, da 15 anni circa si sta sviluppando un nuovo modo di progettare e costruire edifici rappresentato dal concetto di *Zero Energy Building*, un edificio il cui bilancio energetico tra la fase di costruzione e vita utile sia nullo, grazie ad un ridotto uso di energie in cantiere e in opera, affiancato da sistemi di produzione energetica basati su fonti di energia sostenibile.

La riduzione dei consumi durante l'uso dell'edificio si basa sull'implementazione di concetti di bioclimatica, noti ben prima che il fenomeno del surriscaldamento globale rappresentasse un problema per l'umanità. Uno dei pionieri delle costruzioni passive fu George Frederick Keck, che costruì nel 1933 l'edificio conosciuto con il nome di *House of Tomorrow*, realizzato completamente in vetro (Thompson and Blossom, 2015). Durante la costruzione della struttura, infatti, gli operai notarono che era possibile lavorare all'interno dell'edificio indossando solo una maglia a maniche corte durante le soleggiate giornate invernali, in una località come Chicago, dove gli inverni sono molto rigidi. L'importanza delle superfici vetrate per riscaldamento passivo di ambienti fu implementata da Frank Lloyd Wright nella villa a due piani costruita per i coniugi Jacobs in Winsconsin dieci anni dopo l'esposizione di Keck. Come mostrato in figura 1.4 il progetto di Wright *The Solar Hemicycle* rappresenta una delle basi della bioclimatica per l'intelligente uso di facciate vetrate esposte a sud, utilizzo del suolo terrestre come massa termica e la prima applicazione di sistema radiante a pavimento.

Durante gli anni '50 la progettazione di edifici passivi si diffuse dall'America al resto del mondo e nel 1956 l'ingegnere francese Felix Trombe brevettò una delle più famose tecnologie di climatizzazione naturale: il muro di Trombe. Il sistema consiste in un muro il cui strato più esterno è di colore scuro e rivolto verso un'intercapedine di 5-10 cm chiusa da una superficie vetrata. La radiazione solare infrarossa trasmessa attraverso il vetro riscalda l'aria nella cavità grazie al muro che agisce da collettore solare ed attraverso apposite aperture nel muro stesso è possibile climatizzare l'ambiente interno in 4 differenti configurazioni illustrate in figura 1.5.

La prima definizione di edificio passivo si deve ad un progetto di ricerca condotto da la University of Lund/Sweden sotto la supervisione del Professor Bo Adamson, in cui una casa passiva è definita come un edificio avente una fabbisogno energetico per il riscaldamento estremamente ridotto, anche se soggetto al clima tipico dell'Europa centrale, così da non necessitare di sistemi di riscaldamento attivo. Tale concetto teorico fu messo in pratica per la prima volta nel 1991 con la realizzazione di 4 villette a schiera in Germania, riscaldate unicamente da sorgenti di calore interne ed energia solare, inoltre le dispersioni termiche erano ridotte al massimo grazie al recupero di calore tramite il sistema di ventilazione ed un involucro esterno opaco super isolato, unito a serramenti a triplo vetro (Webster, 2014).

## 0.2 Luce naturale e salute

L'intensità con cui la luce naturale raggiunge un punto della crosta terrestre varia su base giornaliera, mensile, stagionale e annuale, secondo le condizioni climatiche, l'inclinazione dell'asse terrestre e la posizione relativa Terra-Sole. In particolare secondo studi scientifici (Boyce et al., 2003), poter avvertire il cambiamento dell'intensità luminosa dovuta alla radiazione solare durante il corso della giornata aiuta a ridurre i livelli di stress ed aumentare la produttività dell'uomo.

L'Organizzazione Mondiale per la Sanità definisce la salute come uno stato di completo benessere fisico, mentale e sociale (WHO, 2006), infatti non riguarda solamente assenza di malattie o infermità fisiche, è influenzata da molteplici aspetti e tra questi anche la presenza di luce naturale nei luoghi occupati da esseri umani. Molti studi riportano una diminuzione in assenteismo e riduzione della fatica in ambienti di lavoro, sintomi da Disordine Affettivo Stagionale e depressione ridotti, migliori prestazioni visive e un impatto positivo su disturbi comportamentali causati dal morbo di Alzheimer per soggetti esposti a maggiori quantità di luce naturale rispetto alla condizione media a cui l'umanità è esposta ogni giorno. I modi in cui la radiazione solare interagisce con il corpo umano sono molteplici, alcuni hanno effetti positivi come stimolo cutaneo nella produzione di vitamina D ma altri possono causare una risposta negativa da parte dell'organismo, come eritema, melanoma, fotoinvecchiamento cutaneo, danneggiamento del DNA e degli occhi (Webb, 2006).

In particolare la vitamina D è necessaria per metabolizzare il calcio, prevendendo l'osteoporosi, ed abbassare la pressione sanguigna, responsabile di malattie cardiovascolari, tuttavia pochissimi alimenti la contengono quindi più che essere assunto tale sostanza organica viene autoprodotta dall'organismo attraverso una reazione fotosintetica innescata dai raggi UVB, cosicché di recente non è più considerata una vitamina ma un ormone steroideo. Purtroppo le conseguenze dell'esposizione ai raggi UV sono conosciute ai più come negative, senza distinzione tra i vari tipi di radiazioni UV esistenti e molto spesso la soluzione adottata è di limitare l'esposizione solare causando una ridotta produzione di vitamina D, quando sarebbe sufficiente evitare una sovra esposizione alla radiazione UVR assicurandosi la necessaria quantità di luce (WHO, 2006).

La luce solare non interagisce con l'organismo umano solo a livello fisico tramite la pelle, essa ha anche influenza su aspetti e abitudini comportamentali, conosciuti come effetti non visivi o biologici della luce naturale. Attraverso l'apparato visivo la radiazione solare ci permette di percepire visivamente il mondo attorno a noi ma anche di regolare la produzione di ormoni influenzando il metabolismo e i bisogni dell'organismo umano. L'occhio, organo di senso principale dell'apparato visivo è costituito principalmente da una lente, la cui curvatura è regolata dai muscoli ciliari per poter mettere a fuoco gli oggetti a seconda della distanza dall'osservatore, e dalla retina, un tessuto fotosensibile raggiunto dai raggi luminosi attraverso la lente, una più dettagliata schematizzazione dell'occhio è mostrata in figura 3.1. Le cellule di tale tessuto sono di due tipi e chiamate coni e bastoncelli; la loro funzione e differente e complementare:

- i coni hanno un’elevata densità nella parte centrale della retina, chiamata fovea, e sono responsabili alla visione fotopica ovvero alla percezione dei colori. In particolare esistono tre tipi di coni adibiti a percepire lunghezze d’onda nell’ordine del rosso, verde e blu (figura 3.2). La visione fotopica è anche detta visione diurna e caratterizzata oltre che dalla capacità di riconoscere i colori anche da quella di permettere di cogliere i dettagli di qualsiasi oggetto messo a fuoco all’interno del campo visivo.
- I bastoncelli sono molto circa 20 volte più numerosi dei coni (120 milioni circa) ma hanno densità minore, sono maggiormente presenti nella parte periferica della retina e responsabili della cosiddetta visione scotopica. Essendo molto più sensibili dei coni (basta 1 fotone ad attivarli contro i 100 necessari per un cono) permettono la visione notturna che tuttavia risulta essere priva di colori e poco dettagliata

Nel 2002 è stato scoperto un nuovo fotorecettore presente nella retina dei mammiferi, chiamato cellula gangliare retinale fotosensibile (ipRGC), responsabile della regolazione di molteplici effetti biologici di cui il ritmo circadiano, la temperatura corporea, produzione di cortisolo e melatonina sono i principali. Sebbene non vi siano fattori che escludano l’influenza dei coni e dei bastoncelli sul ritmo circadiano, il ruolo principale appartiene agli ipRGCs, avendo una connessione preferenziale attraverso il nervo ottico con il nucleo soprachiasmatico, presente nell’ipotalamo e scientificamente riconosciuto come l’orologio biologico del cervello.

Il ritmo circadiano è la combinazione di cambiamenti fisici, mentali e comportamentali che si susseguono in un ciclo di 24 ore dettato primariamente dall’alternanza luce-buio nell’ambiente in cui vive l’uomo (NIGMS, 2012). Esso è diverso dal più noto orologio biologico, sebbene vi sia strettamente dipendente. In accordo con l’orologio interno di ogni individuo, il ritmo circadiano è re-inizializzato ogni giorno al fine di sincronizzarsi con il naturale ciclo notte-dì influenzato giornalmente da stimoli esterni come la quantità di luce solare a cui si è esposti, la temperatura ambiente e stimoli sociali. In assenza di stimoli sincronizzanti, il ritmo circadiano è sempre presente ma può risultare sfasato, non più basato su 24 ore: il ciclo sonno-veglia può arrivare a stabilizzarsi su 36 ore mentre quello della temperatura corporea su 25 ore.

La relazione tra ritmo circadiano e luce solare consta nel fotopigmento melanopsina, contenuto all’interno delle cellule della retina, che nulla ha a che vedere con la vista, infatti anche le persone affette da cecità hanno come responso la soppressione della produzione di melanopsina se esposte alla luce. Tale fotopigmento invia stimoli al nucleo soprachiasmatico, che li interpreta ed ordina la produzione di melatonina alla ghiandola pineale, presente nell’epitalamo. In figura 3.6 è riportata una schematica rappresentazione dell’interazione tra ghiandole e produzione di ormoni nel corpo umano.

Numerosi studi hanno riportato che i livelli necessari a soddisfare i bisogni non visivi sono ben diversi da quelli necessari a svolgere differenti attività che richiedano l’uso della vista: i secondi sono molto più bassi di quelli legati alla sincronizzazione del ritmo circadiano e gran parte dell’umanità non è esposto a quantità di luce opportuni nei più appropriati momenti della giornata. Tuttavia l’esposizione ad una grande quantità di luce deve sempre essere confrontata con il concetto di comfort visivo.

Parlando di comfort la soggettività di ogni persona è molto importante e non è sempre semplice riconoscere quando una condizione di illuminazione sia appropriata per qualcuno o causi discomfort ad altri. Alcuni fattori che risultano arrecare disagio in generale sono l’abbagliamento, un eccessivo illuminamento alle spalle dell’osservatore, illuminazione eterogenea e livelli di luce troppo elevati. Essi si possono presentare anche solo per brevi periodi nell’arco della giornata e una stessa condizione più essere avvertita con disagio in un memento del giorno ma essere tollerata in un altro, poiché il comfort visivo si evolve dalla mattina alla sera seguendo il ritmo circadiano (Leclercq et al., 2008).

L’abbagliamento è il principale fenomeno di discomfort, causato da aree all’interno del campo visivo con eccessiva luminanza o elevato contrasto dovuto a presenza di sorgenti luminose (Marszal et al., 2011). Oltre all’abbagliamento solare noto ai più, vi sono due diversi tipi di abbagliamento: quello disabilitante e quello molesto. L’abbagliamento disabilitante non permette all’osservatore di vedere chiaramente alcuni oggetti nella scena, spesso è causato dalla riflessione dei raggi luminosi all’interno della cavità oculare e può essere accentuato dall’avanzare dell’età o da malattie quali la cataratta; esso non implica necessariamente la presenza di abbagliamento molesto, che si presenta quando i livelli di illuminamento sono troppo elevati e quindi fa riferimento alla soggettività del singolo (Reinhart and Wienold, 2011). L’abbagliamento disabilitante è più semplice da riscontrare, mentre i meccanismi psicologici o di percezione legati all’abbagliamento molesto sono ancora incerti, sebbene due metodi scientifici si stanno affermando per la valutazione di tale situazione di discomfort: l’indice unificato di abbagliamento UGR e il parametro VCP (Halonen et al., 2010).

Tenendo conto dei pro e dei contro legati alla presenza della luce naturale, vi sono occasioni in cui è preferibile o necessaria un'altra sorgente luminosa: la luce generata da energia elettrica. Anch'essa tuttavia ha sia benefici che aspetti negativi. La luce artificiale ci permette di svolgere attività in luoghi dove la luce naturale non arriva, o in condizioni di insufficiente illuminazione solare, permette di ridurre contrasti dovuti a eccessive zone d'ombra e con opportune caratteristiche ha anche scopo terapeutico. Tuttavia la luce da sorgenti artificiali ha uno spettro di emissione molto diverso dalla luce naturale e non fornisce i giusti stimoli generando risposte differenti da parte dell'organismo umano. Per esempio un'esposizione a sorgenti di luce blu, come i LED ormai utilizzati in gran parte dei dispositivi elettronici come schermi di televisori e computer, specie se in ore serali, è un grado di produrre uno sfasamento nel ritmo circadiano, ritardando l'orario in cui il corpo si prepara al sonno. Inoltre la luce elettrica ha la peculiarità di essere pressoché constante in intensità, privando l'utente della percezione del trascorrere del tempo durante la giornata. La luce artificiale può anche causare discomfort se soggetta al fenomeno dello sfarfallio, anche detto effetto flicker, causato dalla fluttuazione della luce emessa da una sorgente artificiale che può causare mal di testa, dolore oculare ed in generale una ridotta qualità visiva.

L'ottimizzazione nell'uso della luce naturale in ambienti all'interno di edifici non è solo da preferirsi per motivi di salute, ma anche economici. Infatti l'energia utilizzata per l'illuminazione di interni rappresenta il 20% del consumo di energia globale (IEA, 2010), e nella maggior parte dei casi tale percentuale potrebbe essere abbattuta perché utilizzata per illuminare ambienti non occupati ed illuminare interni più del necessario.

## *0.3 Prestazioni energetiche degli edifici*

Il fenomeno di surriscaldamento globale, causato da inquinamento e scorrette politiche comportamentali adottate dall'umanità negli scorsi secoli, rappresenta un problema di interesse globale, palesato da studiosi ed ambientalisti. I principali punti delle strategie elaborate per porre rimedio a tale fenomeno sono la riduzione di emissioni di $CO_2$, controllo dei consumi energetici e maggior uso di fonti di energia rinnovabili, le quali si prevede saranno le uniche utilizzate in futuro.

Gli edifici ad uso commerciale, e primi tra essi quelli per uffici, hanno un consumo energetico annuo molto elevato, che varia tra 100-1000 kWh/m$^2$ a (Dubois and Blomsterberg, 2011) a seconda della posizione geografica, uso e tipologia di dispositivi utilizzati, tecnologie costruttive, uso di sistemi HVAC, tipologia di apparecchi illuminanti e molti altri fattori. Edifici per uffici situati in Nord Europa hanno un fabbisogno energetico variabile tra 306-150 kWh/m$^2$ yr (Dubois and Blomsterberg, 2011), valori molto elevati, tuttavia alcuni studi rivelano che i moderni edifici ad uso ufficio hanno un potenziale di risparmio energetico molto elevato. La direttiva europea sul rendimento energetico degli edifici 2010/31/UE pone elevati standard richiesti in termini di prestazioni energetiche proprio per promuovere il risparmio energetico ed una progettazione orientata verso gli edifici ad energia zero.

Il consumo di energia elettrica per l'illuminazione di interni è uno dei settori con maggior potenziale in termini di risparmio energetico e riduzione nelle emissioni di anidride carbonica, sia per nuove costruzioni che per ristrutturazioni. Tuttavia ancora oggi non vi sono codici normativi e direttive per l'illuminamento di ambienti quando luce naturale ed artificiale sono contemporaneamente presenti (Bellia et al., 2011), le strategie progettuali si basano sull'esperienza e l'attenzione prestata a tale aspetto da parte dei progettisti.

L'uso della luce naturale mirato a contenere i consumi di energia elettrica risale al 1784 quando Benjamin Franklin (Aries and Newsham, 2008) istituì la cosiddetta ora legale, più accuratamente chiamata orario di risparmio della luce diurna (DST). Durante il XXI secolo i maggiori vantaggi derivanti dall'adozione dell'ora legale si sono registrati nel settore dell'edilizia residenziale e non in edifici per uffici, poiché soltanto quelli di recente costruzione hanno un sistema di illuminazione che adatta le emissioni al livello di luce naturale presente mentre la maggior parte di edifici nel settore terziario prevedono l'uso di luce artificiale per tutta la durata delle ore lavorative e ad intensità luminosa costante. Tuttavia l'orario di risparmio della luce diurna presenta pareri discordanti circa l'effettivo risparmio energetico ad essa legato: avere luce naturale durante le ore serale fa di certo risparmiare sui consumi elettrici per l'illuminazione ma la stessa quantità di energia o maggiore è necessaria per raffrescare gli ambienti in estate o riscaldarli durante le fredde mattine autunnali e primaverili. Queste sono in parte le ragioni per cui negli anni alcune nazioni hanno deciso di non adottare più o affatto la DST.

Da quando l'uso della luce artificiale per l'illuminazione di ambienti interi è diventato tecnologicamente ed economicamente possibile per i più, la gente ha cominciato a trascorrere sempre più tempo al chiuso, così dal 1973 al 2012 l'uso di energia elettrica per illuminazione è duplicato. Secondo numerosi scienziati (Ihm et al., 2009) un aumento nell'uso della luce naturale per l'illuminazione di interni può ridurre dal 30% al 70% i consumi energetici; tale risultato può essere ottenuto tramite sorgenti luminose più efficienti e sistemi di controllo a compensazione dei livelli di luce diurna. Le tre principali tipologie di sensori per il controllo dell'uso di energia elettrica per l'illuminazione sono: IDDS (Individual Daylight Dimming System) che regola il flusso luminoso emesso dalla sorgente in funzione della quantità di luce diurna presente nell'ambiente tramite un sensore presente dell'apparecchio illuminante; MDS (Movement Detection Switching) basato su un sensore di occupazione a reggi infrarossi che spegne o accende la luce artificiale quando rileva movimenti nell'ambiente; MDD (Movement Detection Dimming) anch'esso basato su un sensore di occupazione ad infrarossi ma riduce l'intensità luminosa emessa dalla sorgente anziché spegnere completamente la luce artificiale. I tre tipi di sensori per controllo dei consumi elettrici hanno efficienza maggiore in diverse configurazioni, ad esempio il MDS è più appropriato per uffici singoli mentre il MDD per uffici openspace. Tuttavia il controllo dei consumi energetici non deve mai ignorare l'aspetto legato al comfort visivo degli utenti e la loro approvazione nell'uso di sistemi di controllo automatico della luce artificiale, altrimenti le potenzialità del risparmio energetico si annullerebbero.

L'attenzione rivolta alla riduzione di emissioni nel settore delle costruzioni ha cominciato a crescere quando scienziati ed ambientalisti hanno individuato nelle errate attività umane la causa del surriscaldamento globale, cominciato verso la metà del XX secolo, che proseguirà per tutto il XXI secolo ed anche oltre pur adottando comportamenti volti a contenere i danni futuri. Nel 1990 l'Intergovernmental Panel on Climate Change (Gruppo intergovernativo di esperti sul cambiamento climatico, IPCC) pubblicò un'inchiesta riportando uno stimato aumento della temperature del nostro pianeta di circa 0.15-0.3°C per decade dal 1990 al 2005 e valutazioni a posteriori rivelano che tali proiezioni non erano del tutto sbagliate, essendosi verificato un aumento medio della temperatura di 0.2°C per decade. Secondo simulazioni ambientali anche se le emissioni di $CO_2$ fossero tenute costanti ai livelli dell'anno 2000 vi sarebbe un ulteriore innalzamento della temperatura globale per due decadi a causa del lento responso degli oceani. Numerose sono le conseguenze negative del surriscaldamento globale, pertanto politici di tutto il mondo hanno deciso di unire le forze e stipulare accordi per ridurre le emissioni di gas serra: nel giugno 1992 durante il Summit della Terra tenutosi a Rio de Janeiro i membri dell'ONU firmarono la Convenzione quadro delle Nazioni Unite sui cambiamenti climatici (UNFCCC); nel 1995 i membri della UNFCCC si incontrarono a Berlino per stilare le linee guida di un accordo conclusosi con la firma del Protocollo di Kyoto nel 1997, promulgato solo nel 2005. Con quest'ultimo accordo gli stati membri si impegnarono a ridurre le emissioni di gas serra in percentuale differente a seconda dello sviluppo economico della nazione al tempo della firma, in particolare i paesi sottosviluppati furono esonerati dal raggiungere i risultati ambizioni fissati dal protocollo. La scadenza del trattato internazionale in materia ambientale era fissata per dicembre 2012, pertanto nel 2009 la direttiva europea 2009/29/EC fu promulgata con periodo di validità dal 2013 al 2020 e con il fine di far raggiungere a tutti gli stati membri i seguenti obiettivi:

- Ridurre del 20% le emissioni di gas serra da parte degli stati della comunità europea rispetto ai livelli del 1990;
- Raggiungere la quota di 20 % di energia prodotta da fonti rinnovabili misurata sui consumi finali di ogni stato europeo;
- Ridurre del 20% la domanda energetica.

La pianificazione di un programma per il contenimento del surriscaldamento globale da parte dei membri dell'Unione Europea va già oltre il 2020: gli stati membri hanno l'obiettivo di ridurre le emissioni del 40% rispetto ai livelli del 1990 per il 2030 e ridurre l'emissione di gas serra in Europa del 80-90% per il 2050.

Le strategie su cui si basano tali obiettivi prevedono un miglior uso delle risorse nel settore delle costruzioni, con la direttiva europea 2010/31/EU sugli Edifici ad Energia quasi Zero (NZEBs) (IEA, 2013) il sistema edificio è passato da produrre gas serra ed inquinamento a generare energia, condizione che è possibile raggiungere solo tramite una progettazione integrale che unisca tutte le competenze sin dai primi stadi della progettazione.

### 0.3.1 Soluzioni tecnologiche dell'involucro esterno

L'uso della luce naturale in ambienti chiusi va progettato per realizzare il perfetto equilibrio tra prestazioni illuminotecniche ed energetiche e molteplici sono le soluzioni tecnologiche che permettono di illuminare naturalmente uno spazio. Prima tra tutte vi è la finestra, che ad oggi è molto più di una semplice superficie vetrata dell'involucro esterno di un edificio. Le soluzioni più moderne mirano a migliorare le prestazioni termiche degli infissi, spesso riducendo quelle visive; a seconda dei requisiti fissati dal tipo di ambiente che si sta progettando, il vetro utilizzato può avere diverse caratteristiche: vi è il vetro piano (il più semplice ed usato prima dell'imposizione di elevati standard energetici), il doppio vetro o triplo vetro (costituito da due/tre lastre di vetro separate da una camera d'aria contenente un gas inerte per un maggiore isolamento termico), vetro riflettente (nelle ore diurne ha effetto specchiante e riflette la luce del sole garantendo grande intimità e comfort visivo), vetro anti-riflettente (l'opposto del precedente, permette grande chiarezza e trasparenza), vetro con trattamento basso emissivo (un processo sofisticato che permette la formazione sulla superficie delle lastre di depositi o ossidi di metallo che consentono di sfruttare al meglio la luce naturale), il vetro vuoto (basato sulla stessa tecnologia del triplo vetro ma con in vuoto nell'intercapedine), finestre con isolamento in aerogel (evita il movimento di aria nell'intercapedine permettendo allo stesso tempo il passaggio dei raggi luminosi), smart windows (parte multifunzionale della facciata in grado di adattare le proprie caratteristiche in risposta ai cambiamenti climatici e alle preferenze dell'utente).

Altri sistemi di illuminazione permettono di portare la luce naturale in ambienti privi di finestre, essi sono: il sistema di illuminazione diurna tubolare (TDD, un tubo con superficie interna di riflettanza 99,5% che capta la luce solare e con appositi diffusori la incanala portandola in qualsiasi ambiente), sistemi verticali (simili agli TDD ma con un collettore solare che segue il percorso del sole nel cielo), sistemi orizzontali (utilizzano un sistema di lenti per captare la luce diurna), sistemi a fibra ottica.

Nell'ambito della luce naturale anche i sistemi schermati ricoprono un ruolo importante, sia a fini termici che di comfort visivo. Essi possono essere esterni o interni, fissi o mobili, regolabili o retrattili.

### 0.3.2 Edificio ad energia zero

Solo nel 2010 l'idea di un edificio ad energia zero era considerata una possibilità per un futuro assai lontano, oggi, cinque anni dopo, essa risulta essere la migliore soluzione per la riduzione di emissioni di $CO_2$ e di consumi energetici nel settore delle costruzioni. Gli edifici ad energia zero, conosciuti con l'acronimo ZEB, hanno molteplici definizioni a seconda del settore in cui il singolo edificio risulta avere emissioni o consumi nulli. Quattro definizioni sono possibili in quest'ottica: sito ZEB (in un anno consuma tanta energia quanta ne produce grazie a pannelli solari, collettori solari, energia del vento), risorse ZEB (in un anno consuma tanta energia quanta ne produce in termini di energia primaria), emissioni ZEB (l'edificio produce come minimo la stessa quantità di energia rinnovabile priva di emissioni quanta energia che genera emissioni consuma) e costi ZEB (in un anno il proprietario dell'edificio riceve un utile in termini di denaro per l'energia esportata nella rete che è pari alla cifra spesa per ricevere energia dalla rete stessa).

Edifici ad elevata efficienza energetica cono statti realizzati sin dai primi anni del XXI secolo, ma solo recentemente hanno raggiunto l'obiettivo di produrre più energia di quanta ne consumino. Gli Stati Uniti d'America con l'Energy and Security Act nel 2007 (EISA, 2007) prescrivono la realizzazione edifici ad energia zero per tutti le costruzioni nel settore commerciale entro il 2030. L'unione Europea, con l'articolo 9 della EPBD recast richiede agli stati membri che tutti gli edifici di nuova costruzione occupati da autorità pubbliche siano Nearly Zero Energy Buildings entro la fine del 2018, tuttavia la definizione fornita dalla norma per un edificio ad energia zero è altamente generica e lascia spazio a interpretazioni su scala nazionale.

### 0.3.3 Certificazioni energetiche

Tale mancanza di linee comuni per la progettazione di edifici ad energia zero ha portato alla nascita di molteplici organismi certificatori nelle diverse nazioni, ciascuno con diversi requisiti di prestazioni energetiche. I maggiori metodi di certificazione energetica sono: BBC-EFFINERGIE (molto attivo in Francia, richiede che la domanda energetica totale in termini di energia primaria non superi i 50 $kWh/m^2$ a), BREEAM (ha carattere internazionale, nato in Inghilterra ha allargato il territorio di competenza con sottosezioni a livello nazionale), DGNB (nato in Germani, promuove edifici sostenibili ed economicamente efficienti, il comitato conta oltre 1200 professionisti tra architetti, ingegneri, scienziati ed esperti del mondo delle costruzioni), klimaaktiv (organismo certificatore austriaco, basato su un sistema a punteggio che attribuisce ad una costruzione da quattro a sei stelle), LEED (organismo certificatore americano, è uno dei primi a considerare parametri illuminotecnici dinamici nell'attribuzione del punteggio di certificazione), Passivhaus (elaborato dall'istituto indipendente di ricerca Passive House Institute è il metodo di certificazione più influente a livello internazionale).

## *0.4 Metodologia*

L'analisi delle prestazioni illuminotecniche dell'Edificio ad Energia Zero utilizzato come caso studio sono state condotte parallelamente con due metodi: il metodo scientifico di misurazioni in sito e simulazioni tramite appositi software, al fine di operare un confronto tra i risultati ottenuti.

La misurazioni sono state effettuate seguendo il protocollo di monitoraggio riconosciuto a livello internazionale e accreditato dall'Agenzia Internazionale dell'Energia (IEA), un'organizzazione autonoma fondata nel 1974 per generare ed incoraggiare il dialogo tra le nazioni sul tema energetico. Nel 1977 la IEA ha istituito un programma chiamato "The Solar Heating and Cooling Programme" al fine di raccogliere le conoscenze di esperti da tutta Europa e promuoverne la collaborazione attraverso lo sviluppo di progetti di ricerca altamente specifici all'interno dell'ampio mondo del riscaldamento solare e raffrescamento di ambienti interni. I progetti previsti dal programma sono chiamati Tasks e al momento ve ne sono 10 attivi; uno tra questi, la Task 50, riguarda Soluzioni di illuminamento innovative in edifici ristrutturati e all'interno della Subtask D presenta un protocollo di monitoraggio che permette di misurare parametri illuminotecnici statici grazie a grandezze fotometriche, comfort dell'utente e consumi energetici. Il caso studio è analizzato unicamente in relazione agli aspetti di illuminamento degli ambienti e soddisfazione dell'utente, mentre l'efficienza energetica ed i costi sono lasciati per indagini future.

Il protocollo di monitoraggio prevede due livelli di accuratezza nel condurre le misure, detti essenziale e completo, la cui scelta è basata sulla tipologia e quantità di strumenti a disposizione dell'operatore, dimensione dell'ambiente da analizzare e numero di utenti che è possibile intervistare. Sulla base delle caratteristiche del caso studio è stato possibile condurre un'analisi di tipo essenziale, che prevede la misurazione di parametri illuminotecnici nelle due diverse condizioni metereologiche di cielo coperto e sereno, inoltre la procedura deve essere esplicata entro un mese prima o dopo uno dei due equinozi, infine alcune grandezze devono essere misurate in totale assenza di luce diurna così da individuare le caratteristiche del sistema di illuminazione artificiale.

I parametri analizzati durante la procedura di monitoraggio sono raggruppati in otto categorie: distribuzione della luce naturale (riflettanza delle superfici, trasmittanza della luce visibile delle finestre), illuminamento, fattore medio di luce diurna, abbagliamento, direzionalità della luce naturale, colore delle superfici nell'ambiente analizzato, sfarfallio, vista e soddisfazione dell'utente.

Circa le simulazioni illuminotecniche, esse sono state effettuate tramite il software Relux, che permette di calcolare il fattore medio di luce diurna, la distribuzione di illuminamento e luminanza sia in condizioni di luce naturale che artificiale; il software Radiance è stato utilizzato per l'analisi dei parametri di luminanza rilevabili da fotografie scattate con un obiettivo fish-eye.

## *0.5 Il caso studio: Powerhouse Kjørbo*

Powerhouse è una collaborazione di aziende aventi l'obiettivo comune di costruire un edificio ad energia zero in aree aventi condizioni climatiche ardue come quelle presenti nei Paesi Scandinavi. Essa è stata istituita originariamente nel 2011 da Entra Eiendom, una delle maggiori compagnie immobiliari norvegesi, la compagnia di costruzioni e sviluppo progettuale Skanska, lo studio d'architettura Snøhetta, l'organizzazione ambientale ZERO e l'azienda specializzata nella lavorazione dell'alluminio Hydro. La collaborazione è cresciuta nel 2013 grazie all'azienda di profili in alluminio Sapa e l'azienda di consulenza Asplan Viak.

Partendo dai requisiti fissati dal programma 20-20-20, Powerhouse mira ad una collaborazione tra tutte le parti coinvolte nel processo edilizio, dal committente all'impresa di costruzione, dai progettisti ai locatari poiché ognuno e chiunque può essere parte della soluzione finale. Lo statuto dell'associazione definisce una Powerhouse come un edificio che deve produrre in situ una quantità di energia rinnovabile almeno pari a quella necessaria durante la fase di costruzione, produzione di materiali, ristrutturazione, demolizione e vita in opera. Inoltre l'edificio deve soddisfare i requisiti di casa passiva fissati dalla norma norvegese NS 3701 [1], riportati nelle tabelle 6.1a e 6.1b.

Al momento la collaborazione ha due progetti all'attivo:

- Powerhouse Brattørkiaia: il primo edificio di nuova costruzione realizzato dal programma Powerhouse, sito a Trondheim in Norvegia. La fase progettuale ha avuto inizio nel 2012, è stato approvato dal comune alla fine del 2014 e la parte operativa avrà luogo nella seconda metà del 2015.
- Powerhouse Kjørbo: il primo progetto powerhouse ad essere completato ed in primo edificio in Norvegia a ricevere l'attestato di ECCELLENTE da parte della BREEAM-NOR, il più elevato livello nella certificazione. Esso è utilizzato come caso studio nel presente documento di tesi.

### 0.5.1 Il contesto urbano

Il progetto Powerhouse Kjørbo consiste nella ristrutturazione di due edifici all'interno di un parco di dieci immobili ad uso ufficio, situati a Sandvika, in centro amministrativo del comune di Bærum, a 15 km ad ovest di Oslo. Bærum si trova a circa 60 gradi di latitudine nord, con una temperatura media annuale di 5,9°C en una irradiazione orizzontale media annuale di circa 110 W/m².

Il complesso di edifici si trova presso la riva del fiume Snadvikselva, con vista sul quinto fiordo più grande della Norvegia. Tali elementi fanno sì che la vista di cui si può godere dall'interno dei vari edifici sia piacevole, nonostante la vicinanza alla strada Europea E18 ed al più grande centro commerciale norvegese.

Otto su dieci edifici, nel progetto indicate come blocchi, hanno forma di parallelepipedo a pianta quadrata ma dagli angoli smussati, con altezza variabile tra i 3 e 4 piani fuori terra. Tutti ed otto i blocchi hanno la normale alla facciata nord ruotata di 35° rispetto al nord geografico, come mostrato in figura 6.1.

### 0.5.2 Il processo costruttivo

Il complesso residenziale è stato costruito negli anni 1980 e i vari blocchi furono acquistati da diversi proprietari. Con riferimento alla numerazione in figura 6.1, I blocchi da 1 a 6 sono di proprietà dei Entra Eiendom e comprendono cinque edifici per uffici ed un centro servizi che ospita una mensa, sale riunioni e la reception. I blocchi 2 e 3 sono correntemente affittati dall'azienda leader in project management Technip, mentre i blocchi 4 e 5 sono affittati dall'agenzia di consulenza Asplan Viak. I blocchi da 7 a 10 sono di proprietà del comune e occupati dalla polizia.

Il progetto Powerhouse Kjørbo consiste nella ristrutturazione dei blocchi 4 e 5 con il fine di ottenere la certificazione BREEAM-NOR Eccellente, trasformando i due edifici ad energia positiva. Dopo la sottomissione del progetto al comune di Bærum nel 2012, il permesso di ristrutturare i due blocchi fu accordato con particolari specifiche da rispettare: gli edifici devono continuare ad avere un rivestimento esterno scuro e i corpi scala devono restare bianchi, così da avere continuità con gli altri elementi del complesso per uffici. La fase operativa di costruzione ha avuto inizio nel marzo 2013 e si è conclusa circa un anno dopo, a febbraio 2014.

### 0.5.3 Caratteristiche costruttive

I blocchi 4 e 5, oggetto della ristrutturazione, hanno pianta quadrata di area 830 $m^2$ circa e rispettivamente quattro e tre piani fuori terra, pertanto l'area complessiva oggetto di intervento è di circa 5 180 $m^2$. Con una capacità di 240 persone, il progetto prevede circa 22 $m^2$ di superficie calpestabile per persona.

I due blocchi realizzati negli anni 1980, prima del progetto Powerhouse, avevano pianta aperta su tutti i piani, con un numero esiguo di stanze adibite ad uso privato in favore di grandi openspace come mostrato in figura 6.3 e nell'appendice F. I muri esterni avevano rivestimento in vetro oscurato, che dopo 30 anni di vita in opera necessitavano di un rinnovo. La struttura portante a telaio è composta da sette pilastri circolari posti su due lati di un fittizio quadrato costituente il core dell'edificio e nove pilastri a sezione rettangolare per ciascun lato esterno della pianta. Assieme ai solai in calcestruzzo, tutta la parte strutturale è stata mantenuta durante il ripristino dell'edificio, consentendo di contenere l'impatto ambientale delle operazioni.

Circa l'aspetto energetico, il sistema di riscaldamento era di tipo centralizzato mentre quello di raffrescamento era basato su una centrale di raffreddamento collegata a condotti che raggiungevano vari punti del soffitto ad ogni piano praticando la ventilazione meccanica. Tali soluzioni contribuivano ad un uso di energia rinnovabile di circa 240 kWh/$m^2$ ripartito tra elettricità (~ 125 kWh/$m^2$), riscaldamento centralizzato (~ 75 kWh/$m^2$) e raffrescamento (~40 kWh/$m^2$) (Førland-Larsen, 2012).

Gli interni dell'edificio apparivano essere alquanto cupi a causa del basso controsoffitto con apparecchi illuminanti incassati, vetro oscurato in cacciata e del rivestimento tessile a pavimento di color marrone. Il confronto con gli interni dell'edificio dopo la ristrutturazione è presentato in figura 6.2.

Al fine di rispettare le prescrizioni del comune circa la facciata dei blocchi 4 e 5, il rivestimento esterno degli edifici rinnovati è costituito da perline di legno carbonizzato, molto sostenibile in quanto derivante da pioppi locali. Le finestre sono state sostituite da infissi a triplo vetro e camera ad Argon, di dimensioni leggermente maggiori rispetto a quelle degli edifici originali così da migliorare le prestazioni illuminotecniche da luce diurna. Le prestazioni termiche dell'involucro esterno sono state migliorate grazie ad una migliore strategia di isolamento termico incentrato sul ridurre al minimo i ponti termici ed incrementare di 200 mm lo spessore dello stato isolante nei punti in cui i solai incontrano la facciata. Tali solai sono utilizzati come massa termica poiché esposti a soffitto, smorzando le variazioni di temperatura durante il corso della giornata.

La pianta è stata completamente riorganizzata, ad ogni piano metà dell'area in pianta è adibita ad uffici privati e la restante metà ad openspace; la parte centrale dell'edificio è il posto per servizi igienici e locali tecnici, che non necessitano di luce naturale in quanto gli utenti vi trascorrono un periodo di tempo molto limitato. Le porte in vetro e la partizioni tra gli uffici ed il corridoio sono realizzati in vetro riciclato, utilizzato in facciata nei vecchi edifici. L'assenza di controsoffitti permette di avere un'altezza degli ambienti maggiore rispetto agli edifici originari, sebbene l'altezza di interpiano sia la stessa; questo contribuisce ad avere ambienti più luminosi se unito a finestre di dimensioni maggiori e superfici interne di colore chiaro.

Il sistema di riscaldamento è basato su due pompe di calore geotermiche, una per il riscaldamento di ambienti e l'altra per l'acqua calda sanitaria. Il sistema di climatizzazione prevede ventilazione a dislocamento a bassissima velocità, con una riduzione nei consumi di energia ad 1/8 rispetto ai sistemi convenzionali. I pannelli solari posti sul tetto permettono la produzione di 200 000 kWh di cui solo 145 000 kWh all'anno vengono utilizzati per ventilazione, illuminazione, riscaldamento e raffrescamento d'interni.

Il sistema di illuminazione è basato sulla compensazione della luce diurna, grazie ad un sensore incorporato nell'apparecchio illuminante, che misura il livello di illuminamento sul piano di lavoro oltre che la presenza di utenti nell'ambiente di competenza, modificando l'intensità luminosa emessa dalle lampade fluorescenti T5 al fine di avere minimo 300 lux sulla scrivania. Negli uffici privati vi è un solo apparecchio illuminante ed esso è provvisto di sensore, le sorgenti luminose negli openspace invece sono controllate da un sensore a gruppi di 4-5 apparecchi illuminanti. Il livello di illuminazione di ambienti interni è inoltre controllato dai sistemi schermanti costituiti da tende avvolgibili in tessuto non tessuto di colore scuro, regolabili sia manualmente tramite interruttori a muro che automaticamente da sensori posti sul lato esterno delle facciate nord-ovest, sud-ovest e sud-est. Quando tali sensori rilevano una radiazione solare troppo elevata il dispositivo schermante entra in funzione al fine di assicurare non più di 500 lux alla postazione di lavoro e prossime vicinanze.

### 0.5.4 L'analisi

L'analisi dei parametri illuminotecnici statici è stata condotta per sei stanze ad uso ufficio privato o sale riunioni, poiché più correttamente gestibili da un solo operatore in fase di misurazione e di minor intralcio per lo svolgimento delle attività quotidiane in azienda. La scelta delle stanze da analizzare si basa su uno studio illuminotecnico effettuato da esperti in fase di progettazione, mirando ad analizzare le condizioni di illuminamento più sfavorevoli in termini di raggiungimento dei requisiti necessari per la certificazione BREEAM-NOR.

Tutte le stanze analizzate hanno uguale geometria ad eccezione di una stanza al quarto piano del blocco 4. Le dimensioni in pianta sono 2,375 m x 3,613 m e l'altezza dell'ambiente è 3,3 m. lungo entrambi i lati corti vi sono superfici vetrate: la porta di ingresso alla stanza e il muro stesso, che danno sul corridoio, sono in vetro oscurato mentre nel muro esterno vi è la finestra, più bassa che larga. Le partizioni interne tra gli uffici sono realizzati con due strati di lastre in cartongesso montate su una struttura di supporto, per uno spessore totale di 125 mm mentre i muri esterni sono spessi 424 mm e composti da pannelli in legno rivestiti internamente da lastre in cartongesso ed esternamente da perline di pioppo bruciato. I quattro muri interni sono di colore bianco, così come il soffitto, mentre il pavimento è rivestito da un tappeto a fantasia geometrica, che risulta essere abbastanza scuro.

Le finestre hanno il telaio fisso e mobile di colore bianco verso l'interno e scuro verso l'esterno, esse hanno due ante orizzontali e solo quella inferiore, di dimensioni minori (2,375 m x 3,613 m) è apribile; la parte superiore ha dimensioni 2,8 m x 0,825, come mostrato in figura 6.11.

Gli arredi sono molto semplici e comuni a quasi tutte le stanze: quattro stanze su sei hanno una scrivania grigia al altezza regolabile, sedia da ufficio di colore nero, una lampada da scrivania a led bianca. Negli uffici privati vi è una libreria con ante bianca, di altezza 1.1 m, tutti gli uffici hanno un apparecchio illuminante mentre le sale riunioni ne hanno due.

#### 0.5.4.1 Misurazioni

Le misurazioni sono state condotte durante i giorni 13 (condizione di cielo sereno) e 14 (completamente coperto) Aprile 2015 unicamente negli edifici ristrutturati a causa di mancanza di permessi da parte delle aziende affittuarie locate nei vecchi edifici. È stato possibile misurare a 0,8 m dal pavimento la distribuzione di illuminanza in ciascuna stanza, il fattore medio di luce diurna ai vertici di una griglia appositamente individuata per ciascun ambiente come mostrato in figura 6.8, la luminanza delle superfici interne, presenza di abbagliamento o riflessi su apparecchi videoterminali, valutazione della qualità della vista. Per la rilevazione di grandezze fotometriche, data la loro elevata variabilità in funzione della radiazione solare da cui le superfici sono raggiunte, è stato necessario ripetere le misure come minimo tre volte e riportare i valori ottenuti come media delle misurazioni. Alcuni valori come la trasmittanza luminosa degli infissi o i colori delle superfici sono stati misurati per una sola delle sei stanze e poi riportati per tutte le altre poiché indipendenti dallo specifico ambiente di misura.

#### 0.5.4.2 Simulazioni con Relux

Durante la costruzione del modello digitale si sono rese necessarie alcune approssimazioni quali: ignorare gli effetti della riflessione della luce solare sulla superficie del fiume che circonda il complesso di edifici poiché l'indice di riflessione è molto variabile in base alle condizioni metereologiche, profondità del letto del fiume e condizioni del letto stesso; assumere la riflettanza del prato attorno agli edifici pari al valore di riferimento del 15%; modellare solo in parte il contesto per simulare elementi schermanti, attribuendo riflettanza pari a 15% per la facciata esterna e 20% per corridoi vetrati; circa gli edifici prima della ristrutturazione la costruzione del modello, specialmente per i valori del fattore di riflessione delle superfici interne, si è basata su stime elaborate a partire dalla foto in figura 6.2, così come la trasmittanza del vetro oscurato in facciata.

#### 0.5.4.3 Intervista agli utenti

A causa della mancata disponibilità delle aziende locatarie dei blocchi non rinnovati non è stato possibile condurre un'analisi del comfort ambientale percepito dagli utenti degli edifici 1, 2 e 3, mentre riguardo i due blocchi del progetto Powerhouse è stato possibile raccogliere impressioni generali sulle condizioni di illuminazione naturale ed artificiale, i cui risultati sono presentati in seguito.

### 0.5.5 I risultati

I risultati dello studio sono presentati come confronto tra le caratteristiche illuminotecniche degli ambienti prima e dopo la ristrutturazione, tra le misurazioni e le simulazioni effettuate tramite software dedicati per i blocchi 4 e 5 ed infine in termini di comfort ambientale da parte degli impiegati dell'azienda Asplan Viak, affittuaria dei locali.

#### 0.5.5.1 Confronto tra simulazioni digitali

In seguito a cambiamenti operati nella geometria delle superfici trasparenti e dei valori di riflettanza delle superfici opache, il fattore medio di luce diurna presenta valori differenti tra i vecchi ed i nuovi edifici: in riferimento alla tabella 6.12 il fattore medio di luce diurna è maggiore negli edifici rinnovati ed in generale la condizione di illuminazione risulta essere più uniforme, con un $FLD_{max}$ minore ed un valore minimo più elevato. Tale miglioramento nei valori di FLD è dovuto a molteplici fattori, alcuni dei quali sono elevata riflettanza delle pareti, maggiore rapporto tra superficie finestrata e calpestabile (40/60) per ciascun ufficio e ridotta profondità della stanza.

#### 0.5.5.2 Confronto tra valori misurati e calcolati

I parametri che possono essere studiati sia da misure in sito che tramite modello digitale sono il fattore medio di luce diurna, la distribuzione dei valori di illuminamento su un piano posto a 0,8 m di altezza dal piano di calpestio dovuto a luce diurna ed artificiale in modo distinto. Inoltre tramite immagini HDR della stanza è stato possibile verificare l'affidabilità del programma Radiance per il rilevamento dei valori di luminanza tramite confronto con valori misurati dall'operatore tramite un misuratore di luminanza.

- Fattore medio di luce diurna

  In generale si può osservare, con riferimento alle figure 6.20 e 6.21, che vi è sempre una certa differenza tra i valori calcolati e misurati sul luogo. L'analisi è presentata secondo due diverse condizioni: l'orientamento della superficie finestrata e la tipologie di elementi schermanti al di fuori di essa. Se in figura 6.20 non è possibile trovare una regola che descriva la variabilità dei risultati ottenuti poiché presentata in termini di esposizione geografica, una spiegazione può essere individuata in relazione al contesto urbano in cui si trovano le stanze analizzate: partendo dal presupposto che le condizioni interne dei vari ambienti sono identiche per geometria e tipologia di arredamento, i valori calcolati sono maggiori dei misurati per le stanze R4102 e R5114 le cui finestre si affaccino su un corridoio vetrato posto a distanza molto ravvicinata; al contrario per le stanze R4209, R5206 e R4112 i valori calcolati sono minori di quelli misurati poiché si affacciano su spazi aperti o hanno elementi schermanti opachi. Si può supporre che i due risultati siano dovuti ad incertezze di calcolo del software quando si ha a che fare con superfici trasparenti ed inter-riflessioni. È comprensibile che i valori di FLD non siano regolati dall'esposizione della superficie finestrata poiché per definizione il fattore medio di luce diurna è indipendente dalla posizione geografica poiché il cielo completamente coperto è rotazionalmente simmetrico rispetto all'asse verticale (Mardaljevic, 2008).

  Conducendo un'analisi sull'affidabilità dei software di calcolo illuminotecnico e delle misurazioni in sito, l'errore relativo commesso è importante oggetto d'indagine. Con riferimento alla figura 6.22, l'errore commesso dalle simulazioni digitali nella valutazione del valore massimo di fattore di luce diurna risulta essere abbastanza elevato ed inaccettabile a fini scientifici, essendo del 22,55% in valor medio. L'errore relativo del fattore di luce diurna minimo per ogni stanza analizzata è ben più grande, con un valor medio di 54,97% e quindi inaccettabile, tuttavia ciò che interessa maggiormente in fase di progettazione è il fattore medio di luce diurna, che risulta avere un errore relativo del 11,59% e quindi del tutto accettabile, poiché tiene conto delle approssimazioni effettuate nella modellazione dell'ambiente ma anche degli errori sistematici ed accidentali derivanti dalla procedura di misurazione.

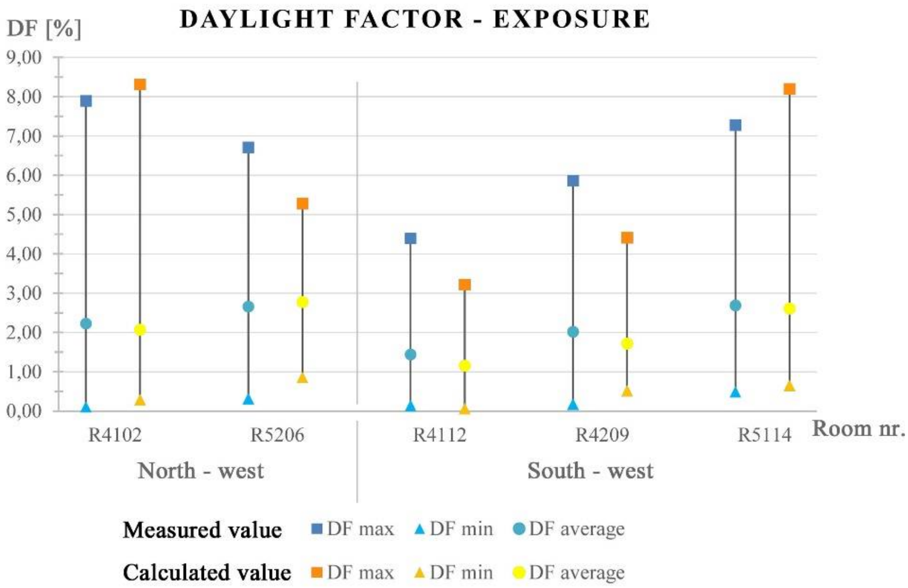



**Figura 6.20** Confronto tra i valori di fattore di luce diurna calcolati e misurati per ciascuna stanza analizzata, presentati in termini di esposizione della superfice vetrata esterna.

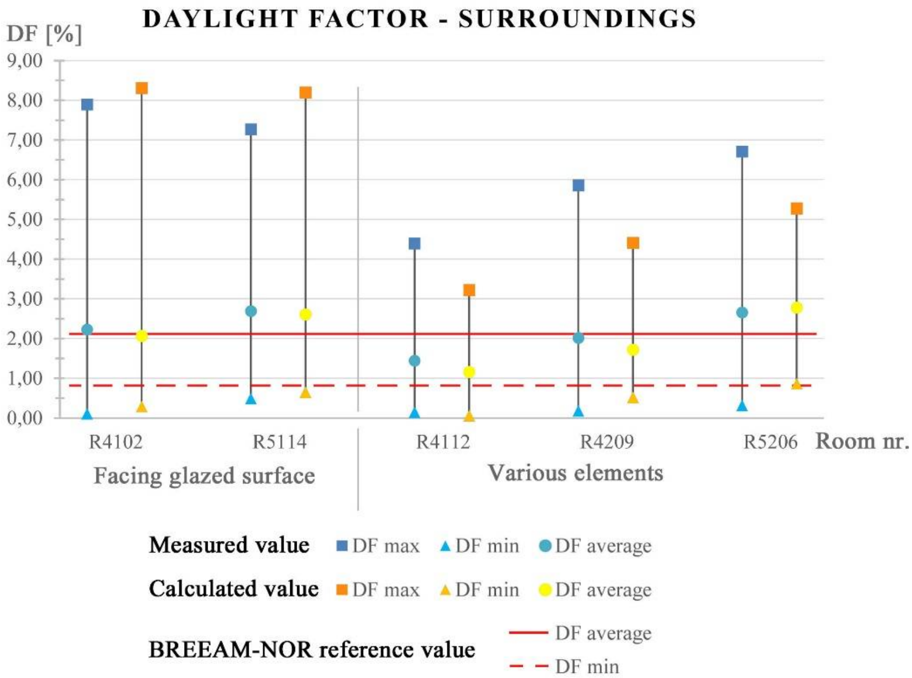



**Figura 6.21** Confronto tra i valori di fattore di luce diurna calcolati e misurati per ciascuna stanza analizzata, presentati in termini di tipologia di elementi schermanti esterni.

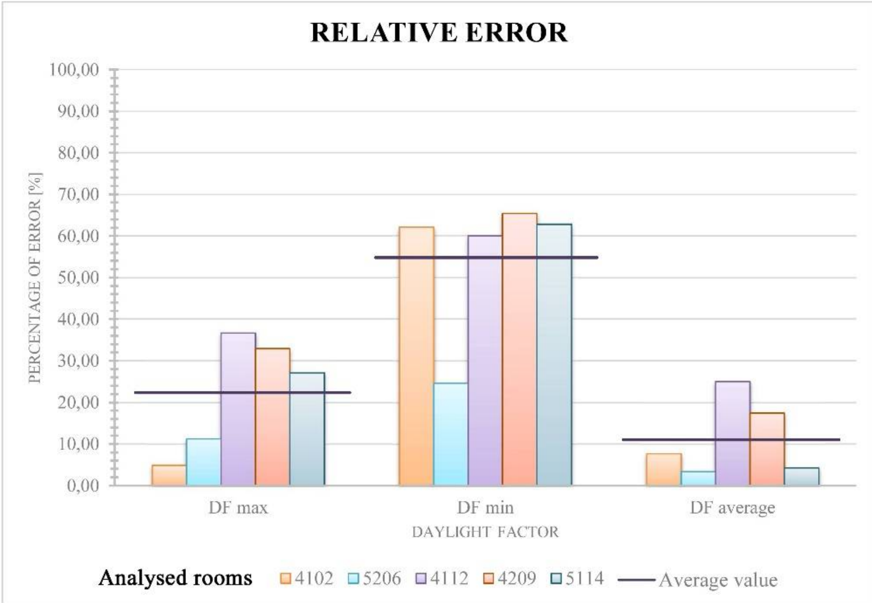



**Figura 6.22** Errore relativo per ciascuna stanza analizzata, per ciascuna categoria di fattore medio di luce diurna.

- Distribuzione dei valori di illuminamento da luce diurna

  Il confronto tra i valori misurati e calcolati nei punti dell'ipotetica griglia mostrata in figura 6.8 in termini di illuminamento riporta una maggiore uniformità rispetto al caso del fattore medio di luce diurna, tuttavia non può essere effettuato un confronto puntuale tra le varie stanze in quanto le misurazioni sono state svolte in momenti diversi della giornata e quindi i valori misurati sono altamente variabili da caso a caso.

- Distribuzione dei valori di illuminamento da luce artificiale

  Al fine di verificare l'affidabilità delle simulazioni digitali e delle misurazioni manuali la distribuzione dell'illuminamento è stata analizzata anche interini di luce artificiale. Tutte le stanze analizzate hanno uguale geometria, eccetto per la R4411, ma arredi diversi e numero di apparecchi illuminanti variabile. Come presentato in figura 6.24 la distribuzione di E sul piano orizzontale è simile per le stanze R4102 e R4112, poiché adibite a sale riunioni e quindi aventi due apparecchi illuminanti: l'illuminamento risulta molto uniforme attorno al valore di 300 lux. Tuttavia le due stanze hanno arre di differenti e questo comporta leggere differenze dei valori di illuminamento.

  Le stanze R4209, R5114 e R5206 hanno tutte un solo apparecchio illuminante, pertanto la distribuzione di illuminamento è differente dalle precedenti e l'area di illuminamento 300 lux è molto più contenuta. Inoltre la stanza R5206 ha un grande tavolo scuro posto al centro della superficie calpestabile, pertanto i valori di illuminamento sono ridotti in generale.

  La stanza R4411 ha geometria diversa da tutte le altre e tre apparecchi illuminanti, pertanto appare essere la più luminosa.

  I valori ottenuti dalle simulazioni digitali risultano essere consistenti con le misurazioni, confermando la reciproca affidabilità dei valori quando si tratta di studi legati a sorgenti di luce artificiale, ma non riguardo alla luce diurna, i cui effetti sono molto difficile da modella re e misurare.

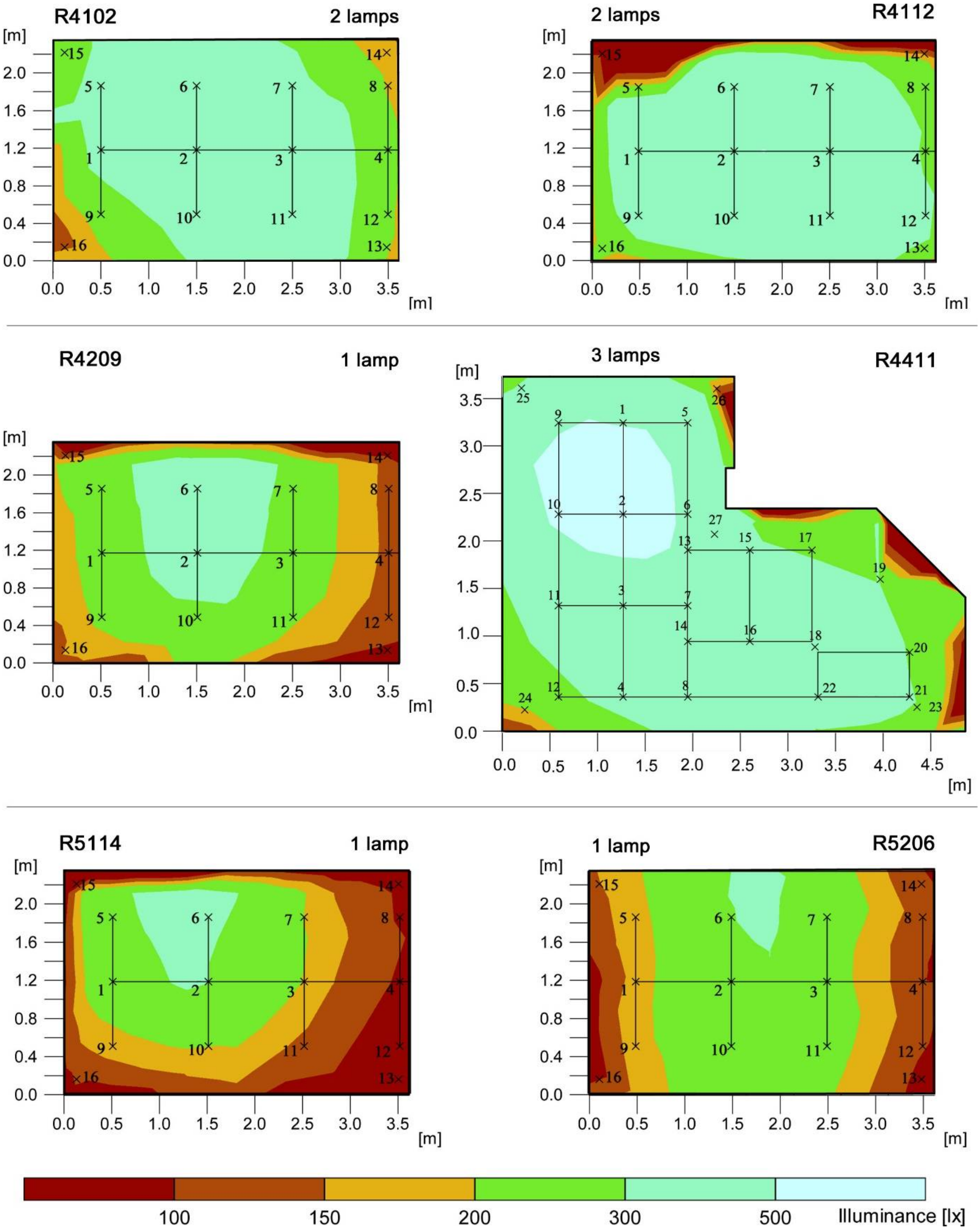



**Figura 6.24** Distribuzione dei valori di illuminamento su un piano a 0,8 m dal pavimento, dovuti a sorgenti di luce artificiali, prodotta tramite simulazioni illuminotecniche digitali.

- Confronto dei valori di luminanza

Con riferimento alla figura 6.15 i valori di luminanza misurati quando la foto analizzata è stata scattata sono stati misurati e risultano essere abbastanza diversi da quelli calcolabili tramite il software Radiance. In particolare l'errore commesso è maggiore per superfici chiare piuttosto che in zone d'ombra.

0.5.5.3 Confronto con requisiti da certificazione BREEAM-NOR

I risultati dell'analisi condotta sono stati confrontati con i valori richiesti dalla sezione 5.0 del manuale BREEAM-NOR per la certificazione energetica con riferimento al comfort visivo.

- Il valore di fattore medio di luce diurna richiesto per un edificio situato ad una latitudine compresa tra o 55° e 60°, misurati ad un'altezza di 0,8 m dal piano di calpestio deve essere di 2,1% per almeno l'80% degli ambienti interni per poter guadagnare un punto nella certificazione. Inoltre se $FLD_{average} > 3{,}15$ % un'ulteriore punto viene guadagnato per raggiungere il livello esemplare. Con riferimento all'analisi condotta in fase progettuale, tutte le stanza analizzate dovrebbero raggiungere il valore minimo per il livello esemplare eccetto l'ufficio R4112, tuttavia né la simulazioni né la misure effettuate confermano tali previsioni.
- La condizione richiesta per il minimo valore di FLD in un edificio situato ad una latitudine compresa tra o 55° e 60°, misurati ad un'altezza di 0,8 m dal piano di calpestio deve essere di 0,84% per almeno l'80% degli ambienti interni per poter guadagnare un punto nella certificazione. Inoltre se $FLD_{min} > 2{,}26$ % un'ulteriore punto viene guadagnato per raggiungere il livello esemplare. Come si può notare dalla tabella 6.20 nessuna delle stanze analizzate soddisfa tale requisito, sia in termini di valori misurati che calcolati.
- Nella sezione 5.0 Salute e benessere del manuale tecnico BREEAM-NOR (NGBC, 2012), si richiede che il valore minimo di FLD segnalato precedentemente sia soddisfatto unitamente alla condizione

$$\frac{d}{w}+\frac{d}{HW}<\frac{2}{\left(1-RB\right)} \tag{4.1}$$

  Che dipende in gran parte dalle caratteristiche geometriche dell'ambiente analizzato essendo d la profondità della stanza, w la larghezza in pianta, HW l'altezza della parte superiore della superficie finestrata misurata dal piano di calpestio e RB il valore medio di riflettanza delle pareti nella metà posteriore dell'ambiente. Pertanto tale condizione può essere calcolata per un ufficio e considerate valida per tutti I restanti.

  Per la stanza R4209:

  d = 3613 mm

  w = 2375 mm

  HW = 2200 mm

  RB = 0.4372

  Si ottiene la condizione 3,16 < 3,54, pertanto il requisite è rispettato ma non lo è quello relativo al valore minimo del fattore di luce diurna.
- In alternativa alle ultime due richieste, si può fare riferimento al fattore si uniformità ($U_o$) che deve essere maggiore di 0,4, tuttavia come mostrato in tabella 6.22 tale requisito non è rispettato.

Si può concludere che Powerhouse Kjørbo non soddisfa a pieno i requisiti per ottenere il livello Eccellente in termini di condizioni illuminotecniche, pure essendo un validissimo esempio di edificio ad energia positiva.

Con riferimento alla normativa nazionale norvegese NS 7201-01 si è calcolato il valore dell'indicatore numerico del requisito energetico per l'illuminazione (LENI) per le cinque stanze analizzate, ottenendo valori di gran lunga inferiori al limite massimo di 12,5 kWh/m$^2$ anno fissato dalla suddetta normativa. I valori del fattore LENI ottenuti sono mostrati in tabella 6.23.

0.5.5.4 Comfort visivo degli utenti

Il livello di soddisfacimento da part degli utenti nei riguardi dei livelli di illuminazione in Powerhouse Kjøbo è stato valutato a partire da un'intervista scritta al rappresentante degli impiegati, figura di riferimento per eventuali lamentele. I maggiori commenti negativi riguardano le postazioni di lavoro negli openspace, in cui specie in inverno ed in orari serali le condizioni risultano insufficienti per lettura e scrittura, nonostante la presenza di lampade da tavolo, che tuttavia causano abbagliamento poiché sprovviste di elementi schermanti.

In generale la condizione di insoddisfazione è dovuta a ad una combinazione di fattori:

- Quando la luce diurna è la principale fonte di luce solare è molto comune avere fastidiosi riflessi su apparecchi videoterminali. Ciò potrebbe essere facilmente risolto attivando i sistemi schermanti, tuttavia molti impiegati evitano di utilizzarli fino a che non subiscono il fenomeno dell'abbagliamento; risultano molto più inclini a cambiare postazione di lavoro piuttosto che abbassare le tende oscuranti.
- Quando i sensori in facciata rilevano le condizioni base per l presenza di abbagliamento, i dispositivi schermanti vengono attivati automaticamente eliminando il problema, tuttavia l'ambiente risulta essere più cupo e il sistema di compensazione della luce diurna con sorgenti luminose artificiali entra in funzione.
- In late condizione, ma anche dopo il tramonto, i livelli di illuminamento risultano spesso insufficienti a causa dei sensori collocati in un apparecchio illuminante per ogni gruppo di 4-5 apparecchi, infatti se nessuno siede alla scrivania in corrispondenza del sensore esso può non rilevare la presenza di altri impiegati, che sono costretti ad alzarsi spesso per attivare i sensori. Tale condizione è dovuta ad una scorretta scelta progettuale dettata da condizioni economiche, infatti inizialmente ogni apparecchio illuminante doveva essere provvisto di un sensore ma in un secondo momento la committenza ha deciso di tagliare i costi riducendo il numero di sensori, non tenendo conto che a lungo termine una scelta del genere costa di più in termini di consumi elettrici, come suggerito dall'azienda di consulenza. Tale problema non si presenta negli uffici singoli.

## *0.6 Conclusioni*

Lo studio condotto presenta l'analisi delle condizioni di illuminazione da luce naturale in un edificio per uffici ristrutturato, le cui tecnologie costruttive sono state implementate al fine di realizzare un edificio ad energia zero. Tale analisi è stata condotta tramite simulazioni digitali di parametri illuminotecnici statici e misurazioni in sito eseguite secondo il protocollo di monitoraggio emesso dall'Agenzia Internazionale dell'Energia nell'ambito della Task 50 Subtask D del programma SHC.

In generale le condizioni illuminotecniche sono migliorate con la ristrutturazione, innalzando il valore del fattore medio di luce diurna e garantendo una migliore distribuzione dei valori di illuminamento su un piano a 0,8 m dal pavimento. Tale incremento delle prestazioni è dovuto ad un maggiore rapporto superficie vetrata/superficie calpestabile, eliminazione del controsoffitto, elemento comune a molti edifici nel settore terziario, e incrementando la riflettanza delle pareti interne.

Per quanto riguarda il confronto tra i valori misurati e calcolati per gli ambienti dei blocchi rinnovati, quando si tratta di luce diurna le incertezze ad essa legate sono molteplici a causa dell'elevata variabilità della sorgente luminosa e delle approssimazioni necessarie, che rendono difficile avere una stima precisa di parametri quali FLD ed illuminamento. Come mostrato in figura 6.20 la differenza nella valutazione del fattore medio di luce diurna presente tra i valori calcolati con le due metodologie, è molto elevata per $FLD_{min}$, ma molto più contenuta in termini di $FLD_{average}$. Come mostrato in figura 6.21 l'errore relativo commesso durante la valutazione dei valori massimo e minimo del fattore medio di luce diurna nelle varie stanze non può essere ritenuto accettabile a fini scientifici.

Nel momento in cui le misurazioni sono state condotte, è stato possibile valutare anche parametri riguardanti il comfort visivo degli utenti quali la qualità della vista dalla finestra, la presenza di riflessi su superfici lucide nella stanza e la possibilità che si verifichi abbagliamento. Essendo i due blocchi situati lungo la riva di un fiume, con affaccio diretto sul fiordo di Oslo, il contesto naturale in cui si trovano gli uffici è in generale molto piacevole alla vista, anche se vi sono differenze a seconda dell'esposizione del singolo locale. Circa l'abbagliamento, l'azione combinata dei sensori posti in facciata che controllano il sistema di schermature e i sensori incorporati negli apparecchi illuminanti, rende possibile evitare grandi condizioni di discomfort visivo e allo stesso tempo risparmiare energia elettrica per l'illuminazione di interni. Infatti, secondo ricerche condotte sul comportamento degli occupanti di ambienti di lavoro in cui si svolgono mansioni legate al terziario in relazione alla presenza ed utilizzo di sistemi di schermatura mobili, una volta che la luce diurna colpisce direttamente la superficie di un VDT, gli oscuranti regolabili manualmente vengono utilizzati per ore, giorni o addirittura mesi, anche quando la condizione che causa abbagliamento è ormai inesistente (Reinhart et al., 2006).

Anche se la presenza di un utente passivo permette di risparmiare energia, i progettisti non possono prescindere dal benessere psicologico degli occupanti di un ambiente, infatti in generale la gente si sente molto più a suo agio quando è nella posizione di poter scegliere se avere solo illuminamento da luce diurna o se affiancare ad essa l'uso di luce artificiale. Ciò è dovuto alla percezione umana nei confronti della luce naturale, che viene vista dai più come una sorgente di luce più salutare.

Considerando gli effetti positivi e negativi dell’uso di sensori in sistemi di illuminazione, si può presentare un’ulteriore miglioramento nel caso dell’edificio oggetto di studio: quando i sensori regolano l’intensità luminosa emessa dalle sorgenti artificiali in funzione della percentuale di occupazione dello spazio illuminato, il risparmio energetico è maggiore se le luci vengono spente anziché regolate su una condizione di illuminamento minimo in caso di assenza di utenti; pertanto un sistema di questo tipo è preferibile in uffici singoli o sale riunioni, mentre il sistema di attenuazione è preferibile in ampi openspace per ragioni di comfort visivo. Secondo lo studio condotto da Roisin et al. (2008), sensori di tipo IDDS sono sempre preferibili in caso di percentuale di occupazione maggiore di 44%, mentre un sensore di occupazione è da preferire se la percentuale è inferiore a 27%.

Un’ulteriore suggerimento che scaturisce a seguito dell’analisi condotta, è quello di prevedere la possibilità in interruttori a muro che consentano di regolare quando attivare o meno il sistema di illuminazione artificiale, specie negli uffici privati, poiché a volte l’utente entra ed esce dall’ambiente molto rapidamente e in condizioni normali non accenderebbe la luce artificiale, che al contrario viene attivata dal sensore di presenza e tenuta accesa per circa 15 minuti da allora, anche se non vi è nessuno nella stanza. La presenza di interruttori per il controlla manuale delle condizioni di illuminazione è inoltre raccomandato da BREEAM-NOR (sezione 4.1 dell’apposito manuale).

In alternativa si potrebbe calibrare il sensore incorporato nell’apparecchio illuminante in modo che, quando 500 lux sono rilevati sul piano di lavoro, la sorgente luminosa artificiale venga spenda del tutto e non solo affievolita come succede al momento, permettendo di risparmiare ulteriormente energia.

Sarebbe stato interessante poter svolgere il protocollo di monitoraggio negli edifici prima della ristrutturazione, così da avere maggiori possibilità di confronto e valutazione dei miglioramenti in ambito illuminotecnico derivanti dalla ristrutturazione e l’augurio è che a seguito dello studio condotto, le aziende locatarie siano maggiormente disponibili a collaborare.

Ulteriori analisi potrebbero essere condotte sui blocchi 4 e 5, in termini di parametri illuminotecnici dinamici. Ciò sarebbe interessante non solo perché lo studio dinamico permette di valutare le condizioni di illuminamento in modo continuo su un arco temporale, ma anche perché ad oggi non vi sono pubblicazioni riguardo studi condotti in edifici situazioni a latitudini tanto elevate come lo è Powerhouse Kjørbo. Tali analisi permetterebbero di valutare parametri quali l’autonomia di luce diurna (DA) e UDI (Useful Daylight Illuminance), che rendono possibile migliorare le strategie di illuminazione da luce naturale (Cammarano et al., 2014). Lo studio dei parametri dinamici sarebbe di uso appropriato nella valutazione dei miglioramenti derivanti dalla ristrutturazione, più del confronto effettuato sula base del fattore di luce diurna, poiché essendo quest’ultimo indipendente dalla stagione, posizione geografica dell’edificio, condizioni metereologiche variabili e ingresso diretto di luce solare, non permette di elaborare accurate strategie che prevengano il fenomeno dell’abbagliamento, specifiche per la singola facciata dell’edificio.

Tuttavia la comunità scientifica operante nei paesi scandinavi non ritiene indispensabile uno studio di tipo dinamico dei parametri illuminotecnici poiché per circa l’80% dei giorni dell’anno vi è una condizione di cielo coperto, i cui effetti sono ben descritti dal FLD.

# 1 Introduction

## 1.1 Thesis topic

Daylight has always been one of the most important element in humans' everyday life. As far as we know, before electricity invention every man had based his own daily routine on the 24 hours solar cycle. Humans used to do their main activities during the period between sunrise and sunset because they needed and to rest during night time. The described routine is still true for most of the living beings.

Some of the reasons why the light coming from the sun is so important for life are clear to everybody: it allows animals to see the world around them, so they are able so satisfy their primary needs such as find food in the surrounding and find a safe place to rest; it provides heat, necessary to life because preserve the right temperatures for daily physical needs and for having water in the liquid state; it is fundamental for the photosynthesis process, which provides oxygen, essential element for life.

Other aspects about importance of daylight are not so explicit and known by everyone, moreover many studies are still conducted to fully understand how solar radiation influences life and wellbeing on the Earth.

With man creating a more and more antrophized landscape and using all the non-renewable sources of energy on the planet for many years in the past, the Earth has become overloaded by negative factors which could make very hard living on it, one for all the rising emission on $CO_2$ in the atmosphere. Fortunately humanity has realized the danger of the possible incoming crisis and has started switching his behaviour to a more sustainable activity.

Carbon dioxide emissions are dangerous for climate on the Earth, causing high temperature rise, increasing rainfalls and resulting in great issues for the terrestrial biodiversity. $CO_2$ is normally produced by all the organisms, animals and plants, during chemical reactions necessary to life; it is also re-elaborated by Earth's ecosystem and transformed so that the average composition of gases in the atmosphere stays constant. Problems for terrestrial climate are due to the over-production on carbon dioxide coming from energy production, so that in order to invert the devastating trend humans have to use energy in a more responsible way and produce it avoiding too much greenhouse gases production.

More than one third of primary energy in the world is connected to buildings construction and life service (space heating, water heating, ventilation, lighting, cooling, cooking, and other appliances); for this reason one of the main sector to be revised is the design, construction and use of buildings (Angelo, 2014). The building sector is the biggest energy consumer among the three energy-using sectors: transportation, industry and buildings. In US commercial buildings lighting is the leading energy consumer (25%) while in European countries it follows energy consumption for heating, both spaces and water, in domestic and commercial sectors (see figure 1.1 and 1.2) accounting for the 19% of the global electric energy consumption (IEA, 2013).Constructions are not only responsible of greenhouse gases production but also of occupying a big part of Earth's surface, causing reduction of the amount of plants, organisms which are able to produce $O_2$ by $CO_2$ chemical decompositions.

For all those reasons a new design philosophy developed during 1980s and the concept of passive house born. Passive house is a construction utilizing particular expedients and building techniques in order to have a heated indoor environment during winter thanks only to solar radiations. Moreover, when energetic issues on Earth become more and more relevant, researchers started to look at buildings as tools for energy generation and the concept of Zero Energy Buildings and Plus Energy Buildings developed.

Even though many progresses have been done in energy saving/generation technologies to be applied in buildings, an important aspect which highly influence energy consumptions in construction is still under estimated: daylight. In fact, most of attentions and efforts in ZEB design have been focused more on having high-preforming envelope, well-advanced energy production technologies minimizing energy losses and maximizing energy gain, controlling $CO_2$ production both in the construction phase and in the life operating of the building but very few studies has been conducted on daylight related to those energy saving goals. Most of the technologies and researches nowadays are still more focused on how to convert solar energy in different form of energy to be used for everyday life but very little attention is paid on how much energy can be saved if daylight is used at the maximum of its possibilities to light up indoor environments.

In particular I chose to focus my studies on office buildings because they use a lot of energy for electrical lighting of working areas, and studies conducted on this topic show that for most of the time in a sunny day the use of electrical light was not needed to achieve technical standard requirements, but it was used anyway from employee for psychological reasons (Linhart and Scartezzini, 2011). From this point of view it seems clear that not using daylight when it is available is to all intents and purposes an uneconomic energy management.

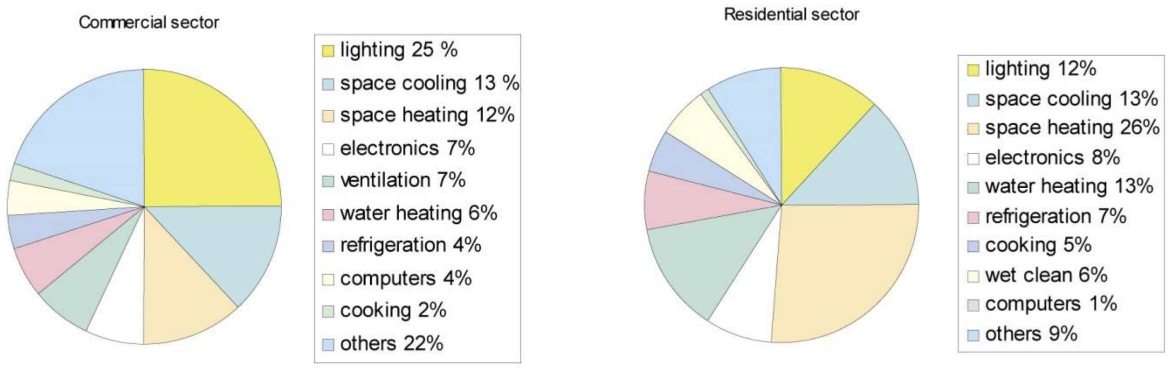



**Figure 1.1** Energy consumption by end use in US commercial and residential buildings. Image taken from Halonen (Bhusal, 2010).

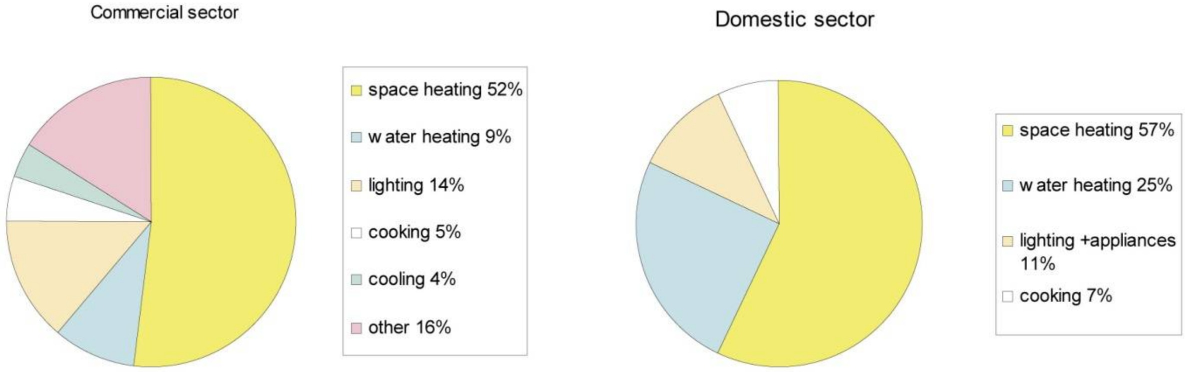



**Figure 1.2** Energy consumption by end use in EU domestic and commercial buildings. Image taken from Halonen (Halonen et al., 2010).

## *1.2 Thesis purpose*

The aim of this study is to state the importance of daylight in indoor spaces and in particular in Zero Energy Office Buildings, because it is able to affect both energy performances and users productivity at work and quality of life. Another goal of the project is to give a scientific foundation for the growing awareness of architects, engineers and certifiers about how much daylight can play an important role in energy saving in a building.

The current study analyses daylight performances of a ZEOB in Norway, in the municipality of Sandvika, near the Norwegian capital city Oslo. What makes this office building a very interesting case study is the fact that it has been recently refurbished, being transformed in a Zero Energy Building and achieving the certification of Outstanding from BREEAM. The purpose of the thesis is collect daylight performance data about the building before and after its refurbishment, through use of software simulations and real state measurements, in order to make a comparison between the two types of buildings but also to evaluate the magnitude of difference in values obtained through software simulations and measured values. I believe it is very important to perform a post-construction check of the expected values during the design phase, because even with the most sophisticated tools, simulations can never take in account all the complex phenomena existing in real situations, especially talking about light.

In an energy saving directed design one of the most important construction elements are openings in the envelope of the buildings. Windows are considered only as source of overheating during summer, heat loss during winter due to thermal bridges along the frame and high thermal conductivity of the glass, for this reason architects find easiest to reduce to the very minimum the area of glazed openings and using particular coatings in order to reduce solar heat gain due to incoming daylight and heat losses due to thermal heat transfer. By considering energy in terms of heat only these solutions seem to produce all positive improvements in the energy saving strategy, but reality is more complex than this. By having a small amount of transparent envelope it is necessary to use a great amount of energy for lighting purposes; according to the International Energy Agency nowadays 2900 TWH are used by lighting systems in indoor spaces and projections, based on the hypothesis that governments will not change their lighting policies, show an increase of more than 40% in lighting consumption by year 2030 (IEA, 2013).

Through the comparison of lighting performances before and after the refurbishment in the study case building, the author wants to investigate which kind of changes occurred in the daylight indoor situation and whether significant improvements had been produced.

## 1.3 Technologic and architectural background

To inattentive design figures, daylight may not have a big relationship with buildings energy consumption, and minimum levels imposed in standards for indoor lighting may be solved by using artificial light. This way of thinking is the foundation for a wrong design and energy management in a building.

Since glass was discovered buildings started to have an increasing number of windows, bigger and bigger, in order to let some light come in, but their presence was never related to enjoy daylight or have a good quality of view. In modern ZEB glass is highly used in relation to its heat-capture properties but sometimes values like visible light transmission are too low, not related to lighting conditions. Only recently architects started paying more attention to that aspect.

One of the pioneers in the passive constructions world is George Frederick Keck, who, in 1933, designed for the Century of Progress exhibition in Chicago a structure named “House of Tomorrow”. It is an all-glass building which made possible to realize the importance of glass for indoor passive heating, in fact the architect noted the workers inside the house wearing only short sleeves shirt during sunny winter days, before any heating and air-conditioning equipment installation. Unfortunately, total glazed surfaces counter posed that advantage to big heat losses during night and overheating during not-winter sunny days, making impossible to live in such a house (Thompson and Blossom, 2015).

In 1943 another precursor of modern architecture understood and implemented glass use in buildings for passive energy purposes in the construction called “The Solar Hemicycle”. He was Frank Lloyd Wright, under the commitment of Jacobs spouses, who designed a semi-circular plan house in Wisconsin, near the municipality of Madison, showed in figure 1.3. This house is highly innovative not only for the smart use of glazing façade south-oriented, but also for the presence of appropriate indoor materials and the first application of radiant-floor heating system.

As it is shown in figure 1.4, The Solar Hemicycle has numerous solutions which have begun a solid base for modern passive strategies: the preliminary study of climate and context in order to find the best orientation for the new construction, use of large glazed surfaces for winter solar heat gains and proper shading solutions to avoid overheating during summer period, presence of massive indoor surfaces for heat storage during the day and heat release during the night, utilization of the stack effect for indoor air-conditioning.

During 1950s design of solar passive buildings spread from US to all over the world, but the leading ideology was not supported by any kind of necessity but architects’ desire of experiment and innovation. In 1973 the big petroleum crisis entail a turning point in the relationship between energy and constructions, countries around the world started developing an environmental awareness, based on better use of resources still available and research of new energy sources, the so called renewable energy (Thompson and Blossom, 2015).

In 1956 another innovation in passive indoor air-conditioning was patented and realized by the engineer Felix Trombe. The so called Trombe’s wall consists of a black painted wall with high mass, situated behind a glass surface, so that it operates as a heat collector. In fact air in the cavity (5-10 cm) between the wall and the glass is heated by infrared waves coming from the sun and then used to heat or ventilate the indoor spaces thanks to specific configuration of the apertures presents on the top and bottom of the wall. There are four possible configurations, showed in figure 1.5. However this passive solution have not diffused a lot during the years due to difficulties in realization, elevated installation costs and difficult maintenance of the glazing and cavity.

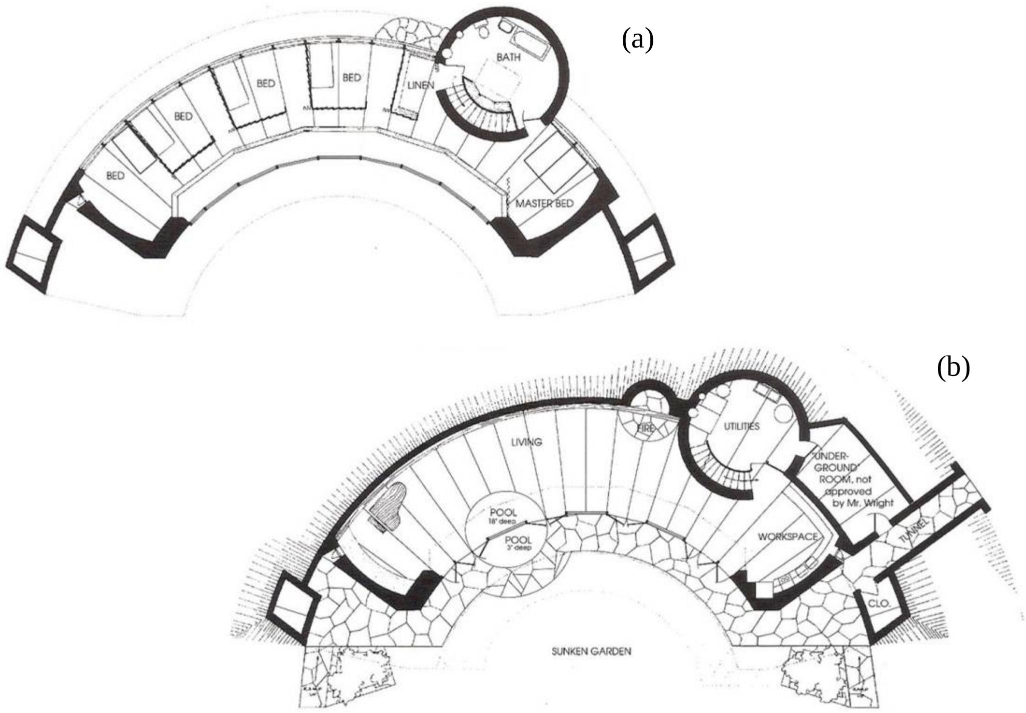



**Figure 1.3** The Solar Hemicycle (Jacobs II), designed by F.L. Wright in 1943 and constructed in 1946-48. The ground floor (b) is a unique big space, without internal walls, enabling air and heat to freely distribute in the indoor environment. The second floor (a) is a balcony, suspended from the roof joists, pulled away from the glazed façade in order to allow solar-heated air to flow from below to the upper and completing the convective loop through a large circular stairwell connecting the two floors. Photo credit: modified figure from © W A Storrer.

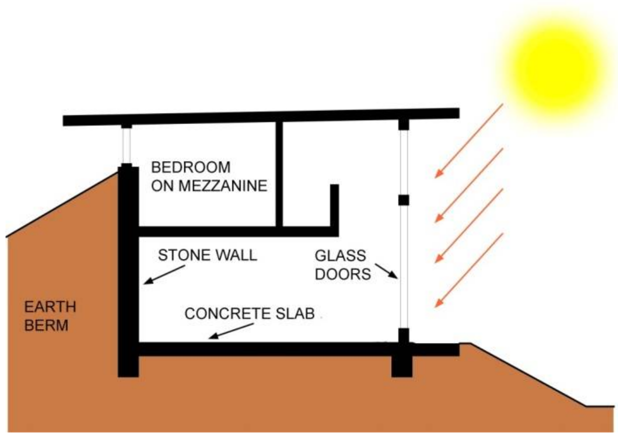



**Figure 1.4** The Solar Hemicycle (Jacobs II), designed by F.L. Wright in 1943 and constructed in 1946-48. Radiant solar energy is collected into the house through the glazed south-oriented façade, accumulated in the high massive concrete slab, in which a radiant boiler-heated system for back-up heating, that emulates and supplements the solar-warmed floor, is integrated. All the interior walls are made of local Wisconsin limestone providing an irregular and enhanced mass surface area for thermal energy exchange and interior temperature stabilization.

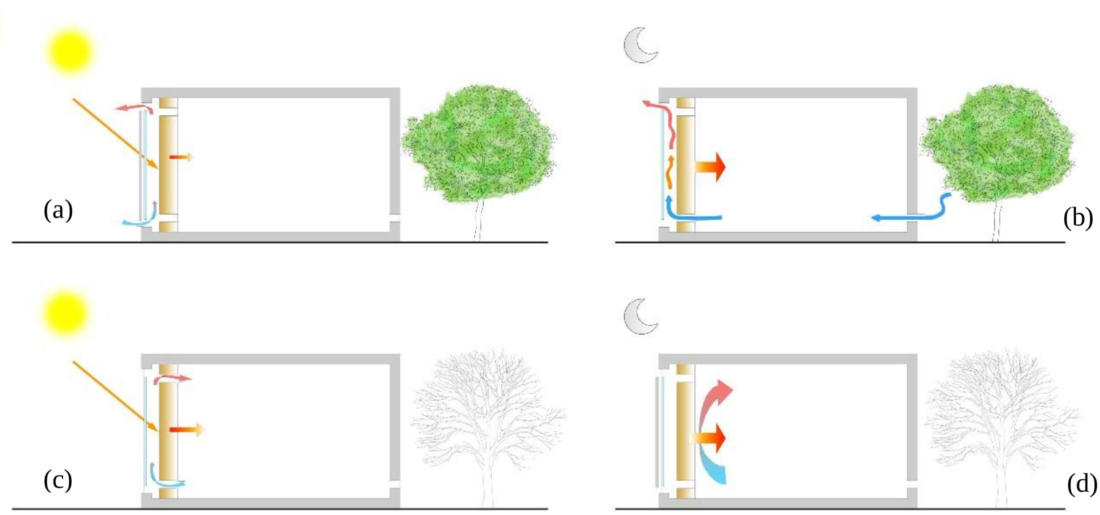



**Figure 1.5** Trombe's wall can have different utilities according to the configuration of apertures in walls and glazing surface. In configuration (a) the basic bioclimatic effect: during winter period the air in the cavity is heater by solar radiation and so it is the massive wall; the glazing surface has also the utility to reduce heat losses towards the surroundings; the indoor space is heater for conduction from the massive wall and for hot air ventilation through apertures in the upper and lower part of the wall. In configuration (b) the glazing surface is partly insulated by shading devices to prevent heal losses during winter night time; the massive wall irradiates towards the interiors the heat gained during day time; all the apertures are closed. In configuration (c) the glazing surface is shaded by solar radiation and apertures on its upper and lower parts are open to increase heat losses from the massive wall. In configuration (d) the indoor space is cooled down by ventilation (solar chimney): apertures of the glazing surface are open, the hot air in the upper part sucks fresh air into the interiors by apertures in the lower part of the wall situated on the opposite side of the Trombe's wall.

In the mid-1980s the low-energy building concept was already developed and legally required as energy standard for new buildings in Sweden and Denmark. It was based on the principles of excellent insulation, prevention of thermal bridges, airtightness, insulated glazing and controlled ventilation, which inspired a research project in 1988 conducted by the University of Lund/Sweden together with the host Professor Bo Adamson. He elaborated the first definition of "Passive House" as a building which has an extremely small heating energy demand even in Central Europe's climate and so it does not need any active heating. The theoretical concept found its first application in 1991 with the construction of a row of four terraced houses, designed by the architectural firm Bott, Ridder and Westermeyer, located in Darmstadt-Kranichstein, Germany. The no heating strategy was possible by using only internal heat sources, solar energy and the minimal heating of fresh air via mechanical ventilation heat recovery, together with a highly insulated envelope, as shown in figure 1.6. In the very first Passive House residences the heat recovery ventilation was located in the cellar, which had an approximate temperature of 9°C in winter, and was the first system to use electronically commutated DC fans (Webster, 2014). Each accommodation unit have a floor area of 156m², solar collector for the provision of domestic hot water and a subsoil heat exchanger for preheating the fresh air coming from the outside; external walls and basement ceiling are insulated with polystyrene boards while the roof has a 445 mm cavity filled with blown-in mineral wool insulation. It refers to the super insulated Saskatchewan House, built in 1977 in Regina, Canada, based on very low thermal transmittance of the envelope ( $0.1\ W/m^2K < U < 0{,}15\ W/m^2K$) and no large windows facing any particular direction. Combining all the technologies, the result is that each of the four houses house have a heating energy consumption of below 12 $kWh/m^2a$, just 10% of a standard home at that time (Passipedia, 2014).

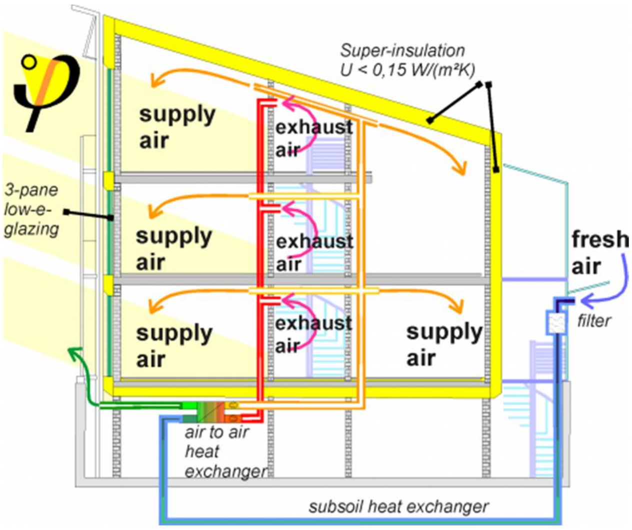



**Figure 1.6** Cross-section of the Passive House in Darmstadt-Kranichstein. The fresh air from outside is introduced in the house after being preheated by a subsoil heat exchanger and an air to air heat exchanger which recover part of heat in the exhaust air. Due to particularly well-insulating and airtight sliding shutters as temporary heat protection, it was even possible to operate one of the accommodation units as a "zero-heating-energy house" without any heating in the years 1994 to 1996. Image from (Passipedia, 2014).

The Passive House is the starting point of a technologic evolution in construction which led to the Zero Energy Building concept, based on a more efficient use of natural resources and reduction of negative building's impact on the environment by limiting the energy loss and consumption while maximizing the energy produced by the building itself from solar, wind and geothermal sources. The world's first carbon neutral and zero energy commercial-scale office building is the Korea National Institute of Environmental Research's 26,910 SF Climate Change Research Building, located in Incheon, South Korea. Constructed over two years between 2008 and 2010 it achieve the status of zero net energy through the incorporation of 66 energy efficiency and renewable energy producing technologies and strategies such as:

- triple pane windows with built-in shades able to automatically open or close to allow just the right amount of light in while sharply reducing heat gains;
- light sensors which automatically shut off LED lights when the natural light is available;
- $CO_2$ sensors opening the windows then fresh air is needed, optimizing natural ventilation;
- A super insulated envelope.
- Solar thermal panels extending out from the roof providing hot water for both consumption and heating;
- A geothermal ground source heat pump heating and cooling system;
- Solar photovoltaic panels covering the south wall to generate electricity but allowing natural daylight in the building at the same time.

Numerous technological solutions have been elaborated and tested during the years and still nowadays architects, engineers and researchers elaborate new and different ways to reduce emissions and produce energy in buildings.

## 1.4 Schematic list and short description of chapters

The thesis is structured in this way:

- Chapter 2: Introduction and explanation of scientific background about daylight topic. Definitions and formulas of the main parameters utilized during the study are presented in this chapter;
- Chapter 3: It presents the relation between daylight and human health, building up the thesis in favour of the importance of natural light in indoor spaces and its interaction with buildings elements. This

chapter presents results from scientific studies, benefits and negative aspects of human exposition to sunlight. It is mainly focused on the influence of daylight on the circadian system;

- Chapter 4: it concerns about buildings energy demand and its consequences on the Earth's climate. Moreover there will briefly summed up standards which historically have provided a certain grade of importance for daylight in buildings design and the reasons why those laws are necessary nowadays. Different definitions of Zero Energy Buildings are presented in this chapter as well as certification committees for sustainable constructions;
- Chapter 5: the scientific method used for performing measurements is described as well as different software simulations are presented;
- Chapter 6: the case study of a Zero Energy Office Building in Norway is presented. It is located in Sandvika, a municipality near Oslo, it is the first building in Norway to achieve the BREEAM certification of "Outstanding" and an added value for this already virtuous construction is the fact of being renovated. The study presents comparisons, differences and improvements from the old building to the renovated one after software analysis and experimental measurements;
- Chapter 7: in the conclusions all the results are presented and summed up.

# 2 Theoretical structure

## 2.1 Values definitions and formulas

In this chapter the theory on which lighting conditions and performance in interiors are based is presented.

### 2.1.1 Light

There are two different theories about light's nature, which for many years had been considered to be in contrast one with the other. Those are the "corpuscular theory" which refers to light as a stream of particles and the "wave theory" which considered light as a wave. After some experiments scientists began believing that light had one or the other behaviour depending on the type of experiment conducted, but in 1905 Einstein stated the double nature of light and finally on March 2015 a group of researchers manage to demonstrate the effective double nature of light that has attracted and aroused scientists' curiosity all over the world during the centuries.

One of the two main scientific theories about light is the classical wave theory, elaborated by the scientist James Clerck Maxwell (1831-1879). In the late 1800s he asserted that light propagates as a wave, incorporating visible light in his theory on the electromagnetic field and elaborating a mathematical formulation. The scientist defined the EM as the simultaneous presence of electric and magnetic field components that are perpendicular to each other and also to the direction of propagation. According to Maxwell light is part of the electromagnetic field because EM-waves propagate at a velocity very close to the measured speed of light.

However the wave theory started with Christian Huygens (1629-1695), who thought at light as a wave, similar to sound but emitted by light sources. According to the Dutch physicist light waves vibrate up and down perpendicular to the direction of the light travels. Nevertheless it is known that mechanical waves cannot propagate in absence of a medium, so at first instance light cannot be considered similar to a sound wave because it propagates in the vacuum from the Sun to the Earth. The importance of Maxwell's theory lies in the incorporation of light wave in the electromagnetic field, which does not require any medium to propagate in.

Almost at the same time as Huygens, Isaac Newton (1642-1727) firmly asserted his corpuscular theory of light according to which light propagates as stream of particles emitted by light sources, moving in the surrounding space at an infinite speed.

During all the XVII century the corpuscular theory took advance, mostly because its theorist was better known and respected in the scientific world. It is true that at that time there were not so many technologies allowing experiments to prove one or the other theory and deny the other. The only two lighting phenomena known to theorists were the reflection and the refraction and both waves and particles can experience those two physical phenomena, but what made the two theories incompatible was that corpuscular-light speed would have increased when passing through a more refracting medium but wave theory of light predicts a speed decrease in the same situation.

During the first years of '900 new phenomena, such as the photoelectric effect (further details in Appendix A), result to be incompatible with the wave nature of light and Albert Einstein (1879-1955) attributed to light a new corpuscular nature, creating the "quantum theory of light". He stated that light radiation is a flux of quanta or photons, particles of pure energy and without mass. Even though quantum mechanics states that light should have both attributes simultaneously, that phenomenon has never been imaged directly until now.

Recent experiments demonstrate that both theories are right and light truly has a double nature. Researchers from École polytechnique fédérale de Lausanne (EPFL) by excitation of a metal surface of a nanowire by UV-rays made vibrate the particles of the plaque. They obtained the source of light for the experiment by creating a standing wave from the meeting of two waves travelling in opposite directions. The scientists then shot a stream of electrons very close to the nanowire and they are able to visualize (Figure 2.1) the standing wave by using an ultrafast microscope. This microscope makes possible to see the change speed occurring in light particles when those interact with the electrons (Piazza et al., 2015).

So light is part of the electromagnetic spectrum, a collection of different waves including radio waves, microwaves, infrared light, visible light, ultraviolet light, X-rays and Gamma rays. The electromagnetic radiation can be expressed by different physical quantities such as wavelength $\lambda$, frequency f or energy J and usually waves in the field are classified according to their wavelength, as it is shown in Figure 2.2.

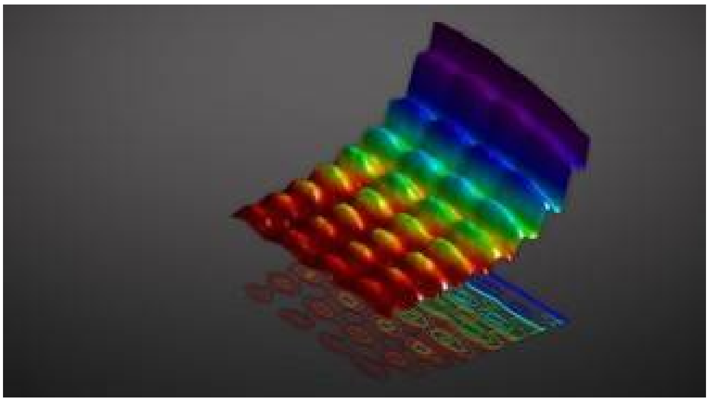


**Figure 2.1** First picture of light both as a particle and a wave. Photo credit: © 2015 EPFL.

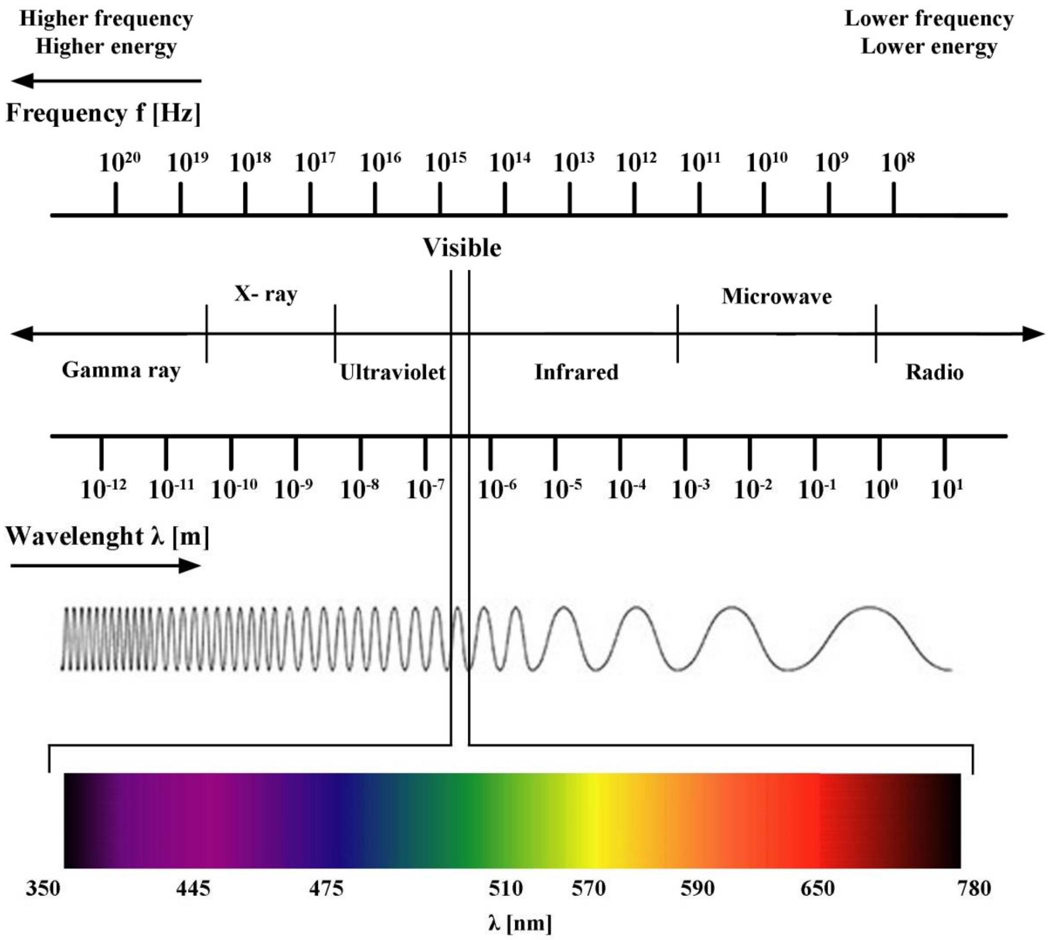



**Figure 2.2** Schematic representation of the EM referring to its three major physical quantity which describe it. For increasing values of wavelength, there is a progressive decreasing in frequency and energy values. Note how the range of radiation is short in the visible spectrum if compared to other types of waves. For different values of wavelength the human eye is able to recognise and distinguish different colours. Correspondence between λ (in nm) and colours is summed up in the figure and better described in Section 2.2.12.

Visible light is the part of the electromagnetic field included between 380 and 780 nm, it is characterized by three values all related one with the others, so whenever one of them changes, the same happens to the others. These values are frequency, wavelength and velocity which depends on the medium in which the field propagates. Being the relation among those three parameters the one reported in equation 2.1 it can be noted that the wavelength depends on the propagation medium:

$$\lambda = \frac{v}{f} \tag{2.1}$$

Where λ is the wavelength in nm

v in the velocity in the medium through which the wave propagates in nm/s

f in the frequency of the wave [$s^{-1}$].

2.1.1.1 Sources of light

The biggest and powerful source of EM known on the Earth is the Sun, but all surfaces at any temperature above absolute zero (-273,15 K) emit electromagnetic radiation and even energy transition, occurring when electrons in excited atoms jump from one energy level to another, can produce electromagnetic waves. It is possible to classify light according to the source which generates it (Gelighting, 2015).

One type concerns natural sources like hot surfaces, related to thermal light: thermal source is any surface having temperature higher than 1000 °C, it can be a candle, a plaque or filament of hot metal, a burning liquid such as oil and the Sun, having temperature of about 6000°C on its surface. The solar electromagnetic field has a continuous spectrum that contains a little over half of its energy in the visible region and extends from infrared and microwaves to ultraviolet, as shown in figure 2.3.

Other thermal sources operates to much lower temperature, so that the radiation has a greater percentage of energy in the infrared region and more red light than blue one in the visible part of their spectrum. As it will be better explained in point 2.1.10 relationship between colour and temperature of the source lays in the concept of colour temperature.

When light is generated by excitation of atoms, it is possible to refer at it as electronic light. Examples of such sources are neon tube, in which an electric current passes through neon gas at low pressure, or fluorescent lamp, in which the electric current passes through a gas of mercury vapour and produces ultraviolet light which excites a fluorescent powder lining the tube. More detailed description on electronic sources can be found in section 4.

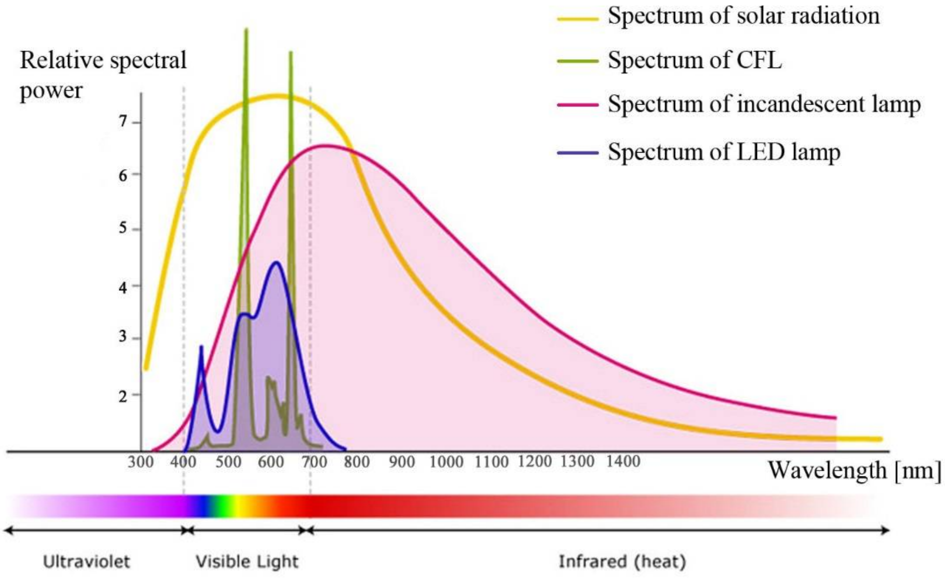



**Figure 2.3** Spectrum of radiation from different light sources, every spectrum has a different percentage of radiation corresponding to specific wavelength. Solar radiation has about half of the energy in the part of the spectrum visible to human eye. Image modified from (Haynes; William, 2011).

### 2.1.2 The Earth's atmosphere

Atmosphere is the sequence of gas layers surrounding the Earth. It extends from the average sea level up to 480 km and five layers can be identified in atmosphere's structure, the interface between every two layers is identified as transition layer. Air pressure in the atmosphere decreases with altitude, from 101325 Pa (1 atm) at sea level to 1,01325*$10^{-6}$ Pa ($10^{-11}$ atm) at 500 km from the Earth's surface. Differently from it, the temperature has a different trend along the atmosphere and the main division of it in the different layers is due to temperature and gas composition changes (Bellia et al., 2011). In figure 2.4 there is a graphical summary of all the layers feature described below.

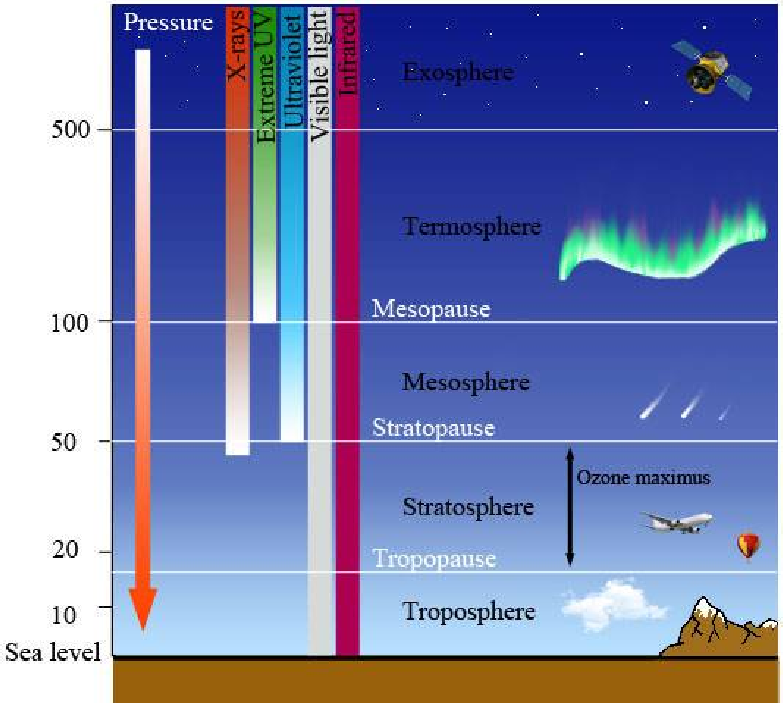



**Figure 2.4** Graphical summary of natural phenomena, human instruments and cosmic rays filter which characterize each layer of the atmosphere.

Atmosphere’s layers are:

- Troposphere (from Greek trópos, alteration): it is the lower layer in the atmosphere, extending to 10-18 km from the Earth’s surface. Its thickness varies along the Earth’s circumference with the latitude, being thinner at the poles and thicker in the Equator area. In the troposphere ¾ of the atmosphere’s mass ($5{,}1 \cdot 10^{18}$ kg) (Bisegna et al., 2010) are concentrated and almost all the water vapour, for this reason it is in this layer that all the climate events occur.

  The troposphere has a constant chemical composition thanks to the continuous air stream motions which mix all the gases in the layer. Temperature decrease with the altitude, in fact air is heated by heat radiated from the Earth’s surface; as a general rule there is a decrease of 6,5 °C/km (vertical geothermal gradient) (CEN, 2005). Also the pressure decrease with the altitude because the column of air causing that pressure is shorter and the air is more and more rarefied.

  The troposphere is separated from the following layer by the tropopause, a transition layer characterized by presence of high speed air currents (200-300 km/h), better known as jet stream, which move in altitude and latitude seasonally.

- Stratosphere ( from French stratosphere, derived from the Latin stratum, layer): it is the second layer of the atmosphere and it starts approximately at 10 km from the Earth’s surface, carrying over to 40-60 km as average values all along the terrestrial cap. Its main features are isothermy in the closest layers to the tropopause (approximately around -55 °C until 20 km of altitude) and temperature inversion with increasing altitude(CEN, 2005).

  The temperature trend is the opposite of the one in the troposphere: lower temperature in the part closer to the Earth’s surface and higher temperature when the altitude increase as shown in figure 2.6. This temperature trend is due to the presence of ozone, in fact most of the $O_3$ present in the atmosphere is concentrate in this layer, absorbing harmful radiations from the Sun which are UV rays, capable to produce heat (Bisegna et al., 2010). Due to the big amount of ozone present in the stratosphere, it is possible to identify the portion of it going from 20 km to 30 km as a defined layer called ozonosphere. Oxygen ($O_2$) is very rarefied here, air is very dry and about a thousand times thinner here than it is at sea level; these characteristics make possible to jet aircraft and air balloon to fly in this layer(CEN, 2008). Typical troposphere’s climate events are absent in the stratosphere, but pollution produced by humanity are present for many years before coming back in the troposphere, falling on the ground.

  The stratosphere is separated from the following layer by the stratopause, where temperature is close to 0°C.

- Mesosphere (from Greek mesos, middle): it extends from 45 to 95 km of altitude and it is characterized by a deep temperature decrease from 0°C to -70 and -90 °C. In this layer happen all the luminous sky events that we call shooting stars, due to meteors coming from the open space which are set on fire when getting in contact with the mesosphere. A big amount of space radiations called cosmic rays interact with particles in this layer, producing ions from dissociation of gas molecules. For this reason it is possible to identify a sub-layer in the atmosphere, from 80 to 500 km, called ionosphere which starts in the mesosphere and carry over to the thermosphere (CEN, 2005).

  The mesopause is the transition layer marking the end of the mesosphere, in this region temperature stops decreasing and its trend is inverted.

- Thermosphere (from Greek thermos, hot): it is the fourth layer of the atmosphere, starting at 95 km and ending at 500 km of altitude. The name of this layer is due to the temperature trend which highly increase up to 1000° around 300 km but reaching 2000°C depending on solar activity, season and latitude. However these temperatures have not the same effect they would have at sea level because the pressure in very low ($10^{-11}$ atm), being in the condition of vacuum. Gases in the thermosphere are ionized or in the atomic state, carbon dioxide, water vapour and ozone lack here. In the thermosphere important electrical and geomagnetic phenomena occur, among them the most known and spectacular are the aurora borealis: luminous events of different colours due to the energy released from excited ions when hit by electrons and protons coming from the Sun. In the layers with the highest electronic density of the ionosphere radio waves are reflected ( between 60-80 km the long waves, 90-120 medium waves, 200-250 km short waves and 400-500 km much shorter radio waves) (CEN, 2005).

  The solar X-ray and extreme ultraviolet radiation (XUV) at wavelengths $\lambda$ < 170 nm is almost completely absorbed within the thermosphere. Transition layer between thermosphere and exosphere is the termopause in which temperature increasing ends.

- Exosphere (from Greek exo, out): it is the external layer of the atmosphere, a transition region in which particles coming from the space and from the Earth mix. Due to the increasing rarefaction it is not possible to locate the exact upper limit but most scientists believe it can carry over to 1000 km because it is at that altitude that most particles manage to escape the terrestrial magnetic field.

Every layer of the atmosphere absorbs radiation of different wavelength in different percentage as shown in figure 2.4 so that when it finally reaches the Earth's surface the irradiance is much lower than it was in the space, see figure 2.5.

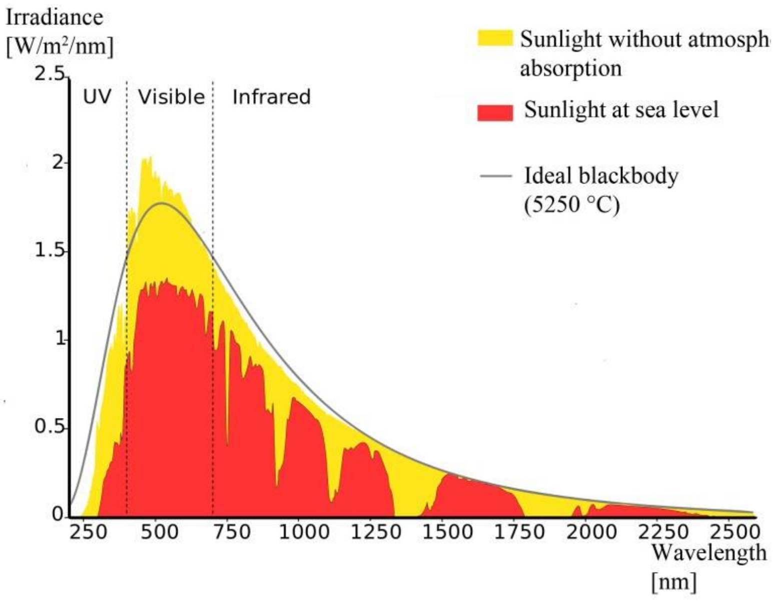



**Figure 2.5** Spectrum of solar radiation in the space and after being filtered by the atmosphere of the Earth, compared to the blackbody radiation, better presented in section 2.1.11.

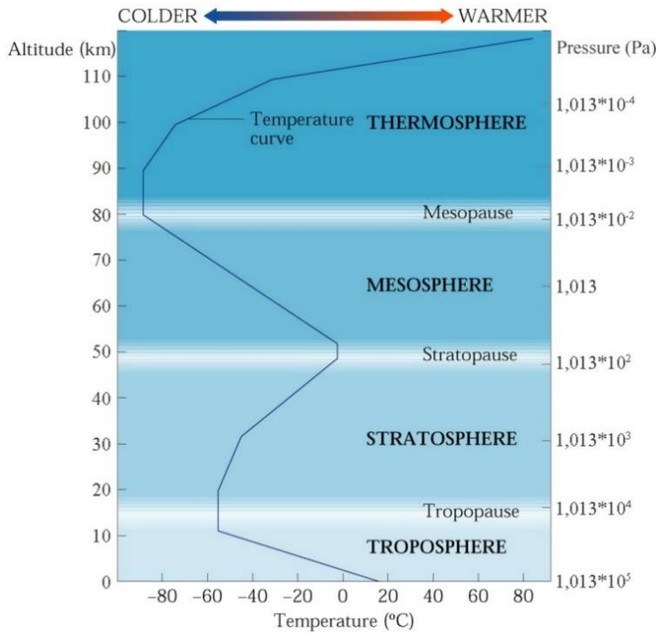



**Figure 2.6** Temperature trend across the atmosphere's layers and relative pressure value. Figure modified from John Wiley & Sons, Inc. (1999).

### 2.1.3 Daylight

Daylight is the light from the sun and in the sky during the day, it is the visible part of the electromagnetic filed reaching the Earth from the solar radiation. Its main feature is that it changes constantly both because of sun position changes in the sky and because of weather local climate conditions change. In particular this last factor can highly and unpredictably affect solar radiation at the surface due to presence of clouds of variable thickness.

Moreover daylight is also depending on the geographic position in which the observer is, in fact the temperature colour of the light and its intensity highly depend on the angle of incidence of solar beams on the Earth' surface. This is why even though sunlight, one of the two components of daylight, refers to parallel light beams coming from the Sun, when those beams reach the atmosphere they are partly scattered through the different layers surrounding our planet. Another variable cause of daylight is the inconstant solar radiation, even though hours of daylight and the diurnal variation are very predictable at any location and season (Ikeda and Nakano, 1986). Depending on season, characterized by a relatively homogeneous height of the Sun in the sky, different meteorological sky conditions (clear sky, mixed sky and overcast sky) can give similar, or very different, daylight levels:

- From January to mid-February and from mid-November to December: daylight level on the working plane is the same except for overcast sky condition;
- During the winter period clear and mixed days have similar daylight levels and overcast sky are significantly lower;
- In spring mixed and overcast days give similar daylight levels and clear sky are significantly lower;

However these rules are not valid for the colour temperature and daylight distribution on different surfaces than the working plan (Begemann et al., 1997).

In a narrower perspective daylight reaching a limited area on the ground is influenced by the topographical conformation and presence of vegetation in a non antrophized region and by the surrounding buildings in a city or small town (Begemann et al., 1997). Focusing on indoors daylight highly depends on exposition of the building itself, planking level of a room, windows shape and position, presence and colour of blinds.

### 2.1.4 Radiometric and photometric units

When it comes to measure the amount of light reaching a surface or leaving a point source, two types of dimension units can be used, those are called radiometric and photometric units.

The difference between photometric units and radiometric units lies in the fact that using radiometric units, it is possible to characterize light in terms of physical quantities such as the number of photons, photon energy and the radiant flux, while photometric units depend on human sensibility. Even though in scientific studies it is important to have objective values, when it comes to light perception by a human being it is irrelevant to work with radiometric units (CIE, 1990).

**Table 2.1** Photometric and corresponding radiometric units

| Photometric unit | Dimension | Radiometric unit | Dimension |
|---|---|---|---|
| Luminous flux | lumen [lm] | Radiant flux (optical power) | W |
| Luminous intensity | candela [cd] | Radiant intensity | W/sr |
| Illuminance | lux | Irradiance (power density) | $W/m^2$ |
| Luminance | $cd/m^2$ | Radiance | $W/(sr\ m^2)$ |

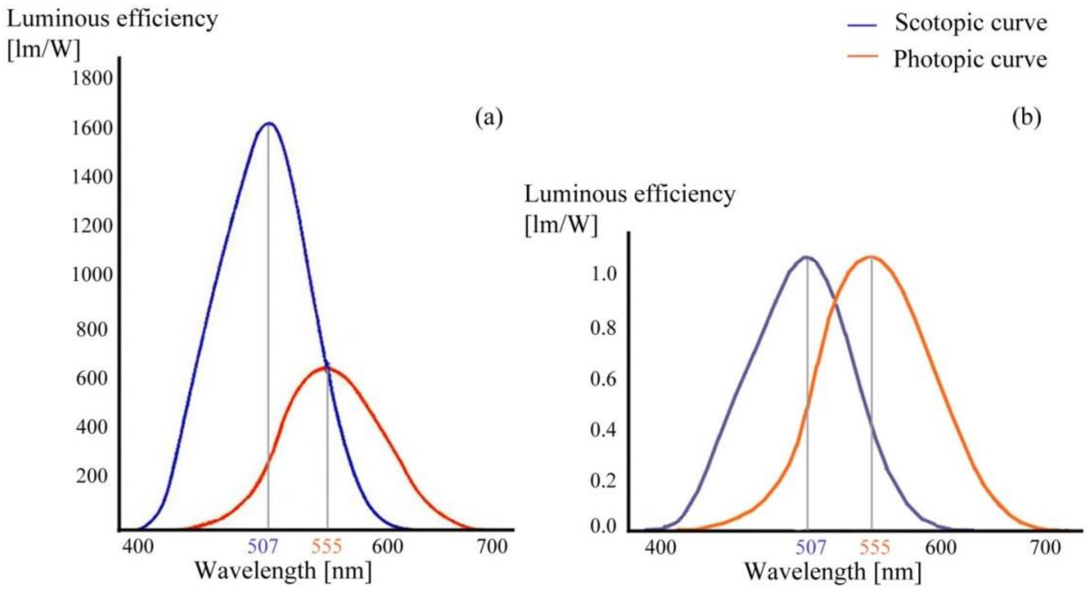



**Figure 20.7** Luminous efficiency for scotopic vision and photopic vision as standardized definition (a) and relative normalized functions (b).

These two types of units can be correlated by using the spectral luminous efficiency function V(λ) and in table 2.1 there is a summary of the radiometric units and corresponding photometric ones.

The spectral sensitivity function of the average human eye under daylight conditions (photopic vision) is defined by CIE as V(λ). The importance of this function is easy to understand knowing that the human eye's sensitivity to light of a certain intensity varies depending on the wavelength, which can assume values between 380 and 800 nm. Under daylight conditions, the average normal sighted human eye is most sensitive at a wavelength of 555 nm. As a consequence of this, green light at $\lambda = 555$ nm produces the impression of highest "brightness" when compared to light at other wavelengths.

As it will be explained more in detail in chapter 3, human eye is characterized by two different types of vision according to the amount of light in the surrounding: photopic vision when there is daylight and scotopic vision in condition of very low levels of light. In these two conditions human eye's sensibility is highly different, as shown in figure 2.7 (a) but for better comparison between those two functions, it is possible to refer to normalized functions, which have 1 as the maximum value.

To find the right way to define the V(λ) function has not been easy for the International Commission on Illumination (CIE) and there are different statement about its characteristics. The first one was elaborated in 1924 as the photopic eye sensitivity function for point-like light sources where the viewer angle is 2° (CIE, 1990). It is internationally identified as the CIE 1931 V( λ ) function and it is the current photometric standard in the United States. In 1978, Judd and Vos introduced a modified V(λ) in order to correct the underestimation of human eye sensitivity in the blue and violet spectral region by the CIE 1931 V(λ) definition. The correction is possible arranging an higher values for V(λ) in the spectral region below 460 nm (CIE, 1990) as shown in figure 2.8. The modified V(λ) is noted as CIE 1978 V(λ) and in the same year CIE legitimate that function by stating *"the spectral luminous efficiency function for a point source may be adequately represented by the Judd modified V( λ ) function"* (Davolio, 2014) and *"the Judd modified V( λ ) function would be the preferred function in those conditions where luminance measurements of short wavelengths consistent with color normal observers is desired"* (Dhawan, 2005).

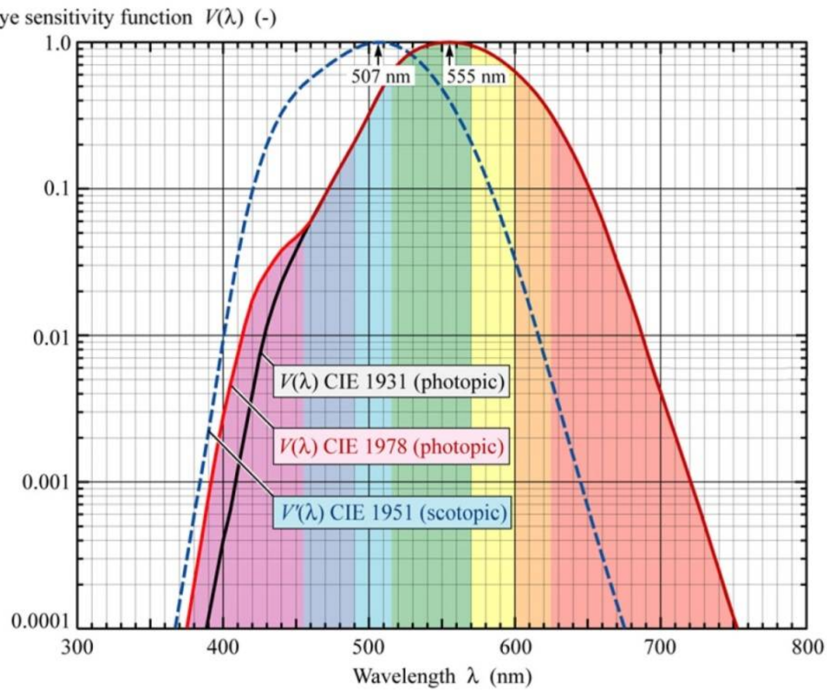



**Figure 2.8** Comparison of CIE 1931 and CIE 1978 V(λ) for the photopic vision and scotopic one CIE 1951 V'(λ). For the photopic vision regime are shown the colours detected from human eye according to the wavelength values. Inspection of the figure also reveals that the CIE 1931 V( λ ) function underestimated the eye sensitivity in the blue spectral range ( λ < 460 nm). Image modified from (CIE, 1990).

### 2.1.4.1 Luminous intensity

I is a photometric unit, defined as the quantity of visible light that is emitted in a defined direction in unit time per unit solid angle, as described in equation 2.3.

$$I = \frac{d\phi}{d\omega} \text{ [cd]} \tag{2.3}$$

Where dΦ is the luminous flux, defined as the power of perceived light, measured in lumen;

dω is the unit solid angle in steradian;

1 lumen is the unit for the quantity of light flowing from a source in any one second.

It is important to highlight the difference between the luminous lux (photometric) and the radiant flux (radiometric), in fact the second one is the total power of emitted light while the luminous flux is evaluated in reference to visual sensation which is dependent on human vision system. The luminous flux is defined as the measure of the brilliance of a source of visible light in terms of the power emitted per unit solid angle from an isotropic radiator, a theoretical point source that radiates equally in all directions in three-dimensional space. The mathematical formulation of this parameter is reported in equation 2.4.

$$\phi = \int 683\phi_{e\lambda} V(\lambda)\, d\lambda \tag{2.4}$$

Where Φ is the total luminous flux, defined as the power of perceived light, measured in lumen;

$\Phi_{e\lambda}$ is the radiation [W] with wavelength λ;

V(λ) is the spectral luminous efficiency function defined by CIE that hallows to switch from the radiometric unit $\Phi_{e\lambda}$ to the photometric unit Φ.

It is present a correction factor in the definition of the luminous flux because at the wavelength λ = 555 nm, there are 683 lumens per watt of radiant power, whereas at other wavelengths the luminous efficiency is less (CIE, 1990).

2.1.4.2 Luminance

L is always referred to a surface source, it is the measure in cd/m$^2$ of the luminous intensity emitted in a given direction from a small element of surface area divided by the projected surface area in that direction as shown in figure 2.9.

$$L_\alpha = \frac{I_\alpha}{A\cos\alpha} \qquad (2.5)$$

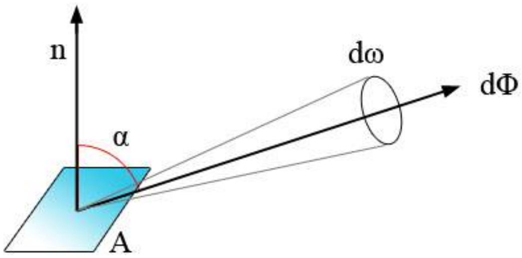



**Figure 2.9** The luminous intensity in a given direction differ from the normal to the surface A by the angle α.

The projected surface area follows the cosine law, according to which the light diffuses from a unit area in a determined direction is proportional to the cosine of the angle between that direction and the normal to the surface:

$$A_{projected} = A_{surface}\cos\alpha \qquad (2.6)$$

Where α is the angle between the direction considered and the vector perpendicular to surface.

In conclusion it is possible to say that luminance is a function of the position of the light sources and the surfaces in relation to the eye of the observer (Milone, 2007).

2.1.4.3 Illuminance

E is the luminous flux incident per unit area, measured in lux according to the SI. According to the intensity of the luminous flux, different environments are classified with specific values of illuminance as shown in table 2.2.

**Table 2.2.** Typical illuminance values in different conditions.

| Illumination condition | Illuminance |
|---|---|
| Full moon | 1 lux |
| Street lighting | 10 lux |
| Home lighting | 30 to 300 lux |
| Office desk lighting | 100 to 1 000 lux |
| Surgery lighting | 10 000 lux |
| Direct sunlight | 100 000 lux |

## 2.1.5 Overcast sky according to CIE

CIE is the International Commission on Illumination, an independent, professional, non-profit organization which has been recognised as the best authority on illumination subject. For this reason it has been recognized by ISO as an international standardization body.

As a way to have a common valuable tool, CIE defined 15 types of sky to be taken as reference in different situations. The most relevant are shown in figure 2.10:

- Clear sky: the luminance in the clear sky varies over both altitude and azimuth, being brightest around the sun and dimmest opposite it, while the brightness of the horizon lies between these two. A clear sky can be defined by the rule of observation. At least 7/8 of the sky must be uncovered for the sky to be considered clear, and the covered patch of the sky must not cover the sun (Dubois et al., 2014)
- Intermediate sky: it is different from the previous one because it is somehow fog, so the brightness of the sun is lower and in general brightness changes are not so drastic;
- Overcast sky: the luminance of the overcast sky changes only with altitude, being three times as bright in the zenith as it is near the horizon. This type of sky is very important for measurement and definition of a fundamental parameter better presented in the following section: the Daylight Factor. Its peculiarity is also that it can be modelled under an artificial sky.
- Uniform sky: it is characterised by a uniform luminance that does not change with altitude or azimuth. It was very useful for hand calculations of use of tables.

  In figure 2.10 are shown the four different types of sky and the differences in their characteristics.

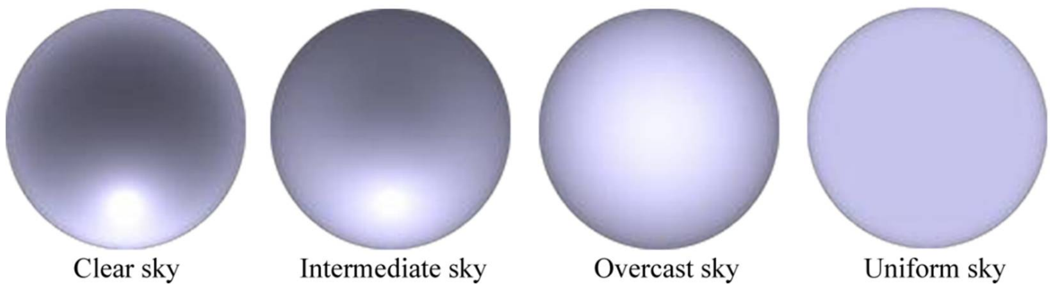



**Figure 2.10:** Representation of the main four types of sky by CIE, notice the difference between the intermediate sky and the clear sky in which luminance degradation is more observable.

Overcast sky is the best condition for monitoring procedure, because allow us to have a standard condition.
It is possible to perform a luminance range check before starting with measurements to be sure that the average horizon luminance is no more than half the zenith luminance (Baker and Steemers, 2002).

### 2.1.6 Daylight factor

The daylight factor is defined as the ratio between the illuminance due to daylight from the CIE overcast sky at a point on an indoor working plane to the simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky.

$$DF = 100\frac{E_i}{E_o} \tag{2.7}$$

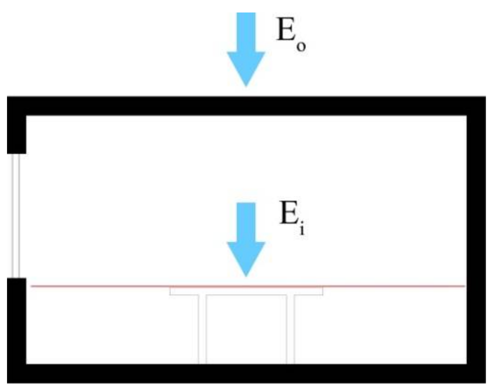



**Figure 2.11** Illuminance outdoor due to overcast sky conditions and illuminance measured on the indoor reference plan in red in a specific point of the working area.

From its definition it can be understood that DF is a value which changes according to the point in which it is measured. In order to define the overall amount of daylight in a space it is more useful to refer to the average daylight factor ADF, calculated ad a function of the angle of sky visible from the centre of the window, the glazing area and transmittance and the area of all the surfaces in the room (ceiling, walls, floor and windows) and their average reflectance. Studies showed that *"the ADF index is a useful predictor of the general daylight level in a space, as well as of the general level of combined daylight and electric lighting"(Galasiu and Veitch, 2006).*

### 2.1.7 Light interaction with solid materials

When light proceeds from one medium to another, three different phenomena may occur: the elementary beam of light can be partly reflected at the interface between the two materials, absorbed and transmitted according to the optical properties of the medium. All those events have both optical and thermal consequences, but for the thesis purpose only the optical ones will presented.

According to the law of the conservation of the energy, the intensity of a beam incident to the surface material must be equal to the sum of the intensities of all the components (transmitted, reflected and absorbed).

$$I_o = I_a + I_t + I_r \tag{2.8}$$

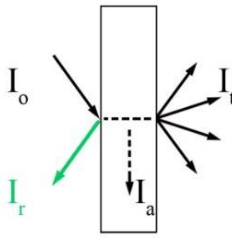



**Figure 2.12** The light beam coming from a light source and hitting a surface is partly absorbed $I_a$, partly transmitted $I_t$ and partly reflected $I_r$. From the image it is also possible to state that the sample of material is perceived as being green from human eyes and that it is a diffuse material, because the portion of transmitted light is scattered in all directions.

Or alternatively the same statement can be expressed with equation 2.9:

$$A + T + R = 1 \tag{2.9}$$

Where $A = I_a / I_o$ is the absorptivity of the medium, the fraction of luminous radiation absorbed by the material;

$T = I_t / I_o$ is the transmissivity of the medium, the fraction of luminous radiation transmitted by the material;

$R = I_r / I_o$ is the reflectivity of the medium, the fraction of luminous radiation reflected by the material.

Depending on the value assumed by each of those terms, a material can be classified as:

- transparent if it is capable of transmitting light with relatively little absorption and reflection, it one can see through them;
- translucent if it transmit light diffusely, which means that light is scattered when transmitted, so object on the other side that the observer are not clearly distinguishable;
- opaque if the reflective and absorptive parts are dominant so that it not possible to see through a specimen of the material.

Reflection and absorption of light waves are responsible of colours that we see, depending on their wavelengths as it will be explicate more at point 2.1.10, while transmission is very important for indoor daylight conditions. Moreover both reflection and transmission can be accompanied by diffusion phenomenon, also known as scattering, which is the deflection of a unidirectional beam into many directions.

However the optical properties of materials are not a constant since they depend on many parameters among which:

- thickness of the sample;
- surface conditions;
- angle of incidence;
- temperature;
- spectral composition of the radiation, in relation to the CIE standard illuminants.

2.1.7.1 Reflectance

Reflectance ρ [%] is the ratio of the reflected energy to the incident energy on a surface. In other words it represents the amount of incident light that is reflected from a surface as a function of the wavelength.

Depending of the characteristics of its surface, a translucent material can be defined as diffusive or semi diffusive. The main feature of the difference between these two terms lies in the roughness of the external layer of a solid; if it has many little surfaces, unevenly oriented in all the directions, then the phenomenon of diffusion occurs: each surface reflects light in a precise direction and the luminous beam reaching the solid is scattered (IEI, 2015). A fundamental feature of a surface perfectly diffusive is that it follows the cosine law, so that it appears equally luminous irrespective of the direction it is seen from, because the area effectively seen from a defined solid angle is inversely proportional to the cosα. An example of what has been described is a white wall.

2.1.7.2 Glazing transmittance

Transmittance τ is the ratio of transmitted energy to incident energy and there are two main type of transmittance according to the characteristics of the analysed material. The normal-normal transmittance $\tau_{nn}$ is measured for a non-diffusing glazing, perpendicularly to the glazing plane. For any glazing (clear, tinted or diffusing) it is useful to measure the transmittance for a diffuse light source such as the CIE overcast sky, called hemispherical-hemispherical transmittance $\tau_{hh}$ (Baker and Steemers, 2002). Only for diffusing glazing it is possible to define the normal-hemispherical transmittance $\tau_{nh}$; all the types of transmittance described are shown in figure 2.13.

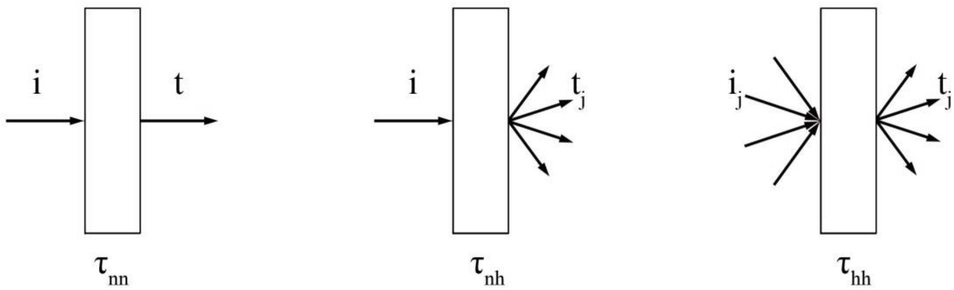



**Figure 2.13** From left to right: normal-normal transmittance, one incident light beam i and one transmitted light beam t (regular or direct transmission); normal-hemispherical transmittance, one incident light beam i and infinite transmitted light beams $t_j$ in all the directions (diffuse transmittance); hemispherical-hemispherical transmittance, infinite light beams striking the surface from every direction $i_j$ and infinite transmitted light beams t in all the directions $t_j$.

## 2.1.8 Dynamic parameters

Since it was formulated in late 20th century, the parameter Daylight Factor has been used to estimate the lighting levels in an indoor space but the assumptions needed for the calculation make it useless to quantify the amount of natural light in a room depending on the specific context of the site. In fact DF does not depends on the orientation of the glazed surface, does not include the contribution of sunlight by using the standard overcast sky condition from CIE; moreover the Daylight Factor refers to a single point measure at a precise moment: it is not adequate to simulate the real daylight conditions during a year.

For those reasons almost fifteen years ago a new daylight estimation theory has been proposed and it is currently still in phase of elaboration. It is called the climate-based daylight modelling (CBDM) and can be used to quantify the daylight availability in an indoor space through a year by using sun and sky conditions that are derived from standardised annual meteorological datasets (Mardaljevic et al., 2009). The luminous quantities predicted by the CBDM as absolute values such as illuminance, radiance and illuminance, depends on the geographic position of the site, windows orientation, geometry of the space and properties of the materials present in the space.

The CBDM can be used in two principal analysis methods, the cumulative and the time-series (Mardaljevic et al., 2009):

- The cumulative analyses is based on the sun conditions derived from climate data which allow to know the cumulative luminance effect of the sky and so predict some aggregate measure of daylight such as the total annual illuminance. It can be used on a period of one year, season or month even though the shorter the period of time, the more specific the results, missing the point of performing a dynamic estimation.
- The time-series analyses is used to evaluate the daylighting potential of a building over one year by predicting the occurrence of glare and taking into account the behavioural models of shading systems and use of electrical light. This is possible by predicting the instantaneous illuminance or luminance starting from hourly values in the annual climate dataset.

The estimation of the dynamic variation of skylight and sunlight conditions during the year as function of the specific climate conditions of the site (seasonal variations and irregular meteorological events) and orientation of the building in the site is possible by using the Dynamic Daylight Performance Metrics (DDPM) based on the two groups of parameter Daylight Autonomies group, Useful Daylight Illuminances group, and on the parameters Annual Light Exposure (Reinhart et al., 2006), Spatial Daylight Autonomy and Annual Sunlight Exposure (Cammarano et al., 2014). What makes possible for the DDPM to become a reliable method for daylight analyses is the sensitivity of its parameters to architectural features of a construction such as window area, room depth, orientation, obstruction angle, allowing specialists to find the appropriate solution for the best balance between daylight and thermal conditions at the design phase (Pellegrino et al., 2011). Without using the DDPM the daylight levels, presence of glare and visual discomfort, and thermal performances due to solar gains have to be studied separately in the static metrics by using DF, sun-path diagrams and thermal features of glazing surfaces (Mardaljevic et al., 2009).

Due to the great sensitivity of the Dynamic Daylight Performance Metrics to the previous aspects, before conduction a dynamic simulation it is fundamental to define: the points where to measure the daylight values into an indoor space; which time of the year over which the study has to be conducted, mostly identified by two categories as the daylit hours during a year or the occupied times of the year for the analysed area; the target illuminance as a threshold value depending on the function of the space, location and climate of the site (Rogers, 2006).

#### 2.1.8.1 Daylight Autonomies group

It is made of three parameters using daylight illuminance in a point at the work plane as indicator of daylight availability in an indoor space over a year. Due to the dynamic variation of illuminance with time, the daylight autonomy is expressed in reference to the threshold values DA, $DA_{max}$ and $DA_{cont}$.

- Daylight Autonomy (DA) first definition as dynamic parameter was elaborated in 2000 by Reinhart and revised in 2001 to take in account the presence and control of movable shading, so that the DA at a sensor is currently defined as *"the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone"* (Reinhart et al., 2006). Its highly generic definition allow the Daylight Autonomy to be suitable for use at any location in the world, in fact the threshold is the illuminance requirement for a considered space according to the reference standards of the site (Cammarano et al., 2014).
- Maximum Daylight Autonomy ($DA_{max}$) is a threshold set to ten times the illuminance requirement, used to evauate the percentage of times when the illuminance levels are so high that glare could occur (Cammarano et al., 2014).
- Continuous Daylight Autonomy ($DA_{cont}$) has been introduced for daylight compensation purposes by using electric lighting. Based on the DA values, the $DA_{cont}$ considers conditions when the minimum required illuminance value is not met but daylight is still quite sufficient so that a dimmed use of electric lighting is necessary. The parameter can be used when a daylight responsive control system is present, allowing to predict the potential energy demand for lighting (Pellegrino et al., 2013).

#### 2.1.8.2 Useful Daylight Illuminances group

It is made by three index which together represent the overall distribution of illuminances throughout the year. Each index, as the one from the DA group, considers the illuminance value at the work plane in a room when daylight levels are useful for the occupants (Reinhart et al., 2006), but in addition it refers the illuminance value to an upper and lower threshold (Cammarano et al., 2014). There are three main ranges on values (Pellegrino et al., 2013):

- $UDI_{fell\text{-}short}$ consist of all the illuminance values for which daylight can be considered substantially lacking. Firstly proposed in 2005 (Reinhart et al., 2006), the $UDI_{fell\text{-}short}$ has 100 lux as upper limit.
- $UDI_{achieved}$ is defined as the annual occurrence of illuminance values across the work plan within a range considered "useful" by the occupants (Mardaljevic, 2008) and can be divide into two sub-ranges called:
    - $UDI_{supplementary}$ having lower and upper threshold respectively 100 and 300 lux, it gives the occurrence of daylight illuminances for which an additional artificial lighting may be needed to supplement the daylight for common tasks such as reading;
    - $UDI_{autonomous}$ ranging between the values 300 and 3000 and giving the occurrence of daylight illuminances for whichadditional lighting will not be needed;
- $UDI_{exceeded}$ defined as the range of overabundant illuminance values for which the phenomenon of glare may occur.

#### 2.1.8.3 Annual Light Exposure

The Annual Light Exposure (ALE) is defined as the cumulative amount of visible light incident on a point of interest over the course of a year and measured in lux hours per year (Reinhart et al., 2006). It describes the daylight available in an indoor space over a year.

#### 2.1.8.4 Spatial Daylight Autonomy

The sDA assesses the sufficiency of annual illuminance in an interior work environment, it is defined as the percentage of an analysed area that meets a minimum daylight illuminance level of 300 lux for 50% of the operating hours in a year (Cammarano et al., 2014).

#### 2.1.8.5 Annual Sunlight Exposure

The ASE expresses the annual glare potential as the percentage of analysed area that exceed a specific direct sunlight illuminance level of 1000 lux for more than 250 hours per year (Cammarano et al., 2014).

### 2.1.9 Directionality

It is the evaluation of the direction of a light source in an indoor space. Depending on the activity performed in a room and the shape of the space, directionality can highly influence the visual comfort and the need of additional light spots in determined areas.

### 2.1.10 Colour

As stated at point 2.1.1, visible light refers to electromagnetic field in the range of wavelength 380-760 nm. If related to human eye's sensibility every λ can be associated to a different colour and despite in daily life colour is attributed to a surface of an object, it is due to the absorption of the part of the spectrum by the pigment of the surface and the reflection of the remaining parts. This is the reason why under an apparently white light, but constituted by different percentages of wavelengths, we see objects of different colours.

As anticipated in section 2.1.1 light that we perceive as white is made of radiation having different wavelengths and colours we see can be related to specific rages in the visible spectrum (Angelo, 2014):

- Violet $380 < \lambda$ [nm] $< 430$
- Blue $430 < \lambda$ [nm] $< 500$
- Cyan $500 < \lambda$ [nm] $< 520$
- Green $520 < \lambda$ [nm] $< 565$
- Yellow $565 < \lambda$ [nm] $< 590$
- Orange $590 < \lambda$ [nm] $< 625$
- Red $625 < \lambda$ [nm] $< 760$

*"Colour is light of a specific wavelength that we perceive as colour"* (Halonen et al., 2010), so from now on we have to refer to colour sensation instead of colour.

In 19th century Tomas Young proposed the tristimulus theory of perception (Gelighting, 2015), stating that any colour sensation can be generated by a combination of three primary colours identified as red, green and blue. According to this theory a combination of any two of these results in a secondary colour sensation, as shown in figure 2.14.

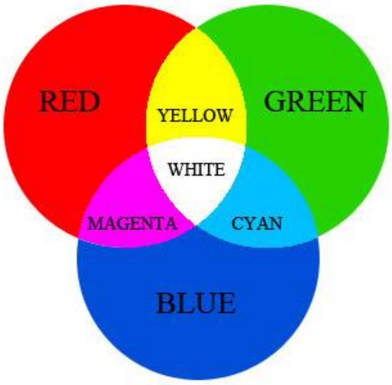



**Figure 2.14** Superimposition of two of the three primary colour lights red, green and blue produces the secondary colours yellow, cyan and magenta. Addition of the three primary colours produces white.

Human eyes can see millions of colours, some people can perceive more and others less depending on personal physical possibilities of colour perception, but give a name to all of them would be impossible. For this reason a common and reliable system is needed. In 1918 the American Albert H. Munsell identified three distinct qualities of colour to be utilized in order to classify any colour: hue, lightness and saturation. Definitions of these values are:

- Hue: *"this is the nominal colour, the name we give to the particular sensation e.g. red, orange, yellow, green etc"* (Gelighting, 2015);
- Lightness: *"a description of the brightness of a colour on a scale 0 to 10, from dark to light. This may vary within one colour, e.g. dark red- light red, or between colours e.g. yellow (light) – violet (dark)"* (Gelighting, 2015);
- Saturation: *"a measure of the degree of vividness of a colour – from a pure hue, through varying tints of decreasing colour to grey"* (Gelighting, 2015).

Using this system, any colour can univocally be revealed by a list of three coordinates in the order hue/lightness/saturation, but the limit of this theory is that one has always to refer to a basic colour sample, as a comparative method.

More modern methods are based on wavelength and sensitivity of the colour receptors of the eye (see section 3.1) to define the colour of a surface. Still based on the three-component theory of vision, the modern XYZ tristimulus theory define a colour by three components in a space as the product of the incident illumination, the reflectance of the surface, and the sensitivity of the eye for a particular wavelength, integrated over the whole visible spectrum (Gelighting, 2015).

In 1931 CIE elaborated a way to graphically represent colours on a diagram by combining chromacity and saturation so that a colour is identified by just two coordinates as shown in figure 2.15, where:

$$x = \frac{X}{X+Y+Z} \text{ and } y = \frac{Y}{X+Y+Z} \ .$$

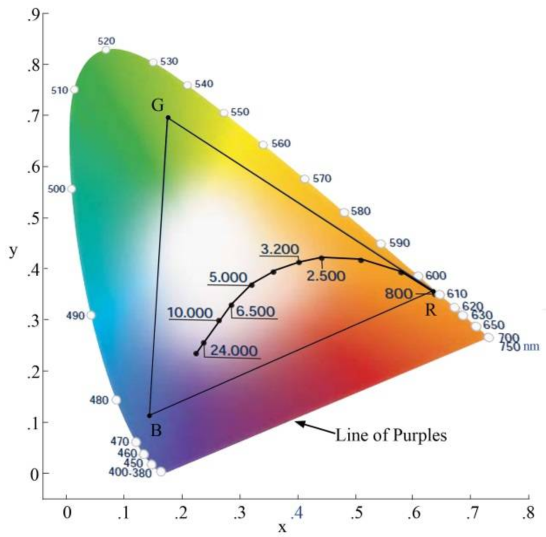



**Figure 2.15** Rough rendering of the 1931 CIE colours on the chromaticity diagram. The black line indicates the Planckian Locus, all the colour temperatures and wavelength that the blackbody can possibly reach. The colour inside the black triangle can all be obtained by mixing the three primary colour green (G), red (R) and blue (B). The lower edge of the diagram is known as line of purples, locus of all the fully saturated colours: there is no monochromatic light source able to generate a purple colour. Instead, every colour on the line of purples is produced by mixing a unique ratio of fully saturated red and fully saturated violet

## 2.1.11 Colour temperature

The concept of colour temperature has been introduced from CIE (??) as the temperature of a black body that gives light of the same colour sensation as the light emitted by a light source. The black body is a theoretical entity, an ideal body or surface capable of absorbing all the electromagnetic radiation falling on it with no reflection and that radiates at all frequencies with a spectral energy distribution dependent on its absolute temperature. The colour temperature only refers to artificial light sources.

All the possible colour temperature of the black body can be represented on the 1931 CIE colour diagram by the so called Plank locus, shown in figure 2.15. This curve originates in the dark red region of the diagram, proceeds through the white region, and ends in blue. Planck's Law can be used to designate the relative colour temperature of a light source and can be expressed as absolute temperature (Kelvin).

Technically, a colour temperature designation can apply to an incandescent lamp only, and for those sources that adhere to the Planckian Curve. However, in illumination engineering, the terms Apparent Color Temperature and Correlated Color Temperature are often used to specify a degree of the whiteness of fluorescent, high-intensity discharge and daylight lamps. Even daylight does not exactly match the black body curve.

Enlarging a section of the 1931 CIE colour diagram, there is an infinite number of chromaticity coordinates that could represent any correlated or apparent colour temperature. For this reason the American National Standards Institute (ANSI) has specified a range of chromaticities acceptable for a specific colour temperature.

## 2.2 List of symbols and abbreviations

The list of all the symbols and abbreviation used in the thesis is presented:

| | | |
|---|---|---|
| A | Absorptivity | [-] |
| ALE | Annual Light Exposure | [lux h/a] |
| ASE | Annual Sunlight Exposure | [%] |
| BIM | Building Information Modeling | |
| CBDM | Climate-based Daylight Modelling | |
| CIE | International Commission on Illumination | |
| $CO_2$ | Carbon dioxide | |
| DA | Daylight Autonomy | [%] |
| $DA_{cont}$ | Continuous Daylight Autonomy | [%] |
| $DA_{max}$ | Maximum Daylight Autonomy | [%] |
| DDPM | Dynamic Daylight Performance Metrics | |
| DF | Daylight factor | [%] |
| E | Illuminance | [lux] |
| $E_{hd}$ | Exterior horizontal diffuse illuminance | [lux] |
| $E_{in}$ | Interior horizontal illuminance | [lux] |
| $E_{out}$ | Exterior illuminance | [lux] |
| EM | Electromagnetic field | |
| ERC | External Reflection Component | |
| f | Frequency | [Hz] |
| FLD | Fattore di luce diurna | [%] |
| HDR | High Dynamic Range | |
| HVAC | Heating, Ventilating and Air Conditioning | |
| I | Luminous intensity | [cd] |
| IEA | International Energy Agency | |
| IRC | Internal Reflection Component | |
| J | Energy | [J] |
| L | Luminance | [cd/m$^2$] |
| $O_3$ | Ozone | |
| R | Reflectivity | [-] |
| SAD | Seasonal Affective Disorder | |
| SC | Sky Component | |
| sDA | Spatial Daylight Autonomy | [%] |
| SHC | Solar Heating and Cooling programme | |
| SPF | Specific Power Fan | [kW/m$^3$/s] |
| T | Transmissivity | [-] |
| UDI | Useful Daylight Illuminance | [lux] |

| | | |
|---|---|---|
| UGR | Unified Glare Rating | |
| VCP | Visual Comfort Probability | |
| XUV | Extreme ultraviolet radiation | |
| $\Phi$ | Luminous flux | [lm] |
| $\Phi_{e\lambda}$ | Radiant flux | [W] |
| $\lambda$ | Wavelength | [m] |
| $\rho$ | Reflectance | [%] |

# 3 Daylight and health

Human race and most of the animals have always lived and evolved under daylight influence and based their life-cycle on the daily path of the Sun in the sky. Human body, in all its complexity, interacts with natural light on many levels: not only through the eyes for vision, but also with the skin providing a layer of pigmentation to protect the body from high radiation intensities. Moreover, even though causes and reasons are still not clearly defined, humans have developed a wide range of physiological and psychological responses to the varied characteristics of daylight (Aries et al., 2013), for this reason more and more often it is common to distinguish between visual and non-visual effects of light.

As presented in chapter 2, daylight is highly variable during a day, a month, seasons and years, depending on many reasons like weather conditions, inclination of Earth's axis and relative Earth-Sun position. According to scientific studies (Boyce et al., 2003) the daily variability is very important to be experienced by humans resulting in stress reduction and increase of productivity. On the other hand, daylight can also cause discomfort, especially in indoor spaces when it provides an uncomfortable level of glare.

The World Health Organization defines health as "a state of complete physical, mental and social well-being" (WHO, 2006), the adjective "complete" implicitly indicate the complexity of relation between different factors which finally result in the healthy status. Health is not only absence of disease or physical infirmity, it is also highly influenced by many subjective responses of the human being to his surrounding and many experimental studies have related daylight with lower absenteeism, reduced fatigue, relief of SAD, decreased depressive symptoms, better vision, positive impact on behavioural disturbances seen in Alzheimer's disease and other advantages (WHO, 2006).

However it is important to take in account all the possible ways of interaction between Sun and humans through solar light; some of them have positive consequences such as the stimulus in the cutaneous synthesis of vitamin D, others have negative consequences as erythema, skin cancer, photoaging, DNA damage, eyes damage (Webb, 2006).

According to numerous studies (Holick, 2004b) vitamin D is necessary for calcium metabolism preventing osteoporosis, lowering blood pressure which if too high is responsible of cardiovascular diseases. Deficiency in this organic nutrient has been associated with increased risks of deadly cancers, multiple sclerosis, rheumatoid arthritis, and type 1 diabetes (Holick, 2004a). Differently from the major part of vitamins, vitamin D is contained in very few food, but our organism is able to self-produce it through a photosynthetic reaction triggered by exposure to UVB radiation (wavelength 290–315 nm). In fact sunlight is the most important source of this organic compound in human body, but the efficiency of production depends on the number of UVB photons that penetrate the skin, a process that can be curtailed by clothing, excess body fat, sunscreen, and the skin pigment melanin. For most white people, a half-hour in the summer sun in a bathing suit can initiate the release of 1.25 mg vitamin D into the circulation within 24 hours of exposure (Mead, 2008). Consequently it results that human skin has a large capacity for vitamin D production, under normal conditions it is able to supply the body with 80 to 100% of vitamin D requirements (Glerup et al., 2000). The fact that the body can produce vitamin D by itself has changed the way this substance is considered, shifting it from being a true vitamin to a steroid hormone. However an excessive and uncontrolled exposure of human skin to solar radiation can cause many serious diseases. Unfortunately for most of the people the best solution to prevent negative consequences is limiting sunlight exposure during the year resulting in vitamin D deficiency, while a conscious understanding of UV-effects related to the individual skin type would be sufficient to avoid UVR overexposure and have the necessary amount of radiation reaching the skin (WHO, 2006).

First among all the possible negative consequences of sunlight exposure is cancer, both benign and malignant. In particular Gallagher et al. (1995) in their studies found out that the probability of developing basal cell carcinoma (BCC) of the skin, the most common neoplasm in white population, is higher for adults whose skin tended to burn rather than tan in the sun during their childhood and adolescence. This is because ultraviolet B radiation is highly mutagenic and carcinogenic compared to UV-A (wavelength 320-400 nm) radiation (Ichihashi et al., 2003). It is highly genotoxic but it does not penetrate farther than the skin and the human skin is extremely well adapted to continuous UV stress (de Gruijl, 1999).

Secondly, excessive sunlight exposure can cause a high number of dermatological diseases such as localized hypomelanism, localized hypermelanism, seborrheic keratoses, senile lentigines, freckles, acne rosacea, spider nevi, varicose veins, venus star, dry skin, wrinkled skin, pterygia, arcus senilis, and a variety of minor oral lesions of the tongue, palate, and buccal mucosa, which could all be easily prevented by conscious skin protection filters (Engel et al., 1988).

Negative or positive influence of sunlight on humans is not applied only on a physical level, in fact the body is a tool in the interaction between light and health. To better understand the division between visual and non-visual effects of light it is important to know how the human visual apparatus is made.

## *3.1 Human body physical structure*

The most important and complex part of the human body interacting with daylight is the visual system. It is made of three main parts:

- the eye: place where all the sensors are present;
- the optic nerve sending information collected by the sensors to the brain as electric stimulus;
- the brain, where all the collected information are elaborated.

Human eye is a highly elaborated organ, it can be considered as a perfect machine for image elaboration. From figure 3.1 it is possible to divide the eye in two parts:

- Part A is made of all those elements that one can see from the outside and it is the way through which the communication between external world and internal part of the human body occurs. It is made of :
    - Cornea, the clear, transparent front portion of the fibrous coat of the eye, acting like a refracting medium;
    - Conjunctiva, a mucous membrane constituent the posterior layer of the eyelids and the anterior layer of the eyeball;
    - Iris, the coloured, circular membrane suspended between the cornea and the lens. It regulates the amount of light entering the eye by adjusting size and pupil thanks to ciliary muscles. Pupillary constriction is highly dependent on the wavelength (SCENIHR, 2012), in humans and primates it is observed at 5 $cd/m^2$ at $\lambda = 482$ nm (Gamlin et al., 2007);
    - Pupil, the opening at the center of the iris. It changes diameter according to the amount of light it is exposed to and to focus on objects at different distances; in particular it contracts when exposed to strong light or when the focus is on a near object and it dilates when in the dark or when the focus is on a distant object;
    - Lens, the transparent tissue behind the iris that bends light rays and focuses them on the retina;
    - Vitreous body, a transparent, colourless mass of soft, gelatinous material that fills the center of the eye behind the lens.
- Part B is the inner part of the eyeball, where different types of sensors and membranes are present and where the light beam coming from the pupil is split and elaborated. It is composed by:
    - Sclera, the tough white protective coat of the eye, covered by the conjunctiva on the portion surrounding the cornea;
    - Choroid, tissue placed behind the retina. It is rich of blood vessels and responsible for the retina's nourishment;
    - Retina, a light-sensitive tissue at the back of the eye which transmits visual impulses via the optic nerve to the brain. It is covered of different types of photoreceptors, the major are rods and cones, except for one point, called the blind point, where there is the connection between the retina and the optic nerve;
    - Fovea, the part of the retina where the most of the cones are located. Here the eye keeps the viewed image in focus by its accommodation mechanism involving adjustments of the lens curvature by contraction of ciliary muscles;
    - Macula lutea or "yellow spot", the pigmented central area of the retina having a diameter of about 2 mm. It lacks of blood vessels and its main role is to filter blue light coming to the fovea and limiting big damages due to staring at strong light sources. It is the most sensitive area of the retina and is responsible for fine or reading vision;
    - Optic nerve, the nerve at the back of the eye that carries visual impulses from the retina to the brain. The area at which the optic nerve connects with the retina is known as the optic disc or blind point.

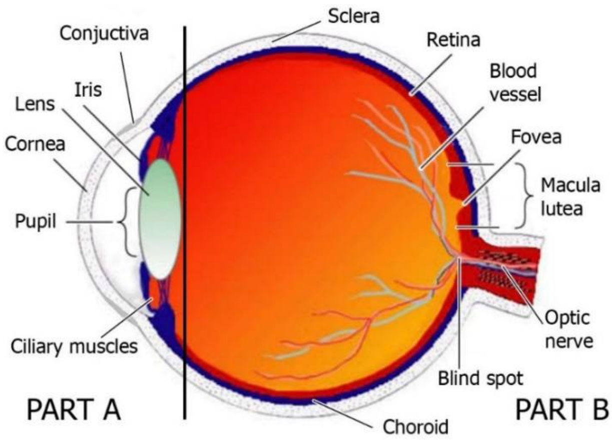



**Figure 3.1** Human eye cross section, division in part A, in contact with external world, and part B, internal part. Image modified from (Schubert, 2006).

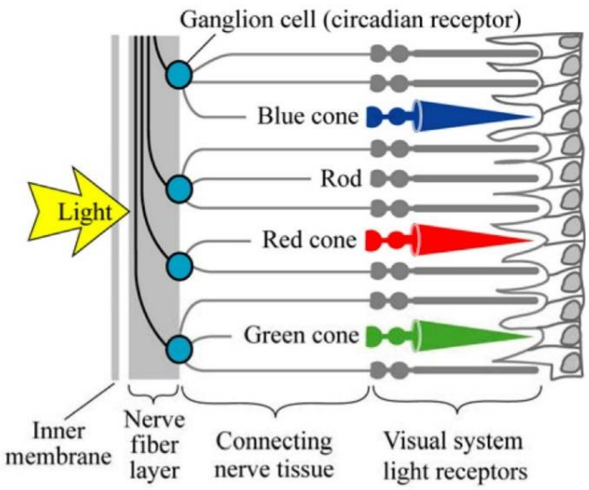



**Figure 3.2** In the retina's cross section it is possible to identify the three types of cone cells, each of them responsible for detection of one colour among red, green and blue. Image from (Schubert, 2006).

A photoreceptor is a light-sensitive receptor cell present in the retina, able to transform light into neutral activity. For more than 150 years, scientists considered the existence of only two type of photoreceptors in the eye: rods and cones. The rods are the most light-sensitive cells and the ones with higher quantity in the retina, in fact there are approximately 120 million rods (Fontoynont, 1999). They are more present at the outer edges of the retina, for this reason they are mainly responsible for the peripheral vision. Rods provide the so called "scotopic vision", a low-acuity monochrome vision occurring at low ambient light levels (luminance < 0.003 cd/m$^2$) (Schubert, 2006). Due to impossibility of colour detection by rods, in the scotopic vision range objects lose their colour and appear in different shades of grey. The cones are less present than the rods but with higher density in the fovea; there are approximately 6 million of cone cells, divided in three types, each sensitive to either blue, green or red light due to the pigments present in those photoreceptors, having peak wavelengths respectively around $\lambda_{max}$ = 440 nm, $\lambda_{max}$ =535 nm and $\lambda_{max}$ = 575 nm depending on the individual, while pigments in the rods have $\lambda_{max}$ = 498 nm. Due to those peaks, cones are denoted as the red-sensitive, green-sensitive, and blue-sensitive cones, or simply as the red, green, and blue cones (figure 3.2). Besides the three type of photoreceptors responsible of colour vision are also identify as L, M or S-cones as abbreviation of the long, medium and short wavelengths they respond to. Due to their privileged position in the fovea and light sensitivity characteristics (3 cd/m$^2$ < luminance < 10$^4$ cd/m$^2$) (Schubert, 2006), cones provide high-acuity vision called "photopic vision". In the range between the scotopic and photonic vision, the two previous regimes compete simultaneously giving origin to the mesopic vision, as shown in figure 3.3.

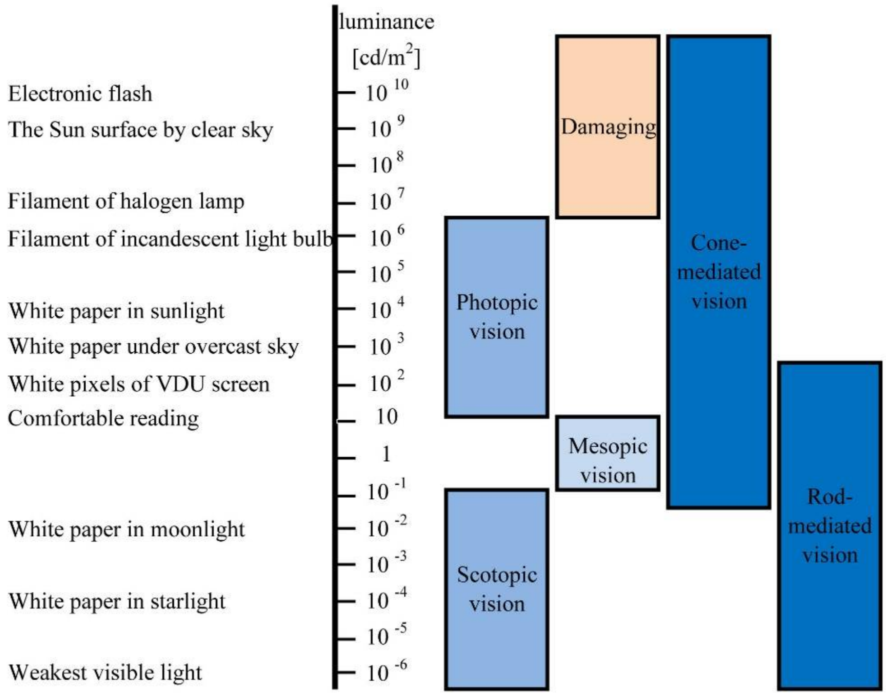



**Figure 3.3** Photopic and scotopic luminance ranges and relative light sources.

Structurally both the photoreceptor types have the same cone-like shape, which is possible to divide in three parts (Strettoi et al., 2010):

- Outer segment, characterized by cell membranes called disks, containing a transmembrane protein in which the photo pigments exist. The membrane shape provides more surface area for light to affect the pigments. One difference between rods and cones lays in the position of those disks: attached to the outer membrane in the cones or pinched off in rods;
- Inner segment, with an interior nucleus, organelles and all the elements necessary to the cell metabolism. It is connected to the outer segment by a cilium;
- Synaptic terminal forming bridge for signal transmission by a synapse from the photoreceptor to the bipolar cell.

Only in 2002 scientists from the Brown University (USA) (Berson et al., 2002) discovered a third photoreceptor cell in the retina of mammals, called intrinsic photosensitive retinal ganglion cell (ipRGC) responsible to regulate many non-visual biological effects like circadian rhythm, body temperature, heat rate, cortisol production, melatonin production and alertness. Even though it is not excluded that also rods and cones can play a role in influencing those aspects, it is correct to believe that most of the credit belongs to the ipRGCs because they have their own nerve connections in the part of the brain called suprachiasmatic nucleus (SCN), scientifically known as the place for the biological clock of the brain (Bellia et al., 2011). Moreover light reaching the ganglion cells also influences hormones production because the SCN is connected to the pineal gland, responsible for their regulation.

The suprachiasmatic nucleus, made of about 20˙000 nerve cells, is located in the hypothalamus, a structure of the central nervous system responsible to link the nervous system to the endocrine system. The hypothalamus synthesizes and secrets neurohormones, controlling body temperature, hunger, attachment behaviours, thirst, fatigue, sleep and the circadian rhythm through the SNC.

## *3.2 Circadian system*

The circadian rhythm is the combination of physical, mental and behavioural changes occurring in a roughly 24-hours cycle, primarily responding to light and darkness sequence in an organism's environment (NIGMS, 2012). It is different from the biological clock but the two are related because the second one drives the circadian rhythm.

The circadian rhythm is every day reset according to an individual internal clock, synchronized with natural day-night cycle by external stimuli such as sunlight and temperature in the surrounding but also by social stimuli such as having lunch all days at the same time. External daily changes influence the circadian rhythm because the suprachiasmatic nucleus gets light information through photosensitive cells on the retina and, working on a 24-hours cycle, it sets our biological rhythms on the day-night shift by releasing more or less amount of certain hormones. When the synchronizing stimuli are missing, the circadian rhythm is still active but the individual experiences a shift in the duration of this cycle: the sleep-awake rhythm can last up to 36 hours and the body temperature one has a period of 25 hours. In normal conditions “the human circadian rhythm needs to be reset each day, in order to maintain an appropriate phase relationship with the environment” (Linhart and Scartezzini, 2011).

The most important hormone controlling the body activity and responses to the surrounding is the melatonin, responsible of the sleep-awake regulation. For a normal clock-set organism melatonin production stops in the range between 6:00-8:59 am, at the same time the stress hormone cortisol production increases, inducing an alert state in the organism: we are awake. Between 9:00 and 11:59 am the cortisol has a peak, leading to maximum concentration and organism activation. As consequence the body temperature, which started rising since the awakening, reaches its peak around midday together with the main cognitive functions. Short-term memory and working memory, responsible for the multitasking, are at their best: it is the most productive period in the day. From 12:00 to 14:59 usually the individual eats and the body is occupied in the complex action of digestion, generating a general sleepy feeling. The grade of how sleepy a person feels also depends on the nature of the meal: high glucose levels in the blood induce a stop in the production of the protein orexin, crucial for the maintenance of the wakefulness status. The range between 15:00 and 17:59 is perfect for physical activity, in fact the body temperature naturally rises again, heart and lungs have the highest efficiency in the day, muscles are more tonic. Between 18:00 and 20:59 it is time for a light dinner, getting closer to the sleeping time makes digestion harder for liver and intestine. From 21:00 to 23:59 the pineal gland starts producing the melatonin, body temperature decreases resulting in a sleepy feeling, but this natural process can be modified if a person practice physical exercises after dinner, because body temperature and heart beat will need more time to stabilize on necessary levels. Moreover also exposition to smartphones, tablets and pc influence our sleepiness, in fact the light emitted by those screen is more in the blue range, slowing the melatonin production (Focus.it, 2015). In figure 3.4 the variability in level of three hormones during a circadian cycle of 24-hours is shown and in figure 3.5 a summary of hormones secretion is presented.

The circadian system is the complex mechanism that makes possible having those crucial moment in everyday life, affecting our sleep-awake clock, body temperature, melatonin and serotonin production, cortisol concentration, physical and mental performances, eating and drinking habits, potassium, sodium, calcium, magnesium and phosphor concentrations in urine and growth hormone production, linked to the biological clock.

The relationship between circadian rhythms and light lays in the vitamin-A photo pigment melanopsin, contained in the retinal ganglion cells distributed across the inner retina (SCENIHR, 2012), this is the reason why both blind people and colour blind people experience melatonin suppression when exposed to light: they still have intact neutral pathways between eye and SCN (Webb, 2006). The melanopsin sends information about light exposure from the retina to the suprachiasmatic nucleus, which interprets it and stimulates the secretion of the hormone melatonin by the pineal gland, a tiny structure located in the epithalamus (Matusiak, 2014). A schematic representation of hormones production and glands interaction is shown in figure 3.6.

A circadian rhythm aligned with the 24-hours daily cycle is influenced by many factors such as personal habits (which activities carried out during a day and at what time), amount of light the individual is exposed to but also the intensity and wavelength of this luminous radiation. In fact melanopsin is highly reactive to blue light, in a range of wavelength going from 420 to 470 nm (Dacey et al., 2005). As shown in figure 2.8, section 2.1.4, daylight provides a strong radiation in the blue region, being a natural melanopsin regulator, moreover the pineal gland results to be more reactive in the early morning with a peak of sensitivity around 4 am, when even low intensity light can influence a positive phase shift. During the rest of the day the pineal gland’sensitivity become lower and lower and higher intensity or longer light exposure have the same effect than a short exposure in the morning (Matusiak, 2014). According to the mathematical model elaborated in 1990 by Kronauer (Jewett et al., 1999), there is a cross over point around 2 pm in the day after which the more exposure to daylight, the slower the circadian rhythms.

However despite many studies conducted and mathematical elaboration of standard models, “*different people have different responses to the same lighting level because circadian cycle and body performance are different*” (Begemann et al., 1997).

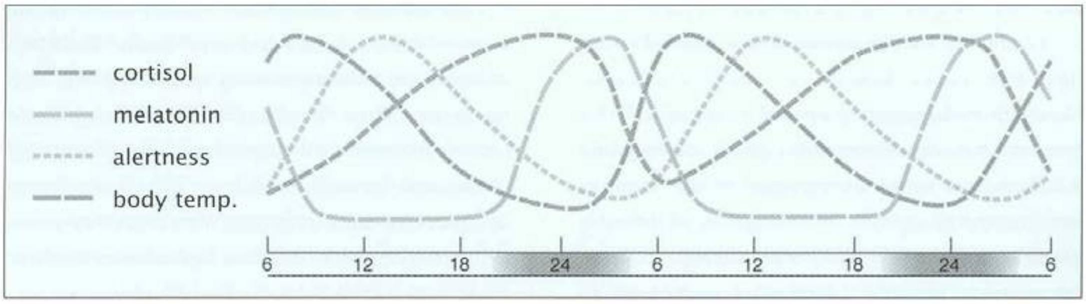



**Figure 3.4** Plot of typical daily rhythms of cortisol, melatonin, resulting alertness and body temperature in humans for a natural 24-h light/dark cycle.

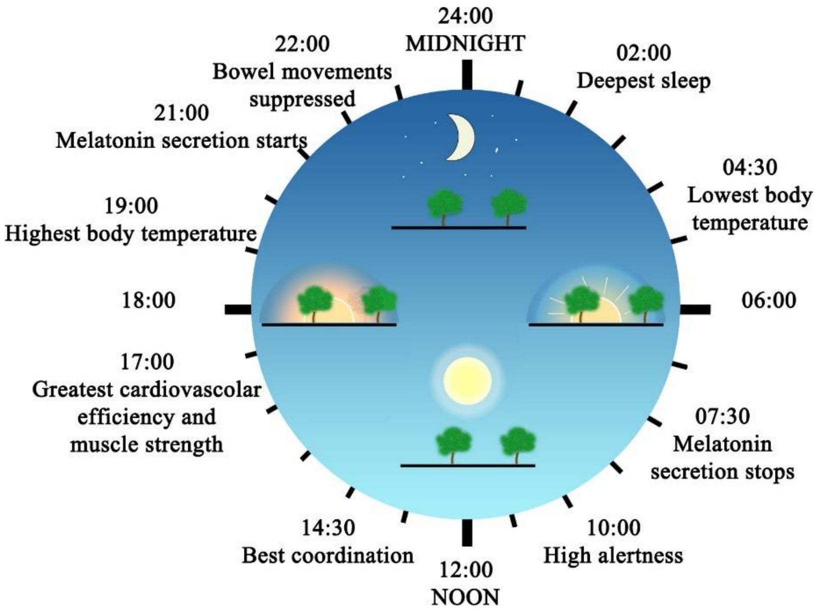



**Figure 3.5** Principal events of the circadian rhythm through a 24-hours cycle.

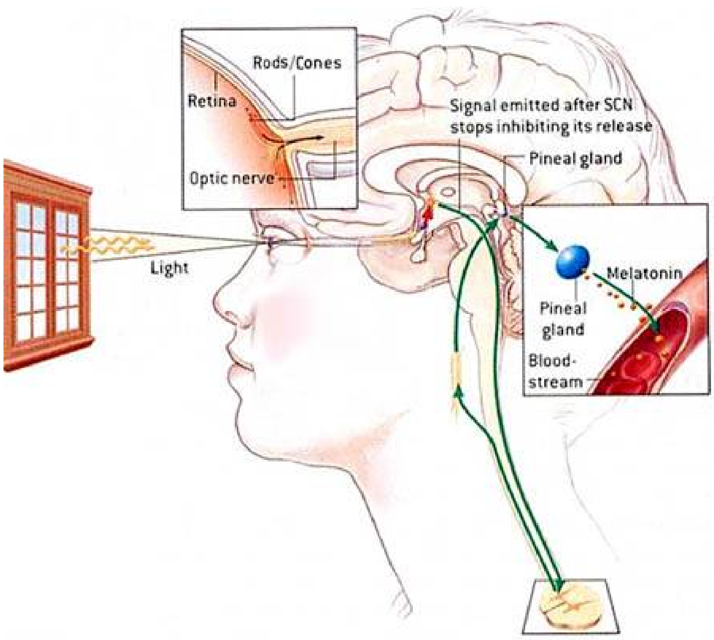



**Figure 3.6** Representation of glands and organs involved in the circadian rhythm regulation. Image source “The Visible Embryo” (TVE, 2011).

### 3.2.1 Daylight conditioning the circadian rhythm

What is commonly defined as non-visual effects of light is the group of physical and behavioural aspects influenced by light such as sleep/awake cycle, daily patterns of hormone secretion and body temperature cycles. This is possible because, as previously described, once in the eye, stimuli from light are elaborated both by the visual system, allowing us to see objects, and another system, made of the SCN and pineal gland with secretion of hormones.

Medical research have shown that a prolonged lack of "light vitamin" can cause health problems, ranging from minor sleep to depression, and in his study Begeman (1997) calls this group of diseases "ill-lighting syndrome". It is mostly experienced by people working in indoor environment devoid of windows or with very low lighting levels.

A more general but similar syndrome is the SAD (Seasonal Affective Disorder), that affect about 5% of the population in northern countries, both children and adults, especially during winter months. It is caused by light underexposure over a long time and results in increase susceptibility, mood disorders and weakening of the immune system (Matusiak, 2014). The Seasonal Affective Disorder is a scientific recognized pathology and three evidence-based treatments exist: antidepressant medications, light therapy and psychotherapy, on the other hand SAD's causes are still only hypothesis, due to acute observation of human behaviours. Studies on mice (Roecklein et al., 2013) show an abnormal production in melanopsin levels when genetic mutations in ganglion cells are present, but at the same in normal organism, winter nights results in a longer duration of melatonin, leading to biological changes in feeding and sleeping habits.

If the SAD is very general and influence every aspect of patients' life, another circadian rhythm pathology is more specific and called "circadian rhythm sleep disorders", a family of sleep disorders affecting the timing of sleep. People with this kind of pathology are unable to sleep and awake at the times required for normal work and social needs, if forced to follow the common 24-hours cycle they wake up unrested and feel sleepy all the time. They are generally able to get enough sleep only if allowed to sleep and wake at the times dictated by their body clocks (ScienceDaily, 2015).

Secondary effects of non-sufficient intensity of light reaching the retina during a day is the shift of the circadian rhythm from 24-hours to 25.1 hours due to a gradual slowing down in the pineal gland's release of melatonin. In fact if melatonin is secreted at the wrong time of the day, the individual experience a constant lethargy and drowsiness. Also according to the age and the practiced activities during the day, young people could experience a "delay sleep phase disorder", feeling tired and unlikely to work, experiencing lack of concentration, while on the other hand elderly people may experience "onset insomnia and maintenance insomnia", waking up very early in the morning and falling asleep randomly during the rest of the day (Matusiak, 2014).

In the last few years, the growing understanding of the circadian rhythm and its relation with light is encouraging scientists to find light-based solution to circadian disorders both caused by artificially and naturally reduction of light quantity and by possibly common living conditions such as travel jet-lag, shift work, sleep disorders (Linhart and Scartezzini, 2011).

## *3.3 Visual comfort*

Based on the division between visual and non-visual effects of light, it is important to wonder about necessary light levels in relation to these two main function of light. In fact lighting level required for visual needs is much lower than the one required for well-being purposes, on the contrary too high illuminance values result to be not pleasant for human eyes. In the wide meaning on well-being previously presented, one more important aspect has to be considered: visual comfort. When dealing with comfort, subjectivity of users play the main role and it is never easy to decode whether a certain lighting condition is appropriate for every human being or not, however it is possible to note some criteria of discomfort that it is necessary to avoid in order to tend towards a good level of optic comfort in any case. Some discomfort factors are glare, backlighting, shadows, heterogeneous lighting and too low light levels; those can be present in a space only for short periods in a day, moreover visual comfort highly depends on the task to be performed and on the time over da day, as it evolves from morning to night following the biological rhythm (Leclercq et al., 2008).

### 3.3.1 Glare

Glare is a sensation of visual discomfort caused by high luminance or excessive luminance differences in the visual field due to the presence of bright light source, bright surface, the sky or the sun. The glare caused by the sun is called solar glare and it is the most serious form of glare since the luminous intensity of the sun is extremely high compared to all known electrical light sources (Marszal et al., 2011). Glare is a subjective human sensation because it occurs when the *"light within the field of vision is brighter than the brightness to which the eyes are adapted"* (EFFIENERGIE, 2008), causing annoyance, discomfort or loss in visual performance and visibility.

There are two admitted types of glare: disability and discomfort glare. Disability glare is the inability of a person to see certain objects in a scene due to glare and it doesn't necessarily implicate the simultaneous condition of discomfort glare, which refers to the sensation one experiences when the overall illumination is too bright, so it is more related to a single person's satisfaction (Reinhart and Wienold, 2011).

Disability glare is often caused by the inter-reflection of light within the eyeball and can be accentuate by old age or optical diseases such as cataract or corneal edema (EIS, 2015). Between the two types of glare, the disability one is the easiest to identify, while for the evaluation of the magnitude of discomfort glare some scientific systems are established such as Unified Glare Rating (UGR), Visual Comfort Probability (VCP) or British Glare Rating system, but on the other hand the physiological or perceptual mechanism for discomfort glare is not established yet (Halonen et al., 2010).

Considering the visual field of a standard user as a cone of approximately 140° apex, it is possible to divide it into three sections with quite different characteristics, named: area of central vision, ergorama and panorama. Detection of glare is not based on absolute vales of luminance but on relative ratios among the sections, variable depending on the working task to be performed. Definitions of the three parts of the visual field are (Baker and Steemers, 2002):

- Area of central vision a restricted zone bounded by a cone of 1° apex, also called task point. All the visual system adjusts in order to reach the best focus on this area, because the light rays reflected by objects in the area of central vision reach the retina on the fovea, where is possible the most acute vision.
- Ergorama is a circular zone delimited by 60° apex, encircles the central area. The light from the zone is mostly perceived by rods so that the vision is progressively more blurred and indistinct as the distance from the centre of the area increases. Usually most of the objects needed to perform a working task are contained in the ergorama.
- Panorama is the outer part of the visual field and cannot be considered to be circular as it is delimited by the nose, forehead and cheeks. Objects in the area are hardly noticeable unless they move.

Moreover also the daylight factor can be linked to the probability of glare to occur, in general scientific studies found out that is DF>10% glare problems definitely occur (Dubois et al., 2014). The first solution to be applied in order to avoid this cause of visual discomfort is the reduction of illuminance values in the room when too high; a Japanese study (Mardaljevic, 2008) revealed that the occurrence of illuminances greater than 2.500 lux have to be avoided but not completely eliminated because a moderate occurrence could be useful for the circadian system, however the optimal level of exposure is not known yet.

### 3.3.2 Required values for visual needs vs. non visual demands

Unfortunately so far most of the lighting design in indoor spaces only has the goal to fulfil standard requirements, based on vision related tasks. The main European standard about indoor lighting is EN 124641-1:2011, which specifies lighting requirements for people in indoor work places, meeting the needs for visual comfort and performance of people having normal ophthalmic capacity. In this standard the main lighting design parameter is the horizontal illuminance on the working plane, but it is not relevant for non-visual stimulation which depends on the vertical illuminance ad the eye (Aries, 2005). Another difficulty concerning lighting design lays in the highly subject-dependent response to light of users in a building; in fact required values are based on statistic measurements performed on a representative group of visually normal endowed humans. This great variability in responses to the same lighting level regards both visual needs and circadian cycle or body performance. “The preferred lighting environment is related to individual sensitivity to light, individual sleep quality, synchronization of the biological clock and fluctuations in degree of discomfort and well-being” (Begemann et al., 1997).

Lighting that meets both the human visual and non-visual demands without causing visual discomfort is called ‘healthy lighting’, but only recently some producers in the lighting field have started paying attention to lighting products with a spectrum that provides more natural lighting environments.

Demonstration of how different are the design for visual needs and the one regarding non-visual requirements are first of all the specification referring to the two processes: illuminance, luminance, daylight factor for visual tasks and intensity, timing, dynamics, direction and spectral composition of ocular light exposure for non-visual requirements. In fact even though exact values are not yet known but literature shows that a high lighting level is the prime requirement for a healthy work environment (Aries, 2005).

In her study, conducted over 10 office buildings analysing a total of 87 workstations, Aries (2005) found out that even though all the visited offices met the visual criteria and users were satisfied with the lighting conditions at their desks, non-visual lighting criteria were not satisfied, resulting in employees fatigue and bad sleep quality. The results of this research show a direct correlation between levels of vertical illuminance and fatigue and sleep quality, reaching a high chance for complete users' satisfaction if the luminance level of bright light source is kept below 1500 cd/$m^2$.

According to EN 12464-1:2001 the recommended horizontal illuminance ($E_{hor}$) level of the task position has to be in the range between 200 and 700 lux; even an $E_{hor}$ = 500 lux is required for office desk position, a value of $E_{hor}$ > 800 lux is preferred by users. There are also prescribed levels of maximum luminance especially for office work with visual display terminal (VDT's): the standard recommends to limit the average luminance of lighting fixtures, window or other surfaces that can be reflected in the computer screen to 1000-1500 cd/m$^2$ (UNI, 2011). A summary of the requirements from the European standard is presented in table 3.1.

Looking at non-visual demands, literature and standards present a requirement of 1000-1500 lux for light intensities on the vertical plane, but not continuously during all day: a dynamic light dosage is highly recommended. Even there are no particular luminance demanding for non-visual performance, experiments based on work with VDT's showed that with increasing lighting levels in the room the visibility at the computer monitor may get critical and the visual comfort limits of human beings could be reached. There are three factors universally known as being responsible of visual comfort (Boduch and Fincher, 2009):

- Light levels based on the principle the more intense is the task, the brighter the light required;
- Contrast according to the formulation the greater the contrast, the easier the comprehension;
- Glare, which is undesirable because it makes difficult to see object of attention.

A healthy lighting that meets both visual and non-visual demands of people without causing visual discomfort is not easy to realize, requiring at the same time 800 lux horizontally at the desk, 1000 lux vertically at the eye with luminance levels lower than 1500 cd/m$^2$.

Unfortunately indoor daylight values rarely reach the values required to activate circadian rhythms, according to some researchers E > 1000 lux is required on the retina to excite the circadian system, a values much higher than the one needed for visual purposes (Matusiak, 2014).

**Table 3.1** Visual and non-visual demands. The ergorama is a cone of 60°, centered about the main line of sight while the panorama is a cone of 120-140° centered about the line of sight (Fontoynont, 1999).

| Parameter | | Visual demand | Non-visual demand |
|---|---|---|---|
| Horizontal illuminance | | 200-700 lux | 500-800 lux |
| Vertical illuminance | | 1000-2000 lux | Same levels for visual demands but with attention not to have a too bright light source and a certain variability in levels during the day. |
| Luminance | | 1000-1500 cd/m$^2$ | In well lit rooms $L_{max}$ = 1500 cd/m$^2$ |
| Luminance ratios surrounding task poin (valid for VDT's) | Ergorama | 3:1 | |
| | Panorama | 10:1 | |

### 3.3.3 Subjective daylight perception

As it happens for visual comfort, the subjectivity of the user determine how one perceives natural light in indoor spaces. Galasiu and Veitch (2006) conducted a study in many office buildings, measuring illuminance values on employees' desk, combined with interview to users and variable lighting conditions; the results of this study showed that when asked to estimate the amount of daylight reaching their working position, people tend to overestimate the contribution of natural light on the overall illumination even when electric light is simultaneously present and the degree of overestimation is directly proportional with the distance from the window. This phenomenon is due to the unconscious influence of daylight on users' comfort, in fact daylight is seen as a healthier light source if compared to electric light. Moreover if people can choose to dim the electric light in the room they tend to adjust the amount of electric light for three main reasons: energy saving, too high illuminance levels causing eye discomfort, willing in take advance of daylight. In the experiments conducted by Galasiu and Veitch this last psychological conditioning made people add on average between 150-400 lux of electric light to the daylight available on their desk with an average value of 280 lux even when daylight levels were below 100 lux. A good reason for people to prefer daylight to artificial light in indoor spaces is that in enables better visual performances because there are higher light quantity and often a better colour rendering index (Aries et al., 2013).

### 3.3.4 View out

Also the quality of view out from windows highly influence users' comfort. Studies conducted by Markus (1999) reveal that the amount of information possibly gathered from a window set the satisfactory or unsatisfactory quality of the view out.

Many questions have been formulated about how evaluate the view, a study conducted at the Norwegian University of Science and Technology was used in 2013 to test which parameters may influence that evaluation (Galasiu and Veitch, 2006). There are two big categories of measures:

- Quantitative: view width, view depth, number of view layers, fragmentation of the view, and the presence of greenery;
- Qualitative: beauty (aesthetical quality) of objects dominating the view and the composition of the view.

It resulted that to be satisfactory, a view has to be highly complex in the number of visible elements but those elements should be of high aesthetic quality and in a satisfactory composition, moreover they should be organized in 3 layers along the view depth: foreground, background and portion of visible sky. From these results it is easily understandable that view of countryside and coats are more pleasant for users that urban landscapes, which unfortunately usually surround office buildings.

The positive psychological consequences due to a pleasant view influence also the visual comfort, in fact research showed that discomfort glare from daylight appears to be tolerant to much higher degree than expected if there is a pleasant view from the window causing glare (Osterhaus, 2005).

## *3.4 Daylight vs electric light health impact*

As presented at the beginning of the chapter daylight has a strong influence on human health, there are documented cases (Hobday, 1999) of psychiatric patients affected by depression getting better if exposed to sunlight in hospitals, heart attack victims having a better chance of recovery if being in sunlit rooms, fewer pain-killer and less chance to get infections for patients in hospitals able to see sun patches. But daylight is also responsible for better condition in the visual apparat, in fact surveys presented by Aries et al. (2013) have shown that increased amounts of time outdoors protect against the development of myopia, an eye condition currently affecting about 1.45 billion people (a quarter of world's population) which are predict to be around 2.5 billion by 2020 (BHVI;, 2015). According to some scientists light intensity may be an important factor in this field, causing a more constriction of pupils with a consequent greater depth of field and less image blur. However the most confirmed reason for correlation between myopia and time spent outdoor is that in a highly variable environment like the outdoor one the eye is in continuous exercise to focus on different distances contrary to what happen in indoor spaces where the eye is constantly stuck on the same focal length looking at TV screens, laptops or books.

Another important and highly diffuse health effect operating through the visual system is eyestrain: a condition of pain and fatigue of the eyes due to tightening of the ciliary muscles. Studies reveal less incidents of eyestrain for people whose workstations received large proportions of natural light (Aries et al., 2013). It is believed that the major cause of eyestrain is electrical light and that daylight opening can provide a point of relaxation for the eye while and higher incident light can reduce the pain. "Amongst other things, people who suffer from migraine are more sensitive to light than other people" (Aries et al., 2013).

On the other side having too much daylight entering the room can cause discomfort to the user in terms of discomfort glare when a glazed surface will result to be too bright to the observer. Glare from windows is usually due both to direct sunlight, when it get in the indoor space reaching the eye of the occupants or is reflected by the surfaces surrounding the visual task, and sunlight reflections off exterior surfaces making the luminance of the window being too high (Osterhaus, 2005). Occupants may not notice when discomfort glare is present but they might experience some physiological symptoms later on such as headaches.

Due to cultural, social and working demands in today's society, people tend to spend more and more time indoor (about 80% of a day), with low level of natural light and being increasingly exposed to prolonged hours of artificial light that extends well into the night. Moreover most hospitals and care-giving facilities often have 24-hour lighting, causing a misalignment in melatonin release to the 24-hours circadian rhythm resulting in sleep disturbances, mood disorders and their consequent effects on metabolism (Hatori and Panda, 2010). For this reason exposition to artificial light during the night should be avoided, especially if it has a high component in the blue region of the spectrum. Thanks to all the scientific world performing studies on correlation between light and health lightning manufacturers and architects/engineers are able to design lighting conditions which simulate daylight both in luminous intensity variation during the day and colour.

Taking in account daylight positive impact on human health, glare caused both from sunlight and electric light, and visual needs, the best solution in indoor environment is to adopt a daylight control system acting both on electrical light compensation and automatic shading devices.

### 3.4.1 Flicker

There is a silent phenomenon that sometimes can occur when electric light is on, causing headaches, eye strain and general eye discomfort, it is called light flicker and refers to quick, repeated changes in light intensity with light resulting flutter and unsteady. Flicker is produced by the fluctuation of light emitted by an artificial light source, so possible causes of flicker are changing in the voltage supplied to the light source or fluctuation in power line voltage itself. Light sources operating with AC supply produce a regular fluctuation in light output, whose visibility depends on the frequency and modulation of the fluctuation. In order to minimize flicker from light source a stable supply voltage can be used (Halonen et al., 2010).

The magnitude of severity of the flicker depends on many factors:

- How often and regularly the voltage fluctuates;
- How much of a voltage change occurs;
- The kind of artificial light;
- The percentage of change in light intensity when the voltage fluctuates, called gain factor;
- The amount of light in the lighted area.

Depending on the frequency of the flicker people can see lights flicker, as average value people can see lights flashing on and off in the 50 Hz frequency. When a light is flickering at a frequency greater than 50 Hz, most people can no longer distinguish the phenomenon and the flashes appear to fuse into a steady, continuous source of light. This happens because the response to the light stimulus in the brain lasts longer than the flash itself. For this reason most people are not able to visually notice the flicker in fluorescent light having a frequency of 120 Hz, but in some individuals the sensory system can still detect it (CCOHS;, 2003).

Flicker can cause discomfort and for some people it can even cause hazard to health, but sometime flickering light can also be used for entertainment purposes.

## *3.5 Importance of daylight in buildings*

Artificial light has different spectral characteristics than the one generated from the sun, so as presented in the previous section it has different effects of human health. Moreover different artificial sources provide different emission in the light spectrum. With the growing awareness that light influences not only biological aspects but also physiology, behaviour and mood, which artificial light does not have the ability to affect (Webb, 2006). For all those reasons the way a building is designed highly influence how and how long a place will be used, in fact studies conducted on a large number of office buildings (Aries et al., 2013) showed that people in indoor spaces like to learn, work and live near daylight opening but the current design buildings does not allow this for all users. Moreover the maximum distance to the window for a good daylight experience is not known and most of the design process is based on technical values visual related, one example for all the daylight factor.

Daylight in indoor spaces does not have to be considered only for its non-visual positive effects on users but also for highly potential energy saving purposes. So far it is usually seen ad source of discomfort glare or overheating, but by using sensors for daylight compensation and covering materials able to diffuse the light coming from the window rather than absorb it we would be able to save a lot of electric energy on the annual energy consumption for a building. Researchers in the field consider buildings with a conscious daylight as part of the solution to pollution, raising global warming and climate changing, in a vision of sustainable design strategy (Wienold and Christoffersen, 2006).

Unfortunately many architects still do not take advance of daylight energy saving possibilities even though they are able to design more and more structures made in steel and glass. In the biggest skyscrapers all over the world highly reflected glass is used continuously all along the façades but then massive shading devices are used and a lot of energy is spent both for cooling down and lit the indoor space. It is true that high radiation intensities are not always desired because of the high amount of energy contained in those kind of radiation causing overheating, but on the contrary high light levels are beneficial for groups of people such as older adults who require more light to perform well visually (Aries et al., 2013)

Improving the use of daylight buildings results not only in healthier working conditions for users but also in an energy saving strategy because lighting represents almost 20% of global electricity consumption (IEA, 2010). Even though energy saving strategies are more and more promoted both at high political levels and to common people, we still illuminate rooms when we’re not there, we over-light spaces, we squander available daylight with not conscious lighting design and we underutilise the most efficient street lighting and non-residential building lighting technologies (IEA, 2006).

### 3.5.1 Office buildings

Office buildings together with shops are the major consumers of electric light for lighting purposes and about 30% of the energy consumption of office buildings come from artificial lighting (Linhart and Scartezzini, 2011). In this optic office buildings must consume less energy in order to reduce greenhouse gas production and preserve the natural environment. A natural and smart way of reduce electric energy consumption might be to utilize daylight for indoor lighting as much as possible.

Many studied have been conducted for more than 20 years now about users preferences in artificially lit office spaces and the current knowledge can be summed up in the following points (Galasiu and Veitch, 2006) (Linhart and Scartezzini, 2011):

- Employees prefer to work in workplace lit by daylight, this is explained by a diffuse belief that daylight supports better health (but not necessary that artificial light is harmful);
- There is a moderate variety in window's shape and size preference, but in general larger windows, wider that taller, are preferred so that the user can experience a wide lateral view;
- If there subsist the possibility of self-adjust shading devices, one tends to set them and rarely change them;
- Preferred illuminance levels provided from daylight are highly variable according to the subjectivity of the individual, and desired quantities of additional electric light vary with the type of task performed and distance from the window;
- Discomfort glare is highly variable on the individual visual system, moreover it depends in part on the distance from the window and relative quality of the view out but also on the working task required to the user;
- Users better perceive an artificial lighting system if it is possible to control it by the user rather than have an automatic photo controlled system; the same is applied to photo controlled shading systems;
- Consequently integrated controls for both lighting and shading can be acceptable, but the level of acceptance is higher if a good degree of manual control is provided;
- Control systems are more acceptable to both occupants and facility managers when they are simple and easy to use;
- In general in office rooms the horizontal illuminances on workplaces must be sufficiently high, the light on the work plane has to be properly distributed and discomfort glare must be avoided.

Daylight conditions and presence of windows in office buildings are not only a matter of comfort and preferences, a study conducted by researchers from the University of Illinois (Boubekri et al., 2014) showed correlation between daylight exposure and time of sleep during the night. Why is daylight presence so important in work places? Because we spend about 90% of our time in a day in office buildings (EPA, 2014) and in this way we don't get enough "positive" radiation from natural light. In their studies, Boubekri et al. found out that workers sitting next to glazing surfaces with outdoor view tend to sleep 8 ½ hours per night against the 6 ½ of employees working in windowless rooms. Moreover people exposed to daylight at work were also found to be more active, spending even more time in natural light outside of work. A general well-being of employees should be a good goal to achieve by the employers, in fact the primary consequence would be to have more productive workers.

In a society where money count more that people, company's chiefs could think at windows as source of distraction for the employees, while they are able to increase both capacity of focus and productivity. Moreover on the construction and selling market a commercial building without is estimated 20% less per square foot even though it cost more to be built and they provide a fair energy saving range in terms of electric light even using highly efficient lamps.

# 4 Building performances

The increasing global warming caused by pollution and wrong humanity habits have awaken men's conscience all over the world. Politicians, urged by scientists and environmentalists, have established new goals for the next future with the purpose of invert the destroying process of the Earth. The main points of the saving strategy are the reduction of $CO_2$ emissions, and consequently of energy consumption, together with the use of renewable energy sources.

Commercial buildings, and first among them office buildings, are responsible of the highest energy consumption; in fact the total annual energy use in this type of constructions varies in the range between 100-1000 kWh/$m^2$ yr (Dubois and Blomsterberg, 2011) depending on the geographic location, use and type of office equipment, operational schedules, type of envelope, use of HVAC systems, type of lighting, and many other reasons. For offices all over Europe the energy intensity used is about 306 kWh/$m^2$ yr and 150 kWh/$m^2$ yr of them refer to electric energy. In Northern Europe, office energy intensity lies in the range 269–350kWh/$m^2$ yr (Dubois and Blomsterberg, 2011). Fortunately, according to previous research, modern office buildings have a high energy saving potential and most of the new constructions are designed to achieve the best energy use, urged by the recent 2010 Energy Performance of Buildings Directive (EP, 2010) which sets high standard levels in order to have more and more office buildings with near-zero energy use levels.

In particular electric lighting is one area where energy savings are possible at reasonable costs both in new buildings and retrofit projects: recent studies confirm that investing in energy-efficient lighting is one of the most cost-effective ways to reduce $CO_2$ emissions. By the help of new technologies, it is possible to take in account daylight contribution for indoor spaces lighting, resulting in a remarkable energy saving. Unfortunately, as already highlighted in the previous section, there are no code or recommendation for lighting design referring to condition in which daylight and electric lighting are contemporary present (Bellia et al., 2011). The only possible way to change this situation is making designers and technicians more and more aware about the benefits coming from taking into account daylight during the earlier design phases.

So far daylight has mostly been looked at as source of heat energy, developing multiple technologic solutions, from the first Trombe's wall to the photovoltaic panels, but it is still not capitalised for lighting interior spaces. It would be very convenient to consider daylight energy saving potential in relation with its lighting properties, especially in commercial buildings with wide open-plan where the lighting system is on all day long, so that it has a high influence on the energy consumption.

Since 1784, when Benjamin Franklin (Aries and Newsham, 2008) instituted the Daylight Saving Time (DST), natural light was seen as the easiest way for saving energy, but time passes by, cultural and social habits had changed through the years and in 21st century the major effect of DST is present in residential buildings. In fact only the newest commercial and industrial buildings have lighting controls that responds to external conditions, while most of the buildings in this category have the light on at the same level for all working hours and in some cases also during the night. Furthermore many studies have proved the existence of a great controversy in DST application: if on one side having one more hour with daylight in the evening reduces electric energy demand for residential lighting, the same amount of energy and even more is needed for cooling purposes on summer evenings and heating needs in early spring and late fall mornings (Choi, 2009). For these reasons some countries that adopted the Daylight Saving Time at first ended up with not using it anymore; a map with countries resetting the clock depending on the period of the year is showed in figure 4.1. However not all recent analyses suggest that Daylight Saving Time is negative: in 2008, during a conference at the U.S. Congress results of a study showed that a month of extension of daylight time had saved half of the nation's electricity consumption per day with 1,3 trillion watt-hours in total. That amount could power 100 000 households for a year. However measured data are highly variable through years and geographic locations, so conclusion of many scientists is that the disparities between regional and national results could reflect climate differences between states.

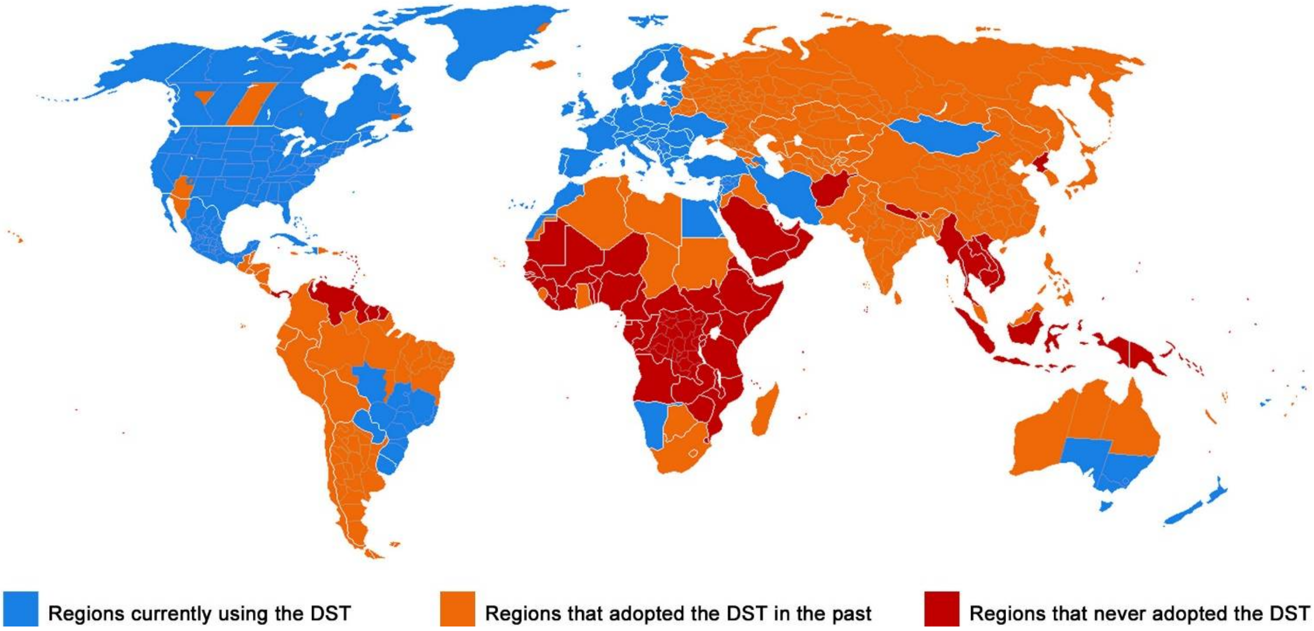



**Figure 4.1** Daylight Saving Time -World-Subdivisions (Eggert, 2012).

## *4.1 Buildings energy consumption for lighting*

Since the first artificial lighting source was affordable by the major part of the population in the world, people tend to spend more and more time in indoor spaces. As shown in figure 4.2 the use of electric energy in buildings from 1973 has duplicated; this is both because of increasing use of technologies in houses and commercial buildings and for an increasing use of lighting devices both during daytime and nighttime. Moreover from 1973 to 2012 the total final energy consumption has duplicated, in particular the electricity consumption reveals an exponential growth mostly due to primary and tertiary sectors as shown in figure 4.3.

All these data support what stated in the IEA Annual Report (IEA, 2014a) where it is presented that the Energy Technology Policy Division has made a plan in order to achieve the world's 2050 energy and climate change goals. In particular the 2014$^{th}$ edition of Energy Technology Perspectives 2014, launched in Seoul in May 2014, had a strong focus on actions needed to support development of sustainable options in electricity generation, distribution and consumption. This because electricity is seen as the leading energy system in the next future, but so far in most of the countries in the world fuel is still the primary source of energy (IEA, 2014b).

By studying a shorter and more recent period of time, it is possible to see as the global energy consumption over 10 years has significantly increased. In fact, the total energy consumption all over the world has grown of about 2.30% from 2012 to 2013, but as shown in graph 4.1 this tendency is due to the non-OECD countries energy consumption. The OECD (Organisation for Economic Co-operation and Development) members and especially countries from European Union have become more and more virtuous in energy saving, with a reduction of 0.3% between 2012 and 2013 consumption. However the world consumption of primary energy is still very high, about 12 730.4 Million Tonnes Oil Equivalent (Mtoe) against the 9 943.8 Mtoe in the 2003. In 2013, 11 595.4 Mtoe of consumed global energy came from non-renewable energy sources (natural gas, coal, oil, nuclear energy) and only 1 135.1 Mtoe from renewable energy sources such as hydro-power, used for electricity production (BP, 2014).

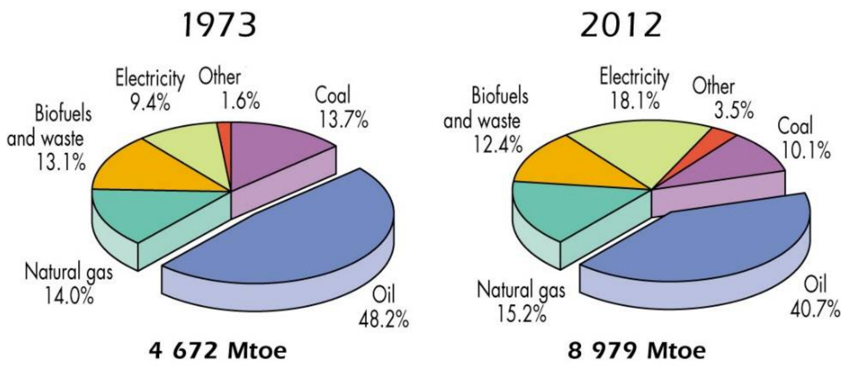



**Figure 4.2** World total final consumption in 1973 and 2012. Data from peat and oil shale are aggregated with coal, data for biofuels and waste final consumption have been estimated for a number of countries. The category other includes geothermal, solar, wind and heat. Mtoe expresses million tonnes of oil equivalent. Image modified from (IEA, 2014b).

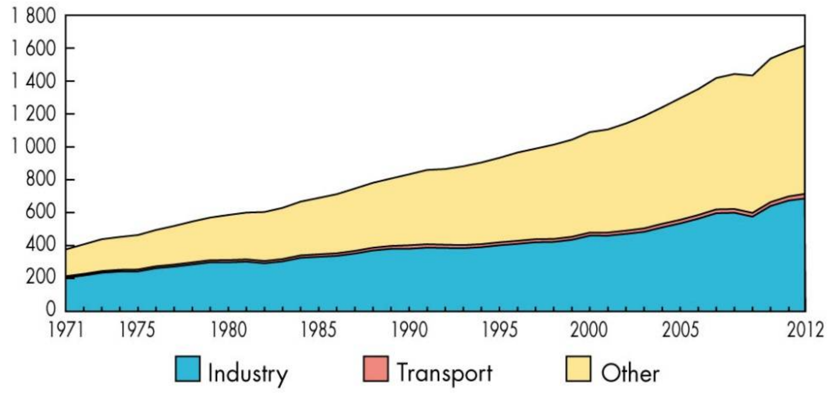
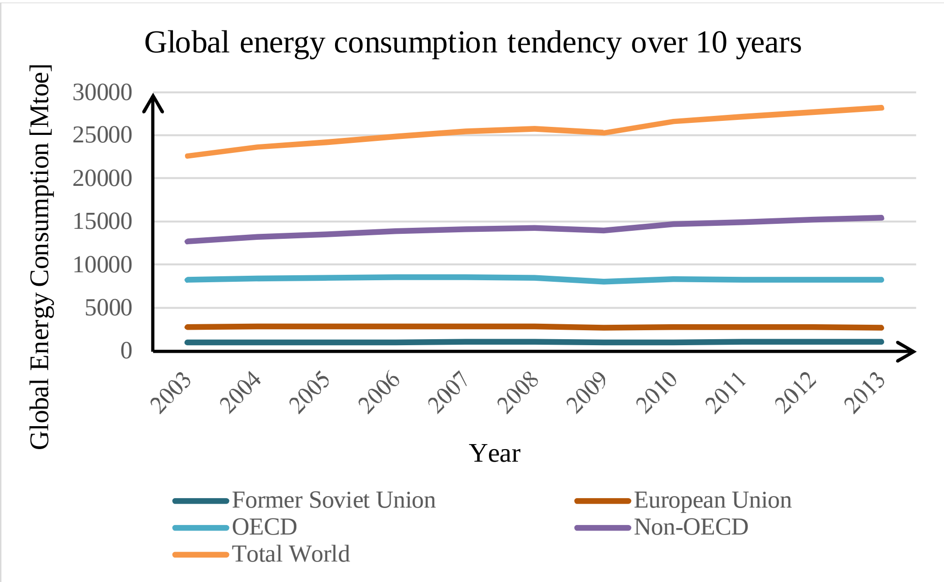



**Figure 4.3** Electricity total final consumption from 1971 to 2012 by sector. The value of total energy consumption regarding electricity increased fourfold from 1971 with 440 Mtoe to 1626 Mtoe in 2012. Mtoe expresses million tonnes of oil equivalent. Image modified from (IEA, 2014b).




**Graph 4.1** In the total energy consumption tendency from 2003 to 2013, the increasing consumption from non-OECD nations is slightly contrasted by reduction in energy consumption from OECD members, European Union nations and former Soviet Union countries. Graph elaborated from data in (BP, 2014).

The newest energy saving strategies are also based on use of different energy sources, with higher efficiency in transformation and less $CO_2$ emissions. Following the common division in category, an energy source can be non-renewable or renewable; among the renewable energy sources there is the Sun. Solar energy has the most abundant source available on the Earth and newest technology are continuously improved in order to achieve the highest results from the greenest of the energy sources. However many researchers (Onaygıl and Güler, 2003) believe that an increase in daylight use for lighting purposes would significantly reduce buildings energy consumption. In particular "through sensors and controllers, daylighting can reduce and even eliminate the use of electrical lighting required to provide sufficient illuminance levels inside office spaces. Simulation analyses as well as field-monitoring studies have reported that daylighting controls can result in significant lighting energy savings ranging from 30% to 77%" (Ihm et al., 2009). In particular one research has shown that daylight-linked lighting control systems such as automatic on/off and continuous dimming have the potential to reduce the electrical energy consumption in office buildings around 30–60% (Dubois and Blomsterberg, 2011).

With the rising awareness of daylight importance for energy saving, new technologies and luminaries based on sensors have been developed, although values of energy saving can vary according to geographical location, month, season, sky condition and lighting control system installed. One of their first application field is the tertiary sector and, in particular, office buildings. Daylight compensation in that type of interiors is very useful, because offices require a constant and high level of lighting comfort, but people working there are generally very busy so they don't have any time to switch off or adjust the artificial lighting. Therefore, lights are usually on from morning till the end of the working day, regardless of daylight level.

However quantifying energy saving according to the type of sensor utilized is still matter of investigations. According to Ihm et al. (2009) occupancy sensors can save up to 20% of energy and a daylight dimming control system up to 26% if compared with manual switching. To make it clearer, it is necessary to present the three major types of sensors today used in tertiary constructions (Roisin et al., 2008):

- Individual Daylight Dimming System (IDDS): the lamp light flux is controlled according to the daylight availability. The sensors (one per luminaire either one controlling a group of luminaires) are fixed on the luminaires and measure the reflected illuminance of the plane located under them;
- Movement Detection Switching (MDS): this system, based on an infrared occupancy sensor, switches the light on and off, according to movement detection. The length of the delay can be chosen in order to limit the number of switch on and switch off cycles;
- Movement Detection Dimming (MDD): as the MDS, it is based on an infrared occupancy sensor, but dims the light to a chosen flux in case of absence. This flux can be chosen by a set of dip switches located on the sensor.

By studying and comparing lighting conditions in office rooms with different orientations, geographic location and occupancy factor, researchers from Belgium found out that the only system whose gains are influenced by the orientation and the location is the IDDS, while MDS and MDD only depend on occupancy. Among the three locations investigated (Athens, Brussels and Stockholm) the Swedish capital is the perfect reference for lighting design in Norway. As shown in figure 4.4 the combined use of IDDS and MDS leads to the highest reduction in energy consumption with a light dependency on room orientation.

The results from the study also allow architects and engineers to choose the best lighting control system according to the type of indoor space in which it will be installed; in fact MDS results more suitable for single office rooms, while the MDD system is interesting for landscape offices as it prevents people to be placed in a bright spot, compared to the average room illuminance, when working alone in the office room. It is important to highlight that the study assumed a passive occupant who does not care about switching on or off the lights in function of available daylight. A further improvement to these installed technologies would be to have an absence detector (manual on/automatic off) because not always the occupant turn on the light when entering in his office even if there is not 500 lux on the desk. This would save even more energy but could have an impact on comfort, profitability and eyestrain.

Last but not least taking into account the daylighting can not only allow an artificial lighting consumption reduction, but also a reduction of the lighting internal loads and thus of the cooling loads (Bodart and De Herde, 2002).

There is a good cooling, heating and lighting energy balance that can only be reached by an integrated approach combining the daylighting and the thermal aspects. It is difficult to evaluate the energy saving coming from the artificial lighting dimming as function of the daylighting availability even though many researchers have tried to achieve this result: the estimation ranges from 77% to 20% of lighting saving and 14% of the total energy saving. The high variability in values is due to the huge number of parameters influencing the measurements and simulations, in particular climate, sky conditions and building orientation. However the lighting management cannot leave out of consideration visual comfort and acceptance of automatic management system from the employees, otherwise the energy saving can be decreased to zero.

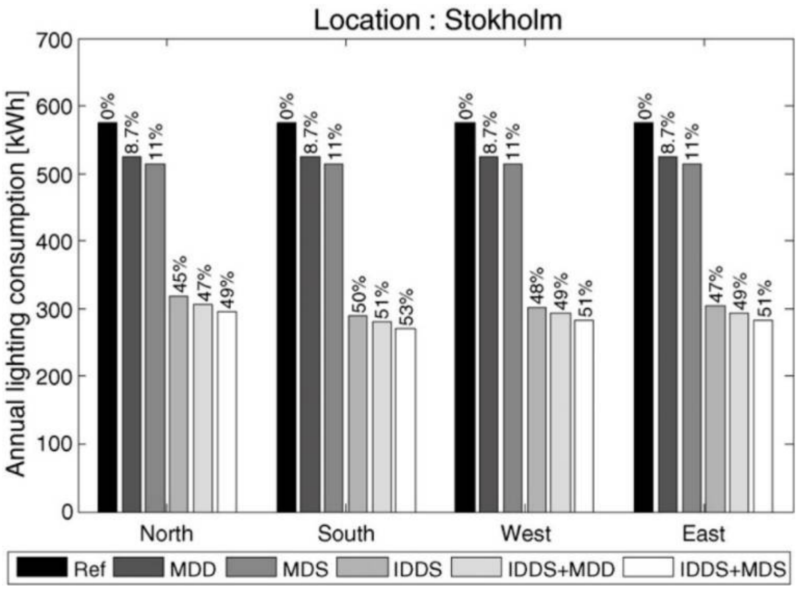



**Figure 4.4** Annual lighting consumption and gains for Stockholm. Image from (Roisin et al., 2008)

## *4.2 History of laws, agreements between Nations and proposals*

The interest in reduction of emissions from the construction sector started developing when scientists and environmentalists realized that the increasing global warming is due to man's activity. Global warming started around the middle XX century and previsions believe that it will continue through all the XXI century and maybe even further. Only becoming conscious of the current situation, humanity as a whole can stop the destroying mechanism started in the past. In 1990 the Intergovernmental Panel on Climate Change (IPCC) published a report about temperature rising projections, estimating an increase between about 0.15-0.3°C per decade from 1990 to 2005. Observed values show that projections were not wrong, there has been a temperature increasing of 0.2°C per decade (IPCC, 2007). According to model experiments, even keeping emission levels constant at 2000 year values, a further warming would occur for two decades more because of the slow response of the oceans. The rising temperature provides a chain of many negative consequences: percentage of areas covered by snow is decreasing and sea level is rising, hot extremes, heat waves and heavy precipitation events will continue to become more frequent, tropical cyclones will become more intense, very high increase in precipitations in high latitudes and decreases in subtropical land regions as shown in figure 4.5, reduction of lands results in increasing the fraction of anthropogenic emissions that remains in the atmosphere.

In order to conduct accurate projections, the IPCC in 2007 released a Special Report on Emission Scenarios identifying four possible situations in the next future, those are (IPCC, 2007):

- A1: it describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In this scenario social and cultural interactions have increased, resulting in a convergence among regions, better capacity in building and reduction in regional differences in per capita income.

  For this category SRES presents three sub-scenarios characterized by alternative directions in energy system technology: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B);

- A2: its storyline and scenario describe a very heterogeneous world, with strong willing in preservation of local identities. "Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines" (IPCC, 2007);

- B1: this scenario sketch a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1, but with rapid change in economic structures toward a service and information economy. In this world all is committed to reach global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives;

- B2: it describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines.

In the Special Report on Emission Scenarios IPCC states that all the scenarios should be considered equally possible. Results of the projections estimate a 66% in possibilities of temperature rising between about 1.1°C and 6.4°C by the end of XXI century, as shown in figure 4.6.

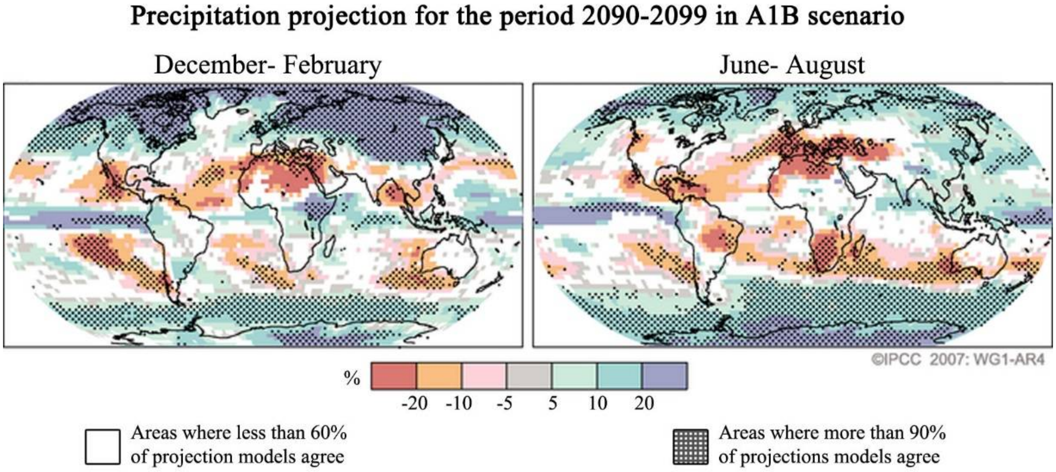



**Figure 4.5** Relative changes in percentage of precipitation for the period 2090-2099, relative to 1980-1999. Estimation based on the SRES A1B scenario for December to February on the left and June to August on the right. Image modified from (IPCC, 2007).

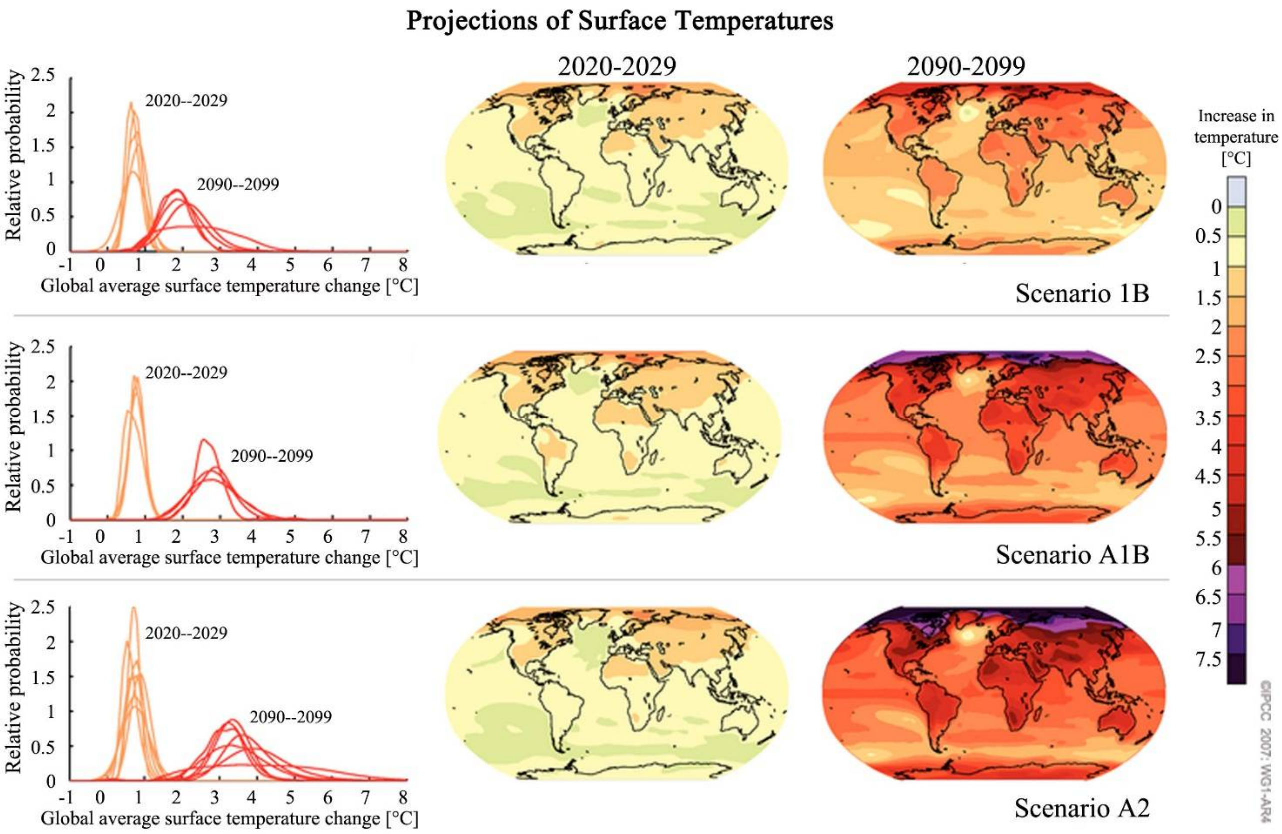



**Figure 4.6** Projected surface temperature changes for the early (2020-2029) and late (2090-2099) 21st century relative to period 1980-1999. The scenario patterns are similar to the ones observed over the past several decades. Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and part of the North Atlantic Ocean. Image modified from (IPCC, 2007).

All those possible negative future situations were one of the reasons why politicians from all over the world met and discussed in which direction let economy, culture and society develop. In June 1992 during the Earth Summit in Rio de Janeiro, the United Nations conference on environment and development, the ONU members signed the agreement called United Nations Framework Convention on Climate Change (UNFCCC) with the goal of reducing greenhouse gas emissions, main source of the global warming. In 1995 the UNFCCC members met in Berlin in order to define the key lines for the agreement ending in the signature of the Kyoto Protocol in 1997, but only in 2005 it was enacted. The State Parties undertook the reduction of greenhouse gases emissions, but with different responsibility depending on the economic development of each country at that time. In particular the underdeveloped countries were exonerated from following the ambitious limits in the protocol because it could result in slowing down their economic development. With the Kyoto Protocol expiring in December 2012, a plan for further sustainable policies was needed, so in 2009 the Emissions Trading Directive 2009/29/EC was released with a period of validity from 2013 to 2020.

The main content of the directive is to present the 2020 climate and energy package, a set of binding legislation which aims to ensure the European Union meets its ambitious climate and energy targets for 2020. Those target are mostly known as the “20-20-20” targets because set on (EC, 2009):

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU’s energy efficiency.

The 2020 package presents four measure to achieve the targets, those are (EC, 2009):

- The reform of the EU Emissions Trading System ( EU ETS), whose aim is cutting industrial greenhouse emissions in the most effective way;
- Promotion of the system called “Effort sharing extra EU-ETS”, which refers to the reduction of greenhouse gas emissions as well but from sectors not covered by the EU ETS, such as housing, agriculture, waste and transport. Emissions from these sectors represent around 60% of EU’s total emissions. In the period between 2013-2020 each nation has to meet different targets, depending on the Member State’s relative wealth and report them annually under the EU monitoring mechanism;
- Renewable Energy Directive whose target is to produce the 20% of each national total energy consumption from renewable energy sources by 2020, but different national targets have been established for the years between 2013 and 2020 according to Member States’ different starting points;

Carbon capture and storage, referred to a directive creating a legal framework for the environmentally safe use of carbon capture and storage technologies. It plans to capture $CO_2$ emitted by industrial processes and store it underground so that it will not contribute to global warming.

In the fight against global warming Europe has always been the most active, in fact under the Kyoto Protocol UE members set the limit of 8% emissions compared to 1990 levels by the years 2008-2012 and they managed to over-achieve it. In its virtuous behaviour Europe has committed to cut its emissions to 20% below 1990 levels by 2020, offering to increase the target to 30% if other major emitting countries in the developed and developing worlds commit to undertake the same effort. Looking at the future, European Union members have already made a plan pursuing the target of reducing emissions to 40% below 1990 levels by 2030, and reducing Europe's greenhouse gas emissions by 80-95% compared to 1990 levels by 2050.

After the setting of 20-20-20 targets the whole building construction system seems to be back to building principles before heating and electricity were introduced in constructions, being based on passive strategy for air-conditioning, use of local materials (before to economic purposes, now for reduction of $CO_2$ emissions) and limited use of energy (Thompson and Blossom, 2015).

With the European Directive 2010/31/EU on Nearly Zero Energy Buildings (NZEBs) (EAI;, 2013) the building is going to be transformed into an energy generation system, resulting in a change in the design process: it is necessary to operate an integrated design, where all different parties collaborate together since the first phases in order to find the best energy saving solution in every field.

## *4.3 Constructive technologies about daylight*

The increasing demand in reduction of emissions and energy consumption in buildings requires a continuous development in technologic solutions to be applied in constructions. In this section I present the main innovations about daylight and lighting in general for energy saving.

### 4.3.1 Glazing surfaces

The first source of natural light in indoor spaces are windows or more in general glazing surfaces as part of the envelope. Since the first use of glass for closing apertures in the façade, many innovative types of windows have been developed. Most of these new solutions have the goal to improve thermal properties of glazed areas and secondly acoustics purposes, but all of them have also impact on indoor visual performances. Depending on the required performances and use of the glazed element, different type of glass can be used in the window system:

*Float glass*: is the standard flat, clear glass, it was the most and almost uniquely type of glass used before energetic issues where analysed in the energy demand of a building (GR;, 2015).

*Insulated glazing* (IG): also called double glazing or double-pane is made of double glass window panes separated by vacuum or an inert gas such as Argon, Xenon and Krypton, where the last two are considerably more expensive. The distance between the two layers is constant and the presence of the cavity allow the window to have higher thermal and acoustics performances, even more if it is filled with inert gases being non-toxic, odourless, invisible and with a lower heat transfer coefficient (Archtoolbox, 2015) (PWF, 2015).

*Three glazing pane*: triple glazing is based on the same principles of the double one and it provides higher performances with a 30% less reduction in heat losses if compared to an insulated glazing (Witsoffer, 2015). Both for double and triple glazing European standards require to have fully tempered glass, designed to be around 3 times as strong as normal glass, perfect for security applications also because when broken it shatters into small fragments that avoid causing major harm (GR;, 2015).

*Reflective glass*: a metallic coating is added to a float glass in order to minimise the solar heat that passes through. The metallic coating has a mirror effect so that it reflects back the light and prevents view in from people being outside. Its major field of application is office building facades, and it can be produced in two different ways (GR;, 2015):

- Pyrolitic: during the float glass process, semi conducted metal oxides are adhered to the glass while it is still hot. Negative aspect is that these hard coatings are quite harmful to the environment;
- Vacuum/magnetron: Metal oxide layers are applied to the glass under a vacuum. This is a soft coating, and for this reason it is sensitive to harsh conditions. It must therefore be used on the inner side of the glass.

They are commonly used in office buildings, but only occasionally chosen for residences because even though they may have very low solar heat gain coefficients, they block so much of the light and view that they are not normally desirable in homes (Warner, 1995).

*Anti-reflective glass*: is the opposite of the reflective one. The standard float glass undergoes a dipping process that coats it with metal oxide layers. The result is that it reflects a low percentage of light, but still allows for clarity and transparency. Anti-reflective glass is great for use in places such as a building with a wall of glass keeping the visuals clear, it also increases the glass sheets durability (GR;, 2015).

*Low-emissivity glass*: or commonly called low-e glass is a type of energy efficient glass designed to prevent heat escaping through the windows by an invisible metal coating which reduces heat transfer and reflects about 90% of interior heat back into the room (Witsoffer, 2015).

The most interesting solutions are the emerging glass technologies, today available or nearly on the market, here I present the state of art (EW, 2015):

*Evacuated windows*: based on the same technology of double or triple glazing but improved by the principle that the most thermally efficient gas fill would be no gas at all: a vacuum. They are also called vacuum-insulated glass (VIG), in which the space between the panes is evacuated. If the vacuum pressure is low enough, there would be no conductive or convective heat exchange between the panes of glass, thus lowering the U-factor. A vacuum glazing must have a good low-E coating to reduce radiative heat transfer because the vacuum effect alone is not adequate, in fact it can eliminate conduction and convection but not radiation, so a low-E coating is necessary on the pane of glass. At the current level of technology the evacuated windows still present some problems regarding both mechanical properties and maintenance. In order to satisfy the structural requirement to resist normal air pressure and variable pressures caused by wind and vibration it is necessary to place small pillars or spacers between the panes, resulting in window clarity reduction. Moreover the highly insulating performances can be preserved only if the vacuum remains intact for the entire life of the window, through manufacture, transportation, installation, and normal operation. For these reason the main important requirement is that the airtight seal around the unit edge must be maintained and it is still a great challenge.

*Insulation-Filled Glazings*: the cavity between the glazing panes is filled with aerogel, honeycombs, or capillary tubes. These materials provide diffuse light but not a clear view, and some of them are used in Europe for passive solar applications: aerogel is a silica-based material present as foam whose microscopic cells entrap air (or another gas) preventing convection while still allowing light to pass. It is also able to reduce conduction because the cells size is smaller than the mean free path of air/gas molecules. Moreover long-wave thermal radiation is virtually eliminated because the wave are absorbed and reradiated within the multiple cell layer. The particles that make up the thin cell walls slightly diffuse the light passing through, creating a bluish haze similar to that of the sky. Aerogel has received research attention for its ability to be both highly transparent and insulating. It should be technically possible to produce windows made of aerogel with a center-of-glass U-factor as low as 0.05, but as it has only be produced in small quantities, it has been used only in small sized samples for research purposes. The main problem for application of aerogel in common windows is that they will result to be diffusing and not able to provide view out.

*Switchable windows*: also known as smart windows or dynamic windows, they are presented to be a multifunctional part of the façade, combining the classic benefit of windows to integrated shading systems, having variable optical and thermal properties that can be changed in response to climate and occupant preferences. By actively managing lighting and cooling, smart windows could reduce peak electric loads, increase daylighting benefits, improve comfort, and potentially enhance productivity in homes. Switchable windows are based on the idea that the ideal window would be one with optical properties that could readily adapt in response to changing climatic conditions or occupant preferences. Depending on which aspect the designer choose to privilege, two different types of smart windows can be used: passive devices that respond directly to a single environmental variable such as light level or temperature, and active devices that can be directly controlled in response to any variable such as occupant preferences or heating and cooling system requirements. The main passive devices are photochromics and thermochromics, while active devices include liquid crystal, suspended particle, and electrochromics.

- Passive devices:

Photochromic materials change their transparency in response to light intensity, for this reason they can be used for daylight regulation, allowing the right amount of light to get in for lighting purposes and cutting out excess sunlight that can create glare and overload the cooling system. Although small units have been produced in relation with a consumer product, cost-effective, large, durable glass for windows is not yet commercially available.

Thermochromic materials are able to change transmission continuously over a range of temperatures reducing heat loads (especially at times of peak demand) and maximizing daylight efficiency use. If properly designed, the thermochromic layers are minimally sensitive to changing outdoor or ambient temperatures but respond dramatically to changing amounts of direct sunlight on the windows. Moreover thermochromic layers help reduce glare, fading and noise, and increase safety.

- Active devices:

Electrochromic (EC) windows: today considered as the most promising switchable window technology. The technologic construction consist of a ceramic metal oxide coatings with three electrochomic layers sandwiched between two transparent electrical conductors, deposited on a glass substrate and is typically about one micron thick. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up. This field moves various coloration ions (most commonly lithium or hydrogen) reversibly between the ion storage film through the ion conductor (electrolyte) and into the electrochromic film, resulting in the glazing being switched between a clear and transparent blue-gray tinted state with no degradation in view, similar in appearance to photochromic glass.

Gasochromic windows: they produce a similar effect to electrochromic windows, with a different technologic solution: diluted hydrogen is present in the cavity in an insulated glass unit in order to colour the window. If exposed to oxygen, the window returns to its original transparent state. The optically active component is a porous, columnar film of tungsten oxide, less than 1 micron thick. This eliminates the need for transparent electrodes or an ion-conducting layer. Variations in film thickness and hydrogen concentration can affect the depth and rate of coloration.

Polymer Dispersed Liquid Crystal Device (PDLC): the cavity between a double-pane window is filled with a thin plastic film containing a very thin layer of liquid crystals sandwiched between two transparent electrical conductors. When the power is off, the liquid crystals are in a random and unaligned state so that they scatter light and the glass appears as a translucent layer, which obscures direct view and provides privacy. The material transmits most of the incident sunlight in a diffuse mode, thus its solar heat gain coefficient remains high.

Suspended Particle Device (SPD) Windows: the main element is an electrically controlled film which utilizes a thin, liquid-like layer in which numerous microscopic particles are suspended. In its unpowered state the particles are randomly oriented and partially block sunlight transmission and view. Transparent electrical conductors allow an electric field to be applied to the dispersed particle film, aligning the particles and raising the transmittance.

Another highly innovative type of glazing is the *photovoltaic vision glass* which integrates a thin-film, semi-transparent photovoltaic panel with an exterior glass panel in a traditional double-pane window or skylight. The difference between all the other PV types and the thin-film photovoltaics is that only the last one is translucent, but all of them can be integrated and/or laminated in glass. Electric wires extend from the sides of each glass unit and are connected to wires from other windows, linking up the entire system. If the PV cells are part of the vision glass, various degrees of transparency are possible since the PV cells offer shade and produce electricity. Smaller PV systems can be used to power facade equipment directly instead of being connected to the electrical grid in the building as stand-alone devices. Vertically oriented PV panels have higher efficiency if not positioned toward the sun. One approach to position the PV panels more perpendicular to the sun is to place them into fixed shading devices on the facade or on movable shading panels, using the generated power to track the shades to the optimal solar angle.

### 4.3.2 Daylight systems

When placing windows in the envelope of a part of the building is not possible or in underground indoor spaces need to be lit, many other constructive solutions are possible. They can all be identified in the category of daylight systems: systems that collect natural light through collectors in the roof, and transport it to diffusers into interior spaces, delivering it. There are four main types of daylighting system (Poyan, 2012): Tubular Daylight Devices (TDDs), vertical systems, horizontal systems, fibre optical devices. In table 4.1 a summary of daylight systems features is presented.

TDDs consist of a fixed ocular that collects light from the roof of a building and directs it into a tubular 'pipe' lined with a highly-reflective surface. In this way the light is reflected down the tube by this surface to diffusers in the interior of the building that direct it into occupied spaces.

Vertical systems are very similar to TDDs, but they use a powered tracking system to point a light collector towards the sun, and a series of mirrors and lenses that concentrate the light before directing it into distributing tubes.

Horizontal systems use lenses to collect natural light from external walls and transport it through flat light ducts above the ceiling to diffusers placed deep inside the building. They make use of a polymer material that combines a high reflectivity with the practicality of a hollow duct similar to a ventilation duct.

Fibre optical systems collect light with mirrors and lenses which track the sun and transport it into building interiors through fibre optic cables. They require little space, for this reason they can deliver light almost anywhere in a building and diffusers can be replaced by point lights.

**Table 4.1** Comparison of the principal daylight systems: advantages and disadvantages.

| Daylight system | Advantages | Disadvantages |
|---|---|---|
| TDDs | No mechanical parts | One ocular per tube is needed |
| | Relatively inexpensive | Significant loss of light where there is a change of direction in the tube |
| | Tubes can easily be run through the walls being only 10 inches in diameter | Significant loss of light beyond 10 meters → practical to transport light up to 3 floors only |
| | It can harvest relatively low levels of light | |
| Vertical systems | Can collect more light than TDDs thanks to the tracking system | 60 cm opening required in the roof |
| | Can deliver light 3 to 7 times deeper than TDDs into the building | |
| | Relatively inexpensive | |
| Horizontal systems | High reflectivity on the material covering the light duct | Relatively untested |
| | Very practical to be placed in the building | Expensive |
| Fibre optical systems | Relatively flexible → can be installed as electric cables and bent in any direction (minimum bending radius is 50 mm) | Collect mostly direct light (rather than diffuse) |
| | Can deliver anywhere in a building because they require little space | Expensive |

In terms of visual comfort, the advantages offered by daylight systems are important: the illuminance gradient between illuminance on the work plane and in the deeper zone of a room is much lower than when such a device is absent. This leads to a higher level of luminous comfort because right distribution and uniformity of the luminous field are optimal. Consequently also visual fatigue is prevented and reduced. Moreover direct irradiation, glare and overheating are avoided. Studies conducted by Canziani et al. (2004) showed that this group of dynamic devices for daylight deliver can highly contribute to energy saving on both the electric and thermal point of view.

### 4.3.3 Shading devices

Another element which influences the amount of daylight in indoor spaces and the possibility to achieve visual comfort are the shading systems. A shading device is an opaque element of a building which has the purpose to protect the interiors from daylight or more in general from solar radiation and to prevent view inside. Moreover, depending on the type of shading device, they can also act on the thermal balance of the space and on the amount of air flow entering the room. The shading systems can be classified as fixed or operable and the latter can be further divided in adjustable and retractable according to the degree of possible change of their configuration (Baker and Steemers, 2002). A summary of daylight shading devices features is presented in table 4.2 and the different types are here presented:

- Fixed shading devices can be horizontal such as overhangs and light shelves or vertical as for example fins. They are an integral part of the building structure so they cannot be adjusted by the user to meet his visual and thermal needs (Givoni, 1998). This type of devices reduces all radiation, both visible and non-visible, diffuse and direct, at all times in the same proportion, having a great impact to illuminance values in the interiors and so affecting the use of artificial light. They act obstructing part of the sky and are more active for high solar angles, for these reasons they are considered directionally selective. The best solution when designing overhangs is to have horizontal shading elements for south-oriented façades and vertical devices for east and west oriented glazed surfaces. The fixed shading devices reduce both thermal and visual contributions but they do no act at all on the inflow air.

- Operable shading devices can be external or internal: the first type of solution is the most effective way of controlling solar gain in buildings with highly glazed façade, while the second one is more effective for visual comfort control, because even as close to the glazed surface as it can be, there will always be an important part of solar radiation being absorbed into the glass and then released towards the indoor space.

  Considering retractable devices, one refers to elements that can be completely or partially removed from the window aperture such as roller blinds, shutters and louvres. They allow unobstructed view and ventilation when retraced but in case of overheating the use of the device will reduce the amount of radiation entering the room and at the same time the ventilation, which could be pleasant to have. Depending on the material by which they are fabricated the degree of reflected radiation can be different, but in any case, according to the European Directive ED 89/654 EEC all the retractable products have to provide a certain degree of adjustment of natural light (CEN, 2005).

  In relation to the reflected and transmitted radiation, for fabric blinds and curtains the colour is very important: for dark-coloured blinds the transmitted radiation is highly reduced resulting in low illuminance values and transformation of a great amount radiation in heat causing the use of artificial light and the overheating of the room; light-coloured blinds have better performance because they reflect away a large part of visual radiation but at the same time they have high transmittance which in case of light diffusing properties of the material may cause glare.

  The adjustable devices are elements which remains in the window aperture but the light transmittance characteristic can be changed by the user, as it happens for the louvres of venetian blinds. By tilting the slats the light transmittance can vary continuously being at the maximum when they are at about 45° above the horizontal. When completely closed there is almost no light transmitted and when completely open (perfectly horizontal) the view is still obstructed. The slats let the light reflected from the ground in and reflect the direct sunlight away.

**Table 4.2** Advantages and disadvantages of the different types of shading devices.

| Shading device | Advantages | Disadvantages |
|---|---|---|
| Fixed (overhangs, light shelves and fins) | Reduction of glare and cooling loads | Design should be integrated with the architecture of the façade |
| | Unobstructed view | Not adjustable according to the user's needs |
| | Unobstructed ventilation | Effective only for specific solar angles. |
| | No or very low maintenance required | |
| Operable external | Great limit of heat gains | Impact on the aesthetics of the façade |
| | Unobstructed view out when completely retracted | Partial obstruction of the view when in use |
| | Reduction of illuminance values indoor and glare | Reduced air inflow |
| | Adjustable by the user | |
| Operable retractable internal | Unobstructed view out when completely retracted | Partial obstruction of the view when in use |
| | Reduced but still possible air flow when not completely extended | No air flow permitted when completely extended |
| | Reduction of illuminance values indoor and glare | High percentage of solar radiation transmitted inside |
| | Adjustable by the user | |
| Operable adjustable internal | Reduction of illuminance values indoor and glare | Obstructed view even when completely open |
| | Reduced but still possible air flow when not completely extended | No air flow permitted when completely extended |
| | Continuous variation of light transmittance | High percentage of solar radiation transmitted inside |
| | Adjustable by the user | |

## *4.4 Zero Energy Buildings*

Only in 2010 the Zero Energy Building (ZEB) concept was perceived as a concept of a remote future (Marszal et al., 2011) and now, five years later, it is the best real solution for the reduction of $CO_2$ emissions and energy consumption in the constrictions sector. In fact even though High Performance Buildings have been realized since the beginning of the XXI century, only in the recent years they have finally reached the goal of producing more energy than they consume. Zero Energy Buildings are the future and both USA and Europe have made a plan in order to have more and more virtuous buildings. USA within the Energy Independence and Security Act of 2007 (EISA, 2007) authorizes the Net Zero Energy Commercial Building Initiative to support the goal of net zero energy for all new commercial buildings by 2030. It further specifies a zero-energy target for 50% of U.S. commercial buildings by 2040 and net zero for all U.S. commercial buildings by 2050. The European Union with the article 9 of the recast of the Directive on Energy Performance of Buildings (EPBD, 2010) requires that all new buildings in the member states occupied and owned by public authorities are Nearly Zero Energy Buildings by the end of 2018 and to reach the same goal for all the new buildings by the end of 2020. Due to the heterogeneity of climate, economy, materials availability present through all the European nations, the EPBD recast does not prescribe a uniform approach for implementing nearly Zero Energy Buildings and neither does it describe a calculation methodology for the energy balance, delegating to national plans the proposal of solutions for increasing the number of ZEBs according to national, regional or local conditions.

According to the definition given in the Directive 2010/31/EU, also known as EPBD recast, a Zero Energy Building is "a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (EPBD, 2010). Unfortunately this definition is highly generic and it leaves room for national interpretations, for this reason many definitions of a nearly ZEB has been developed, according to the aspect one focuses on the most.

### 4.4.1 Definition

The acronym ZEB can have a double meaning, in fact it can be read as:

- Zero Emission Building for a building emitting a very scarce amount of carbon dioxide in the surrounding;
- Zero Energy Building for a building not consuming at all or consuming a limited amount of energy to execute the complex system of function for which it has been designed.

Lately a large amount of different definitions have been developed, because innovations in the construction fields make possible to differentiate buildings performances according to the main goals of different experts involved in a project. Moreover a new class of buildings has been created, in order to identify buildings which are able to produce more energy than they need, transferring the surplus to the global grid. Those are Plus Energy Buildings. According to Asl et al. (2013) a zero energy building is a type of energy efficient building (EEB) whose use is possible with zero net energy consumption and therefore zero carbon emissions in a year. From this definition it is possible to derive two different types of ZEB:

- Zero Net Energy Buildings which deliver as much energy to the supply grids as they use from the grids; the success of net-zero energy buildings design is driven by location and availability of renewable energy sources;
- Zero Carbon Buildings that over a year do not use energy that implicate carbon dioxide emission.

However from literature there are many different possible field of ZEB definition, which can be connected to four main categories: site ZEB, source ZEB, emissions ZEB and cost ZEB. All of those, according to Torcellini et al. (2006), refer to buildings not connected to any energy grid and they are defined as:

- Net Zero Site Energy: A building which produces at least as much energy as it uses in a year, thanks to roof-mounted PV or solar hot water collectors, small-scale wind power, parking lot-mounted PV systems, and low-impact hydro;
- Net Zero Source Energy: a building which produces at least as much energy as it uses in a year, considered in terms of primary energy used to generate and deliver the energy to the site. To calculate a building’s total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers;
- Net Zero Energy Costs: when the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year;
- Net Zero Energy Emissions: a building which produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

The reason why those definitions are not internationally used lays in the fact that they are not univocal in their meaning. For example according to the site ZEB definition the values of various fuels at the source are not considered, so one energy unit of electricity used at the site is equivalent to one energy unit of natural gas at the site, even though electricity is more than three times as valuable at the source. In this case for all-electric buildings, a site ZEB is equivalent to a source ZEB.

### 4.4.2 Certifications in the world

Other uncertainties about ZEB definition lays in the absence of a standardized calculation method which can assess a building as “zero”. Voluntary organizations as LEED or BREEAM have developed certification methods but without having the ZEB definition as main goal. The “zero balance” goal can be achieved in many field regarding a building such as primary energy, $CO_2$ equivalent emissions, energy, the cost of energy or other parameters defined by national energy policy (Marszal et al., 2011). Each energy certification is are based on specific criteria that, if satisfied or not, give a certain amount of points. All the scores from each category can be summed up, influencing the final result, depending on the percentage of importance of the category.

Here I present a list of Energy certificatory organizations active in Europe and US (Thompson and Blossom, 2015) in alphabetic order and a comparison between the most active in the world is shown in table 4.3:

- BBC-EFFINERGIE (Bâtiment Basse Consommation): the association is active in France, the meaning of its acronym is Low Energy Consumption Building. Its certification criteria require that building’s primary energy requirements for heating, cooling, ventilation, hot water and lighting do not exceed 50kWh/m$^2$ yr (Aries et al., 2013).

- BREEAM (British Building Research Establishment Environmental Assessment Method): It sets the standard for best practice in sustainable buildings design, ranking their performances by a system of benchmarks regarding building's specification, design, construction and use from energy to ecology (BREEAM;, 2000). BREEAM has an international influence in buildings certification and specific divisions and criteria for seven European countries: Austria, Germany, Netherlands, Norway, Spain, Sweden, and United Kingdom. In particular, for the last one, a specific method for residential buildings has been developed, it is called Code for Sustainable Homes (CSH). It is an environmental assessment method for rating and certifying the performance of new homes based on BRE Global's EcoHomes scheme, a Government owned national standard intended to encourage continuous improvement in sustainable home building.

  The BREEAM certification covers nine categories of sustainable design: energy and $CO_2$ emissions, water, materials, surface water run-off, waste, health and wellbeing, pollution, management, ecology. The first six categories in the list represent mandatory performance requirements, while all other performance requirements are flexible. It is possible to achieve an overall level of between zero and six depending on the mandatory standards and proportion of flexible standards achieved. The awarding scale is composed of the following levels: PASS, GOOD, VERY GOOD, EXCELLENT (70% overall score) and OUTSTANDING (85% overall score).

- DGNB (deutsche Gesellschaft für Nachhaltiges): The German Sustainable Building Council, even it was founded only in 2007, todays counts more than 1 200 members throughout the entire world among architects, planners, investors, scientists and experts from the construction industry (DGNB;, 2007). Its aim is to promote sustainable and economically efficient buildings and to increase the number of those buildings in the future.

- HQE (Haute Qualité Environnementale): the High Quality Environmental standard is a standard for green building in France, based on the principles of sustainable development first set out at the 1992 Earth Summit. It is controlled by the Association pour la Haute Qualité Environnementale (ASSOHQE) in Paris. (HQE;, 2013) Its main focuses regard: managing the impacts on the outdoor environment by minimizing energy and water use, waste production in operations, an integrated choice of construction methods and materials; creating a pleasant indoor environment by acoustic control measures, visual attractiveness, air quality control, water quality control.

- klimaaktiv: is the Austrian climate protection initiative launched by the "Federal Ministry of Agriculture, Forestry, Environment and Water Management", embedded in the Austrian federal climate strategy (klimaaktiv, 2014). Its certification system is based on the number of stars given to each project depending on the results achieved. The Austrian Building Star focuses on energy efficiency, health and user comfort, avoidance of environmentally harmful construction material, and high construction quality. In particular the rating of the certification system "Austrian Green Building Star" provides for 4 to 6 stars:
  - Where the basic criteria are complied with, the building is a very comfortable and environmentally optimised nearly zero-energy building and receives four stars of the Austrian Green Building Star system.
  - Five stars can be obtained if, in addition, the building also complies with the passive house standard.
  - Six stars are granted if the building has a neutral or even a positive energy balance.

- LEED (Leadership in Energy and Environmental Design): the American green building certification program that recognizes best in class building strategies and practices. It is organized in many different rating systems, each of them studied to best fit a specific category of building. Prerequisites and credits differ for each rating system. The LEED certification is one of the first to consider dynamic daylight parameters for rating such as the sDA and the ASE (Cammarano et al., 2014).

- Passivhaus (or Passive House in English) (Germany) the most internationally influential standard, elaborated by the Passive House Institute (PHI), an independent research institute in Germany. The first pilot project in 1990 was the Europe's first inhabited multi-family house to achieve a documented heating energy consumption below 12 kWh/$m^2$ yr (PHI, 2000) and today there are more than 40.000 buildings certified to the Passive House standard. Certification criteria for non-residential buildings are (Perez et al., 1990):
  - Annual energy demand for heating and cooling will not exceed the 15kWh/$m^2$ yr;
  - Energy consumption will not exceed a peak heat load of 10 W/$m^2$;

- Total annual primary energy consumption of a building should not surpass 120 kWh/m$^2$;
- About airtightness, getting a pressure test result lower than 0.6 h$^{-1}$.

**Table 4.3** International protocols for building sustainability. The number of certified buildings for LEED, BREEAM and HQE is a rough estimation.

| | | Green building certification program | | | | | |
|---|---|---|---|---|---|---|---|
| | | LEED | BREEAM | HQE | DGNB | klimaaktiv | Passivhaus |
| Origin | | US | UK | FR | DE | | |
| Type of construction | New | X | X | X | X | X | X |
| | Refurbishment | X | X | X | | X | X |
| Number of building certified in the world | | 13 000 | 40 000 | 1 000 | 179 | - | 1605 |
| Use classification that is possible to certify | Residential | X | X | | X | X | X |
| | Tertiary | X | X | X | X | X | X |
| | Accomodating | X | | X | X | | |
| | Commercial/Retail | X | | X | X | | |
| | Schools | X | | X | X | | |

#### 4.4.2.1 BREEAM in Norway

Norway is one of the six countries whose have a national green building certification program BREEAM-derived. It is called BREEAM NOR and is operated by the Norwegian Green Building Council (NGBC) under licence from BRE Global (BREEAM;, 2000). According to BREEAM NOR, the following conditions must be met in order to certify a building at the Outstanding BREEAM rating level:

- The building must achieve a final BREEAM Score ≥ 85%
- The minimum performance standards (table 4) for the Outstanding rating level must have been met
- Provision of material for the production and publication of a case study on the Outstanding rated building. In this way the building could act as exemplars for the following projects

##### 4.4.2.1.1 About daylight

Within the criterion 5.0 Health and Wellbeing, lighting requirements are considered. First among all is that building users have to have sufficient access to daylight and in order to achieve this goal it is required that at least 80% of the floor area is properly daylit according to:

- Average daylight factor measured at a height of 0,8 meters should be in the range 1.5 - 4.4 % depending on the latitude at the building location and number of storey. The suggested values are presented in table B.1 in appendix B;
- A uniformity ratio of at least 0.4, which is increased to 0.7 for spaces with glazed roofs, or a minimum point daylight factor variable from 0.84 to 3.08 according to the latitude at the building location. The suggested values are presented in table B.2 in appendix B.

  Or a view of sky from the desk (0.7 m height) is achieved.
- Satisfaction of the room depth criterion: $$\frac{d}{w}+\frac{d}{HW}<\frac{2}{(1-RB)} \quad (4.1)$$

Where d= room depth

w= room width

HW= window head height from floor level

RB= average reflectance of surfaces in the rear half of the room

The project can also achieve innovation credits if the following criterion is satisfied:

- At least for 80% of all rooms for permanent occupation, when the previous requirements are satisfied, the average daylight illuminance is equal or above 300 lux for 2650 hours per year in multi-storey buildings.

Important definitions of values needed for the certification can be found in appendix B.

In the same section, the BREEAM NOR technical manual (NGBC, 2012) also proscribes solutions for visual comfort, more specifically:

Regarding the view out, the green building certification confirm the importance of providing an adequate view out by having the window/opening area ≥ 20% of the total inside wall area. The view should contain a landscape or buildings rather than just the sky at seated eye level (1.2 – 1.3 m) in the relevant building area and it cannot be an internal view across the room, usually obstructed by partitions.

In order to reduce the risk of glare in occupied areas, an occupant-controlled shading system on all windows, glazed doors and rooflights in all relevant areas should be provided.

# 5 Methods

The analyses of daylight performance in the Zero Energy Office Building used as study case is performed in parallel by using of two different methods. One of these is the scientific method, it concerns measurements in situ, performed in some room offices; the second method is based on software simulations used to estimate part of the parameters that can be measured during the monitoring procedure.

## *5.1 Utilized scientific method*

In order to preform accurate measurements, it has been chosen to follow a procedure internationally recognised for being reliable because acknowledged by the International Energy Agency (IEA). It is an autonomous organization, founded in 1974 to create and encourage dialogs between members about energetic issues. The IEA is made up of 29 member countries and all of them had to prove they have strict policies about energy demand control and reduction, in particular they are obliged to hold oil stocks equivalent to 90 days of their net imports (IEA, 2000). In 1977 the International Energy Agency established a specific program named “The Solar Heating and Cooling Programme” in order to enhance collective knowledge and application of solar heating and cooling through international collaboration of experts from all the member countries. The IEA SHC primary activity is to develop research projects to study different aspects of the wide solar heating and cooling topic. In particular the Executive Committee, who heads the program and is made of one representative from each Member country and Sponsor organization, selects an “Operating Agent”, a project manager responsible of the single project.

The IEA SCH refers to these projects as Tasks and at the moment it has 10 projects currently active. One of those is the Task 50 “Advanced Lighting Solutions for Retrofitting Buildings”, whose main goal is to “accelerate retrofitting of daylighting and electrical lighting solutions in the non-residential sector using cost-effective, best practice approaches” (Dubois et al., 2014). To achieve this goal the task is organized in four subtasks all interconnected and named from A to D.

The measurements performed followed the indications presented in the subtask D, named “Case Studies” and for this reason the work presented in Chapter 6 will be insert in the Task 50 before the publication. The IEA SHC Task 50 Subtask D presents a monitoring protocol for assessment of lighting and daylighting performance in different types of buildings, among which office buildings. Only two of the four key aspects covered by the protocol are used in the current project, the ones regarding Light environment and Users’ satisfaction, while Energy efficiency and Costs remain non-analysed.

According to the monitoring program there are two levels of perform the measurements, named essential monitoring and complete monitoring. The difference between the two procedures lies in the level of accuracy during the measurements, which is influenced by the type of instruments available by the person/institution performing the protocol, dimensions of space analysed and number of users who is possible to interview referring to the users’ satisfaction aspect.

Depending on all those factors, the essential monitoring results to be the most appropriated, in fact the instruments, property of the Faculty of Architecture and Fine art used for the measurements, do not allow to measures values such as the colour characteristics of light in space, determinate by measuring the correlated colour temperature (CCT) and the general colour rendering index (CRI). Moreover regarding the users’ satisfaction investigation it is necessary to interview up to 30 users of the building and it was not possible for the study case.

Here I present an overview of the values to be measured and the procedure to follow suggested by the IEA SHC Task 50 Subtask D. Regarding the essential monitoring, the measurements have to be performed in two different sky conditions: completely overcast and sunny day; the measurement days have to be chosen during ± 1 month from one of the two equinox and the measurements of some values have to be performed both with daylight only and electric light on only.

The investigation focus on many parameters here organized in the following eight categories.

### 5.1.1 Distribution of daylight entering the room

#### 5.1.1.1 Reflectance of surfaces

The reflectance of internal surfaces of a room can be measured by use of luminance meter and lux meter. Moreover it is recommended to record reflectance values of significant interior surfaces onto a fish eye photograph of the interior. A later comparison between the measured value and the one obtained by image processing is possible and interesting to perform. In case measurement of reflectance is performed under artificial light, it is recommended to ensure that light levels are stable.

It is possible to measure the reflectance of a surface using one of the two methods here described:

- Method 1: Illuminance – luminance (Fontoynont, 1999)

Procedure:

- Place the illuminance meter as close to the point of measurements as possible, without casting any shadows over the point of measurement.
- Move directly above the sample and aim the luminance meter down at 90° to the sample. Inevitably this will produce some shadows over the sample but in a diffusely lit environment the illumination of the sample will remain substantially uniform. Care should be taken to stand in a similar position for all readings. If possible the luminance meter could be mounted on a tripod and this position held. Focus the luminance meter to the correct distance.
- When both meters are set up, take the readings simultaneously, this is so that the conditions cannot change between the two readings. The following equation can be used to calculate the reflectance from the two readings:

$$\rho(R) = \frac{L\pi}{E} \tag{5.1}$$

Where $\rho\ (R)$ is the reflectance

$L$ is the luminance [cd/m$^2$]

$E$ is the illuminance [lux]

- Method 2: Luminance – luminance (IEA, 2013)

This method involves using a sample whose reflectance is known and another that has an unknown reflectance. The sample whose reflectance is known can be a matt white disc with an accurately known reflection factor. Using the luminance meter (as in method 1) to record values for both the known and the unknown samples (cautiousness should be accounted for by not moving the meter between readings and also not to shadow the sample), the reflectance value of the unknown sample can be determined by:

$$\rho_{unknown} = \frac{L_{unknown}}{L_{known}} \cdot \rho_{known} \tag{5.2}$$

Where $\rho_{unknown}$ is the reflection value of the examined surface

$\rho_{known}$ is the reflection value of the known reference surface

$L_{unknown}$ is the luminance of the examined surface [cd/m$^2$]

$L_{known}$ is the luminance of the known reference surface [cd/m$^2$]

Caution should be taken when measuring the reflectance of strongly colored surfaces since it depends heavily on the spectral distribution of the illuminant and on the visual sensitivity function response of the measuring instrument.

5.1.1.2 Glazing transmittance

The glazing transmittance can be obtained only from values measured under the overcast sky condition. There are two types on transmittance possibly measurable, those are:

- Normal-normal transmittance:
  - Measure luminance of an object outdoor with the window closed $t_{close}$, by holding the luminance meter perpendicular to the glazing plane;
  - Measure luminance of the same object outdoor with the window open $t_{open}$, by holding the luminance meter perpendicular to the glazing plane;

- Calculate the ratio (Baker and Steemers, 2002)

$$\tau = \frac{t_{close}}{t_{open}} \tag{5.3}$$

- Repeat the measurements several times;
- Calculate the average value of the taken measurements.

▪ Hemispherical-hemispherical transmittance of clear translucent glazing:

- Measure the illuminance behind the window, by holding the lux meter perpendicular to the glazing plane $t_{in}$;
- Measure the illuminance on the front of the window, by holding the lux meter perpendicular to the glazing plane and located outside of the glazing $t_{out}$;
- Calculate the ratio (Baker and Steemers, 2002)

$$\tau = \frac{t_{in}}{t_{out}} \tag{5.4}$$

#### 5.1.1.3 High Dynamic Range photography with fisheye lens

A HDR picture is a post-processing task of taking a series of a finite number of images and combining them, adjusting the contrast ratios in order to display the same lighting conditions perceived by the human eye. A single picture has only one single aperture and shutter speed, two parameter which highly influence the amount of light recorded in a scene by a camera. The best way to obtain a HDR photography is to take at least three photos of the same scene, each at different shutter speed, having an overexposed (very bright), balanced and underexposed (very dark) picture according to the amount of light entering in the lens. By a software process is possible to combine all the information collected by the photo regarding details, shadows and light spots. The final image shows the same lighting conditions perceived by human eye.

In reference to the Subtask D the scene is the working spot and its ergorama and panorama. It is recommended to put a reference grey surface in the scene (for example fixed at the top of the computer screen) and measure the luminance on that surface, for a calibration of luminance data that can be derived from the HDR picture. Even better is to measure also the luminance of the main surfaces in the room to check the reliability of the tests. In order to take pictures that can be combined by the software, those have to be precisely identical, and in order to have that it is necessary to set the camera on a tripod and take pictures by a remote shutter, avoiding any possible movement of the camera.

### 5.1.2 Illuminance

In order to obtain fundamental daylight parameters as daylight factor and illuminance distribution in indoor spaces, different types of illuminance have to be measured. The measurement instrument appropriate for assessing illuminance value in one point is the lux meter. Three types of illuminance have to be measured during the study.

#### 5.1.2.1 Exterior illuminance $E_{out}$

It refers to illuminance under the unobstructed horizon in overcast sky conditions, measured outdoor. It is recommended to use a waterproof lux meter in case of rainfalls or snow and to be sure that there is not any element (trees, buildings, the operator himself) shadowing the sky.

#### 5.1.2.2 Exterior horizontal diffuse illuminance $E_{hd}$

It is the measure of the illuminance in a point outdoor, due to sunny sky conditions. The measurement is focused on the diffusing part only, due to the blue sky, neglecting the component due to direct solar beams striking the lux meter sensor. In order to measure the value it is necessary to shade the lux meter in the area of the sensor only. The shading device can be whether a ball or a small disk to be fixed to a support (like a tripod) so it doesn’t move while measuring.

#### 5.1.2.3 Interior horizontal illuminance $E_{in}$

It refers to illuminance due to overcast sky conditions, measured at a point in indoor spaces. It has to be measured in a certain number of point placed at the work plane height, along a line in a central position with respect to the window geometry in the room. According to the essential monitoring protocol it is recommended to realize a grid with a finite number of measurement points; a suggestion for the grid geometry is to consider the first point along the central line at a distance of 0,5 m from the window wall and n-other points distant 1 m one to the other in the direction of the opposite wall. For a more detailed assessment of illuminance distribution in the room, it is possible to consider measurement points along lines parallel to the central one, at distance 0,5 from the side walls. Moreover it is possible to measure illuminance values in four additional points at the dark corners of the indoor space.

The number of points and measurements line depends on the geometry and floor area of the room where the measurements are performed. The work plane height is variable in reference to the national standards of each Country; in order to measure the illuminance always at the same height, the sensor of the lux meter can be placed on a tripod. It is important to pay attention in not shadowing the sensor by standing between it and the window while measuring.

### 5.1.3 Daylight factor

For definition of DF, it is the rate of $E_{in}$ and $E_{out}$ measured simultaneously. Two lux meters are needed, before taking any measurement it is necessary to calibrate the instruments by measuring the illuminance on the horizontal plane, at the same height, in two points: one out of a window and one inside, facing the same window, the rate of the two obtained values will give the percentage of calibration.

The measurement of $E_{in}$ and $E_{out}$ has to be performed simultaneously for every indoor point in order to calculate the ratio and then apply the correction by the percentage of calibration.

### 5.1.4 Glare

In the essential monitoring protocol the level or possibility of glare can be measured only through estimation based on the operator, because it depends on the adaptability of human eye, and some physical values (Wienold and Christoffersen, 2006). The estimation is possible by:

- Observations: it is necessary to be present in the evaluated room during a significant part of the testing period, because of the very dynamic behavior of daylight, especially under clear sky conditions. It is recommended to pay attention to undesirable sun patches in the room by notes and photographs, and to areas with high luminance. The evaluation of luminance values on different surfaces in the room can be performed by software able to obtain such information from the HDR pictures and compared with the luminance values measured at the moment when the picture is taken.

- Detection of veiling reflections: it is sufficient to note down veiling reflections in the room, especially on computer screen or paper.

### 5.1.5 Directionality of natural light

- Observation of light incident on objects in the room. It is easier to be determined under overcast than clear sky conditions.

- Detection of shadows: study the shadows of objects in the room looking at the light side of the object, the shadow side, the cast shadow and the presence of reflected light. It is sufficient to note down every abnormality or quality.

### 5.1.6 Colour

A simple characterization of the colours of main surfaces in the room is possible, in reference of the NCS chart system. The procedure consists of comparing each surface in the room to the NCS chart by placing the colour sample directly on the surface in order to determine the closest standardized colour by visual inspection. Note down the colour code of the sample.

#### 5.1.6.1 Colour standard systems

In order to have a univocal characterization of colour of surfaces, it is necessary to refer to a standard definition of all the different nuances of colour. To do that, many colour standard systems have been developed all over the world; these are used not only in the constructions field but in every context that need a colour codification. The most known colour standard systems are:

- Natural Colour System (NCS);
- RGB system where the three letters stay for Red Green and Blue, it is the most used in Europe;
- RAL standing for the German “State Commission for Delivery Terms and Quality Assurance” (Reichsausschuss für Lieferbedingungen);
- BS 4800 is the British Standard Colours;
- Pantone.

### 5.1.7 Flicker

Presence of flicker from electric light sources can be detected by observations and visual check by using a simple mobile phone camera having a screen refresh rate of 30 frames per second (Dubois et al., 2014).

### 5.1.8 View

A careful analyses of the view out from a window in each room has to be carried out. For the essential monitoring protocol it is sufficient to shortly describe the view from a key position in the room, which can be the working area, paying attention to elements that define a higher or lower quality of the view, such as:

- Record of number of view layers (excellent view if there are 3 layers: the sky, the landscape and the ground);
- Note down *location* (orientation regarding water, food, heat, sunlight, escape routes, destination), *time* (environmental conditions which relate to our innate biological clocks), *weather* (need for clothing, need for shelter, heating/cooling, opportunities for sunbath), *nature* (the presence of trees, bushes, plants, insects, birds and other animals), *people* (the presence of people and their activities);
- Describe quality of view through shading devices, in particular the description should include, whether a view through the shading device is possible, and to which degree the information about time, weather, nature and people can still be achieved;

Moreover it is required to calculate the width of the view for the center of the position of a work place by the equation:

$$\alpha_{view} = 2 * \arctan\left(\frac{b_{glazing}}{d_{room}}\right) \tag{5.5}$$

Where $b_{glazing}$ is the total of the width of the glazing of all windows

$d_{room}$ is the depth of the space.

### 5.1.9 User’s satisfaction

The protocol indicates to collect some background information about number of users and time available for data collection. The opinion of occupants is useful in order to discover local or transient unpleasant occurrences, hard to find out when visiting the space for few days in a year.

If possible it is useful to distribute a short written questionnaire (appendix C1) to all the employees, which combine open and closed questions involving both daylight and electric lighting issues.

## *5.2 Utilized software*

Both for elaboration of measured values and production of daylight condition simulations, it is necessary to use different software. Regarding collected data elaboration the following computer programs are utilized:

- Microsoft Excel: it is used for organization of the layout of tables needed during the monitoring procedure and further data elaboration, using simple formulas as rates, calculation of average values and percentage. It is also needed for the presentation of the analysis results by graphs and tables.
- Picturenaut: it is a free use HDR program which combines many picture of the same scene but with different exposure due to different values of shutter time, producing a unique picture having the same

lighting conditions as they are perceived by human eye. The interface is very user friendly and the final file produced after the combination of the source pictures can be saved in many formats, one among all the .hdr. The choice of using Picturenaut for HDR file generation is due to the impossibility of using the software WebHDR, suggested by the monitoring protocol of IEA SHC Task 50 - Subtask D.

- WebHDR: it is another HDR program, it is possible to use it for free by visiting the website http://www.jaloxa.eu/webhdr/ but many restrictions in the use made the elaboration of HRD pictures very problematic. Some of the reasons are:
    - It is possible to upload a series of up to 9 exposure-bracketed images but the total size of the uploaded files cannot exceed 12 MB. This is a valuable issue because by using a good quality camera for taking pictures, the file to be uploaded have great dimensions. Two solutions at this problem are:
        - Use Photoshop and save the file as web format. This reduce the file size but causes a loss of important information stored in the file details, necessary to the software for further elaborations (i.e. the shutter speed).
        - Use Photoshop and re-scale all the images, reducing their dimensions. For example a 6060 pixel image can be scaled to a 1600 pixel ones, reducing the file dimensions and preserving all the file information.
    - After uploading the images on the WebHDR server, where they are processed, the results report a warning: to set the white balance of the camera on florescent or tungsten for indoor pictures and sunny or cloudy for outdoor before taking any picture, but never having it on automatic. This is because the camera would adjust colours on the final showed image, however this kind of setting should not affect the luminance values at all.
    - When using an old lens, which doesn’t communicate with the camera, there is a lack of information in the needed detail for the image processing. In the study case the fisheye lens was too old for the camera, in fact the aperture was set from the aperture ring, as well as the focus. When trying to elaborate the images by WebHDR the following problem was detected: “unable to find the aperture, the process cannot proceed”. This represents a big obstacle especially to universities and research groups because professional equipment are highly expensive and it is not possible to change them very frequently. To solve this problem one suggested solution is to try to insert data in the file by using Adobe Bridge.
    - Once processed the images, it was not possible to download the result file because of a problem in the server of WebHDR, in particular the server is not able to solve for response function and this kind of error happens every now and then. A possible solution to this is to upload other exposure-bracketed sequences taken with the same camera until one or more of them do produce an HDR image. Those images would be associated to a RSP plot, which is possible to re-use for all the other sequences of images uploaded to WebHDR. As this procedure resulted too much time consuming, it was chosen to switch to another HDR program.
- Photoshop for image elaboration in terms of dimensions.
- Radiance: a ray-tracing software system, download free, used for obtaining luminance values from HDR pictures.

In reference to the software simulation and modelling of the indoor spaces, many software are used to achieve different results. Here the software used during the study are presented:

- Autodesk Revit: software for buildings design, specifically built for BIM (Building Information Modeling). All the architectural information about the project have been gained from the source model provided by the project manager. By using all the software features is possible to produce dwg files, reading walls stratigraphy and consequently thermal and visual proprieties of surfaces in the analysed rooms.
- Autodesk Autocad: software for computer-aided design and drawing, used for elaboration of basic plan and section drawing of the project, based on Revit-exported files.
- Relux: a software specific for light simulations, with a calculation code based on the technique of ray-tracing. It is used in the current project for modelling the interior on each room to be analysed and some exterior obstructions when necessary. Possible outputs from Relux are static values both about daylight and artificial light such as daylight factor, luminance, illuminance but also render of the interiors.

As far as lighting calculations are concerned, it is important to distinguish artificial lighting and daylight effects and components, because they involve different factors in the calculation. Artificial light effects estimation is limited to input data about artificial light sources characteristics and materials present in the surrounding (IBA_HAMBURG, 2006), while when daylight is considered as light source, the amount of natural light that reaches a point inside the building is determined by the sum of three components: the Sky Component (SC), the External Reflection Component (ERC) and the Internal Reflection Component (IRC) (Milone, 2007). All those components vary by time, period of the year and weather (CIE standard) condition.

Even by using the best simulation tools, estimation of light behaviour carries many uncertainties and errors, due to necessary approximations of light modelling such as assuming some opaque materials as perfectly diffusive even though in most of the cases it is semi diffusive, but also the impossibility to insert in the model the newest technological solution about natural lighting as rooflights or innovative transparent materials.

The lighting condition of a space is determined by the interaction of light source emissions and surfaces they strike on, software results are more reliable if calculations consider both direct illuminance and inter-reflections on every surface present in the surrounding. The multiple reflections can be modelled according to three algorithms called ray tracing, radiosity and photon mapping.

- Ray tracing: it is excellent in simulation of specular reflection phenomena, producing both a good quality render and numerical values of photometric units but only if related to a precise direction of observation.
- Radiosity: it is excellent in simulation of diffuse inter-reflection phenomena, producing precise and reliable quantitative values but a medium graphic representation of the space. Calculation algorithms in radiosity consider a surface as it is the combination of sub-surfaces (mesh) made of discrete elements having homogeneous photometric proprieties. Fundamental assumption of the algorithms is that all the surfaces are ideal diffusors, reflecting light equally in every direction but the advantage is that once calculated, the luminous distribution of a scene can be analysed independently from the point of observation.
- Photon mapping: it is a global illumination algorithm, based on the simulation of light beams emission. It is mostly used in computer graphic to simulate light interaction with different types of materials. The graphic performances have very high quality, allowing to simulate interaction with transparent materials and reflections of metals but also visual effects due to smoke or vapour.

Most of the simulation software are specific for studying and designing lighting conditions under artificial light sources, more easy to control, with a further implementation for evaluation of static daylight parameters. Nowadays no software exist to evaluation and characterization of dynamic effects of light, giving results monthly or hours based, as there are many for thermophysics software.

Relux is a free software based on the combination of ray tracing and radiosity methods.

- SketchUp: it is a 3d modelling software, based on creation of solids to which it is possible to associate materials, tailoring colours and visual parameters at the discretion of the user. In the project it is used to model furniture specific for each room, in order to have a model the most close to the reality as possible.

# 6 Case study: Powerhouse Kjørbo

## *6.1 Project overview*

Powerhouse is a collaboration of companies whose goal is to build energy positive buildings in challenging climate conditions as those present in Northern Countries. The Powerhouse alliance was originally established by Entra Eiendom, one of Norway's leading real estate companies, the construction company and project developer Skanska, the architectural company Snøhetta, the environmental organisation ZERO and the aluminium company Hydro in 2011. The partnership was extended in 2013 by two new members: the aluminium profiles company Sapa and the consultancy company Asplan Viak.

The important design method, that makes Powerhouse succeeding in the realization of its projects, is the firm belief that no-one can build energy-positive buildings alone regardless the level of experience and knowledge in innovation technologies owned by the, staff because a ZEB is a complex system in which every aspect has to be analysed and implemented in order to have the highest efficiency possible.

Starting from the 20-20-20 European targets, Powerhouse developed its goal of building energy-positive buildings believing that everyone from tenants to workers, and not only designers, construction companies or innovation developers, have to contribute. Everyone can be a part of the solution (Powerhouse, 2012).

Powerhouse alliance has its own statute, which defines a Powerhouse as *"a building that shall produce at least the same amount of energy from on-site renewables as the energy used during construction, manufacturing of materials, renovation, demolition and operation. […] In addition the exported energy shall in average not have less quality than the imported energy. […] The building shall also as a minimum fulfil all the requirements of the Passive House standard according to NS 3701 [1]* " (Tyholt, 2013b); the requirements set from the standard NS 3701 for office buildings are reported in tables 6.1a and 6.1b.

Being a new collaboration, so far Powerhouse has only two active projects, both successful and challenging:

- Powerhouse Brattørkaia: Norway's first new build office building located in Brattøra, an urban site currently under development sited in Trondheim. The project started in 2012 with the planning phase, it has been approved by the municipality by the end of 2014 and building operation will start in the second half of 2015. The new construction is designed for reaching the goal of exceeding the energy used to create the building with the energy produced during the building's operational lifetime (Snøhetta, 2012).
- Powerhouse Kjørbo: the first Powerhouse project to be completed by the collaboration and the first building to achieve the rate of Outstanding under BREEAM-NOR, the highest level of environmental classification that can be achieved in Norway (Entra, 2015).

**Table 6.1a** Energy requirements for the Passive House standard according to NS 3701-1.

| Parameter | Requirement | Condition |
|---|---|---|
| Heat loss coefficient for transmission and infiltrations $H''_{tr,infl}$ | $H''_{tr,infl}$ < 0,40 W/m$^2$K | For Passive office buildings having $A_{fl} \geq 1000$ m$^2$ |
| Highest estimated net specific energy for heating | $W_{heat}$ < 21,44 kWh/m$^2$ a | For Passive office buildings having $A_{fl} \geq 1000$ m$^2$ and annual mean outdoor temperature < 6,3 C° |
| Highest estimated net specific energy for cooling | $W_{cool} \leq$ 2,8 kWh/m$^2$ a | For Passive office buildings having $A_{fl} \geq 1000$ m$^2$ and average outdoor temperature in summer conditions > 20 C° |
| Highest estimated net specific energy for lighting | LENI ≤ 12,5 kWh/m$^2$ a | For Passive office buildings |
| Average power requirements in operation time | $W_{light, av} \leq$ 4,0 W/m$^2$ | For Passive office buildings |

**Table 6.1b** Minimum requirements for building parts, components, systems and leakage coefficient for the Power House according to NS 3701-1.

| Parameter | | Requirement | Condition |
|---|---|---|---|
| *U* -value window and door | | ≤ 0,80 $W/m^2$ K | For Passive house |
| Normalized thermal bridge | | ≤ 0,03 $W/m^2$ K | For Passive house |
| Annual average temperature efficiency for heat recovery | | ≥ 80% | For Passive house |
| SPF ventilation factor | | ≤ 1,5 $kW/m^3/s$ | For Passive house |
| Leakage coefficient at 50 Pa, $n_{50}$ | | ≤ 0,60 $h^{-1}$ | For Passive house |
| Lighting | Dynamic daylight and constant light | At least 60% of installed power for lighting is subject management system | |
| | Dynamic demand control | At least one control zone per room or one control zone per 30 $m^2$ in large rooms | |

### 6.1.1 The site

The Powerhouse Kjørbo project consist in the renovation of two of the ten blocks sited in Sandvika, the administrative center of the municipality of Bærum, 15 km west to Oslo. Bærum is located at approximately 60 degrees north latitude, and with an annual mean outdoor temperature of about 5,9°C and an annual mean horizontal irradiation of about 110 W/m² (955 kWh/m²a).

The office building estate is sited by the Sandkivselva river waterfront, flowing into the Indre Oslofjord, the fifth biggest fjord in Norway. Even being located in a highly dense urban context, near the biggest shopping center in Norway and the European route E18 (about 1,890 km long running from Northern Ireland to Saint Peterburg in Russia) the constructions are surrounded by natural elements thanks to a wide park with many trees and the river flowing along two sides on the perimeter of the area. The park of the hold manner Kjørbo gård has its own marina and it is easily accessible by cyclists and cars as well as at a short walk distance from the railway station.

Eight to ten buildings have same similar black cubical shape but different height, variable between 3 and 4 floors, and symmetrical mutual position. Each building, in the project indicated as block, has the four corners almost directed towards the cardinal points, with an orientation angle of 35° from the North. The strategic position of the blocks are stragger along lines parallel to the façades to minimize the possibility in production of reciprocal shadows, but at the same time preserve the façades parallel one to the others and harmonize the squared geometry of the plan with a circular organization on the urban scale, as shown in figure 6.1.

### 6.1.2 History of the project

The building estate was built in the 1980s and the blocks were bought by different tenants. All the buildings in the area are named blocks and indicated by progressive Arabic numerals as shown in figure 6.1. Blocks from 1 to 6 are owned by Entra Eiendom, an industry leader in developing and managing energy efficient buildings. The Kjørbo office park comprises five office buildings and a service center with a canteen, meeting rooms and reception in block 6. The blocks are rented to two companies: blocks 2 and 3 are rented by Technip, a world leader company in project management, engineering and construction for the energy industry; Blocks 4 and 5 are currently rented by consultant company Asplan Viak. Blocks from 7 to 10 are currently occupied by the police of Bærum municipality.

The Powerhouse project concerns blocks 4 and 5 and since the beginning sets high energy performance standards for the renovated buildings such as achieving the rating of Outstanding from BREEAM-NOR. The aim of the project is to fully rehabilitate the two office blocks and transform them into energy positive buildings. In 2012 the planning work in the project began and received the approval from the city council with specific requirement for the buildings to retain their original appearance: *"the black cubes had to continue to be black cubes after the rehabilitation of the building, and the white, curved staircases that connect the buildings also needed to be retained"*(FutureBuilt, 2014). Construction work started in March 2013 and was completed in February 2014.

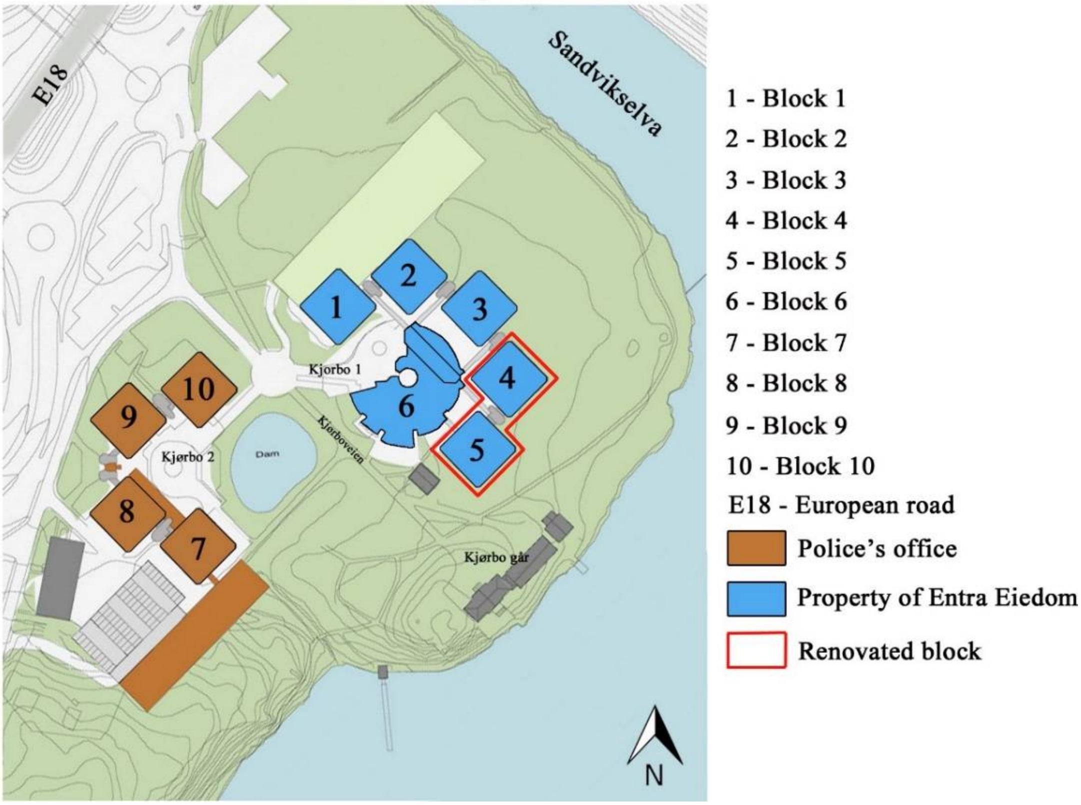



**Figure 6.1** The ten buildings of the Kjørbo office park are located in Kjørboveien, by the river Sandvikselva and near the European Road E18. The block 6 is different in the geometry from all the others.

### 6.1.3 Constructive features

Blocks 4 and 5, subjected to renovation, have squared plan of area 830 m$^2$ c.a. per floor; block 4 is a four-storey building while block 5 has three levels, so that the net surface area of the renovation project is about 5.180 m$^2$. Having an estimated capacity of 240 people, the buildings are designed for having an average area of 22 m$^2$ per person.

The blocks from 1980s had open plan at all floors, with very few office rooms in favour of big open spaces, as shown in figure 6.3 and appendix F. The external walls were originally covered with black façade glass and after almost 30 years they were in high need of renovation. The concrete frame structure, made of seven pillars arranged along two sides of a square as inner core and nine concrete pillars along each side on the external perimeter distant 2,3 m one from the other, was preserved during the renovation as well as the concrete slabs constituting the floor. Keeping the existing structure reduces the environmental loads.

Concerning energetic aspects, the heating system was based on water from district heating, while the cooling one had a central cooling of inlet air for mechanical ventilation combined with cooled beams. All those solutions contributed to an annual renewable energy use of about 240 kWh/m$^2$ divided in electricity (~ 125 kWh/m$^2$), district heating (~75 kWh/m$^2$) and district cooling (~40 kWh/m$^2$) (Førland-Larsen, 2012). From visual analyses of picture of the interiors, the office space appears to be quite dark, with low false ceiling and luminaires built in it. Even having white furniture, the space appears gloomy due to the dark glass on the façade and the brown carpet covering the floor. An overview of a typical office space before and after the refurbishment is shown in figure 6.2.

In the new building the municipal direction for preserving the exterior appearance as similar to the original as possible has been realized by using charred wood cladding, a more environmentally friendly material because it is locally produced aspen. A detail of the materials used in the new façade is reported in figure 6.4. The windows have the same design but use a three glazing pane with cavity filled by Argon, moreover the size has been increased in order to improve view and daylight conditions, a comparison between the two types of windows is shown in figure 6.11.


**Figure 6.2** Picture of the open space office in the blocks before (on the left) and after (on the right) the renovation. The space appears smaller, more chaotic and gloomier in the old building because of the low false ceiling and dark windows glass.

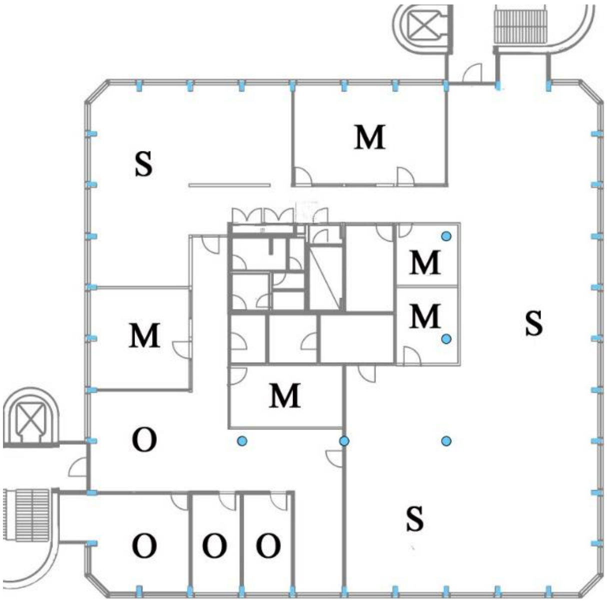
On the whole the thermal performance of the façade are increased thanks to better thermal insulation, in particular the design phase was focused on thermal bridges avoidance regarding mounting windows, insulation thickness increased by 200 mm where concrete slabs meet the façade, general reduction of amount of thermal bridges by using wood as main material in the façade. In indoor spaces the concrete slabs are used as thermal mass by being exposed in the ceiling and this helps to even out the temperature throughout the day. The excellent external wall insulation makes possible to have a low thermal transmittance value, containing and reusing the building's energy as shown in table 6.2.

The interiors are completely reorganized as shown in figure 6.3: half of the floor area at each level is occupied by office rooms and the other half is used as open space. The inner core is the place for toilettes, rest rooms, print rooms and technical rooms. The concrete slabs are exposed in the ceiling, helping to even out the temperature throughout the day. Acoustic solutions for sound attenuation are achieved by highly innovative technologies such as the baffles in the ceiling and lamellas on the core walls made of recycled plastic bottles. Glass doors and partition walls inside Powerhouse Kjørbo are made of recycled glass plates which covered the previous construction. The absence of a false ceiling allows to have a higher floor-to-ceiling height, bigger windows resulting in a more luminous appearance of interiors, also thanks to white painted walls; this can be noted in figure 6.2.

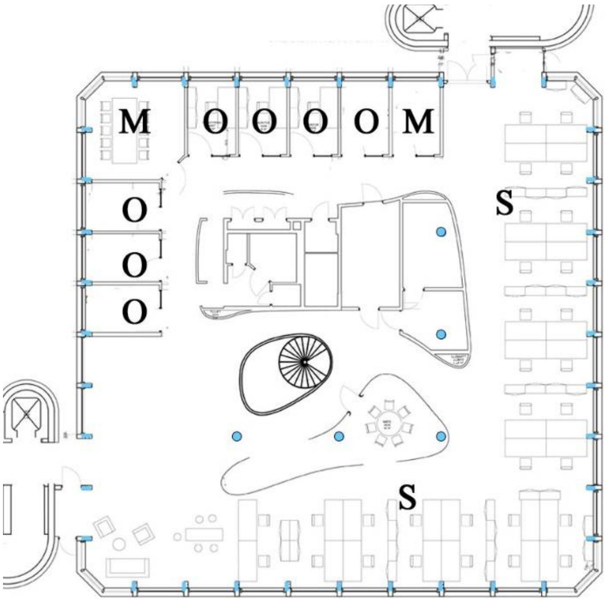
The new building is based on recycling energy and resources philosophy, minimizing energy use and losses: energy for heating is taken from the depth of the Earth into the building by two heat pumps, one for room heating and one for tap water heating. As the warm air arrives up to the stairwell, which operates as a ventilation shaft, it circulates throughout the entire space: a natural air conditioning system, based on displacement ventilation with low velocity. In this way the energy used for fans is reduced to 1/8 of conventional systems. The pipes for the ventilation are placed above the suspended ceiling in the building cores. Solar panels placed on the rooftop give renewable and clean electric energy. The estimated annual solar energy production is about 200 000 kWh and only 145 000 kWh per year are used for ventilation, lighting, heating and cooling purposes. Powerhouse Kjørbo is effectively a positive energy building thanks to this surplus production of energy.

The lighting system is designed for daylight compensation, every luminaire in office rooms has a sensor mounted in it, which adjust the luminous intensity of the T5 fluorescent lamp in order to have a minimum 500 lux at the working point. In the open spaces the luminaires are connected to a sensor in group of 4-5 lamps so that they can operate at different intensities according to the lighting condition of the portion of area underneath them. Indoor lighting levels are controlled also by shading devices as external dark movable blinds, mounted in the façade with lateral guides. The shading devices are automatically activated when sensors situated on three façades measure an excess of illuminance entering the room with respect to the set points: 100 lux for path ways, 500 lux for working places and immediate surroundings. Luminaires, sensors and shading devices are all connected together by a router-system, which hallow to customize and so optimize the use of the sensors. The sensors used are highly technologic because combine the measurement of daylight values and the eventual presence of users in the room: the lights are switched off in case of absence of people in a space for more than 15 minutes while are switched on but dimmed to 10% if someone is in the room and the daylight alone would be sufficient. Especially for visual comfort in darker hours, the system can detect if there is people on a floor activating or not lights all along the core and the stairwell. Only in the toilettes and print-rooms the MDS is used.

The lighting system is almost fully controlled by sensors, with no switchers on the walls for manual user control except for the meeting rooms, which have both sensors and a switcher on the wall which can switch on and dim the light level to 4 different scenario, in order to fully adapt to the needs of the users: from presentation on the luminous screen, to analysis of projects or meeting with customers.




Block 4 – Before the renovation




Block 4 – After the renovation

**Figure 6.3** The first two pictures show block 4 before the refurbishment; from the plan can be noted the low amount of individual office rooms (marked as O) and the prevalence of open spaces (marked as S) and meeting rooms (marked as M). The façade is fully glazed and appears very dark. The picture in the lower row show the current situation in block 4 after the renovation: there are more office, the open space is better organized, in the centre of the plan there is a winding staircase, important element for the ventilation of the space. The new façade is still dark as requested from the municipality but the cladding is made of aspen panels. The structural elements are marked in light blue, it is possible to note that nothing has changed in that part of the building.

**Figure 6.4** On the left schematic representation of the external wall having charred wood cladding as exterior layer and massive wood structure with a gypsum board on the internal side. The window in horizontally divided in two parts not equally high. On the right the external appearance of the building.

**Table 6.2** Summary of thermal properties and building service systems characteristics for the blocks before and after the renovation. Little or no energy is lost through the external envelope. Definition of the LENI number can be found in appendix A. Data from documentation produced by experts involved in the design process (Tyholt, 2013b) (Førland-Larsen, 2012).

| Thermal properties | Before renovation (Expected values) | After renovation (Average value) |
|---|---|---|
| U-value external walls | 0.30 W/m²K | 0.13 W/m²K |
| U-value roof | 0.22 W/m²K | 0.08 W/m²K |
| U-value floor on ground | 0.15 W/m²K | 0.14 W/m²K |
| U-value windows and doors | 2.5 W/m² | 0.80 W/m² |
| “Normalized” thermal bridge value, (per m² heated floor area) | 0.15 W/m²K | 0.02 W/m²K |
| Air tightness, air changes per hour (at 50 Pa) | 3.5 | 0.50 |
| **Building service systems** | **Before renovation (Expected values)** | **After renovation (Average value)** |
| Lighting system LENI number | - | ~9 kWh/m²a |
| Heating system | Water based heating system | Air heating delivered from ventilation system combined with radiators in the wave wall in the center of the building |
| Cooling system | Central cooling of inlet air for mechanical ventilation in combination with cooled beams | Central air cooling – mechanical and displacement ventilation |
| Renewable energy systems | District heating | Preliminary ground based heat pump<br>310 kW PV system for electric generation to produce 230 000 kW/a |

## 6.2 The analyses

Practical considerations and estimate daylight values from the design phase regarding the buildings after renovation are the main aspects considered to choose which part of the building should be analysed during the study. The first decision regards the choice of analysing office rooms instead of the open spaces area because more circumscribed and best suitable for measurements to be performed by one single person. If a team of students was responsible of the measurement phase and many more measuring instruments could be provided, a monitoring of the open space office would be interesting. Moreover choosing single office rooms results to be the best condition also for the company renting the blocks, in fact by limiting the measurements in one single room at the time, most of the employees can carry out their own daily activities without being distracted.

The second choice regards how many and which office rooms have to be analysed. Starting from the distribution of offices in the plan, two orientations can possibly be studied, in fact at each floor, half of the room are north-west exposed and the other half have windows in direction south-west. The initial proposal is to analyse two rooms per floor having different exposition. Furthermore, as it can be seen from tables in appendix G, in the four-storey block, 2$^{nd}$ and 3$^{rd}$ floor are alike for functional distribution of indoor spaces and daylighting conditions, so the decision of taking measurements only at one of these two floors was taken in order to not having redundant analysis.

The main criterion for picking rooms to be analysed was the daylight condition: starting from a survey based on as-built values of the project, performed by the daylight expert Marit Tyholt from Skanska, the construction company of the project. Considering rooms at the first floor of block 4, the software simulation realized by the expert divided the offices into three categories: rooms satisfying the exemplary level in reference of values prescribed to achieve the Outstanding rate from BREEAM-NOR (in yellow), rooms satisfying the exemplary level in an even better way thanks to absence of shadowing elements (in green), rooms not satisfying the exemplary level (in red). As shown in figure 6.5 the three categories of offices are marked with different colours. The current project analyses the areas not meeting the BREEAM-NOR Outstanding values when presents or the yellow areas.


**Figure 6.5** 1$^{st}$ floor plan of block 4, results from the daylight performance analysis conducted by Marit Tyholt. The coloured areas are the rooms proposed for the analyses to the renting company Asplan Viak. The numbers indicate the order of preference between many alternatives. Image modified from (Tyholt, 2013a).

**Table 6.3** Summary of the analysed rooms with respect to the proposal during the first stage of the study.

| Proposed room | Analysed room | Reason for eventual change | Typology |
|---|---|---|---|
| 4102 | 4102 | - | Originally meeting room, now used as office |
| 4112 | 4112 | - | Meeting room |
| 4202 | - | Access not possible because it is a private office | Private office room |
| 4211 | 4209 | Both rooms are private offices, the person in room 4209 was out most of the time so that it was available | Private office room |
| 4402 | - | Access not possible because it is a private office | Private office room |
| 4411 | 4411 | - | Private office room |
| 5106 | - | Access not possible because it is a private office | Private office room |
| 5114 | 5114 | - | Free office room |
| 5206 | 5206 | - | Free office room |

Even after a meeting with contact people from Asplan Viak in the preliminary phase, the effective choice of the rooms to analyse occurred the same day of the scheduled measurement operations. This was due to the particular organization of the company about working positions: some office rooms are private offices assigned to employees or chiefs of the company, other rooms are free access offices and employees are free to choose every day whether to work at the position in the open space or to occupy an office room even just for few hours.

It resulted more easy and convenient for the company to allow measurements in those free office rooms when available, so that the employees were not distracted by the measurements operations. When the monitoring procedure had to be performed in private office buildings, a necessary condition is to do it late in the afternoon, when the office is empty. In table 6.3 the suggested rooms and the effective analysed ones are reported with reference to the exemplary plan in figure 6.5. Plans of all the analysed floors can be found in appendix E.

Once the individuation of the task rooms was accomplished, daylight software simulations were performed for the same indoor spaces and a questionnaire was submitted via email to the employees. Throughout all the analyses the assumption of passive user was considered to be valid due to the massive and prevalent automatic control of lighting conditions in the working place.

### 6.2.1 Description of the analysed rooms

All the rooms have 3,3 m floor-to-ceiling height and, except for the one at the 4$^{th}$ floor of block 4, same rectangular plan shape and dimensions 2,375 m x 3,613 m.

Along both the short sides there are glazing surfaces: dark glass door and glazed internal wall towards the corridor and a short window on the external wall. The partition walls on the long sides are 125 mm thick, made of two layers of gypsum board mounted on a supporting structure. The external walls are 424 mm thick, made of wood panels mounted on a frame structure, the external façade is realized by charred wood cladding and the internal layer is realized by gypsum boards. Five to six internal surfaces of the room are painted in pure white, while the floor in covered by a three colours pattern carpet, resulting very dark.

The windows have white frame (fixed) and sash (movable) on the internal side and dark elements on the outside. All the analysed rooms except for the number 4411 belong to the same typology: triple low-e glazing (4-4-6) filled with Argon, horizontal double-hung sash, it is possible to open only the lower part which is an awning window. However the aperture allows only air flows but it is not possible to introduce any object, even the smallest, between the sash and the frame. The windows have dimensions 2.28 m x 0,575 m the smallest and 2,8 m x 0,825, including a frame 5 cm high along each side, and white internal window sill 17,5 cm deep.

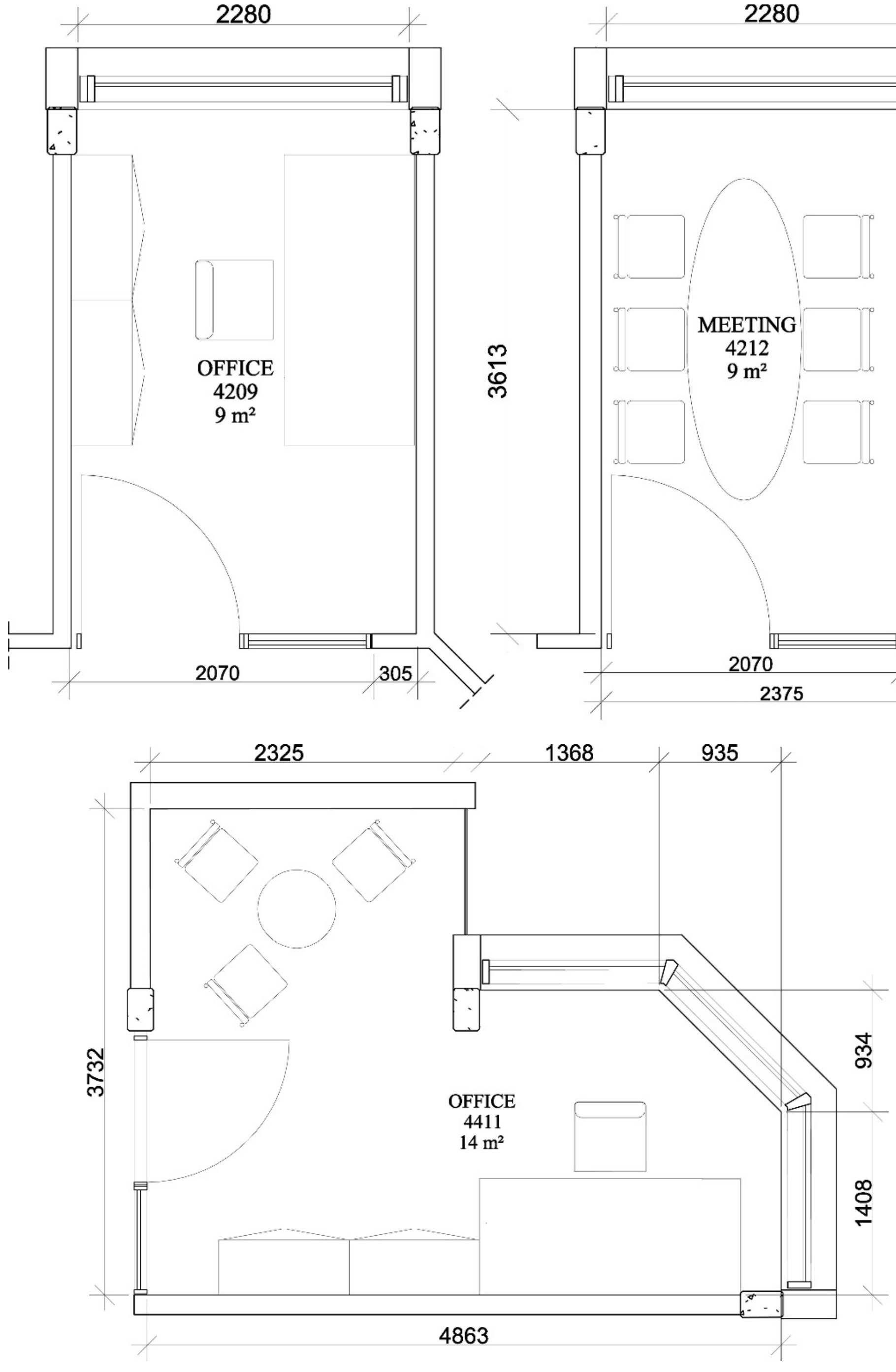



**Figure 6.6** Example of room typologies. Up on the left a typical private office room, up on the right a meeting room, below those the plan of room 4411, a private office of one of the chief of the company.

The furniture are very simple and equal for most of the rooms: four to five office rooms have a grey desk, whose height is adjustable by the user, arranged along the right side wall, a dark office chair, a white desk lamp. When it is a private office, a four-door white shelf is present on the opposite wall to the desk. All the offices has one luminaires placed above the desk, while the meeting rooms have two luminaires.

Room 4411 has polygonal plan shape (figure 6.6), three windows placed in the blunted corner and a narrow window along the north-east external wall. It has the same furniture of the other offices and in addition a small white table with three chairs is placed in the part closest to the narrow window. This particular window is different from all the others, in fact both the frame and sash are black, and the height different horizontal parts is bigger so that it can be opened towards the outside.

Room 5206 in a special office room: it can be used by two or three people working on the same project at the same time. For this reason it has a large brown table, which occupy most of the room, and a grey couch along the right wall.

The meeting room has different types of furniture: the room 4112 has a long white one leg table placed at the center of the room and six stools in light colour. Both the leg of the tables and stools are made of tube-shape highly reflective metal. It is present a screen for presentation on the right wall closer to the glazed partition wall and on the same wall but close to the window there is a small brown shelf.

### 6.2.2 Measurements

Due to permission problems, it was possible to perform measurements only in the renovated blocks but not in the old ones, in fact even though Entra Eiendom owns all the blocks from 1 to 6, block 1 was in the refurbishment phase and it was not possible to access, blocks 2 and 3 are rented by companies different from Asplan Viak and did not give the permission for entering in the buildings.

#### 6.2.2.1 Equipment description

All the equipment used during the monitoring procedure was provided by the Faculty of Architecture and Fine are of the Norwegian University of Science and Technology. The instruments used to perform the essential monitoring procedure were:

| | |
|---|---|
| ▪ Flexometer 3 m long;  | ▪ Reference grey surface;  |
| ▪ Masking tape;  | ▪ NCS reference colour chart;  |
| ▪ 1 hand-held lux meter for exterior;  | ▪ 1 hand-held lux meter for interior;  |
| ▪ 1 hand-held luminance meter;  | ▪ 1 Nikon D700 digital camera;  |

| | |
|---|---|
| ▪ 1 fisheye lens for digital camera;<br> | ▪ Software to synchronize the digital camera to a laptop;<br> |
| ▪ 1 laptop for remote shutter control;<br> | ▪ 1 tripod;<br> |

To measure the exterior diffuse horizontal illuminance is necessary to create a shading element for the sensor of the lux meter. To realize the lux meter shading sensor it is possible to use: grey cardboard, any pen or marker, scissors, any standard standard PVA glue, a wooden stick; the used material is shown in figure 6.7a. Draw two circles on the grey cardboard (figure 6.7b) and cut them out. Glue together the two circles to make a unique one, thicker and resistant (figure 6.7c). Wait until the glue between the two parts is perfectly dried and glue the wooden stick to one side of the circle (figure 6.7d). Now the shading system is ready (figure 6.7e) and it can be used by fixing the free extremity of the stick to a tripod and shading the lux meter sensor.

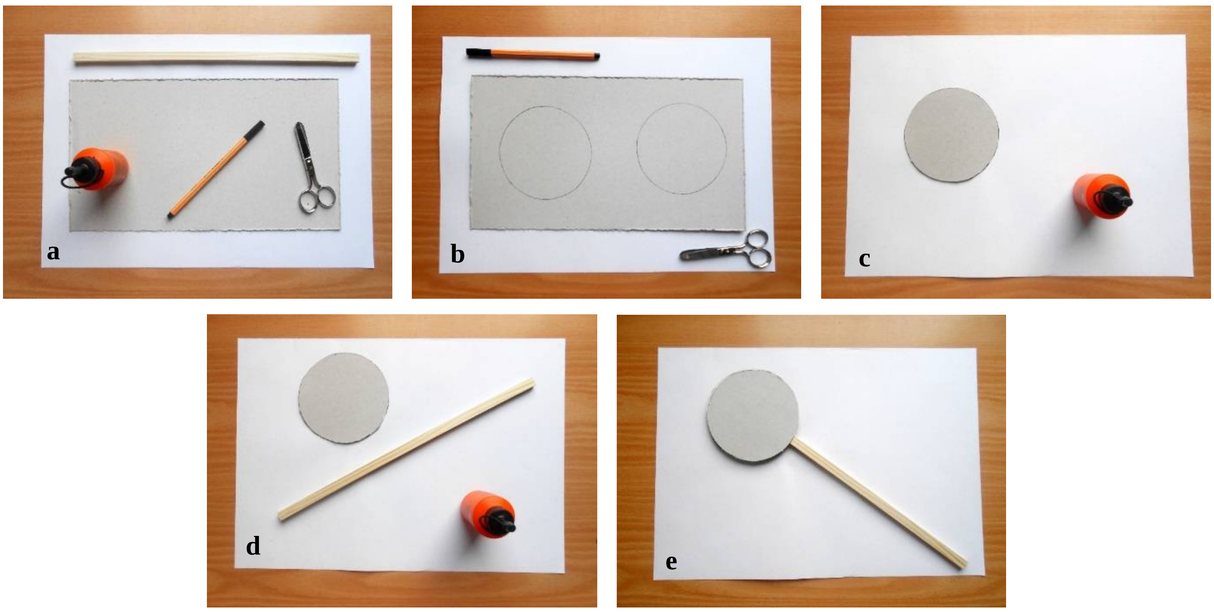



**Figure 6.7** Steps for create a shading element for the lux meter sensor.

6.2.2.2 Preparatory phase

Before visiting the site and perform the measurement it was necessary to study the monitoring procedure and elaborate tables for collecting the data. The procedure was divided in nine tasks and further subtasks, all the tables generated are reported in appendix D.

Since illuminance values depends on the point where they are measured, it was necessary to preliminary elaborate a grid to individuate exactly in which point realize the measurements. The grid geometry follows the indications given from IEA SHC Task 50 – Subtask D, it is showed for one general office room in figure 6.6 and reported for each analysed room in appendix D.

Once on site, before starting any phase of the monitoring procedure, it was necessary to mark the points indicated on the grid on the floor of each room by using a flexometer and masking tape.

#### 6.2.2.3 Renovated blocks

The measurements were performed during week 16, in dates 13th and 14th April 2015, within one month from the spring equinox according to the limits imposed by the monitoring protocol for IEA SHC Task 50 – Subtask D. During these days the perfect weather conditions required for taking measurements were present in fact April 13th was a sunny day, with perfect clear sky in the morning and small percentage of covered sky late in the afternoon; during that day it was possible to take HDR picture for studying luminance distribution and glare at the task point, to measure indoor illuminance distribution and exterior diffuse illuminance $E_{hd}$, to detect sun patches and veiling reflections, to observe the directionality of the light entering the rooms, to note down colour surfaces and evaluate the view out. On April 14th, having overcast sky conditions, it was possible to collect luminance and illuminance values of the main surfaces in the rooms in order to determine their reflectance, to measure the glazing transmittance, and the indoor and outdoor illuminance for DF calculations, to perform nighttime measurements.

In the preliminary phase it was necessary to solve some problems that could add inaccuracy to the measurements. First among all it was necessary to switch off the light in the room when performing the daylight measurements; if it appears to be not a big deal in most of the indoor spaces, it was a challenge in Powerhouse Kjørbo due to the automatic remote control of the lighting system: the absence of the switchers on the wall apt to manual user control at first could be a great obstacle. It was not possible to disable the whole sensors system at one floor because the employees needed light for working, so a rough solution was to unscrew the lamp in the luminaire of the analysed room in order to avoid electric contact. Finally the problem was solved by having the chance to use a remote controller, acting on the sensor of the single lamps which could be switched off for about 20 minutes.

Another issue related to daylight in indoor spaces measurements is the automatic and autonomous activation of the shading devices to avoid glare thanks to sensors on the façade measuring illuminance values that could generate glare in the room: it can happen that the black curtain avoids daylight to get into the office by shading the window while one is measuring. However it is sufficient to manually force the shading device to be off by the switcher on the wall to reset the condition needed for the monitoring task.

When it comes to the measurement of the outdoor illuminance for the calculation of the daylight factor, it was necessary to have access to the roof of block 5 and the help of the person responsible of the safety in the building was needed given that the door to the roof is locked twenty-four-seven. Once the access was free, the operator could stand only in a narrow area of the roof, very close to the door and so to the wall of the block 4, one storey higher than the roof level. This limitation is due to the solar panels occupying 90% of the floor area on the roof. It was very important to find the right position for the lux meter so that the sensor was not shadowed.

Regarding the measurement of glazing transmittance, to be performed as described in section 5.1.1.2, it was not possible to act on any office's window because, as anticipated in section 6.1.3, the window was not suitable to be open. For this reason the measurement was performed on a glazed door having the same characteristics of the windows, separating an indoor space from the outdoor.

A last main problem was related to the availability of a room for measurements performing, in fact, as presented in subsection 6.2.1, the private office rooms are daily occupied by employees. In order to not interfere with working activities the measurements in those rooms were performed late in the day, when the occupants left. Consequently it was not possible to collect illuminance data when the sun was at its highest point in the sky and especially for room 4411 it was impossible to perform measurements with electrical light fully off.

To illustrate how the whole procedure was conducted, measurements taken in room 4209 are reported in this section as an example; the collected data from all the other rooms are reported in appendix E. When presenting the performed measurements a distinction can be made between values specific for the described room and general observations about elements used in all the rooms.

- Specific analysis:

During day April 13th the clear sky condition was present and the procedure in room 4209 started at 11:30 measuring the **illuminance value** at the working task height of 0,8 m. The lux meter with extensible sensor was used for indoor measurements by fixing the sensor to the tripod head set to the right height; in this way one is sure to measure the illuminance always at the same height when moving the sensor from one point to the other and not to cast any shadow on the sensor because it is possible to read the measure far from it. Because of the high variability of solar radiation, changing continuously, it is always good to repeat the measure at least 3 times and calculate an average value of the illuminance in one point. The sketch of the plan grid is reported in figure 6.8 and the measured values are shown in table 6.17.

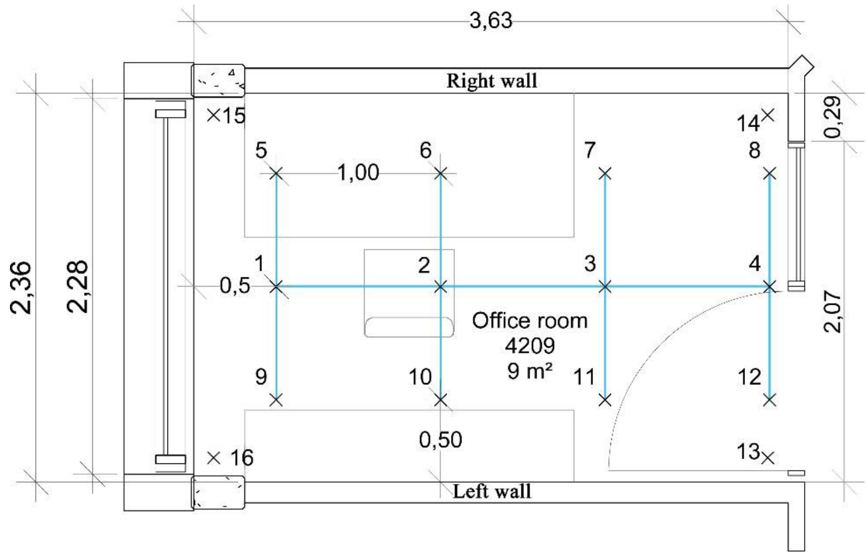



**Figure 6.8** Plan of the office room 4209. In blue the grid for the measurements, it is 0,5 m distant from the side walls and there is a distance of 1 m between two consecutive points. The points from 13 to 16 have no defined distance position, they mark the requirement of measuring values at the four corners of the room.

Next step consisted in taking pictures of the working area (desk position and eventual computer monitor) with the fisheye lens for post-hoc analysis of the **HDR image** produced by image processing software such as Picturenaut 3.2. By placing a grey reference surface on the picture, whose luminance value can be instantly measured, in the elaboration of the results phase it is possible to normalize the luminance values in the HDR pictures obtained with Radiance. To have an additional check, the luminance values were measured for the main surfaces around the task point. The image analysed by radiance is shown in figure 6.17 and the measured values are reported in table 6.16.

After placing the camera in the tripod and finding the right position from which taking picture, by remote controll on a laptop is possible to set the settings: aperture F10, ISO 100, exposure zero and consequent best shutter time. The remote control and the tripod are needed because it is necessary to take picture of the same exact view without any movement of the camera. By changing the exposure in the range ± 5 and taking picture at any unit one will get over exposed (+) ad under exposed (pictures).

From time to time during the day it was necessary to come back in every analysed room in order to note down eventual presence of **sun patches and veiling reflections** in the indoor space. Sun patches were detected during the afternoon between about 16:00 and 20:00, in particular the areas with high illuminance were present on the right wall (see notation in figure 6.6) starting very close to the window edge but extending to the working area later in the afternoon. Due to absence of glossy surfaces and the avoided interaction of sun patches with the glass surfaces on the partition wall at the corridor side, the only veiling reflections in the room were caused by the computer screen. An example of the descripted situation is reported in figure 6.9.

The next step concerned the evaluation of the **quality of the view out**. As can be observed in figure 6.10, the view from the room is full of elements but not all the three main layers are present: it is possible to see the ground and the sky but there is no chance to have a deep view with a background due to the close buildings surrounding block 4. Due to dirty glazed façade and a building under construction, the view does not result very pleasant, but it is still possible to recognise some natural elements as trees, grass and flying birds. Thanks to the view of the sky, the human needs of knowing the time and the weather conditions are satisfied.

**Figure 6.9** Veiling reflection caused by sun beams entering the room. The picture refers to room R5209 but the same phenomenon occurs in each room.

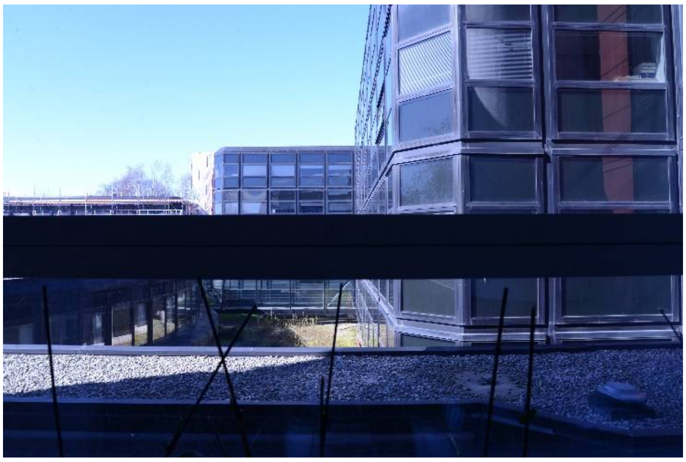


**Figure 6.10** View out from room R4209. It is reach of elements and layers but the quality of the view is highly affected by the horizontal frame dividing the two elements composing the window. The view would be more pleasant if the window was made of a unique big element.

On the 14th April it was completely overcast, with snow falling down during the afternoon. There were the perfect weather conditions for measuring luminance and illuminance values on the main surfaces in the room so that it was possible to calculate the **reflectance** of those areas. It is important to know the reflectance of surfaces because it is a parameter used to obtain well balanced luminance distribution and to avoid glare or veiling reflections.(Bellia et al., 2011). The values were measured three times per each surface and the average reflectance was calculated obtaining the values in table 6.13.

The most important phase of the monitoring procedure is the calculation of the DF at the points of the grid. In order to get it, illuminance value measurement has to be taken simultaneously indoor, at the point one has to measure, and outdoor, being aware that nothing is shadowing the sensor, even the operator himself. Before starting the measurements, the two lux meters were calibrated: the percentage of calibration results 99%. With the help of an employee standing on the roof and measuring the external illuminance, by telephonic contact it was possible to get the exterior and interior illuminance values simultaneously for every point of the grid. However even if it was necessary, the measurement was performed only one time for each point due to the small amount of time during which the help of a second person was possible. The measured values are reported in table 6.4.

During the evening, the **illuminance distribution** under artificial light was measure. The procedure is the same as for daytime of securing the lux meter sensor to the head of the tripod and be aware of not shadowing the sensor. However for how accurate the operator can be, the luminous intensity from the luminaire was variable from room to room because the sensor adjust the emitted light depending on the luminance at the surface just underneath it. For example if a white object is under the sensor the light emitted from the lamp would be lower than the case of a dark surface. The measured values are presented in table 6.18.

**Table 6.4** Indoor and outdoor illuminance values measured simultaneously for the calculation of the daylight factor.

| Measurement point | Indoor illuminance [lux] | | Exterior global illuminance on an horizontal plane $E_{ho}$ | | DF |
|---|---|---|---|---|---|
| | Value | Magn. | Value | Magn. | |
| 1 | 405 | 1 | 725 | 10 | 5,59 |
| 2 | 134 | 1 | 754 | 10 | 1,78 |
| 3 | 592 | 0,1 | 766 | 10 | 0,77 |
| 4 | 226 | 0,1 | 780 | 10 | 0,29 |
| 5 | 420 | 1 | 782 | 10 | 5,37 |
| 6 | 177 | 1 | 792 | 10 | 2,23 |
| 7 | 391 | 0,1 | 782 | 10 | 0,50 |
| 8 | 313 | 0,1 | 783 | 10 | 0,40 |
| 9 | 332 | 1 | 781 | 10 | 4,25 |
| 10 | 725 | 0,1 | 794 | 10 | 0,91 |
| 11 | 412 | 0,1 | 796 | 10 | 0,52 |
| 12 | 216 | 0,1 | 796 | 10 | 0,27 |
| 13 | 142 | 0,1 | 798 | 10 | 0,18 |
| 14 | 441 | 0,1 | 801 | 10 | 0,55 |
| 15 | 228 | 1 | 802 | 10 | 2,84 |
| 16 | 477 | 1 | 814 | 10 | 5,86 |
| **Average daylight factor** | | | | | **2,02** |

- Generic considerations:

Under sunny conditions, on the 13th April, the quality of the effects of the **shading devices** was evaluated: being a dark plastic fabric with micro holes the opacity of the element is good but not total, the vision of outside light is still possible when the device is in the closed position. On the other hand the solar protection device is able to reduce the high luminance in the room due to the solar spot on the work surface and its immediate surroundings and to prevent disturbing reflections on visual the display. When fully extended the shading element prevent any exterior view and the indoor space gets much darker, for these reasons it is reported that the solar protection device does not optimize the available daylight or reduce the time period during which the artificial light is required.

The **colour of surfaces** in the room can be applied to all the analysed spaces of the building, with exception of piece of furniture specific of certain rooms. A summary of colour of the main surfaces in the office rooms is presented in table 6.5.

The measure of the **exterior horizontal diffuse illuminance** was carried out only one time throughout the whole period of monitoring in the space outside the entrance of block 4, a sunny place without any element shadowing the area nearby. To measure $E_{hd}$ the lux meter for external use was placed on the ground and the lux meter shading sensor was secured to the tripod and placed in such a position that only the sensor was shadowed. The measurement was taken ten times as showed in table 6.10 and an average value was calculated to take in account the variability of the solar radiation.

**Table 6.5** Colours of the main surface in a typical office as room 4209.

| Surface | NCS colour code | Description | Graphic representation |
|---|---|---|---|
| Door wall | NCS S 0300-N | Traffic white | |
| Right wall | NCS S 0300-N | Traffic white | |
| Left wall | NCS S 0300-N | Traffic white | |
| Window wall | NCS S 0300-N | Traffic white | |
| Floor | NCS S 4030-Y20R | Brown beige | |
| Door | NCS S 3030-Y20R | Brown | |
| Desk | NCS S 4502-G | Traffic grey A | |
| Chair | NCS 9000 N | Black brown | |
| Shelve | NCS 1000-N | White | |

**Table 5.6** Measurement of the exterior horizontal diffuse illuminance taken outside the block 4 and 5 on a sunny day.

| Measurement nr. | Illuminance [lux] | |
|---|---|---|
| | Value | Magn. |
| 1 | 150 | 100 |
| 2 | 150 | 100 |
| 3 | 150 | 100 |
| 4 | 157 | 100 |
| 5 | 156 | 100 |
| 6 | 154 | 100 |
| 7 | 153 | 100 |
| 8 | 152 | 100 |
| 9 | 151 | 100 |
| 10 | 148 | 100 |

Under the overcast sky in date 14$^{th}$ April, it was possible to measure the glazing transmittance with reference to the glazed door used as access to the roof. With a lux meter right outside the door and the other one inside, both horizontally oriented, the illuminance values was recorded ten times and the average value of the hemispherical-hemispherical transmittance was obtained. By using a luminance meter and noting down the luminance values taken alternatively with the door closed and open, focusing always on the same object outdoor, the arithmetic mean normal-normal transmittance was calculated. The values are reported in table 6.7.

**Table 6.7** In the table on the left are presented the luminance values measured for determine the normal-normal transmittance. In the table on the right there are the illuminance values needed to determine the hemispherical-hemispherical transmittance.

| Measurement nr. | Luminance [cd/m$^2$] | | Transmittance τ |
|---|---|---|---|
| | Window close | Window open | |
| 1 | 183,9 | 249,5 | 0,737 |
| 2 | 157,5 | 200,5 | 0,786 |
| 3 | 121,1 | 173,6 | 0,698 |
| 4 | 149,8 | 165,6 | 0,905 |
| 5 | 117 | 198,3 | 0,590 |
| 6 | 162,5 | 169,6 | 0,958 |
| 7 | 118,5 | 179,8 | 0,659 |
| 8 | 176,7 | 275,1 | 0,642 |
| 9 | 129,2 | 160,8 | 0,803 |
| 10 | 147,5 | 181,5 | 0,813 |
| **Mean normal-normal transmittance** | | | **0,759** |

| Measurement nr. | Illuminance [lux] | | | | Transmittance τ |
|---|---|---|---|---|---|
| | Inside | | Outside | | |
| | Value | Magn. | Value | Magn. | |
| 1 | 315 | 10 | 105 | 100 | 0,300 |
| 2 | 310 | 10 | 102 | 100 | 0,304 |
| 3 | 340 | 10 | 998 | 10 | 0,341 |
| 4 | 365 | 10 | 102 | 100 | 0,358 |
| 5 | 352 | 10 | 108 | 100 | 0,326 |
| 6 | 368 | 10 | 109 | 100 | 0,338 |
| 7 | 349 | 10 | 106 | 100 | 0,329 |
| 8 | 312 | 10 | 980 | 10 | 0,318 |
| 9 | 287 | 10 | 930 | 10 | 0,309 |
| 10 | 316 | 10 | 941 | 10 | 0,336 |
| **Mean hemispherical-hemispherical transmittance** | | | | | **0,326** |

### 6.2.3 Software simulations

General assumptions made when creating the model are:

- Effects of light reflection from the river are neglected because the water is quite far from the constructions, moreover the reflectance is influenced by the depth of the river, clearness of the water and weather conditions. In fact under overcast sky the water act as a glass when interacting with light, most of the light passes through the water surface, while in presence of clear sky the phenomenon of specular reflectance occurs and light is reflected towards the surroundings.
- The reflectance of the grass nearby the block is assumed to 15% as reference value.
- Only the relevant part of the surrounding blocks are modelled as shadowing objects, assuming the reflectance of the façade at the value 15% and 20% for the reflectance of the glazed corridors.

Specific assumptions needed to be done when performing software simulations on the old building due to a lack in information; those are:

- The fake room has a rectangular plan shape, similar to the rooms in the new building but with slightly different dimensions to better adapt to the space in which it is insert. The new dimensions are 2,53 m x 4,85 m x 2,8 m . The height is reduced to 2,8 m due to the presence of the fake ceiling.
- The reflectance of surfaces has to be estimated by the few pictures available; values are reported in section 6.2.3.1.
- The light transmittance of the old windows has been estimated by considering the flat pane glass with dark colour. The dimension of windows has been estimated by reducing the width and keeping the same height with respect to the geometry of the window in the new building. Moreover it has been considered the presence of only one element, eliminating the intermediate horizontal frame present in the new window.

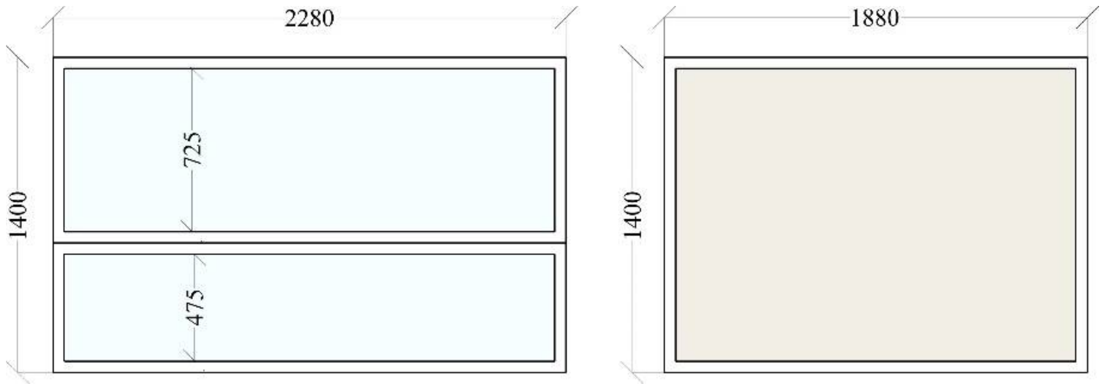



**Figure 6.11** To the left the window used in the renovated blocks, to the right the estimated dimensions for the old type of window.

6.2.3.1 Before refurbishment

Due to lack of information from as built documents or design drawings, all the reflectance values of the interior surfaces in the not renovated block have been assumed based on the picture of the open space office reported in figure 6.2. The assumed reflectance is: 40% for the floor, 60% for walls, 70% for the ceiling, and 85% for the white pillars.

As can be observed in figure 6.4 in block 4 there are no office rooms North-west or south-west exposed and the same situation is present in block 5, for this reason the analyses was conducted on a fake office room placed at the second floor of block 4, on the north-west façade, created by adding a partition wall as showed in figure 6.12.

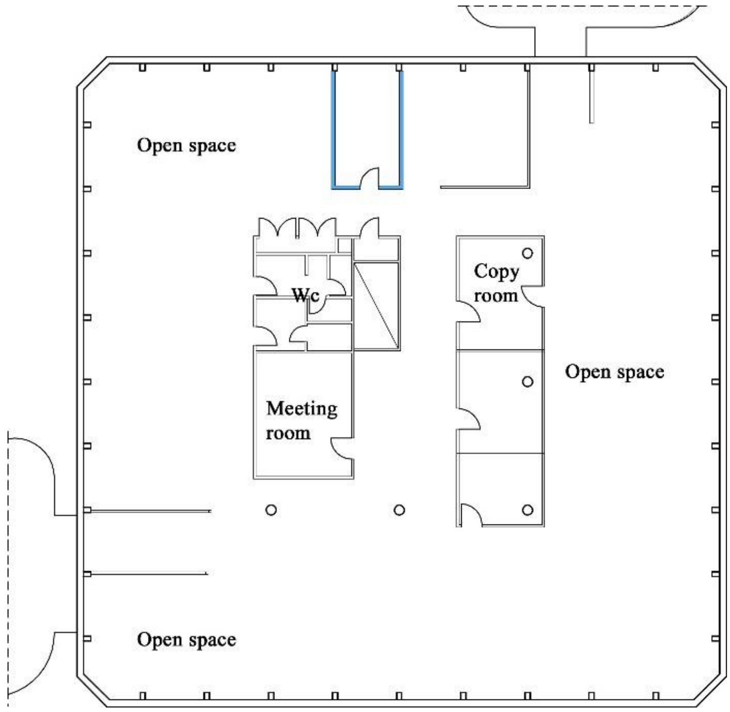



**Figure 6.12** Plan of block 4, 2nd floor. The room added for the software simulations is marked in blue.

The main focus in the daylight simulation performed on the old building was the daylight factor, the most reliable value in prevision of a comparison with the renovated blocks. It fact the illuminance distribution under clear sky was not considered a relevant subject for confronts due to the highly variability of the illuminance at any time and point depending on many factors. The study of the illuminance distribution under artificial light could not be performed due to lack of information about the lighting system.

The DF values were analysed at height 0.8 m from the floor, Norwegian standard for working areas. The results of the simulation are reported in section 6.3.1.

#### 6.2.3.2 After refurbishment

The generation of the model for the renovated blocks started from the project drawings for geometry of the rooms and relative distance with the surroundings; reflectance of surfaces was set by converting the colours reported in the as built documents from any colour system to RAL. When necessary the reflectance was adjusted according to the measured values in order to have a model as accurate and close to the reality as possible. The most elaborate surface to model was the floor and the particular pattern of the carpet, obtained by the combination of three different colours.

In order to model the effect of the glazed surfaces on the partition wall towards the corridor, the room was modelled as a polygonal shape, but still rectangular, so that it was possible to set different values for adjacent walls. With reference to figure 6.13 on the long side walls, two parts were distinct: the walls of the office room and two opposite black surfaces in order to model the depth of the corridor. The glazed surface was modelled as a working surface mad of glass and some cubes represented the door's frame.

Window's geometry was equal to the real element, frame on the internal side was set as white and on th external side as dark brown. From the ray-tracing material library in Relux, the window was insert as a three glazing pane with Argon.

All the furniture were specifically modelled in SketchUp, in order to reproduce the same geometry and colour, the acoustic panels were placed at the ceiling and the luminous intensity distribution curve of the same luminaire placed in the real building was imported in the software.

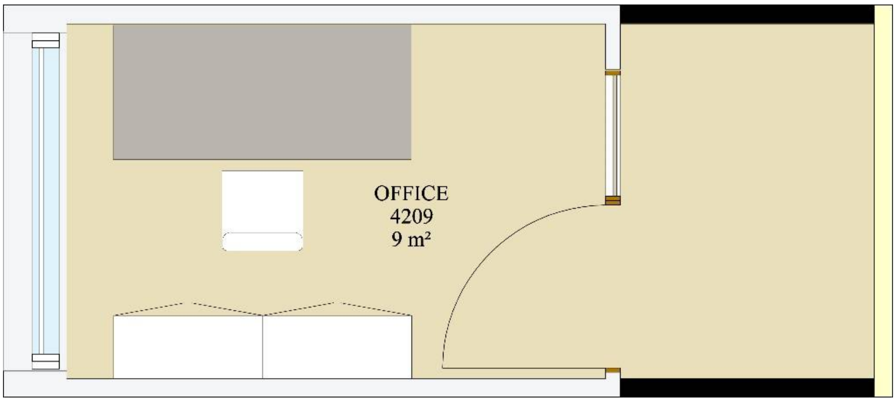



**Figure 6.13** Plan of the modelled room. In order to simulate the presence of the corridor, the two walls perpendicular to the direction of the corridor (in black) are considered having 0% reflectance.

The simulations were performed, at exactly the same dates and time when the measurements had been taken, in three conditions: for daylight simulation under overcast sky to obtain the DF values and clear sky to obtain the illuminance distribution due to daylight, at nighttime with electrical lights on for artificial illuminance distribution. For all the cases the ray-tracing materials were taken in account and the number of inter-reflections was set to 8 in order to have a truthful result.

### 6.2.4 Users interviews

Due to the not availability of companies renting the not renovated blocks it was not possible to conduct any survey about users' satisfaction in one of the blocks 1, 2 or 3. Regarding the refurbished blocks, at first the chance to submit questionnaire to the employees occupying the specific rooms analysed was presented as a possibility. Once on the site however, due to the fact that it was possible to take measurements in empty rooms only, the questionnaire proposed from IEA SHC Task 50 – Subtask D resulted to be not appropriated. Some information about how users perceive the working place were collected by short talks in the corridors and other common areas, but most of the comments regarded the open space area.

Later an electronic survey was created in the form of short multiple choice questions to be filled online and a request for sending the survey to any employees by email was made to the employees' representative person. The questionnaire can be found in appendix C2. Unfortunately due to the great amount of retrofitting analysis performed at Powerhouse Kjørbo from many different research centres and master students, the company Asplan Viak could not diffuse the questionnaire to avoid stress to the people working in the buildings.

The representative of users showed his availability to answer to general questions about employees' satisfaction, the results are presented in section 6.3.3 and the whole questionnaire can be found in appendix C3.

## *6.3 Results*

In this section the results from measurements and software analysis are presented and related one with the others. In particular the software lighting performances elaborated for the blocks before and after the renovation are compared in order to verify whether a significant improvement was achieved with renovation or not, while software simulations and measurement results are presented for the refurbished offices to check if design values are really achieved in the as-built project.

### 6.3.1 Comparison between software simulations

In order to have comparable values, the simulation in the old building has been performed in a room appositely designed at the second floor of block 4, so that exposition and surrounding shading elements are the same as for room R4209 in the renovated building.

The daylight factor resulting from software simulation performed for both the old building and the refurbished one shows some difference as it may be expected. With reference to table 6.12 the average daylight factor of the space has been improved in the renovated building as declared in the design phase. In general the room results better lit in the refurbished block in terms of uniformity of the light level: the $DF_{max}$ is lower and the $DF_{min}$ has been increased. As showed in figure 6.14 the light level in the room before the renovation is high in points very close to the window, but it decreases very fast resulting in very low values from almost half of the room depth to the wall opposite to the window one. A very different behaviour can be noted in room R4209, where the decrease in light level is more restrained.

The improvement in daylight performance for the new building is due to many factor: higher reflectance of surfaces, higher window-to-floor ratio (40/60), reduced room depth.

**Table 6.8** Summary of the principal DF values in the renovated and old building with reference of room R4209 in the new building and the fake room created for the study in the building before the refurbishment.

| Building | Parameter | Value |
|---|---|---|
| Before the renovation | $DF_{average}$ | 1,25 % |
| | $DF_{max}$ | 6.68 % |
| | $DF_{min}$ | 0.21 % |
| | $U_o$ | 0.17 |
| After the renovation | $DF_{average}$ | 1,72 % |
| | $DF_{max}$ | 4,41 % |
| | $DF_{min}$ | 0,52 % |
| | $U_o$ | 0.30 |

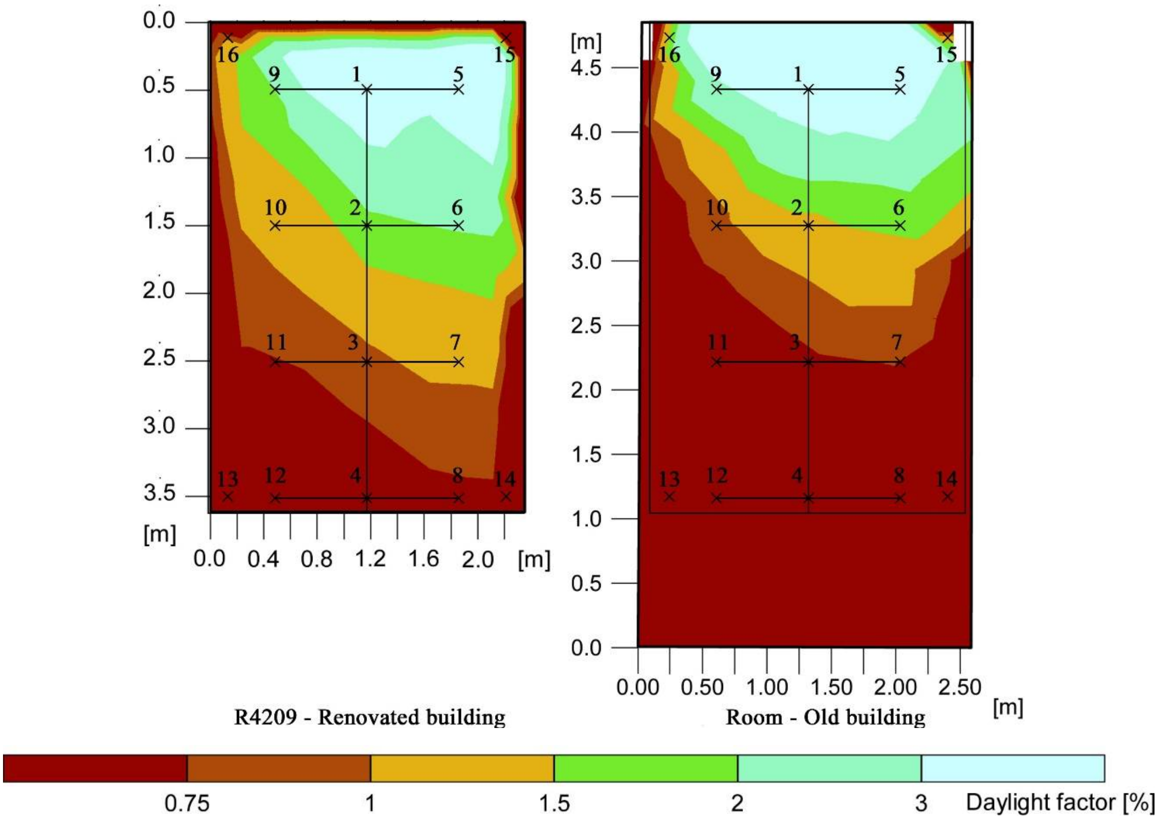



**Figure 6.14** On the left the DF at the height of the working area in a room of the refurbished block, on the right the DF at the same height from the floor in a space appositely designed to fit with the new room in exposition and shadowing elements. The numbers on the floor area represent the grid points.

## 6.3.2 Measurements and simulation results for the renovated rooms

The lighting characteristics of the rooms that can be studied both by simulations and measurements in situ are the daylight factor distribution and the average value for each room, the illuminance distribution under daylight on a sunny day and the illuminance distribution due to artificial light, all measured at the working area height of 0,8 m. Moreover it is possible to test the reliability of luminance investigation from a fisheye lens picture elaborated by the software Radiance by comparing some values with the ones measured by a luminance meter when the picture was taken.

A schematic presentation of the measurement results is now reported for room R4209 as example, with the appropriate contrasts to the software simulations when possible.

**Block 4 – Room 4102**

The space is a private office, so two white shelves are added along the left wall with respect to the basic furniture of a standard office. It is also present a white chair in the corner next to the glazed partition wall. The room is north-west oriented, it is located at the center of the façade (figure 6.6). There are no shading elements facing the window in a short distance as can be seen in figure 6.15.

By measuring the luminance of the main surfaces in the room and illuminance in the same points, the reflectance values reported in table 6.9 were calculated and used in the digital model; the lighting-related settings of windows in the model were adjusted according to the measured values showed in table 6.10.

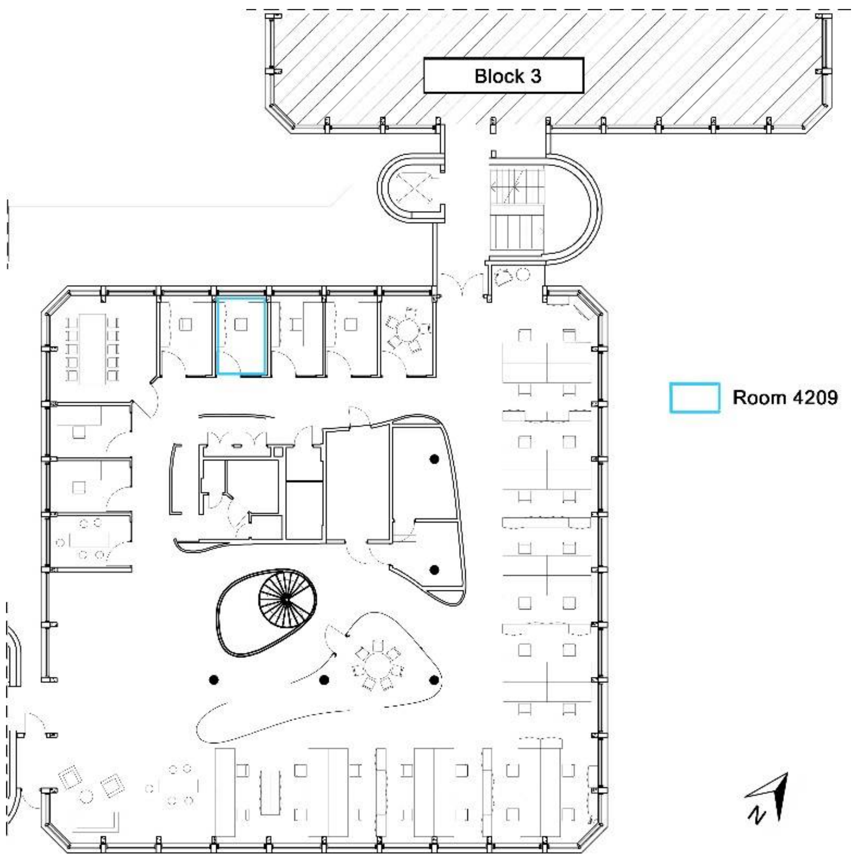



**Figure 6.15** Plan of the 2nd floor of block 4. In blue the analysed room. It is possible to check that there are no shading elements outside the window of the office.

**Table 6.9**

| Surface | Average reflectance [%] |
|---|---|
| Door wall | 82,72 |
| Right wall | 74,02 |
| Left wall | 84,31 |
| Window wall | 73,77 |
| Floor | 10,60 |
| Door | 37,23 |
| Desk | 18,86 |
| Chair | 1,80 |
| Shelves | 65,97 |

**Table 6.10**

| Type of transmittance | Average transmittance τ |
|---|---|
| Normal-normal | 0,759 |
| Hemispherical-hemispherical | 0,326 |

From the HDR analyses, the luminance distribution showed in figure 6.15 is obtained. At the moment when the picture was taken, the luminance was measured in few points in order to have a numerical validation whether the calculate values were reliable, measurements are reported in table 6.11. The luminance values calculated by Radiance from the HDR image show a gap from the measured values and it can be noted that the error committed by the software is higher at brighter surfaces, an example is the difference between the error for the luminance at the white and lit wall and the point on the floor, under the desk.


**Figure 6.15** Fisheye image elaborated by Radiance to obtain luminance value in relevant points, values are reported in table 6.15.

**Table 6.11** Luminance values measured on site and calculated by Radiance from a HDR fisheye lens. The relative error is calculated in reference to the average luminance of the grey reference. In grey the points where the comparison is possible, in white the points where only calculations were performed.

| Surface | Point | Luminance [cd/m$^2$] | | Error |
|---|---|---|---|---|
| | | Measured | Calculated | [%] |
| Grey surface | | 18,99 | 54,90 | 97,20 |
| Right wall | 1 | 92,20 | 141,00 | 132,09 |
| | 2 | 31,67 | 51,80 | 54,49 |
| | 3 | 18,31 | 26,70 | 22,71 |
| | 6 | | 233,60 | |
| | 7 | | 46,60 | |
| | 8 | | 73,20 | |
| Floor | 4 | 2,44 | 6,60 | 11,27 |
| | 5 | 1,99 | 4,90 | 7,88 |

The daylight factor analyses showed quite different values between the simulation and the measured values as reported in table 6.12. Moreover neither the measured values nor the simulation ones reach the requirement $DF_{averge}$= 2,5%, necessary for at least 80% of the rooms in a building in order to achieve the rating of Outstanding in the BREEAM certification. For a visual comparison one can refer to figure 6.16 where the measured DF values are presented in a matrix instead of a table to make an easy confront with the software simulation. The causes of the gap between the results may be many and various: the simplification of the digital model for example when setting reflectance values of the surfaces in the room and of the external objects but also making the approximation of considering the objects as perfectly diffusive when in the reality the finish is most likely semi-diffusive; the number of inter-reflections set could be higher, in fact the higher the inter-reflection the more precise the result of the simulation but on the contrary it is more time consuming; when measuring the parameter in the room the only presence of the instruments and operator affects the way light is reflected from one surface to another and the value of the absorbed component is higher; most important is to be aware that as elaborated and technically advanced the algorithm can be, the solar electromagnetic field is very unpredictable and changes constantly so that the model is always an uncertain approximation. All those factors contribute to increase the gap between the calculated and measured values and have to be considered also for the analyses of the illuminance distribution.

**Table 6.12** Summary of calculation characteristics and analyses results.

| | Simulation | Measurement |
|---|---|---|
| Date | 14/04/2015 | 14/04/2015 |
| Time | 14:30 | 14:30 |
| DF average | 1,72 | 2,02 |
| DF max | 4,95 | 5,86 |
| DF min | 0,54 | 0,18 |

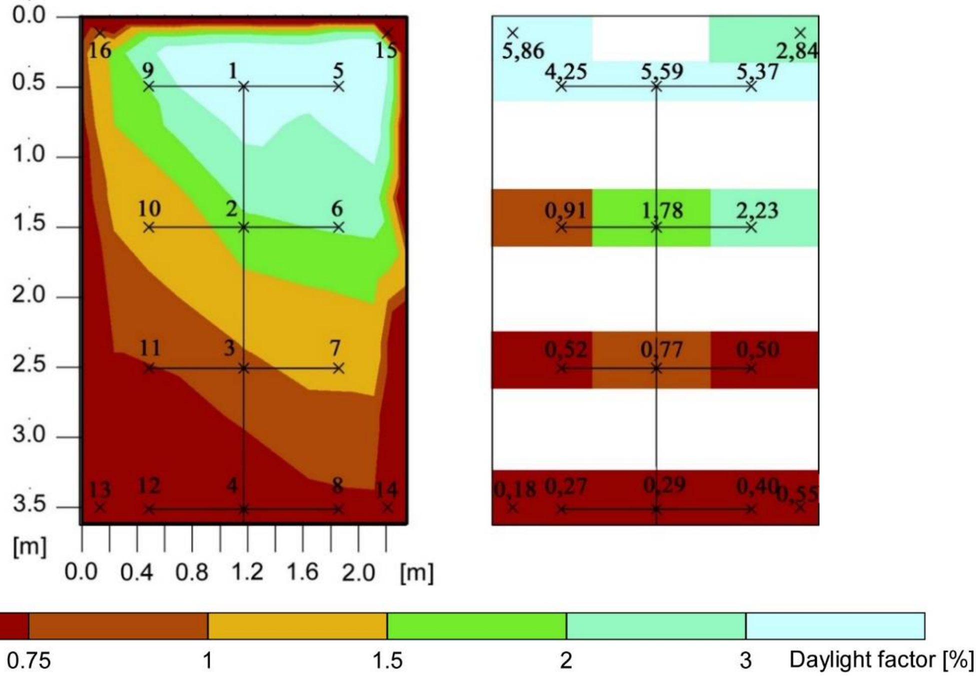
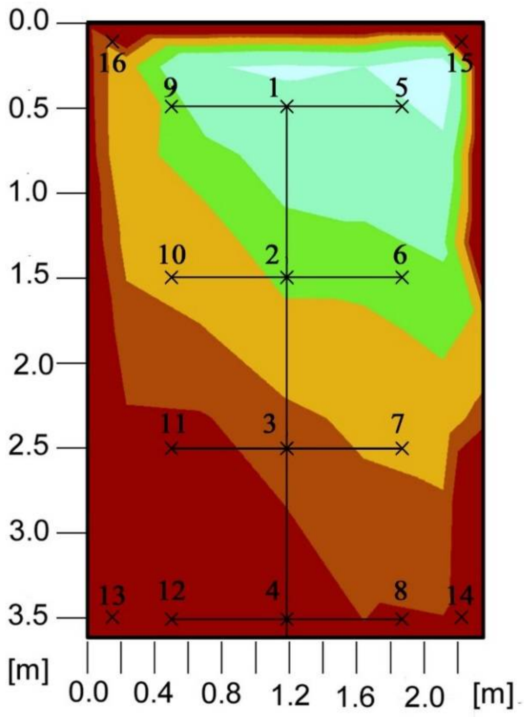



**Figure 6.16** With reference to the scale of colours it can be noted that the measured values are lower than the ones obtained from software simulations. The numbers on the floor area represent the grid points.

The analyses of illuminance distribution in the room refers to the date 13th April at 18:00. At that time the sun is low enough to create very bright areas and very dark ones as can be noted in figure 6.17. A confront with the measured values is possible by looking at the values in table 6.13.

**Table 6.13** Illuminance values from measurements. Values were not taken for points 4, 8 and 12 because the values could be affected by the presence of light in the corridor facing the glazed partition wall.

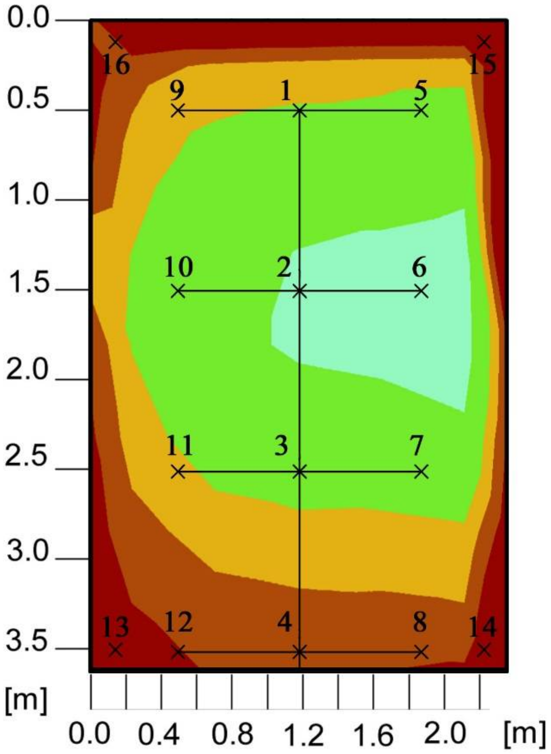



| Point measurement | Illuminance [lux] | | | | Average value |
|---|---|---|---|---|---|
| | Measured value | | | Magn. | [lux] |
| 1 | 299 | 286 | 255 | 1 | 280 |
| 2 | 198 | 206 | 211 | 1 | 205 |
| 3 | 139 | 122 | 127 | 1 | 129 |
| 4 | 711 | 709 | 705 | 0,1 | 71 |
| 5 | 308 | 309 | 310 | 1 | 309 |
| 6 | 201 | 203 | 204 | 1 | 203 |
| 7 | 138 | 137 | 138 | 1 | 138 |
| 8 | 101 | 100 | 100 | 1 | 100 |
| 9 | 265 | 268 | 272 | 1 | 268 |
| 10 | 125 | 126 | 125 | 1 | 125 |
| 11 | 709 | 717 | 718 | 0,1 | 71 |
| 12 | 548 | 625 | 590 | 0,1 | 59 |
| 13 | 502 | 486 | 497 | 0,1 | 50 |
| 14 | 987 | 954 | 977 | 0,1 | 97 |
| 15 | 254 | 236 | 235 | 1 | 242 |
| 16 | 224 | 215 | 232 | 1 | 224 |


**Figure 6.17** Illuminance distribution from software evaluation under sunny conditions. The numbers on the floor area represent the grid points.

The illuminance distribution due to artificial light appears to be more uniform both from software evaluation and measurements. A comparison between the two situations is presented in figure 6.18 and table 6.14.

**Table 6.14** Measured data of illuminance at the working area height under artificial lighting conditions. Note that differently from the values measured in daylight conditions, there is no big difference in illuminance measured at the same point because electrical light had a quite stable luminous flux. In order to perform the measurements is necessary to wait some minutes to let the luminaire reach a stable emission, compromised by light flickering right after one switches it on.




| Measurement point | Illuminance [lux] | | | | Average value |
|---|---|---|---|---|---|
| | Measured value | | | Magn. | [lux] |
| 1 | 220 | 221 | 221 | 1 | 221 |
| 2 | 327 | 328 | 328 | 1 | 328 |
| 3 | 257 | 258 | 257 | 1 | 257 |
| 4 | 126 | 127 | 126 | 1 | 126 |
| 5 | 185 | 185 | 185 | 1 | 185 |
| 6 | 313 | 312 | 313 | 1 | 313 |
| 7 | 279 | 280 | 279 | 1 | 279 |
| 8 | 164 | 163 | 161 | 1 | 163 |
| 9 | 182 | 178 | 177 | 1 | 179 |
| 10 | 248 | 245 | 126 | 1 | 206 |
| 11 | 208 | 312 | 208 | 1 | 243 |
| 12 | 113 | 113 | 113 | 1 | 113 |
| 13 | 907 | 908 | 909 | 0,1 | 91 |
| 14 | 141 | 141 | 141 | 1 | 141 |
| 15 | 167 | 167 | 167 | 1 | 167 |
| 16 | 254 | 254 | 254 | 1 | 254 |

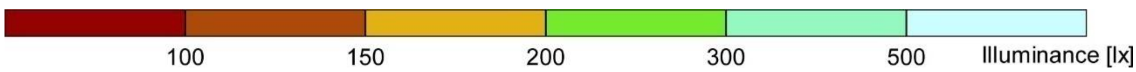



**Figure 6.18** Illuminance distribution from electric light. The numbers on the floor area represent the grid points.

Sun patches were detected during the afternoon between about 16:00 and 20:00, in particular the areas with high illuminance were present on the right wall (see notation in figure 6.6) starting very close to the window edge but extending to the working area later in the afternoon. Due to absence of glossy surfaces and the avoided interaction of sun patches with the glass surfaces on the partition wall at the corridor side, the only veiling reflections in the room were caused by the computer screen.

The view out of the window is full of elements but not all the three main layers are present: it is possible to see the ground and the sky but there is no chance to have a deep view with a background due to the close buildings surrounding block 4. Due to dirty glazed façade and a building under construction, the view does not result very pleasant, but it is still possible to recognise some natural elements as trees, grass and flying birds. Thanks to the view of the sky, the human needs of knowing the time and the weather conditions are satisfied.

When it comes to light in Zero Energy Buildings, the Lighting Energy Numeric Indicator (LENI) is a very important factor to be evaluated. With reference to the UNI EN 15193/2008 the LENI has been calculated for the five analysed rooms and then compared with the maximum value prescribed by the BREEAM-NOR manual. The method for calculate the LENI requires information about the characteristics of the surroundings, geometry of the room, lighting system and users behaviour. Some of those aspects are the same for all the analysed rooms while others such as the obstruction angle from the horizontal and the vertical fins obstruction angles, depending on the external obstructions vary from office to office.

With reference to the geometric features showed in table 6.15, taking as transmission factor τ of the fenestration the value measured during the monitoring so that the correction factors for dirt glazing $k_2$ and the one accounting for not normal light incidence on the façade can be neglected, with the frame of the fenestration system accounting for the 27%, it was possible to calculate the correction factors marked in blue in table 6.15.

**Table 6.15** Geometric features and obstruction factors for room R4209, calculated according to the standard UNI EN 15193:2008. Obstruction angles calculated with reference to figure 6.19.

**Features of the analysed rooms**

| | | | |
|---|---|---|---|
| Room | | | R4209 |
| Location | | | Sandvika |
| Latitude | | ° | 59,89 |
| **ZONE SIZE** | | | |
| Width | | m | 2,35 |
| Depth | | m | 3,615 |
| Height of the working area | | m | 0,8 |
| Width of facade with fenestrations | | m | 2,35 |
| **FENESTRATIONS** | | | |
| Total area of fenestration on the facade | $A_c$ | | 3,15 |
| Height of upper edge of the window | $h_{Li}$ | | 2,122 |
| Transmission factor | τ | | 0,75 |
| Frame reduction factor | $k_1$ | | 0,77 |
| Dirty glass factor | $k_2$ | | 1 |
| Not normal light incidence on the façade factor | $k_3$ | | 1 |
| **OBSTRUCTIONS** | | | |
| Vertical obstruction angle | $\gamma_{O,OB}$ | | 37 |
| Horizontal obstruction angle | $\gamma_{O,OV}$ | | 0 |
| Vertical fins obstruction angle | $\gamma_{O,VF}$ | | 47 |
| **RESULTING PARAMETERS** | | | |
| | $I_{O,OB}$ | | 0,57 |
| | $I_{O,OV}$ | | 1,00 |
| | $I_{O,VF}$ | | 0,84 |
| | $I_{O,CA}$ | | 1,00 |
| | $I_{O,GDF}$ | | 1,00 |
| | $I_O$ | | 0,48 |
| | $I_T$ | | 0,37 |
| | $I_{DE}$ | | 2,73 |
| | $A_d$ | | 8,50 |

Another important aspect influencing the Lighting Energy Numeric Indicator is the occupation time of the zone, which depends on the building function. With reference to table 6.16 the daylight and non-daylight usage time were calculated, neglecting the emergency lighting charge time due to lack of information

.

**Table 6.16** Calculation of daylight usage time ($t_d$) and non-daylight usage time ($t_n$) in hours for room R4209

**Zone occupation time**

| | | | |
|---|---|---|---|
| Room | | | R4209 |
| **Type of building** | | | Office |
| Absence factor | $F_a$ | | 0,3 |
| Emergency lighting charge time | $t_{em}$ | | |
| **RESULTING PARAMETERS** | | | |
| | $t_d$ | h | 2250 |
| | $t_n$ | h | 250 |

The last and most important step was to consider the features of the lighting system. As described in section 6.1.3 it is characterized by automatic control both for lighting on and off, with dimming of the emitted luminous flux in case the daylight only is sufficient to satisfy visual requirements, information useful for the absence factor and constant illuminance factor calculation reported in table 6.17. Moreover the electric system works on two parallels circuits, one with continuous operation and the other one that stops to operate when the last user leaves the building. For this reason the estimation of parasitic power was not easy and as simplification it has been chosen to take into account the power for emergency lighting only, as it can be seen in table 6.18.

**Table 6.17** Calculation of absence factor ($F_A$) and constant illuminance factor ($F_C$).

**Lighting system features**

| | | | |
|---|---|---|---|
| Room | | | R4209 |
| Average Illuminance | | lux | 500 |
| Total power of luminaire | | W | 36 |
| Maintenance factor | | | 0,8 |
| Luminaire parasitic energy consumption | | W | 0 |
| Charging power of emergency lighting luminaires | | W | 1 |
| **GROUP OF LUMINAIRES** | | | |
| One group only | | | x |
| Different groups parallel to the facade | | | |
| **DAYLIGHT CONTROL** | | | |
| Manual | | | |
| Automatic, depending on daylight levels | | | x |
| **OCCUPATION CONTROL** | | | |
| Manual on/off | | | |
| Manual on/off + timer | | | |
| Auto on - dimming off after 5 min | | | |
| Auto on - auto off after 15 min | | | x |
| Manual on - dimming off after 5 min | | | |
| Manual on -auto off after 15 min | | | |
| **RESULTING PARAMETERS** | | | |
| | $F_A$ | | 0,3 |
| | $F_{OC}$ | | 0,9 |

**Table 6.18** Lighting system consumption and Lighting Energy Numeric Indicator for the room R4209 calculated according to the UNI EN 15193:2008.

LIGHTING SYSTEMS CONSUMPTION

| Room | | | R4209 |
|---|---|---|---|
| Daylight factor | D | % | 2,159 |
| | Level | | medium |
| Constant illuminance factor | $F_C$ | | 0,9 |
| Daylight dependency factor | $F_D$ | | 0,583 |
| Occupancy dependency factor | $F_O$ | | 0,8 |
| | | | |
| Energy | $W_L$ | kWh | 40 |
| | $W_P$ | kWh | 0 |
| | W | kWh | 40 |
| | | | |
| **LENI ZONE [kWh/m$^2$ yr]** | | | **4,76** |

The obtained value for the LENI is much lower than the maximum value set in the national standard NS 7301-01 as threshold to define passive a building, but at the same time it has to be considered that many simplifications have been made during the calculation.

**Plan Room R4209**

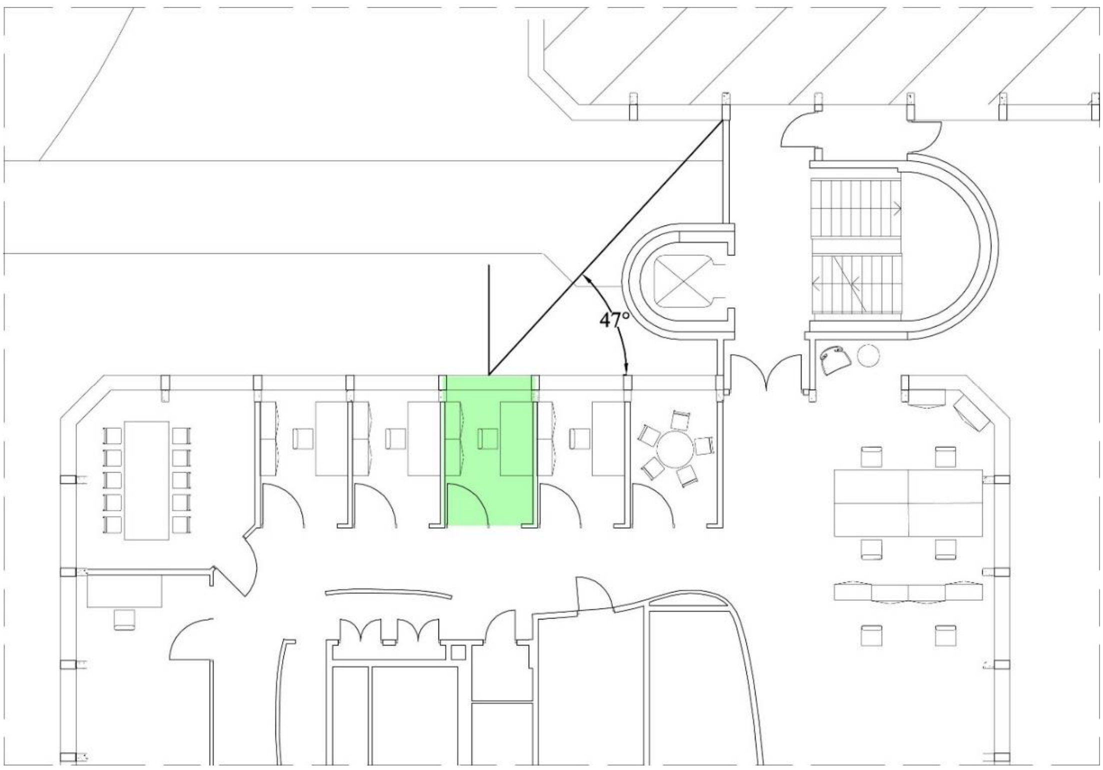



**Figure 6.18** Plan of Block 4 and external obstructions relative to room R4209 marked in green. The obstruction angle for vertical fins is showed.

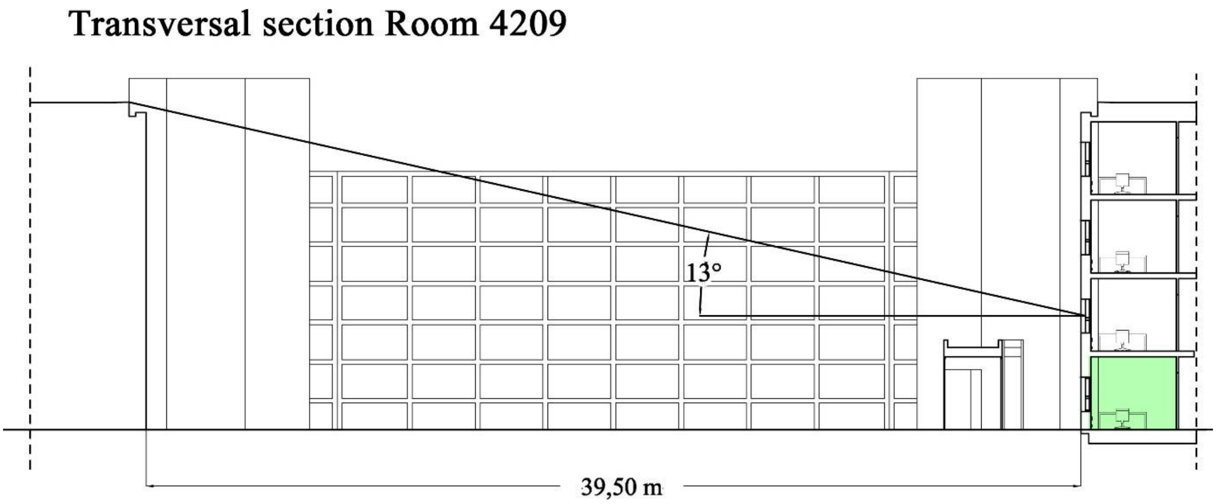



**Figure 6.18 B** Section of Block 4 and external obstructions relative to room R4209 marked in green. The obstruction angle on the horizontal is showed.

## Users interview results

The users' satisfaction has mostly been evaluated by interviewing the representative of the employees in Asplan Viak, who is responsible to collect and report eventual complaints, being the renovated blocks under constant monitoring within the Powerhouse program.

The main complaints concern the light level in the open space, in general considered insufficient for reading and writing in most of the working positions despite the presence of a LED-table lamp with dim possibility. The model of desk lamps used from the company have no lamp screen, so even when turned on to light up the working area it blinds the user. Moreover the position of the desk lamp is not suitable for writing because placed on the right side of the desk, casting shadows of the hand on the sheet.

In general the non-satisfactory condition of light levels is due to a combination of factors:

- When daylight is the prevalent source of lighting, the phenomenon of veiling reflections occurs frequently on the computer screen at working positions near the windows. This could be easily avoided by manual activation of the zip screen of the closest window but employees prefer not to adopt this solution until the phenomenon of glare occurs. They are more willing to move and change working position when possible rather than act on the shading devices.
- When the sensors on the façade record an illuminance value higher than the set point, the shading system is activated, avoiding glare and eliminating veiling reflections. However the interior space gets darker and the daylight compensation system in the luminaires starts working.
- Both when the shading devices are on and during nighttime, the lighting level results insufficient in some areas of the open space due to an incorrect operation of the sensors in the luminaires. In fact at the design phase each luminaire at each the floor was supposed to have a sensor for the best optimization of daylight compensation possible, but in order to low down the costs of the project the costumer asked to reduce the number of sensors, preferring to have cheaper lighting solutions instantaneously. However that choice does not result to be the best solution to reducing costs because, in a long term, a better daylight compensation can definitely reduce lighting costs and other aspects could have been revised. With only one sensor controlling a group of 4-5 luminaires it happens quite often that even when there are people in the operation area of the sensor, the luminaires stay off because the presence sensor cannot notice them. This results to be very annoying for users because they have to move, walking around the area to activate the sensor or try to wave their hands. After the first months by the end of the refurbishment works, some luminaires were switched in position to have a better activation of the sensors but the problem still remains.

As far as the lighting conditions in office rooms are concerned the observations reported about veiling reflection are the same. Much better is the situation concerning the daylight compensation because with one sensor controlling one single lamp in a small space the light levels are always optimal.

When asked if the users feel satisfy about having no control on the lighting system due to absence of any switcher, the response was that they would like to be less passive by choosing whether to switch on the light in the open spaces due to the malfunctioning of the presence sensors but they do not think is necessary any manual control of the lighting level because the daylight compensation operated by the luminaires is acceptable. Apparently no one of the employees seem to care about electrical light constantly on, but conveniently dimmed, when people are in the room and only daylight would be sufficient.

### 6.3.3 General summary

The best parameter to be analysed in order to make a comparison between all the studied rooms is the DF, in fact due to its definition it allows to compare the light level in a room without taking into account the time during the day when measurements were taken and calculations were performed. In general it has been observed that there is always a gap between the measured values and the results of simulations, with reference to figure 6.20 and 6.21 the comparison between the two categories has been conducted according to two variables. Starting from the consideration that the conditions inside the analysed spaces are equal in all the rooms (same reflectance of surfaces, same geometry of the room and of windows, same furniture), the exterior conditions are what can determine a higher or lower gap between the results.

The first of these to be used as distinguishing factor is the exposition of the window of the room: the results presented in figure 6.20 are analysed according to the north-west and south-west orientation and apparently no rule is showed for the interpretation of the gap existing between the two categories of values. This is because DF is insensitive to either the building orientation (being the overcast sky rotationally symmetrical about the vertical axis) or the intended locale (since it is simply a ratio) (Mardaljevic, 2008).

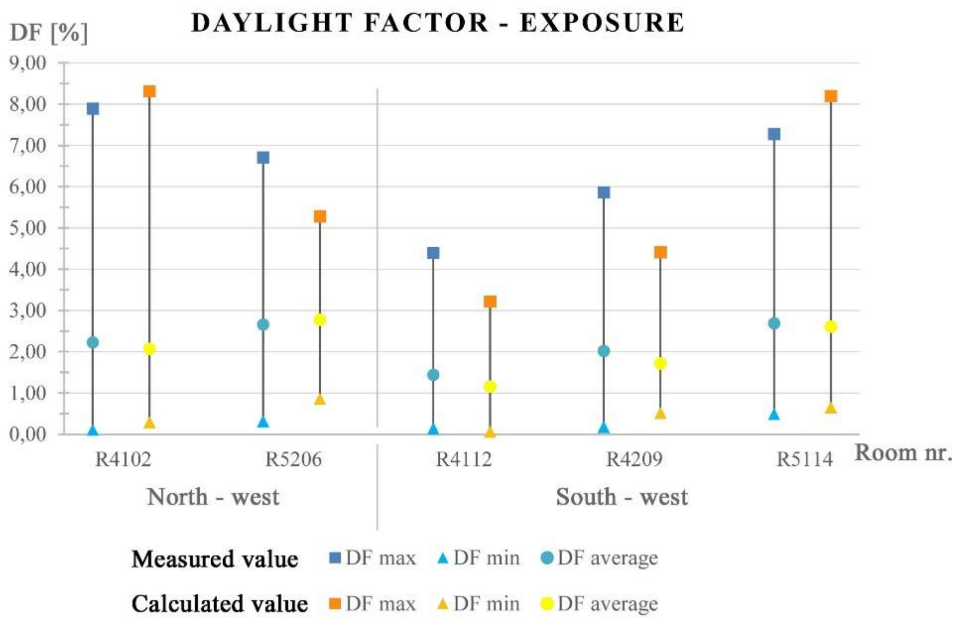



**Figure 6.20** Comparison between measured and calculated DF values, having the exposition of the room as parameter of the analyses.

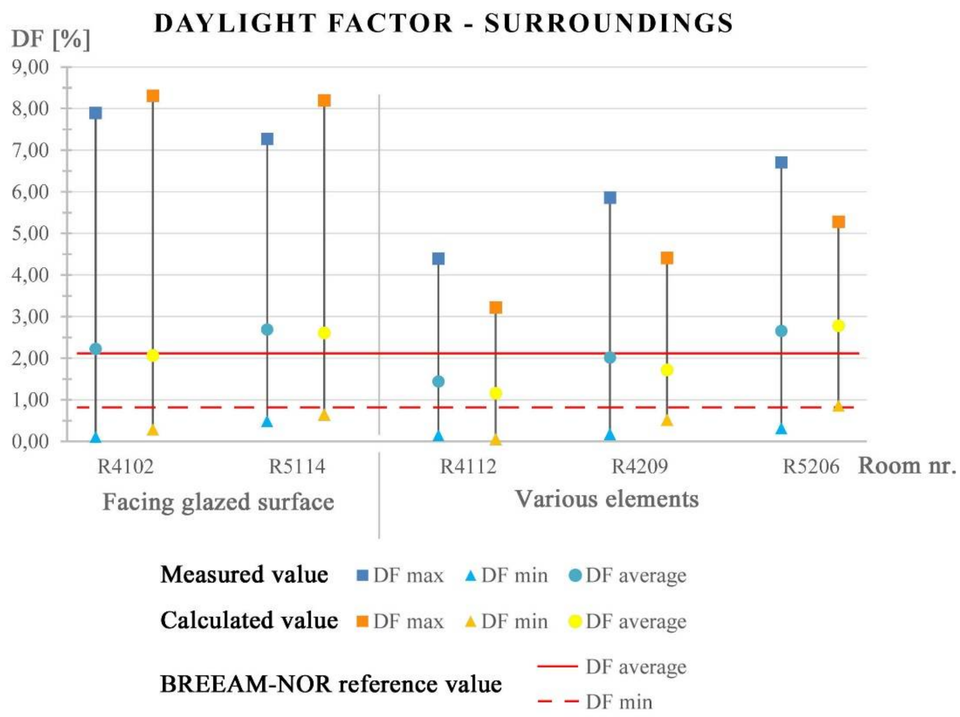



**Figure 6.21** Comparison between measured and calculated DF values, having the characteristics of the surroundings as parameter of the analyses.

But when analysing the results in relation to the shading elements right outside the façade (figure 6.21) it can be noted a relation between the trend of $DF_{max}$ and the characteristics of the surroundings: the calculated values are higher than the measured ones for rooms R4102 and R5114 whose windows face a glazed corridor extending for a long distance on both sides of the room, moreover the gap between those values is very low if compared to the one of the remaining rooms; the calculated values are lower than the measured ones for rooms R4209, R5206, having opaque exterior shading elements, and for R4112 which faces a glazed corridor but only for half of the window's width. The rooms have decreasing values of $DF_{max}$ according to the crescent obstruction factor relative to each glazed surface, in fact room R4112 has an obstruction angle of 75° due to the very close glazed corridor present on the external side of the window while room R5114 has an obstruction angle of only 17°. The obstruction angle of all he analysed rooms are showed in Appendix D.

When operating an analyses of the reliability of the calculated values and measured values it is interesting to look at the relative error with reference of the mean value of $DF_{average}$ for each room. From figure 6.22 the error committed by software simulations in the evaluation of the $DF_{max}$ results to be quite high and unacceptable for the daylight level evaluation having an average values of 22,55%. The same error for the $DF_{min}$ resuts to have an even higher magnitude, being the average value 54,97%. Much more lower are the relative errors committed for the $DF_{average}$ with an average relative error of 11,59%, a value still acceptable due to the approximations made when modelling the spaces. Moreover it has to be considered that also the measured values are subject of errors, depending on the calibration of the instruments, accuracy of the measurements, random errors caused by unpredictable fluctuations in the readings of a measurement apparatus and by the operator, errors due to the not perfect synchronism in taking the measurements which have a great impact when the measured values has high fluctuations like the solar radiation has.

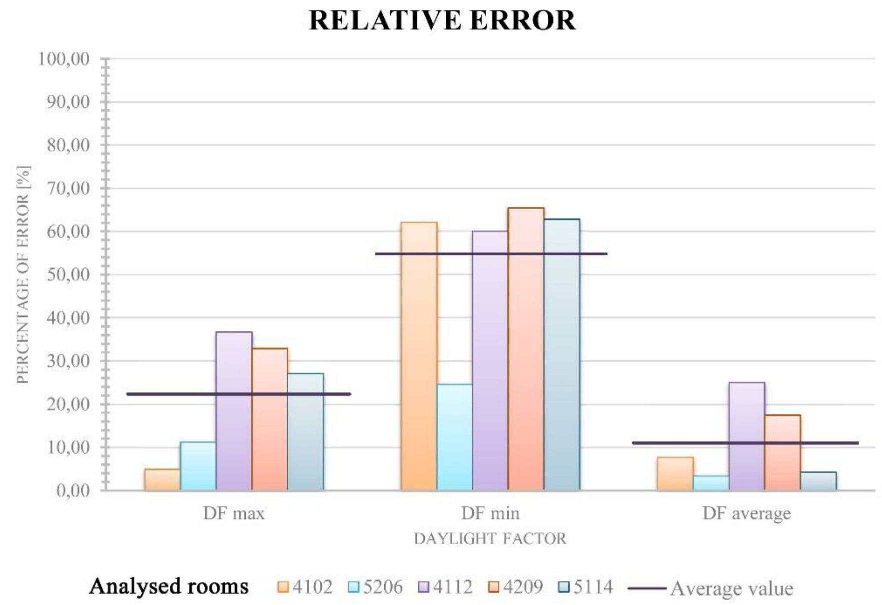



**Figure 6.22** Relative error for each room concerning the three categories of DF values analysed.

**Figure 6.23** View out of the window of room R5206.

Despites of error percentage, in general the rooms having another glazed surface right outside the window results to have an higher daylight factor both from measured values and from simulations as maximum value while the highest average daylight factor is present in room R5206. Once again the condition of the exterior shading elements plays an important role in the analyses, in fact the room has only a small two storey building, more than 20 m far from the block façade as shown in figure 6.23.

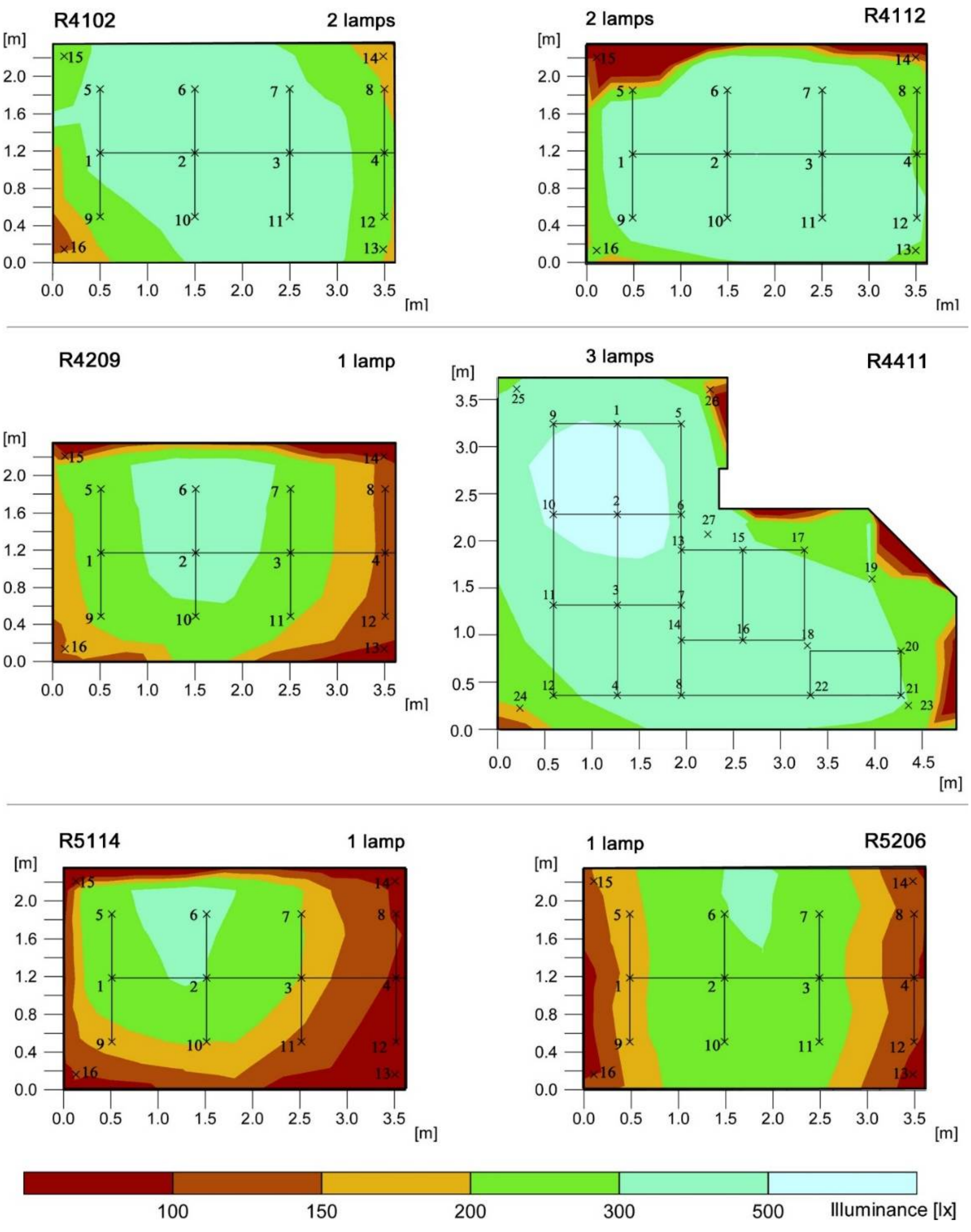



**Figure 6.24** Illuminance distribution on a plan at 0,8 m height from the floor due to electric lights, software simulations. The numbers on the floor area represent the grid points.

In order to estimate the reliability of both measurements and simulations, the values concerning the electric lighting are presented and compared. The analysed rooms have equal geometry and surfaces' reflectance but different furniture and number of luminaires. The two rooms of block 4 located at the first floor were designed as meeting rooms even though room 4102 ended up to be used as private office; as presented in section 6.1.3 all the meeting rooms have 2 luminaires so this is the reason why room 4102 and 4112 results to have a more uniform illuminance distribution around the 300 lux value. However the two rooms have different furniture and this lead to a similar but not completely alike lighting situation.

Rooms 4209, 5114 and 5206 have one luminaire and the illuminance distribution is quite different from the previous two, having a small area where E is about 500 lux and always in correspondence with the position of the desk in the room as prescribed in the design phase. The differences in the illuminance in the three rooms is due to the different furniture in fact room 4209 has white shelves at the opposite wall from the desk while rooms 5114 and 5206 do not. Moreover room 5206 has a big dark table in the middle of the room and a grey couch, while room 5114 has the usual grey desk. Room 4411 is different from all the others because it has 3 luminaires and completely different geometry. Due to the position of two lamps, quite close one to the other and white furniture under them, the illuminance is higher than in any other room in one portion of the working plan as shown in figure 6.24.

The results obtained from software simulations are consistent with the simulations, confirming a mutual reliability despite approximations made in both the fields. This check is easier to be performed under artificial lights than under natural light conditions due to the high variability of the solar radiation, whose effects are difficult to be simulated but also measured.

#### 6.3.3.1 Reference to BREEAM-NOR certification

The results from the study have to be compared to the requirement for the BREEAM-NOR certification, being Powerhouse Kjørbo rated as Outstanding. From daylight requirement the following observations can be made, with reference to tables 6.19, 6.20 and 6.21:

- The requirement for the average Daylight Factor in a building located in a site at latitude between 55° and 60°, measured at a height of 0,8 meters is 2,1% in at least 80% of the rooms in order to get one point. If the $DF_{average}$ > 3,15 % another point is added in order to achieve the exemplary level. According to the analysis performed during the design phase, all the analysed rooms are expected to reach the required value for the exemplary level, except for the room 4112, but neither the measurements nor the calculation confirmed the expectations. However results from the study confirm that room 4112 does not satisfy the first credit requirement, but the same coherence with daylight analysis from the design phase is not found in room 4209. In fact it should be the one with the best lighting conditions in the group of analysed rooms but does not have the highest $DF_{average}$. Moreover none of the analysed room reaches the requirement for the exemplary level DF = 3,15 %.
- The requirement for the minimum value of Daylight Factor in a building located in a site at latitude between 55° and 60°, measured at a height of 0,8 meters is 0,84% in at least 80% of the rooms in order to get one point. If the $DF_{min}$ > 2,26 % another point is added in order to achieve the exemplary level. As can be noted in table 6.19, none of the rooms satisfies any requirement, both the measured and calculated values are much smaller than the BREEAM-NOR imposed level.
- In section 5.0 Health and Wellbeing from the BREEAM-NOR technical manual (NGBC, 2012), it is prescribed that the minimum value of DF from the previous point has to be achieved together with the condition previously presented in section 4.4.2.1.1:

$$\frac{d}{w}+\frac{d}{HW}<\frac{2}{(1-RB)} \qquad (4.1)$$

  The condition depends mostly on geometric conditions, except for the parameter RB the average reflectance of surfaces in the rear half of the room. For this reason the condition can be verified for one room and applied to all the others.

  In room 4209:

  d = 3613 mm

  w = 2375 mm

  HW = 2200 mm

  RB = 0.4372 calculated considering reflectance values from table 6.13 for the back side wall, floor and door frame.

  The condition results to be satisfied being 3,16 < 3,54, but it has to be true together with the requirement concerning the $DF_{min}$ and this is not the case.
- Alternatively to the latest two conditions, the uniformity factor ($U_o$) can be considered as parameter for determining whether an indoor space is well daylit when the $DF_{average}$ condition is achieved. The prescribed value is reported in table 6.20 and one can note that none of the rooms meet the $U_o$>0,4 condition.

- Regarding the artificial lighting BREEAM-NOR refers to values presented in the national best practice lighting guides such as the standard NS-EN 12464-1:2008. The prescribed illuminance value for office rooms is 500 lux at the working area, requirement satisfied by the luminaires adopted in Powerhouse Kjørbo.

In conclusion not all the rooms analysed from Powerhouse Kjørbo meet all the requirements necessary for getting the point from Health and Wellbeing, both from calculations and measurements in situ, but it has to be considered that numerous simplifications have been made, affecting the final results. This is true in particular when it comes to the calculated values, while the measure ones are more close to the required values.

The national standard NS 7301-01 sets the reference value of 12,5 $kWh/m^2$ a as maximum for the LENI in order to define *passive* a building. The parameter has been calculated for all the five analysed rooms and all of them resulted to have a LENI value far lower than the reference value as showed in table 6.22. The main difference in the LENI calculation for the five rooms lays in the geometry of the external obstructions as showed in figure 6.25, 6.26 and in the appendix D.

**Table 6.19** Average Daylight Factor comparison between measured, calculated and required values according to the BREEAM-NOR certification. The colours associated to the rooms shows the previsions from the design phase, used as a guide when choosing which rooms to include in the study, with reference to figure 6.5.

| Room | | 4102 | 4112 | 4209 | 5114 | 5206 |
|---|---|---|---|---|---|---|
| DF Measured | | 2,23 | 1,44 | 2,02 | 2,69 | 2,66 |
| DF calculated | | 2,07 | 1,16 | 1,72 | 2,61 | 2,78 |
| DF required | First credit | 2,1 | | | | |
| | Exemplary level for multi-storey buildings | 3,15 | | | | |

**Table 6.20** Minimum Daylight Factor comparison between measured, calculated and required values according to the BREEAM-NOR certification.

| Room | | 4102 | 4112 | 4209 | 5114 | 5206 |
|---|---|---|---|---|---|---|
| DF Measured | | 0,11 | 0,15 | 0,18 | 0,49 | 0,32 |
| DF calculated | | 0,29 | 0,06 | 0,52 | 0,65 | 0,86 |
| DF required | First credit | 0,84 | | | | |
| | Exemplary level for multi-storey buildings | 1,26 | | | | |

**Table 6.21** Uniformity factor from measurements in situ and software simulations compared with the required value.

| Room | 4102 | 4112 | 4209 | 5114 | 5206 |
|---|---|---|---|---|---|
| Uo measured | 0,05 | 0,10 | 0,09 | 0,18 | 0,12 |
| Uo calculated | 0,14 | 0,05 | 0,30 | 0,25 | 0,31 |
| Uo required | 0,4 | | | | |

**Table 6.22** Uniformity factor from measurements in situ and software simulations compared with the required value.

| Room | 4102 | 4112 | 4209 | 5114 | 5206 |
|---|---|---|---|---|---|
| LENI calculated | 4,76 | 5,67 | 4,76 | 3,17 | 3,17 |
| LENI required | < 12,5 kWh/m$^2$ a | | | | |

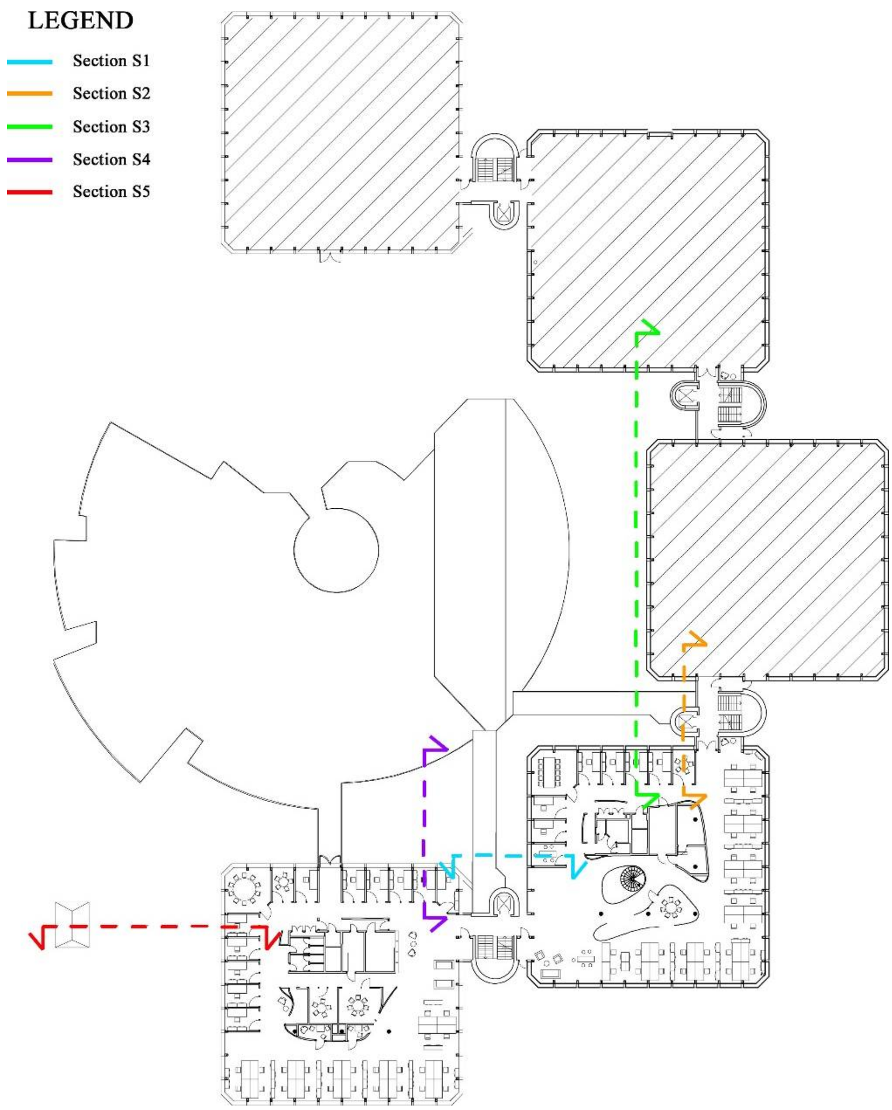



**Figure 6.26** Reference plan of blocks 4 and 5 for obstruction factor on the horizontal.

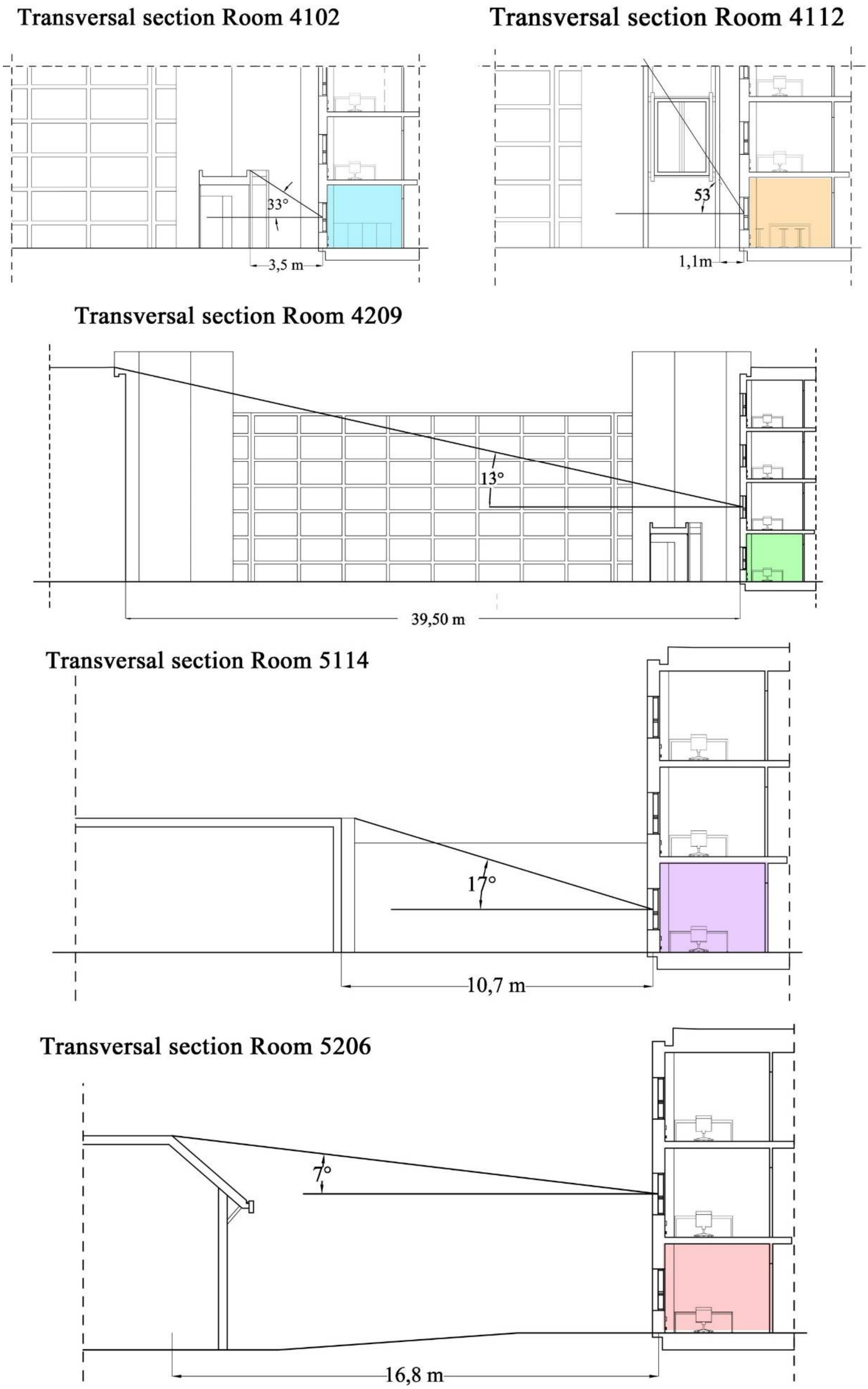



**Figure 6.27** Obstruction angles on the horizontal for the five analysed rooms.

# 7 Conclusions

The current study presented the analyses of daylighting conditions in a refurbished office building, whose technological constructive solutions were implemented in order to realize a Zero Energy Building. The analysis were performed in six rooms in the renovated buildings both as measurements, following the monitoring protocol in Task 50 Subtask D from IEA SHC, and as software simulations. Doing so it was possible to examine reliability of each method and the differences between them. Moreover a comparison with software simulations conducted about the building before the refurbishment was possible.

In general the daylighting conditions resulted to be improved by the renovation, with higher $DF_{average}$ in office rooms and a better illuminance distribution measured at height 0,8 m from the floor. Such enhancement was achieved since the design phase by increasing the dimensions of windows, now having a window to wall ratio of 40/60, avoiding the use of the fake ceiling, common element in most of the office buildings, and having higher reflectance of internal surfaces.

Concerning the comparison between measurements and simulations conducted for the renovated blocks, when it comes to daylight uncertainties, variability of the emitting source and needed approximations make difficult to have a precise valuation of parameters like Daylight Factor and illuminance at one point. As shown in figure 6.20 the difference in estimation of DF between the two methods is very high for $DF_{max}$, but more restrained in terms of $DF_{average}$. From figure 6.21 the error committed when evaluating the maximum value of Daylight Factor cannot be considered acceptable for scientific purposes.

When performing the measurements, it was possible to evaluate also parameters regarding users' visual comfort such as quality of the view out, presence of veiling reflections and glare. The blocks are located by a river and have the view on a fjord, so the surroundings are in general very pleasant even though there are some differences according to the exposition of the offices. Regarding glare, the combined action of sensors at the façade, which control the shading system, and the sensors inbuilt in the luminaires make possible to avoid great discomfort and at the same time save electric energy for lighting. In fact, according to research on occupant use of shading devices, once daylight strikes on VDT surfaces, manually regulated blinds are in use by hours, days or even months even when the glare conditions have disappeared (Reinhart et al., 2006).

If having a passive user is useful in terms of energy saving, at the same time the user himself feels more comfortable when he is able to choose whether to have only daylight or supply it with artificial light. This happens because, when it comes to daylight, people have psychological conditionings that make them think about natural light as healthier than the artificial one.

Considering positive and negative effects of using sensors, when it comes to the lighting system a further implementation for the analysed building can now be proposed: when adjusting the light level depending on the occupation rate, energy savings are higher if the lights are switched off than if they are simply dimmed in case of absence, therefore a shut off system is preferable for single offices or meeting rooms whereas a dimming system is interesting for large landscape offices, for visual comfort reasons. According to a study conducted by Roisin et al. (2008) the IDDS is always better for occupancy rate higher that 44% while an occupancy sensor is preferable if the rate is less than 27%.

Another recommendation after the analyses is to introduce switchers in office rooms, because sometimes a person will enter in the room only for a moment and then will leave, without the need of turning on the light, but with the presence sensor the luminaire is suddenly switched on and kept on for at least 15 minutes. Moreover the presence of switchers for absence detector is recommended by the BREEAM-NOR manual certification in section 4.1.

Regarding sensors in the lamps, a suggestion is to set them so that when 500 lux are measured at the desk surface, the luminaire would be completely switched off in order to save energy, differently from the dimming performed at the current situation.

It would have been interesting to perform measurements in the old building in order to have a better comparison between the results and the hope is that the companies renting those buildings will be more willing to let researchers in after this study.

Further studies could be conducted about daylight in Powerhouse Kjørbo, based on the CBDM theory. It would be very interesting also because so far there are no published studies on buildings at so high latitudes, moreover, based on the artificial daylight compensation strategy already adopted in Powerhouse Kjørbo, it would provide estimations about DA and UDI useful for improve the daylighting strategy (Cammarano et al., 2014).

According to the CBDM theory the analyses of dynamic parameters would be very appropriate in evaluating the improvements in the daylight performances of the building, more than the one based on the Daylight Factor, because the latter gives design recommendations that are equal for all the façade orientation and building locations. Being independent from season, building location, variable sky conditions and direct solar ingress, daylight factor investigations do not allow to develop glare prevention strategies specific for each façade orientation. However many experts operating in the Scandinavian context believe that an analyses of daylight conditions based on dynamic parameters would not produce many better results due to the non-high-variation of the weather conditions in that part of the globe. In fact in northern countries the sky is completely overcast for almost 80% of the time during a year and in such a condition the DF is still a valid parameter to be used for daylight estimations.

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# 9 Appendices

## *Appendix A*

The *photoelectric effect* is the phenomenon experienced when a surface, usually a metallic one, emits a stream of negative elementary electric charges, called electrons, after being hit by an electromagnetic radiation at a certain frequency.

*Standard Illuminants*: In addition to the black body curve located at the center of most CIE diagrams, there are also alpha-numeric designations: A, B, C, and D65. These represent standard illuminants that have been identified by the CIE and other standardization committees including ANSI. Known as CIE Standard Illuminants, they are mathematical reference models used for performing visual or instrumental calculations. The physical simulation of an illuminant is called a light source. Some illuminants (A, B, D55, D65 and D75) can be represented by actual light sources. Others (such as C) cannot. Therefore, all light sources can be illuminants, but not all illuminants can be light sources.

*LENI:* Lighting Energy Numeric Indicator was originally defined by BS EN 15193:2007, Energy performance of buildings. It is applied to non-residential buildings over a period of months or over one year and it is an indicator of the efficiency of an entire lighting installation, including controls. LENI is expressed in terms of energy per square metre per year ($kWh/m^2$ yr), being the sum of energy use (daytime, night-time and parasitic energy use) divided by the area of the analysed interior space. The LENI formula is:

$$LENI = W/A \tag{A.1}$$

Where $W = W_L + W_P \left[ kWh/year \right]$

$$W_L = \sum \left\{ \left( P_n * F_C \right) * \left[ \left( t_D * F_O * F_D \right) + \left( t_N * F_O \right) \right] \right\} / 1000$$

is the annual lighting energy required to provide illumination so that the building may be used

$$W_P = \sum \left\{ \left\{ P_{PC} * \left[ t_Y - \left( t_D + t_N \right) \right] \right\} + \left( P_{em} * t_e \right) \right\} / 1000$$

is the annual parasitic energy required to provide charging energy for emergency lighting systems and standby energy for lighting control systems

$$P_n = \sum P_i$$

is the total installed lighting power and Pi is the luminaire power in watts

$F_c$ is the Constant illuminance factor, relating to the usage of the total installed power when constant illuminance control is in operation in the area

$F_o$ is the Occupancy dependency factor, relating the usage of the total installed lighting power when occupancy control is in operation in the area

$F_D$ is the Daylight dependency factor, relating the usage of the total installed lighting power to daylight availability in the area

$t_D$ are the Daylight operating hours

$t_N$ are the Non-daylight operating hours

$$t_O = t_D + t_N$$

Is the Annual operating time, the annual number of hours with the lamps operating

$t_y$ is the standard year time, time taken for one standard year to pass, as 8760 hours

$t_e$ is the Emergency lighting charge time

$$P_{pc} = \sum_i P_{ci}$$

is the Total installed control circuit parasitic power

$$P_{em} = \sum_i P_{ei}$$

is the Total installed charging power for emergency lighting, where $P_{ei}$ is the emergency lighting charging power in watts.

## *Appendix B*

**Table B.1** Average daylight factor measured at height of 0.8 meters according to latitude at the building location. Table from BREEAM NOR requisites about daylight, section 5.0 (NGBC, 2012).

| Latitude (°) | Average Daylight Factor | | |
|---|---|---|---|
| | First credit - all buildings | Exemplary level | |
| | | Single-storey buildings | Multi-storey buildings |
| ≤40 | 1.5 | 3 | 2.25 |
| 40-45 | 1.7 | 3.4 | 2.55 |
| 45-50 | 1.8 | 3.6 | 2.7 |
| 50-55 | 2.0 | 4 | 3 |
| 55-60 | 2.1 | 4.2 | 3.15 |
| ≥60 | 2.2 | 4.4 | 3.3 |

**Table B.2** Point daylight factor in office areas according to latitude at the building location. Table from BREEAM NOR requisites about daylight, section 5.0 (NGBC, 2012).

| Latitude (°) | Minimum point daylight factors | | | | | |
|---|---|---|---|---|---|---|
| | First credit | | Exemplary level – single storey buildings | | Exemplary level – multi storey buildings | |
| | All other spaces | Spaces with glazed roofs | All other spaces | Spaces with glazed roofs | All other spaces | Spaces with glazed roofs |
| 55-60 | 0.84 | 1.47 | 1.68 | 2.94 | 1.26 | 2.205 |
| ≥60 | 0.88 | 1.54 | 1.76 | 3.08 | 1.32 | 2.31 |

Definitions of reference values for BREEAM NOR certification (NGBC, 2012):

*Point daylight factor: A point daylight factor is the ratio between the illuminance (from daylight) at a specific point on the working plane within a room, expressed as a percentage of the illuminance received on an outdoor unobstructed horizontal plane. This is based on an assumed overcast sky, approximated by the 'CIE (Commission Internationale de l'Eclairage) overcast sky'. Computer simulations are the most appropriate tools to allow for point daylight factors to be displayed. Alternatively, the DF can be measured and computed in a scale model under an artificial sky with the use of lux meters. 2% daylight factors isolux contours (i.e. lines connecting all the points that have the same point daylight factor value) will need to be mapped on the room plan to check the area where point daylight factors are 2% or higher. Mapping should be done based on a minimum calculation grid of 50x50cm and 50cm from the wall.*

*Average daylight factor: The average daylight factor is the average indoor illuminance (from daylight) on the working plane within a room, expressed as a percentage of the simultaneous outdoor illuminance on a horizontal plane under an unobstructed CIE Standard Overcast Sky.*

*Illuminance: The amount of light falling on a surface per unit area, measured in lux.*

*Uniformity: The uniformity is the ratio between the minimum illuminance (from daylight) on the working plane within a room (or minimum daylight factor) and the average illuminance (from daylight) on the same working plan (or average daylight factor).*

*View of sky / no-sky line: Areas of the working plane have a view of sky when they receive direct light from the sky, i.e. when the sky can be seen from working plane height. The no-sky line divides those areas of the working plane, which can receive direct skylight, from those that cannot.*

*Working plane: the horizontal, vertical or inclined plane in which a visual task lies. The working plane is normally taken as 0.7-0.8 m above the floor.*

*Relevant building areas are any areas of the building where there are, or will be, workstations/benches or desks for building users.*

*Occupied space: A room or space within the assessed building that is likely to be occupied for 30 minutes or more by a building user and, with respect to this issue, where it would be desirable to limit the potential for glare or provided a system of glare control.*

# *Appendix C*

C1.Users questionnaire from Task 50 -  Subtask D IEA SCH

C2. Questionnaire edit by the author

C3. Question submitted to representative of employees

## *Appendix D*

Plans of the analysed rooms

Plan of sections for obstruction angles

Sections of rooms for obstruction angles

Tables on LENI calculation

## *Appendix E*

Monitoring procedure data for room R4102 as example.

## *Appendix F*

Plans of Powerhouse Kjørbo before renovation, courtesy of Entra Eideom AS, Norconsult, Snøhetta Architects. Modified from fire security plans, legend in Norwegian.

## *Appendix G*

Plans of Powerhouse after renovation

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