POLITECNICO DI TORINO

PhD thesis

Daylighting design for energy saving in a building global energy simulation context

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April 2015

Politecnico di Torino
Doctoral course in Energetics
XXVI cycle
2011·2012·2013·2014

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Acknowledgements

The more sincere acknowledgements are directed to my supervisors, prof. Chiara Aghemo and prof. Anna Pellegrino, for their endless willingness and their capability of support during all phases of my research.

I'm indebted to prof. Valerio Lo Verso, for providing me with excellent guidance and help until the completion of this thesis.

Furthermore I would like to sincerely acknowledge Wilfried Pohl, for giving me the opportunity to spend a training period during my research activity in the R&D team at Bartenbach LichtLabor, in Innsbruck. Many warm thanks to Robert Weitlaner and David Geisler-Moroder for their excellent supervision of my work and for providing me with an unforgettable experience during my stay in Innsbruck.

It's my pleasure to thank all my colleagues at Politecnico di Torino, in particular Lorenza Bianco, Louena Shtrepi, Giusi Puglisi, Ilaria Ballarini, Tomás Mendez and Paolo Tecchio for their advices and their constant back-up.

Last but not least, I would like to thank my whole family, my husband Stefano, my parents and my brother for their generous and wholehearted support.

Torino, 30 April 2015

Abstract

A key factor to substantially reduce the energy consumption for electric lighting consists in a more widespread exploitation of daylight, associated with the use of the most energy efficient lighting technologies, including LEDs or electric lighting controls. At the same time daylight harvesting in indoor spaces can influence the global energy performance of a building also in terms of heating and cooling loads. For this reason, it's always necessary to account for the balance between daylighting benefits and energy requirements.

Furthermore the increasing awareness of the potential benefits of daylight has resulted in an increased need for objective information and data on the impact that different design solutions, in terms of the architectural features, can have on the daylighting condition and energy demand of a space.

Within this frame the research activity has been focusing on three main aspects:

– Analyzing limits and potentials of the current daylighting design practice and proposing synthetic information and tools to be used by the design team during the earliest design stage to predict the daylight condition within a space.
– Analyzing the effect of a proper daylighting design approach on energy requirements for electric lighting, associating with the use of efficient lighting technologies and control systems.
– Assessing the influence of energy demand for electric lighting on the global energy performance.

The methodology that was adopted relies on dynamic simulations carried out with Daysim and EnergyPlus used in synergy to perform a parametric study to assess the indoor daylighting conditions and the energy performance of rooms with different architectural features. Within the first phase the database of results of the lighting analysis was used to assess the sensitivity of new metrics which have been proposed by the scientific community as predictors of the dynamic variation of daylight. Furthermore it was analyzed how indoor daylight can be influenced by room's architectural features..

Than the energy demand for electric lighting for all simulated case studies have been analyzed so as to examine the influence of a proper daylighting design in presence of different lighting control systems.

Finally results related to the amount of daylight available in a space were compared with annual energy demand for lighting, heating and cooling to highlight the influence of a proper daylighting design on the global energy performance.

Sommario

Un fattore chiave per ridurre sostanzialmente il fabbisogno di energia elettrica per la luce artificiale consiste in un maggiore sfruttamento della luce naturale, associato all'utilizzo di tecnologie per l' illuminazione energeticamente efficienti, come le sorgenti LED e i sistemi di gestione e controllo della luce. Allo stesso modo favorire un'integrazione fra la luce naturale e artificiale può influenzare la prestazione energetica complessiva di un edificio in termini di carichi di riscaldamento e raffrescamento. Per questo motivo è sempre necessario favorire un corretto bilancio tra i benefici della luce naturale e il fabbisogno energetico globale.

Inoltre la crescente consapevolezza dei benefici derivanti dall'ottimizzazione della luce naturale in ambiente sta portando ad una sempre maggiore necessità di informazioni e dati oggettivi sull'impatto che diverse soluzioni progettuali, in termini di caratteristiche architettoniche, possono avere sulla disponibilità di luce naturale in ambiente e sul conseguente fabbisogno energetico.

All'interno di questo quadro l'attività di ricerca si è focalizzata su tre aspetti principali:

- Analizzare limiti e potenzialità della attuale pratica progettuale nel campo dello studio della luce naturale proponendo informazioni sintetiche e strumenti semplificati che possano essere utili ai progettisti durante le prime fasi di progetto nell'ottica di prevedere le condizioni di illuminazione naturale all'interno di un ambiente.
- Analizzare l'influenza di un corretto approccio al progetto di luce naturale sul fabbisogno di energia elettrica per la luce artificiale, considerando l'impatto di sorgenti ad elevata efficienza energetica e l'utilizzo di sistemi di gestione e controllo della luce.
- Valutare l'influenza della domanda di energia elettrica per la luce artificiale sul rendimento energetico globale.

La metodologia adottata per lo studio si basa su simulazioni dinamiche effettuate con Daysim e EnergyPlus utilizzati per effettuare uno studio parametrico per valutare le condizioni di illuminazione naturale e artificiale e la prestazione energetica di ambienti con diverse caratteristiche architettoniche.

Nella prima fase di analisi il database dei risultati è stato utilizzato per valutare la sensibilità dei nuovi indici proposti dalla comunità scientifica come indicatori della variazione dinamica della luce in ambiente.

Successivamente è stata analizzata l'influenza di diverse caratteristiche architettoniche sulla disponibilità di luce naturale e sul conseguente fabbisogno di energia elettrica per la luce artificiale.

In ultimo è stata valutato l'impatto che un corretto approccio al progetto della luce naturale e artificiale possa avere sulla prestazione energetica complessiva di un ambiente, confrontando risultati relativi alla quantità di luce naturale con il fabbisogno energetico annuale per l'illuminazione, il riscaldamento e il raffrescamento.

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Part I
Introduction and summary

CHAPTER 1

Introduction

1.1 Background

Daylighting has always been an essential and irreplaceable resource for architecture.

It is a resource in a design perspective, since it significantly contributes to create the character and appearance of indoor spaces in buildings. In fact it's a resource for people who use the buildings. A daylit luminous environment and the presence of openings are essential aspects for users' health and well-being, from both a physiological and a psychological point of view. Several benefits for people are traditionally attributed to the presence of daylight in buildings. Intensity, spectrum and variability of daylight can positively affect the human circadian rhythms and reduce the seasonal affective disorders (Mardaljevic et al., 2009).

Daylight is also a resource in an economical perspective, since daylight availability and the quality of daylighting design contribute in defining the economic value of buildings, whilst the quantity of daylight available during the occupancy hours of a space allows a reduction in the use of electric lighting and consequently in the expenses for energy.

Recent directives and legislation aimed at reducing energy consumption in private and public buildings. This has noticeably changed the focus on the building design approach over the last decade. These requirements have increased the attention given to the energy performance of a building (Directive 2009/28/CE, 2009; EN 15603, 2008; COM 772, 2008; Directive 2010/31/CE, 2010).

In the lighting field, a substantial reduction in electricity consumption for electric lighting could be obtained through a greater use of daylight, together with the use of the most energy efficient lighting technologies, including LEDs or lighting controls, and an increased and more conscious implementation of building automation principles.

Improving both building energy performance and ambient quality implies the need for a more accurate and optimized daylighting design approach: it is necessary to overcome all limitations concerned with performance indicators such as the traditional Daylight Factor and to account for dynamic skylight and sunlight conditions on a year basis and for the specific climate conditions of the design site. The Daylight Factor is actually the only quantitative performance metric which is used nowadays by standards to assess the daylight amount within a space. Through a totally different approach, the daylight availability during the course of a year in a space can also be quantified via the 'Climate-Based Daylight Modelling (CBDM)' approach (Mardaljevic, 2006). This consists of a daylighting analysis, based on local weather data, which involves the calculation of indoor illuminances at predefined time-steps, for variable periods (usually a full year). This kind of approach allows daylighting to be studied taking into account the contribution of both direct and diffuse solar radiation as well as the variation of local climate conditions over a period of time. In this context, new metrics, called ‘Climate-Based Daylight Metrics’ (CBDM), have been proposed and tested in order to summarize the huge number of data that can be obtained through a climate-based modelling into synthetic performance parameters (Mardaljevic, 2006; Mardaljevic, 2009; Reinhart et al., 2006; Rogers, 2006). The CIE, through the research activity carried out by the Technical Committee TC 3-47, has assessed and validated their consistency, reliability and applicability.

Recently, two new daylight metrics have been defined and adopted by the Illuminating Engineering Society of North America, IESNA (IES, 2012). The spatial Daylight Autonomy (sDA), which assesses the sufficiency of annual illuminance in an interior work environment, and the Annual Sunlight Exposure (ASE), which expresses the annual glare potential risk.

It is important to note that the above metrics have been adopted in the rating system of the ‘LEED Reference Guide for Building Design and Construction’ (USGBC, 2014) as possible options to get the credit concerned with the quantity of daylight.

CBDM requires the use of dedicated software, which, at present, is not used often by designers and practitioners, partly because the existing standards are still based mainly on the Daylight Factor and partly because software for climate-based modelling is not always within the reach of all designers, in particular at the early design phases, due to prohibitively long computation times and to simulation processes that are too complicated (Galasiu & Reinhart, 2008; Reinhart & Fitz, 2006; Reinhart & Wienold, 2011). In the lighting sector, packages such as Daysim (http://daysim.ning.com), Radiance (Ward & Shakespeare, 1998), EnergyPlus (http://apps1.eere.energy.gov/buildings/energyplus) or Spot (Rogers, 2006) are available, free-of-charge, for daylighting and energy simulations, but they require a high level user expertise to correctly define the input and the simulation parameters as well as to correctly interpret the simulation results. Furthermore, this kind of simulation-based daylighting and energy analysis is mainly devoted to advanced phases of the design process, when detailed 3D models of the design solution are available.

The increasing awareness of the potential benefits of daylight has resulted in an increased need for objective information on the impact that different design solutions can have on the daylighting condition within a space, in terms of its architectural features. One key design decision in low energy buildings is thus the selection of a sufficient, yet non excessive, glazing area that allows a satisfying view to the outside while preventing overheating, glare and a waste of cooling and heating energy (Dubois & Flodberg, 2013). An appropriate daylighting design approach can influence the global energy performance of a building as well as the interior visual and thermal comfort for the occupants, also in terms of heating and cooling loads. In fact the internal gains from lighting can be affected by the solar radiation that enters through the openings and by the electric lighting systems' load. For this reason, it is always necessary to consider a balance between daylighting benefits and energy requirements, as indicated in a number of recent studies (Chan & Tzempelikos, 2013; Didonè & Pereira, 2011; Haase, 2011; Moret et al., 2013; Nielsen et al., 2011; Shen & Tzempelikos, 2011; Tzempelikos & Athienitis, 2007).

1.2 Problem statement

While the CBDM approach is becoming more and more widespread within the scientific community, it still results hard to be fully understood and correctly applied by designers. This is partly due to some inherent characteristics of the new metrics being proposed and partly to the simulation tools which are necessary to perform the climate-based annual analyses.

On the other hand, it is worth stressing that no target values have been provided for CBDM to benchmark the daylighting analyses. Recently the IES committee introduced new targets for the $sDA_{300/50\%}$ and $ASE_{1000,250h}$ metrics thanks to which a space can be rated 'favorably', 'neutral' or 'non-sufficient' daylit. Furthermore most of daylighting design tools now available to calculate CBDM are seldom user-friendly and are usually based on Radiance, with the result that expert skills are needed to carry out simulations.

In general, it could be said that there is a lack of simple but sufficiently accurate prediction tools for a design team to optimize a project during the conceptual design phase and on which to base the first, but crucial, decisions about the building shape and orientation, window sizes and characteristics of glazing and shading systems. Furthermore there are few synthetic informative metrics about the effect that different architectural features have on the daylight availability within a space that can be used as simplified rules of thumb during the earliest stage of the design process.

Moreover, it has been demonstrated that the potential of global energy savings by integrating daylight availability in the electric lighting management is high. Nevertheless nowadays there are few outcomes about the importance of considering daylight during the earliest phases of the design process in order to immediately reach a balance between daylight benefits and energy requirements for lighting, heating and cooling. Following this approach there are still no comparison in the current literature between spatial Daylight Autonomy target values and the related global energy demand.

1.3 Objectives

The study presented in this thesis focuses on four aspects related to the main problems found in current literature:

- Analyzing drawbacks and potentials of new indicators concerned with the dynamic daylight modelling, starting from some limits found in the current state of the art. Within this first frame, a comparison between Climate-Based Daylight Metrics and the conventional Daylight Factor approach have been carried out, in order to analyze the consistency of new indicators for a dynamic daylighting analysis.

- Proposing synthetic information and tools to be used by the design team during the earliest design stage to predict the indoor daylighting condition. Within this frame an analysis of the effect of different architectural design solutions on daylight availability through a CBDM has been carried out and a simple graphical tool has been proposed. This is intended to be used by the design team to quickly verify the influence of preliminary design solutions on the daylight amount in a space.
- Analyzing the effect of a proper daylighting design on energy requirements for electric lighting, associated with the use of efficient lighting technologies and control systems. CBDM values have been directly compared with energy demand for electric lighting results exploring the influence of different lighting control systems on the daylight amount in a building space.
- Assessing the influence of a design strategy based on the optimization of daylight on the global energy performance of a space. The aim of this frame is testing if a space which is sufficiency daylit could at the same time imply a low global energy demand.

1.4 Approach

The approach which was used in the thesis relies on a parametric study to assess how the daylight availability and energy requirements for lighting, heating and cooling vary as the building/room architectural characteristics vary. The parametric study has been structured in two different phases:

- During the first phase the parameters that influence the daylight amount in an indoor space were identified. A single room was used as 'case study' and lighting simulations were performed using the validated dynamic daylight software Daysim (Reinhart, 2006). Several rooms' settings have been analysed changing the characteristics of the room in terms of latitude and climate, orientation, room depth, window area, external obstruction angle, visible glazing transmittance, average target illuminance on the workplane and lighting control systems. Daysim has been chosen to perform daylighting analyses since it allows accurately estimating the annual amount of daylight in a space and calculating the CBDM as well as the annual energy demand for electric lighting.

  The overall database of results was then analysed and used to propose a simple graphical tool. This is intended to be a useful tool for the design team during the earliest design stages to quickly predict the daylighting performance of a space varying its architectural features and control systems.

- During the second phase, the lighting analyses have been integrated with thermal analyses. In particular the output from Daysim (such as the status of all lighting and shading groups in the space) were used as input in EnergyPlus (US-DOE). In this context, the jEplus tool has been used (www.jeplus.org) to again carry out a parametric study. jEplus allows a parametric analysis to be performed, that can be applied to all the design variables present in a model simultaneously calling the EnergyPlus simulation engine.

  As final output, annual energy demands for lighting, heating and cooling were calculated and converted into primary energy data for every room's configuration. Some considerations were finally drawn comparing daylight availability with primary energy demand results.

1.5 Thesis outline

The thesis is structured in five chapters. The background for the research is presented in Chapter 2: findings from the literature about how assessing daylight within a space are highlighted, presenting the current methods to quantify energy requirements for electric lighting in buildings and which is the role played by daylighting design in a building global energy simulation context. Furthermore, some information about daylighting and global energy simulation methods are given. Chapter 3 focuses on daylight analyses and evaluations: the research methodology is described and the findings for each objectives of the thesis related to the current daylighting design practice are presented. Chapter 4 analyses the whole building energy performance as a consequence of a proper daylighting design approach. Chapter 5 discusses the research findings and gives overall conclusions about the research project.

The second Part of the thesis contains seven papers which have been presented in international conferences and submitted to international journals in order to disseminate the overall course of the PhD research:

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CHAPTER 2

Literature review

Daylight has always been an essential and irreplaceable resource for architecture.

It is a resource in a design perspective, since it significantly contributes to create the character and appearance of indoor spaces in buildings: thanks to features like quantity, distribution and direction, through effects of light and shadow, and moreover as a result of its variability in space and time, due to the presence of direct and diffuse light from sun and sky, to the succession of the seasons or the hours of the day, and also due to the specific visual climate of every place on the earth.

It is a resource in economical perspective, since the daylight availability and the quality of the daylighting design contribute towards defining the economic value of buildings, whilst the quantity of daylight available during the occupancy hours of spaces allows a reduction in the use of electric lighting and in the consequent energy costs (Mardaljevic et al., 2009).

But daylight is moreover a resource for people who use buildings. A daylit luminous environment and the presence of openings towards outside are essential aspects for users health and well-being, from both physiological and psychological point of view.

Several benefits for people are traditionally recognised to the presence of daylight in buildings. Intensity, spectrum and variability of daylight can positively affect the human circadian rhythms and reduce the seasonal affective disorders. In general a proper exposure to daylight (both diffuse and direct sunlight) for people who spend a large amount of time in buildings is to be desired, like desirable is the possibility to keep a visual connection to the outdoor, again for both physiological and psychological reasons (eye relaxation, perception of the flow of time, spatial relation to the outdoor context, etc.).

Daylight can also affect the productivity and the comfort sensed in carrying out visual tasks. In the visual comfort perspective it brings both benefits and drawbacks. The large amount of light that can reach the workplane, the high colour rendering and the spectrum variability are generally perceived as benefits, conversely the high luminance of daylight sources can produce direct glare or reflected glare on glossy surfaces.

2.1 Daylight and human factors

2.1.1 Non-visual Effects of Light

Recent medical and biological researches have demonstrated that daylight, other than providing visual stimulation, has also an important non-visual effect on most of the body’s biological processes (Veitch, 2005).

Boyce et al. (2003) recognised three routes by which luminous signals interact with human functions: visual, circadian and perceptual. When light passes through the eye, its signals are carried out not only to the main visual areas but also to the parts of the brain responsible for hormonal regulation. Visible radiation hence results in stimuli involving the whole of the physical (energetic exchanges), physiological (transformation of energetic fluxes into nervous stimuli) and psychological (brain interpretations of those stimuli) aspects that inform the body and the mind about the characteristics of the surrounding environment and contribute to the biological metabolism of the human organism.

Other than simply providing visual information, adequate daylight received during the day synchronises the circadian clock, stimulating circulation, increasing the production of vitamin D, enhancing the uptake of calcium in the intestine, regulating protein metabolism, and controlling the level of hormones such as serotonin, dopamine (the 'pleasure hormone'), cortisol (the 'stress hormone') and melatonin (the 'sleep hormone', which distributes internal temporal information to the body).

For almost two centuries of ophthalmic research, the whole of these processes have been attributed to the role of only two photoreceptors in the human eye: the cones, active mainly in bright light conditions, and the rods, which regulate visual information in dim environments. As light reaches these cells, a chemical reaction occurs which determines electrical impulses to be sent via a nerve pathway to the visual cortex located in the back of the brain where these impulses are interpreted as 'vision'. However, new studies have shown that the biophysical processes that govern circadian regulation are very different from those that govern visual effects (Altomonte, 2008).

Berson at al. (2002) have discovered a third cell-type of photoreceptor - defined as an 'intrinsically photosensitive retinal ganglion cell' (ipRGC) - which seems to be the main responsible for the regulation of biological, non-visual metabolic processes. This discovery is leading towards a substantial revision of the characteristics that the luminous environment should have to sustain both the visual and the biophysical human well-being (Van Bommel, 2006).

Aries et al. (2005) suggests that a key role in the triggering of the photobiological process is played by the vertical illuminance received in the retina. This result implies that the vertical spatial distribution of the luminous signal is also a significant factor for biological stimulation.

Also the dynamics of lighting in terms of intensity and spectral composition during the day seem to play an influent role on the metabolic production of hormones (Aries, 2005).

In this context cortisol and melatonin play a fundamental role in regulating the level of alertness and sleep, controlling the amount of sugar in the blood and, thus, the availability of energy to 'power' human activities. Cortisol levels increase in the morning with exposure to daylight and then, during the day, decrease gradually reaching a minimum around midnight

(Figure 2.1). On the contrary, melatonin drops in the morning and rises during the night (Van Bommel & Van den Beld, 2004).

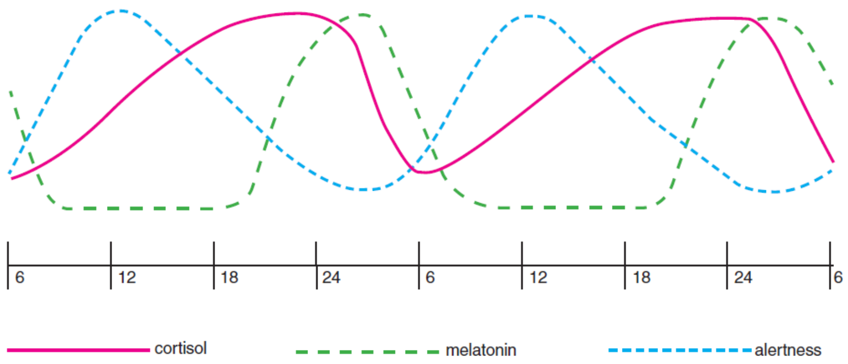


Figure 2.1 2x24-hour diagram of different circadian rhythms in the human body.

A sufficient amount of retinal illumination to regulate biological processes can eventually be provided also by electric lighting alone, even if Boyce (2003) suggests that this is less likely to obtain the same results as daylight.

Finally, due to new findings, it becomes quite clear how daylight, other than just providing vision, orientation in space and time and environmental stimulation, can also mediate and control a large number of biochemical processes in the body, which are fundamental for human health. However, current practice for lighting design in buildings is still related to visual criteria and target task illuminance (e.g. lux on the working plane, Daylight Factor, etc.) and luminance (e.g. glare). To truly enhance the sustainability of built environments - guaranteeing energy savings and fostering the health and well-being of their occupants - these criteria have to be extended to non-visual factors.

2.2 Daylight in buildings

The use of daylight in buildings, with its variation, its spectral composition and the provision for external views, is of great importance for the comfort and well-being of occupants. In a workplane environment , for instance, daylight can positively influence the health of people, improving efficiency and resulting in greater benefits for enhanced productivity. If properly designed, a daylight strategy can bring massive energy savings, as long as it minimises energy use for electric lighting and prevents glare and other visual discomfort (such as contrast, adaptation problems and internal reflections). However, the overall energy efficiency of windows depends also on thermal effects, i.e. solar gains and heat losses through glass, and their balance against heat production of electric lighting systems.

A daylight strategy has to be designed according to the needs of users and the requirements of the building. Specifying daylighting solutions for energy efficiency, comfort and well-being can be a very complex task where many variables can diverge from each other making selection and optimisation extremely difficult (Altomonte, 2008).

The challenge for a designer is to identify the most appropriate properties of daylight systems that provide adequate levels of daylight and improve the visual comfort of the space. In order to design energy efficient built environment, variables such as illuminance, luminance, and colour rendering need to be coupled with qualitative and behavioural factors such as directionality of light, spectral composition of radiation, time/duration of exposure, metabolic rhythms and personal preferences. Recent findings suggest that visual comfort can be extremely influenced by physiological parameters.

The presence of daylight in buildings should maximise the potential of architectural features while optimizing human comfort and visual perception. Daylight can reveal the experience of architecture, define and manipulate the space of a built environment, uncovering the link between inside and outside and separating or connecting internal spaces.

Scientific research has proven the relationship between lighting conditions, well-being and the perception of the surrounding environment. Exposure to daylight has constantly provided the direct stimuli needed to mark the rhythm of life and contribute to feel well and healthy (Boyce et al., 2003).

2.2.1 Daylighting strategies and devices

In order to control the amount and distribution of daylight within a space and to ensure a comfortable and healthy luminous environment a proper daylighting design strategy should be based on more than a simple opening in the façade (window) or on the roof (skylight). New efficient solutions and devices can be used, depending on the latitude, the orientation and the function of a space. Providing a well daylit environment requires a design balance between many factors. As such the daylight and lighting strategy must be developed early in the design process, where the lighting designer works closely with the architect and other design team members. There are a lot of factors that must be considered such that the daylighting strategy delivers the required solution without negatively impacting on other functional and aesthetic requirements of the building. Whilst these considerations can be applied to both new-build and refurbishment, some design elements will be more difficult to achieve with refurbishment projects due to existing building orientation and form. However this does not exclude the designer from reviewing every aspect of the building and creating the best environment achievable (SLL, 2011).

Building form and orientation

Understanding the site and the building orientation allows the placement of room types where the lighting requirements are different. The façade design can also progress as the availability of daylight is established and is matched to the requirement of the rooms. Preferred views out and sight lines can also be established. Understanding the form and continuing to progress the façade design allows more detailed examination of the quality and quantity of daylight that penetrates the building and individual rooms. A review of both the light and shadows is required to establish the quality of the light within the building.

Building fabric

The thermal design of the building will drive some elements of the building fabric and therefore the wall thickness. The wall thickness will affect the quantity of light which enters the internal space; however it could also act as a shade to reduce heat gains. Where the building fabric creates a wall thickness of more than 300 mm then the lighting designer and architect should consider how to make use of the horizontal element as this could effectively be a light shelf.

External building obstructions

In city center locations or on more compact sites, external buildings will reduce the availability of daylight and views. Understanding the quality and quantity of daylight throughout the building will enable one to advise on adjusting the room positions, window dimensions, window angles and furniture arrangements to improve views and daylight levels. The façades of external obstructions also need to be reviewed to identify if a potential reflection discomfort could occur or if there is an opportunity to improve the brightness of the building to improve the view.

The glazing

The glass is a critical element in delivering daylight to the internal spaces. As the façade solution is progressed to satisfy the architectural intent, the daylight and the thermal requirements of the building, the selection of the glass will be fixed to achieve a required light transmittance, thermal and solar transmittance. Care should be taken to ensure the glazing specification is maintained throughout the design process as value engineering can often deliver alternatives that satisfy the thermal performance, but significantly reduce the light transmittance.

In selecting the glazing consideration should also be given to the frame arrangement. Some glazing systems are well designed and use small frames that lead to reduce visual and light obstruction. The quantity of glazing and the arrangement of glazing will have an impact both on the quantity and quality of daylight. The sill and head heights designed to accommodate the end users will deliver good views out and satisfy a key element in delivering good quality daylight spaces. Figure 2.2 shows main window types and daylight distribution systems (SLL, 2011).

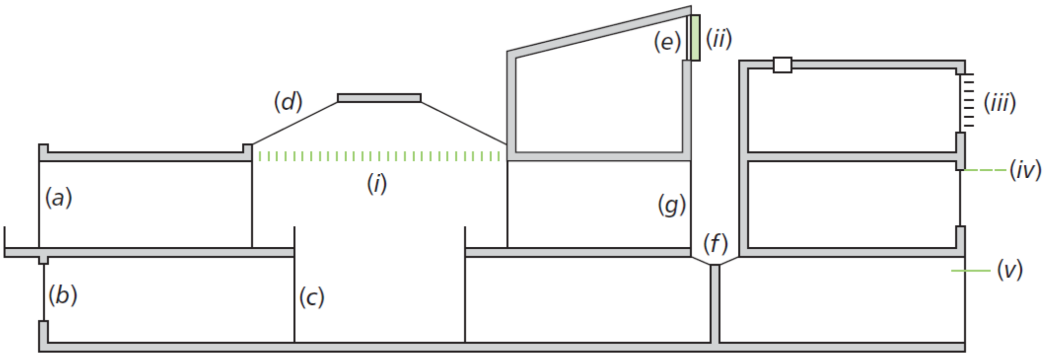


Figure 2.2 Main window types and daylight distribution systems.

(a) *Full height glazing*: provides very good views out and the maximum level of daylight available through the facade. The high level glazing delivers light deep into the space thus creating a visually balanced light distribution. Consideration should be given to visual security for the lower section of the glazing. Also if the furniture is placed adjacent to the glazing then the lower level of glazing will not contribute to the useful daylight within the space, therefore any analysis should not include the lower section of glazing.

(b) *Traditional glazing*: a solid section of wall makes up the lower portion of the wall, typically just over desk height, with a solid upper section downstand element. The glazing is horizontal and can be full width or broken by solid sections. The downstand element can impact on light reaching the full depth of the room.

(c) *Internal glazing ('borrowed light')*: internal glazing will provide views into the atrium as well as secondary daylight via the atrium. Consideration should be given to the potential requirement for privacy into the room or to reduce distraction for some end users.

(d) *Rooflights*: the atrium rooflight can provide the quality and quantity of daylight, both within the atrium and within the adjacent rooms. The design of the rooflight and any required shading is critical in achieving the quantity and quality of daylight.

(e) *Clerestory*: clerestory windows provide light from the highest and brightest part of the sky and will not generally be affected by external obstructions. They allow a view of the sky but not typically a view of the immediate outside area. In allowing a view of the brightest part of the sky the contrast between the inside and outside is likely to be higher than other window types, thus likely to cause glare. They will provide light deep into the space.

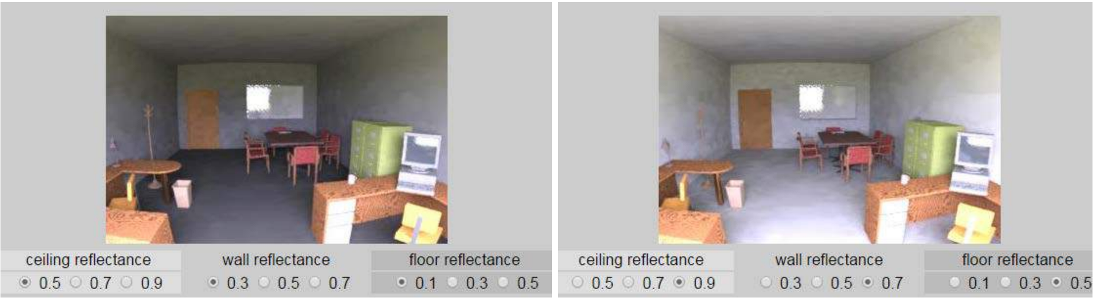
(f) *Lightwell rooflight*: where site constraints limit external facades and views, secondary light to a space can be provided via a lightwell. Depending on the depth of the lightwell, the light will typically be diffuse and glare free. The glazing must be acoustically sound to avoid noise transfer to adjacent rooms.

(g) *Lightwell window*: Semi-translucent glazing can provide a sense a brightness of rooms via the lightwell daylight.

Surface reflectance

The more reflective the surfaces the more light will be distributed around a space. Selecting surfaces and colours requires care to ensure that a balance of visual quality exists within the space. Window walls should always be light to reduce contrast and thus reduce the risk of glare.

It has been demonstrated that increasing the rooms reflectance has a modest influence on the increase of the Daylight Factor while, on the other hand, it improves the uniformity. Increasing the surface reflectance increases the internal light reflected components (Figure 2.3).



ceiling	walls								
	0.3			0.5			0.7		
	floor			floor			floor		
	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
0.5	1.10	1.12	1.15	1.19	1.22	1.24	1.28	1.32	1.35
0.7	1.20	1.21	1.25	1.29	1.32	1.35	1.39	1.43	1.48
0.9	1.28	1.31	1.35	1.38	1.42	1.47	1.51	1.56	1.61

Figure 2.3 Effect on DF measured in the center of the room for different configurations of surface reflectances (Source: www.new-learn.info).

Typically reflectance values for walls are in the range 0.3-0.7, ceilings 0.5-0.9 and floors 0.1-0.5. Windows are generally taken to have a low reflectance since they reflect a small amount of daylight, depending on the incident angle. The effect of changing the surface reflectance is shown in the Figure 2.3.

Glare control

Providing shading is a very important strategy for daylit spaces to minimise glare (and reduce overheating). The challenge for all shading is to reduce unwanted glare and/or solar gains whilst at the same time admitting as much useful daylight as possible. Shading devices can be broadly broken down into internal and external forms.

Eternal shading can be active (dynamic), such as louvres or brise-soleil or passive (static), such as overhangs. Overhangs can make use of parts of the architecture blocking the direct sunlight. Louvres can be horizontally or vertically. The angle of the louvres is normally fixed, but it can be set to allow winter sun coming into the space while blocking summer sun. Modern moveable louvre system often employ prismatic materials. Retractable awnings are more popular in Europe and can be adjusted by the building occupant depending on the daily or seasonal requirements.

Fabric blinds can reduce glare by balancing luminance ratios across a scene. The light transmittance of fabric blinds varies by material. The mayor drawback of fabric blinds is that they block the view to the outside and they offer only one value of transmittance when lowered (Figure 2.4).

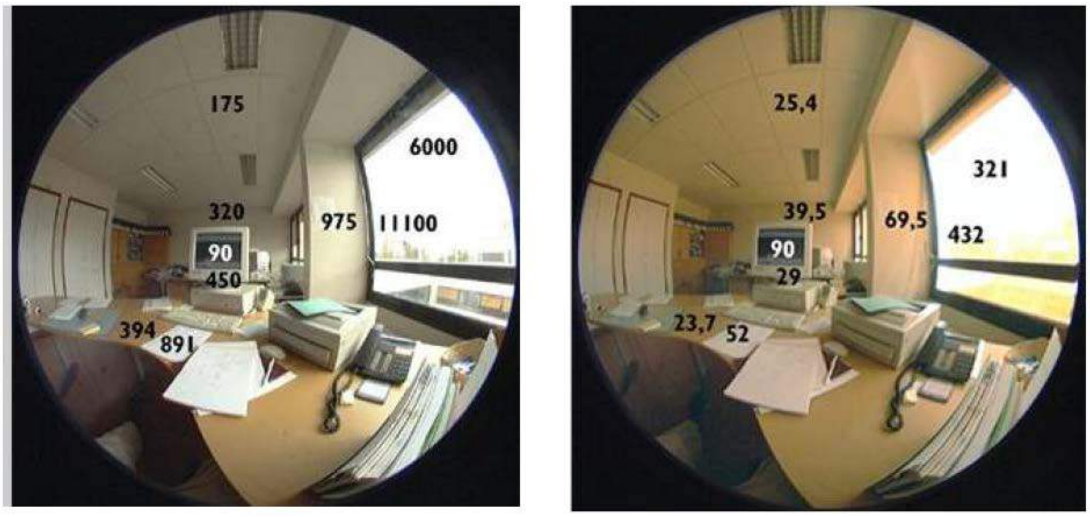
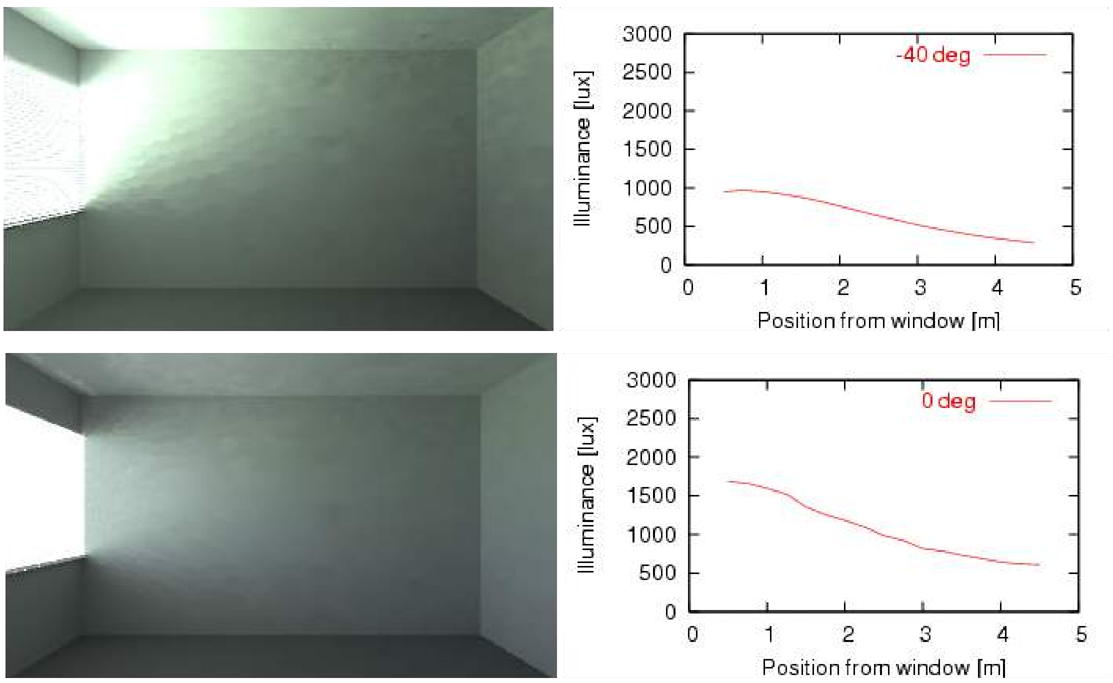


Figure 2.4 Spot luminance values across a scene without (left) and with (right) fabric blinds pulled down (Source: www.new-learn.info).

Venetian blinds, on the other hand, can maintain a view with the outside and at the same time block direct sunlight and also offer a wide range of transmittances (Figure 2.5).



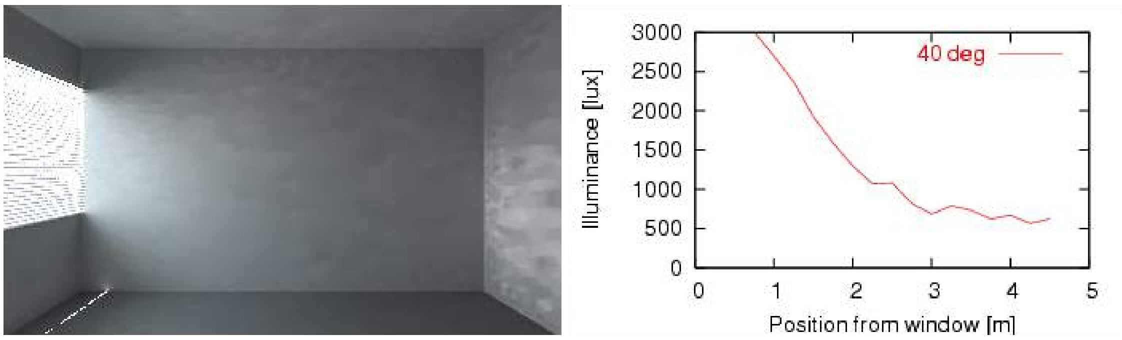


Figure 2.5 The effect on illuminance values and distribution for a South-facing room on a clear day with venetian blinds set at different tilt angles (Source: www.new-learn.info).

Good daylighting strategies can start exploring some simple solutions (window size, placement, self-shading) and then integrating advanced elements if required. The performance of advanced and dynamic systems usually depends on maintenance and durability of components. The position of shading devices depends mainly on orientation: generally horizontal shadings are used for South-facing façades while vertical shadings are used more frequently on Est and West-facing façades. If internal blinds are used to control glare they should be made of diffusive material.

In terms of operational strategies, each user should be able to manage daylight devices so as to suit his own preferences. However, it has to be considered that when blinds are closed to reduce luminous discomfort, the manual control can often cause the blinds to be kept closed even after the source of disturbance has ceased (Escuyer & Fontoynont, 2001).

Daylight systems overview

A daylight system couples a glazing with some other elements that enhance the delivery or control of daylight into a space. Ordinary windows properly deal with the need of daylight into a space but there are new technologies and solutions which improve the indoor performance more than the conventional solutions. The aim of these new technologies are:

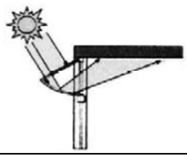
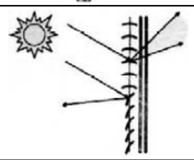
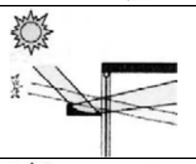
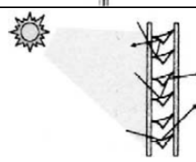
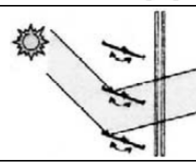
- Providing useful daylight at greater depths from the window wall than is possible with conventional design;
- Increasing usable daylight for climates with predominantly overcast skies;
- Increasing usable daylight for very sunny climates where control of direct sun is required;
- Increasing usable daylight for windows that are blocked by exterior obstructions;
- Transporting usable daylight to windowless spaces.

There's a wide choice of daylighting systems. Daylighting systems range from simple static (louvers, light-shelves, fixed overhangs, laser-cut panels, prismatic elements, anidolic systems etc.). to adaptable dynamic elements (blinds, movable lamellae, advanced glazing, holographic optical elements etc.) and/or combinations of these (IEA Task 21, 2000).

Daylighting systems with shadings

Shading systems have been designed to first block direct sunlight and to admit diffuse daylight. The use of conventional shading systems to avoid overheating and glare effects also reduces the use of daylight for visual tasks indoors. In order to increase the use of daylight, new shading systems have been developed able to redirect diffuse daylight into the depth of the space.

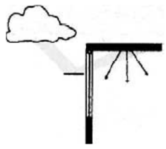
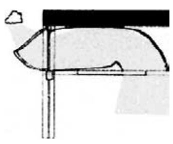
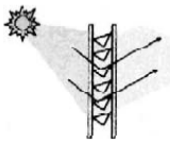
In the following tables the different types of window systems are shown highlighting their differences in terms of their ability to control glare, the view to the outside, the amount of daylight into the depth of a room, the daylight uniformity and the energy saving potential.

Daylighting systems with shadings			
System		Attachment	Criteria for the choice of elements
Light guiding shade		Vertical windows above eye height	- glare protection - outside view - light into the depth of the room - uniform illumination - energy saving potential
Louvers and blinds		Vertical windows	- glare protection - outside view - light into the depth of the room - uniform illumination - need for tracking
Lightshelf for redirection of sunlight		Vertical windows	- outside view - light into the depth of the room - uniform illumination - energy saving potential
Glazing with reflecting profiles (Okasolar)		Vertical windows, skylights	- glare protection - outside view - light into the depth of the room - uniform illumination - variable solar heat gain coefficient
Turnable lamellas		Vertical windows, skylights	- glare protection - light into the depth of the room - uniform illumination - energy saving potential - need for tracking

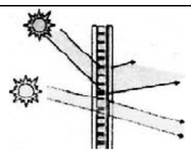
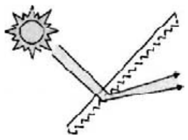
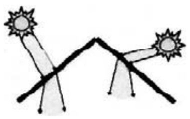
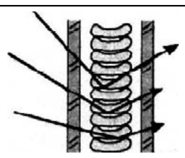
Daylighting systems without shadings

Daylight systems without shadings are designed primarily to redirect daylight to areas far away from a window or a skylight opening. These systems can be divided into four categories:

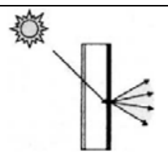
- **Diffuse light-guiding systems**. Under overcast sky conditions, the area around the sky zenith is much brighter than the area close to the horizon. The zenith light is normally being used near the window opening. The use of light guiding elements that redirect the light from these areas into the depth of the room allows an improved utilisation of daylight. Another reason for using those elements are high external obstructions which shade the room against the diffuse skylight. Thus the rooms are only well lit nearby the window. Diffuse light guiding elements can solve this problem.

Diffuse light-guiding systems			
System		Attachment	Criteria for the choice of elements
Lightshelf		Vertical windows	- outside view - light into the depth of the room - uniform illumination - energy saving potential
Anidolic integrated system		Vertical windows	- outside view - light into the depth of the room - uniform illumination - energy saving potential
Anidolic ceiling		Vertical façade above viewing window	- outside view - light into the depth of the room - uniform illumination - energy saving potential
Fish system		Vertical windows	- glare protection - outside view - light into the depth of the room - uniform illumination - energy saving potential

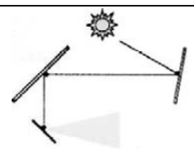
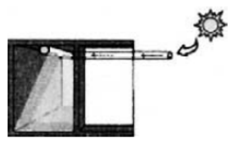
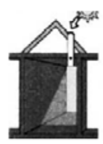
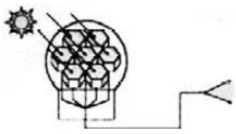
– **Direct light-guiding systems.** Rooms can be illuminated by direct sunlight, when glare effects and overheating problems are avoided. A high efficient redirection and distribution of sunlight can reduce the risk of glare also avoiding the cooling loads.

Direct light-guiding systems			
System		Attachment	Criteria for the choice of elements
Laser Cut Panel (LCP)		Vertical windows, skylights	- outside view - light into the depth of the room - uniform illumination - energy saving potential
Prismatic panels		Vertical windows, skylights	- outside view - light into the depth of the room - energy saving potential
Holographic Optical Elements in the skylight		Skylights	- outside view - uniform illumination
Light guiding glass		Vertical windows, skylights	- glare protection - outside view - light into the depth of the room - uniform illumination - energy saving potential

– **Light scattering or diffusing systems**. These systems are usually used for sky light openings in toplit rooms. If these systems are used in vertical window apertures, they may produce huge glare problems. Their location has to be studied very carefully in order to prevent glare problems.

Light scattering systems			
System		Attachment	Criteria for the choice of elements
Scattering systems: Light diffusing glass Capillary glass Frosted glass		Vertical windows, skylights	- light into the depth of the room - uniform illumination - energy saving potential

– **Light transport systems**. These systems collect and transport daylight through a light guiding media (light wave guide) over long distances to the core of a building without any window opening.

Light transport systems			
System		Attachment	Criteria for the choice of elements
Heliostat			- light into the depth of the room - energy saving potential - need for tracking
Light-Pipe			- light into the depth of the room - uniform illumination - energy saving potential
Solar-Tube		Roof	- light into the depth of the room - energy saving potential
Fibres			- light into the depth of the room - uniform illumination - energy saving potential - need for tracking

2.2.2 The relation between daylight and room's architectural features

The increasing awareness of the potential benefits of daylight has resulted in an increased need for objective information and data on the impact that different design solutions can have on the daylighting condition within a space, in terms of the architectural features. Over the last few years, a number of studies were performed to obtain information on this issue. However, few of them have focused on parametric studies with considering a wide set of variables.

Reinhart (2002) investigated the influence of various design variables on daylight availability in over 1000 open-plan office settings with different external shading contexts, glazing types, façade orientations, ceiling designs and partition arrangements in five different climatic sites. The daylight performance of the offices was expressed in terms of their daylight autonomy distribution.

Ünver et al. (2002) compared daylight illuminance in three offices with different types of glass and 'transparency ratios'. Daylight illuminance was calculated considering average sky model and using statistical meteorological data for Istanbul.

Krarti et al. (2004) presented a simplified analysis method to evaluate how daylight can be used to reduce energy consumption from electric lighting for four combinations of building geometries, various window sizes and glazing types in four geographical areas.

Ghisi and Tinker (2004) presented a methodology to predict the potential for energy savings due to daylight using an 'Ideal Window Area' concept, i.e. a window area which allows a balance to be obtained between solar thermal load and daylight supply. This methodology was developed using ten differently sized and five differently shaped rooms considering two climatic conditions. The potential daylight availability was assessed using a method based on the Daylight Factor.

Recently, Shen and Tzempelikos (2010) have presented a calculation model that combines the radiosity method with one-bounce ray-tracing to predict hourly indoor illuminances and annual daylighting metrics in order to help designers make better decisions on how to optimize the daylighting performance of a building. The study considered different façade parameters (window size, properties, orientation and geometry).

Dubois and Flodberg (2013) presented a study on daylight utilization in perimeter office rooms at high latitudes and investigated, through an annual lighting simulation, how the internal daylight availability was influenced by various variables, such as the Glazing-to-Wall Ratio (GWR), visible glazing transmittance, inner surfaces reflectance, orientation and latitude.

2.2.3 Controlling electric lighting in response to daylight

Lighting controls are electrical devices added to the installed lighting circuit to manipulate the light output of the luminaires according to a pre-planned program or automatic detection regime or to operator managed actions. The control devices maybe placed remote or be incorporated into the luminaires. In general they consist of detectors (PE, PIR, etc.), signal carriers (mains borne, wireless or wired, etc.) and activators (switch, dimming ballast, DALI ballast, etc.).

In most cases, lighting controls offer positive benefits to the surrounding environment as well as positively affecting occupants. There are three main reasons to apply lighting controls in commercial, institutional and industrial buildings:

- Make use of potential energy savings (e.g. occupancy sensing, daylight harvesting, time scheduling, demand response);
- Improvement of user satisfaction, mood and performance (e.g. personal control, glare control, user demand control, algorithmic stimulation lighting);
- Support building appearance, ambience and company representation (e.g. scene setting)

Each of these reasons will address a different group of decision makers, like facility managers and building owners, human resource managers and health specialists for occupational safety and health services, architects, lighting designers, marketing managers and product designers, as well as end users.

Energy saving is often the major driving factor as well as the most tangible and objective justification for lighting controls. Nonetheless, it must not create a detrimental effect on an occupant's perceived lighting quality to the point where the occupant performance suffers. In order to properly design lighting controls (and to maximize potential energy savings), the designer should have an understanding of occupant behaviour towards lighting control.

Research has indicated that the effectiveness of these controls is not achieved if the user does not have the feeling to be able to intervene with the controls when required (Moore et al., 2004). Personal control is essential when applying (other) lighting control systems. When automatic controls are combined with manual controls, the users of these systems become more positive towards these systems (Moore et al., 2002; Moore et al., 2003).

Manual control

Personal or individual control covers a wide range of technology including rocker switches, push buttons, pull cords, infra-red, radio, sonic, ultrasonic and telephone handset controls. Traditional control is by a switch panel near the door, but more recent systems offer flexible control by individual occupants using pull cords on the luminaires, hand held controllers, telephones or computers. Compared to conventional switching, flexible control can reduce wiring costs and allow flexible partitioning of open plan areas.

Personal control is an important area of lighting control strategies used for both energy savings and the comfort and satisfaction of users. Extensive research has been carried out on this subject in the literature, mostly focusing on the potential for energy savings and the photometric results created on work surfaces as well as the effect of lighting controls on the mood, satisfaction and performance of users. A study by Tregenza et al. (1974) shows that occupants prefer the ability to choose the lighting conditions rather than being forced to accept conditions chosen for them, even if these are objectively better.

There's a consensus on the occurrence of a wide range of chosen lighting levels, which increases the need to justify for individual controls. While some studies report chosen illuminance levels that are above current standards (Begemann et al., 1997), the majority of studies indicate that users work under illuminances that are below recommended lighting levels, resulting in savings up to 54% (Moore et al., 2003). A study by Newsham et al. (2008) implies that manual control of electric lighting in a daylit space results in higher levels of energy savings compared to a space without daylight. In combination with other controls, such as occupancy sensing and/or daylight harvesting, additional savings through personal control of 11 to 29% (Galasiu et al., 2007; Maniccia et al., 1999) were found.

The most apparent and important finding in the literature is the positive effect of personal controls on the satisfaction, comfort and performance of users (Moore et al., 2002; Galasiu et al., 2007; Newsham et al., 2008; Moore et al., 2004).

While most studies report improved satisfaction and performance of users, it is also important to note that with the complexity of control systems, there may be a detriment to the performance of users as well. The literature strongly shows that systems should be designed so as to maximize the likelihood that all users feel equally empowered to use the controls (Moore et al., 2004).

There are conflicting research results on the activation of systems with manual control. In some studies occupants set an initial preferred illuminance level and rarely changed it afterwards (Maniccia et al., 1999; Moore et al., 2003); other studies indicate a more frequent use of lighting control systems (Escuyer & Fontoynont, 2001).

Daylight harvesting

As far as the integration between daylight and electric lighting is concerned, a good combination between the two can make possible to gradually dim the amount of electric lighting required when daylight is sufficient for the task activity. The aim of this control function is to assure a required illuminance level on the working place as a combination of daylight and electric lighting.

Daylight availability is strongly associated with sun position on the sky and weather conditions, which means that geographical location and climatic zones have to be specified considering daylight utilisation. Effectiveness of the daylight harvesting in interiors depends on:

– shapes, dimensions and placements of windows in the enveloping constructions;
– dimensions and shape of rooms;
– window orientation;
– optical properties of transparent materials;
– optical properties of relevant indoor and outdoor reflective surfaces;
– optical properties of devices for shading, redirection and transport of sun light and sky light indoors;
– visual task requirements and glare protection in interiors;
– dimensions and location of workplaces;
– working time.

In order to convert the savings potential offered by the daylight availability in the room into actual energy savings, controlled luminaires are preferably divided into groups running parallel to the windows. Each group needs to have separate electrical power supply and/or need to be controlled according to the available daylight. The available daylight can be measured for each group or individual luminaire and can become a control function or strategy taking into account measured value of daylight. In places with roof lights the layout should be of regular array of luminaires controlled individually or in zones to ensure good illumination coverage, comfort indoor luminous environment (balanced luminance distribution of surrounding surfaces) as well as to avoid disturbing contrast and glare.

A key element of all type of daylight responsive dimming system is the sensor, which detects the presence or absence of daylight and sends a signal to a controller that will adjust the lighting accordingly. The location of the sensor is important because it influences the type of control algorithm used (see Figure 2.6). The photoelectric cell or sensor is often located on the ceiling and it's calibrated on site to maintain a constant illuminance level.

Some studies showed that users tend to switch lighting on or off only when entering or leaving the room (Reinhart & Voss, 2003). Workplaces close to the windows or other sources of daylight can normally, at least part of the day, be sufficiently illuminated with daylight only so the electric lighting can be completely switched off. During the rest of the day or during unfavourable weather conditions the so called temporary supplementary electric lighting need to be used to assure the minimum needed illuminance levels. In larger rooms some of the workplaces are positioned so far away from the daylight sources that they need additional electric lighting during all working hours to balance the brightness distributions in the room.

In both cases a lighting control system (daylight harvesting control) is used to maintain the needed illuminance on workplace and to reduce electrical energy use for lighting. Switching or dimming in daylight harvesting can be completely automatically or automatically off and manually on.

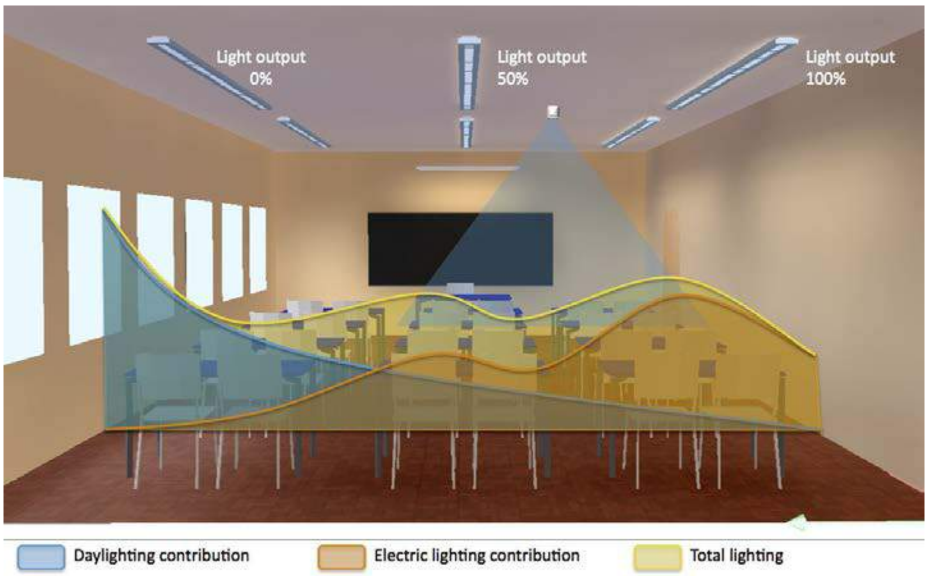


Figure 2.6 Daylight responsive dimming system.

Using a daylight responsive dimming system becomes an appropriate option to reduce the electric lighting energy consumption in spaces where daylight can be a useful source of illumination (Li & Lam, 2003).

The basic algorithm prevalently implemented in a controller are open-loop, closed loop and integral reset control algorithm (Doulos et al., 2008; Li & Lam, 2003).

Doulos et al. (2008) compared the performance of eighteen samples of electronic dimming ballast from five manufacturers to quantify their impact on energy savings in daylight responsive dimming systems for two control algorithm: closed loop and integral reset. The authors concluded that the control algorithm dominates the performance of the daylight responsive dimming system. Closed loop algorithm performed much better than integral reset to meet the target illuminance for more hours during the day.

Bodard and De Herde (2002) evaluated by simulation the impact of lighting management as a function of daylight availability in office buildings in Belgium. The simulations were performed for nine different glazing types with visible transmittance ranging from 0 to 81%. The results shows an annual energy saving of 35 % to 45% depending on the window orientation and glazing transmittance.

2.2.4 Daylighting design and overall energy performance

An appropriate daylighting design approach can influence the global energy performance of a building as well as the interior visual and thermal comfort for the occupants. For this reason, it is always necessary to consider a balance between daylighting benefits and energy requirements, as indicated in some recent studies (Chan & Tzempelikos, 2013; Didonè & Pereira, 2011; Haase, 2011; Moret et al., 2013; Nielsen et al., 2011; Shen & Tzempelikos, 2011; Tzempelikos & Athienitis, 2007).

Coupling daylighting and thermal simulations is necessary for a comprehensive analysis (Citherlet et al., 2001).

Bodard and De Herde (2002) proposed a study about the influence of lighting energy saving due to daylight on the global energy consumption of office buildings. They found that the global primary energy saving coming not only from the reduction of the lighting consumption but also from the reduction of lighting internal loads could then reach 40% for a type of glazing usually used in office buildings.

Clarke et al. (1998) compared the annual energy performance of three different types of glazing using ESP-r and found reduction of about 4.5%, 10.9% and 6% in maximum heating capacity, maximum cooling capacity and total energy consumption respectively. Daylight availability was evaluated by Daylight Factor only, which was slightly affected by glazing type.

The effect of solar shading devices

Reviews of lighting energy saving techniques including daylighting and shading control recognize the potential for a reduction in the global energy consumption (Colaco et al., 2008).

Solar shading is an effective strategy to reduce overheating and diffuse direct sunlight, thus reducing energy consumption. Moreover, problems associated with glare and visual discomfort are inevitable when direct solar radiation is transmitted into the room. To avoid overheating and glare problems, it has been suggested that direct sunlight should not be allowed to enter within a space. Shading provision is necessary to prevent visual and thermal discomfort (Vartiainen, 2001).

Window blinds have different purposes: they often act as a combined heat and glare protection device to maintain adequate visual and thermal comfort conditions under sunny ambient sky conditions or to reduce cooling loads (Choi & Sung, 2000). Dynamic exterior shading devices are more effective than interior shading devices in reducing solar heat gain because they block radiation before it passes through a window (Loutzenhiser et al., 2007).

Several studies report that overheating and glare are the first factors that trigger occupants to manually operate window blinds. Occupants usually alter the shading position only when they are exposed to extreme discomfort and not to optimize the quality criteria of the space. A field study carried out by Reinhart and Voss (2003) demonstrated that people in offices close their blind to avoid direct sunlight above 50 W/m^2 and incoming solar gains above 450 W/m^2. These actions consequently affects the building energy performance.

Automated control of blinds can be an efficient and promising way to overcome human inertia and to improve occupants comfort and energy performance. The major requirement for real time control is the automatic determination of blind tilt angle required to reduce glare, solar gains and at the same time provide the maximum possible amount of daylight into a space (Tzempelikos & Athienitis, 2002).

Lee et al. (1998) explored the potential energy saving offered by automated Venetian blind operating in synchronization with daylighting controls in Oakland, California. The measurement of cooling load and electric lighting power consumption were carried out in two side by side offices. For the energy consumption analysis the authors considered a base case and a prototype office system. In the base case system venetian blind was set to one of three fixed static positions: 45° (nearly closed), 15° (partly closed) and 0° (horizontal) for simulating the ‘manual’ operating throughout the day. For the prototype system the venetian blinds were activated every 30 s to block direct sunlight and maintain daylight design illuminance of 540-700 lx. For both systems a daylight responsive dimming system was used. They found that savings with integration of automated venetian blinds with daylighting controls ranged from 7% to 15% and 19% to 52% for cooling and lighting loads respectively compared to a static 45° blind angle.

Moeseke et al. (2007) investigated the impact of shading device control method on energy demand and overheating hours via simulation and found that the complex control rule combining internal temperature and solar irradiation surpassed the control rule based on solar irradiation or internal temperature alone in balancing comfort and energy saving.

Nielsen et al. (2011) quantified the potential of dynamic solar shading façade components comparing the total energy demand of a private office under three shading conditions: no shading, fixed shading and dynamic shading. Their results showed a significant potential for energy reduction.

Guillemin and Morel (2001) developed and tested user adaptive controllers for integrated operation of blinds, electric lighting and HVAC. The authors applied fuzzy logic techniques for automated shading device controller capable of adapting to the user behaviour and to the room characteristics. The function of shading devices was split into two parts depending on the user presence. With the detection of room occupancy priority was given to visual comfort, while unoccupied priority was given to thermal aspects (heating/cooling/energy saving). The authors concluded that due to the predictive ability of the controller the integrated system could save 25% of energy during 94 days of experiments.

In daylight simulations, the approach to including shading systems has been to model them explicitly or in a more simplified way in which the shading corresponds to a reduction in light transmittance.

In the daylight simulation program Daysim (Reinhart, 2010), this latter approach is referred to the simple blind model. This model uses a simplified algorithm to consider the effect of a generic Venetian blind system on annual daylight availability: Daysim uses the basic Radiance scene to calculate indoor illuminances when the blinds are retracted. During times of the year when the blinds are lowered due to direct glare, Daysim simply assumes that a generic blind system blocks all direct sunlight and transmits 25% of diffuse daylight (Reinhart, 2010). In this mode, glare is defined as when the irradiance on the working plan exceeds $50W/m^2$, which is an empirically established threshold found in the PhD study of Reinhart (2001).

The development of the Three Phase Method simulation approach in Radiance has made it possible to simulate with complex fenestration systems (CFS), described through their bidirectional scattering distribution function (BSDF). This development is a huge improvement in terms of both simulation time and the modelling of fenestration systems. Now the fenestration system can be described using the BSDF, which can be obtained from Window6, and measured in a goniospectrophotometer or generated with the genBSDF routine in Radiance (McNeil, 2010).

2.3 Light in the practice of design

Today people spend up to 90% of their time indoors (Leech et al., 2002), in buildings with much less daylight than before. Today, however, the need to create sustainable buildings has led to increased emphasis on daylit spaces in buildings that use lighting controls to reduce electrical energy needs.

2.3.1 How can we assess daylighting conditions within buildings

Daylighting is notoriously the most difficult building performance strategy to evaluate. One of the difficulties is understand what represents a good daylighting and which are the different professions concentrate on its different aspects.

This observation proposes the question how effectively LEED, or a comparable green building rating system, can help a design team to implement good daylighting.

The exploitation of daylight is recognized as an effective means to reduce the electric lighting requirements of non-domestic buildings.

Buildings, including residential, commercial, and institutional buildings account for more than one third of primary global energy demand. The building sector is the biggest energy consumer among the three energy-using sectors: transportation, industry and buildings. Global energy demand in the building sector has been increasing at an average rate of 3.5% per year since 1970. Energy is consumed in buildings for various end use purposes: space heating, water heating, ventilation, lighting, cooling, cooking, and other appliances. Lighting is the leading energy consumer (25%) in US commercial buildings ahead of space cooling (13%) while lighting energy consumption is less than that of space heating, space cooling and water heating in residential buildings (Figure 2.7) (IEA, 2010).

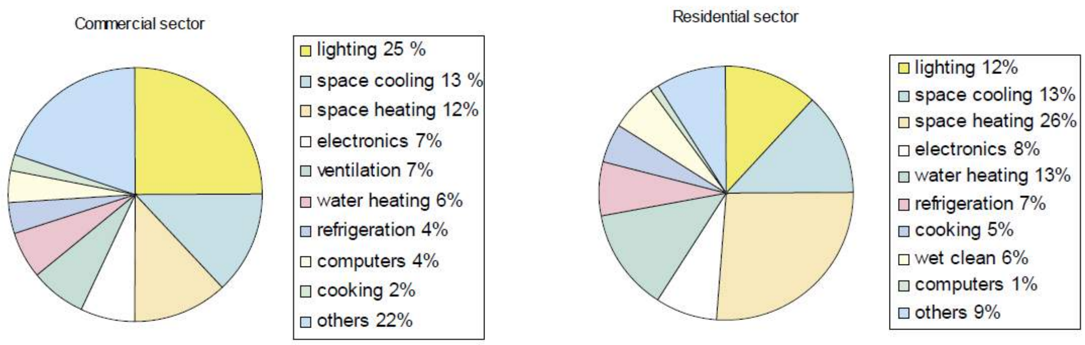


Figure 2.7 Energy consumption by end use in US commercial and residential buildings (DOE 2009).

In Italy, electric lighting corresponds to about 11% of global electric energy consumption, this in turn being about one third of energy globally consumed within the country. On this awareness and the consequent attention being paid to a sustainable use of energy sources are based several national and international projects aimed at involving different subjects who operate in the field of lighting. In particular, the need of a more rational use of energy through a better exploitation of daylight and its conscious integration into the building-HVAC system has become a major issue in the field of lighting.

Furthermore, the need of a more sustainable and ‘green’ daylighting design is also linked to the increased use of large glazed surfaces as major technology for envelope design of non-residential buildings. Connected to this design trend, a particular attention has to be paid to new domains of problems concerned with both building energy behaviour and luminous environment quality (visual comfort).

So it’s important to analyze in detail potentials and limits connected to a daylighting design approach able to get over all limitations concerned with performance indicators such as the obsolete Daylight Factor and to account for dynamic daylight and sunlight conditions on a year basis and for the specific design site.

And also it’s important to analyze the tools and methodologies for assessing the luminous environment in both objective and subjective terms in presence of glare phenomena due to sunlight through windows.

Daylight metrics: Daylight Factor (DF) vs Climate-Based Daylight Modelling (CBDM)

The Daylight Factor in currently the sole quantitative performance metrics used nowadays to implement daylight in a building. It has been in existence through most of the 20th century, although it evolved greatly over time. Its modern form consists of a sum of three components: the direct component, the externally reflected component and the internally reflected component. The direct component, originally the only one considered, started purely as a measure of the fraction of the sky vault visible from the window. It was also sometimes called ‘sky factor’, and that term is still used today when describing this sky vault view (Wu & Ng, 2003). This direct component went through several iterations of correction factors for CIE overcast sky luminance distribution, glass transmittance, and other factors (Collins, 1984), until it was put in its final form in 1968 by J. A. Lynes, who added weighting corrections based on the measurement position in a rectangular room (Lynes, 1968). The externally reflected component, like the direct component, was calculated by angular view, and then divided by 5, under the assumption that the ground and all building materials have an average reflectance factor of 20% (Collins, 1984). For the internally reflection component, there was no good calculation until Hopkinson et al. (1954), published what they called the ‘split-flux method’. This method divides the light flux entering a rectangular room into two parts: one seen by the upper part of the room and affected by the average reflectance factors from the higher spaces, and one seen by the lower part of the room and affected by the reflectance factors of the floor and lower walls (Hopkinson et al., 1954; Hopkinson et al., 1966). All together, these three components add to produce the total Daylight

Factor, which is defined, for any point in a space, as the fraction of the illuminance that one would receive on a horizontal plane under an unobstructed view of a CIE overcast sky.

It's well known that the Daylight Factor concepts allows determining the quantity of daylight which is available within a space as a percentage of the external daylight availability. In this way, it turns out to be a synthetic and dimensionless indicator to characterize the window-environment performance and possibly to determine the internal illuminance if local external climate data are available for the design site. The Daylight Factor definition is based on a series of simplified assumptions with respect to the real phenomenon: if these are somewhat necessary so as to identify a simplified method to determine the Daylight Factor value, on the other hand they turn out to make it less representative of the actual daylight/sunlight availability within a space during the day and the course of the year and hence not suitable to exploit daylight to reduce building energy consumption while maintaining high ambient comfort conditions. In fact actual daylight illumination conditions deviate markedly from the overcast sky paradigm.

The Daylight Factor has been the dominant method of analyzing daylight for the better part of a century. It analyzes the geometry of a building without reference to location, orientation, or weather, but these characteristics are seen more as a weakness than a strength. In his 1968 book Principals of Natural Lighting, Lynes notes that DF only applies 'when the pattern of sky luminance is static […]. The use of Daylight Factor is therefore restricted in practice to solidly overcast weather' (Lynes, 1968). Then in 1980, Tregenza's study of the internal illuminances of several models found DF to be unreliable under real skies. This was mainly because the CIE overcast sky distribution is idealized and uncommon (Tregenza, 1980). More recently, Reinhart did a study in which several daylight analysis methods were compared, and his data shows DF often vastly underestimated the illuminance values in comparison with other analysis tools (Reinhart & Herkel, 2000). Mardaljevic also published a paper which compared standard Daylight Factors to those measured in life. He found that the standard DF tended to underestimate the real DF by at least 20% (and in many cases as much as 40-77%) (Mardaljevic, 2004). One of the primary reasons given for this discrepancy was again the difference between the CIE overcast sky and real skies. In essence, DF is an idealized worst-case scenario, and its application promotes the design of fully-glazed buildings (Reinhart et al., 2006). The use of only overcast skies also precludes any mechanism for studying automatic or occupant shading control.

This brief historical excursion suggests that the Daylight Factor was never meant to be a measure of good daylighting design but a minimum legal lighting requirement. It remains the most widely used performance measure for daylighting and for the majority of practitioners the consideration of any quantitative measure of daylighting begins and ends with it.

Its popularity probably stems from the fact that Daylight Factor remains the only widely accepted quantitative performance measure for daylighting, because it has the advantage that predictions are intuitive and easy to communicate within a design team.

How does the Daylight Factor influence the practice of daylighting design and evaluation? Some form-giving features that are generally associated with good daylighting are indeed promoted by Daylight Factor: high window-head heights, high reflective ceiling and wall finishes, narrow floor plans, large façade and skylight openings with high transmittance glazing. A Daylight Factor optimized building admits as much daylight as possible into the building, following a 'the more the better' approach. Practitioners encounter guidelines and recommendations for target DF values that they know are likely to result in over-glazed buildings with excessive solar gain and/or heat loss. Thus daylighting guidelines founded on DF are often in conflict with design criteria for other parameters, for example conduction losses or solar gain. This is hardly surprising given the orientation-insensitive and climate-insensitive nature of DF.

What are the limitations of the Daylight Factor metric? As a matter of fact, the Daylight Factor concept does not account for direct solar radiation and refers to an overcast sky conditions, that is to say a condition for which the sky vault luminance distribution is azimuthally symmetric; finally the predicted percentage value does not account for the site latitude, resulting unable to distinguish if the same analyzed room is located in North or South of Europe, or the season or the time of the day. The same applies if the analyzed room is South or West or East or North oriented, due to the sky symmetric about the vertical axis, i.e. about the zenith.

Many design teams are aware of the above cited limitations of the Daylight Factor and consider the avoidance of direct sunlight in parallel with Daylight Factor predictions. Direct sunlight studies can be performed using simulations or scale model measurements. The objective is to design facades that avoid direct sunlight in the building during the cooling season. A consequent combination of Daylight Factor predictions and direct shading studies leads to a building in which facade openings are reduced to the minimum possible size and a required minimum Daylight Factor can be maintained within a desired area adjacent to façade and ceiling openings. In combination with a direct shading analysis the Daylight Factor is reduced to its initial historic scope: a minimum level of interior daylight by which the users can 'get by'.

Buildings that are the result of this 'combined approach' (weighting DF against unwanted solar gains) should exhibit a considerably better energy balance than those designed following a Daylight-Factor-only approach.

During the last few years the scientific community is moving towards a more advanced daylighting analysis which takes into account weather, statistical realistic skies, location and building occupancy over the period of a full year. This type of approach is called Climate-Based Daylight Modelling (CBDM). The term does not have a formally accepted definition (it was first coined by Mardaljevic in a title of a paper given at the 2006 CISBE National Conference) (Mardaljevic, 2006; Mardaljevic, 2007; Mardaljevic, 2008): it's the prediction of various radiant or luminous quantities (irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets (Figure 2.8). Climate-based modelling delivers predictions of absolute quantities that are dependent both on the locale and the building orientation, in addition to the building's composition and configuration.

It's generally taken to mean any evaluation that is founded on the totality (sun and sky components) of contiguous daylight data appropriate to the locale for a period of a full year. In practice this means sun and sky parameters found in the standard meteorological data files which contain hourly values for a full year.

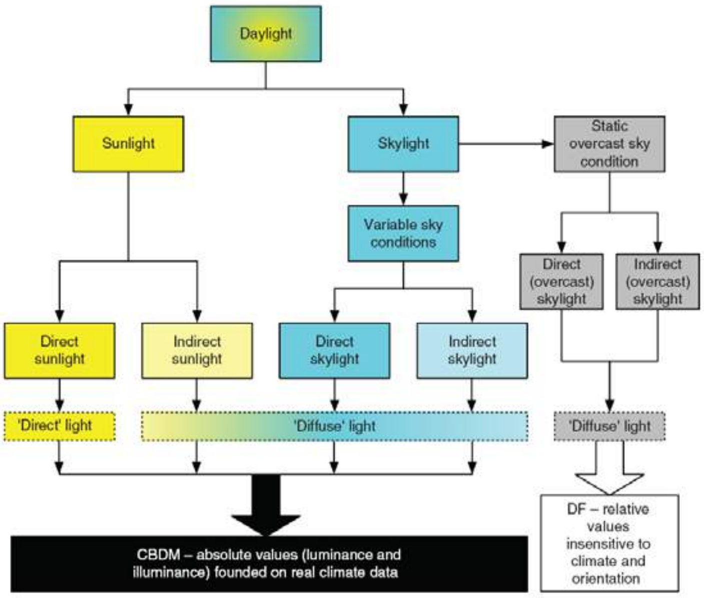


Figure 2.8 The components of daylight and their relation to the DF and Climate-Based Modelling approaches.

Given the self-evident nature of the seasonal pattern in daylight availability, an evaluation period of a full year is needed to fully capture all of the naturally occurring variation in condition that is represented in the climate dataset. Climate datasets are however representative of the prevailing conditions measured at the site.

There are a number of possible ways to use Climate-Based Daylight Modelling: the two principal analysis methods are cumulative and time-series: a cumulative analysis is the prediction of some aggregate measure of daylight (e.g. total annual illuminance) founded on the cumulative luminance (or radiance) effect of hourly sky and sun conditions derived from the climate dataset. It's usually determined in a period of a full year, or on a seasonal or monthly basis, i.e. predicting a cumulative measure for each season or month in turn. The cumulative method can be used for predicting the micro-climate and solar access in urban environments and the determination of seasonal dynamics of daylight and/or shading at the early design stage.

Time-series analysis involves predicting instantaneous measures (e.g. illuminance) based on all the hourly (or sub-hourly) values in the annual climate dataset. These predictions are used to evaluate, for example, the overall daylighting potential of the building, the occurrence of excessive illuminance or luminance, as inputs to behavioural models for light switching and/or blinds usage, and in assessing the performance of daylight responsive lighting controls.

Evaluation founded on the cumulative approach have the potential to influence the design of the building form at the very earliest stages of conception. As the design evolves, cumulative monthly analyses could be used to disclose the prevailing levels and seasonal dynamics of daylight exposure. The cumulative approach, therefore, has the potential to become a valuable tool to guide the design of the building from the initial conception.

A practical limitation of the combined approach is that only static shading devices such as light shelves can be considered, whereas the performance of dynamic shading devices such as venetian blinds remains elusive. It remains therefore difficult to compare the performance of a light shelf or a translucent glazing to arguably the most common solution for sidelight spaces: a window with manually operated venetian blinds.

Also, even though the combined approach considers building orientation and latitude, the actual climate in which the building is placed is not considered.

Finally the combined approach completely ignores building type and occupant requirements of the building.

Daylight quantity metrics

Following the CBDM approach new metrics have been proposed and tested during the last few years in order to summarize the huge number of illuminance results derived from the calculation. These metrics are called Climate-Based Daylight Metrics (CBDM) (Reinhart et al., 2006).

Climate-Based Daylight Metrics are based on a time series of illuminance or luminance within a building. These time series usually extend over the whole calendar year and are based on external annual solar radiation data for the building site. The advantage is that they consider the quantity and character of daily and seasonal variations of daylight for a given building site together with irregular meteorological events:

- Daylight Autonomy (DA) (Reinhart & Walkenhorst, 2001; Walkenhorst et al., 2002): the definition of Daylight Autonomy is ‘the percentage of the year when a minimum illuminance threshold is met by daylight alone’. In 2001 Reinhart and Walkenhorst redefined daylight autonomy at a sensor as the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone. In later publications the concept of daylight autonomy was further refined by combining it with a manual blind control model that predicts the status of movable shading devices at all time steps in the year.
- Useful Daylight Illuminance (UDI) (Nabil & Mardaljevic, 2005): it’s proposed by Nabil and Mardaljevic in 2005, is a dynamic daylight performance measure that is also based on work plane illuminance. It aims to determine when daylight levels are ‘useful’ for the occupant,

neither too dark (<100 lx) nor too bright (>2000 lx). The upper threshold is meant to detect times when an oversupply of daylight might lead to visual and/or thermal discomfort. The suggested range is founded on reported occupant preferences in daylight offices. UDI results in three metric: the percentage of the occupied time of the year when the UDI was achieved (100-2000 lx), fell-short (<100 lx), or exceeded (>2000 lx). The last range is meant to detect the likely appearance of glare.

The same authors later increased the upper illuminance threshold from 2000 lx to 3000 lx (Mardaljevic et al., 2011).

- Continuous Daylight Autonomy (DA_{con}): it's proposed by Rogers (2006). In contrast with the earlier definition of daylight autonomy, partial credit is attributed to time steps when the daylight illuminance lies below the minimum illuminance level. For example, in the case where 500 lx are required and 400 lx are provided by daylight at a given time step, a partial credit of 400 lx/500 lx=0,8 is given for that time step.
- Maximum Daylight Autonomy (DA_{max}) (Rogers, 2006): it's reported together with DA_{con} to indicate the percentage of the occupied hours when direct sunlight or exceedingly high daylight conditions are present. It was defined to be a sliding level equal to ten times the design illuminance of a space. For example, for a computer lab with a design illuminance of 150 lx DA_{max} corresponds to 1500 lx. This criteria is essentially a measure of the occurrence of direct sunlight or other potentially glare conditions and can give an indication of how often and where large illuminance contrasts appear in a space.
- Annual Light Exposure (CIE, 2004; Mardaljevic, 2006): it's an already established performance indicator to design spaces that contain light-sensitive artwork. It's defined as the cumulative amount of visible light incident on a point of interest during the year. Annual light exposure is measured in lux hours per year.

Recently, two new daylight metrics have been defined and adopted by the Illuminating Engineering Society of North America (IES, 2012). Spatial Daylight Autonomy (sDA), which assesses the sufficiency of annual illuminance in an interior work environment, and Annual Sunlight Exposure (ASE), which expresses the annual glare potential:

- Spatial Daylight Autonomy ($sDA_{300/50\%}$) is defined as the percent of an analyzed area that meets a minimum daylight illuminance level of 300 lx for 50% of the operating hours per year.
- Annual Sunlight Exposure ($ASE_{1000,250h}$) is defined as the percent of an analyzed area that exceeds a specified direct sunlight illuminance level of 1000 lx for more than 250 hours per year.

It is important to note that the above metrics are starting to be included in lighting design guides and recommendations. For instance, the UK Education Funding Agency for the Priority Schools Building Programme (UK Education Funding Agency, 2014) uses the $UDI_{achieved}$ and the

DA as daylighting design criteria for teaching spaces. The Society of Light and Lighting guideline ‘Lighting Guide 5: Lighting for education’ (SLL, 2011) also refers to the UDI concept.

sDA and ASE metrics are instead adopted in the rating system of the ‘LEED Reference Guide for Building Design and Construction’ (USGBC, 2014) as possible options to assess indoor daylighting.

Some comparison between DF and CBDM have been carried out during the last years by the scientific community in order to evaluate the sensitivity and the consistency of the new proposed metrics. One of the most meaningful is the research presented by Nabil and Mardaljevic in 2006 (Nabil & Mardaljevic, 2006), whose aims was to compare the evaluative potential of three daylight assessment techniques (Daylight Factors, Daylight Autonomy and Useful Daylight Illuminance) through an examination of their sensitivity to changes in the building design.

A simple 3D model of a four-storey open-plan building with a central light-well was constructed using Radiance scripts and surface generators. The reflectivity of the walls, ceiling, floor and overhangs was set to be 0.5, 0.7, 0.3 and 0.7, respectively. The four facades had glazing 1.7 m high starting at a window sill height of 1 m from the floor. The glazed facades and the light-well were modelled as double glazing with a visible glazing transmittance of 0.74.

There were modelled three different types of scenario, summarized in Figure 2.9:

– Base case: all four facades and light-well were unshaded, i.e., no overhangs included in the model, with the top of the light well glazed and flush with the rest of the building roof.
– Variant 1: shading overhangs were added to the East, South, and West facades, where the thickness of the overhangs was 0.3 m starting at the top of the glazing at 2.7 m from the floor. The width of the overhangs was 1 m extending at right angles to the building facades, as shown in the middle diagram of Fig. 1. Overhangs were not deemed necessary on the North facade since only northern-hemisphere locales were considered in this study.
– Variant 2: in addition to the facade overhangs used for variant 1, a lantern was added to the top of the light-well. The height of the lantern was 1.7 m. The sides were glazed, and an opaque roof with shading overhangs extending 2 m on the East, South, and West sides was added.

To summarise the results shown in Figure 2.10, the highest level of Daylight Autonomy (and the highest Daylight Factor) are indicated for the base case building without shading. The UDI exceedance plot for the base case reveals that illuminances greater than 2000 lx are expected for around 60% and 40% of the working year for perimeter and central areas, respectively.

Occupant studies suggest that these levels of illumination will produce discomfort for significant periods of the year. They are also likely to be indicative of high levels of solar gain. In contrast, the highest levels of UDI are achieved for the variant 2 design that has perimeter and lantern shading.

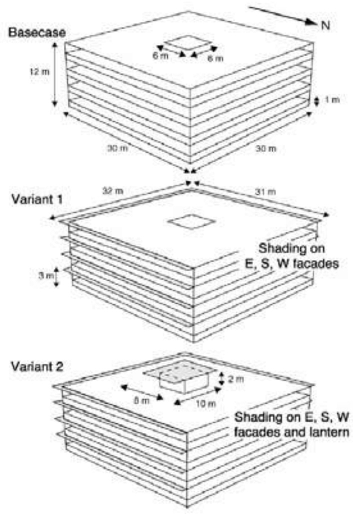


Figure 2.9 Building model and design variants (Nabil & Mardaljevic, 2006).

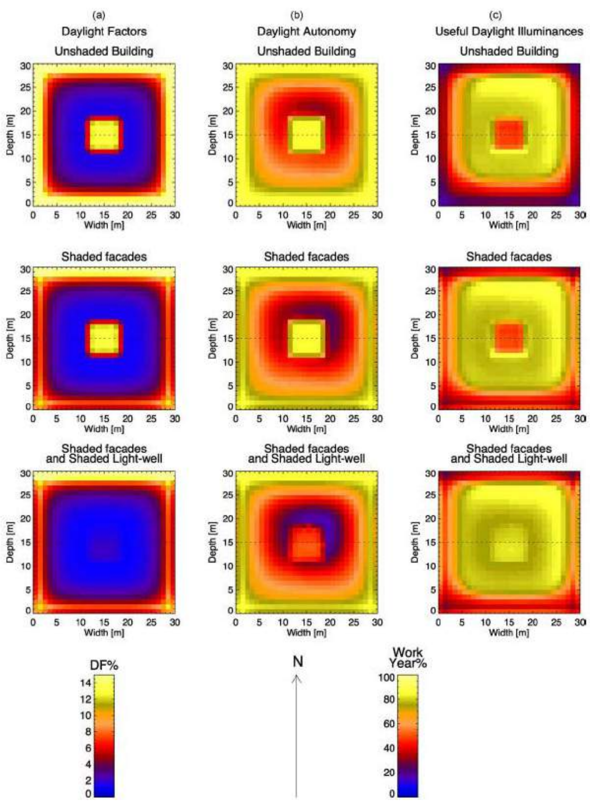


Figure 2.10 Daylight Factor, Daylight Autonomy and Usefull Daylight Illuminance area plots (Nabil & Mardaljevic, 2006).

Daylight quality metrics

There are at least seven recognized glare indexes: British Glare Index, Discomfort Glare Rating, Visual Comfort Probability, CIE Glare Index, Unified Glare Rating, Daylight Glare Index and Daylight Glare Probability (Hopkinson, 1957; Eble-Hankins & Waters, 2004; Rubiño et al., 1994; Nazzal, 2001; Wienold & Christoffersen, 2006).

These metrics are the result of half a century of research involving user studies and simulations of various types of glare sources, although the majority were created in reference to electrically-produced glare sources. For this reason, they work with unequal accuracy for electric and daylit sources (Nazzal, 2001; Nazzal & Chutarat, 2001), and it has been suggested that it is less practical to use them to predict daylight glare (Österhaus, 2005). In addition, glare varies with observer position, view direction, and the adaptability of the eye, so it is no wonder that glare calculations are not standard in lighting design tools.

A commonly adopted glare control analysis in practice is to evaluate it either based on renderings generated for at most one or two viewpoints and a few moments in time, or to not evaluate it at all. As a result, interior blinds are often required after construction. Yet proper control of glare is essential to ensure visual comfort, and some occupants' passive habits – which involves pulling the blinds at the first sign of glare, and then leaving them drawn interminably (Rea, 1984; Reinhart, 2004) – can ruin a daylighting strategy and increase lighting loads (Reinhart, 2004).

Most light quality metrics are based on luminance, because it's what our eye sees. There is a perceptible range of luminances for every adaptation luminance level, and this range gets more restrictive the closer we get to the centre of our visual field. Therefore if the difference between two luminances within our field of view is greater than the range that our eye can handle, we experience a visual discomfort known as 'disability glare' (Vos, 2003). Another form of glare is 'discomfort glare', which is defined generally as 'glare that causes discomfort', although Vos has suggested breaking this further into a new definition of discomfort glare – which would encompass glare that is severe enough to be distracting – and 'dazzling glare', in which there is actually organic, not just visual, discomfort caused by bright light (Vos, 2003).

Despite their differences, most glare metrics agree that quantifying glare depends on some combination or subset of these variables: glare source angular size, glare source luminance, glare source position in view field, background luminance, adaptation luminance, and vertical illuminance at the eye. Although research in glare dates back to the first decade of the 20th century (Vos, 2003), the first recognizable glare metric came from the research of Hopkinson and Pretherbridge in the 1950's and was later known as the British Glare Index, or BGI (Hopkinson, 1957; Hopkinson, 1972; Rubiño et al., 1994). The BGI ranges from 0 to above 30, with 10 representing imperceptible glare and 28 representing intolerable glare.

At around the same time, Lukiesh and Guth began studies that would turn into the Discomfort Glare Rating (DGR) and Visual Comfort Probability, or VCP. The DGR was based on Lukiesh's work on glare sensation in the 1920's, and it formed the basis of the VCP, which is defined as the probability that a person will find the visual environment comfortable, and was based on participant studies (Eble-Hankins & Waters, 2004; Rubiño et al., 1994). All of these metrics were based on point-source glare, and are not easily applicable to large-area glare situations caused by daylight.

The CIE Glare Index, or CGI, was proposed in 1978 by a CIE committee led by Einhorn. It did not attempt to create new human subject studies, but used the current metrics and the information available to create a synthesized metric which would also account for the effect of the glare source on the adaptation level (thus making it better suited to larger area glare sources) (Österhaus, 2005; Eble-Hankins & Waters, 2004). The next CIE committee decided then to remove the new detailed definition of adaptation level and created a compromise rating in 1995, the Unified Glare Rating (UGR), which was simplified to appeal to a wider audience; it produces results very similar to the BGI (Österhaus, 2005; Eble-Hankins & Waters, 2004). Like the BGI, the UGR has a scale ranging from 0 to 30 with the same thresholds, and each step in the scale is meant to be a uniform change in glare perception. Another attempt to correct the weaknesses of the original glare equations is known as the Cornell equation or the Daylight Glare Index (DGI). Despite its name, it was formulated with user studies that employed direct and diffuse electric light sources, and has been shown less accurate for actual daylight sources (Wienold & Christoffersen, 2006). There have been more recent suggestions regarding changes to the DGI which involve actual daylight sensor readings, but no further human studies (Nazzal, 2001; Nazzal & Chutarat, 2001). DGI also uses the scale from 0 to 30.

The only glare metric which was formulated from daylight-based human studies is the Daylight Glare Probability, or DGP, developed by Wienold and Christoffersen (2006). The metric represents the percent of persons disturbed by (not those comfortable with) the scenario, and it has demonstrated good correlation with human responses to daylit environment (Wienold, 2007). It's a very promising glare metric for daylighting, since it's the only one based on user response to actual daylit scenarios.

2.3.2 Standards, certification protocols and guidelines

There are a lot of standards, certification protocols and guidelines which should be taken into account in order to achieve a proper daylighting design and a suitable integration with electric lighting.

Different references from the current literature have been considered to define the methodology to assess daylighting and electric lighting during the course of this thesis.

The first one is the Italian Standard UNI 10840 (2000), which specifies the general criteria for daylighting and electric lighting design for schools and educational buildings. As for daylighting, the Daylight Factor is the metric adopted to define the minimum required daylight availability. The Standard requires a DF≥3% for all types of classrooms and laboratories and a DF≥1% for offices.

The second reference is the LEED Reference Guide for Building Design and Construction (USGBC, 2014). Both the LEED v4 and the LEED 2009 have been analyzed. The LEED green buildings certification program is based on reaching a number of credits aiming to define the level of sustainability of a building. The credits related to daylight are included in the Indoor environmental quality category and have the intent to evaluate the occupants comfort by checking the daylight availability, the potential glare and the visual connection to the outdoors.

The last version (LEED v4) provides three options to get credits from daylight. The first option requires to calculate the spatial Daylight Autonomy and Annual Sunlight Exposure, two new daylight metrics recently proposed by the Illuminating Engineering Society of North America (IES, 2012). The calculation has to demonstrate that spatial Daylight Autonomy ($sDA_{300/50\%}$) of at least 55%, 75%, or 90% of the regularly occupied floor area is achieved. The second option provides the calculation of illuminance levels, demonstrating that illuminance levels will be between 300 lux and 3000 lux for 9 a.m. and 3 p.m., both on a clear-sky day at the equinox, for at least 75%, or 90% of the regularly occupied floor area. The third option is related to the measurement of illuminances. Two times of measurements during the year have to be defined. The measurement has to demonstrate that illuminance levels between 300 lx and 3000 lx of at least 75% or 90% of the regularly occupied floor area are achieved.

The 2009 version of LEED proposes the same method of LEED v4 to get credits from daylight including also a prescriptive option, which is based on the calculation of the product of the glazing visible transmittance (τ_{vis}) and Window-to-Floor area Ratio (WFR). This product has to be between 0.15 and 0.18.

Another reference which have been considered during the research is the English guideline 'Baseline designs and strategies for schools' elaborated within the Priority School Building Programme (PSBP) (UK Education Funding Agency, 2014). The aim of the baseline designs was to ensure sufficient levels of balanced glare-free light to all teaching spaces. The guideline is based on the Climate-Based Daylight Modelling approach to assess the dynamic variation of daylight within spaces and in particular it uses the Useful Daylight Illuminance achieved (UDI-a) as daylight metric. The minimum target for UDI-a was set to 80% for each learning space.

As far as the calculation of energy demand for electric lighting is concerned, the European Standard EN 15193 (2008), recently revised in 2014, have been taken into account. The new version of the standard is part of a set of standards developed to support EPBD directive implementation, called 'EPB standards'. EPB standards deal with energy performance calculation and other related aspects to provide the building services considered in the EPBD directive.

The convention and procedure in the standard assumes that the designed and installed lighting scheme conforms to good lighting practices. The lighting conditions required vary for different buildings, activities and visual tasks and these are well defined in the CEN lighting application standards EN 12464-1 for indoor work places (EN 12464, 2011).

The standard also assumes that the building can have access to daylight to provide all or some of the illumination required in the rooms and that in addition there will be adequate amount of electric lighting installed to provide the required illumination in the absence of dylight.

The standard defines the methods for estimating or measuring the amount of energy required or used for lighting in buildings. The methodology provide values for the Lighting Energy Numeric Indicator (LENI) and it will also provide input for the heating and cooling load estimations for the combined total energy performance of building indicator.

The LENI for a building is established using the following question:

$$LENI = \frac{W}{A}\left[\frac{kWh}{m^2}\right]$$

where

W is the total annual energy used for lighting [kWh/year]

A is the total useful floor area of the building [m^2]

The total estimated energy required for lighting for a period in a room or zone of the building is estimated by using the equation:

$$W = W_L + W_P \text{ [kWh/ year]}$$

W_L is the estimated lighting energy required to fulfil the illumination function in a room or zone of the building. It's established using the equation:

$$W_L = \Sigma\{(P_n \cdot F_C)[(t_D \cdot F_O \cdot F_D) + (t_N \cdot F_O)]\}/1000\,[\mathrm{kWh}]$$

W_P is the estimated standby energy required during non-lighting periods to provide charging energy for emergency lighting and the activation energy for lighting controls in a room or zone of the building. It's established using the equation:

$$W_P = \Sigma\{P_{pc} \cdot [t_S - (t_D + t_N)]\} + (P_{EM} \cdot t_{EM})\}/1000\,[\mathrm{kWh}]$$

The terms involved in the calculation are:

- P_n: the required installed power for the lighting system installed in each area of the building [W/m^2];
- t_D: daylight time [h];
- t_N: daylight absence time [h];
- F_C: constant illuminance factor;
- F_O: occupancy dependency factor;
- F_D: daylight dependency factor;

2.4 Daylight simulation

A daylight simulation is a computer-based calculation which aims to predict the lighting situation in a building under a specific daylight situation (Reinhart, 2001). A daylight simulation program requires:

- Information on the building;
- Information on the prevailing sky conditions;
- A simulation algorithm which calculates indoor illuminances and luminances based on the former two data complexes (Figure 2.11).

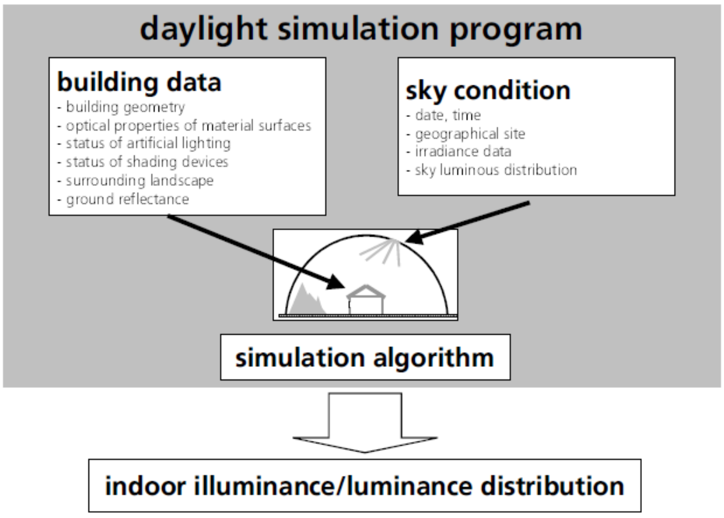


Figure 2.11 A daylight simulation tool requires information on the building and the prevailing sky conditions to calculate indoor illuminance or luminance distribution (Reinhart, 2001).

Building data: the description of a building takes into account the geometry of the building, information on the optical properties of the involved material surfaces in the building and on the surrounding landscape. The building geometry, usually modelled in CAD related design or other construction tools, needs to be completed with the information of optical properties like color, reflection and transmission of the involved building materials. Opaque surfaces are usually characterized by their diffuse and specular reflection properties while for glazing the angle dependant visible transmission is needed.

Sky condition: in order to calculate illuminance levels due to daylight under a specific sky conditions the sky luminance distribution is needed. This physical quantity is usually presented by a two dimensional function which yields luminance values in different sky directions. Practical daylight simulation methods use theoretical sky models based on widely available input data. Until the beginning of the 1990s the CIE sky model was the most widely used (Doigniaux, 1973). The model differentitaties between clear and overcast skies.

Because real skies are infinite in variety, it is better to be able to model a spread of different intermediate skies. Darula and Kittler have defined many individual steps between the

CIE clear and overcast skies (Darula & Kittler, 2002) while Igawa et al. (1999) have made a similar set of distinct sky distributions based on their intermediate sky model.

The Perez All-Weather sky luminance model has been developed in the early nineties by Richard Perez. It requires date, time, site and direct and diffuse irradiance values to calculate the sky luminous distribution for a given sky condition. It uses a single equation which, given brightness and clearness index inputs, can define any number of realistic sky distributions (Perez et al., 1993). Although this sky model has been validated to a reasonably high accuracy, only Radiance and 3ds Max Design can easily be used to model a Perez All-Weather sky (Ward & Shakespeare, 1998; Reinhart & Breton, 2009). Figure 2.12 shows a clear sky modeled with Perez and a bright overcast sky modeled with Perez and CIE.

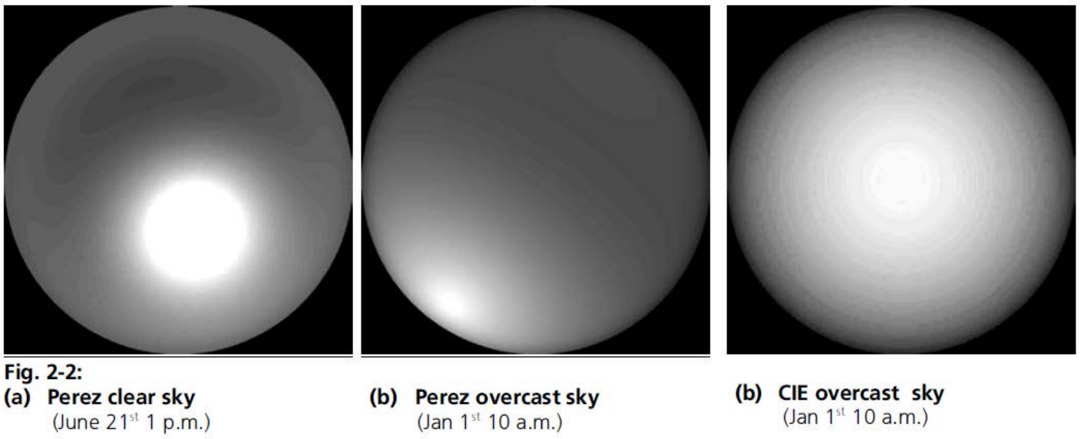


Figure 2.12 Clear sky modeled with Perez (a) and a bright overcast sky modeled with Perez and CIE (b). (Reinhart, 2001).

Daylight simulation algorithm: two main different numerical approaches were identified in the past to simulate illuminances in three dimensional spaces: radiosity and raytracing.

In radiosity each surface is treated like a perfectly diffuser reflector with a constant luminance so that the radiation exchange between two surfaces can be described by a single number which depends on the reflective properties of the surfaces and the scene geometry. To calculate the indoor luminance distribution in a room due to daylight, the imcoming luminous flux through all transparent parts of the building envelope is set equal to the available flux within the building. This assumption defines a set of equations that uniquely determine the luminances of all considered surfaces.

The idea behind (backward) raytracing is to simulate individual light rays in space to calculate the luminous distribution in a room from a given viewpoint. Therefore, rays are emitted from the point of interest and traced backwardly until they either hit a light source or another object. The luminance distribution function of the light source determines the luminance contribution at the view point. If a ray hits an object, the luminance of the object needs to be calculated by secondary rays which are emitting from the object (Reinhart, 2001).

An advantage of radiosity compared to raytracing is that it requires less calculation times for straightforward geometries which don't contain too many surface elements. This adavantage diminishes when rising model complexity.

A basic problem of all daylight simulation algorithm is that they provide no estimate of the remaining calculation errors. Simulation results can be too low if a raytracer misses a small window or skylight in a room with the consequence of underestimating the real illuminance level.

2.4.1 Existing annual illuminance calculations

Usually it's necessary to calculate the daily and seasonal development of indoor illuminances and/or luminances to evaluate the effectiveness of a given daylighting concept. Daylight simulation methods yield the time development of indoor illuminances under multiple sky conditions. Several daylight simulation methods have been proposed in the past which yield hourly mean indoor illuminances for a given building geometry.

The most basic method relies on the *Daylight Factor* method while more advanced, integrated thermal and daylighting simulations tools use refined methods like the *statistical sky* and *daylight coefficients*.

The method based on 'Daylight Factor' interpolation was originally developed for the energy simulation program DOE-2 (Winkelmann & Selkowitz, 1985). This method finds the Daylight Factor and clear-sky illuminance ratios (although it also refers to these ratios as 'daylight factors') for a predetermined set of 20 solar positions and then interpolates the illuminance ratios for all hourly points in between. These 20 data points are fixed for all latitudes, so the clear skies created using them are sometimes theoretical rather than realistic. Using the interpolated ratios, this method finds interior illuminances based on the hourly horizontal illuminances from TMY type weather files.

Proposed by Tregenza and Waters in 1983, the daylight coefficient method assigns to each 'sensor' location a coefficient, or weight, dependent upon room geometry, reflectivity, sky visibility, etc, similarly to the concept of Daylight Factor (Tregenza & Waters, 1983). Unlike DF, however, these coefficients can take small changes in each angular segment of the sky into account. After the daylight coefficients are calculated for a particular model, the sky can be defined by any brightness and luminance distribution, and each additional moment is merely one more set of weighted sums rather than a time-intensive simulation.

For a point and orientation x a daylight coefficient $DC_{\alpha}(x)$ related to the sky segment S_{α} is defined as the illuminance $E_{\alpha}(x)$ at x caused by the sky segment S_{α} divided by the luminance L_{α} and the angular size ΔS_{α} of the sky segment (Figure 2.13).

The advantage of the daylight coefficient method is that the daylight coefficients for a given point in a building merely depend on the building geometry, material characteristics and the division of the surrounding sky and ground into segmets.

A complete set of daylight coefficients can be coupled with an arbitrary sky luminance distribution L_α (with α=1…, N) by a simple linear superposition to calculate the total illuminance E(x) at x:

$$E(x)=\sum_{\alpha=1}^{N} DC_\alpha (x) L_\alpha \Delta S_\alpha$$

Using this equation, annual daylight simultions can be carried out under simulation times in the order of minutes to hours while still allowing to model short-time-step variances of the available daylight.

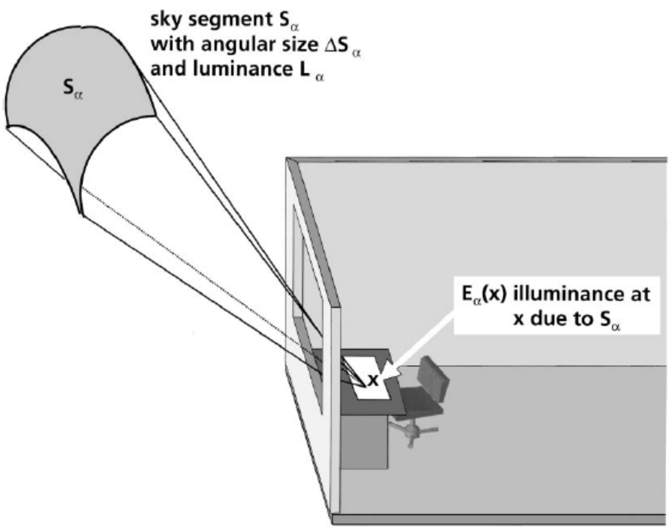


Figure 2.13 Graphical definition of a daylight coefficient DC_α (x) for a point and orientation x (Reinhart, 2001).

Mardaljevic suggested a daylight coefficient method based on 145 diffuse sky patches (as was Tregenza’s), but also on 100,366 direct sun positions and an indirect sun component from each of the 145 diffuse patches (Mardaljevic, 2000).

A more recent idea, called Dynamic Daylight Simulations or DDS, has been suggested in which daylight coefficients are based again on 145 diffuse sky patches, 2596 direct solar positions (in which the one nearest to the actual sun position is used in each calculation), and also indirect solar calculations from the center of the 145 sky patches, where the indirect contribution is weighted similarly to the direct solar contribution in Daysim (Bourgeois & Reinhart, 2006; Bourgeois et al., 2008).

A more complicated strategy for making a subset of annual calculations was suggested by Herkel (1997). Herkel’s method uses the similarity of 3 factors – direct irradiance, diffuse irradiance, and solar altitude – to separate a series of annual lighting simulations into ‘bins’, reducing thousands of simulation moments to a few hundred. But because the objective is only to reduce calculation time, this method discards information such as solar azimuth. Solar azimuth plays a critical role in the internal distribution of daylight and greatly affects the choice of building orientation. This method also precludes the possibility of producing realistic, chronological renderings which might be of use to the designer.

2.4.2 Daylighting simulation software

Although there are many other sofware, the tools presented in this section are the one which have been studied and used during the research project: Radiance, Daysim and Lightsolve.

RADIANCE

Radiance is a sophisticated lighting visualisation system. Originally started off as a research project at the Lawrence Berkeley Laboratories, it has evolved into an extremely powerful package that is capable of producing physically correct results and images that are indistinguishable from real photographs (Ward, 1994; Ward & Shakespeare, 1998).

It takes as input a three-dimensional geometric model of the physical environment and produces a map of spectral radiance values in a color image. The technique of ray-tracing follows light backwards from the image plane to the source(s). Because it can produce realistic images from a simple description, RADIANCE has a wide range of applications in graphic arts, lighting design, computer-aided engineering and architecture.

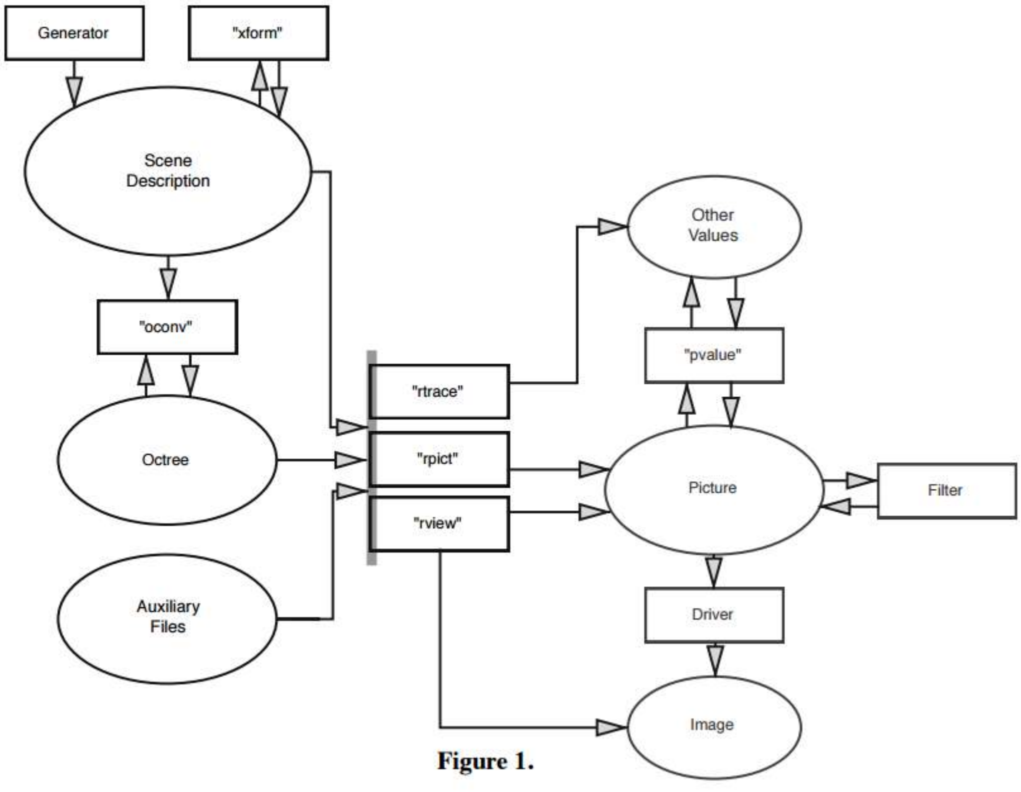


Figure 2.14 Radiance general workflow.

The diagram in Figure 2.14 shows the flow between programs (boxes) and data (ovals). The central program is rpict, which produces a picture from a scene description. Rview is a variation of rpict that computes and displays images interactively. Other programs (not shown) connect many of these elements together, such as the executive programs rad and ranimate, the interactive rendering program rholo, and the animation program ranimove. The program obj2mesh acts as both a converter and scene compiler, converting a Wav efront .OBJ file into a compiled mesh octree for efficient rendering.

A scene description file lists the surfaces and materials that make up a specific environment. The current surface types are spheres, polygons, cones, and cylinders. There is also a composite surface type, called mesh, and a pseudosurface type, called instance, which facilitates very complex geometries. Surfaces can be made from materials such as plastic, metal, and glass. Light sources can be distant disks as well as local spheres, disks and polygons.

From a three-dimensional scene description and a specified view, rpict produces a two-dimensional image. A picture file is a compressed binary representation of the pixels in the image. This picture can be scaled in size and brightness, anti-aliased, and sent to a graphics output device. A header in each picture file lists the program(s) and parameters that produced it. This is useful for identifying a picture without having to display it. The information can be read by the program getinfo.

It allows performing calculations of daylight using the Perez sky model. Radiance might also be the most validated lighting simulation tool and that is probably the reason why more than half of the other software commonly used in the industry use Radiance as their solving engine (Reinhart & Fitz, 2006).

The only drawback of Radiance is that it’s not a user-friendly tool. It does not have a graphical interface and required a considerable amount of practice in order to enable the user to use it properly.

DAYSIM

Daysim is a RADIANCE-based daylighting analysis tool that has been developed at the National Research Council Canada and the Fraunhofer Institute for Solar Energy Systems in Germany (Reinhart, 2010). While RADIANCE has been primarily developed to simulate luminances and illuminances under selected sky conditions, Daysim uses the RADIANCE simulation algorithms to efficiently calculate illuminance distributions under all appearing sky conditions in a year.

In order to calculate annual illuminance profiles, one could in principle also use the standard Radiance programs and start thousands of individual raytracing runs for all sky conditions of the year. This approach is not practical as a Radiance simulation for a single sky condition can take hours so that an hourly annual simulation would literally require years of calculation time. To keep simulation times short, Daysim uses the Radiance algorithm (based on the Perez sky model) coupled with the daylight coefficient approach.

The philosophy behind the daylight coefficient calculation in Daysim is to reduce the number of raytracing runs necessary to calculate a complete set of daylight coefficients and still correctly model all light rays which might contribute to the total illuminance at a point. Daysim distinguishes between contributions from the diffuse day-light, ground reflections and direct sunlight.

$$E(x) = \sum_{\alpha=1}^{145} DC_\alpha^{diffuse}(x) L_\alpha^{diffuse} \Delta S_\alpha^{diffuse} + \sum_{\alpha=1}^{3} DC_\alpha^{ground}(x) L_\alpha^{ground} \Delta S_\alpha^{ground} + \sum_{\alpha=1}^{65} DC_\alpha^{direct}(x) L_\alpha^{direct} \Delta S_\alpha^{direct}$$

The celestial hemisphere is divided into 145 sky segments according to the Tregenza division for the diffuse daylight coefficients and three ground segments according to Reinhart and Herkel for the ground daylight coefficients (Reinhart & Herkel, 2000).

Contributions from direct sunlight are modeled by 65 representative sun positions which are a subset of all possible sun positions throughout the year.

The calculation of a complete set of daylight coefficients for a given point in a building and a site on earth is the most time consuming part during a dynamic daylight simulation. To reduce this calculation time, Daysim calculates the daylight coefficients with an adapted version of the backward raytracer RADIANCE. Due to this adaptation all 145 diffuse, 3 ground and some 65 direct daylight coefficients can be calculated in two single raytracing runs.

Once the daylight coefficients are available, they have to be coupled with the mean luminances of their associated sky segments for a given sky condition, calculated with the Perez all weather sky model.

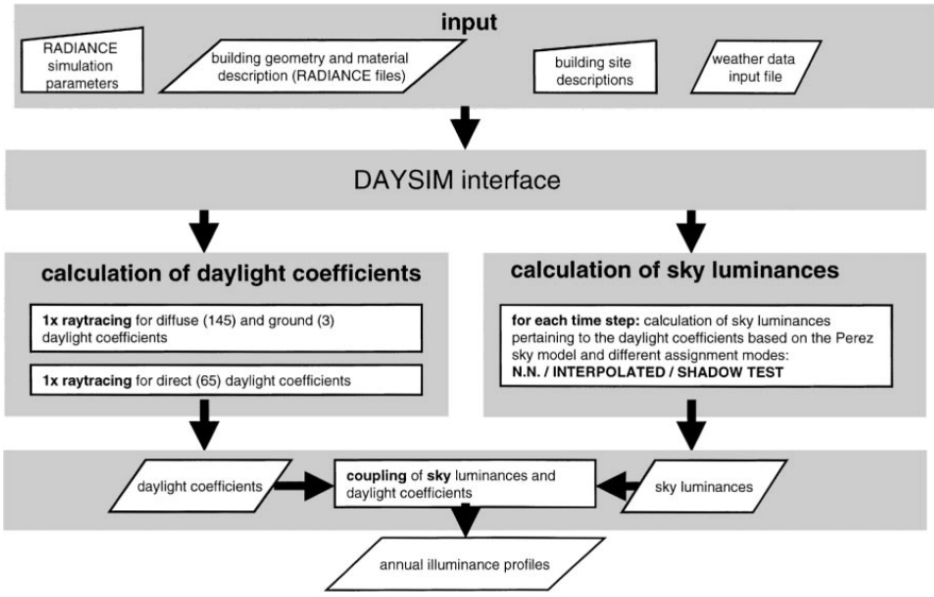


Figure 2.15 Flow chart of the Daysim method.

Figure 2.15 shows the different input parameters and simlation steps of a dynamic daylight simulation with Daysim.

Lightsolve

Developed in a first time at the M.I.T. Daylighting Lab (Andersen et al., 2008; Kleindienst et al., 2008; Lee et al., 2009; Lee & Andersen, 2009; Kleindienst, 2010) and later at EPFL to support the design team using a climate-based approach. The software performs a rather quick calculation returning annual data sets for which illuminance and glare temporal maps and spatial renderings are the graphical outputs. For user-defined illuminance thresholds, the temporal maps give an outcome with different colours, based on the portions of the results that meet, overstep or don't reach the goals set by user.

The Lightsolve algorithm is based on a time-segmetation method. The time-segmentation method starts by averaging hourly typical meteorological year data over a limited number of periods, during which sun positions and weather conditions are similar. The year is divided into 56 periods: the day is divided into 7 intervals, and the year into 8 (Figure 2.16). The seven daily intervals are spaced equally from sunrise to sunset, so that representation of the passing day does not change seasonally or by latitude (so that short days are not underrepresented and long days are not overrepresented).

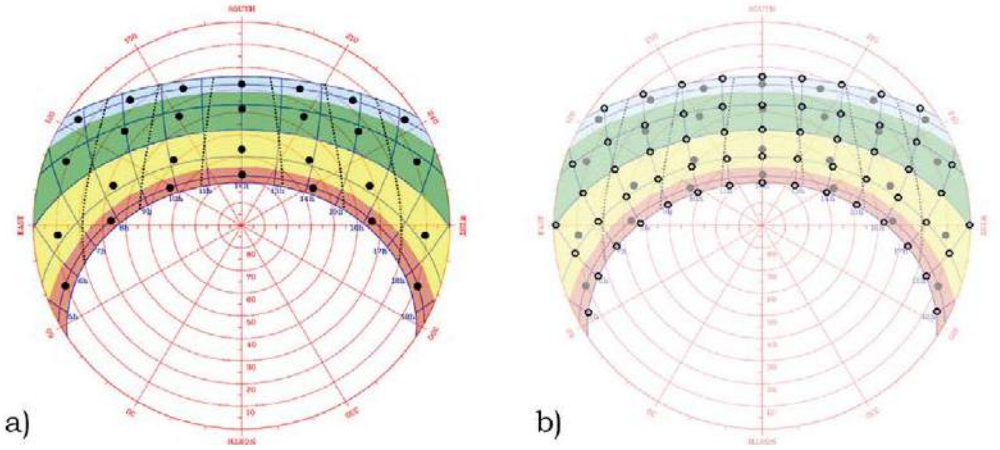


Figure 2.16 Sun course diagram: a) the 56 similar periods (28sun positions) and b) the sun positions at which Daysim performs direct sun contribution calculation. The colored bands show the division of the year, and the dotted lines show the division of the day.

Hourly Typical Meteorological year data are averaged over each period using the ASRC-CIE sky model developed by Perez (Perez et al., 1992). This model integrates simulations using the four standard CIE sky model (overcast, intermediate, clear, clear turbid) into one set of illuminance value.

It was deemed the most appropriate sky model because conducive to averaging many skies in a realistic way. The model can find an average horizontal illuminance separately for each sky types and the percent chance of the sky type occurring within that period. Using these averaged values and weights the model can create four realistic, instantaneous sky maps which still represent the entire period in question.

The governing equation is:

$$E_{vc} = b_c E_{vc,cie,c} + b_{ct} E_{vc,cie,ct} + b_i E_{vc,cie,i} + b_o E_{vc,cie,o}$$

where E_{vc} is the illuminance at a sensor point and $E_{vc,cie,c}$, $E_{vc,cie,ct}$, $E_{vc,cie,i}$, $E_{vc,cie,o}$ are the illuminance at that sensor point under a standard CIE clear sky, a standard CIE clear turbid sky, a CIE intermediate sky and a CIE overcast sky.

The weighting factors b_c, b_{ct}, b_i, b_o depend on sky clearness ε and brightness Δ. They are calculated using the horizontal diffuse irradiance, the normal incident irradiance and the solar zenith angle. They are assigned on the probability of each sky occurring.

For each of the 56 periods the average bj coefficients are calculated, together with the average diffuse horizontal illuminance. Point illuminance value are then calculated using the central sun position for the considered period, each of the four sky types and the weighted sum is calculated using the average b_c, b_{ct}, b_i, b_o coefficients.

To be ‘intuitive’, immediate, and in line with the way architects and building designers typically work, information should be displayed graphically whenever. A very promising way to represent annual variation visually was found in the ‘Spatio-Temporal Irradiation Maps’ (STIMAPs) format suggested by Mardaljevic (2004). This format allows the user to see at a glance the way that hourly and seasonal changes affect the availability of daylight within or around a particular building design and is derived from data representing the full year.

An example of such a map is shown in Figure 2.17, displaying the range of outside illuminances that can be expected on a North-facing facade in Sydney, Australia. This map was created with MATLAB using the 105,120 data points calculated by DAYSIM – one for every 5-minute interval during the year. The days of the year are plotted along the x-axis, the time of day (solar time) along the y-axis (Andersen et al., 2008).

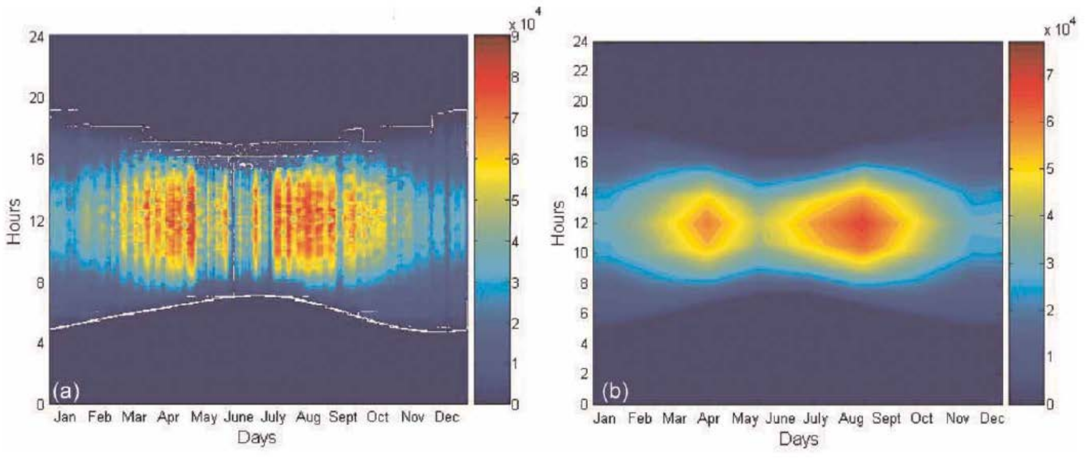


Figure 2.17 Temporal maps for a North-facing facade in Sydney displaying outside vertical illuminance in lux, based on (a) 5-minute interval illuminance data calculated with DAYSIM and (b) a reduced set of 56 data points (interpolated) using the time-segmentation method for Lightsolve.

2.5 Global energy simulation methods

Although whole building simulation programs have daylighting calculation modules, they are mainly focused on the thermal domain. In fact, a survey made on 2008 showed that at that time, even though developers of these tools viewed lighting control as worthy of support, just a few software accepted the full complexity of blinds or translucent facade elements.

The most common energy simulation tools area ESP-r and EnergyPlus.

ESP-r (ESRU, 2013) is an integrated energy modelling tool for the simulation of the thermal, visual and acoustic performance of buildings and the energy use and gaseous emissions associated with associated environmental control systems. By addressing all aspects simultaneously, ESP-r allows the designer to explore the complex relationships between a building's form, fabric, air flow, plant and control. ESP-r is based on a finite volume, conservation approach in which a problem (specified in terms of geometry, construction, operation, leakage distribution, etc.) is transformed into a set of conservation equations (for energy, mass, momentum, etc.) which are then integrated at successive time-steps in response to climate, occupant and control system influences. ESP-r comprises a central Project Manager around which are arranged support databases, a simulator, various performance assessment tools and a variety of third party applications for CAD, visualisation and report generation.

EnergyPlus (US-DOE: www.energy.gov) has its roots in both the BLAST and DOE–2 programs. BLAST (Building Loads Analysis and System Thermodynamics) and DOE–2 were both developed and released in the late 1970s and early 1980s as energy and load simulation tools (Winkelmann & Selkowitz, 1985). EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up, associated mechanical systems, EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control set points, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment.

In general, energy-performance-simulation tools are not well prepared for detailed lighting analysis. Limitations are, for example, visual comfort analysis such as the calculation of the Daylight Glare Probability that, for detailed calculations, requires rendering an image (Wienold, 2009; Molina, 2014).

2.5.1 Integrated lighting and thermal simulation methods

One possible option to couple lighting and thermal analysis is to develop a mathematical model for each case to analyze. Tzempelikos and Athienitis (2007) analyzed a perimeter office room using the Radiosity method for the illuminance level calculations and a thermal network approach for the thermal and energy performance calculations. In the study controlled roller shades were considered and modelled as perfectly diffusers.

Since creating a new model for each case can be time consuming and complex, some researchers have worked on combining two single-domain solutions programs. An example is the work proposed by Janak (1997) that did a direct run-time coupling Radiance and ESP-r, which enabled modelling the interactions between electric lighting control and the rest of the building (Molina, 2014).

Another attempt of performing coupled simulations in both domains is proposed by Wienold et al. (2011) where Daysim and ESP-r were indirectly coupled. In this methodology on annual simulation had to be made for window/position of shading combination.

Then, a control algorithm was implemented to choose the shading positions and the electric lighting power required for each time step.

Finally a schedule of electric lighting power and shading positions were passed to ESP-r, used to modify the internal gains and the BSDF description of the CFS on each time step of the simulation. In this approach ESP-r and Daysim are considered to be indirectly coupled because all the control has to be made using lighting sensors (Molina, 2014).

2.5.2 Integrated lighting and thermal simulation software

iDbuild

iDbuild is probably the most standard Thermal-Lighting coupled simulation tool (Petersen & Svendsen, 2010) which implements custom mathematical models for performing integrated analysis. This tool is focused on the early design stage. It’s programmed in Matlab and uses a graphical user interface to accept input and provide results.

It’s essentially the combination of a lighting calculation module called Light Calc (Hviid et al., 2008) and a thermal simulation module called BuildingCalc (Nielsen, 2005). The tool couples both domains by hourly feeding the daylighting calculation results into the thermal calculations.

The main limitation of this software is that it only allows rectangular rooms with one window. BuildingCalc, the thermal module, models the room as a two-node thermal network with one overall thermal transmittance and a lumped effective thermal heat capacity. On the other hand, the solar heat gains are modeled more realistically, being corrected by the incident angle and shading. It calculates hourly values of indoor temperature, heating and cooling demands by solving the thermal network’s differential equation, and allows implementing several systems as shading, heat recovery, variable ventilation, variable insulation, heating and cooling.

LightCalc, on the other hand, uses a simple ray-tracing approach and the luminous existence method (Park & Athienitis, 2003), which is similar to the radiosity method. These calculations have been validated against detailed Radiance calculations, showing that they are accurate enough to be used in early design stages (Molina, 2014).

OpenStudio

Open Studio Software Development Kit (Guglielmetti et al., 2011) is being developed as a way of providing building designers with a full-featured software framework to support rigorous and multidisciplinary building simulations.

It's, in summary, a cross-platform collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. It's an open source project to facilitate community development, extension, and private sector adoption. OpenStudio includes graphical interfaces which include the Trimble SketchUp Plug-in, RunManager, and ResultsViewer. The Trimble SketchUp Plug-in is an extension to Trimble's popular 3D modeling tool that adds EnergyPlus context to the SketchUp program. The Plug-in allows users to quickly create geometry needed for EnergyPlus using the built-in functionality of Trimble SketchUp including existing drawing tools, integration with Google Earth, Building Maker, and Photo Match. RunManager manages simulations and workflows and gives users access to the output files through a graphical interface. ResultsViewer enables browsing, plotting, and comparing EnergyPlus output data, especially time series. The Radiance capabilities of Open Studio allow implementing the Daylight Coefficient method, the Three-phase method, and calculating simplified Daylight Glare Probability.

CHAPTER 3

Daylighting analysis

3.1 Methodology

The approach that was adopted involves a parametric study to assess how the daylight availability vary as the building/room architectural characteristics vary. Therefore the annual daylighting conditions were analysed, through the dynamic lighting simulations, for several configurations of a target room.

The study was entirely performed using the validated dynamic daylight simulation software Daysim 3.1b (Reinhart & Walkenhorst, 2001; Reinhart, 2010), which is based on the backward-raytracer RADIANCE (Larson & Shakespeare, 1998). Daysim uses the daylight coefficient method (Tregenza & Waters, 1983) to efficiently calculate illuminance distributions under all sky conditions in a year and a Perez sky model (Perez et al., 1993).

A single room was used as a ‘case-study’. Its width, height and reflection properties were kept constant, while other parameters, such as room depth, window area, obstruction angle ‘seen’ by the window, orientation, target illuminance etc. were changed.

As a result, a huge database of Daysim simulations was created and used to investigate both indoor daylighting conditions and energy demand for electric lighting while changing the room’s characteristics.

The database of case-studies which were used to generate the models was built so as to account for the main aspects which influence the energy demand for lighting within a room: indoor daylight availability, space usage and characteristics of the lighting system. The daylight amount within a space and its related electric lighting energy need actually depend on different aspects, mainly concerned with:

- the external daylight availability for the design site, which depends on the site latitude and weather data.
- the architectural building features, mainly linked to the glazing area and visible transmittance, room sizes and internal surface reflectance, orientation and sky angle ‘seen’ by the windows.
- the building usage, in terms of target illuminance, user occupancy profile and behaviour towards the control of both electric lights and shading devices.

<u>3.1.1. Definition of a parametric study for daylighting simulations</u>

The lighting analysis was carried out by chancing the characteristics of the target room in terms of:

- **latitude and climate**: simulations were repeated for three sites, Berlin, Germany (latitude: 52.1°N), Turin, Italy (latitude: 45.2°N) and Catania, Italy (latitude: 37.5°N). The climate file corresponding to each site was used (US-DOE).
- **orientation**: the same room was set with the opening facing South, West and North, so as to account for the different position of the Sun in the sky during the course of the year. The East orientation was not modelled as the daylight amount and the resulting energy use for lighting were assumed to have been described well through the simulations carried out for the west orientation, as also shown in previous studies (Dubois & Flodberg, 2013).
- **room depth (RD)**: this was varied from a minimum of 3 m, so as to represent a particularly narrow periphery room, to a maximum of 12 m, so as to represent a deep open-plan office, with intervals of 1.5 m, resulting in seven different room depths.
- **window area (expressed in terms of Window-to-Wall Ratio, WWR)**: all the spaces were sidelit through vertical windows, whose area was varied to determine WWR values of 0.2, 0.3, 0.4, 0.5 and 0.6. The window height was kept constant at 1.6 m, with the sill set to a distance of 1 m from the floor. The number of WWR configurations which were actually modelled depended on the room depth: for each room depth, the WWR was kept to a minimum value so as to meet the criterion according to which the Window-to-Floor area ratio was always greater than 0.125, which is a reference value assumed in several Italian local regulations for ventilation purposes. Figure 3.1 visualizes the different combinations of WWR and RD values.
- **visible glazing transmittance (τ_{vis})**: this was set to values equal to 90%, 70%, 50% and 35%, in order to cover a broad spectrum of transparencies which are commonly used for building glazing.
- **external obstruction angle (γ)**: the target room is located within a building whose height was varied so as to be constantly the same as a facing obstruction building: this is positioned 20 meters away from the target room façade with a variable height which determines 6 obstruction angles in the range 0° (unobstructed condition) to 75° (highly obstructed urban setting), with increments of 15°.
- **average target illuminance** over the working plane: this was initially set to 500 lx, a typical value required for reading or VDT-based activities, according to European standard CEN 12464-1 (EN 12464-1, 2011), and then set to lower and higher values to also consider other types of activities: the assumed illuminances were 150 lx, 300 lx, 500 lx and 750 lx.

The room width and height were kept constant at 12 m and 3 m, respectively. All the walls and window frames had a diffuse reflectance of 50%, while the diffuse reflectance values of the floor and the ceiling were set to 30% and 70%, respectively.

In terms of **occupancy profile**, the room was considered to be continuously occupied Monday to Friday from 8:30 a.m. to 6:30 p.m., over the whole year, including daylight saving times. Different occupancy profiles can be found as references for time-based (annual) simulations: from 8 a.m. to 5 p.m. in European standard EN 15193 (EN 15193, 2008) for the calculation of the Lighting Energy Numerical Indicator, or from 8 a.m. to 6 p.m. in the IES Approved Method LM-83 on Daylight Metrics (IES, 2012). However, in this research project, rather small differences (max 5%) were observed with a shift of 30 minutes in the occupancy profile (8:30 a.m. – 6:30 p.m. with respect to 8 a.m. – 6 p.m.).

The **user behaviour** was assumed to be a 50%-50% combination of two different stochastic models, based on field study data, which are implemented in Daysim to mimic how the building occupants interact with manual controls shading systems: 'active' users who open the blinds in the morning and partly close them to avoid visual discomfort; 'passive' users who keep the blinds lowered throughout the year.

The annual daylight illuminance values, used to determine the consequent daylight metrics, were calculated over the working plane: a grid with a 0.50 m spacing was used, whose extent was set so as to cover the whole room area and to account for desks which can in principle occupy any position within the space, except a strip of depth equal to 0.50 m all along the room perimeter.

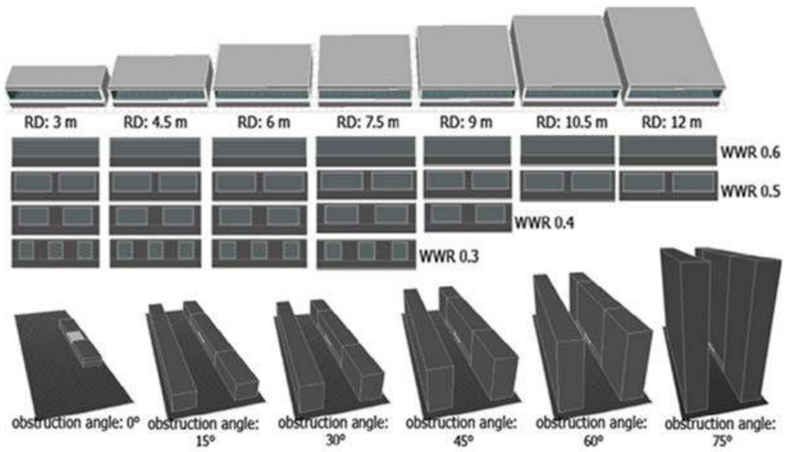


Figure 3.1 Visualization of some of the simulated case-studies. In particular the variation of room depth, Window-to-Wall ratio and the obstruction angle as 'seen' by the opening are shown.

The effect of an automated shading system, consisting of a Venetian blind with a diffuse transmittance of 25% (when in the closed position), was considered in the simulations so as to account for the need of reducing glare and overheating phenomena over the working plane. In particular, the algorithm implemented in Daysim and adopted in this study to account for the use of shading systems assumes that the blind is automatically pulled down whenever an irradiance of 50 W/m^2 hitting any point of the working plane is detected (Reinhart, 2010). The use of the blind was only simulated for South and West-facing spaces and it was excluded for the corresponding North-facing ones. This choice was done in accordance with common design strategies to control sunlight: however, a preliminary analysis, through which the movable blind was modelled for North-facing spaces as well, showed that the results of its use was very limited throughout the occupancy profile during the year, even in the case of unobstructed rooms with less depth and larger window area (for instance, the frequency of using the blind during the year in an unobstructed North-facing room with a depth of 3 m and a WWR of 0.6 was found to be 0,12%).

The Radiance simulation parameters were set as: ab = 6; ad = 1000; as = 20; ar = 300; aa = 0.05; the simulations were run using the climate files of Turin, Catania and Berlin with a time-step of 5 minutes.

Site	Orientation	RD [m]	WWR [-]	γ [°]	τ_{vis} [%]	E_{target} [lx]
Turin (45.1°N)	South	3	0.3	0	35	150
Catania (37.5°N)	North	4.5	0.4	15	50	300
Berlin (52.5°N)	West	6	0.5	30	70	500
		7.5	0.6	45	90	750
		9		60		
		10.5		75		
		12				

Table 3.1 Design variables used in the overall parametric study: the results presented in the thesis refer to a sub-dataset highlighted with a grey background.

The set of variables described above was taken from the overall parametric study carried out at Politecnico di Torino by the lighting team of the TEBE research group to investigate daylighting and the electric lighting building energy demand, and which has already been the subject of some publications (Pellegrino & Aghemo, 2009; Pellegrino & Lo Verso, 2010). In this PhD research a sub-dataset, which is shown with a grey background in Table 3.1, was used.

The annual daylight illuminance values were elaborated to derive the following daylight metrics: spatial Daylight Autonomy ($sDA_{300/50\%}$), Daylight Autonomy (DA), Continuous Daylight Autonomy (DA_{con}), Maximum Daylight Autonomy (DA_{max}), Useful Daylight Illuminance (UDI) and Annual Light Exposure (ALE).

These metrics form a rather heterogeneous group, as they were proposed by different authors, with different objectives. In principle, it seems possible to identify three main groups:

- Annual Light Exposure, ALE (CIE, 2004; Mardaljevic, 2006): this describes the daylight available within a room throughout the year as the cumulative amount of daylight incident on a point of interest over the course of a year (daylight dose).
- the Daylight Autonomies group, DA, DA_{con}, DA_{max} (Reinhart & Walkenhorst, 2001; Rogers, 2006): these use the time-varying daylight illuminance at a point as an indicator to assess daylight availability within a room throughout the year, in particular by referring the dynamic variation in illuminances to the threshold values. The threshold for DA is the illuminance required for the considered space usage according to the standards in force; this means assessing the percentage of the occupied times of the year when the illuminance requirement is met by daylight alone. A second threshold (ten times the illuminance requirement) is also

considered to account for the occurrence of direct sunlight or other potentially glary conditions (DA_{max}).

– the Useful Daylight Illuminances group, $UDI_{fell\text{-}short}$, $UDI_{achieved}$, $UDI_{exceeded}$ (Nabil & Mardaljevic, 2005; Nabil & Mardaljevic, 2006): these also consider work plane illuminance to assess daylight availability within a room throughout the year, but they refer the dynamic variation of illuminance values to both an upper and lower threshold, i.e. they express the percentage of the occupied times of the year when illuminances lie within one of the three resulting ranges: a range that includes illuminance values for which daylight can be considered substantially lacking ($UDI_{fell\text{-}short}$); a range that includes illuminance values which are considered 'useful' ($UDI_{achieved}$); a range that includes illuminance values that can result overabundant and which are therefore meant to detect the likely appearance of glare ($UDI_{exceeded}$). The three indexes together provide a synthetic view of the overall distribution of illuminances throughout the year.

Recently, two new daylight metrics have been defined and adopted by the Illuminating Engineering Society of North America (IES, 2012). Spatial Daylight Autonomy (sDA), which assesses the sufficiency of annual illuminance in an interior work environment, and Annual Sunlight Exposure (ASE), which expresses the annual glare potential. Spatial Daylight Autonomy ($sDA_{300/50\%}$) is defined as the percent of an analysed area that meets a minimum daylight illuminance level of 300 lx for 50% of the operating hours per year, while Annual Sunlight Exposure ($ASE_{1000,250h}$) is defined as the percent of an analysed area that exceeds a specified direct sunlight illuminance level of 1000 lx for more than 250 hours per year. In more detail, two target levels have been established for the $sDA_{300/50\%}$ to assess the luminous performance of a space: a space can be rated as 'neutral' when $sDA_{300/50\%}$ meets or exceeds 55% and 'favorably' daylit when $sDA_{300/50\%}$ meets or exceeds 75%. A space with $sDA_{300/50\%}$ below 55% is considered as an insufficiently daylit space.

It is important to note that the above metrics are starting to be included in lighting design guides and recommendations. For instance, the UK Education Funding Agency for the Priority Schools Building Programme (UK Education Funding Agency, 2014) uses the $UDI_{achieved}$ and the DA as daylighting design criteria for teaching spaces. The Society of Light and Lighting guideline 'Lighting Guide 5: Lighting for education' (SLL, 2011) also refers to the UDI concept.

sDA and ASE metrics are instead adopted in the rating system of the 'LEED Reference Guide for Building Design and Construction' (USGBC, 2014) as possible options to assess indoor daylighting.

3.2 Results

3.2.1 Drawbacks and potentials of daylight metrics

Sensitivity in describing daylight amount of DF compared to Annual Light Exposure

Among the group of the CBDM that were calculated in this study, the ALE is the metric which describes the overall daylight availability inside a room, resulting for this reason somewhat comparable to the DF, as they both assess the indoor daylight quantity without referring it to a threshold value. Obviously it is important to stress out how the Daylight Factor is a ‘static’ metric, expressed as the indoor to the outdoor unobstructed illuminance ratio, accounting for diffuse skylight in presence of overcast sky conditions only, while the ALE is a dynamic climate-based indicator which accounts for ‘realistic’ direct sunlight and diffuse skylight conditions.

A first analysis dealt with comparing the Daylight Factor DF and the Annual Light Exposure ALE, in order to assess the sensitivity of both metrics in describing the indoor daylight amount. In Figures 3.2 and 3.3 Daylight Factors and Annual Light Exposures are compared in order to point out their different sensitivity in considering room orientations and site climate. In particular, in Figure 3.2 the mean Daylight Factor calculated for each case-study is plotted versus the corresponding mean Annual Light Exposure for the three considered orientations (South, West and North-facing rooms). In spite of the inherent differences of the two metrics, a close fit can be observed between them if the data are correlated separately for the 3 orientations (a linear fit was found with $R^2 > 0.95$) The different gradient of the three functions confirms how the ALE metric accounts for the orientation of the room.

In Figure 3.3_a, the sensitivity of the two metrics with respect to the room orientation is further analysed: in particular, the relative difference between North-facing and South-facing rooms located in Torino is shown. In Figure 3.3_b, the relative differences of DF and ALE for a same room located in Torino or in Palermo is plotted, so as to analyze how the two metrics account for the specific climate of the site.

In both cases the relative differences (ΔDF and ΔALE) were calculated considering the working plane mean value.

The data shown in both figures confirm how the Daylight Factor is not sensitive to orientation nor to the site latitude: the mean value of the relative DF differences between South and North-facing rooms is ΔDF_m= 0.5% and ΔDF_m= 0.05% for Palermo-based and Torino-based rooms. In other words, the difference tends to zero (if it is not equal to zero, as expected from DF definition, this is due to the simulations, which are based on Radiance which in turns relies on a Monte-Carlo algorithm to generate rays: this means that repeating the same simulation may result in slightly different results).

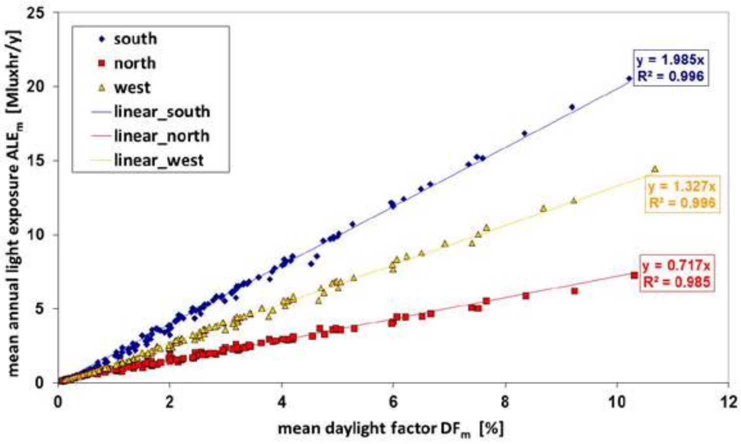


Figure 3.2 Mean Daylight Factor vs. mean annual light exposure for all case-studies relative to Turin: South, West and North-facing rooms are shown separately to highlight the fit between the 2 metrics.

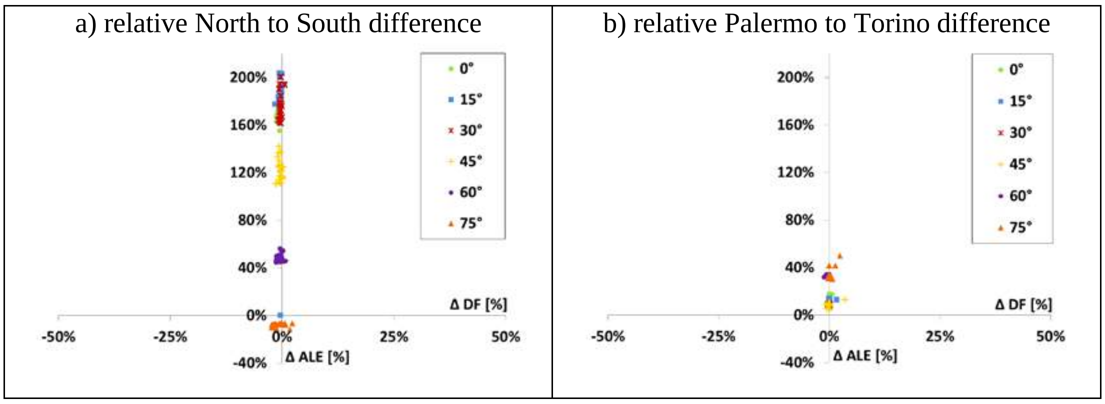


Figure 3.3 Relative difference of DF and ALE values for different room orientations and sites.

On the contrary, the ALE relative differences change in case of both different room orientation and site latitude: the mean relative difference between North oriented and South oriented configurations is ΔALE_m = 117%; the mean relative difference between Palermo-based and Torino-based rooms is ΔALE_m =19%. In particular, as far as the effect of orientation is concerned, the relative differences between North to South-facing rooms located in Torino are quite high for unobstructed configurations or in case of obstruction angles γ up to 30° (ΔALE_m = 179%). As the obstruction angle raises, though, the relative differences decrease (ΔALE_m = 85% for obstruction angles of 45° and 60°) and become negative for highest obstructions (ΔALE_m = -8% for γ = 75°). In this latter case, in Torino the sun results shaded throughout the year: as a consequence, the role played by the orientation in achieving different daylight provision is drastically reduced. Negative ΔALE values, which imply a higher daylight availability inside North-facing rather than South-facing rooms, seem to be related to the multiple reflections of direct sunlight on both the obstruction and the target building itself.

On the other hand, the highest values of relative ALE differences between Torino and Palermo are observed for highest obstruction angles of 60° and 75° (ΔALE_m = 34%), while they decrease for lower obstruction angles (ΔALE_m = 11% for γ up to 45°). This seems to be related to the different sun position, higher in Palermo than in Torino for the same time-step: the higher the obstruction and the more frequently direct sun rays are shaded in Torino while they are not in Palermo.

Sensitivity in describing daylight amount of CBDM compared to DF and Annual Light Exposure

Analyzing the database of results from the parametric study, it was observed that metrics inherently referred to threshold values (the groups of Daylight Autonomies and of Useful Daylight Illuminances) show to be more sensitive in describing the daylighting conditions obtained in a room with various architectural features (window area, room depth, orientation and obstruction angle) than the Daylight Factor or the Annual Light Exposure which account for the global daylight availability without referring to threshold values.

The aim of this analysis is to highlight the sensitivity of threshold-based Climate-Based Daylight Metrics compared to Daylight Factor and Annual Light Exposure, since they both describe the overall daylight availability within a space without referring to a threshold value.

For this type of study it was decided to analyse to variation of daylight between a medium deep room (RD = 7.5 m) and a small room (RD = 3 m). A reduction of room depth from 7.5 m to 3 m causes an average 126% and 122% increase of DF and ALE respectively. This increment results almost constant for variation of obstruction angles, window sizes and orientations. This is confirmed by the value of the relative standard deviation (calculated as standard deviation to mean value ratio) that is 10% for the Daylight Factor and 18% for the Annual Light Exposure. Figure 3.4 shows the relative difference of the two metrics for different WWR, orientation and obstruction angles.

It is interesting to stress out how results are rather different if the relative difference between the 7.5 m and 3 m rooms is assessed through threshold-based CBDM: the percentage variation of these metrics changes significantly with the room architectural features, as shown in Figure 3.5 and 3.6 and Table 3.2.

Statistic parameter	ΔDA_m	$\Delta DA_{con,m}$	$\Delta DA_{max,m}$	$\Delta UDI_{fell\text{-}short,m}$	$\Delta UDI_{achieved,m}$	$\Delta UDI_{exceeded,m}$
Mean	155.4%	74.6%	88.8%	-55.4%	54.2%	200.2%
Relative standard deviation [%]	37.6%	91.1%	91.1%	-32.5%	132.2%	137.8%

Table 3.2 Mean relative difference of CBDM (variant: room depth from 7.5m to 3m) and relative standard deviation.

In particular, analysing data shown in Figure 3.5, it can be observed how, if the room depth is reduced from 7.5 m to 3 m, the relative difference of the Daylight Autonomy ΔDA increases as the window area decreases, the obstruction angle increases and, for low obstruction angles, in presence of North-facing rooms. Highest obstruction angles, which determine the minimum daylight availability within the room, result in a decrease of the influence of the other room architectural features (window area and orientation).

The relative differences of the Continuous Daylight Autonomy ΔDA_{con} show similar trends to the ones observed for the Daylight Autonomy ΔDA.

The relative differences of the Maximum Daylight Autonomy ΔDA_{max} equal to zero in presence of high obstruction angles and for North-facing rooms: in these cases, illuminance values remain below the threshold value of 5000 lx independently of the room depth.

Similarly, as far as the group of UDI metrics is concerned, it emerges how the relative differences between room depths of 3 m and 7.5 m are influenced by room architectural features (Figure 3.6). It could be noted that for low obstruction angles, if the room depth is reduced from 7.5 m and 3 m, the relative difference of the $UDI_{exceeded}$ (ΔUDI_{2000}) increases because of a highest amount of daylight above 2000 lx available in the space. This is valid for all orientations which have been considered. On the contrary the relative differences of the $UDI_{fell\text{-}short}$ (ΔUDI_{100}) and $UDI_{achieved}$ ($\Delta UDI_{100\text{-}2000}$) decrease.

Increasing the obstruction angle (for instance γ=75°) results in an increase of the relative differences of the $UDI_{achieved}$ ($\Delta UDI_{100\text{-}2000}$) and in a decrease of the relative differences of the $UDI_{exceeded}$ (ΔUDI_{2000}), in particular for North-facing rooms.

As already shown for DAs values, highest obstruction angles, which determine the minimum daylight availability within the room, result in a decrease of the influence of the other room architectural features (window area and orientation) on UDIs trends.

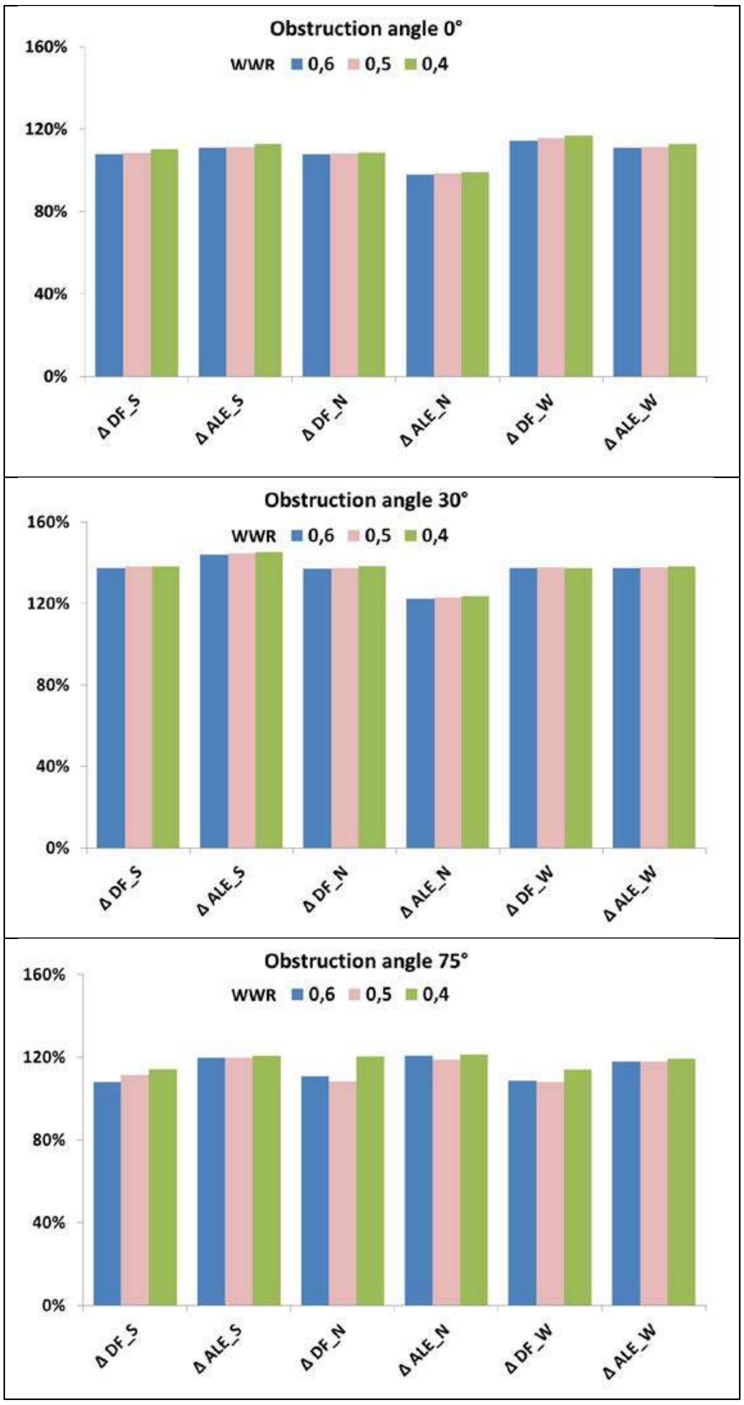


Figure 3.4 Relative increment of DF and ALE, for different window areas (WWR values), orientation and obstruction angles (γ), when the room depth is reduced from 7.5 m to 3 m. Case-studies with more meaningful WWR and γ values are shown.

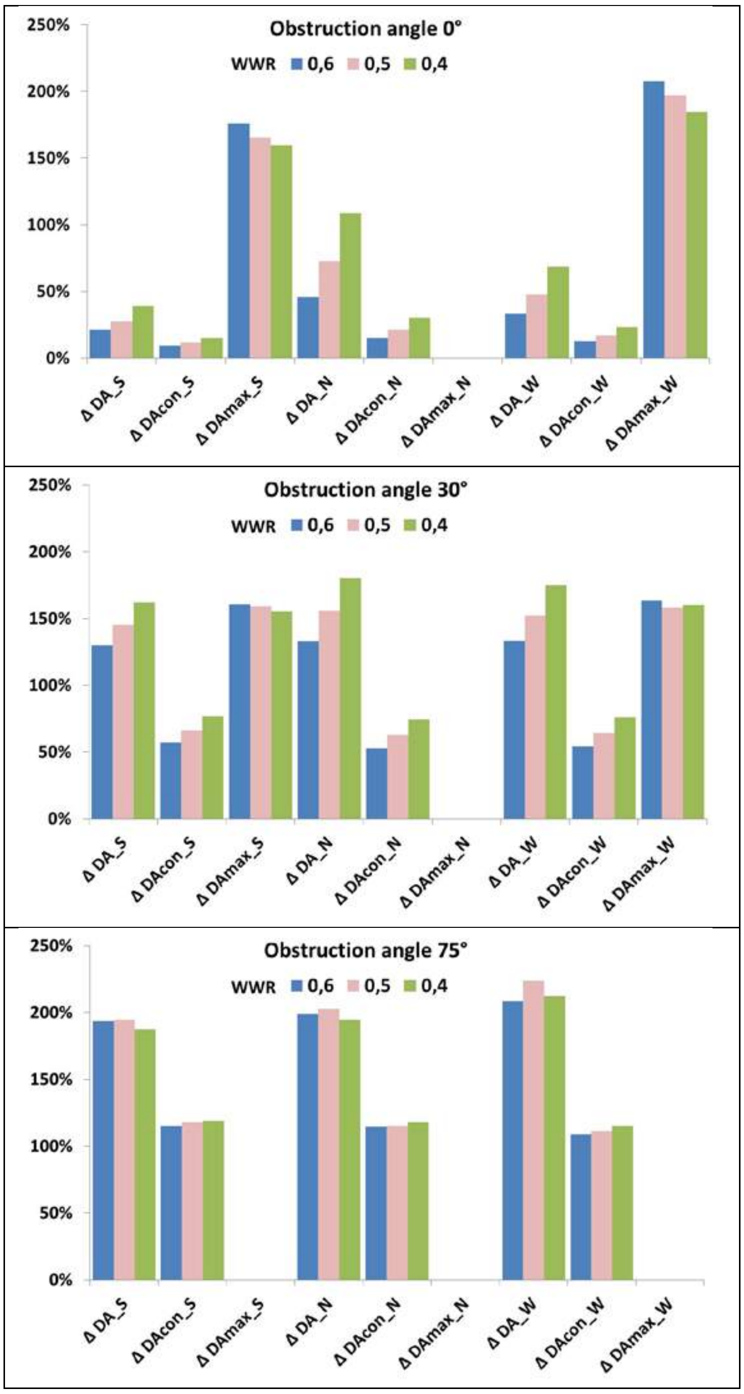


Figure 3.5 Relative differences of DAs metrics, for various window areas (WWR values), orientation and obstruction angles (γ), when the room depth is reduced from 7.5 m to 3 m. Case-studies with more meaningful WWR and γ values are shown.

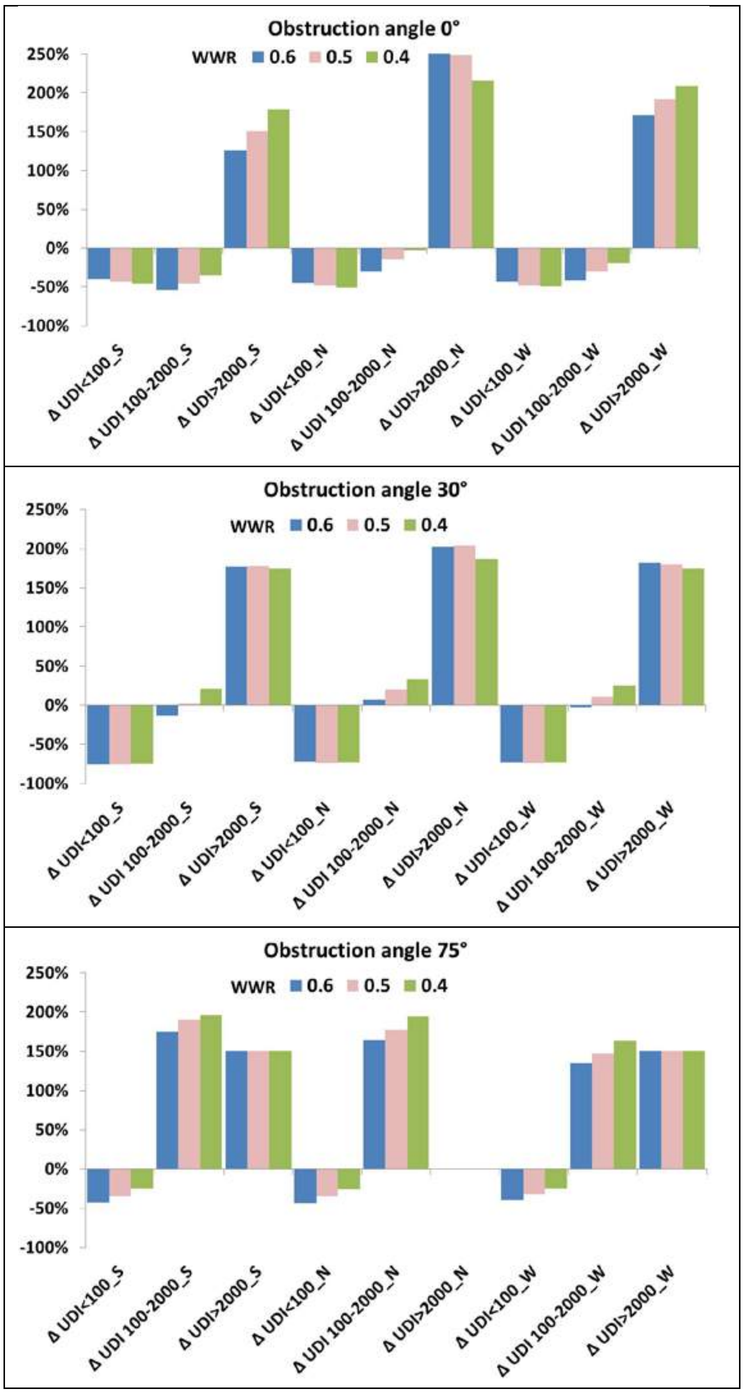


Figure 3.6 Relative differences of UDIs metrics, for various window areas (WWR values), orientation and obstruction angles (γ), when the room depth is reduced from 7.5 m to 3 m. Case-studies with more meaningful WWR and γ values are shown.

3.2.2 Synthetic information for the earliest daylighting design phases

Variation of daylight availability as expressed by CBDM

A synthesis of the results obtained in the first phase of the study (with reference to the sub-dataset of configurations indicated in Table 3.1) is presented in this section.

The results are described in different sub-sections, in which the effect of each variable (orientation, Room Depth, Window-to-Wall Ratio and external obstruction angle) on the amount of daylight within the considered rooms is analyzed.

The results shown in the following graphs are expressed in terms of Annual Light Exposure (ALE), Daylight Autonomy (DA), Maximum Daylight Autonomy (DA_{max}) and $UDI_{achieved}$. The 'useful' range of illuminances for the calculation of the $UDI_{achieved}$ was considered between 100 and 2000 lx ($UDI_{100\text{-}2000}$), consistently with what was proposed by Nabil and Mardaljevic (2005) and Nabil and Mardaljevic (2006). However, it should be observed that these authors later increased the upper illuminance threshold from 2000 lx to 3000 lx (Mardaljevic et al., 2011).

The obtained results required a great deal of effort, in terms of data synthesis and representation. The effect of the variation of each variable on daylight availability is highlighted in the graphs below. The maximum, minimum and mean values obtained from the whole set of considered configurations are shown in the graph. The percent variation of the considered metrics, obtained by changing the architectural features of the room, are also shown. $\Delta DA_{3\rightarrow 4.5}$ therefore represents the relative percent variation of DA results when the room depth is increased from 3 m to 4.5 m.

Effect of orientation

The effect of orientation on the daylight amount in the different room configurations is shown in this section. The presented results refer to unobstructed spaces (γ= 0°), considering all RD and WWR.

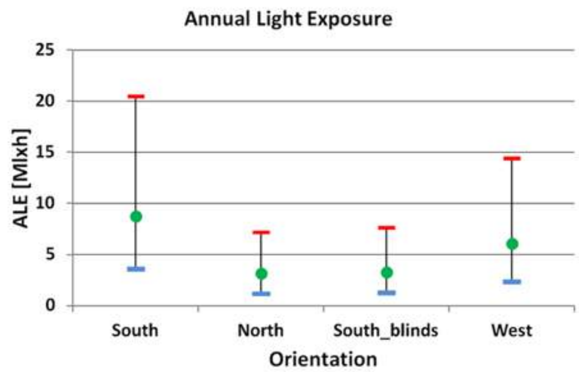


Figure 3.7 ALE ranges (maximum, minimum and mean values) as a function of orientation.

As illustrated in Figure 3.7, the overall daylight amount, which does not refer to a target illuminance and is therefore expressed in terms of annual light dose (ALE), is higher for South-facing rooms without blinds (ALE_m= 8.7 Mlxh) than for West-facing (ALE_m= 6.1 Mlxh), North-facing rooms (ALE_m= 3.2 Mlxh) and South-facing rooms with blinds (ALE_m= 3.2 Mlxh); the ALE values are similar for South-facing rooms with blinds and North-facing rooms, in mean value and range of variation terms.

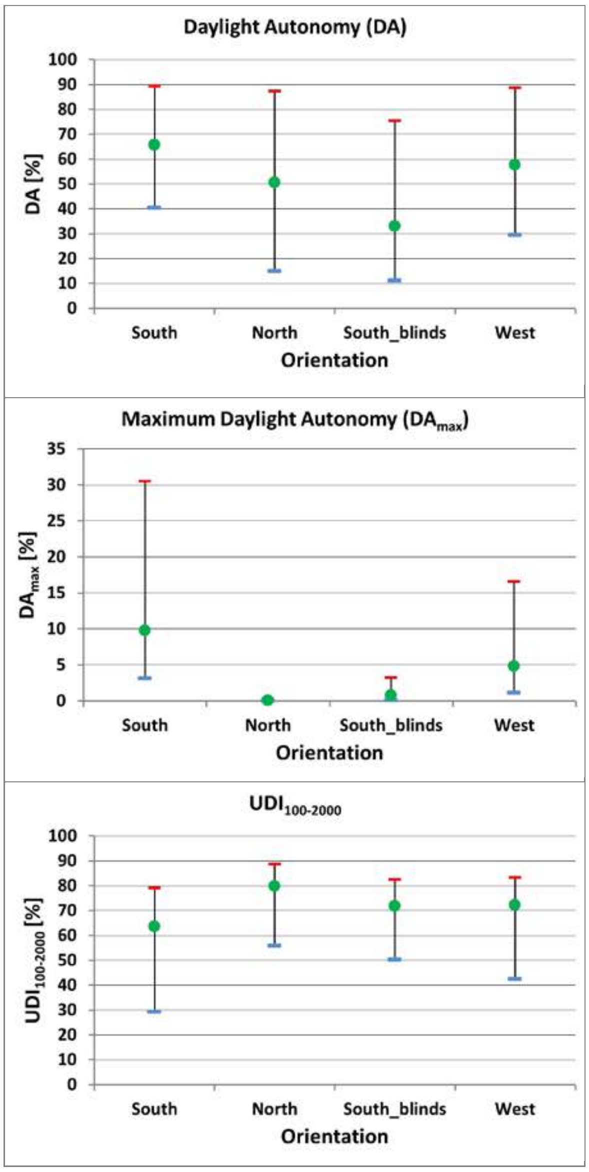


Figure 3.8 DA, DA_{max} and $UDI_{100\text{-}2000}$ ranges (maximum, minimum and mean values) as a function of orientation.

If daylight availability within a space is evaluated in terms of Daylight Autonomy, considering a target illuminance of 500 lx, the results are slightly different (Figure 3.8). South-facing rooms without blinds, on average, still have higher values (DA_m= 65.7%) than West-facing (DA_m= 57.7%) and North-facing rooms (DA_m= 50.6%). It has also been observed that South-facing spaces with blinds have lower Daylight Autonomy values than their corresponding

North-facing spaces: the DA_m value for the former spaces drops to 33% and, in general, individual DA results are always lower than 80%, while they rise to over 80% for some North-facing space configurations.

For potential glare conditions (expressed through the DA_{max} metric), North-facing and South-facing rooms with blinds show a very low risk of glare as their DA_{max} values tend to 0 ($DA_{max,m}$= 0.03% and 0.8%, respectively), while West-facing rooms ($DA_{max,m}$= 4.8%), and especially South-facing rooms without blinds, show a higher potentiality for glare conditions ($DA_{max,m}$= 9.8%). In the latter two cases, the range is very wide, with maximum values of 16.5% and 30.5%, respectively.

According to the $UDI_{100-2000}$ results, North and South-facing rooms with blinds show a good daylight performance, since the percentage of the occupied times of the year when illuminances lie between 100 and 2000 lx is high ($UDI_{100-2000,m}$= 80% and 72%, respectively). Slightly lower values are obtained for East-facing and South-facing rooms without blind.

Effect of Room Depth (RD)

The effect of room depth on the daylight amount in the different room settings is shown in this section. The results refer to North and South-facing rooms (the latter with blinds).

As shown in Figure 3.9, a progressive increase in room depth results in a decrease in DA; this DA reduction appears to be greater for small and medium RD (RD ≤ 6 m) than for RD over 6 m: the average percent difference of DA (ΔDA_m) when the room depth is increased from 3 m to 4.5 m and from 4.5 m to 6 m is ΔDA_m= -30%, while the average ΔDA percent difference for RD > 6 m is lower (ΔDA_m= -18%).

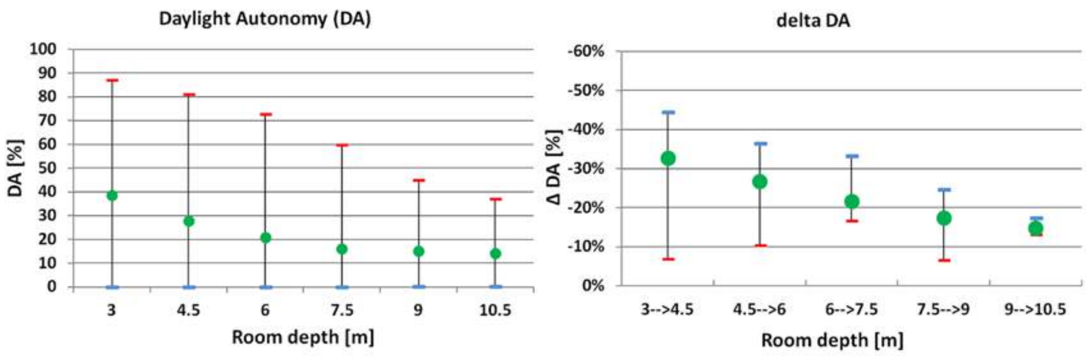


Figure 3.9 DA (maximum, minimum and mean values) and ΔDA ranges as a function of RD.

If the amount of daylight in a space is analysed through the $UDI_{100-2000}$ metric, it can be observed that the progressive increase in room depth has a less effect on the $UDI_{100-2000}$ variation, since the average percent difference ($\Delta UDI_{100-2000}$) is always in the -10% ÷ -20% range (Figure 3.10). It should be noted that the range of the $UDI_{100-2000}$ results is very wide for each room depth.

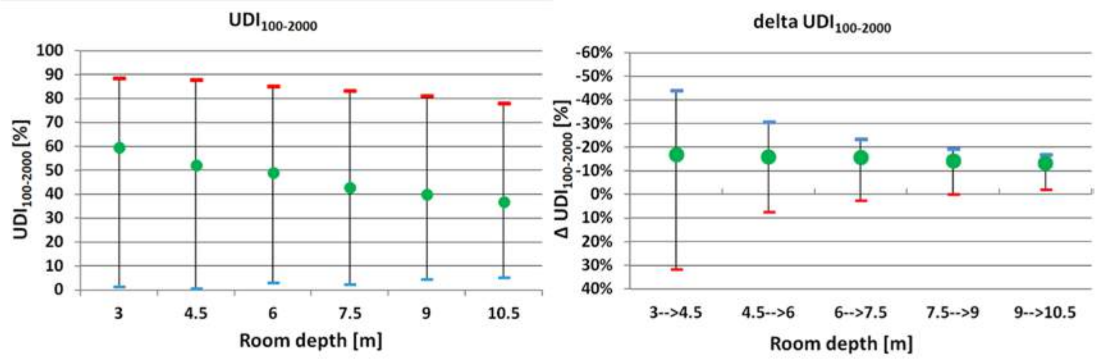


Figure 3.10 $UDI_{100-2000}$ (maximum, minimum and mean values) and Δ $UDI_{100-2000}$ ranges as a function of RD.

Effect of Window-to-Wall Ratio (WWR)

The effect of Window-to-Wall Ratio on the daylight amount in the different room configurations is shown in this section. As in the previous section, the results refer to North and South-facing rooms with blinds (Figures 3.11 and 3.12).

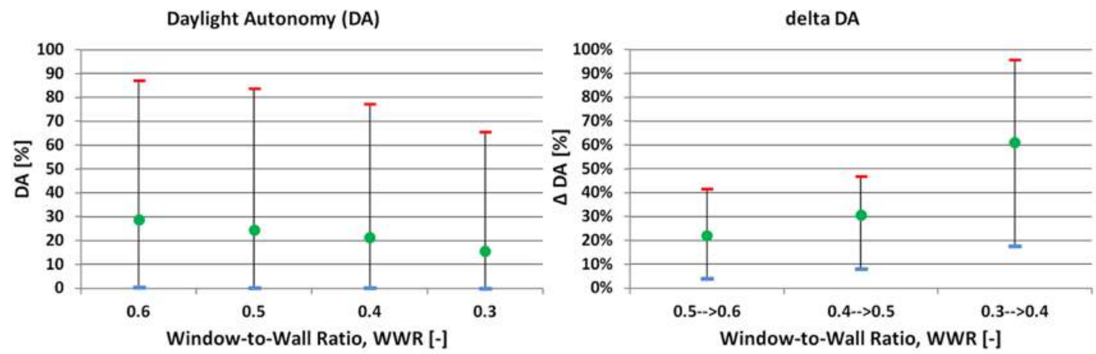


Figure 3.11 DA (maximum, minimum and mean values) and ΔDA ranges as a function of WWR.

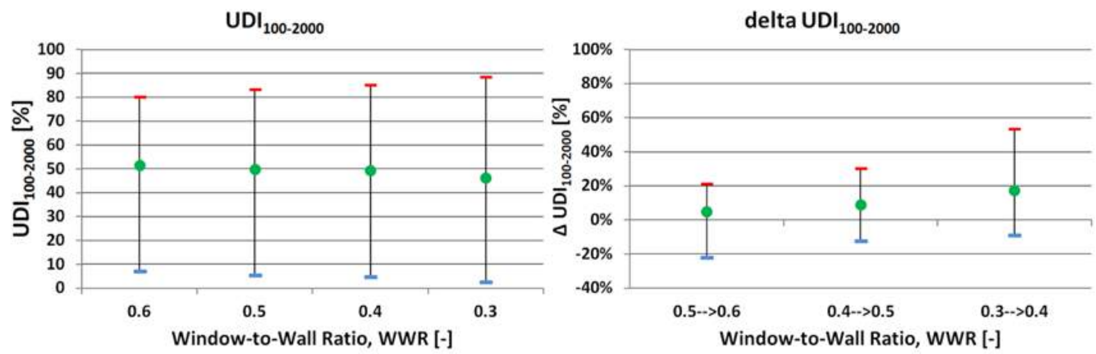


Figure 3.12 $UDI_{100-2000}$ (maximum, minimum and mean values) and Δ $UDI_{100-2000}$ ranges as a function of WWR.

A slight increase in the average value can be seen in the graphs when the WWR is increased, even though a wide range of values is obtained for each WWR. The DA percent variation is higher when WWR is increased from 0.3 to 0.4 (ΔDA_m = 61%) than from WWR=0.4 to 0.5 (ΔDA_m = 30%) or from WWR=0.5 to 0.6 (ΔDA_m = 21%).

The corresponding average increments in UDI values for the same WWR increments are lower: $\Delta UDI_{100\text{-}2000,m}$ = 19% for a WWR increment from 0.3 to 0.4, $\Delta UDI_{100\text{-}2000,m}$ = 9% for a WWR increment from 0.4 to 0.5 and $\Delta UDI_{100\text{-}2000,m}$ = 5% from a WWR increment from 0.5 to 0.6.

In conclusion, it appears that an increase in WWR from 0.3 to 0.4 produces the highest percent variation in the interior daylight amount.

Based on the same database a different approach was used to evaluate how varying the window area can influence the daylight availability within a space as a function of room depth: in particular the impact of increasing the window area in little deep rooms compared to medium deep rooms was analysed. A summary of the most meaningful results is shown in Table 3.3. For this type of analysis the group of UDI metrics was used, so as to take advantage of the fact that three sub-ranges of $UDI_{fell\text{-}short}$ (UDI_{100}), $UDI_{achieved}$ ($UDI_{100\text{-}2000}$) and $UDI_{exceeded}$ (UDI_{2000}) cover continuously the overall range of illuminance values. The Annual Light Exposure is also shown to represent the variation of the annual global daylight availability.

Variant	Room depth [m]	Mean relative difference of UDI and ALE [%]			
		ΔALE	ΔUDI_{100}	$\Delta UDI_{100\text{-}2000}$	ΔUDI_{2000}
WWR: 0.2 → 0.4	small depth	191	-47	196	251
WWR: 0.4 → 0.6	small depth	56	-28	2	72
	medium depth	57	-23	19	76

Table 3.3 Relative differences in UDI and ALE metrics for the variation of the window area for different room depths.

As far as the role played by the window area is concerned, the most meaningful results can be summarised as follows:

- For little deep rooms (relative difference averaged over 3 m and 4.5 m), increasing the window area from WWR = 0.2 to WWR = 0.4 seems an effective solution as the $UDI_{100\text{-}2000}$ increases considerably, the UDI_{100} decreases accordingly and even though the $UDI_{exceeded}$ shows a considerable increase, it remains quite low in terms of absolute values.
- For little deep rooms, increasing the window area from WWR = 0.4 to WWR = 0.6 does not result as effective as one might expect: actually, a reduction of UDI_{100} occurs but on the other hand $UDI_{100\text{-}2000}$ remains almost unchanged and UDI_{2000} increase considerably.

  As a result, notwithstanding the absolute daylight availability increase (ΔALE = 56%) a real improvement of the daylight condition is not achieved.
- For medium deep rooms (relative difference averaged over 6 m, 7.5 m and 9m), increasing the window area from WWR = 0.4 to WWR = 0.6 assures a little increase of $UDI_{100\text{-}2000}$, whilst on the other hand UDI_{2000} raise up more considerably.

Effect of external obstructions

Since buildings are normally placed in urban settings, it is important to point out the effect of external obstructions (γ) on daylight availability.

As shown in Figures 3.13 and 3.14, an increase in the obstruction angle results in a decrease in the DA and $UDI_{100\text{-}2000}$ values. All the simulated spaces show lower DA values than 50% (maximum DA of 38%) for highly obstructed urban settings (obstruction angles over 45°). A progressive increment in the height of the obstructing building results in an increase in the average DA percent difference (ΔDA_m), which is lower for an obstruction angle of 0° to 15° and of 15° to 30° than for increments over 30°.

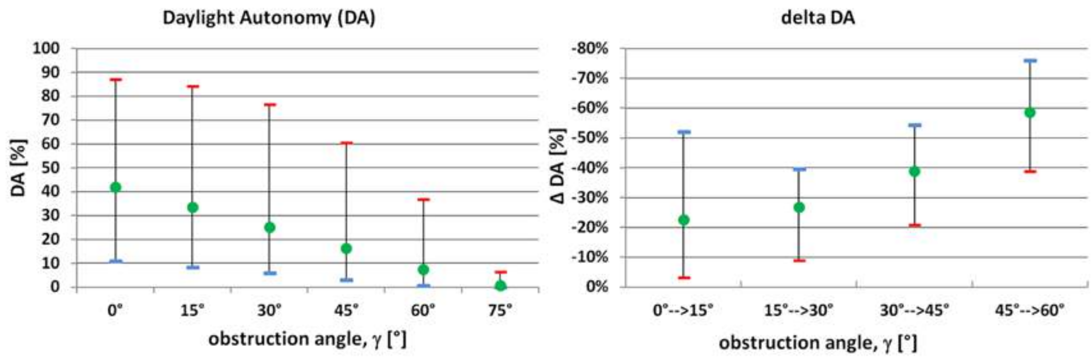


Figure 3.13 DA (maximum, minimum and mean values) and Δ DA ranges as a function of γ.

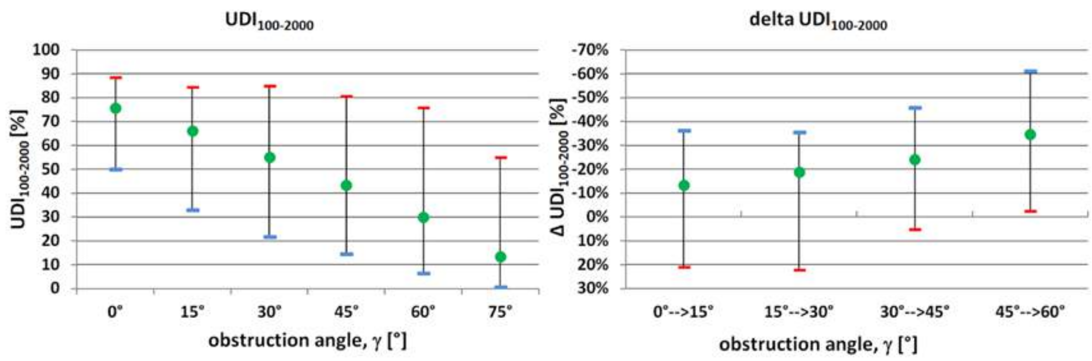


Figure 3.14 $UDI_{100\text{-}2000}$ (maximum, minimum and mean values) and Δ $UDI_{100\text{-}2000}$ ranges as a function of γ.

These results suggest that higher external obstructions than 30° could seriously affect the performance of room daylighting.

This is also confirmed by the $UDI_{100\text{-}2000}$ results (Figure 3.14): the average $UDI_{100\text{-}2000}$ for external obstruction angles of up to 30° is always lower than 50%; a progressive increment in the obstruction angle results in an increase in the average $UDI_{100\text{-}2000}$ percent difference, as was also previously shown for the DA metric.

Based on the same database a different approach was used to evaluate how varying the obstruction angle can influence the daylight availability within a space as a function of the room depth: in particular the impact of low and high-raise obstructions have in rooms of small, medium or high depth was analysed.

A summary of the most meaningful results is shown in Table 3.4. For this type of analysis the group of UDI metrics was used, so as to take advantage of the fact that three sub-ranges of $UDI_{fell\text{-}short}$ (UDI_{100}), $UDI_{achieved}$ ($UDI_{100\text{-}2000}$) and $UDI_{exceeded}$ (UDI_{2000}) cover continuously the overall range of illuminance values. The Annual Light Exposure is also shown to represent the variation of the annual global daylight availability.

Variant	Room depth [m]	Mean relative difference of UDI and ALE [%]			
		ΔALE	$\Delta UDI_{fell\text{-}short}$	$\Delta UDI_{achieved}$	$\Delta UDI_{exceeded}$
γ: 0° → 30°	small depth	-32	95	43	-46
	medium depth	-38	234	-14	-47
	high depth	-39	252	-41	-46
γ: 0° → 60°	small depth	-85	546	47	-93
	medium depth	-86	619	-48	-93
	high depth	-86	439	-67	-92

Table 3.4 Relative differences in UDI and ALE metrics for the variation of the obstruction angle for different room depths.

As far as the role played by the obstructions is concerned, the most meaningful results can be summarised as follows:

- For little deep rooms, increasing the obstruction angle from γ = 0° to γ = 30° results in an increase of $UDI_{100\text{-}2000}$ to which correspond a decrease of UDI_{2000} values.
- For medium and very deep rooms (relative difference averaged over 6 m - 12 m), increasing the obstruction angle from γ = 0° to γ = 30° produces, despite a ΔALE similar to the previous case, a higher increase of UDI_{100} to which correspond a decrease of $UDI_{100\text{-}2000}$.
- Increasing the obstruction angle from γ = 0° to γ = 60° results in an increase of UDI_{100} for all room depths, to which correspond a decrease of $UDI_{100\text{-}2000}$ values in the case of medium and very deep rooms. For little deep rooms, on the contrary, the $UDI_{100\text{-}2000}$ is increased to the detriment of UDI_{100}.

3.2.3 A graphical tool to express the daylighting performance

The large number of case-studies that were simulated resulted in a huge database of daylight metrics values, which describes variations in daylighting conditions within the considered rooms as a function of variations in the architectural features.

A simple graphical tool, which is able to summarize the amount of information on the daylighting condition in spaces with different characteristics and to allow readers to quickly read and comprehend the data, has been developed.

Figure 3.15 shows the rationale on which the graphical tool was developed; it considers all the variables involved in the study: room depth (along the x-axis), obstruction angle (along the y-axis) and WWR, Window-to-Wall Ratio, from 0.6 to 0.3 (represented by a number of partially overlapping circles for each room depth and obstruction angle). The diameter of the circles is proportional to absolute value of the metrics and the colour corresponds to the interval in which the metric value lies. The possible scale of values of each metric (0-100%) was subdivided into five ranges (<20%; 20-40%; 40-60%; 60-80%; >80%).

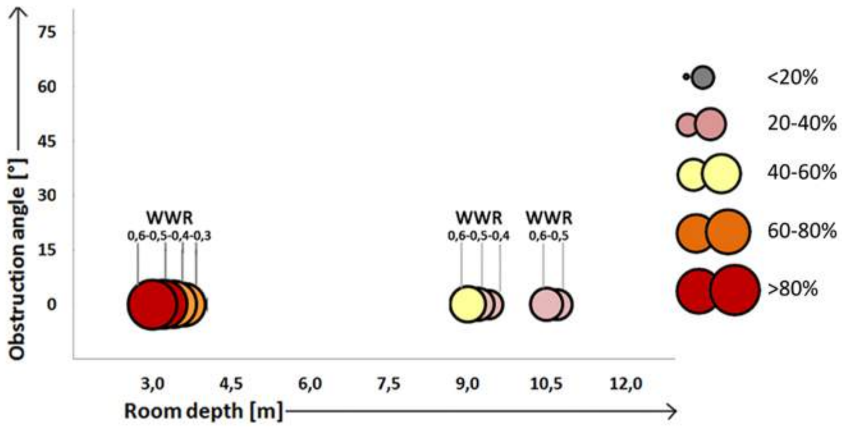


Figure 3.15 Schematic representation of the format of the graphical tool.

This type of tool can be used by practitioners to quickly verify the influence of preliminary design solutions on daylight availability within simple environments. For a given room depth, obstruction angle and Window-to-Wall Ratio combination, designers can identify the daylighting condition on the graph as expressed by each metric and they can assess the influence of the variations in the architectural characteristics of the room on the daylight condition.

Figure 3.16 and 3.17 shows the graphical tool that was created to visualize the results presented in the previous sections, i.e. for North and South-facing rooms with blinds located in Turin, with a visible glazing transmittance set to 70%, and considering a target illuminance value of 500 lx.

The data reported in the graphs correspond to the mean values calculated over the working plane. The considered metrics are $sDA_{300/50\%}$, DA, DA_{con}, $UDI_{achieved}$ ($UDI_{100-2000}$) and $UDI_{exceeded}$ (UDI_{2000}).

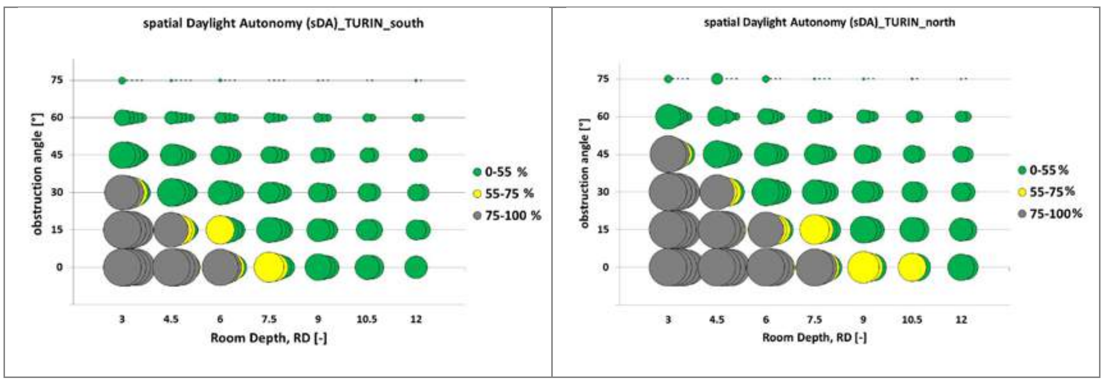


Figure 3.16 $sDA_{300/50\%}$ results for case-studies relative to North and South-facing rooms located in Turin with a glazing visible transmittance of 70%

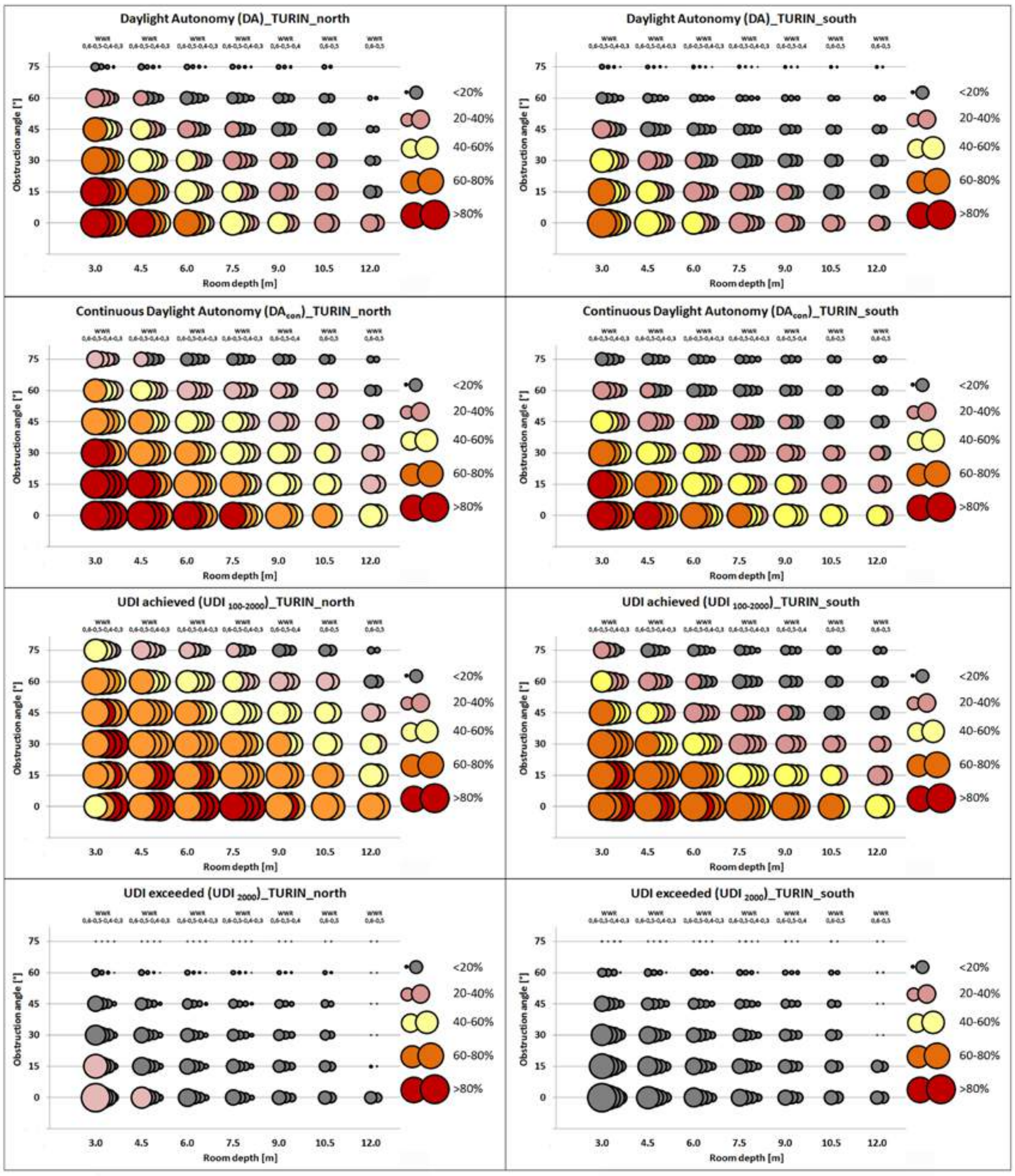


Figure 3.17 CBDM results for case-studies relative to North and South-facing rooms located in Turin with a glazing visible transmittance of 70%.

Examples of possible uses of the graphical tool

The proposed graphical tool can be used by practitioners in two different ways.

In the first approach, the design team can verify the corresponding daylighting performance for a specific space under examination. As an example (Figure 3.17), for a North-facing room with a depth of 4.5 m and an obstruction angle of 15°, it is possible to verify how the daylighting condition changes as a function of the designed window area. With reference to the DA metric, a WWR of 0.6 or of 0.5 results in a DA in the 60%-80% range, while reducing the window area to a WWR of 0.4 or 0.3 results in a decrease in DA (in the 40-60% or 20-40% ranges, respectively).

Instead, referring to the $UDI_{achieved}$ metric, a WWR of 0.6 determines a $UDI_{achieved}$ in the 60%-80% range while, for lower window areas (WWR 0.5, 0.4 and 0.3), $UDI_{achieved}$ results of over 80% are determined with an increasing trend. On the other hand, the $UDI_{exceeded}$ metric progressively decreases as the room depth and the obstruction angle increase and the WWR decreases. The design team can hence establish that modifying the window area does not result in a significant change in the daylighting performance of the room, if expressed in $UDI_{achieved}$ terms, but plays a crucial role on the potential energy saving pertaining to the percentage of time of electric light use in the presence of a manual lighting control system, as can be seen from the variation in the DA values.

With the second approach, the design team can use the tool to identify the different classes of daylighting performance that can be achieved for different combinations of architectural room features. As an example, three performance classes were assumed for this part of the study:

- 'low' daylight amount: $DA \leq 40\%$
- 'acceptable' daylight amount: $40\% < DA < 60\%$
- 'high' daylight amount: $DA \geq 60\%$.

By defining performance class ranges, practitioners can quickly verify which combinations of architectural features are able to provide high, acceptable or low daylight amounts within a room.

Figure 3.18 shows the examined architectural features that fall within the three performance classes, considering North-facing rooms.

The 'low' daylight amount mainly occurs for rooms with the following architectural features:

- profound depths ($RD \geq 9$ m);
- high obstruction angle ($\gamma \geq 60°$);
- medium deep rooms (6 m - 7.5 m), low obstruction angles (γ between 0° and 15°) and small Window-to-Wall Ratios (WWR < 0.4);
- medium deep rooms (6 m - 7.5 m) and medium obstruction angles (γ between 30° and 45°);
- room depth of 4.5 m, obstruction angle $\gamma = 45°$ and WWR < 0.5.

The 'high' daylight amount mainly occurs for rooms with the following architectural features:

- limited depths ($RD \leq 4.5$ m) and small obstruction angles (γ between 0° and 15°);
- room depth of 3 m, medium obstruction angle (γ between 30° and 45°) and high Window-to-Wall Ratios (WWR > 0.4);

– room depth of 6 m, obstruction angle γ = 0° and high Window-to-Wall Ratio (WWR > 0.5).

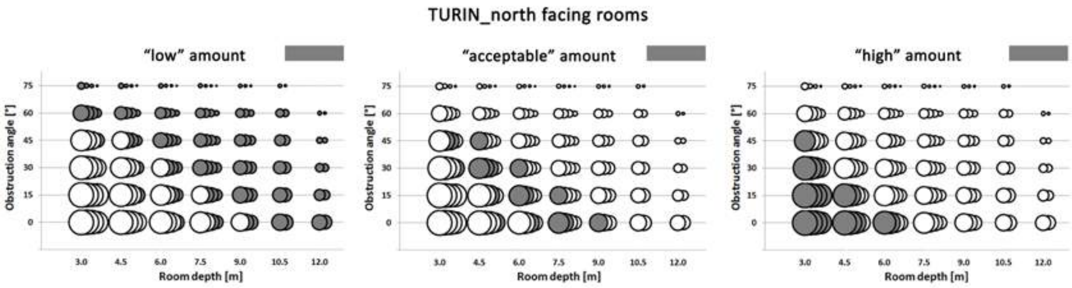


Figure 3.18 Visualization of combination of architectural features falling into the defined daylight performance classes (North-facing spaces locates in Turin).

Figure 3.19 shows the architectural features which fall within the three performance classes for South-facing rooms with movable blinds.

The 'low' amount mainly occurs for rooms with the following architectural features:

– medium and profound depths (RD ≥ 6 m);
– limited depths (RD = 3 m and 4.5 m) and obstruction angle γ ≥ 30° (with the exception of very small rooms with high WWR and γ ≥ 30°);
– limited depths (RD ≤ 4.5 m), small obstruction angles (γ between 0° and 15°) and small WWRs.

The 'high' amount mainly occurs for rooms with the following architectural features:

– limited depth (RD = 3 m), obstruction angles γ between 0° and 15° and WWR > 0.5.

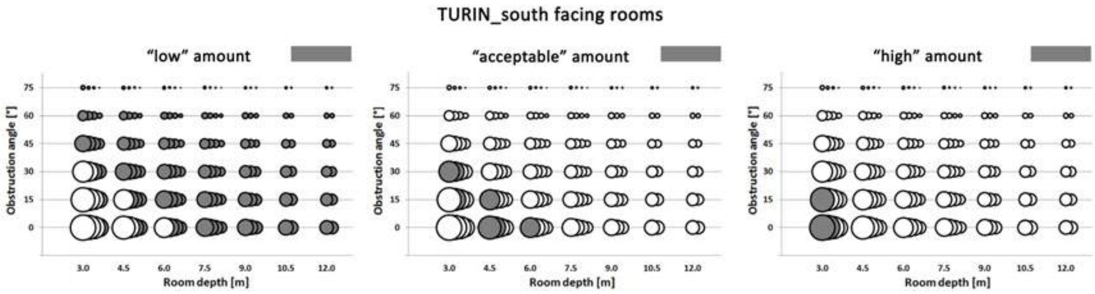


Figure 3.19 Visualization of combination of architectural features falling into the defined daylight performance classes (South-facing spaces with blinds located in Turin).

Comparison with other prediction tools

So as to evaluate potentials and drawbacks concerned with the proposed graphical tool, as well as its applicability and utility for the design team, a comparison with other prediction tools currently available for daylighting analyses during the earliest design stage was carried out.

In general terms it can be observed that current daylighting design practice still favours prior experiences and rules of thumb and largely relies on the average Daylight Factor approach, which is limited to the verification of the amount of diffuse skylight under an overcast sky condition. In particular the equations to calculate the Daylight Factor provided by the European Standard EN 15193 (EN 15193, 2008) to define the 'room daylight penetration class' is considered.

On the other hand, the need for a more detailed information on room daylighting even in the earliest design stage has led to the development of new simulation tools, such as Lightsolve, developed at the M.I.T. Daylighting Lab (Andersen et al., 2008; Kleindienst et al., 2008; Kleindienst, 2010) to support the design team using a climate-based approach. The software performs a rather quick calculation returning annual data sets for which illuminance and glare temporal maps and spatial renderings are the graphical outputs. For user-defined illuminance thresholds, the temporal maps give an outcome with different colours, based on the portions of the results that meet, overstep or don't reach the goals set by user (Figure 3.20).

In this paragraph, the information that might be drawn from the graphical tool presented in this thesis was compared to the information given by the above mentioned Daylight Factor formula and by the illuminance temporal maps provided by the simulation tool Lightsolve.

In particular, as an example, two case-studies, corresponding to rooms with quite different daylighting conditions, were analyzed: a room with a high daylight availability (RD = 3 m and $\gamma = 0°$) and a room with higher depth and partly obstructed (RD = 7.5 m and $\gamma = 15°$). For both cases the variation of the window area (WWR values of 0.3 and 0.6) was also considered.

The results found through the different prediction tools are summarized in Figure 3.21. Carrying out a direct comparison of the results which are obtained through the various examined approaches may result hard at a first glance, as each approach provides with a different kind of information. For example, the analytical equations allow quantifying the average Daylight Factor, i.e. the amount of diffuse skylight within the considered space. To better assess if the obtained value can be considered a poor or an valuable result, the Daylight Factor value is integrated with the daylight penetration class ('none, 'weak', 'medium', 'strong') according to the EN 15193.

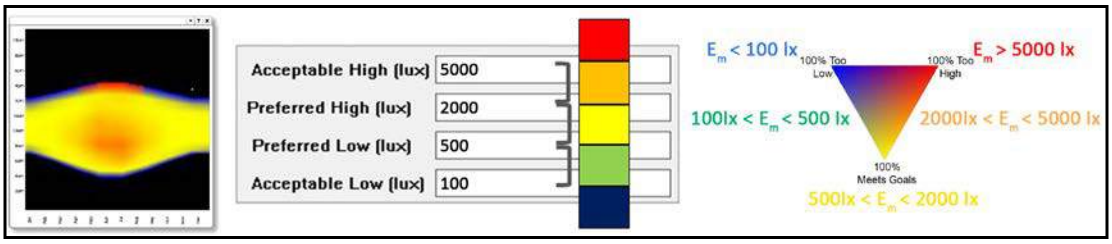


Figure 3.20 User-defined illuminance thresholds as input for Lightsolve simulations.

Differently, the graphical tool presented in this thesis gives percentages of Daylight Autonomies or Useful Daylight Illuminance, while Lightsolve provides the design team with temporal maps with the variation of average illuminance values during the year. The results are not therefore directly expressed with the same metrics. In order to favour the comparison to the graphical tool outcomes (DAs and UDIs), the following user-defined illuminance thresholds were input to run Lightsolve simulations: 100 lx, 500 lx, 2000 lx and 5000 lx (see Figure 3.20).

This way, the colors displayed by the program in the output image represent the $UDI_{fell\text{-}short}$ value (blue area), the $UDI_{achieved}$ value (green + yellow area), the $UDI_{exceeded}$ value (orange + red area), the DA value (yellow + orange + red area) and the DA_{max} value (red area).

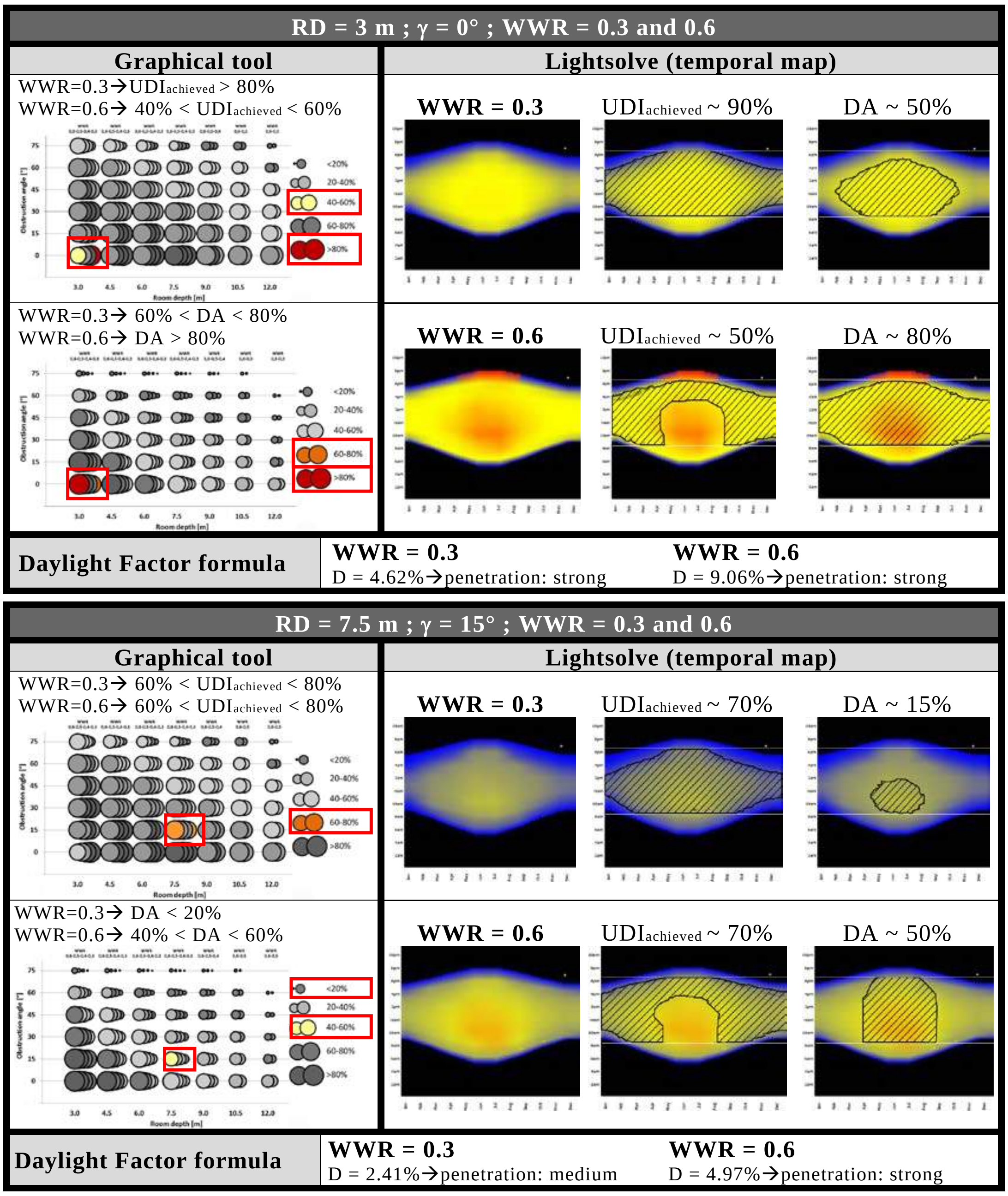


Figure 3.21 Results obtained through the graphical tool proposed in this thesis, the average Daylight Factor formula and Lightsolve.

At this point, a comparison can be carried out: for this purpose, as shown in Figure 3.21, the coloured area roughly corresponding to $UDI_{achieved}$ and DA are highlighted through a dashed hatch on the temporal map between 8.30 a.m. and 6.30 p.m. (i.e. the occupancy profile during the year), so as to assess the percentage of the temporal map area corresponding to CBDM values. This simplified qualitative comparison shows how the results obtained through the different approaches are generally in good agreement, and in particular this is true for the two tools based on CBDM (the graphical tool and Lightsolve): for example, for the case-study of the 3 m deep unobstructed room with a WWR of 0.3, the $UDI_{achieved}$ region in the illuminance temporal map generated by Lightsolve covers almost entirely the map itself (about 90%), which is consistent with the result in the graphical tool ($UDI_{achieved}$ over 80%), while the DA region in the image covers about half of the image and the corresponding DA read in the graphical tool is in the range 60%-80%. The average Daylight Factor for the same case-study is 4.62% according to the formula of the standard EN 15193, which determines a ‘strong’ daylight penetration. For the same room but with a WWR of 0.6, the regions in Lightsolve maps corresponding to the $UDI_{achieved}$ and DA are respectively about 50% and 80% of the image area, which is in agreement with the data read in the graphical tool ($UDI_{achieved}$ in the range 40%-60% and DA over 80%). The daylight penetration defined with the EN 15193 method is ‘strong’ as the average Daylight Factor is 9.06%.

Similar correspondences were observed for the 7.5 m deep room with an obstruction angle of 15°: in the case of a WWR of 0.3, the areas corresponding in the Lightsolve illuminance map to the $UDI_{achieved}$ and to the DA are about 70% and 15% of the image area (versus corresponding values read in the graphical tool in the range 60%-80% and lower than 20% respectively), with a ‘medium’ daylight penetration according to the EN 15193 calculation method (D = 2.41%), while in the case of a WWR of 0.6, the $UDI_{achieved}$ is about 70% in the Lightsolve image and in the range 60%-80% in the graphical tool and the DA is about 50% in the Lightsolve image and in the range 40%-60% in the graph. In general, the daylight penetration calculated with the EN15193 method is ‘strong’ for all cases, except for the room with RD of 7.5 m, obstruction angle of 15° and WWR of 0.3 in which the daylight penetration is ‘medium’.

CHAPTER 4

Overall energy performance analysis

4.1 Methodology

The approach that was adopted involves the same parametric study used to assess the daylight availability vary as the building/room architectural features vary. The entire parametric study has been described in the previous chapter and all variables are summarized in Table 4.1. The later step was evaluating the related energy demand for electric lighting as well as the energy demand for heating and cooling for each room's configuration.

Site	Orientation	RD [m]	WWR [-]	γ [°]	τ_{vis} [%]	E_{target} [lx]	Lighting power density [W/m^2]	Lighting control systems (LMS)
Turin (45.1°N)	south	3	0.3	0	35	150	12	On-off manual (MAN)
Catania (37.5°N)	north	4.5	0.4	15	50	300	8	Automatic daylight responsive (DR)
Berlin (52.5°N)	west	6	0.5	30	70	500		
		7.5	0.6	45	90	750		
		9		60				
		10.5		75				
		12						

Table 4.1 Design variables used in the overall parametric study: the results presented in the thesis refer to a sub-dataset highlighted with a grey background.

Simulations were performed using a 2-step process. In step 1, Daysim 3.1 (Reinhart, 2010) was used to calculate the annual illuminance profile as well as the corresponding annual electric lighting demand of each space configuration for different lighting control systems based on available daylight. The annual illuminance values were used to calculate the energy demand for electric lighting, LENI (EN 15193, 2008). The LENI method calculates the performance of lighting in terms of energy per square metre per year. It assumes that the buildings can have access to daylight to provide all or some of the illumination required in the rooms and that in addition there will be an adequate amount of electric lighting installed to provide the required illumination in the absence of daylight. It depends on the installed electric lighting power density as well as the cumulated time per year when the lighting system is activated (either automatically or by the occupants).

In order to evaluate the sustainability of a space in terms of energy demand for electric lighting the rating proposed by the 'Non-domestic building service compliance guide' was used as reference (HM Government, 2013). The guide has been recently proposed in England for non-domestic buildings as a source of guidance on complying with Building Regulations requirements for space heating and hot water systems, mechanical ventilation, comfort cooling, fixed internal lighting and renewable energy systems. The section about lighting provides guidance on specifying lighting for new and existing non-domestic buildings to meet relevant energy efficiency requirements in the Building Regulations. The approach used in the guide considers lighting energy limits specified for a given illuminance and hours run. In fact when designing lighting a level of illuminance is usually selected for the task being done in a particular area. It's also necessary to determine how many hours per year the lighting will be needed. One both the illuminance and the hours are known it is possible to look up the lighting energy limit shown in Figure 4.1. For example an office may be lit to 500 lx and used for 2500 hours per year. Values of 2500 hours and 500 lx give a lighting energy limit of 20.82 kWh/m^2.

Table 44 Recommended maximum LENI (kWh per square metre per year) in new and existing buildings

Hours			Illuminance (lux)								Display lighting	
Total	Day	Night	50	100	150	200	300	500	750	1000	Normal	Shop window
1000	821	179	1.11	1.92	2.73	3.54	5.17	8.41	12.47	16.52	10.00	
1500	1277	223	1.66	2.87	4.07	5.28	7.70	12.53	18.57	24.62	15.00	
2000	1726	274	2.21	3.81	5.42	7.03	10.24	16.67	24.70	32.73	20.00	
2500	2164	336	2.76	4.76	6.77	8.78	12.79	20.82	30.86	40.89	25.00	
3000	2585	415	3.31	5.72	8.13	10.54	15.37	25.01	37.06	49.12	30.00	
3700	3133	567	4.09	7.08	10.06	13.04	19.01	30.95	45.87	60.78	37.00	
4400	3621	779	4.89	8.46	12.02	15.59	22.73	37.00	54.84	72.68	44.00	96.80
5400	4184	1216	6.05	10.47	14.90	19.33	28.18	45.89	68.03	90.17	54.00	
6400	4547	1853	7.24	12.57	17.89	23.22	33.87	55.16	81.79	108.41	64.00	
8760	4380	4380	10.26	17.89	25.53	33.16	48.43	78.96	117.12	155.29	87.60	192.72

Figure 4.1 Non-domestic building service compliance guide: recommended maximum LENI [kWh/m^2 per year] in new and existing buildings.

The methodology for the overall energy performance analysis not only provides values for the Lighting Energy Numeric Indicator (LENI) but it will also provide input for heating and cooling load estimations for the combined total energy performance of building indicator. Among the simulation results, Daysim also provides a Comma Separated Value (CSV) file which contains hourly schedules of the status of all lighting and shading groups within the model.

In step 2, this output was directly used as input in EnergyPlus (US-DOE). The parametric analysis in EnergyPlus was conducted using jEPlus, a graphical interface which allows setting alternative values for all the parameters and simultaneously running multiple simulations calling EnergyPlus (www.jEplus.org).

As final output of the 2-step process, annual energy demands for lighting, heating and cooling were calculated and converted into primary energy data for every room's configuration.
In Figure 4.2 the overall simulation methodology is explained.

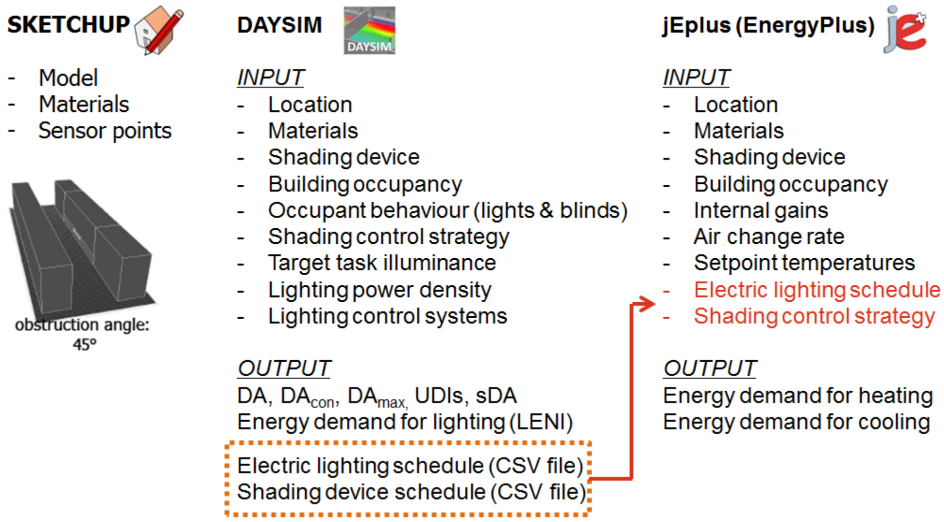


Figure 4.2 Overall simulation methodology.

4.1.1 Input parameters

In order to provide the calculation of LENI input data related to the lighting power density installed in the room and the type of lighting control system were defined:

– **lighting power density**: lighting power density technically represents the load of any lighting equipment in any defined area. It depends on the required target task illuminance, on the space's characteristics and on the type of luminaires. For this study it was decided to consider two different lighting power densities, assuming to install a direct lighting plant into the space with fluorescent and LED's lamps. In order to reach the target task illuminance of 500 lx it was decided to set the lighting power density equal to 12 W/m^2 and 8W/m^2 respectively.

– **lighting control systems**: two different controls were simulated in Daysim, namely a manual on-off switch (MAN) and a daylight responsive dimming system (DR) which takes advantage of the daylight availability over the working plane and reduces, potentially, the electric light use by dimming the luminaires. The manual on-off switch is based on the Lightswitch manual lighting control model implemented in Daysim (Reinhart, 2004), defined to predict electric lighting use in indoor environments based on probabilistic behavioural patterns. The **user behaviour** assumed for this study is a 50%-50% combination of two different stochastic models: 'active' users who operate the electric lighting in relation to ambient daylight condition, open blinds in the morning and partly close them to avoid visual discomfort; 'passive' users who keep the electric lighting switched on throughout the working day and keep the blinds lowered throughout the year.

As far as the EnergyPlus simulations are concerned, it was assumed that the space has only one wall which is exposed to the outdoor environment. As a consequence interior walls, floor and ceiling were modeled as adiabatic elements.

The wall and the window facing the outdoor environment were modeled with a thermal transmittance of 0.25 W/m^{2}K and 1.6 W/m^{2}K, respectively. The glazing visible transmittance and the Solar Heat Gain Coefficient were set equal to 0.7 and 0.67, respectively. The shade is considered to be perfect diffuser, with a visible transmittance of 0.25.

The occupancy index and air change rate were fixed according to the Italian Standard UNI EN 10339:1995 (CTI, 1995) while internal loads (people and equipment) were set according to the Italian Technical Standard UNI TS 11300-1:2008 (CTI, 2008). Winter and summer setpoint temperatures are based on the Italian Standard UNI EN 15251:2008 (CTI, 2008).

The input parameters used in the study are all summarized in Table 4.2.

HVAC systems were modelled in EnergyPlus considering an ideal air load simplification. This object permits to assess the theoretical thermal loads needed to achieve the thermal balance at any time step of the simulation.

Parameter	**Definition**	**Source**
U-value window	1.6 W/m^{2}K	DPR 59/2009
U-value wall	0.25 W/m^{2}K	DPR 59/2009
Visible transmittance (τ_{vis}), glazing	0.7	
SHGC (g)	0.67	
Visible transmittance (τ_{vis}), shading	0.25	Daysim
Shading control	Active if $I_{direct, workplane}$ >50W/m^2	Daysim (Lightswitch)
Occupancy hours	Monday to Friday 8:30 a.m. - 6:30 p.m.	
People definition	0.12 people/m^2	UNI 10339
People loads	70 W/person	UNI TS 11300-1
Air change rate	11 l/s·person	UNI 10339
Equipment loads	3 W/m^2	UNI TS 11300-1
Lighting power density (LPD)	12 W/m^2 8 W/m^2	
Lighting management systems (LMS)	Manual on-off (MAN) Daylight responsive (DR)	
Winter setpoint temperature	21 °C (7:00 a.m. - 9:00 p.m.) 18 °C (9:00 p.m. - 7:00 a.m.)	UNI EN 15251
Summer setpoint temperature	26 °C (7:00 a.m. - 9:00 p.m.) 28 °C (9:00 p.m. - 7:00 a.m.)	

Table 4.2 Input parameters for the lighting and thermal simulations.

4.1.2 Definition of an integrated approach

In order to evaluate the global energy demand of each space configuration and the influence of the daylighting design project on internal loads, the assumptions made for the lighting analysis needed to be coupled with the thermal analysis. In particular the control strategy used for the venetian blind and the control system adopted to automatically dim electric lighting in Daysim generate a schedule of the status of all shading and lights that has to be used for the thermal simulation.

For the present study this connection was realized using the jEPlus tool (www.jeplus.org). jEPlus allows to perform a parametric analysis that can be applied to all the design variables present in a model simultaneously. It can create and manage multiple simulation jobs and collect results afterwards.

The parametric analysis starts with the use of jEPlus graphical interface, which allows specifying a search string with all alternative values for each parameter that has to be varied: site, orientation, Room Depth, Window-to-Wall Ratio, external obstruction angle and visible glazing transmittance. Then jEPlus allows opening one single EnergyPlus IDF model and putting search strings in the places of each parameter. Then the software picks the set of values which were specified, it puts them in every search string in the IDF model and then calls EnergyPlus.

The general jEplus concept is summarized in Figure 4.3.

Two specific search strings were elaborated to pick up for each room configuration the output provided by Daysim related to the use of electric lighting and blinds as a function of daylight availability.

This kind of approach can represent a reliable method to evaluate a building whole energy performance exploring multiple design options, starting from a detailed Climate-Based Daylighting analysis.

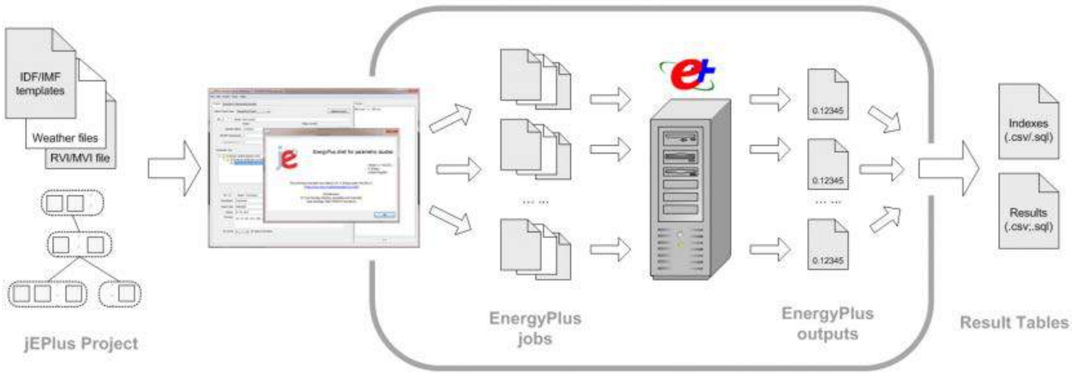


Figure 4.3 The jEplus concept.

A synthesis of the results that could be obtained after this integrated approach is presented in this section, with reference to the sub-dataset of configurations highlighted in Table 4.1.

Results are divided in two different subsections. The first subsection refers to the simulations conducted in Daysim and presents a comparison between $sDA_{300/50\%}$ values and energy demand for electric lighting (LENI) results.

The second subsection refers to the simulations conducted in EnergyPlus using the jEPlus interface analysing the overall energy performance of each room configuration compared with the amount of daylight available in the space.

In order to correctly sum lighting (Q_{EL}), heating (Q_H) and cooling (Q_C) energy, the primary energy equivalent demand has been considered and calculated as follows:

$$EP_{glob} == \frac{Q_H}{\eta_H} + \left(\frac{Q_C}{EER} \cdot \eta_{el} \right) + Q_{el} \cdot \eta_{el}$$

where η_H is the mean thermal energy generation efficiency, EER is the Energy Efficiency Ratio of a 'reference' air-to-air chiller and η_{el} is the mean National electricity generation efficiency. For the present study the following values were assumed: $\eta_H = 0.85$; EER = 3; $\eta_{el} = 2.17$.

4.2 Results

4.2.1 Daylight availability and energy demand for electric lighting

The parametric analysis conducted in Daysim generated results about the influence that different architectural features have on daylight availability and, consequently, on the energy demand for electric lighting.

The second phase of the analysis was focused to analyse the relation between different orientations and architectural features and energy demand for electric lighting (LENI), in presence of multiple daylighting conditions and lighting control systems. Two different lighting control systems were considered: a manual on-off switch (MAN) and a daylight responsive dimming system (DR).

The aim of the study is to prove the influence of a daylight optimization strategy on the reduction of energy demand for electric lighting. A daylighting optimization strategy corresponds to an increase in the indoor daylight amount and to the use of a daylight responsive dimming system.

Results obtained for both lighting control systems are shown in this section in comparison with a 'base-case', which consists in the 'worst' situation, with lights turned *always on* during the whole working hours. Furthermore the maximum LENI value recommended by the *Non-domestic building services guide* was used as reference: for office spaces the target was set to 20.82 kWh/m^2·y, considering that an office may be lit to 500 lx and needs lights for 2500 hours per year (Figure 4.1).

The results shown in Figure 4.4 refer to North and South-facing rooms located in Turin with a glazing visible transmittance of 70% and external obstruction angles of 0°, 30° and 60°. It could be noted that LENI values are on average lower for North-facing than South-facing rooms, in particular for low obstruction angles. This is mainly due to the presence of movable shading device which avoid direct sunlight on the workplane and admits 25% of diffuse light only into the space. For higher external obstructions than 30° movable shadings are less used because of the lack of direct solar radiation.

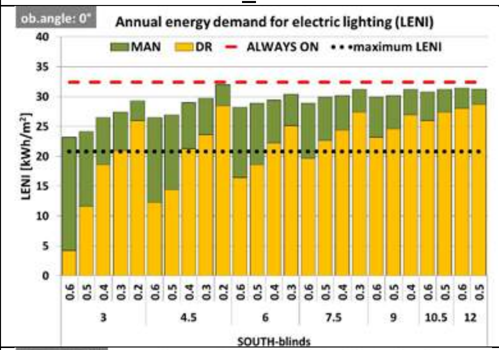
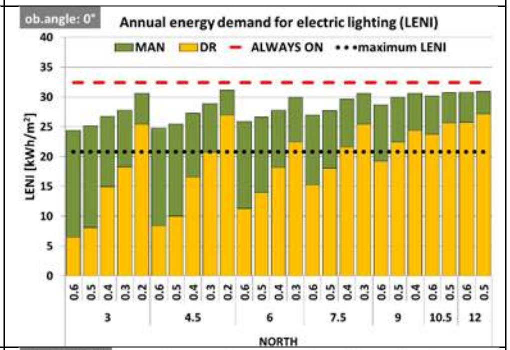
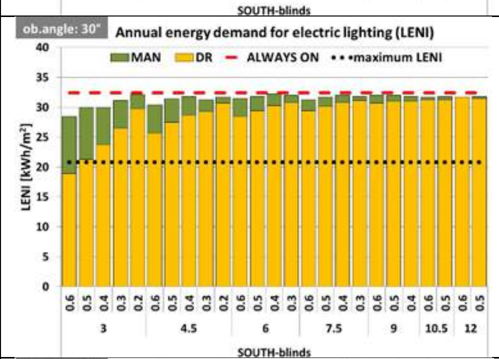
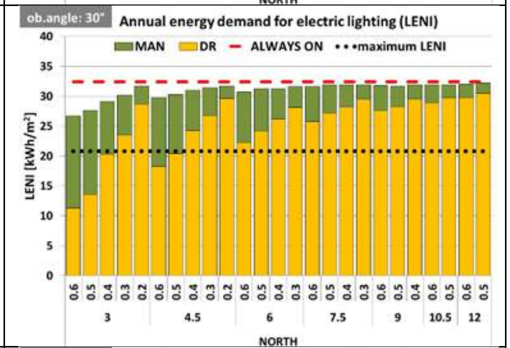
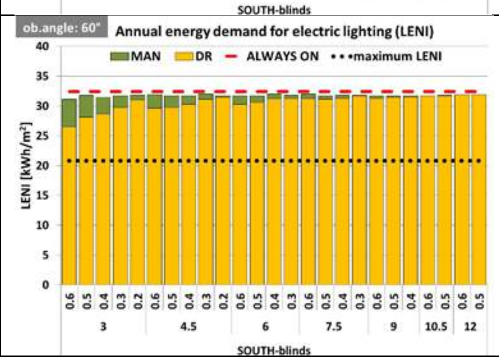
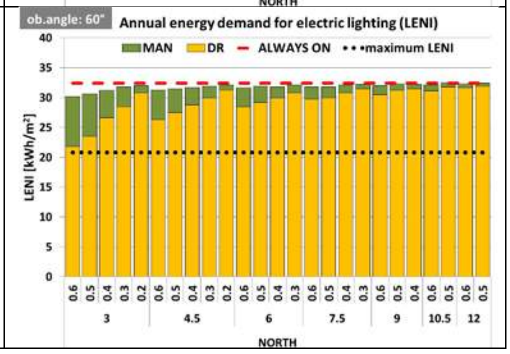
	LENI [kWh/m²] South_blinds	LENI [kWh/m²] North
γ=0°		
γ=30°		
γ=60°		

Figure 4.4 Annual energy demand for electric lighting (LENI) for South and North-facing rooms' configuration with γ=0°, 30° and 60°.

Without external obstructions (γ=0°) and in presence of a daylight responsive dimming system the mean LENI for South and North-facing rooms is 21.7 and 18.8 kWh/m^2·y respectively. The LENI maximum value of 20.82 kWh/m^2·y is not exceeded only by small rooms (3 m – 4.5 m) and medium deep rooms (6 m – 7.5 m) with WWR between 0.4 and 0.6. In presence of a manual on-off switch results for all rooms' configurations are higher than the maximum LENI target.

Furthermore it could be noted that increasing the WWR has an influence in particular for small and medium deep rooms and low obstruction angles. Higher obstruction angles than 30° could seriously affect the energy demand for electric lighting.

A progressive increment in the obstruction angle results in an increase in the average LENI values. For instance for γ=60° the mean LENI for South and North-facing rooms (30.6 and

29.4 kWh/m^2·y respectively) is very closed to the 'base-case' situation result, even in presence of a daylight responsive dimming system.

In order to compare with a more effective approach the energy demand for electric lighting with the respective daylight availability, the sDA metric suggested by IESNA was used as reference (IES, 2012) to assess the indoor daylighting performance since it's the only Climate-Based Daylight Metric for which target levels have been established: a space can be rated as 'neutral' when $sDA_{300/50\%}$ meets or exceeds 55% and 'favorably' daylit when $sDA_{300/50\%}$ meets or exceeds 75%. A space with $sDA_{300/50\%}$ below 55% is considered as an insufficiently daylit space.

Starting from these criteria a comparison between $sDA_{300/50\%}$ and energy demand for electric lighting (LENI) values have been carried out, considering the presence of two lighting control systems. The entire database of results was then divided according to these criteria, as explained in Figure 4.5.

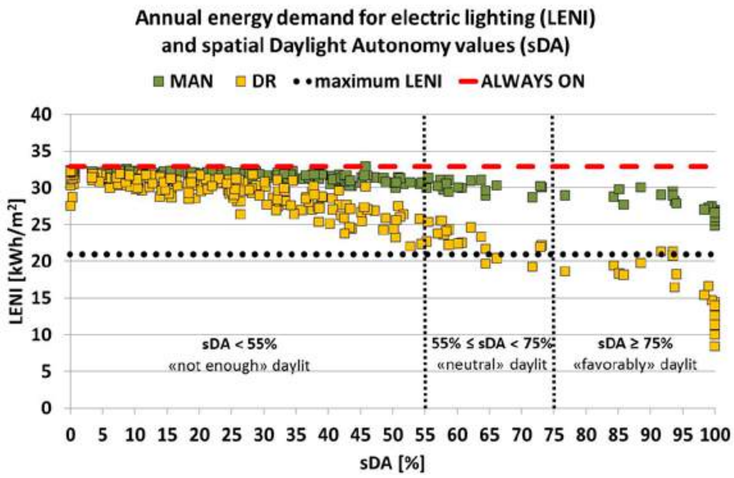


Figure 4.5 Overall database of LENI and sDA results (North and South-facing rooms).

For each performance class and for each type of lighting control (manual and daylight responsive) the maximum, minimum and mean annual energy demand for electric lighting ($LENI_{,m}$) values were calculated (Figures 4.6 and 4.7).

Two levels of analysis have been developed:

- for the same lighting control system the influence of increasing daylight on LENI results was evaluated;
- for the same indoor daylighting performance class the influence of lighting control systems was analyzed in comparison with the 'base-case' with lights always turned on during working hours.

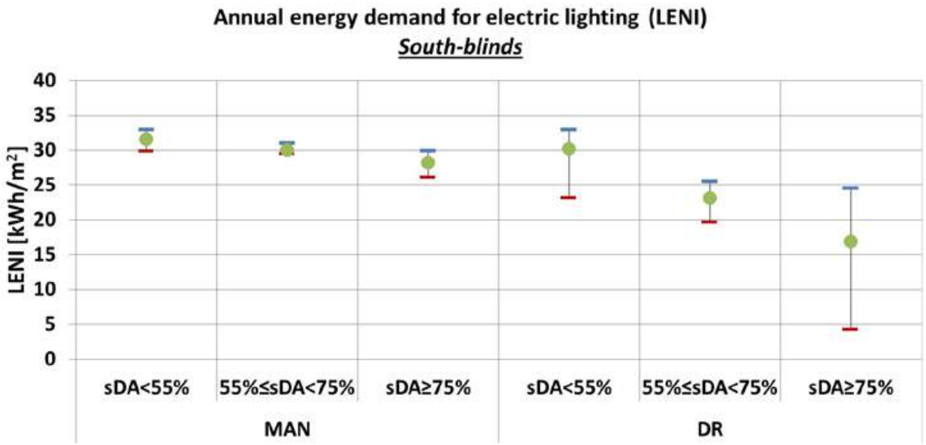


Figure 4.6 Maximum, minimum and mean LENI values for every sDA performance class (South-facing rooms).

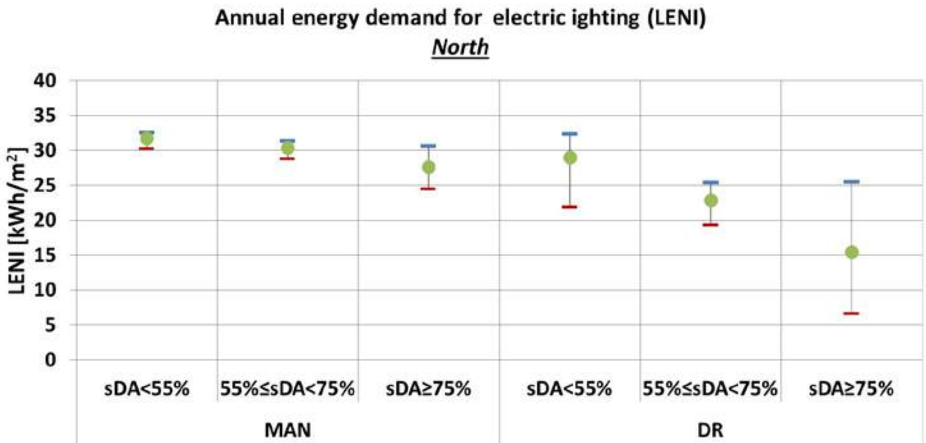


Figure 4.7 Maximum, minimum and mean LENI values for every sDA performance class (North-facing rooms).

The influence of increasing daylight

As already explained in the previous section, the daylight amount in a room is assessed in this study using the spatial Daylight Autonomy value and its reference values. Therefore increasing daylight means reaching a $sDA_{300/50\%}$ at least above 55% even if the optimal level is set to 75%.

It could be noted that increasing daylight results in a decrease of energy demand for electric lighting (Figure 4.8). The highest energy demand reduction can be obtained achieving a spatial Daylight Autonomy above 75%: the mean LENI percentage differences between cases with $sDA_{300/50\%}$ <55% and cases with $sDA_{300/50\%}$ ≥ 75% are -11% and -44% for South-facing rooms and -13% and -47% for North-facing rooms (in presence of a manual on-off switch and a daylight responsive dimming system, respectively).

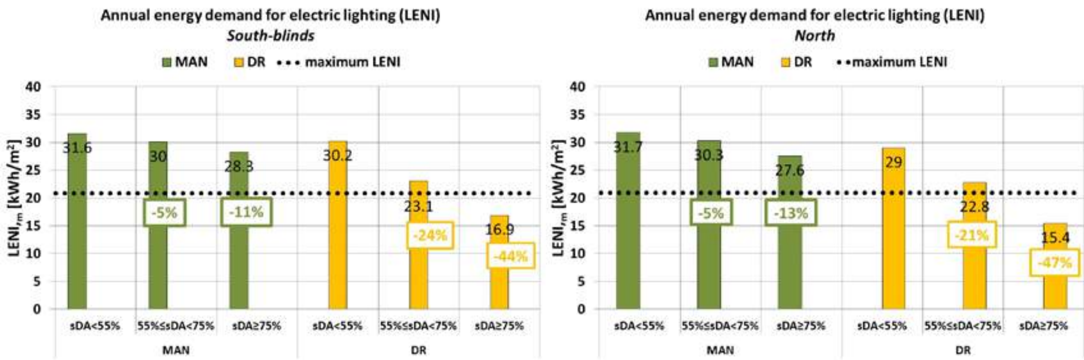


Figure 4.8 Mean LENI values and percentage differences for every sDA performance class.

As a consequence it could be said that on average only ‘favorably’ daylit spaces ($sDA_{300/50\%} \geq 75\%$) equipped with a photosensor dimming system don’t exceed the maximum LENI value of 20.82 kWh/m^2 recommended by the *Non-domestic building services guide.*

The influence of lighting control systems

This section is focused on analysing the influence of lighting control systems for the same indoor daylighting performance class in comparison with the ‘base-case’ with lights always turned on during working hours.

The results presented in the following graphs are strictly related to the algorithm implemented in Daysim, called Lightswitch, to mimic how users interact with personal controls (light switches, blinds, window openings) (Reinhart, 2004; Reinhart, 2010). Lightswitch assumes the presence of active and/or passive users. Active users operate the electric lighting in relation to ambient daylight conditions, passive users keep the electric lighting on throughout the working day. The strategy adopted during the simulation for the manual on-off switch refers to a mixed behaviour, i.e. both type of users were assumed to equally influence the light control.

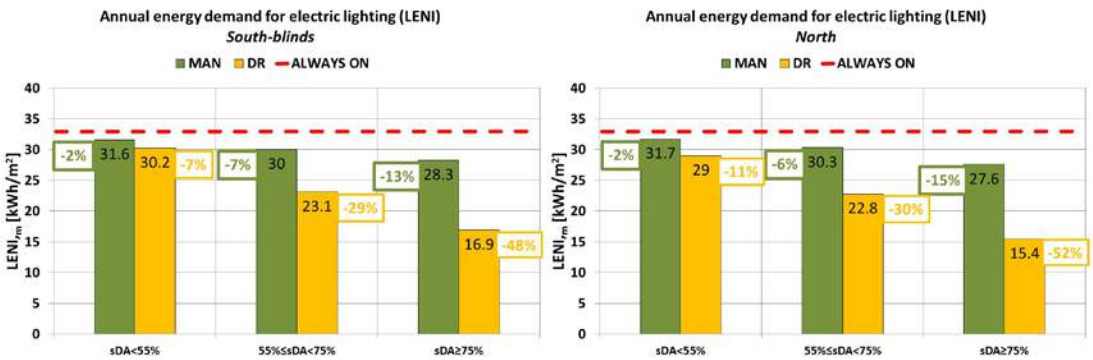


Figure 4.9 Mean LENI values and percentage differences for every lighting control system.

Figure 4.9 shows the percentage decrease of the mean LENI values with respect to the ‘base-case’ for every spatial Daylight Autonomy performance class. As one might expect, the higher the daylight availability ($sDA_{300/50\%} \geq 75\%$), the lower the energy demand for electric lighting, especially in presence of a daylight responsive dimming system. This was observed for both orientations: the mean percentage difference with respect to the case with lights always on can reach -48% for South orientation and -52% for North orientation.

Values of $sDA_{300/50\%}$ below 55% (showing that the amount of daylight is not sufficient) result in a lower reduction in the energy demand for electric lighting, even in the presence of a daylight responsive dimming system (-7% for South orientation, -11% for North orientation).

With a manual on-off switch the reduction in the energy demand for electric lighting is quite low, even if the space is ‘favorably’ daylit: the mean percentage difference with respect to the case with lights always on can reach -13% for South orientation and -15% for North orientation.

4.2.2 Daylight availability and overall energy performance evaluation

The parametric analysis conducted in EnergyPlus using the jEplus interface allows the global energy performance of a room with multiple design options to be analyzed.

This section focuses on how a design strategy based on the optimization of daylight can influence the global energy demand of a room (EP_{glob}). As explained in the previous paragraph a daylighting optimization corresponds to an increase in the $sDA_{300/50\%}$ and to the use of a daylight responsive lighting control system. For this reason this third part of the research will only focus on results obtained for cases with a daylight responsive dimming system in comparison with the ‘base-case’, with lights turned *always on* during the whole working hours.

The results shown in Figure 4.10 refer to North and South-facing rooms located in Turin with a glazing visible transmittance of 70% and external obstruction angles of 0°, 30° and 60° with light management system (LMS) always on and daylight responsive. In the graphs the Room Depth was shown on the x-axis in terms of S/V ratio (surface which is exposed to the outdoor environment to the space volume ratio).

Without external obstructions (γ=0°) the presence of a daylight responsive dimming system allows to reduce the global energy performance if compared to cases with lights always turned on. The mean EP_{glob} are 92.7 kWh/m^2 and 122.1 kWh/m^2 respectively, with a mean energy saving of 24%. As far as the effect of the orientation is concerned it could be said that South-facing rooms revealed a lower heating demand mainly because of the benefit of the direct solar radiation coming into the space, but at the same time a higher lighting and cooling demand than North-facing rooms.

Increasing the obstruction angle results in an increase of the lighting and heating energy demand in presence of a daylight responsive dimming system. For cases with lights always turned on the lighting energy demand is always the same since it does not depend on the daylight coming into the space. Heating energy demand increases both for South and North-facing rooms and cooling energy demand decreases, mainly because of the lack of direct solar radiation which is blocked by the external obstructions.

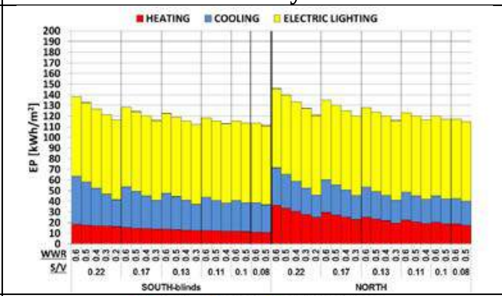
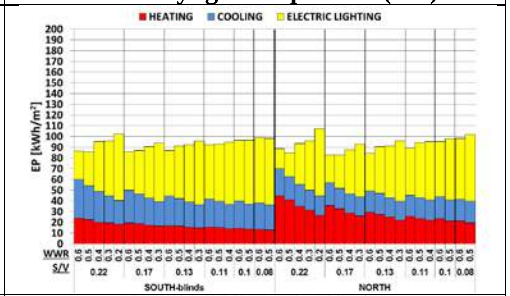
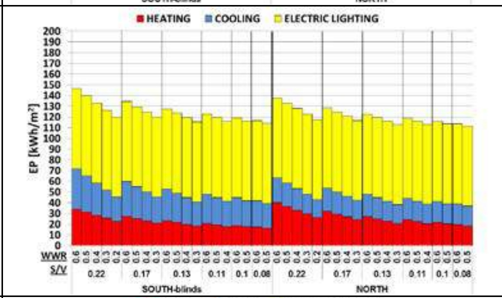
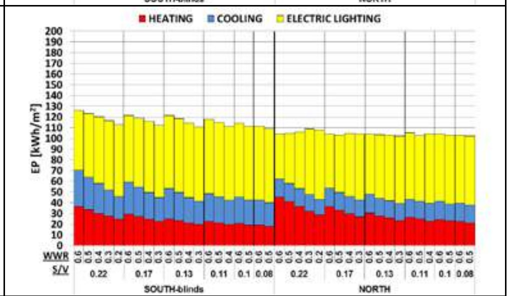
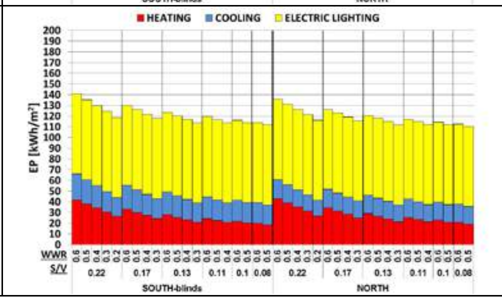
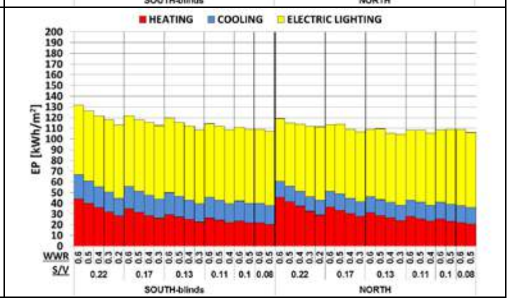
	EP_{glob} [kWh/m²] LMS: Always on	EP_{glob} [kWh/m²] LMS: Daylight Responsive (DR)
γ=0°		
γ=30°		
γ=60°		

Figure 4.10 Annual primary energy equivalent demand (EP_{glob}) for South and North-facing rooms' configuration with γ=0°, 30° and 60°.

In order to compare with a more effective approach the global primary energy demand with the respective daylight availability, the sDA metric suggested by IESNA was used again as reference (IES, 2012) to assess the indoor daylighting performance since it's the only Climate-Based Daylight Metric for which target levels have been established: a space can be rated as 'neutral' when $sDA_{300/50\%}$ meets or exceeds 55% and 'favorably' daylit when $sDA_{300/50\%}$ meets or exceeds 75%. A space with $sDA_{300/50\%}$ below 55% is considered as an insufficiently daylit space.

Starting from these criteria a comparison between $sDA_{300/50\%}$ and primary energy demand for lighting, heating and cooling values have been carried out, considering the daylight responsive dimming system in comparison with the 'base-case' with lights always turned on.

The entire database of results was then divided according to these criteria. In Figure 4.11 the relation between $sDA_{300/50\%}$ and the primary energy demand for lighting, heating and cooling is shown.

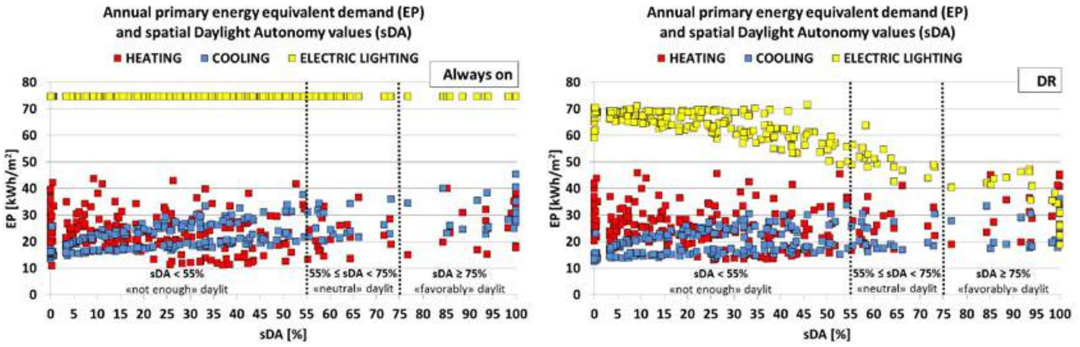


Figure 4.11 Overall database of EP for lighting, heating and cooling and sDA results (Always on and daylight responsive dimming system).

Furthermore the mean primary energy demand for lighting, heating and cooling together with the mean global primary energy demand ($EP_{glob,m}$) were calculated for each lighting control system and performance class of $sDA_{300/50\%}$, as shown in Figure 4.12.

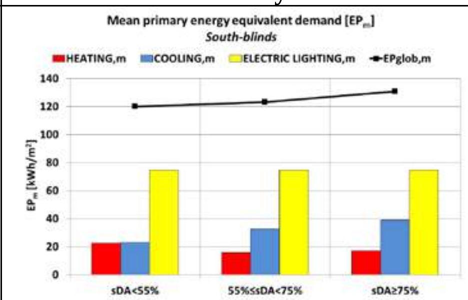
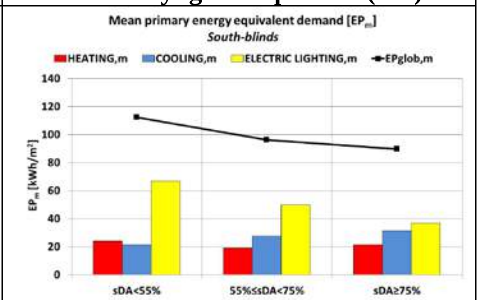
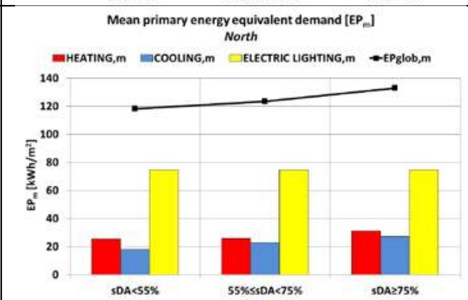
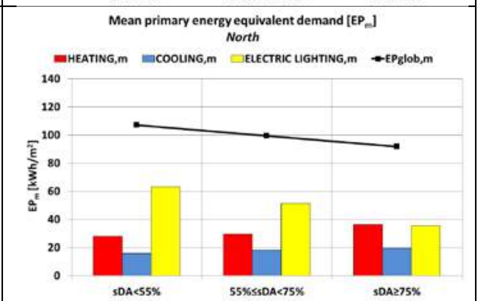
	EP_m [kWh/m²] **LMS: Always on**	**EP_m [kWh/m²]** **LMS: Daylight Responsive (DR)**
South-blinds		
North		

Figure 4.12 Mean EP for lighting, heating and cooling and mean EP_{glob} for each sDA performance class and lighting control system.

It could be noted that the higher the amount of daylight available in a space ($sDA_{300/50\%}$ ≥ 75%) the lower the global primary energy demand ($EP_{glob,m}$), in particular in presence of a daylight responsive dimming system. For both South and North-facing rooms the mean global primary energy demand is lower for spaces rated 'favorably' daylit ($sDA_{300/50\%}$ ≥ 75%) than for spaces not enough daylit ($sDA_{300/50\%}$ < 55%). For South-facing rooms the mean annual global primary energy demand is 112.4 kWh/m²·a when $sDA_{300/50\%}$ is below 55% and 89.7 kWh/m²·a when $sDA_{300/50\%}$ is above 75%. The mean global reduction that can be obtained is 20%. For North-facing rooms the mean annual global primary energy demand is

107.1 kWh/m^2·a when sDA$_{300/50\%}$ is below 55% and 91.7 kWh/m^2·a when sDA$_{300/50\%}$ is above 75%. The mean global reduction that can be obtained is 14%.

In presence of a lighting system always on the global primary energy demand increases as indoor daylight availability increases.

The influence of lighting control systems

The whole database of results was divided according to the type of lighting control systems which have been used during the simulations. In the previous paragraph it has been demonstrated that the highest lighting energy demand (LENI) reduction could be obtained in ‘favorably’ daylit spaces (sDA$_{300/50\%}$ ≥ 75%) and in presence of a daylight responsive dimming system. This combination is representative of a daylight optimization approach and the aim of this section is to analyze its influence on the global energy performance of a space.

Figure 4.13 shows the entire database of results derived from the simulations in jEplus divided according to lighting control systems and sDA performance classes.

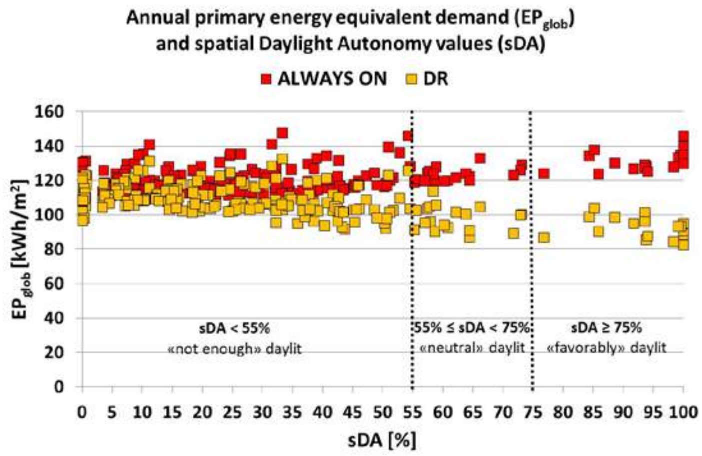


Figure 4.13 Annual primary energy equivalent demand (EP$_{glob}$) for each lighting control system.

Than the mean global primary energy demand (EP$_{glob,m}$) was calculated for each performance class of sDA$_{300/50\%}$ and for each lighting control system.

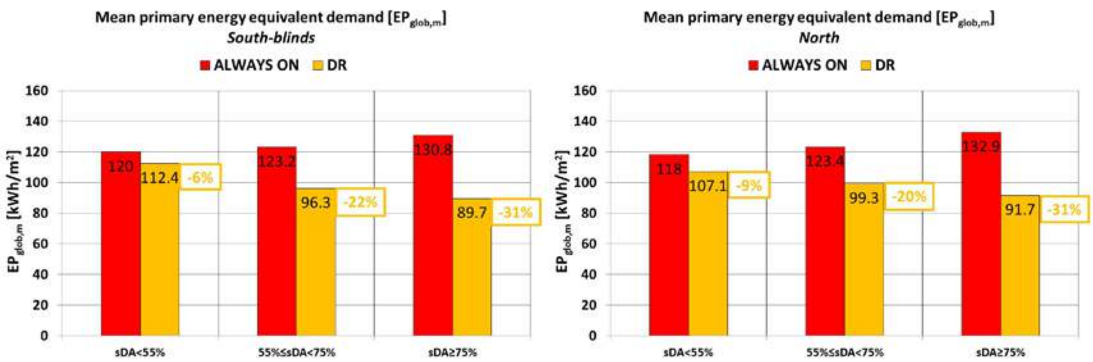


Figure 4.14 Mean primary energy equivalent demand (EP$_{glob,m}$) for each lighting control system and sDA performance class (South and North-facing rooms).

Figure 4.14 shows the results for South and North-facing rooms. The results are expressed in terms of mean percentage difference between $EP_{glob,m}$ values for the 'base-case' control system (lights always on) and $EP_{glob,m}$ values with a daylight responsive dimming system.

For both South and North-facing rooms, the maximum mean reduction in the global primary energy equivalent demand (-31%) can be reached for 'favorably' daylit cases, i.e. cases with $sDA_{300/50\%} \geq 75\%$.

In spaces with a non-sufficient level of daylight ($sDA_{300/50\%} < 55\%$) the mean global primary energy demand is higher and the reduction that could be obtained in presence of a daylight responsive dimming system doesn't exceed -9%.

The influence of efficient lighting technologies

Solid-state lighting sources are revolutionizing an increasing number of applications.

The high efficiency of solid-state sources already provides energy savings and environmental benefits in a number of applications. However, solid-state sources offer controllability of their spectral power distribution, spatial distribution, colour temperature, temporal modulation and polarization properties. Such 'smart' light sources can adjust to specific environments and requirements, a property that could result in some benefits in particular in lighting design applications.

Installing the right lights in offices, for instance, is important in order to create a pleasant working environment: they create a pleasant mood and increase productivity. Planners, operators and users therefore have very high expectations of lighting systems. Modern solutions satisfy these demanding requirements by creating the perfect conditions for the relevant visual tasks.

The combination of daylight, electric lighting and light management systems provides optimal lighting conditions and allows light control system to maximize energy efficiency.

During the last phase of the PhD research project the influence of LED sources on the global energy performance of a space has been analyzed. The aim of this last phase was to extend the concept of daylight optimization improving the performance of the whole system, including efficient lamps.

In order to provide 500 lx within the space it was assumed to install LED sources with a lighting power density of 8 W/m^2. A low lighting power density allows to first reduce the energy demand for electric lighting and to decrease the internal gains coming from electric lighting, influencing at the same time the cooling energy demand.

A new set of simulations was performed assuming to install a lighting power density of 8 W/m^2 for cases with a daylight responsive dimming system. Figure 4.15 shows the entire database of results derived from the simulations in jEplus divided according to lighting control systems, lighting power density and $sDA_{300/50\%}$ criteria.

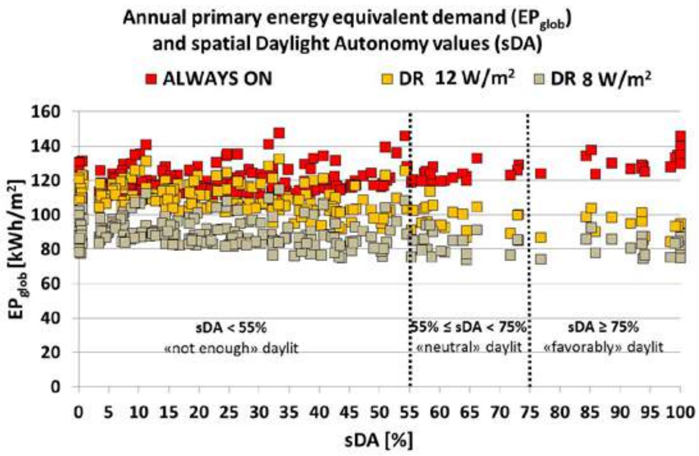


Figure 4.15 Annual primary energy equivalent demand (EP_{glob}) for each lighting control system and lighting power density.

Than the mean global primary energy demand ($EP_{glob,m}$) was calculated for each lighting control system and lighting power density and for each $sDA_{300/50\%}$ performance class.

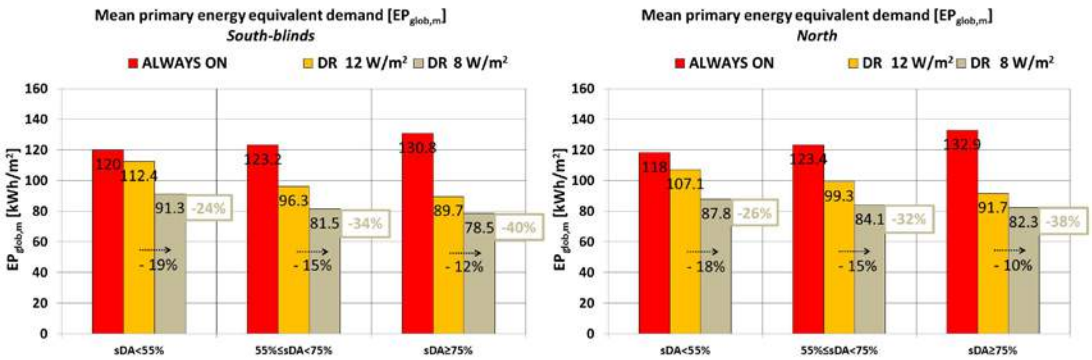


Figure 4.16 Mean primary energy equivalent demand ($E_{P,glob,m}$) for each lighting control system, lighting power density and sDA performance class (South and North-facing rooms)

Figure 4.16 shows the results for South and North-facing rooms. The results are expressed in terms of mean percentage difference between $EP_{glob,m}$ values for the 'base-case' (lights always on) and $EP_{glob,m}$ values with a daylight responsive dimming system and a lighting power density of 8W/m^2.

For both South and North-facing rooms, the maximum mean reduction in the global primary energy equivalent demand can be reached for 'favorably' daylit cases, i.e. cases with $sDA_{300/50\%} \geq 75\%$. The reduction is about 40% for South-facing spaces and 38% for North-facing spaces.

It has to be said that, in presence of a daylight responsive dimming system, a lower lighting power density has a good influence on the reduction of the global energy performance even for 'non-sufficient' daylit spaces ($sDA_{300/50\%} < 55\%$). This is probably due to the time in which lights are turned on: the lower the amount of daylight available in a space

($sDA_{300/50\%}$ < 55%) the longer the time in which lights are turned on, even in presence of a daylight responsive dimming system. For this reason the reduction from cases with a lighting power density of 12 W/m^2 is higher when the daylight availability is low (-19% for South orientation and -18% for North orientation) than when the daylight availability is high (-12% for South orientation and -10% for North orientation).

CHAPTER 5

Conclusion

The study presented in this thesis focuses on four aspects related to the main problems found in current studies about daylight and energy saving:

- Analyzing limits and potentials of new indicators concerned with the climate-based daylight modelling: a comparison between Climate-Based Daylight Metrics and the conventional Daylight Factor approach has been carried out, in order to analyze the consistency of new indicators for a dynamic daylighting design.
- Proposing synthetic information and tools to be used by the design team from the earliest design stage onward to predict daylighting conditions in building spaces, in order to enable the design team to quickly verify the influence of preliminary design solutions on the daylight amount in a space.
- Analyzing the effect of a proper daylighting design on energy requirements for electric lighting, in association with the use of efficient lighting control systems.
- Assessing the influence of a daylight-optimized design strategy on the global energy performance of a space, so as to analyze if a space which is sufficiency daylit and equipped with efficient lighting technologies could require at the same time low global energy demand.

The approach that was adopted relies on a parametric study to assess how the daylight availability and energy requirements for lighting, heating and cooling vary as the building/room architectural characteristics vary. The methodology was based on the use of both Daysim and EnergyPlus, which were employed in synergy to assess the lighting and energy performance of rooms with different architectural features.

5.1 Main achievements

Drawbacks and potential of Climate-Based Daylight Metrics

The higher sensitivity of Climate-Based Daylight Metrics (CBDM) with respect to static simulation (that considers a single overcast sky condition) is pointed out by comparing the Daylight Factor (DF) results to the Annual Light Exposure (ALE) results. The two quantities are correlated but, unlike DF, the dynamic metric ALE is sensitive to the variation of orientation and latitude. Furthermore, among the CBDM, metrics based on one or more threshold values provide more detailed information on actual annual daylighting conditions as a consequence of the specific room architectural features. It has been demonstrated that the relative difference of ALE, for instance reducing the room depth, is kept almost constant independently of the WWR, obstruction angle and orientation. On the other hand, for the same case studies, metrics such as

Daylight Autonomy (DA) and Usefull Daylight Illuminance (UDI) vary in a quite different way. These results show the importance of analysing the illuminance distributions rather than calculating the global amount of annual daylight quantities.

Synthetic information for the earliest daylighting design phases

Further results about the effects of different architectural design solutions on daylight availability through a parametric analysis are presented. The aim was to enhance knowledge on the consequences of the early design solutions on the daylighting performance of a building. The following considerations can be drawn from this analysis:

- if the daylight availability within a space is evaluated in terms of overall daylight amount (ALE), South-facing and West-facing rooms present the highest values. At the same time, if blinds are not used, glare and overheating may occur (as highlighted by the DA_{max} values).
- daylighting performance is better for North-facing rooms than for South-facing rooms with blinds: in both cases the risk of glare is low, but DA and $UDI_{100\text{-}2000}$ values are higher for North-facing rooms than for South-facing rooms with blinds. This results in a lower lighting energy demand and in a better visual comfort condition as blinds can limit the view to the outside.
- an increase in the room depth results in a decrease in DA values; the percent reduction of DA appears to be greater when the room depth is increased from 3 m to 6 m than for RD over 6 m. On the other hand, an increase in the room depth has a lower effect on the 100-2000 lx range since the average $UDI_{100\text{-}2000}$ values are always between 40% and 60%.
- an increase in the WWR results in an increase in DA values. This increase is higher for increments of WWR from 0.3 to 0.4 than from 0.4 to 0.5 or from 0.5 to 0.6. At the same time, no significant increase in $UDI_{100\text{-}2000}$ can be observed for WWR over 0.4. This means that a Window-to-Wall Ratio of 40% is sufficient to guarantee ‘useful’ daylight.
- an increase in the obstruction angle results in a decrease in the DA and $UDI_{100\text{-}2000}$. The DA decrease is lower for γ between 0° and 30° than for γ over 30°. Furthermore, obstruction angles lower than 30° allow a good daylight performance to be achieved, since the $UDI_{100\text{-}2000,m}$ is always higher than 50%.

A graphical tool to express the daylighting performance

Another output of the research activity (presented in detail in Chapter 3) was concerned with the proposal of a graphical tool that could be used to summarize and visualize more clearly the simulation results and to allow an immediate reading of the daylighting conditions within a room with varying architectural features. The graphical tool should be intended as an informative instrument to assist practitioners during the earliest daylighting design phases.

Practitioners could make use of the tool in two different ways: for instance, for a given urban settings, they can establish how the room depth and window area can influence the daylight availability in a room; alternatively, they can size the window and room geometry so as to guarantee a desired daylighting performance.

The graphical tool has the merit of being based on a huge quantity of annual climate-based and Radiance-based simulations, at the same time being a simple and quick-to-use tool for the early design phases, when more detailed design investigations and simulations are still premature and the daylighting analysis of many buildings begins and ends with the use of rules of thumb.

Daylight availability and energy demand for electric lighting

The analysis conducted in Daysim demonstrated, initially, that the daylight amount within a space is strongly influenced by its architectural features: a progressive increase in Room Depth and a decrease in Window-to-Wall Ratio result in a decrease in $sDA_{300/50\%}$ values and in an increase in the energy demand for electric lighting (LENI). LENI values are on average lower for North-facing than South-facing rooms, especially for low obstruction angles. This is mainly due to the presence of movable shading device which avoid direct sunlight on the workplane and admits 25% of diffuse light only into the space. For external obstructions higher than 30° movable shadings are less used because of the direct solar radiation is shaded by the obstructing buildings for most of the year.

Without external obstructions (γ=0°) and in the presence of a daylight responsive dimming system, the mean LENI for South and North-facing rooms is 21.7 and 18.8 kWh/m^{2}yr, respectively. The maximum LENI value of 20.8 kWh/m^{2}yr (HM Government, 2013) is not exceeded only by small rooms (3 m – 4.5 m) and medium deep rooms (6 m – 7.5 m) with WWR between 0.4 and 0.6. In the presence of a manual on-off switch, results for all room configurations are higher than the maximum LENI target.

Increasing the daylight amount in a space results in a decrease of its energy demand for electric lighting. The highest energy demand reduction can be obtained achieving a spatial Daylight Autonomy above 75%: the mean LENI percentage differences between cases with $sDA_{300/50\%} < 55\%$ and cases with $sDA_{300/50\%} \geq 75\%$ are -11% and -44% for South-facing rooms and -13% and -47% for North-facing rooms (in the presence of a manual on-off switch and of a daylight responsive dimming system, respectively).

The highest LENI reduction can be obtained achieving a daylight optimization strategy, i.e. an increase in the availability of daylight (expressed by $sDA_{300/50\%}$) and to the use of a daylight responsive lighting control system.

Daylight availability and overall energy performance evaluation

Analysing the database data, it was observed that the higher the amount of daylight available in a space ($sDA_{300/50\%} \geq 75\%$) the lower the global primary energy demand ($EP_{glob,m}$), in particular in the presence of a daylight responsive dimming control. For both South and North-facing rooms, the mean $EP_{glob,m}$ is lower for spaces rated 'favorably' daylit ($sDA_{300/50\%} \geq 75\%$)

than for spaces not enough daylit ($sDA_{300/50\%}$ < 55%). For South-facing rooms the mean annual global primary energy demand is 112.4 kWh/m^{2}yr when $sDA_{300/50\%}$ is below 55% and 89.7 kWh/m^{2}yr a when $sDA_{300/50\%}$ is above 75%. The mean global reduction that can be obtained is 20%. For North-facing rooms the mean annual global primary energy demand is 107.1 kWh/m^{2}yr a when $sDA_{300/50\%}$ is below 55% and 91.7 kWh/m^{2}yr a when $sDA_{300/50\%}$ is above 75%. The mean global reduction that can be obtained is 14%.

The combination of a high indoor daylight availability and use of a daylight responsive dimming systems can produce an average global energy saving of 31% compared to the case in which lights are always turned on during occupancy hours. In the presence of efficient lighting technologies such as LEDs, this reduction can reach up to 40%.

5.2 Discussion

The research activity presented in this thesis does not cover every possible site or building configuration, but it makes available a set of information and graphical tools that can be useful to inform the design team on the impact of their architectural choices on both the CBDM values for the considered space and on the energy demand for lighting, heating and cooling during the very first stages of the building design process, when the use of simulation tools for more detailed calculation is still premature. Designers are assisted in crucial decisions concerning the window and the room sizing and under which conditions the choice of a daylight responsive control system is worthwhile: for instance, for a given urban settings (for which room obstruction angles are known), designers can find out how room depth and window area influence the room energy performance; or, the other way around, they can size window and room geometry so as to guarantee a desired value of CBDM values or energy demand for lighting.

Focusing on the characteristics of the proposed tool, some limitations can be stressed, concerning, for example, the number of variables that can be visualized. The results presented in the thesis refer to a sub-dataset that includes data on North and South-facing rooms located in Turin with a visible glazing transmittance of 70% and a target illuminance of 500 lx. This data sub-set was useful for the aim of the study, i.e. to show the potential and the utility of the proposed graphical tool. Moreover, data are visualized in ranges (as a consequence, rooms with different characteristics may fall into the same range) as mean values calculated from the spatial distribution of the data. No information is therefore given on the daylight distribution across a space.

It is worth noting how the results and the proposed tool are valid for the assumed boundary conditions (sites, architectural features, building usage and lighting system characteristics, etc.).

The daylight availability and the global energy demand for the room would vary if, for instance, it were located in sites with different latitude, or with same latitude but with quite different annual climates or for a different room usage (in terms of target illuminance, occupation profile or user behaviour) or for different types of lighting control system or for blinds with different characteristics. In this study the blind control strategy is based on the algorithm implemented in Daysim whose aim is to control the direct solar radiation on the workplane.

Furthermore the space was assumed with only one wall exposed to the outdoor environment, considering a central position of a sample office within a building. Results might be different if a corner office were considered. A second input data that can have a massive influence on the energy performance of a space is represented by the type of shading and its control strategy.

Finally one important consideration about the simulation approach is that the 2-step simulation process between Daysim and EnergyPlus could be a big effort for a design team, especially during the first stages of the design process when a parametric analysis could be useful to base the first decisions about the building shape and orientation, window sizes and characteristics of glazing and shading systems. In general, it could be said that there is a lack of sufficiently accurate prediction tools for a design team to optimize a project integrating advanced daylighting analysis into energy analysis.

One further trouble could be the right choice of all the input data needed for an advanced simulation. There's more and more the need for extensive libraries which can fill in automatically all required inputs when a model has to be handled.

5.3 Outlook

The research activity presented in this thesis could be not considered as finished, but is further pursued following two main directions. The first goal is concerned with expanding the result database, including a larger number of sites, and to represent the results through the graphical tool. For instance lighting, heating and cooling demands could be plotted for all variables.

The second goal concerns the use of the result database to develop a set of mathematical prediction models to link the daylight metrics values and the corresponding lighting, heating and cooling energy demands to the factors of influence (architectural features, target illuminance values and sites), and to eventually produce an interactive software program that will allow practitioners to obtain both daylighting and global energy demand results by directly inputting the architectural features of the spaces, the geographical site, the illuminance threshold, the lighting power density values and the thermal characteristics of the space.

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Part II
Appended papers

Paper I:

'Climate-based metrics for daylighting and
impact of building architectural features on daylight availability'

A. Pellegrino, C. Aghemo, V.R.M. Lo Verso, S. Cammarano
In proceedings:
27th Session of the CIE
2011, Sun City, South Africa.

CLIMATE-BASED METRICS FOR DAYLIGHTING AND IMPACT OF BUILDING ARCHITECTURAL FEATURES ON DAYLIGHT AVAILABILITY

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Abstract

This paper presents the results from a parametric study to assess daylight provision for a sample of office rooms with different characteristics: room orientation, depth and window area, as well as obstruction angle. The analysis was repeated for two sites, representative of continental and Mediterranean climate conditions (Torino and Palermo - Italy). For each case-study, the Daylight Factor (DF) and some Dynamic Daylight Performance Metrics (DDPM) were calculated through the Radiance-based software Daysim. The database of results was used to assess the sensitivity of DF and DDPM as predictors of daylight availability within a space and to analyse how indoor daylighting is influenced by room architectural features. Moreover a further approach to describe the time-varying daylight illuminance values predicted by a dynamic simulation is presented .

Keywords: Dynamic Daylight Performance Metrics, Climate-Based Daylight Modelling, Daylight Factor

1 Introduction

In the field of lighting, the need for a more rational use of renewable resources results in an increased use of daylight and its conscious integration with the electric lighting, even through the use of control systems (Mardaljevic et al., 2009). The importance of skylight and sunlight for both building energy performance and environmental quality implies the need for a more accurate design approach which takes into account the dynamic behaviour of daylight. In response to this, a new series of metrics has been recently proposed in literature (CIE, 2008) (Reinhart et al., 2006), the so-called 'Dynamic Daylight Performance Metrics DDPM, which are parameters able to account for the dynamic variation of skylight and sunlight conditions during the course of the year as a function of the specific climate conditions of a site and of the orientation of the considered building.

Within this frame, the paper focuses on the potentials concerned with climate-based daylight modelling. In particular, the research has two objectives: assessing the sensitivity of DDPM as predictors of daylight availability within a space and analyzing how these metrics are influenced by building architectural features. A comparison to the Daylight Factor DF as indicator of daylight availability is also carried out, so as to highlight the differences that the metrics ('static' versus 'dynamic') have in describing the daylight quantity and distribution in buildings.

2 Methodology

The approach relies on a parametric study to assess how the values of the dynamic climate-based daylight performance metrics vary as building/room architectural characteristics vary. The analysis was carried out by estimating, through simulations, the values of DDPM (Daylight Autonomy, Continuous Daylight Autonomy, Maximum Daylight Autonomy, Useful Daylight Illuminance and Annual Light Exposure) of several configuration of a single target office room. Daysim 2.1, a Radiance-based software that calculates daylighting through a dynamic climate-based annual simulation (Daysim website, 2011), was used for this purpose. As a first step, simulations were carried for the single target office room whose characteristics were changed in order to represent and cover typical office lay-outs, in particular: orientation, room depth, window area (expressed in terms of window-to-wall ratio WWR), external obstruction angle. The simulations were repeated for two sites, representative of continental and Mediterranean climate conditions (Torino and Palermo, respectively in the north and in the south of Italy). The configurations considered in this study belong to a huge database of Daysim simulations the authors created and used to investigate the building energy demand for lighting through the calculation of the LENI index according to the European standard CEN 15193 (CEN 15193, 2006), which was the object of a previous dedicated study (Pellegrino et al., 2010).

Table 1 shows all the design variables as well as their specific range and values.

Table 1. Design variables used for the Daysim simulations of a the target office room.

Site	Torino (latitude: 45,1° N)	Palermo (latitude: 38,3° N)					
Room orientation	south	north	west				
Room depth [m]	3	4,5	6	7,5	9	10,5	12
WWR [-]	0,2	0,3	0,4	0,5	0,6		
Obstruction angle γ [°]	0	15	30	45	60	75	

The daylight availability was analysed over the whole working plane (set at a distance of 75 cm from the floor) according to a 50 cm × 50 cm calculation grid. Room width and height were kept to constant values of 12 m and 3 m (net sizes) respectively, whilst the overall space depth varied from 3 m to 12 m with increment intervals of 1,5 m. All spaces are sidelit through vertical windows whose area was varied so as to determine WWR values of 0,2, 0,3, 0,4, 0,5 and 0,6, while the glazing visible transmittance was set to a constant value of 70 %. The window was 1,6 m high (only the window width was varied), with a sill set to a distance of 1 m from the floor. Not all the possible combinations of room depths and WWR were actually modelled and simulated: for deeper rooms larger window areas (resulting in higher WWR values) become necessary. The window-to-floor area ratio was always kept greater than 0,125, which is a reference value assumed in several Italian local regulations. The target room is located within a building whose height was varied so as to be constantly the same as a facing obstructing building: this is positioned 20 meters away from the target room façade with a variable height which determines 6 obstruction angles in the range 0° (unobstructed condition) to 75°, with increments of 15°. The target task illuminance was set equal to 500 lx, as required for most office tasks according to the European standard CEN 12464-1 (CEN 12464-1, 2002). In terms of occupancy profile, the room was considered to be continuously occupied Monday through Friday from 8:30 a.m. to 6:30 p.m.

The Radiance simulation parameters were set as follows: ab = 6; ad = 1000; as = 20; ar = 300; aa = 0,05. Simulations were run using climate files of Torino and Palermo with a time-step of 5 minutes.

3 Results

The use of Daysim allows both static and dynamic daylighting metrics to be calculated. For each case-study, the values over the working plane of DF and DDPM are predicted: these latter are in particular concerned with the Daylight Autonomy DA, the Continuous Daylight Autonomy DA_{con}, the Maximum Daylight Autonomy DA_{max}, the Useful Daylight Illuminance UDI ($UDI_{fell\text{-}short}$, below 100 lx; $UDI_{achieved}$, in the range 100-2000 lx; $UDI_{exceeded}$, over 2000 lx) and the Annual Light Exposure ALE. The various DDPM form quite an heterogeneous group, as they were proposed by different authors, based on different objectives. In principle, it seems possible to identify three main groups:

- The Annual Light Exposure ALE (CIE, 2004): it describes the daylight availability within a room throughout the year as the cumulative amount of daylight incident on a point of interest over the course of a year. This means that daylight availability is expressed in terms of a light dose, in [lux hours per year] and is not referred to any threshold value
- The group of Daylight Autonomies DA, DA_{con}, DA_{max} (Reinhart et al., 2001) (Walkenhorst et al., 2002) (Rogers, 2006): these use the time-varying daylight illuminance in a point as indicator to assess daylight availability within a room throughout the year, in particular referring the dynamic variation of illuminances to threshold values. For DA the threshold is the required illuminance for the considered space usage according to standards, so as to assess the percentage of the occupied times of the year when the illuminance requirement is met by daylight alone. A second threshold is also considered, set to ten times the illuminance requirement, to account for the occurrence of direct sunlight or other potentially glary conditions, giving an indication of how often and where large illuminance contrasts appear in a space (DA_{max})
- The group of Useful Daylight Illuminances $UDI_{fell\text{-}short}$, $UDI_{achieved}$, $UDI_{exceeded}$ (Nabil et al., 2005) (Nabil et al., 2006) (Mardaljevic, 2006): these also use work plane illuminance to assess daylight availability within a room throughout the year, but they refer the dynamic variation of illuminance values to both an upper and lower threshold (respectively 2000 lx and 100 lx), i.e. expressing the percentage of the occupied times of the year when illuminances lie in one of the three resulting

ranges (UDI<100 lx; 100<UDI<2000 lx and UDI>2000 lx). The three indexes together provide a synthetic view of the overall distribution of the illuminances during the year. The range UDI > 2000 lx, that in later publications was changed in UDI> 2500 lx (Mardaljevic, 2009), is meant to detect the likely appearance of glare.

Among the group of the DDPM that were calculated in this study, the ALE is the metric which describes the overall daylight availability inside a room, resulting for this reason somewhat comparable to the DF, as they both assess the indoor daylight quantity without referring it to a threshold value. Obviously it is important to stress out how the daylight factor is a ‘static' metric, expressed as the indoor to the outdoor unobstructed illuminance ratio, accounting for diffuse skylight in presence of overcast sky conditions only, while the ALE is a dynamic climate-based indicator which accounts for ‘realistic' direct sunlight and diffuse skylight conditions.

3.1 Sensitivity in describing daylight availability of DF compared to the dynamic metric ALE

A first analysis dealt with comparing the Daylight Factor DF and the Annual Light Exposure ALE. In Figures 1 and 2 Daylight Factors and Annual Light Exposures are compared in order to point out their different sensitivity in considering room orientations and site climate. In particular, in figure 1 the mean Daylight Factor calculated for each case-study is plotted versus the corresponding mean Annual Light Exposure for the three considered orientations (south, west and north-facing rooms). In spite of the inherent differences of the two metrics, a close fit can be observed between them if the data are correlated separately for the 3 orientations (a linear fit was found with $R^2 > 0,95$) The different gradient of the three functions confirms how the ALE metric accounts for the orientation of the room.

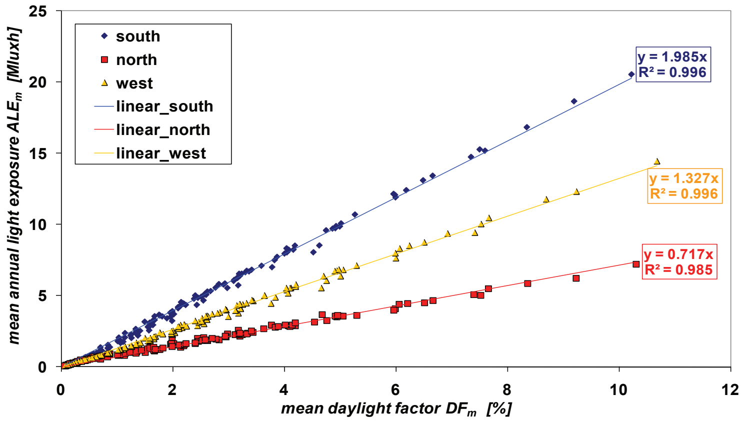

Figure 1. Mean daylight factor vs. mean annual light exposure for all case-studies relative to Torino: south, west and north-facing rooms are shown separately to highlight the fit between the 2 metrics.

In figure 2a, the sensitivity of the two metrics with respect to the room orientation is further analysed: in particular, the relative difference between north-facing and south-facing rooms located in Torino is shown. In figure 2b, the relative differences of DF and ALE for a same room located in Torino or in Palermo is plotted, so as to analyse how the two metrics account for the specific climate of the site.

In both cases the relative differences (ΔDF and ΔALE) were calculated considering the working plane mean value.

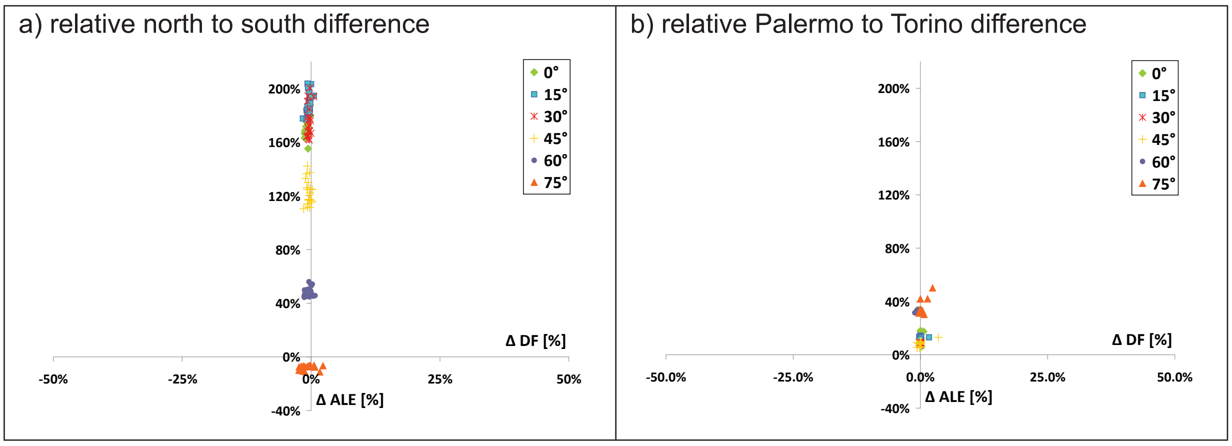

Figure 2. Relative difference of DF and ALE values for different room orientations and sites.

The data shown in both figures confirm how the Daylight Factor is not sensitive to orientation nor to the site latitude: the mean value of the relative DF differences between south and north-facing rooms is ΔDF_m= 0,5 % and ΔDF_m= 0,05 % for Palermo-based and Torino-based rooms. In other words, the difference tends to zero (if it is not *equal* to zero, as expected from DF definition, this is due to the simulations, which are based on Radiance which in turns relies on a Monte-Carlo algorithm to generate rays: this means that repeating the same simulation may result in slightly different results).

On the contrary, the ALE relative differences change in case of both different room orientation and site latitude: the mean relative difference between north oriented and south oriented configurations is ΔALE_m = 117 %; the mean relative difference between Palermo-based and Torino-based rooms is ΔALE_m =19 %. In particular, as far as the effect of orientation is concerned, the relative differences between north to south-facing rooms located in Torino are quite high for unobstructed configurations or in case of obstruction angles γ up to 30° (ΔALE_m = 179 %). As the obstruction angle raises, though, the relative differences decrease (ΔALE_m = 85 % for obstruction angles of 45° and 60°) and become negative for highest obstructions (ΔALE_m = -8 % for γ = 75°). In this latter case, in Torino the sun results shaded throughout the year: as a consequence, the role played by the orientation in achieving different daylight provision is drastically reduced. Negative ΔALE values, which imply a higher daylight availability inside north-facing rather than south-facing rooms, seem to be related to the multiple reflections of direct sunlight on both the obstruction and the target building itself.

On the other hand, the highest values of relative ALE differences between Torino and Palermo are observed for highest obstruction angles of 60° and 75° (ΔALE_m = 34 %), while they decrease for lower obstruction angles (ΔALE_m = 11 % for γ up to 45°). This seems to be related to the different sun position, higher in Palermo than in Torino for the same time-step: the higher the obstruction and the more frequently direct sun rays are shaded in Torino while they are not in Palermo.

3.2 Sensitivity of threshold-based DDPM compared to Annual Light Exposure and Daylight Factor

Analysing the database of results from the parametric study, it was observed that metrics inherently referred to threshold values (the groups of Daylight Autonomies and of Useful Daylight Illuminances) show to be more sensitive in describing the daylighting conditions obtained in a room with various architectural features (window area, room depth, orientation and obstruction angle) than the Daylight Factor or the Annual Light Exposure which account for the global daylight availability without referring to threshold values.

For instance a reduction of room depth from 7,5 m to 3 m causes an average 126 % and 122 % increase of DF and ALE respectively. This increment results almost constant for variation of obstruction angles, window sizes and orientations. This is confirmed by the value of the relative standard deviation (calculated as standard deviation to mean value ratio) that is 10 % for the Daylight Factor and 18 % for the Annual Light Exposure. Figure 3 shows the relative difference of the two metrics for different WWR, orientation and obstruction angles.

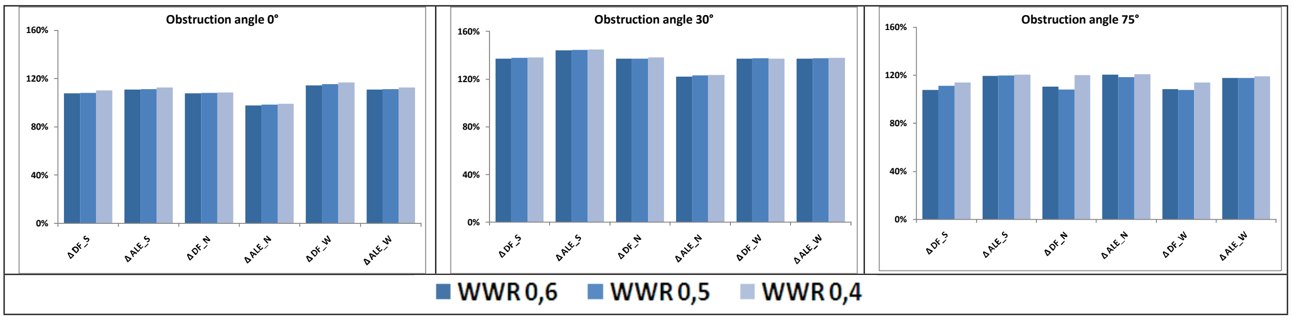

Figure 3. Relative increment of DF and ALE, for different window areas (WWR values), orientation and obstruction angles (γ), when the room depth is reduced from 7,5 m to 3 m. Case-studies with more meaningful WWR and γ values are shown.

It is interesting to stress out how results are rather different if the relative difference between the 7,5 m and 3 m rooms is assessed through threshold-based DDPM: the percentage variation of these metrics changes significantly with the room architectural features, as shown in figure 4 and table 2.

Table 2. Mean relative difference of DDPM (variant: room depth from 7,5m to 3m) and relative standard deviation

Statistic parameter	ΔDA_{m}	$\Delta DA_{con,m}$	$\Delta DA_{max,m}$	ΔUDI fell-short,m	ΔUDI achieved,m	ΔUDI exceeded,m
Mean	155,4%	74,6%	88,8%	-55,4%	54,2%	200,2%
Relative standard deviation [%]	37,6%	91,1%	91,1%	-32,5%	132,2%	137,8%

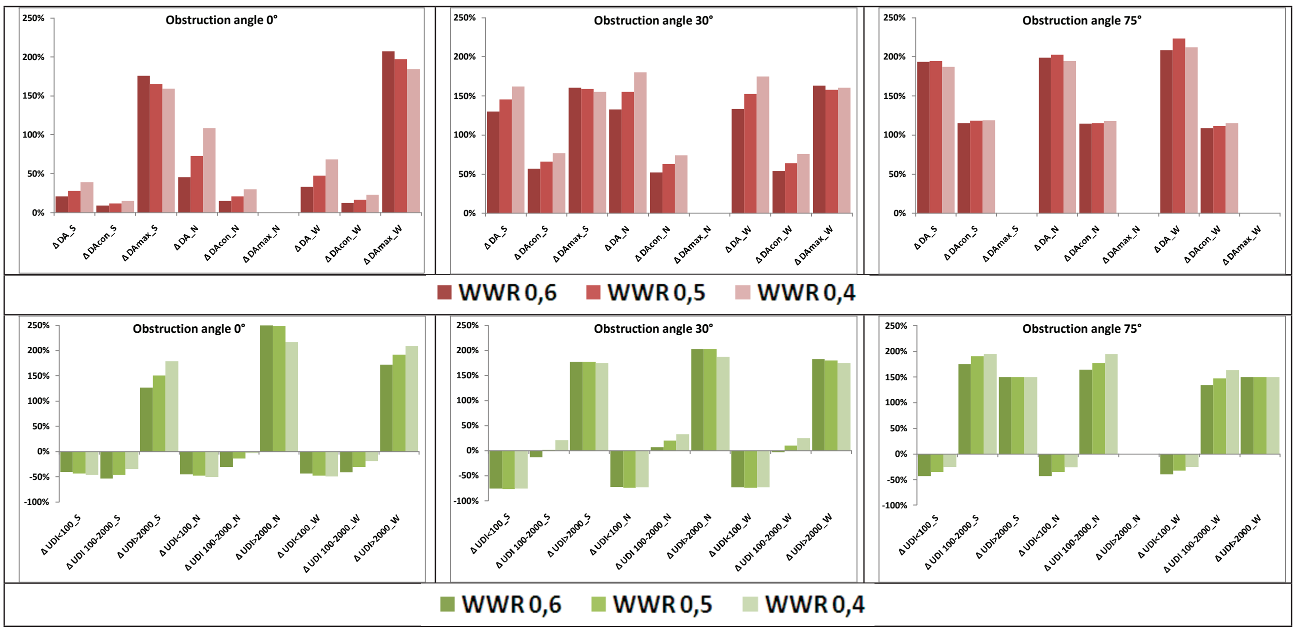

Figure 4. Relative differences of DA and UDI metrics, for various window areas (WWR values), orientation and obstruction angles (γ), when the room depth is reduced from 7,5 m to 3 m. Case-studies with more meaningful WWR and γ values are shown.

In particular, analysing data shown in figure 4, it can be observed how, if the room depth is reduced from 7,5 m to 3 m, the relative difference of the Daylight Autonomy ΔDA increases as the window area decreases, the obstruction angle increases and, for low obstruction angles, in presence of north-facing rooms. Highest obstruction angles, which determine the minimum daylight availability within the room, result in a decrease of the influence of the other room architectural features (window area and orientation). The relative differences of the Continuous Daylight Autonomy ΔDA_{con} show similar trends to the ones observed for the Daylight Autonomy ΔDA. The relative differences of the Maximum Daylight Autonomy ΔDA_{max} equal to zero in presence of high obstruction angles and for north-facing rooms: in these cases, illuminance values remain below the threshold value of 5000 lx independently of the room depth.

Similarly, as far as the group of UDI metrics is concerned, it emerges how the relative differences between room depths of 3 m and 7,5 m are influenced by room architectural features.

3.3 Variation of daylight availability as expressed by DDPM, depending on room architectural characteristics

In this section, the influence on daylight availability of varying room features is assessed. For this purpose, figure 5 summarises the DF and of DDPM which were obtained for all case-studies relative to south-facing rooms located in Torino. The impact of site latitude and room orientation was discussed earlier in this paper; for this reason, this analysis is ‘restricted’ to a single site and orientation.

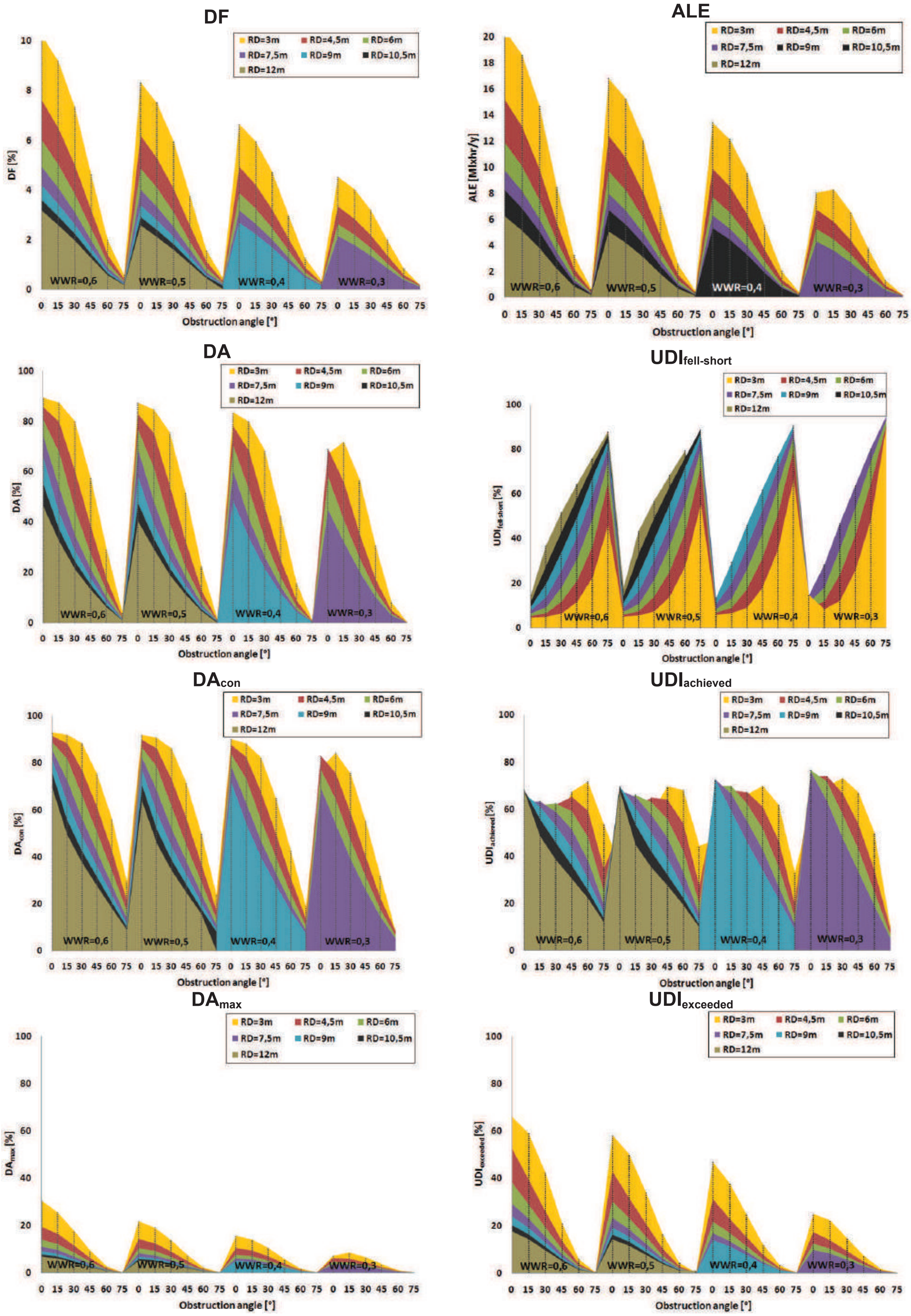

Figure 5. Mean DF and DDPM values for all south-facing case-studies.

Based on the analysed dataset, two aspects were evaluated:

a) How varying window area influences the daylight availability within a space as a function of the room depth; in particular, the impact of increasing the window area in little deep rooms compared to medium deep rooms was analysed

b) How varying the obstruction angle influences the daylight availability within a space as a function of the room depth; in particular, the impact low or high-raise obstructions have in rooms of small, medium or high depth was analysed.

A summary of most meaningful results is shown in table 3. For the analysis, the group of UDI metrics was used, so as to take advantage of the fact that three sub-ranges of $UDI_{fell\text{-}short}$, $UDI_{achieved}$ and $UDI_{exceeded}$ cover continuously the overall range of illuminance values. The Annual Light Exposure is also shown to represent the variation of the annual global daylight availability.

Table 3. Relative differences in UDI and ALE metrics for variation of the window area or of the obstruction angle for different room depths.

Variant	Room depth [m]	Mean relative difference of UDI and ALE [%]			
		ΔALE	$\Delta UDI_{fell\text{-}short}$	$\Delta UDI_{achieved}$	$\Delta UDI_{exceeded}$
WWR: 0,2 → 0,4	small depth	191	-47	196	251
WWR: 0,4 → 0,6	small depth	56	-28	2	72
	medium depth	57	-23	19	76
γ: 0° → 30°	small depth	-32	95	43	-46
	medium depth	-38	234	-14	-47
	high depth	-39	252	-41	-46
γ: 0° → 60°	small depth	-85	546	47	-93
	medium depth	-86	619	-48	-93
	high depth	-86	439	-67	-92

As far as the role played by the window area is concerned, the most meaningful results can be summarised as follows:

- For little deep rooms (relative difference averaged over 3 m and 4,5 m), increasing the window area from WWR = 0,2 to WWR = 0,4 seems an effective solution as the $UDI_{achieved}$ increases considerably, the $UDI_{fell\text{-}short}$ decreases accordingly and even though the $UDI_{exceeded}$ shows a considerable increase, it remains quite low in terms of absolute values
- For little deep rooms, increasing the window area from WWR = 0,4 to WWR = 0,6 does not result as effective as one might expect: actually, a reduction of $UDI_{fell\text{-}short}$ occurs but on the other hand $UDI_{achieved}$ remains almost unchanged and $UDI_{exceeded}$ increase considerably. As a result, notwithstanding the absolute daylight availability increase (ΔALE = 56 %) a real improvement of the daylight condition is not achieved
- For medium deep rooms (relative difference averaged over 6 m, 7,5 m and 9m), increasing the window area from WWR = 0,4 to WWR = 0,6 assures a little increase of $UDI_{achieved}$, whilst on the other hand $UDI_{exceeded}$ raise up more considerably.

As far as the role played by the obstructions is concerned, the most meaningful results can be summarised as follows:

- For little deep rooms, increasing the obstruction angle from γ = 0° to γ = 30° results in an increase of $UDI_{achieved}$ to which correspond a decrease of $UDI_{exceeded}$ values.
- For medium and very deep rooms (relative difference averaged over 6 m - 12 m), increasing the obstruction angle from γ = 0° to γ = 30° produces, despite a ΔALE similar to the previous case, a higher increase of $UDI_{fell\text{-}short}$ to which correspond a decrease of 'good' $UDI_{achieved}$.
- Increasing the obstruction angle from γ = 0° to γ = 60° results in an increase of $UDI_{fell\text{-}short}$ for all room depths, to which correspond a decrease of $UDI_{achieved}$ values in the case of medium and very deep rooms. For little deep rooms, on the contrary, the $UDI_{achieved}$ is increased to the detriment of $UDI_{achieved}$.

3.4 A further approach to describe time-varying daylight illuminances

The climate-based daylight modelling is a tool with high potentials to enhance daylighting design for both energy savings and visual comfort purposes. Earlier studies highlighted that main limits of the CBDM approach are concerned with the huge dataset of results which is the output of the annual modelling and with the subsequent necessity of introducing synthetic metrics to interpret them (CIE, 2008). For this reason, different authors proposed some Dynamic Daylight Performance Metrics, as briefly presented earlier in this paper: in particular, the Useful Daylight Illuminance metrics have the merit to synthesise the time-varying illuminances into three or more indices, each of them expressing the percentage of occupied time when illuminance values lie below, within or over certain thresholds. This way, a synthetic representation of the overall dynamic variation of illuminances throughout the year is given. For instance, in the study presented in this paper, the percentage of occupied time when illuminance values resulted below 100 lx, in the range 100 – 2000 lx and over 2000 lx was identified. In other studies, Mardaljevic (Mardaljevic, 2009) introduced different threshold values (the upper limit was raised up to 2500 lx) and further subdivided the range of achieved illuminance (100-2500 lx) into smaller ranges (100-500 and 500-2500). It is clear how the more illuminance threshold values (and hence resulting ranges) are used and the more detailed is the information on the distribution of illuminance. It is worthwhile noting, though, how the approach based on DDPM has not been standardised yet. The CIE recently established a dedicated Technical Committee (CIE website) to find a shared consensus on these metrics. Presently, the threshold values to consider which illuminance values are "useful" to carry out a visual task, "exceeded" to account for the likely appearance of glare or "fell-shot", i.e. insufficient to guarantee the autonomy of daylight, are still to be defined in an unambiguous way (CIE, 2008).

All this said, as a final output of the study presented in this paper, a further method to represent time-varying illuminances is proposed: this allows both calculating the value of current DDPM and showing at the same time the complete distribution of illuminance values obtained from the CBDM over time and space. This approach is based on graphically plotting the frequency distribution of the overall dataset of calculated illuminance values, associated with the cumulative distribution curve (examples are shown in figure 6). This kind of graphical representation was successfully used in the past by researchers of the TEBE group to evaluate the risk index for conservation of works of art depending on environmental conditions (Filippi et al., 1999) and adopted as standard procedure by a dedicated Italian norm (UNI 1999).

Applied to the CBDM, this representation allows:

- visualising in detail, for user-defined intervals (for instance, intervals down to 100 lx), the distribution of illuminance values over time and space
- identifying, through the cumulative frequency curve, the value of synthetic metrics based on standard or user-defined thresholds by visually and quickly reading the different daylighting availability within different rooms or for different design solutions for a same room.

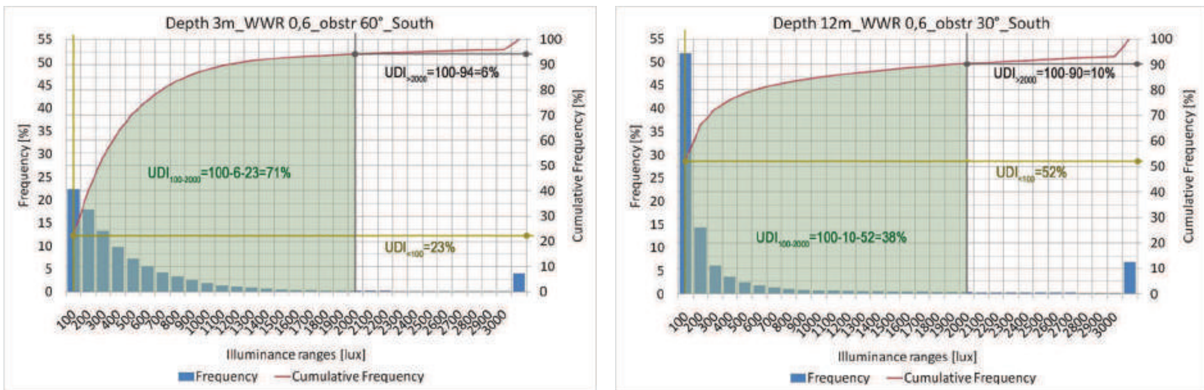

Figure 6. Frequency distributions and cumulative distribution curve for two rooms with different architectural characteristics but similar values of DF_m and ALE_m and identification of the UDI.

As an example, figure 6 shows the distribution frequency and the cumulative distribution curve for the illuminances calculated for two rooms with same orientation (south) and window area (WWR = 0,6), but with different room depth (3 m versus 12 m) and obstruction angle (60° versus 30°). Both rooms are characterised by similar values of DF (DF_m = 1,99 % vs. DF_m = 1,96 %) and ALE (ALE_m = $3{,}23\times10^6$ $Mlx\cdot h\cdot a^{-1}$ vs. ALE_m = $3{,}81\times10^6$ $Mlx\cdot h\cdot a^{-1}$) but the two graphs clearly show how different the daylight conditions are within the rooms in dependency of specific architectural features. This is confirmed by the synthetic UDI metrics, whose values were identified from the cumulative distribution curve.

4 Conclusions and discussion

This paper reports some first results obtained from a large number of climate based daylighting simulations carried out for a reference room with different architectural features. The final goal of the on-going research activity is to provide architects and designers with more detailed information about the consequences on daylighting due to different architectural solutions, as well as, the other way around, with strategies to guarantee a desired energy and/or environmental performance.

In this paper some early considerations about the efficacy of CBDM with respect to a ‘static' modelling approach, the metrics to describe time-varying daylighting and the influence of rooms features on annual daylighting conditions are presented.

In particular, once more, the higher sensitivity of CBDM with respect to static simulation (that considers a single static overcast sky condition), is pointed out by comparing the DF results to the ALE results. The two quantity are highly correlated but, unlike DF, the dynamic metric (ALE) shows to vary with orientation and latitude. Furthermore, among the DDPM, metrics based on one or more threshold values provide more detailed information on actual annual daylighting conditions as a consequence of the specific room architectural features. It was in fact demonstrated that the relative difference of ALE, for instance reducing the room depth, is kept almost constant independently of the WWR, obstruction angle and orientation, while, for the same case-studies, the variation of DA and UDI metrics are quite different. These results show the importance of analysing the illuminance distributions rather than calculating the global amount of annual daylight quantities.

With this perspective a further approach to analyse the huge amount of results obtained from CBDM is here proposed. The tool consists of a graphical representation of the frequency distribution of illuminances, that are obtained over the working plane and during the considered simulation period (a year f.i.), together with the cumulated frequency curve. The graph, if small illuminance ranges are used to calculate the frequency (100 lx f.i.), enables to immediately visualise the overall illuminance distribution and to draw the values of the DDPM, even eventually changing the threshold values on the basis of specific analysis conditions.

Further results presented in the paper deal with the analysis of how indoor daylighting is influenced by room architectural features. Some information about the effectiveness of increasing window area in rooms with different depths or on the influence of external obstructions is given.

All presented results are obtained by simulations of rooms where movable shading devices are not considered. The research activity is in fact still on-going and the adoption of movable shadings as a further variable is part of near future work. It is likely that considering movable shading devices would partially reduce, but not eliminate, the differences between DDPM and static metrics as the presence of direct sunlight inside the rooms, which yields the greatest differences, will be drastically reduced. Similarly the influence of architectural features, when considering shadings could be slightly different.

Acknowledgements

This work was carried out within the national research program PRIN 2008, titled “Daylighting design for energy saving and visual comfort purposes: climate-based daylight modelling, glare indices and integrated ventilation system performances”, co-financed by the Italian Ministry for Universities, Education and Research (see: http://www.polito.it/tebe).

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Paper II:

‘Limits and potentials of different daylighting design approaches based on dynamic simulations’

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In proceedings:
CISBAT: CleanTech for Sustainable Buildings – From Nano to Urban Scale
2011, Lausanne, Switzerland.

LIMITS AND POTENTIALS OF DIFFERENT DAYLIGHTING DESIGN APPROACHES BASED ON DYNAMIC SIMULATIONS

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ABSTRACT

This paper presents the results of some daylighting design applications which were developed within courses and works of theses carried out at the Faculty of Architecture of the Politecnico di Torino. Different approaches were used depending on the characteristics and aims of the analyzed case-study: in particular physical models under a sun simulator facility and numerical tools such as Daysim and Lightsolve. Final goal of the paper is to show potentials and limits concerned with each approach in usefully analyzing and representing the results of a lighting analysis from a designer's point of view and in which stage of the design process its application is more appropriate.

1. INTRODUCTION

During the last decade a number of new metrics and numerical simulation tools have been developed and made available, which allowed passing from a static to a dynamic building modelling. The so-called Dynamic Daylight Performance Metrics DDPM [1] are parameters able to account for the dynamic variation of skylight and sunlight conditions during the course of the year as a function of the specific climate conditions of a site and of the orientation of the considered building. Although the higher level of advance in dynamically analyzing the overall performances of daylit spaces, current daylighting design practice still favors prior experiences and rules of thumbs during schematic design and largely relies on the daylight factor [2]. More over a methodological guideline for applying a dynamic daylighting design approach has not been standardized yet. Most of daylighting design tools presently available are based on Radiance, with the result that expert users are often needed to carry out simulations. As a result, designers still have troubles to adopt a dynamic approach since the early design stages and throughout the whole design process. In the following sections, some case-studies of architectural designs where daylighting was considered as one of the key design factors are presented together with a discussion of how the dynamic approach was addressed during each design stage through different design tools.

2. DAYLIGHTING DYNAMIC DESIGN APPROACHES IN ARCHITECTURAL DESIGN

The presented case-studies are concerned with redesigning a no longer used industrial building to be converted into a public library: this is a type of building for which daylight plays a crucial role with regard to both the visual tasks users have to carry out and their perception of visual comfort conditions. The existing building is characterized by large open-plan spaces which are both sidelit and toplit through large clerestory windows (figure 1). Two projects in particular are described in detail: these were both aimed at optimizing daylighting conditions within the redesigned building through a dynamic design approach, but different procedures and tools were used. Furthermore, different design concepts were assumed: in the first case, a 'conservative' approach was chosen, aimed at keeping the shape and the structure of the existing building, whilst in the second case the whole structure and the roof were completely redesigned. As a result, a totally new building was conceived.

Figure 1: Design site and images of the existing building

2.1 'Conservative' project

The design concept was based on taking advantage of the large open-plan toplit spaces the building offers. For this purpose, a dynamic daylighting design approach was adopted, consisting of the following phases:

1. analysis of direct sunlight penetration for some representative days and hours throughout the year (December 21st from 9 to 16, March 21st from 7 to 18, June 21st from 8 to 20), aimed at visualizing areas where glare/overheating problems due to sunlight might occur;
2. definition of spaces lay-out and first hypothesis for daylighting systems;
3. verification of resulting daylight availability through a Climate-Based Daylight Modeling, CBDM [3], and critical analysis of obtained values of Dynamic Daylight Performance Metrics, DDPM [1];
4. further analysis of direct sunlight penetration to better investigate the contribution of sunlight to DDPM values and to identify time-steps during the year with potential thermal/visual discomfort problems;
5. identification of solutions to correct problems which were observed, based on modifying daylighting systems' properties and on designing specific shading systems;
6. further analysis of daylighting results to verify the efficacy of defined daylighting and shading systems.

Different design tools were used throughout the design stages to achieve above design goals. For the analysis of direct sunlight penetration a 1:100 scale model under the sun simulator available at Politecnico di Torino was used: for each aisle of the building the images of direct sunlight penetration corresponding to different hours of the day and days of the year were superimposed, so as to identify which parts of the floor area may suffer from glare or overheating during the year due to direct sunlight (figure 2a). Architectural strategies in terms of space lay-out and transparent/opaque materials were set based on this analysis (figure 2b shows an example relative to the reading room). The resulting overall annual daylight availability was then verified through a CBDM by means of Daysim 2.1, a Radiance-based software which allows running a climate-based annual simulation (with a time-step down to 5 minutes) and provides with values of the Daylight Factor (DF), and of DDPM based on a user-defined occupancy profile and target illuminance. The results found for the reading room are shown in figure 2c: the average Daylight Factor over the room met the value prescribed by Italian standards (DF_{mean}>3%) but a non-uniform distribution of illuminances was highlighted. The average $UDI_{achieved}$ over the room yielded a high level for most of the reading area. Beside this, values of Maximum Daylight Autonomy over 5% were observed, which suggests a possible occurrence of direct sunlight or other potentially glary conditions [4]. It is important to stress out that DDPM values provide a synthesis of daylighting conditions occurring during a time interval: thanks to this synthesis, they can result useful to identify areas with good daylight potentials as well as areas with potential problems. On the other hand it's not possible to identify if sunlight or diffuse skylight is responsible of the obtained DDPM and for which time-step critic conditions appear. For this purpose, a further set of analyses of direct sunlight penetration was specifically carried out by using a virtual model in

Ecotect with the aim of detecting specific time-steps during the year with potential thermal/visual discomfort problems. Based on this analysis, new design solutions were defined: in particular, movable shading devices and opaque partitions plus fitted glazing were adopted respectively for the skylight clerestory windows and the west-facing windows to reduce sunlight penetration within the reading area. The resulting daylight availability was then calculated through Radiance simulations so as to verify the illuminance distribution within the space for specific time-steps identified through earlier sunlight analysis with Ecotect and for which movable shading devices resulted to be necessary. In this phase, Radiance was used as Daysim doesn't allow running a simulation for a period of time other then the full year and to simulate specifically designed movable shadings.

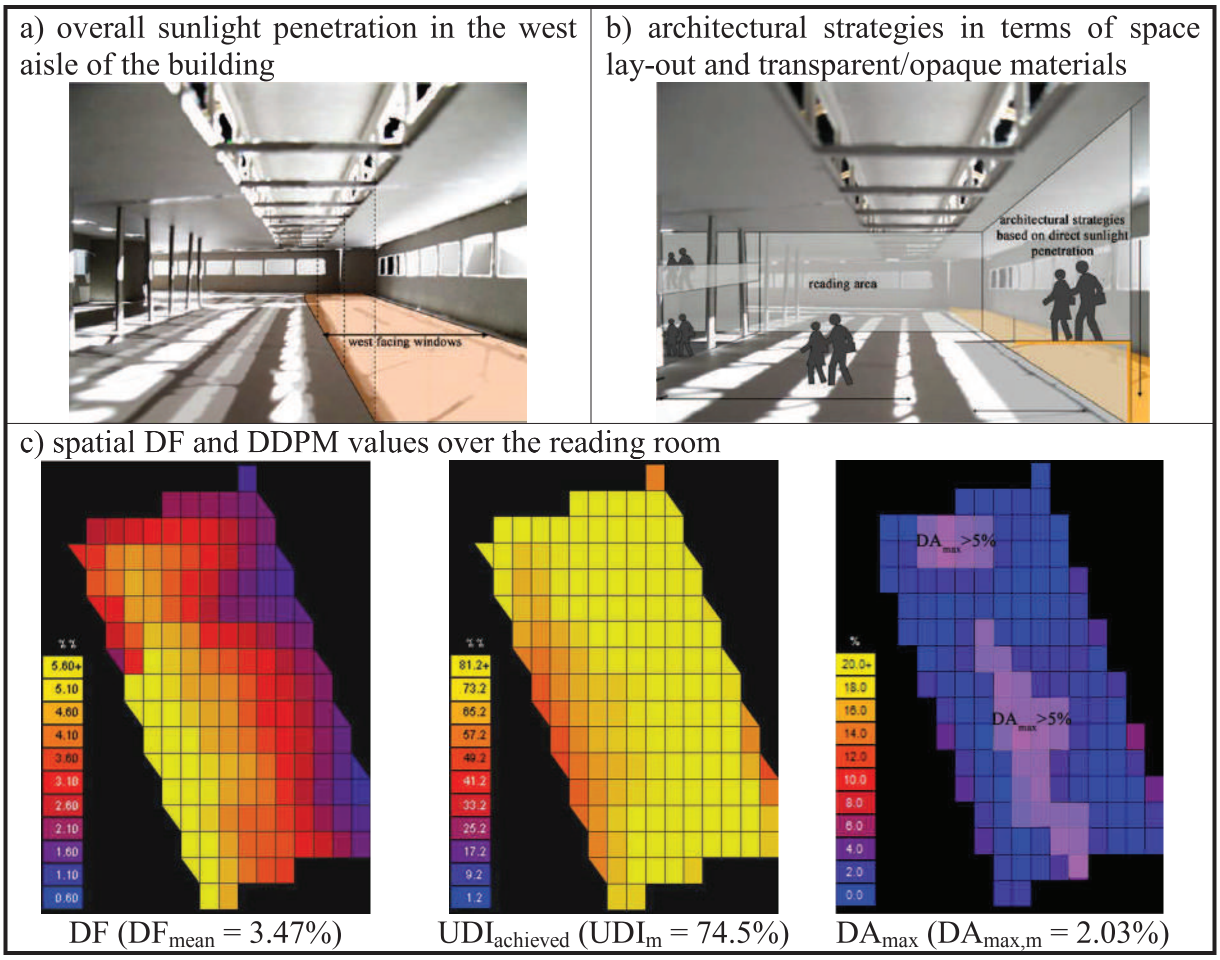

Figure 2: Results of the analyses carried out for the case of the 'conservative' project.

2.2 Design of a new building

The concept of the project was to design a new building with a public terrace on the roof for users of the library. As a consequence, the existing roof, with zenithal daylighting system, was completely redesigned. On this first design hypothesis a dynamic daylighting analysis was carried out to verify the annual daylight availability, and results were used to correct the preliminary project in order to optimize daylighting condition with respect to visual comfort. Unlike the previous example, in this case a single tool was used to study the interaction between daylight and the building, and the analysis was reiterated, modifying different building features such as internal partitions, openings dimension, shape and characteristics, until a satisfactory solution was achieved. The tool adopted for the lighting analysis is Lightsolve, a software developed by the M.I.T. Daylighting Lab, Department of Architecture, Building Technology Program [5,6] whose aim is to support the daylighting design process using a goal-based approach. The tool proposed is a quickly calculating annual data sets for which temporal maps and spatial renderings are the graphical outputs. For user-defined illuminance thresholds, the temporal maps gives an outcome with different colors, based on the portions of the results that meet, overstep or don't reach the goals set by user. The annual data set is simplified splitting the year into 8 periods of similar season and 7 daily moments.

The first step of the daylighting design approach was to create a 3D model of the building and of the outdoor context using Sketch-up. The model was simplified as much as possible, taking care of reproducing all the building elements influencing daylight penetration while simplifying all other details. After preparing the 3D model a simulation with Lightsolve was carried out to evaluate both direct sunlight penetration and global illuminance in different building areas where daylighting was of particular importance, in some case for the need of maximizing its availability in other case for the need of reducing it (reading areas, conference room, multimedia areas, etc.). Results obtained from the first simulation for some representative areas are presented in figure 3a. Illuminance temporal maps pointed out an excessive amount of daylight in the reading areas compared to the designer illuminance requirements. Furthermore, as shown by internal renderings, direct solar radiation, penetrating through skylights and vertical east-facing windows, interested the reading area during most hours of the day and months of the year with high probability of glare and summer overheating occurrence. A number of changes were applied to the initial project on the basis of the daylighting results and new Lightsolve simulation were run until satisfactory results in terms of sunlight protection and daylight availability were achieved for the whole year and for the different library areas. In figure 3b the final solution and the corresponding daylighting results for the previously presented library areas are reported.

3. RESULTS

Applying a dynamic daylighting approach to the case-studies described earlier showed some main potentials and limits concerned with the design tools which were adopted, especially with regards to the different stages of the design process.

With regard to the *early daylighting design stage*, in the case of the 'conservative' project, an analysis of sunlight penetration into the building was carried out with a scale model under a sun simulator. This offered the advantage of a direct visualization of sun patches, but on the other hand evaluations were limited to a number of time-steps and days throughout the year, since an overall annual simulation would have been time-consuming. Furthermore, the analysis was qualitative, limited to the direct sunlight component only, thus without accounting for diffuse skylight, with a consequent lack of quantitative results. This implied to proceed to more detailed, software based, analysis to have an exhaustive description of dynamic daylight availability in indoor spaces. In the second case instead, the early daylighting design stage was addressed through Lightsolve. This produced fast climate-based annual analyses with reasonably comprehensive outputs, hence allowing the design team comparing different design solutions. Available outputs consisted of both quantitative and qualitative data, in terms of temporal maps of illuminances and spatial renderings. The temporal maps display the dynamic variation of illuminances averaged over the space: as a result, no quantitative information is given about the illuminance spatial distribution. This can be qualitatively assessed through rendered images. Moreover, the possibility for users to set the illuminance requirements offers a consistency with the objectives of daylighting design for the specific building usage. On the other hand, main drawbacks appeared to be concerned with some difficulties in setting up the model consistently (Lightsolve can hardly handle increased model complexities) and with the limited number of time-steps the program assumes to run the annual simulation.

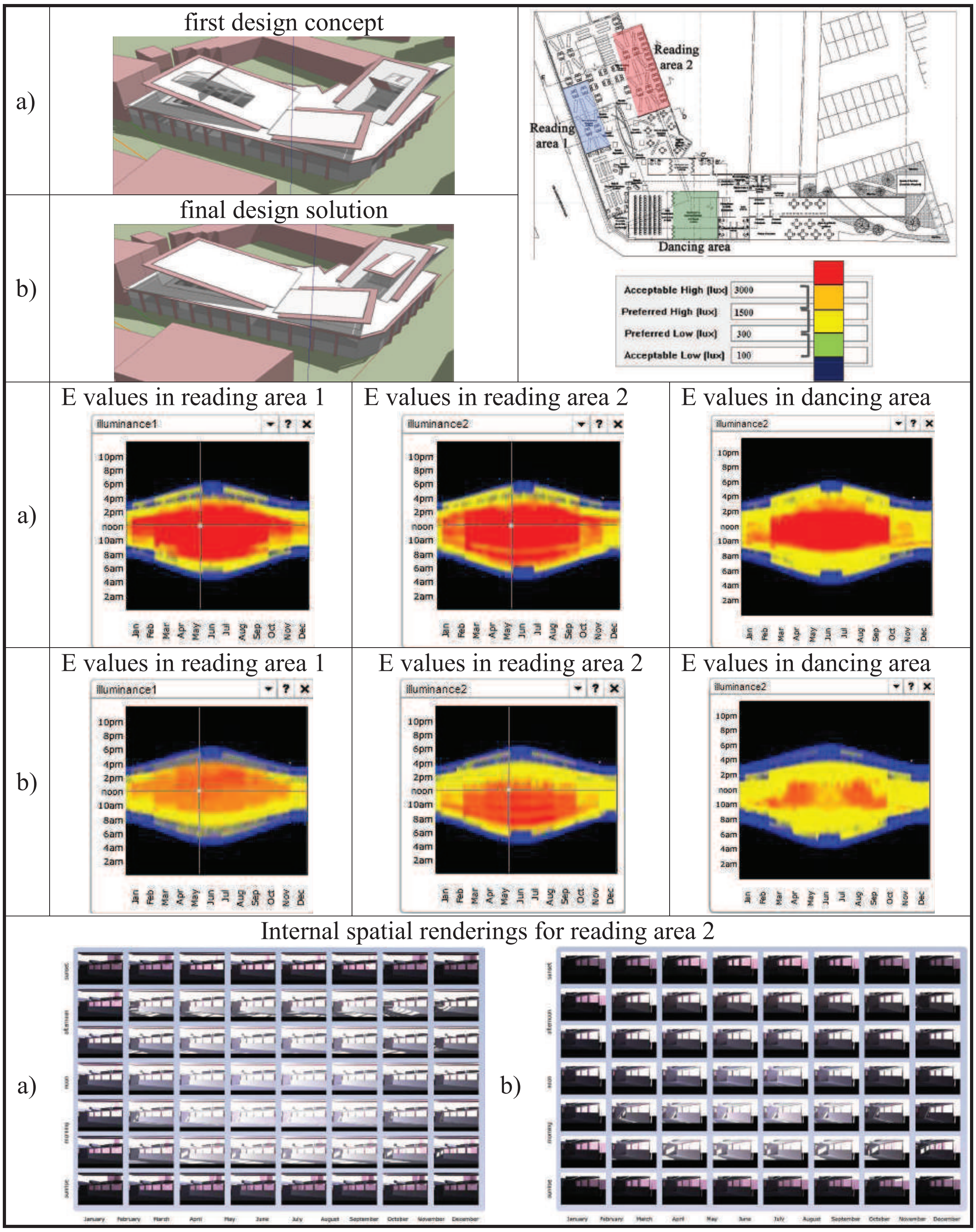

Figure 3: Lightsolve results referred to some of analyzed areas: first design concept (a) and final design solution (b)

In short, Lightsolve proved to be effective in assessing the dynamic annual daylight availability in the early design stage, whilst it appears to be somewhat limited to address a detailed annual analysis, in presence of complex daylighting systems (i.e. movable shadings).

As far as the *more advanced design stages* are concerned, these were addressed for the case of the 'conservative' project only, mainly through Daysim. This allowed running detailed annual simulations taking advantage of short time-steps users can set (down to 5 minutes). The results available for the design team consist of a set of metrics which synthesize the daylight availability throughout the year, including potential occurrence of glary conditions. It is possible to observe the spatial distribution of daylight within a space, but it is not possible to identify the daylight levels which are available for desired time-steps. Other limits seem to be concerned with the impossibility for users to define the illuminance thresholds to which refer the UDI or the DA_{max} calculation and with long simulation times in presence of complex models. Furthermore, being a Radiance based calculation tool, it requires expertise on how to set the calculation parameters with respect to the desired results accuracy.

It is worth noticing that in the case of the design of a new building, the design team did not proceed to a 'detailed' daylighting design, as the information provided by Lightsolve during the early design stage was considered sufficient to prove the efficacy of the design solutions.

4. Conclusions

Addressing a daylighting design through a dynamic approach allows assessing daylight availability within a space with higher accuracy than an analysis based on the daylight factor only, in terms of both determining quantity and quality of daylight and of verifying potential visual and thermal discomfort problems due to direct sunlight penetrating into a room. A dynamic approach allows a more conscious architectural design which is integrated with the design site and its climate conditions, also accounting for the effect of the orientation. Nevertheless, it should be noted that, while the dynamic daylighting design approach is becoming more and more diffuse within the scientific community, it still results hard to be correctly understood and applied by the designers. Certainly as long as building standards and rating scheme have generally remained on static approach designers are not involved to move towards more advanced daylighting analysis [2]. Consequently, a more widespread knowledge of a dynamic daylighting approach is desirable to make accessible to practitioners.

Acknowledgements

Work carried out within the research program 'Daylighting design for energy saving and visual comfort purposes: climate-based daylight modeling, glare indices and integrated ventilation system performances' (http://www.polito.it/tebe). Projects developed respectively by Chiara Tamburini e Abel Silva Lizcano.

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Paper III:

‘A graphical tool to predict the daylight availability within a room at the earliest design stages’

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In proceedings:
CIE Centenary Conference – Towards a new Century of light.
2013, Paris, France.

PP084

A GRAPHICAL TOOL TO PREDICT THE DAYLIGHT AVAILABILITY WITHIN A ROOM AT THE EARLIEST DESIGN STAGES

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Abstract

This paper presents a graphical tool which is intended to be used during the earliest design stages to predict the daylight amount within a space as a function of different architectural features. The daylight amount is expressed in terms of Daylighting Dynamic Performance Metrics, DDPM, resulting from a climate based daylighting simulation. The tool was built based on the results from a parametric study carried out for a sample room with different room orientation and depth, window area, visible transmittance and external obstruction angle. The analysis was repeated for three sites, representative of different climate conditions (Turin and Catania - Italy - and Berlin – Germany). The paper describes the graphical tool which was developed and how it could be fruitfully used by the design team to predict the daylight availability within a space. Potentials and drawbacks of the proposed tool are also discussed in comparison with other tools which are commonly used during the earliest design stages of the daylighting design process (such as the average daylight factor formula or the recent software Lightsolve). It is shown that the information obtained through the different tools is consistent and that the proposed graphical tool can be useful for the design team, as it offers different information about the daylight availability within the designed space.

Keywords: Daylighting design, Climate-Based Daylight Modeling, Dynamic Daylight Performance Metrics

1 Introduction

According to the latest energy certification legislations, the need for a more rational use of renewable resources results in an increased use of daylight and its conscious integration with electric lighting. The amount and distribution of natural light admitted into a space depending on the architectural solutions developed by the design team plays a crucial role both on the environmental quality and on the energy demand due to the HVAC and lighting systems. Daylighting design should be nowadays fully integrated into the overall design process and should therefore be approached since the earliest design stages, when options concerned with the building mass, shape and orientation and the daylighting systems' technologies are initially explored. In this regard, different tools are available along the architectural process: at the beginning, the design team can rely on a number of rules of thumb or simplified analytical equations such as the average daylight factor formula (Reinhart et al., 2010).
At this stage, the daylight availability is quickly and roughly assessed so as verify if the first design solutions are acceptable, postponing to a later stage a more accurate analysis of daylight conditions and energy needs through the use of sophisticated dynamic simulations tools such as Radiance, Daysim or EnergyPlus. In general terms, even if a more advanced daylighting design approach is becoming more and more widespread within the scientific community, designers and practitioners still have problems to adopt it (Reinhart et al., 2011).
Within this frame, a graphical tool was developed to express the daylighting performance of a room depending on its architectural characteristics: room depth, window area and obstruction angle. The tool provides more detailed information compared to other simple and quick evaluation methods, such as the average daylight factor, as it is based on climate based daylight analysis and it returns values of the so-called 'Dynamic Daylight Performance Metrics' (DDPM) (Reinhart et al., 2006) for the considered room. These are recently proposed parameters able to account for the dynamic variation of skylight and sunlight conditions during the course of the year as a function of the specific climate conditions of a site and of the orientation of the considered building (Climate Based Daylighting Modeling - CBDM). This

paper has two primary goals:

1. presenting the graphical tool which was developed and describing how this could be fruitfully used by the design team to predict the daylight availability within a space with different architectural features;
2. discussing potentials and drawbacks of the proposed tool in comparison to other tools which are commonly used during the earliest design stages of the daylighting design process, in particular to the analytical formula to calculate the average daylight factor for a room reported in the European Standard EN 15193 (CEN, 2007) and to a new software called Lightsolve (Andersen et al., 2008), (Kleindienst et al., 2008).

2 Method

The graphical tool was built based on a sub-dataset of results of a more thorough parametric study which has been carried out to assess how both the values of the dynamic climate-based daylight performance metrics and the related energy demand for lighting vary in response to the variation of a number of variables. The analysis was carried out by estimating, through simulations, the values of DDPM (Daylight Autonomy, Continuous Daylight Autonomy, Maximum Daylight Autonomy, Useful Daylight Illuminance and Annual Light Exposure) as well as the annual energy need for several configurations of a target room. Daysim, a Radiance-based software that calculates daylighting through a dynamic climate-based annual simulation, was used for this purpose.

Simulations were carried out for a target room, some characteristics of which were changed in terms of orientation, room depth, window area (expressed in terms of window-to-wall ratio WWR), external obstruction angle. The simulations were repeated for three sites, representative of different latitudes and climate conditions (Turin and Palermo – Italy, Berlin – Germany) and considering North, West and South windows orientation. The indoor daylight availability was analyzed over the whole working plane (set at a distance of 75 cm from the floor) according to a 50 cm * 50 cm calculation grid. Room width and height were kept to constant values of 12 m and 3 m respectively, whilst the overall space depth varied from 3 m to 12 m with increment intervals of 1.5 m. All spaces are sidelit through vertical windows whose area was varied so as to determine WWR values of 0.3, 0.4, 0.5 and 0.6. The window was 1.6 m high (only the window width was varied), with a sill set to a distance of 1 m from the floor. The glass transmittance was varied from 35% to 90%, while the window-to-floor area ratio was always kept greater than 0.125, which is a reference value assumed in several Italian local regulations for ventilation purposes. All walls and window frames had a diffuse reflectance of 50%, while floors and ceiling diffuse reflectance values were set equal to 20% and 80% respectively. The target room is located within a building whose height was varied so as to be constantly the same as a facing obstructing building: this is positioned 20 meters away from the target room façade with a variable height which determines 6 obstruction angles in the range 0° (unobstructed condition) to 75°, with increments of 15°. The target task illuminance was initially set equal to 500 lux, a typical value required for reading or VDT-based activities according to the European standard CEN 12464-1 (CEN, 2011), while in further development of the study it was set at lower and higher values to consider also other type of activities. In terms of occupancy profile, the room was considered to be continuously occupied Monday through Friday from 8:30 a.m. to 6:30 p.m. The effect of an automated shading system, consisting of a Venetian blind with a diffuse transmittance of 25% (when in the closed position), was considered in the simulations so as to account for the need of reducing glare and overheating phenomena over the working plane. In particular, the algorithm implemented in Daysim to account for the use of shading systems assumes that the blind is automatically pulled down whenever an irradiance of 50 W/m2 hitting any point of the working plane is detected (Reinhart, 2006). The use of the blind was simulated for South and West-facing spaces only, while it was excluded for the corresponding North-facing ones.

As a result, a huge database of Daysim simulations has been created by the authors and used to investigate daylighting and the building energy demand for electric lighting, which has been already the object of some previous publications (Pellegrino et al., 2011), (Pellegrino et al., 2010).

For this present study, which focuses on the daylight availability within the considered room, a sub-dataset was used. Table 1 summarizes all the design variables which were assumed in the parametric study as well as their specific range and values: the variables and the range considered for this present study are highlighted in bold and through a grey background.

Table 1 - Design variables used for the Daysim simulations of a target room.

Site	**Turin (L = 45.1°N)**	Catania (L = 37.5°N)	Berlin (L = 52.5°N)				
Room orientation	**South**	**North**	West				
Room depth, RD [m]	**3**	**4.5**	**6**	**7.5**	**9**	**10.5**	**12**
Window-to-wall ratio, WWR [-]	**0.3**	**0.4**	**0.5**	**0.6**			
Obstruction angle, γ [°]	**0**	**15**	**30**	**45**	**60**	**75**	
glazing visible transmittance, τ_{vis} [%]	35	50	**70**	90			
average target illuminance, E_{target} [lux]	150	300	**500**	750			
lighting control system	manual on-of switch	daylight photosensor					

The Radiance simulation parameters were set as follows: ab = 6; ad = 1000; as = 20; ar = 300; aa = 0.05. Simulations were run using climate files of Turin, Catania and Berlin with a time-step of 5 minutes. The use of Daysim allows both static and dynamic daylighting metrics to be calculated. For each case-study, the values over the working plane of DDPM were calculated. The various DDPM form quite a heterogeneous group, as they were proposed by different authors, based on different objectives. In principle, it seems possible to identify three main groups (Pellegrino et al., 2011).
The Annual Light Exposure ALE (Mardaljevic, 2006): it describes the daylight availability within a room throughout the year as the cumulative amount of daylight incident on a point of interest over the course of a year. This means that daylight availability is expressed in terms of a light dose, in [lux hours per year].

The group of Daylight Autonomies DA, DA_{con}, DA_{max} (Reinhart et al., 2001), (Rogers, 2006): these use the time-varying daylight illuminance in a point as indicator to assess daylight availability within a room throughout the year, in particular referring the dynamic variation of illuminances to threshold values. For DA the threshold is the required illuminance for the considered space usage according to standards, so as to assess the percentage of the occupied time of the year when the illuminance requirement is met by daylight alone. A second threshold is also considered, set to ten times the illuminance requirement (in Daysim algorithms), to account for the occurrence of direct sunlight or other potentially glary conditions, giving an indication of how often and where large illuminance contrasts appear in a space ($DA_{max)}$. In general terms, it can be seen from the definitions that the Daylight Autonomy gives information about the potential energy demand for electric lighting taking into account daylight availability with respect to the required illuminance for the considered space usage according to standards, while the Continuous Daylight Autonomy metric (DA_{con}) can give directions about the potential energy demand for electric lighting in presence of a daylight responsive control system, because it also takes into account the portion of daylight which lies below the required illuminance but which can be usefully exploited to reduce electric lighting energy consumption in case of electric lighting plant dimming.

The group of Useful Daylight Illuminances $UDI_{fell-short}$, $UDI_{achieved}$, $UDI_{exceeded}$ (Nabil et al., 2006), (Nabil et al., 2005): these also use work plane illuminance to assess daylight availability within a room throughout the year, but they refer the dynamic variation of illuminance values to both an upper and lower threshold, i.e. expressing the percentage of the occupied times of the year when illuminances lie in one of the three resulting ranges: a range, including illuminance values for which daylight can be considered substantially lacking ($UDI_{fell-short}$); a range including illuminance values which are considered ‘useful’ by occupants ($UDI_{achieved}$); a range including illuminance values which can result overabundant and which are therefore meant to detect the likely appearance of glare ($UDI_{exceeded}$). The three indexes together provide a synthetic view of the overall distribution of illuminances during the year and can be used as indicators of the potentials in terms of visual comfort and glare risks. Initially, the ‘useful’ range was set between 100 lux and 2000 lux ($UDI_{achieved}$) (Nabil et al., 2006), (Nabil et al., 2005). Later on the upper limit was raised up to 2500 lux (Mardaljevic, 2009) and recently the ‘useful’ range was further expanded by setting the upper limit up to 3000 lux and at the same time it was subdivided into two more ranges: a range between 100 and 300 lux, called UDI-supplementary, including daylight illuminance levels that may request electric lighting to supplement daylight for common tasks such as reading; a range between 300 lux and 3000 lux, where additional electric lighting will most likely not be needed (Mardaljevic, 2012). Nevertheless, at the time when all elaborations were carried out, Daysim calculated the UDIs according to the ranges initially defined by the authors (below 100 lux; between 100 and 2000 lux, over 2000 lux). These ranges are therefore the reference ranges used in this paper for the analyses on the UDI metric.

3 A graphical tool to express the daylighting performance depending on room architectural characteristics

The high number of case-studies which were simulated resulted in a huge database. In order to visualize and communicate the results which were found, a simple graphical tool was developed, able to summarize the amount of information about the daylighting availability within spaces with different characteristics and to allow the readers to quickly understanding it and reading it.
Figure 1 shows the rationale on which the graphical tool was developed; it represents all variables involved in the study: room depth (on the x-axis), obstruction angle (on the y-axis) and WWR, Window-to-Wall Ratio, from 0.6 to 0.3 (represented by circles matched side by side for each room depth and obstruction angle). The circles' diameter is proportional to the metric absolute value and the color corresponds to the interval in which the metric value lies. The possible scale of values of each DDPM (0-100%) was divided into five ranges (<20%; 20-40%; 40-60%; 60-80%; >80%). This type of tool can be used by professionals to quickly verify the influence of preliminary design solutions on daylight availability within the room and it can be applicable for simple environment. For a given combination of room depth, obstruction angle and window-to-wall ratio, designers can identify on the graph the daylighting condition as expressed by each DDPM and assess the influence on the daylight condition due to changing of these room architectural characteristics.

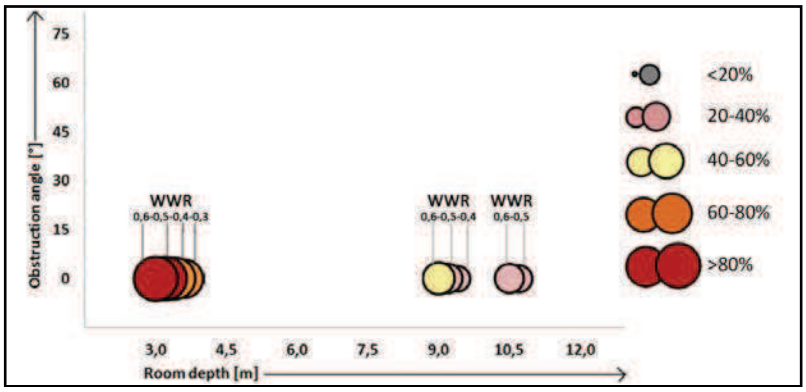

Figure 1 - Schematic representation of the proposed graphical tool

4 Results

In this section, some of the results obtained through the parametric study previously described are presented. In particular, Figure 2 shows the graphical tool created to visualize the DDPM values which were found for North and South-facing rooms located in Turin, with a glazing visible transmittance set to 70% and a target illuminance value of 500 lux. Data reported in the graphs correspond to the average values of DDPM calculated over the working plane. In particular, the DDPM represented in Fig. 2 are DA, DA_{con}, $UDI_{achieved}$ and $UDI_{exceeded}$.

From graphs relative to DA and DA_{con}, it can be noted that for both North and South-facing rooms, an increase of room depth and obstruction angle values and a decrease of WWR values results in a progressive drop of the daylight availability, eventually tending to the value of 0% (note that of course this is valid for the assumed target illuminance of 500 lux). Furthermore, a general trend was observed, according to which South-facing spaces have lower daylight availabilities than their corresponding North-facing spaces: for the former spaces, DA values are always lower than 80%, whilst they happen to rise over 80% for some configurations of North-facing spaces.
For example, an unobstructed space with a depth of 3 m and a WWR value of 0.6 shows a DA value of 75% if South-oriented and of 87% if North-oriented. This difference appears to be due to the presence and to the characteristics of the moveable shading system which was modeled for South-facing room in order to control the admittance of the direct solar radiation, which might cause glare and summer overheating problems. Thanks to the presence of the solar shade, all simulated South-facing rooms show $UDI_{exceeded}$ values lower than 20%, which suggest that conditions of excessive daylight do not occur frequently in such spaces.

Last, but not least, the results found for $UDI_{achieved}$ allow highlighting which combinations of architectural features provide with spaces with the most optimal daylighting conditions, that is to say with the lowest risks of glare or of insufficient illuminances. By comparing the two $UDI_{achieved}$ graphs, it can be observed that North-facing rooms show, in general, higher values of $UDI_{achieved}$ with respect to South-facing rooms. Only in the case of rooms with little depth (RD = 3 m and 4.5 m) and with low or absent external obstructions (γ = 0° and 15°), the trend is opposite: in these cases, the South orientation results in higher UDIachieved values: actually, the presence of the shade reduces the 'excessive' amount of daylight resulting in an increase of the 'useful' daylight availability. This is confirmed by the corresponding $UDI_{exceeded}$ values, which result higher for North-facing rooms.

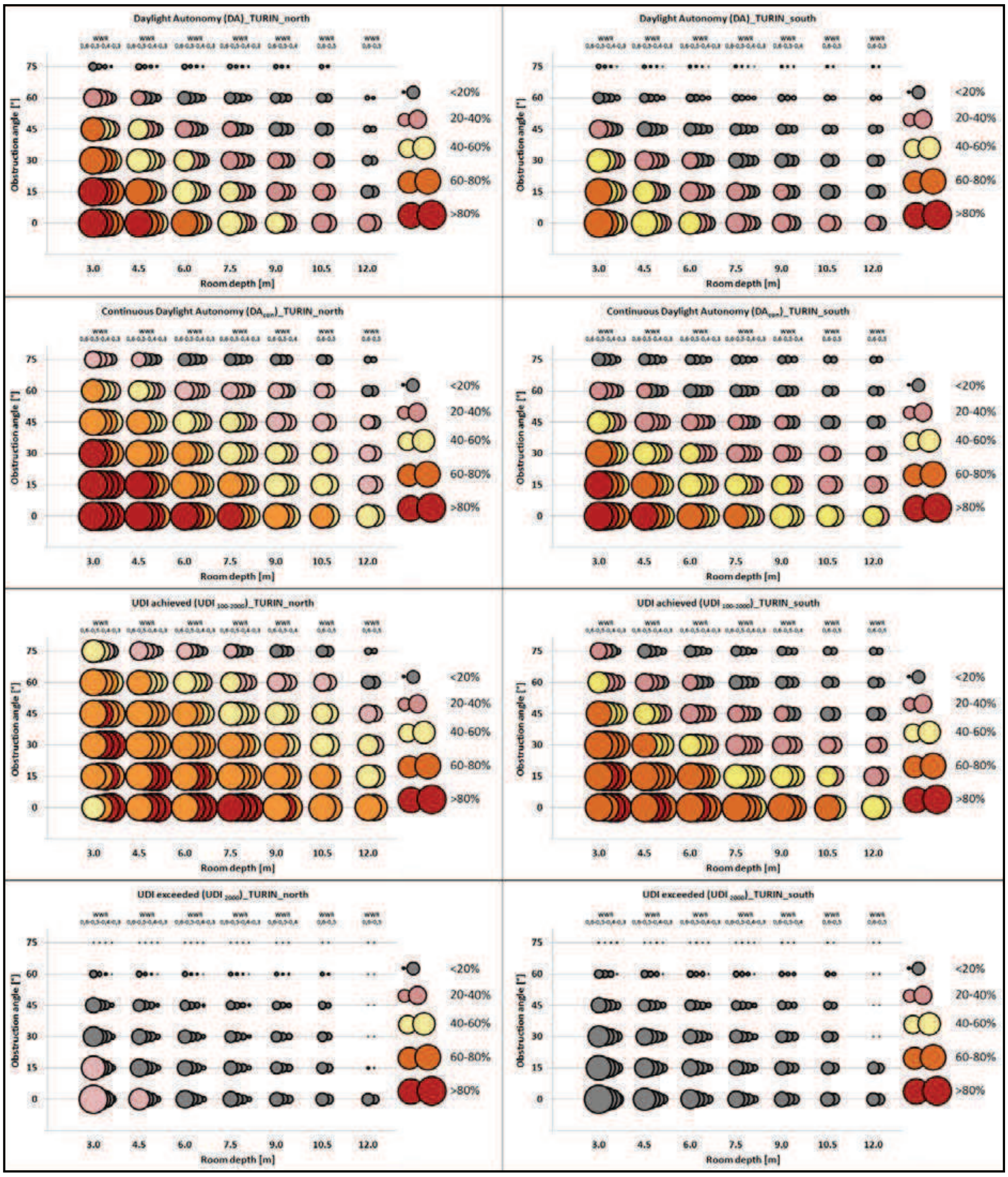

Figure 2 - DDPM results for North/South-facing rooms in Turin; τ_{vis}=70%; E_{target}=500 lux.

4.1 Examples of possible uses of the graphical tool

The proposed graphical tool can be used by practitioners according to two approaches.
According to a first approach the design team has the chance to identify, for the specific space under examination, the corresponding daylighting performance which can be expected, in terms of DDPM values. As an example, for a North-facing room with a depth of 4.5 m and an obstruction angle of 15°, it is possible to verify how the daylight availability will change as a function of the window area: a WWR of 0.6 or of 0.5 will result in a DA in the range 60%-80%, while reducing the WWR to 0.4 or to 0.3 will result in a decrease of DA (40-60% or 20-40% respectively). Instead, referring to the $UDI_{achieved}$ metric, a WWR of 0.6 will determine a $UDI_{achieved}$ in the range 60%-80%, while for lower window areas (WWR 0.5, 0.4 and 0.3) $UDI_{achieved}$ results over 80% with an increasing trend. On the other hand, the $UDI_{exceeded}$ metric, which is based on one threshold value (like the DA and unlike the $UDI_{achieved}$) shows a trend similar to the one observed for the DA values, progressively decreasing as the room depth and the obstruction angle increase and the WWR decreases. The design team hence can collect the information that modifying the window area does not result in a meaningful change of daylighting performance of the room if expressed in terms of $UDI_{achieved}$, but plays a crucial role on the potential energy saving concerned with the percentage of time of electric light use in presence of a manual lighting control system, as shown by the variation of DA. Furthermore, the tool allows to visualize how both North and South-facing rooms with obstruction angles $\gamma \geq 60°$ and room depths RD ≥ 9 m are all characterized by scarce daylight amount, as all examined dynamic metrics show values lower than 40%.
According to the second approach, the design team can use the tool to identify for which combination of the room architectural features the corresponding daylighting performance will be above or below target values, that might be user-defined or, in the future, set by recommendations and standards. As a matter of fact, it should be noted that even thug CBDM has been used successfully in many projects, currently authoritative "targets" for DDPM measures are not available.
In this present paper, to explain this possible use of the graphical tool, three classes of performance, in terms of daylight quantity, were assumed by the authors: "low" (DA≤40%), "acceptable" (40%<DA<60%) and "high" amount (DA≥60%). By defining ranges of performance, practitioners can quickly verify, on the tool, which are the combinations in terms of architectural features able to provide high, acceptable or low daylight amount within a room. Figure 3 highlights the combinations of the examined architectural features which fell within the three performance classes that were defined for the various DDPM, considering both North and South-facing rooms.

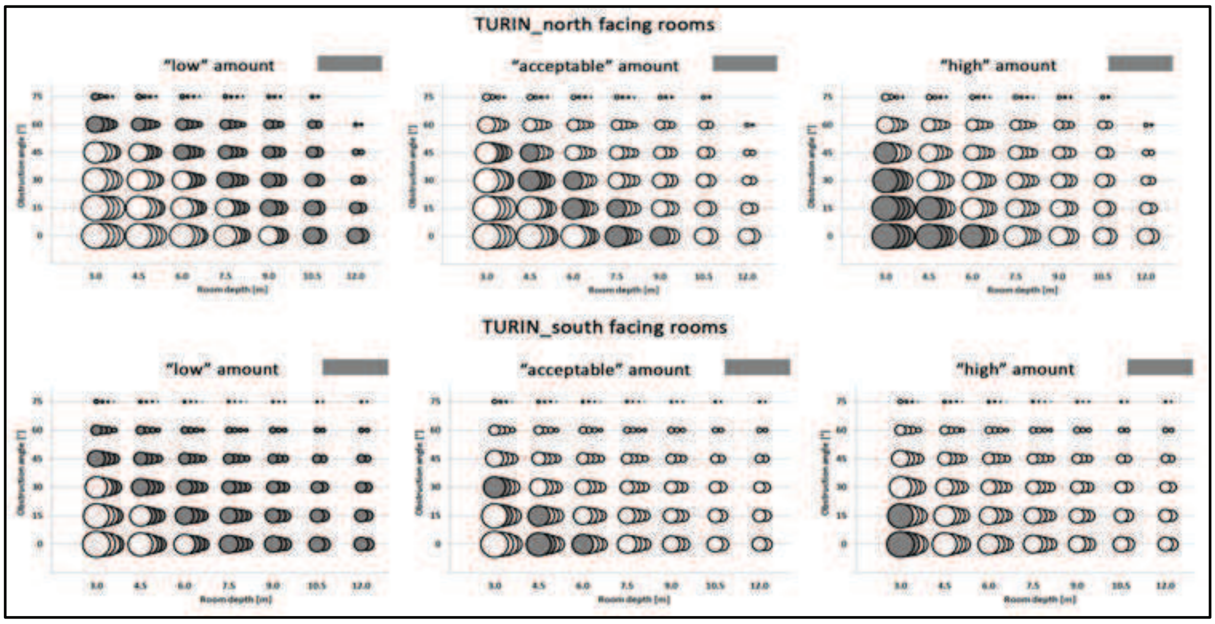

Figure 3 – Combination of architectural features falling into the daylight performance classes (case-studies: North/South-facing rooms in Turin; τ_{vis}=70%; E_{target}=500 lx).

4.2 Comparison with other prediction tools

So as to evaluate potentials and drawbacks concerned with the proposed graphical tool, as well as its applicability and utility for the design team, a comparison with other prediction tools currently available for daylighting analyses during the earliest design stage was carried out.

In general terms it can be observed that current daylighting design practice still favors prior experiences and rules of thumbs and largely relies on the average daylight factor approach, which is limited to the verification of the amount of diffuse skylight under an overcast sky condition. In particular the equations to calculate the daylight factor provided by the European Standard EN 15193 (CEN, 2007) to define the "room daylight penetration class" is considered.

On the other hand, the need for a more detailed information on room daylighting even in the earliest design stage has led to the development of new simulation tools, such as Lightsolve, recently developed at the M.I.T. Daylighting Lab (Andersen et al., 2008), (Kleindienst et al., 2008) to support the design team using a climate-based approach. The software performs a rather quick calculation returning annual data sets for which illuminance and glare temporal maps and spatial renderings are the graphical outputs. For user-defined illuminance thresholds, the temporal maps give an outcome with different colors, based on the portions of the results that meet, overstep or don't reach the goals set by user (Fig.4). In this paragraph, the information that might be drawn from the graphical tool presented in this paper was compared to the information given by the above mentioned daylight factor formula and by the illuminance temporal maps provided by the simulation tool Lightsolve. In particular, as an example, two case-studies, corresponding to rooms with quite different daylighting conditions, were analyzed: a room with a high daylight availability (RD = 3 m and $\gamma = 0°$) and a room with higher depth and partly obstructed (RD = 7.5 m and $\gamma = 15°$). For both cases the variation of the window area (WWR values of 0.3 and 0.6) was also considered. The results found through the different prediction tools are summarized in Fig.5. Carrying out a direct comparison of the results which are obtained through the various examined approaches may result hard at a first glance, as each approach provides with a different kind of information. For example, the analytical equations allow quantifying the average daylight factor, i.e. the amount of diffuse skylight within the considered space. To better assess if the obtained value can be considered a poor or an valuable result, the daylight factor value is integrated with the daylight penetration class ('none, 'weak', 'medium', 'strong') according to the EN 15193. Differently, the graphical tool presented in this paper gives percentages of Daylight Autonomies or Useful Daylight Illuminance, while Lightsolve provides the design team with temporal maps with the variation of average illuminance values during the year. The results are not therefore directly expressed with the same metrics. In order to favor the comparison to the graphical tool outcomes (DAs and UDIs), the following user-defined illuminance thresholds were input to run Lightsolve simulations: 100 lux, 500 lux, 2000 lux and 5000 lux (see Fig.4).

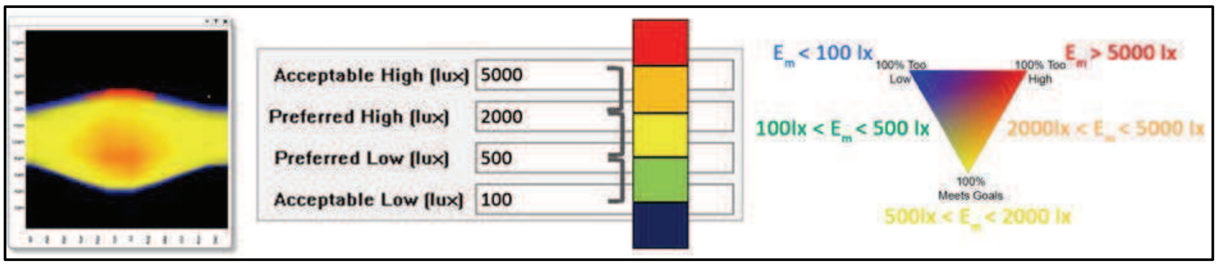

Figure 4 – User-defined illuminance thresholds as input for Lightsolve simulations

This way, the colors displayed by the program in the output image represent the $UDI_{fell\text{-}short}$ value (blue area), the $UDI_{achieved}$ value (green + yellow area), the $UDI_{exceeded}$ value (orange + red area), the DA value (yellow + orange + red area) and the DA_{max} value (red area). At this point, a comparison can be carried out: for this purpose, as shown in Fig.5, the colored area roughly corresponding to $UDI_{achieved}$ and DA are highlighted through a dashed hatch on the temporal map between 8.30 a.m. and 6.30 p.m. (i.e. the occupancy profile during the year), so as to assess the percentage of the temporal map area corresponding to DDPM values. This simplified qualitative comparison shows how the results obtained through the different approaches are generally in good agreement, and in particular this is true for the two tools based on CBDM (the graphical tool and Lightsolve): for example, for the case-study of the 3 m deep unobstructed room with a WWR of 0.3, the $UDI_{achieved}$ region in the illuminance temporal map generated by Lightsolve covers almost entirely the map itself (about 90%), which is consistent with the result in the graphical tool ($UDI_{achieved}$ over 80%), while the DA region in the image covers about half of the image and the corresponding DA read in the graphical tool is in the range 60%-80%. The average daylight factor for the same case-study is 4.62% according to the formula of the standard EN 15193, which determines a ‘strong’ daylight penetration. For the same room but with a WWR of 0.6, the regions in Lightsolve maps corresponding to the $UDI_{achieved}$ and DA are respectively about 50% and 80% of the image area, which is in agreement with the data read in the graphical tool ($UDI_{achieved}$ in the range 40%-60% and DA over 80%).

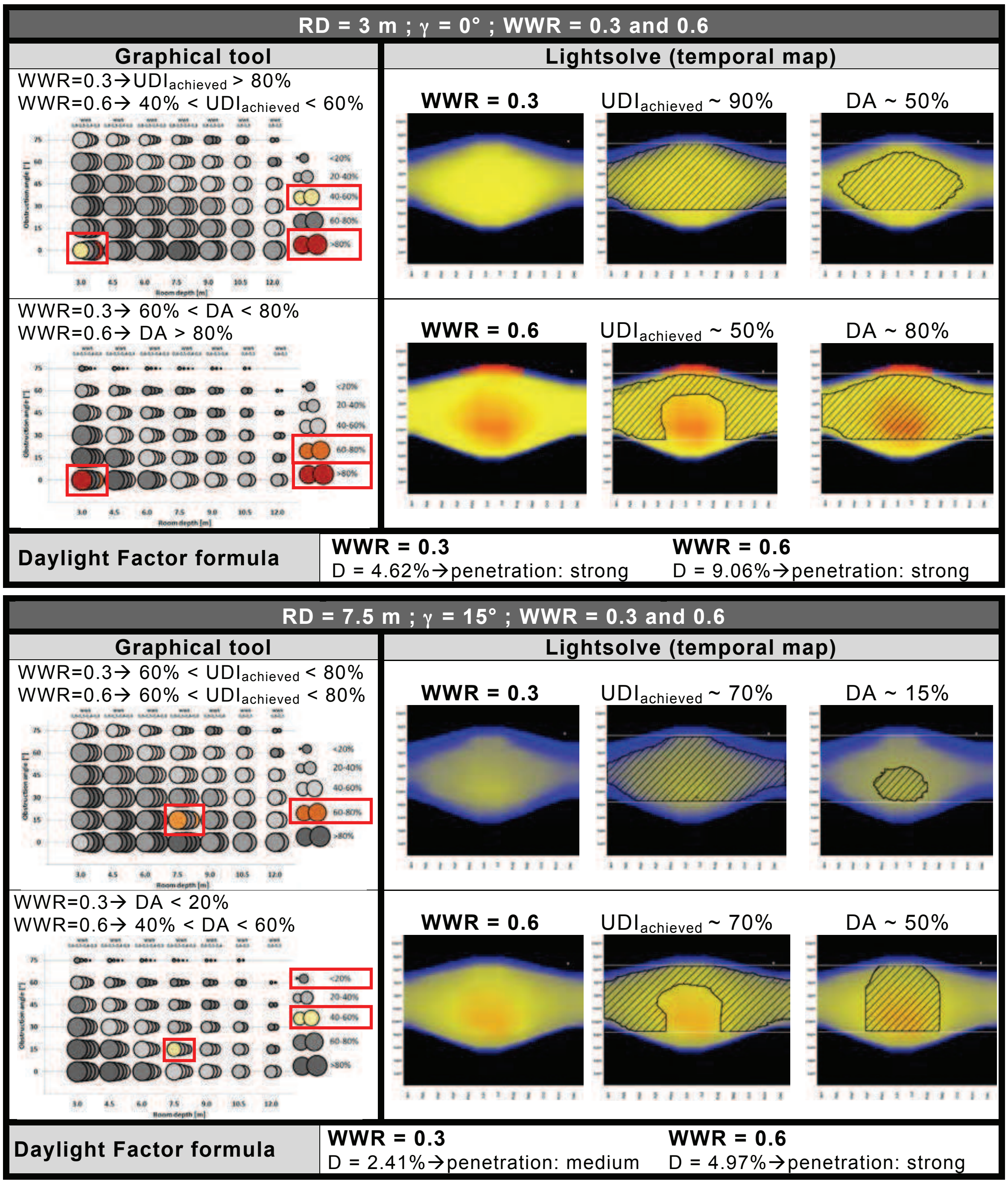

Figure 5 – Results obtained through the graphical tool proposed in this paper, the average daylight factor formula and Lightsolve.

The daylight penetration defined with the EN 15193 method is ‘strong’ as the average daylight factor is 9.06%. Similar correspondences were observed for the 7.5 m deep room with an obstruction angle of 15°: in the case of a WWR of 0.3, the areas corresponding in the Lightsolve illuminance map to the

$UDI_{achieved}$ and to the DA are about 70% and 15% of the image area (versus corresponding values read in the graphical tool in the range 60%-80% and lower than 20% respectively), with a 'medium' daylight penetration according to the EN 15193 calculation method (D = 2.41%), while in the case of a WWR of 0.6, the $UDI_{achieved}$ is about 70% in the Lightsolve image and in the range 60%-80% in the graphical tool and the DA is about 50% in the Lightsolve image and in the range 40%-60% in the graph. In general, the daylight penetration calculated with the EN15193 method is 'strong' for all cases, except for the room with RD of 7.5 m, obstruction angle of 15° and WWR of 0.3 in which the daylight penetration is 'medium'.

5 Discussion

Some considerations about the graphical tool presented in previous section are worth being stressed. With regard to the nature and use of the tool, this has the merit of visualizing in an intuitive and easy-to-read way how the daylight performance of a space varies as a function of its different architectural features, allowing the design team an immediate reading of daylight conditions within a room since the earliest design stages. Such daylight performance is expressed in terms of ranges of DDPM values (Annual Light Exposure, Daylight Autonomies, Useful Daylight Illuminances), that is to say according to a climate-based approach: the annual dynamic variation of sunlight and skylight conditions throughout the year is therefore taken into account as part of the daylighting analysis. The data displayed in the tool account for the room orientation and for a moveable shading system (even though limited to a single type of blind). On the other hand, the inherent characteristics of the proposed tool imply some drawbacks: first of all, the tool available at this stage of the research activity visualizes a sub-dataset of the results which were globally obtained, that is for a restricted number of configurations, relative to spaces located in Turin whose window are equipped with a glazing with a visible transmittance of 70% and in which activities requiring an illuminance level of 500 lux are carried out. Therefore, further series of graphs should be plotted to represent the whole database of DDPM results for all the simulated configurations, including different location, glazing transmittance and task illuminance.
Moreover, the DDPM data are given in ranges (0-20%; 20-40%; 40-60%; 60-80%; 80-100%), with the consequence that rooms with different characteristics might result in the same range. The daylight performance displayed in the tool is the average DDPM value over the room: the data is therefore immediate and synthetic, but no information is given about how the considered DDPM varies across the space, nor during the year.
Based on the comparison which was carried out with other prediction tools, it emerged how each tool has specific peculiarities. The analytical equation to calculate the daylight factor is quite simple and quick to use for first hand evaluations. Furthermore, the formula proposed in the European standard has the merit of introducing the latitude into the final calculated value and of specifying some classes to assess if the daylight penetration within the room is 'none', 'weak', 'medium' or 'strong'. The main limit is concerned with the fact that the only reference sky condition is the overcast sky: the approach is therefore 'static', i.e. the dynamic presence of sunlight during the year is not considered, nor is, as a consequence, the window orientation.
Differently, Lightsolve allows running, in a quite short time, a climate-based annual daylighting analysis and provides as output both quantitative and qualitative data, in terms of temporal maps of illuminances and glare values as well as spatial renderings. The illuminance maps are built for user-defined threshold values. This leaves a great flexibility to the user but specific DDPM values are not provided and the spaces' daylighting performance are drawn from the observation and comparison of temporal maps or renderings images. The use of moveable shading devices is not taken into account for the simulation, while fixed shading systems such as overhangs or vertical fins can be included as part of the model geometry.
Recently a new extension of the Lightsolve program was developed (Gagne et al., 2011). The method always starts with a designer's own initial design of a space and with the definition of performance goals. A user-interactive expert system is able to communicate to designers which is the performance of the space in terms of daylight amount and visual comfort. Then it creates a number of suggestions for design change in order to improve the lighting performance of the space.
This synthetic comparative analysis shows how the three approaches provide with different information, which can be all fruitfully used for early daylighting analyses. In particular, the analytical daylight factor equativo and the graphical tool can be useful at the very first beginning of the design process. Compared to the 'static' daylight factor based approach the proposed tool has the merit of visualizing the DDPM data, hence accounting for a dynamic climate-based approach without even the need of achieving a numerical model of the target building. Both approaches can be used for the first definition of the shape

and volume of the building and sizing of the window and selection of the technologies for the daylighting systems. Some rough considerations about the visual comfort (based on the UDI values) and about the related energy demand for lighting (based on the DA and DA_{con} values) can be also explored. Such first solutions can be then verified in more detail by using the simulation tool Lightsolve.

6 Conclusions and future work

This paper presented a graphical tool which was developed to visualize the results of DDPM values (ALE, DAs and UDIs) obtained through a series of Daysim simulations for a reference room with different architectural features (such as room depth, window area and sky angle 'seen' in presence of an external obstruction) and located in Turin. The proposed tool is intended to allow the design team an immediate reading of daylighting conditions within a room according to the variation of architectural features since the earliest design stages, when the use of advanced simulation tool is still premature. In particular, the practitioners can fruitfully use the tool in two different ways: they have the chance to either predict the daylight availability for a particular combination of architectural features for the considered room or to identify which combinations of architectural features would correspond to specific classes or thresholds of daylighting performance.

A comparison with other tools which are available for the first design stages, ranging from the commonly used formula to calculate the average daylight factor to the recently developed software Lightsolve showed how these three approaches have peculiarities which result in different information being provided. It seems therefore that all tools could be used during the earliest design stage by practitioners to predict with a reasonable level of accuracy the daylight performance of a room, exploring both the potential visual comfort and the related energy needs concerned with a given daylight solution. In particular the proposed tool is as simple and quick to use as the daylight factor formula but offers an accurate climate-based analysis in terms of DDPM values without the need of bulding a 3D model and running a simulation. The graphical tool proposed in the paper covers a sub-dataset of the huge database of climate based daylighting simulations carried out for a reference room with different architectural features and located in different sites. The work is still on-going, aiming, on the one hand at expanding the representation of results through the graphical tool and, on the other hand, at using the database of results to produce an interactive software application that will allow practitioners to get DDPM results by directly inputting the spaces architectural features, geographical site and illuminance threshold.

Acknowledgements

This work was carried out within the national research program PRIN 2008, titled "Daylighting design for energy saving and visual comfort purposes: climate-based daylight modeling, glare indices and integrated ventilation system performances", co-financed by the Italian Ministry for Universities, Education and Research (see: http://www.polito.it/tebe).

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Paper IV:
'Results from a parametric study to assess the daylight amount
in rooms with different architectural features'

S. Cammarano, V.R.M. Lo Verso, A. Pellegrino, C. Aghemo
In proceedings:
CISBAT: CleanTech for Smart Cities and Buildings – From Nano to Urban Scale.
2013, Lausanne, Switzerland.

RESULTS FROM A PARAMETRIC STUDY TO ASSESS THE DAYLIGHT AMOUNT IN ROOMS WITH DIFFERENT ARCHITECTURAL FEATURES

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ABSTRACT

This paper describes the research activity carried out by the Lighting Team of the TEBE Research Group on the daylight availability in interiors. The analysis was done through a parametric study, running a high number of Daysim simulations of a single target room whose architectural features were changed (orientation, window size, room depth and height of an external obstruction). For each case-study, referring to an illuminance of 500 lux and a glazing visible transmittance of 70%, the values of Dynamic Daylight Performance Metrics DDPM and of the energy use for electric lighting (in presence of either a manual on/off switch or a daylight responsive control system) were calculated and the obtained results analyzed to understand how the DDPM and energy demand values change as a function of the architectural features. As a next step, to provide an overall representation of the DDPM results for all simulated case-studies, a graphical tool was developed. The tool was intended to be used by the design team since the earliest design stages to quickly verify the influence of preliminary design solutions on daylight amount. As a further step, which is currently in progress, a set of mathematical models are being developed to predict the daylight availability within a space or the corresponding energy demand for lighting. New sets of simulations were run for this purpose so as to expand the database including more latitudes, illuminance levels and glazing visible transmittances. The final step will deal with the implementation of the models into an interactive software that will allow practitioners getting DDPM and lighting energy demand values by directly inputting the site, spaces architectural features and illuminance threshold. The different steps of the research, the main results which have been obtained during each step and the future developments are described in the paper.

Keywords: Daylight amount, Dynamic Daylight Performance Metrics, room architectural features, tools for early daylighting design stage.

INTRODUCTION

The importance of skylight and sunlight for both building energy performance and ambient quality implies the need for a more accurate design approach which takes into account the dynamic behaviour of daylight. Within this frame, taking advantage of the potentials of a Climate Based Daylighting Modeling (CBDM) and DDPM [1], a research is being carried out at the Politecnico of Turin (Italy), to provide architects and building engineers with information and tools to quickly estimate, since the earliest design stages, the indoor daylighting and the related electric lighting energy demand. The paper has the objective of presenting the research activity carried out during the last years as well as the remaining part of the work which is still ongoing. In particular some basic results about how architectural features influences the daylight amount in a room and how to convert the huge database of results obtained from the parametric study into simple tools to be used during the early daylighting design stages are presented**.**

METHOD

The analysis of the daylight amount within a considered space as well as of the related energy demand for lighting has gone through the following phases.

As a first step, the parameters influencing the daylight amount within a space and its related electric lighting energy need were identified and the daylighting conditions were analyzed by estimating, through simulations, the values of DDPM (Daylight Autonomy, Continuous Daylight Autonomy, Maximum Daylight Autonomy, Useful Daylight Illuminance, Annual Light Exposure) and of the annual energy need for several configurations of a target room. Daysim, a Radiance-based software that calculates daylight through a dynamic climate-based annual simulation, was used for this purpose. A single room was used as 'case study'. Its width, height and reflection properties were kept constant (width: 12 m; height: 3 m; reflectances: 80% for the ceiling, 50% for the walls, 30% for the floor), as well as the glazing visible transmittance (set to 70%) while other parameters were changed to assess their influence on the space's daylighting, namely: room depth, RD (assumed equal to 3, 4.5, 6, 7.5, 9, 10.5 and 12 m); window area, expressed in terms of window-to-wall ratio, WWR (0.6, 0.5, 0.4, 0.3, 0.2); obstruction angle 'seen' by the window, γ (0°, 15°, 30°, 45°, 60°, 75°); orientation (south, west, north). For south-facing rooms both the absence and the presence of a moveable shading system was modelled (a Venetian blind with a diffuse transmittance of 25%, when closed, automatically pulled down whenever an irradiance of 50 W/m^2 hits any point of the working plane, this latter set at a distance of 75 cm from the floor and covering the whole room minus a peripheral strip of 50 cm). During this phase, all rooms were assumed to be located in Turin (Italy, latitude: +45.2°N), continuously occupied Monday through Friday from 8:30 a.m. to 6:30 p.m, and considering a target illuminance of 500 lux. The database of results was then analyzed to understand how the DDPM change as a function of the architectural features. Some considerations are presented in the section 'Results'.

As a later step, with regard to DDPM values, a graphical tool was developed to visualize the huge database of data and thus to allow an immediate reading of daylight conditions within the considered room, without consulting the full database of numerical values from Daysim simulations. The tool is conceived to be used by the design team since the earliest design stages in two possible ways: either to predict the daylight availability for a particular combination of architectural features for the considered room or to identify which combinations of architectural features would correspond to specific classes or thresholds of daylighting performance. The tool is briefly described in the section 'Results'.

As a further development, currently in progress, a set of mathematical models are being developed to predict during the earliest design stages on the one hand the daylight availability within a space as a function of its architectural features and on the other hand the corresponding energy demand for lighting. For this purpose, further simulations were run to expand the database including more latitudes, illuminances and glazing visible transmittances.

The final step of the research will deal with the implementation of the databases into an interactive software that will allow practitioners to get DDPM and lighting energy demand values by directly inputting the spaces architectural features, site and illuminance threshold.

RESULTS

Variation of daylight availability depending on room architectural features

In this section, a synthesis of results concerning the influence on daylight availability of varying room features is presented.

The results shown in the following graphs are expressed in terms of Annual Light Exposure (ALE), to describe the cumulative amount of daylight on the horizontal plane over the course of a year [Mlxh], Daylight Autonomy (DA), to assess the percentage of the occupied times of the year when the illuminance requirement is met by daylight alone [%] and Maximum Daylight Autonomy (DA_{max}), to account for the occurrence of potentially glary conditions during the year [%]. Results are presented to analyze the effect of each variable (orientation, RD, WWR and γ) on daylight availability. For the orientation, data are referred to unobstructed spaces (γ= 0°), considering all RD and WWR, while for room depth, WWR and external obstructions data are referred to rooms facing north and south (this latter with blinds).

Effect of orientation (Figure 1)

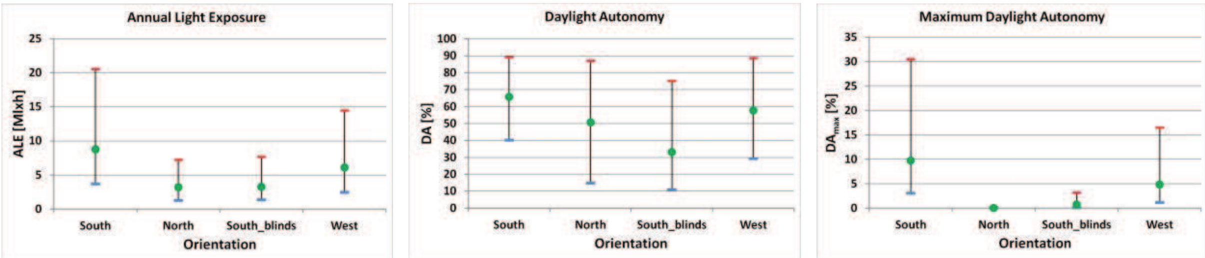

Figure 1: ALE, DA and DA_{max} ranges (maximum, minimum and mean values) as a function of orientation.

The daylight availability is higher for south-facing rooms without blinds (ALE_m= 8.7 Mlxh) compared to west-facing (ALE_m= 6.1 Mlxh) and north-facing rooms (ALE_m= 3.2 Mlxh), while ALE values are similar for south-facing rooms with blinds and north-facing rooms, in terms of both mean values and range of variation. If the daylight availability within the space is evaluated in terms of Daylight Autonomy, results are slightly different. South-facing rooms still have higher values (DA_m= 65.7%) than west-facing (DA_m= 57.7%) and north-facing rooms (DA_m= 50.6%). However the DA_m value for south-facing rooms with blinds drops to 33% (lower than north-facing rooms). As for potentially glary conditions (expressed through DA_{max} metric), north-facing rooms have lower values ($DA_{max,m}$= 0.03%) than south-facing rooms with blinds ($DA_{max,m}$= 0.8%), west-facing rooms ($DA_{max,m}$= 4.8%) and south-facing rooms without blinds ($DA_{max,m}$= 9.8%). In the latter two cases the range is very wide, with maximum values of 16.5% and 30.5%.

Some considerations can be drawn from these results: a) high daylight amount mainly occurs for south-facing and west-facing rooms. At the same time, if blinds are not used, glare and overheating may occur, as expected and already stated in other studies [2]; b) daylighting performance is better for north than for south-facing rooms with blinds. For both orientation the risk of glare is low but DA values are higher for north rooms which may result in a lower lighting energy demand.

Effect of room depth, RD (Figure 2)

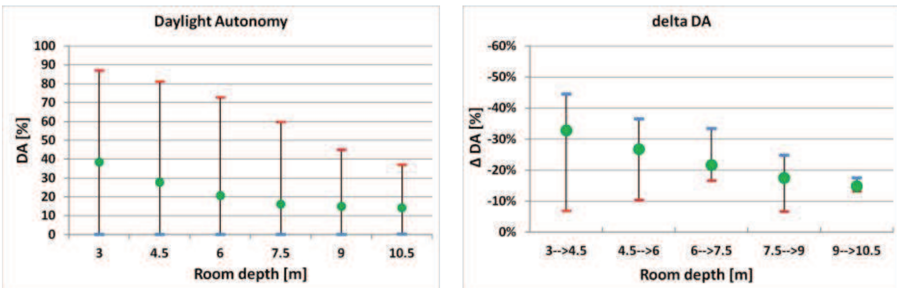

Figure 2: DA (maximum, minimum and mean values) and ΔDA ranges as a function of RD.

Increasing the room depth results in a decrease of DA and the DA reduction appears to be greater for small and medium RD (the average percent difference when increasing room depth from 3 m to 4.5 m and from 4.5 m to 6 m is ΔDA_m= -30%) than for RD over 6 m (ΔDA_m= -18%). These results are consistent with what shown in [2].

Effect of Window-to-Wall Ratio, WWR (Figure 3)

Increasing the WWR results in an increase of DA, higher passing from WWR 0.3 to 0.4 (ΔDA_m = 61%), than passing from WWR 0.4 to 0.5 (ΔDA_m = 30%) and from WWR 0.5 to 0.6 (ΔDA_m = 21%).

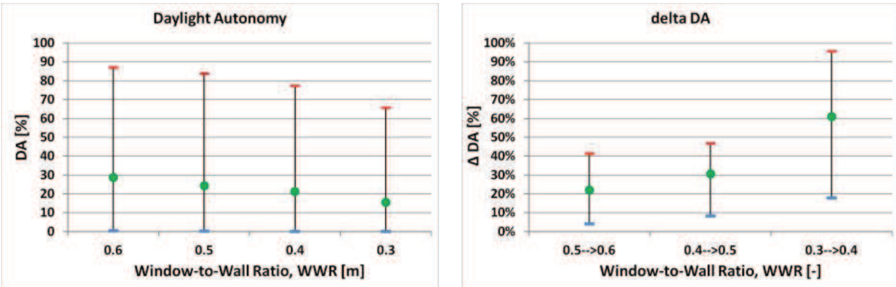

Figure 3: DA (maximum, minimum and mean values) and ΔDA ranges as a function of WWR.

Effect of external obstructions, γ (Figure 4)

Increasing the obstruction angle results in a linear decrease of DA_m. The DA range for γ between 0° and 30° is wider (6%<DA<87.2%) than for γ over 45°. The DA decrease is lower for γ between 0° and 30° (ΔDA_m = -25%), than for γ over 30° (ΔDA_m = -49%).

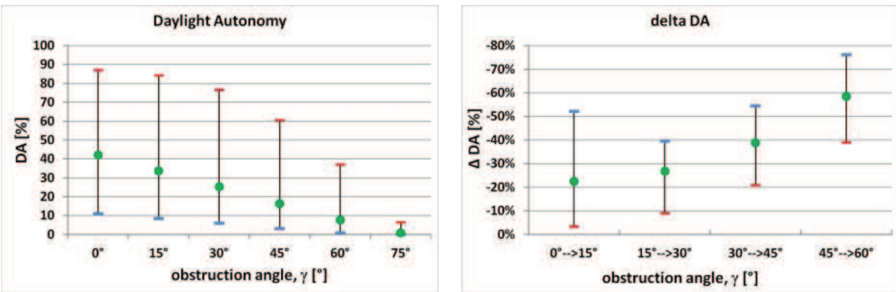

Figure 4: DA (maximum, minimum and mean values) and ΔDA ranges as a function of γ.

Graphs and data presented above are representative of the range of results obtained from a large number of room's configurations (all WWR, RD, γ, and for north and south with blind orientation). The information achievable from this data are quite general and self-evident, while to have more detailed information a different approch in representing the whole database of result should be used.

A graphical tool to express the daylighting performance depending on room architectural characteristics

Figure 5 shows the rationale on which a graphical tool to present the results of the parametric study was developed; it represents all variables involved in the study: room depth (on the x-axis), obstruction angle (on the y-axis) and WWR, from 0.6 to 0.3 (represented by side-by-side circles for each room depth and obstruction angle). The circles' diameter is proportional to the metric absolute value and the colour shows the interval in which the metric value lies. The possible scale of values of each DDPM (0-100%) was divided into five ranges (<20%; 20-40%; 40-60%; 60-80%; >80%). This type of tool can be used by professionals to quickly verify the influence of preliminary design solutions on daylight availability within the room, identifying the daylighting performance of a specific room's configuration or for which combination of the room architectural features the corresponding daylighting performance will be above or below target values, that might be user-defined or, in the future, set by recommendations and standards. In a past paper three classes of performance, in terms of daylight quantity, were assumed by the authors: "low" (DA≤40%), "acceptable" (40%<DA<60%) and "high" amount (DA≥60%) [3]. By defining ranges of performance, practitioners can quickly verify, on the tool, which are the combinations in terms of architectural features able to provide high, acceptable or low daylight amount within a room.

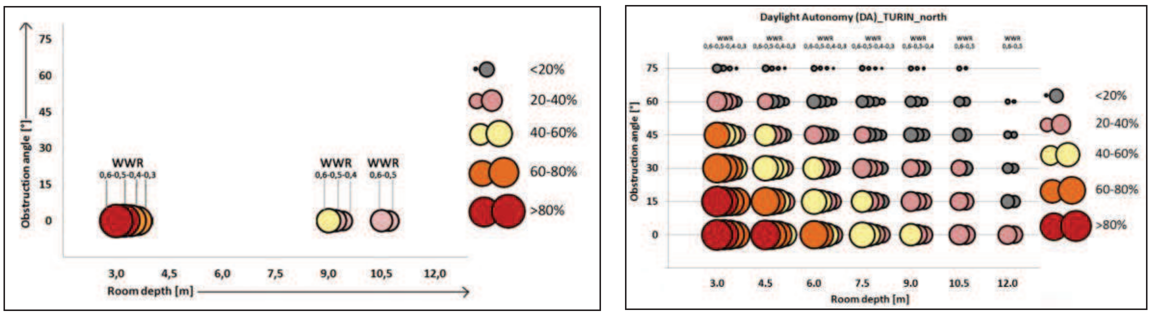

Figure 5: Schematic representation of the format of the graphical tool which was developed to visualize the daylighting conditions within the rooms as a function of the variation of their architectural features.

Figure 6 highlights the combinations of the examined architectural features which fell within the three performance classes considering both north and south (with blinds)-facing rooms.

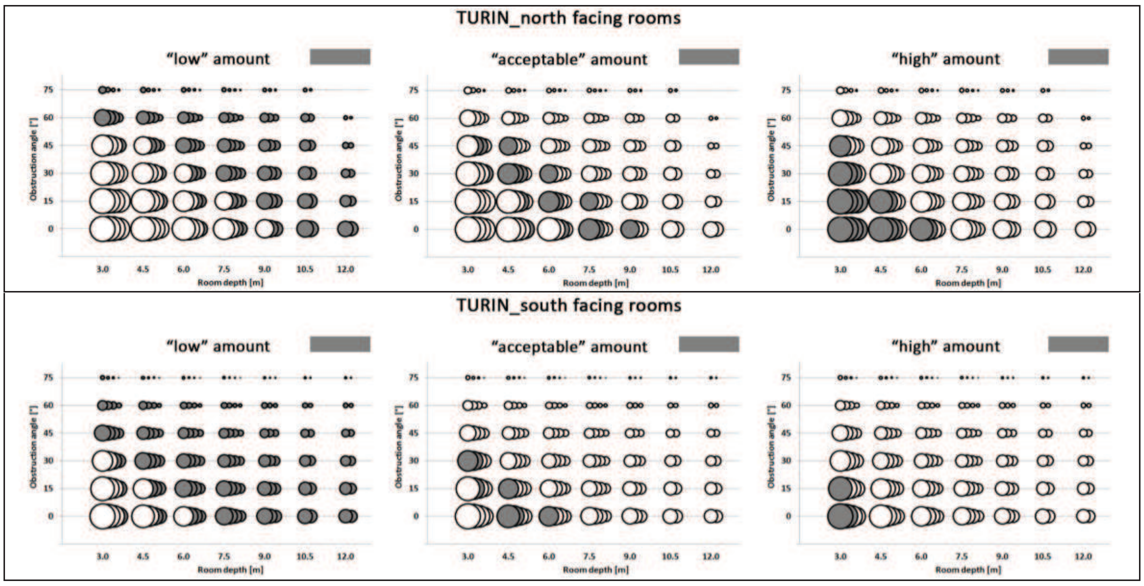

Figure 6: Combination of architectural features falling into the daylight performance classes (case-studies: north/south-facing rooms in Turin; τ_{vis}=70%; E_{target}=500 lx).

Development of a set of mathematical models for the earliest design stages

The developed graphical tool presents some limitations: first of all, it visualizes the results of DDPM for a restricted number of configurations, relative to spaces in Turin, with a τ_{vis} of 70% and in which activities requiring an illuminance of 500 lux are carried out. Moreover, the DDPM data are given in ranges, which implies that rooms with different characteristics might result in the same range. In order to overcome these limitations, a set of mathematical models are being derived from the database to link the daylight availability within the considered space (in terms of DDPM values) or the lighting energy demand to the space architectural features and, for the energy demand values, to the installed control systems and lighting power densities. For this purpose, new sets of simulations were run to expand the databases including more sites (Catania, Italy, latitude: +38.3°; Berlin, latitude: 52.3°N), target illuminances (E = 150, 300, 750 lux) and glazing visible transmittances (τ_{vis} = 90%, 50%, 35%). The definition of the mathematical models in their final version is underway, in particular with regard to the testing and validation phase. Some first results were presented in [4], concerning a multivariate non-linear regression model for the lighting energy demand.

DISCUSSION AND CONCLUSION

The huge research activity presented in this paper does not cover every possible site or building configuration, but it still makes available a set of information, graphical tools or equations that can be useful to inform the design team on the impact of their architectural choices on both the DDPM values for the considered space and on the energy demand for lighting during the very first stages of the building design process, when the use of simulation tools for more detailed calculation is still premature. According to the authors' intent, designers are assisted in crucial decisions concerning the window and the room sizing and under which conditions the choice of a daylight responsive control system is worthwhile: for instance, for a given urban settings (for which room obstruction angles are known), designers can find out how room depth and window area influence the room energy performance; or, the other way around, they can size window and room geometry so as to guarantee a desired value of DDPM values or energy demand for lighting.

On the other hand, it's worth noting how the proposed tools and equations are valid for the assumed boundary conditions (sites, architectural features, building usage and lighting system characteristics, etc.). The daylight availability and the lighting energy demand for the room would vary if, for instance, it would be located in sites with different latitude, or with same latitude but with quite different annual climates or if it would have a different use (in terms of illuminance, occupation profile or user behaviour) or a different type of lighting and control system or if the blind would have different characteristics. Furthermore, the results are based on the use of Daysim as tool to run annual climate based daylight/electric lighting simulations. Again, if a tool other than Daysim was used to complete the parametric study, the result database would change and so would the graphical tool and the mathematical models. Anyway, the considered variables cover a wide range of possible scenarios and the obtained models represent an effective starting point in the direction of providing designers with easy to use tools for the early stages of the design process.

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Paper V:
'Assessment of daylight in rooms with different architectural features'

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Published in:
Building Research and Information. 2014, vol. 43, n.2, pp. 222-237.

BRI Building Research & Information 2015
Vol. 43, No. 2, 222–237, http://dx.doi.org/10.1080/09613218.2014.922359

Routledge Taylor & Francis Group

RESEARCH PAPER

Assessment of daylight in rooms with different architectural features

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Results are presented from a parametric study that assessed the amount of daylight in rooms with different architectural features: the orientation, window size and visible glazing transmittance, room depth, external obstruction angle and site. Annual lighting simulations were run in order to understand how the daylight availability within a space changes as a function of the architectural features. A sub-dataset of the full result database is examined in detail for north- and south-facing rooms in Turin, north-west Italy, with a visible glazing transmittance of 70%. Each feature is analysed for its influence on the daylighting conditions. A simple graphical tool is presented to promote an easier reading of the results. This was developed to provide a synthesis of information to the design team. It shows the influence of preliminary design solutions on the amount of indoor daylight. This allows a design team to assess indoor daylighting from the earliest design phases onwards and to determine which combinations of architectural features are able to provide high, acceptable or low daylight levels within a room.

Keywords: climate-based daylight metrics, climate-based daylight modelling, daylight availability, daylighting design, design tools

Introduction

Recent directives and legislation aimed at reducing energy consumption in private and public buildings has noticeably changed the focus on the building design approach over the last decade. These requirements have increased the attention given to the energy performance of a building (COM 772, 2008; Directive 2009/28/CE, 2009; Directive 2010/31/CE, 2010; EN 15603, 2008).

In the lighting field, a substantial reduction in electricity consumption for artificial lighting could be obtained through a greater use of daylight, together with the use of the most energy-efficient lighting technologies, including light-emitting diodes (LEDs) or electric lighting controls, and an increased and more conscious implementation of building automation principles. Furthermore, an appropriate daylighting design approach can influence the global energy performance of a building as well as the interior visual and thermal comfort for the occupants. For this reason, it is always necessary to consider a balance between daylighting benefits and energy requirements, as indicated in some recent studies (Chan & Tzempelikos, 2013; Didoné & Pereira, 2011; Haase, 2011; Moret, Noro, & Papamichael, 2013; Nielsen, Svendsen, & Jensen, 2011; Shen & Tzempelikos, 2011; Tzempelikos & Athienitis, 2007).

The increasing awareness of the potential benefits of daylight has resulted in an increased need for objective information and data on the impact that different design solutions can have on the daylighting condition within a space, in terms of the architectural features. Over the last few years, a number of studies have been performed to obtain information on this issue. However, few of them have focused on parametric studies with considering a wide set of variables.

Reinhart (2002) investigated the influence of various design variables on daylight availability in over 1000 open-plan office settings with different external shading contexts, glazing types, facade orientations, ceiling designs and partition arrangements in five different climatic sites. The daylight performance of the offices was expressed in terms of their daylight autonomy distribution.

Ünver, Öztürk, Adigüzel, and Çelik (2002) compared daylight illuminance in three offices with different types of glass and 'transparency ratios'. Daylight illuminance was calculated considering an average sky model and using statistical meteorological data for Istanbul, Turkey.

Krarti, Erikson, and Hillman (2004) presented a simplified analysis method to evaluate how daylight can be used to reduce energy consumption from electric lighting for four combinations of building geometries, various window sizes and glazing types in four geographical areas.

Ghisi and Tinker (2004) presented a method to predict the potential for energy savings due to daylight using an 'Ideal Window Area' concept, *i.e.* a window area that allows a balance to be obtained between solar thermal load and daylight supply. This method was developed using ten differently sized and five differently shaped rooms considering two climatic conditions. The potential daylight availability was assessed using a method based on the daylight factor.

Recently, Shen and Tzempelikos (2010) have presented a calculation model that combines the radiosity method with one-bounce ray-tracing to predict hourly indoor illuminances and annual daylighting metrics in order to help designers make better decisions on how to optimize the daylighting performance of a building. The study considered different facade parameters (window size, properties, orientation and geometry).

Dubois and Flodberg (2013) presented a study on daylight utilization in perimeter office rooms at high latitudes and investigated, through an annual lighting simulation, how the internal daylight availability was influenced by various variables, such as the glazing-to-wall ratio (GWR), visible glazing transmittance, inner surfaces reflectance, orientation and latitude.

The increased need and emphasis for daylighting design to take into account the annual dynamic behaviour of a space places new demands upon the design team. There is a need for both simple and detailed methods to predict daylight availability, during both the earliest design phases (when the first daylighting strategies are initially explored) and at the end of the design process (to verify the results that have been obtained).

The daylight availability during the course of a year in a space can currently be quantified via the climate-based daylight modelling (CBDM) approach (Mardaljevic, 2006). This consists of a daylighting analysis, based on local weather data, that involves the calculation of the indoor illuminances at predefined time steps, for variable periods (usually a full year). This kind of approach allows daylighting to be studied by taking into account the contribution of both direct and diffuse solar radiation and variation due to local climate conditions over a period of time. In this context, new metrics have been proposed and tested in order to summarize the huge number of data that can be obtained through climate-based modelling into synthetic performance parameters (Mardaljevic, 2006, 2009; Reinhart, Mardaljevic, & Rogers, 2006; Rogers, 2006). CBDM requires the use of dedicated software, which, at present, is not used often by designers and practitioners, partly because the existing standards are still based mainly on traditional metrics to estimate the daylight contribution to indoor lighting (*e.g.* the daylight factor) and partly because the software for climate-based modelling is not always within the reach of all designers, in particular at the early design phases. This can be due to prohibitively long computation times and to simulation processes that are too complicated (Galasiu & Reinhart, 2008; Reinhart & Fitz, 2006; Reinhart & Wienold, 2011).

In the lighting sector, packages such as Daysim (http://daysim.ning.com), Radiance (Ward & Shakespeare, 1998), EnergyPlus (http://apps1.eere.energy.gov/buildings/energyplus) or Spot (Rogers, 2006) are available, free of charge, for daylighting and energy simulations, but they require a great deal of high levels of user expertise to define correctly the input and simulation parameters as well as to interpret the simulation results correctly. Furthermore, this kind of simulation-based daylighting and energy analysis is mainly devoted to advanced phases of the design process, when detailed three-dimensional (3D) models of the design solution are available.

In general, it could be said that there is a lack of simple but sufficiently accurate prediction tools for a design team to optimize a project during the conceptual design phase and on which to base the first, but crucial, decisions about the building shape and orientation, window sizes and characteristics of glazing and shading systems.

Within this context, the present paper focuses on two main topics, which represent the originality of the research:

- An analysis of the effect of different architectural design solutions on daylight availability through a CBDM. This analysis was conducted by running a large number of annual daylighting simulations of a target room whose architectural features, such as orientation, window size, room depth and external obstruction, were changed.

The results were then elaborated in climate-based daylight metrics to understand how the availability of daylight within a space changes as a function of the architectural features.

- A simple graphical tool, which is proposed to obtain an immediate reading of the parametric analysis results. This is intended for the design team during the earliest design phases so that they can quickly verify the influence of preliminary design solutions on the daylight amount in a space.

Methods: the effect of different architectural features on indoor daylighting

The approach adopted involves a parametric study to assess how the daylight availability varies as the building/room architectural characteristics vary. As a first step, the parameters that influence the daylight amount in an indoor space were identified. These parameters mainly concern:

- the external daylight availability of the design site, which depends on the site latitude and local weather data
- the architectural features of the building, which are mainly linked to the glazing area and visible transmittance, room sizes and internal surface reflectance, orientation and the sky angle 'seen' by the windows

In the study, the daylighting conditions of a target room with several settings were analysed by estimating, through simulations, the indoor daylight illuminances during the course of a year. The simulations were performed using the validated dynamic daylight software Daysim (version 3.1) (Reinhart, 2006; Reinhart & Walkenhorst, 2001). A single room was used as a 'case study' and the analysis was carried out by changing the characteristics of the room in terms of the following:

- *Latitude and climate*
  Simulations were conducted for three sites, Berlin, Germany (latitude: 52.3°N), Turin, Italy (45.1°N) and Catania, Italy (37.5°N). The climate file corresponding to each site was used (http://apps1.eere.energy.gov/buildings/energyplus).
- *Orientation*
  The same room was set with the opening facing south, west and north. The east orientation was not modelled as the daylight amount was assumed to have been described well through the simulations carried out for the west orientation, as also shown in previous studies (Dubois & Flodberg, 2013).
- *Room depth (RD)*
  Varied from a minimum of 3 m to a maximum of 12 m, with intervals of 1.5 m.
- *Window area (expressed in terms of window-to-wall ratio, WWR)*
  All spaces were sidelit through vertical windows, whose area was varied to determine WWR values of 0.2, 0.3, 0.4, 0.5 and 0.6. The window height was kept constant at 1.6 m, with the sill set to 1 m from the floor. The number of modelled WWR configurations depended on the room depth: WWR was set over a minimum value for each room depth so that the window-to-floor area ratio was always greater than 0.125, this being a reference value that is assumed in several local Italian regulations for ventilation purposes. Figure 1 shows the different combinations of WWR and RD values.
- *Visible glazing transmittance* (τ_{vis})
  Set equal to 90%, 70%, 50% and 35% in order to cover a broad spectrum of transparencies commonly used for building glazing.
- *External obstruction angle* (γ)
  Six obstruction angles, calculated on the basis of a facing building, were considered: from 0° (unobstructed condition) to 75° (highly obstructed urban setting), with increments of 15°.
- *Average target illuminance over the working plane*
  Initially set to 500 lx, a typical value required for reading or visual display terminal-based activities, according to European standard CEN 12464-1 (2011), and then set to lower and higher values also to consider other types of activities: the assumed illuminances were 150, 300, 500 and 750 lx.

Room width and height were kept constant at 12 and 3 m, respectively. All walls and window frames had a diffuse reflectance of 50%, while the diffuse reflectance values of the floor and the ceiling were set to 30% and 70%, respectively. The room was considered to be continuously occupied Monday–Friday from 08:30 to 18:30 hours, over the whole year, including daylight-saving times. Different occupancy profiles can be found as references for time-based (annual) simulations: from 08:00 to 17:00 hours in European standard CEN 15193 (2008) for the calculation of the lighting energy numerical indicator, or from 08:00 to 18:00 hours in the IES Approved Method LM-83 on Daylight Metrics (IES Daylight Metrics Committee, 2012). However, in this study, rather small differences (a maximum of 5%) were observed with a shift of 30 min in the occupancy

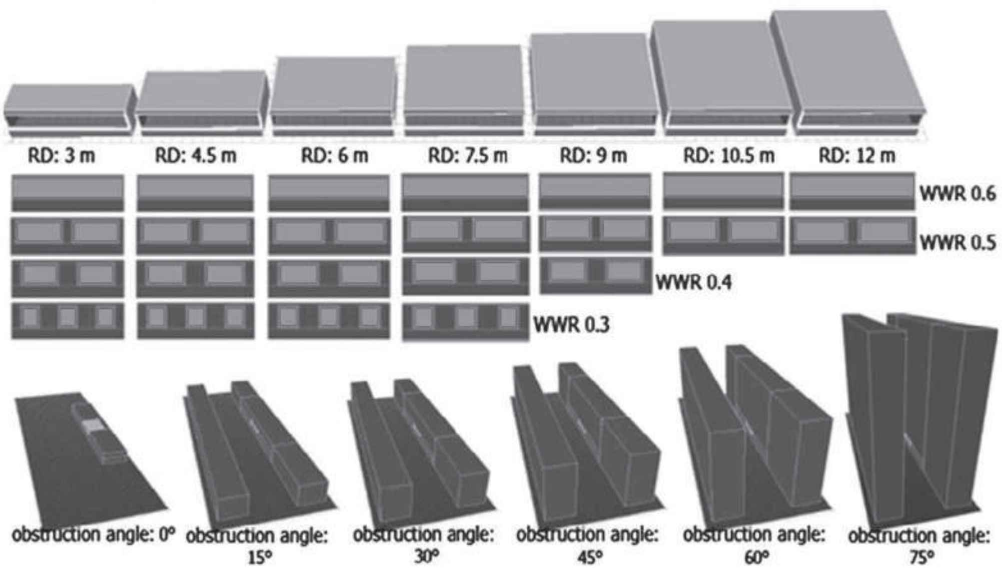

Figure 1 Visualization of some of the simulated case-studies. In particular, the variation of the room depth, window-to-wall ratio and the obstruction angle as 'seen' by the opening are shown

profile (08:30–18:30 hours with respect to 08:00–18:00 hours).

The annual daylight illuminances and the consequent daylight metrics were calculated over a grid with a 0.50 m spacing positioned at the working plane height, but excluding a peripheral strip of 0.5 m along the entire room perimeter. The mean value was calculated from the spatial distribution over the working plane grid and was used as an indicator of the central tendency of the spatial distribution.

The effect of an automated shading system, consisting of a venetian blind with a diffuse transmittance of 25% (when in the closed position), was considered in the simulations to account for the need to control glare and overheating. In particular, the algorithm implemented in Daysim, which accounts for the use of shading systems, assumes the presence of active and/or passive users. The active user opens the blinds in the morning and partly closes them to avoid visual discomfort when direct sunlight above 50 W/m^2 is incident on the work plane sensors. The passive user keeps the blinds lowered throughout the year. The strategy adopted in this study refers to mixed behaviour, *i.e.* both types of users were assumed to influence the blind control equally (Reinhart, 2006). The use of the blind was only simulated for south- and west-facing spaces and it was excluded for the corresponding north-facing ones.

The set of variables described above was used in the overall parametric study carried out by the authors to investigate daylighting and the electric lighting building energy demand, and which has already been the subject of some previous publications (Lo Verso, Pellegrino, & Pellerey, 2014; Pellegrino, Aghemo, Lo Verso, & Cammarano, 2011).

Table 1 Design variables used in the overall parametric study: the results presented in the paper refer to a sub-dataset highlighted with a grey background

Site	Turin (45.1°); Catania (37.5°N); Berlin (52.3°N)
Orientation	south; north; west
RD [m]	3; 4.5; 6; 7.5; 9; 10.5; 12
WWR [-]	0.3; 0.4; 0.5; 0.6
γ [°]	0; 15; 30; 45; 60; 75
τ_{vis} [%]	35; 50; 70; 90
E_{target} [lx]	150; 300; 500; 750

In the present paper, which focuses on the availability of indoor daylight, a sub-dataset, which is shown in Table 1, was used.

The radiance simulation parameters were set as: ab = 6; ad = 1000; as = 20; ar = 300; aa = 0.05; the simulations were run using the climate files of the considered locations with a time-step of 5 min.

The annual daylight illuminance values were elaborated to derive the following daylight metrics: daylight autonomy (DA), continuous daylight autonomy (DA_{con}), maximum daylight autonomy (DA_{max}), useful daylight illuminance (UDI) and annual light exposure (ALE).

These metrics form a rather heterogeneous group, as they were proposed by different authors, with different objectives. In principle, it seems possible to identify three main groups:

- *Annual light exposure (ALE)* (CIE, 2004; Mardaljevic, 2006)

  Describes the daylight available within a room throughout the year as the cumulative amount of daylight incident on a point of interest over the course of a year (daylight dose).

- *Daylight autonomies group (DA, DA_{con}, DA_{max})* (Reinhart & Walkenhorst, 2001; Rogers, 2006)

  Use the time-varying daylight illuminance at a point as an indicator to assess daylight availability within a room throughout the year, in particular by referring the dynamic variation in illuminances to the threshold values. The threshold for DA is the illuminance required for the considered space usage according to the standards in force; this means assessing the percentage of the occupied times of the year when the illuminance requirement is met by daylight alone. A second threshold (ten times the illuminance requirement) is also considered to account for the occurrence of direct sunlight or other potentially glary conditions (DA_{max}).

- *Useful daylight illuminances group ($UDI_{fell\text{-}short}$, $UDI_{achieved}$, $UDI_{exceeded}$)* (Nabil & Mardaljevic, 2005, 2006)

  These also consider work plane illuminance to assess daylight availability within a room throughout the year, but they refer the dynamic variation of illuminance values to both an upper and a lower threshold, *i.e.* they express the percentage of the occupied times of the year when illuminances lie within one of the three resulting ranges: a range that includes illuminance values for which daylight can be considered substantially lacking ($UDI_{fell\text{-}short}$); a range that includes illuminance values which are considered 'useful' ($UDI_{achieved}$); and a range that includes illuminance values that can result overabundant and which are therefore meant to detect the likely appearance of glare ($UDI_{exceeded}$). The three indexes together provide a synthetic view of the overall distribution of illuminances throughout the year.

Recently, two new daylight metrics have been defined and adopted by the Illuminating Engineering Society of North America (IES Daylight Metrics Committee, 2012). Spatial daylight autonomy (sDA), which assesses the sufficiency of annual illuminance in an interior work environment, and annual sunlight exposure (ASE), which expresses the annual glare potential. Spatial daylight autonomy ($sDA_{300/50\%}$) is defined as the percentage of an analysed area that meets a minimum daylight illuminance level of 300 lx for 50% of the operating hours per year, while annual sunlight exposure ($ASE_{1000,250h}$) is defined as the percentage of an analysed area that exceeds a specified direct sunlight illuminance level of 1000 lx for more than 250 hours per year.

It is important to note that the above metrics are starting to be included in lighting design guides and recommendations. For instance, the UK Education Funding Agency for the Priority Schools Building Programme (UK Education Funding Agency, 2014) uses $UDI_{achieved}$ and DA as daylighting design criteria for teaching spaces. The Society of Light and Lighting guideline *Lighting Guide 5: Lighting for Education* (SLL, 2011) also refers to the UDI concept.

sDA and ASE metrics are instead adopted in the rating system of the *LEED Reference Guide for Building Design and Construction* (USGBC, 2014) as possible options to assess indoor daylighting.

Results of the parametric study

A synthesis of the results obtained in the study (with reference to the sub-dataset of configurations indicated in Table 1) is presented in this section.

The results are described in different subsections, in which the effect of each variable (orientation, RD, WWR and γ) on the amount of daylight within the considered rooms is analysed.

The results shown in the following graphs are expressed in terms of ALE, DA, DA_{max} and $UDI_{achieved}$. The 'useful' range of illuminances for the calculation of

$UDI_{achieved}$ was considered between 100 and 2000 lx ($UDI_{100-2000}$), consistently with what was proposed by Nabil and Mardaljevic (2005) and Nabil and Mardaljevic (2006). However, it should be observed that these authors later increased the upper illuminance threshold from 2000 lx to 3000 lx (Mardaljevic, Andersen, Roy, & Christoffersen, 2011).

The obtained results required a great deal of effort, in terms of data synthesis and representation. The effect of the variation of each variable on daylight availability is highlighted in the graphs below. The maximum, minimum and mean values obtained from the whole set of considered configurations are shown in the graph. The percentage variation of the considered metrics, obtained by changing the architectural features of the room, are also shown. $\Delta DA_{3\rightarrow 4.5}$ therefore represents the relative percentage variation of DA results when the room depth is increased from 3 to 4.5 m.

Effect of orientation

The effect of orientation on the daylight amount in the different room configurations is shown in this section. The presented results refer to unobstructed spaces ($\gamma = 0°$), considering all the RD and WWR.

As illustrated in Figure 2, the overall daylight amount, which does not refer to a target illuminance and is therefore expressed in terms of annual light dose (ALE), is higher for south-facing rooms without blinds ($ALE_m = 8.7$ Mlxh) than for west-facing rooms ($ALE_m = 6.1$ Mlxh), north-facing rooms ($ALE_m = 3.2$ Mlxh) and south-facing rooms with blinds ($ALE_m = 3.2$ Mlxh); the ALE values are similar for south-facing rooms with blinds and north-facing rooms in mean value and range of variation terms.

If daylight availability within a space is evaluated in terms of daylight autonomy, considering a target illuminance of 500 lx, the results are slightly different (Figure 3). South-facing rooms without blinds, on average, still have higher values ($DA_m = 65.7\%$) than west-facing ($DA_m = 57.7\%$) and north-facing rooms ($DA_m = 50.6\%$). It has also been observed that south-facing spaces with blinds have lower daylight autonomy values than their corresponding north-facing spaces: the DA_m value for the former spaces drops to 33% and, in general, individual DA results are always lower than 80%, while they rise to over 80% for some north-facing space configurations.

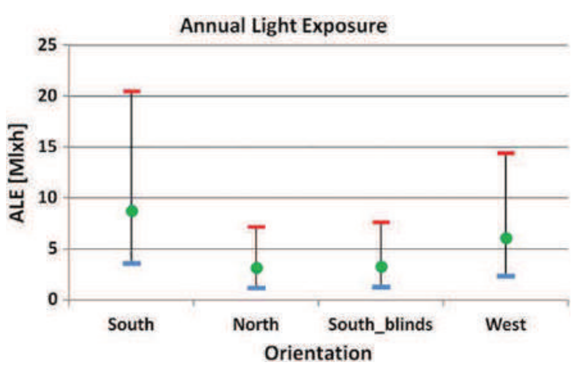

Figure 2 ALE ranges (maximum, minimum and mean values) as a function of orientation
Note: ALE = annual light exposure

For potential glare conditions (expressed through the DA_{max} metric), north-facing and south-facing rooms with blinds show a very low risk of glare as their DA_{max} values tend to 0 ($DA_{max,m} = 0.03\%$ and 0.8%, respectively), while west-facing rooms ($DA_{max,m} = 4.8\%$), and especially south-facing rooms without blinds, show a higher potentiality for glare conditions ($DA_{max,m} = 9.8\%$). In the latter two cases, the range is very wide, with maximum values of 16.5% and 30.5%, respectively.

According to the $UDI_{100-2000}$ results, north- and south-facing rooms with blinds show a good daylight performance, since the percentage of the occupied times of the year when illuminances lie between 100 and 2000 lx is high ($UDI_{100-2000,m} = 80\%$ and 72%, respectively). Slightly lower values are obtained for west- and south-facing rooms without blinds.

Effect of room depth (RD)

The effect of room depth on the daylight amount in the different room settings is discussed in this section. The results refer to north- and south-facing rooms (the latter with blinds).

As shown in Figure 4, a progressive increase in room depth results in a decrease in DA; this DA reduction appears to be greater for small and medium RD (RD ≤ 6 m) than for RD over 6 m: the average per cent difference of DA (ΔDA_m) when the room depth is increased from 3 to 4.5 m and from 4.5 to 6 m is $\Delta DA_m = -30\%$, while the average ΔDA per cent difference for RD > 6 m is lower ($\Delta DA_m = -18\%$).

If the amount of daylight in a space is analysed through the $UDI_{100-2000}$ metric, it can be observed that the progressive increase in room depth has a less effect on the $UDI_{100-2000}$ variation, since the average per cent difference ($\Delta UDI_{100-2000}$) is always in the -10% to -20% range (Figure 5). It should be noted that the range of the $UDI_{100-2000}$ results is very wide for each room depth.

The above results show the important role played by the metric that is used to describe the daylight availability in a space: due to the inherent characteristics of the DA and the $UDI_{100-2000}$ metrics (the former is calculated considering a single illuminance target

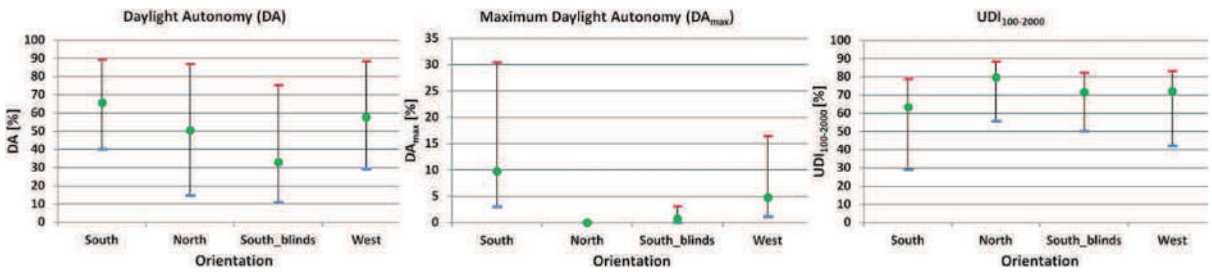

Figure 3 DA, DA_{max} and $UDI_{100-2000}$ ranges (maximum, minimum and mean values) as a function of orientation
Note: DA = daylight autonomy; UDI = useful daylight illuminance

value, the latter considering a broad range of illuminances), DA seems to be more sensitive to variations in architectural features of the room.

An increase in room depth results in a decrease in the average values of both DA and $UDI_{100-2000}$, although the range of values obtained for each RD is quite different. The $UDI_{100-2000}$ range is similar for each RD, while the DA range is reduced considerably when RD is increased. Limiting the room depth to 7.5 m appears to be advisable as the DA is always below 50% over this RD.

Effect of window-to-wall ratio (WWR)

The effect of WWR on the daylight amount in the different room configurations is shown in this section. As in the previous section, the results refer to north- and south-facing rooms with blinds (Figures 6 and 7).

A slight increase in the average value can be seen in the graphs when WWR is increased, even though a wide range of values is obtained for each WWR. The DA per cent variation is higher when WWR is increased from 0.3 to 0.4 ($\Delta DA_m = 61\%$) than from WWR = 0.4–0.5 ($\Delta DA_m = 30\%$) or from WWR = 0.5–0.6 ($\Delta DA_m = 21\%$).

The corresponding average increments in UDI values for the same WWR increments are lower: $\Delta UDI_{100-2000,m} = 19\%$ for a WWR increment from 0.3 to 0.4, $\Delta UDI_{100-2000,m} = 9\%$ for a WWR increment from 0.4 to 0.5, and $\Delta UDI_{100-2000,m} = 5\%$ from a WWR increment from 0.5 to 0.6.

In conclusion, it appears that an increase in WWR from 0.3 to 0.4 produces the highest per cent variation in the interior daylight amount.

Effect of external obstructions

Since buildings are normally placed in urban settings, it is important to point out the effect of external obstructions (γ) on daylight availability.

As shown in Figures 8 and 9, an increase in the obstruction angle results in a decrease in the DA and $UDI_{100-2000}$ values. All the simulated spaces show lower DA values than 50% (maximum DA of 38%) for highly obstructed urban settings (obstruction angles over 45°). A progressive increment in the height of the obstructing building results in an increase in the average DA per cent difference (ΔDA_m), which is lower for an obstruction angle of 0–15° and of 15–30° than for increments over 30°.

These results suggest that higher external obstructions than 30° could seriously affect the performance of room daylighting. This is also confirmed by the $UDI_{100-2000}$ results (Figure 9): the average $UDI_{100-2000}$ for external obstruction angles of up to 30° is always higher than 50%; a progressive increment in the obstruction angle results in an increase in the average

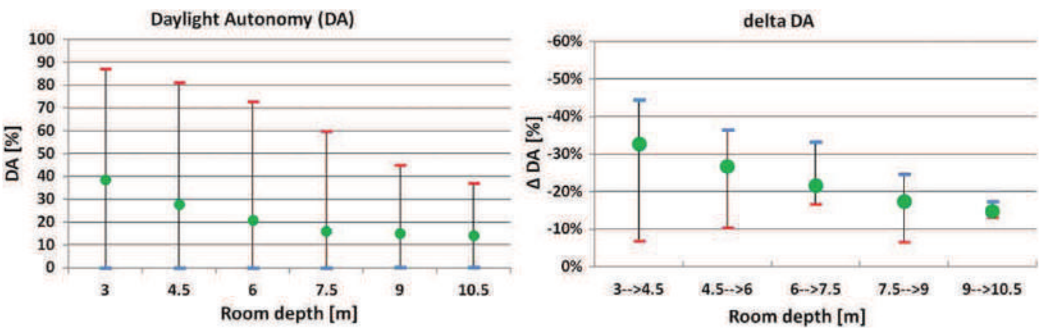

Figure 4 DA (maximum, minimum and mean values) and Δ DA ranges as a function of RD
Note: DA = daylight autonomy; RD = room depth

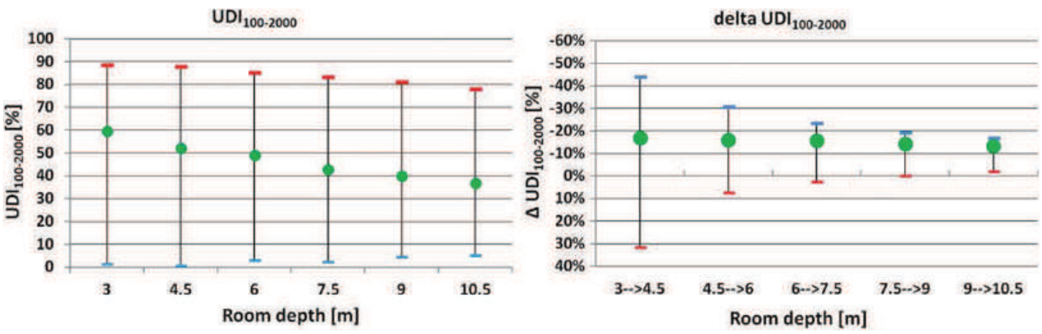

Figure 5 $UDI_{100-2000}$ (maximum, minimum and mean values) and $\Delta UDI_{100-2000}$ ranges as a function of RD
Note: UDI = useful daylight illuminance; RD = room depth

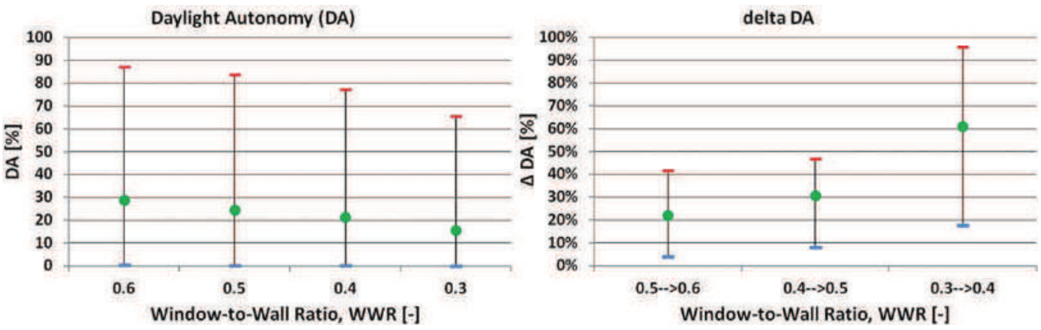

Figure 6 DA (maximum, minimum and mean values) and ΔDA ranges as a function of WWR
Note: DA = daylight autonomy; WWR = window-to-wall ratio

$UDI_{100-2000}$ per cent difference, as was also previously shown for the DA metric.

In conclusion, it should be observed that the graphs and data presented above are representative of the range of results obtained from a large number of room configurations (WWR, RD, γ and for the north and south with blind orientation).

The information that can be obtained from these data is quite general. A different approach to the interpretation of the database is necessary to obtain more detailed information.

Graphical tool to express daylighting performance: incorporating the architectural characteristics

The large number of case studies that were simulated resulted in a huge database of daylight metrics values, which describes variations in daylighting conditions within the considered rooms as a function of variations in the architectural features.

A simple graphical tool, which is able to summarize the amount of information on the daylighting condition in spaces with different characteristics and to allow

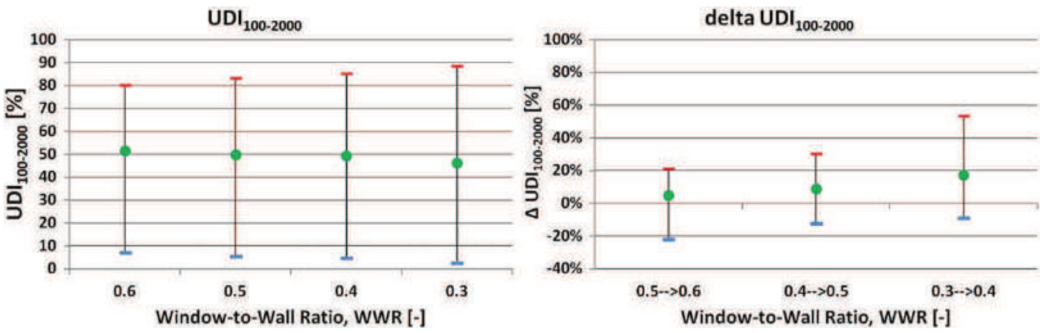

Figure 7 $UDI_{100-2000}$ (maximum, minimum and mean values) and $\Delta UDI_{100-2000}$ ranges as a function of WWR
Note: UDI = useful daylight illuminance; WWR = window-to-wall ratio

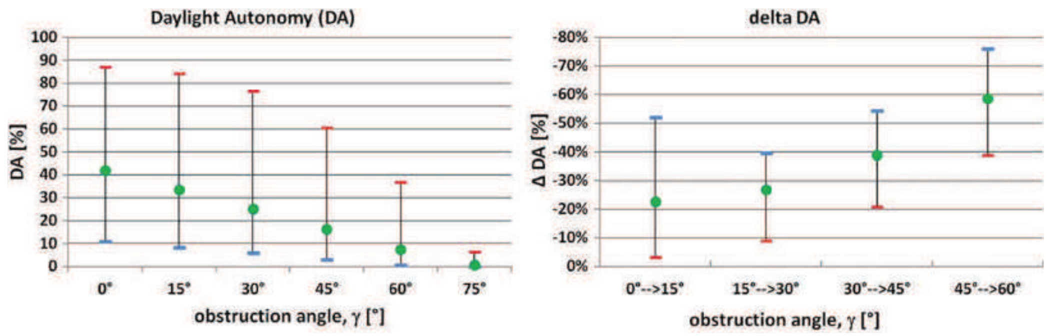

Figure 8 DA (maximum, minimum and mean values) and ΔDA ranges as a function of γ
Note: DA = daylight autonomy; γ = external obstruction angle

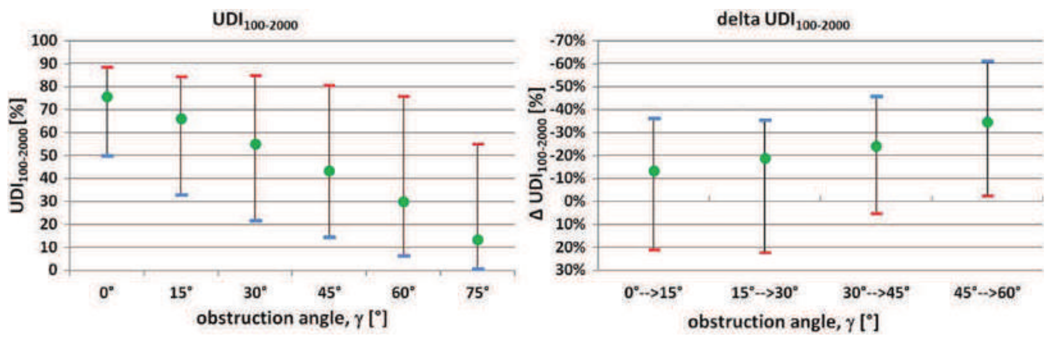

Figure 9 $UDI_{100-2000}$ (maximum, minimum and mean values) and $\Delta UDI_{100-2000}$ ranges as a function of γ
Note: UDI = useful daylight illuminance; γ = external obstruction angle

readers to read and comprehend the data quickly, has been developed.

Figure 10 shows the rationale on which the graphical tool was developed; it considers all the variables involved in the study: room depth (along the x-axis), obstruction angle (along the y-axis) and WWR from 0.6 to 0.3 (represented by a number of partially overlapping circles for each room depth and obstruction angle). The diameter of the circles is proportional to absolute value of the metrics and the colour corresponds to the interval in which the metric value lies. The possible scale of values of each metric (0–100%) was subdivided into five ranges (< 20%; 20–40%; 40–60%; 60–80%; > 80%).

This type of tool can be used by practitioners to verify quickly the influence of preliminary design solutions on daylight availability within simple environments. For a given room depth, obstruction angle and WWR combination, designers can identify the daylighting condition on the graph as expressed by each metric and they can assess the influence of the variations in the architectural characteristics of the room on the daylight condition.

Figure 11 shows the graphical tool that was created to visualize the results presented in the previous sections, *i.e.* for north- and south-facing rooms with blinds located in Turin, with a visible glazing transmittance set to 70%, and considering a target illuminance value of 500 lx.

The data reported in the graphs correspond to the mean values calculated over the working plane. The considered metrics are DA, DA_{con}, $UDI_{achieved}$ ($UDI_{100-2000}$) and $UDI_{exceeded}$ (UDI_{2000}).

Examples of possible uses

The proposed graphical tool can be used by practitioners in two different ways.

In the first approach, the design team can verify the corresponding daylighting performance for a specific space under examination. As an example (Figure 11), for a north-facing room with a depth of 4.5 m and an obstruction angle of 15°, it is possible to verify how the daylighting condition changes as a function of the designed window area. With reference to the DA metric, a WWR of 0.6 or of 0.5 results in a DA in

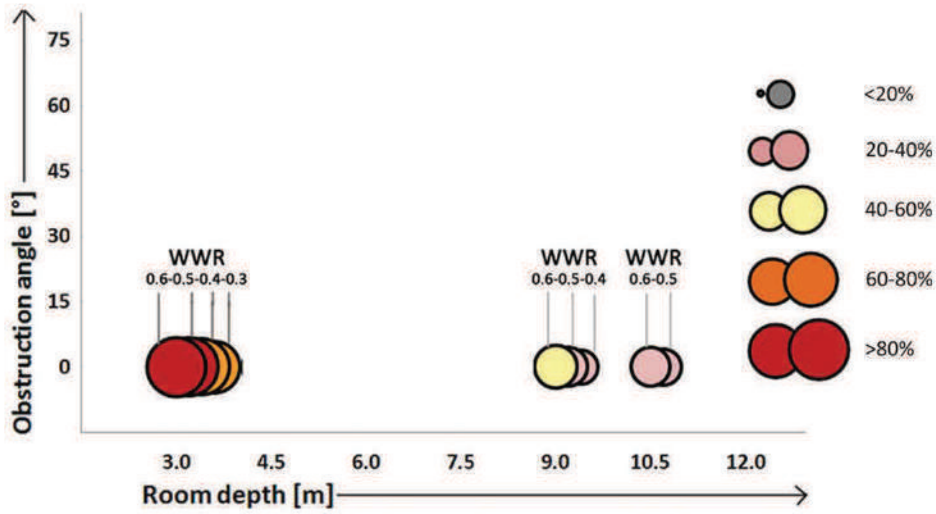

Figure 10 Schematic representation of the format of the graphical tool
Note: This tool was developed to visualize the daylighting conditions within the analysed rooms as a function of the variation of their architectural features

the 60–80% range, while reducing the window area to a WWR of 0.4 or 0.3 results in a decrease in DA (in the 40–60% or 20–40% ranges, respectively).

Instead, referring to the $\mathrm{UDI}_{\mathrm{achieved}}$ metric, a WWR of 0.6 determines a $\mathrm{UDI}_{\mathrm{achieved}}$ in the 60–80% range while, for lower window areas (WWR 0.5, 0.4 and 0.3), $\mathrm{UDI}_{\mathrm{achieved}}$ results of over 80% are determined with an increasing trend. On the other hand, the $\mathrm{UDI}_{\mathrm{exceeded}}$ metric progressively decreases as the room depth and the obstruction angle increase and the WWR decreases. The design team can hence establish that modifying the window area does not result in a significant change in the daylighting performance of the room, if expressed in $\mathrm{UDI}_{\mathrm{achieved}}$ terms, but plays a crucial role on the potential energy saving pertaining to the percentage of time of electric light use in the presence of a manual lighting control system, as can be seen from the variation in the DA values.

With the second approach, the design team can use the tool to identify the different classes of daylighting performance that can be achieved for different combinations of architectural room features. As an example, three performance classes were assumed by the authors in this study:

- ‘low’ daylight amount: DA $\leq$ 40%
- ‘acceptable’ daylight amount: 40% $<$ DA $<$ 60%
- ‘high’ daylight amount: DA $\geq$ 60%

By defining performance class ranges, practitioners can quickly verify which combinations of architectural features are able to provide high, acceptable or low daylight amounts within a room.

Figure 12 shows the examined architectural features that fall within the three performance classes, considering north-facing rooms.

The ‘low’ daylight amount mainly occurs for rooms with the following architectural features:

- profound depths (RD $\geq$ 9 m)
- high obstruction angle ($\gamma \geq 60°$)
- medium deep rooms (6 m–7.5 m), low obstruction angles (γ between 0° and 15°) and small WWRs ($<$ 0.4)
- medium deep rooms (6–7.5 m) and medium obstruction angles (γ between 30° and 45°)
- room depth of 4.5 m, obstruction angle $\gamma = 45°$ and WWR $<$ 0.5

The ‘high’ daylight amount mainly occurs for rooms with the following architectural features:

- limited depths (RD $\leq$ 4.5 m) and small obstruction angles (γ between 0° and 15°)
- room depth of 3 m, medium obstruction angle (γ between 30° and 45°) and high WWRs ($>$ 0.4)
- room depth of 6 m, obstruction angle $\gamma = 0°$ and high WWR ($>$ 0.5).

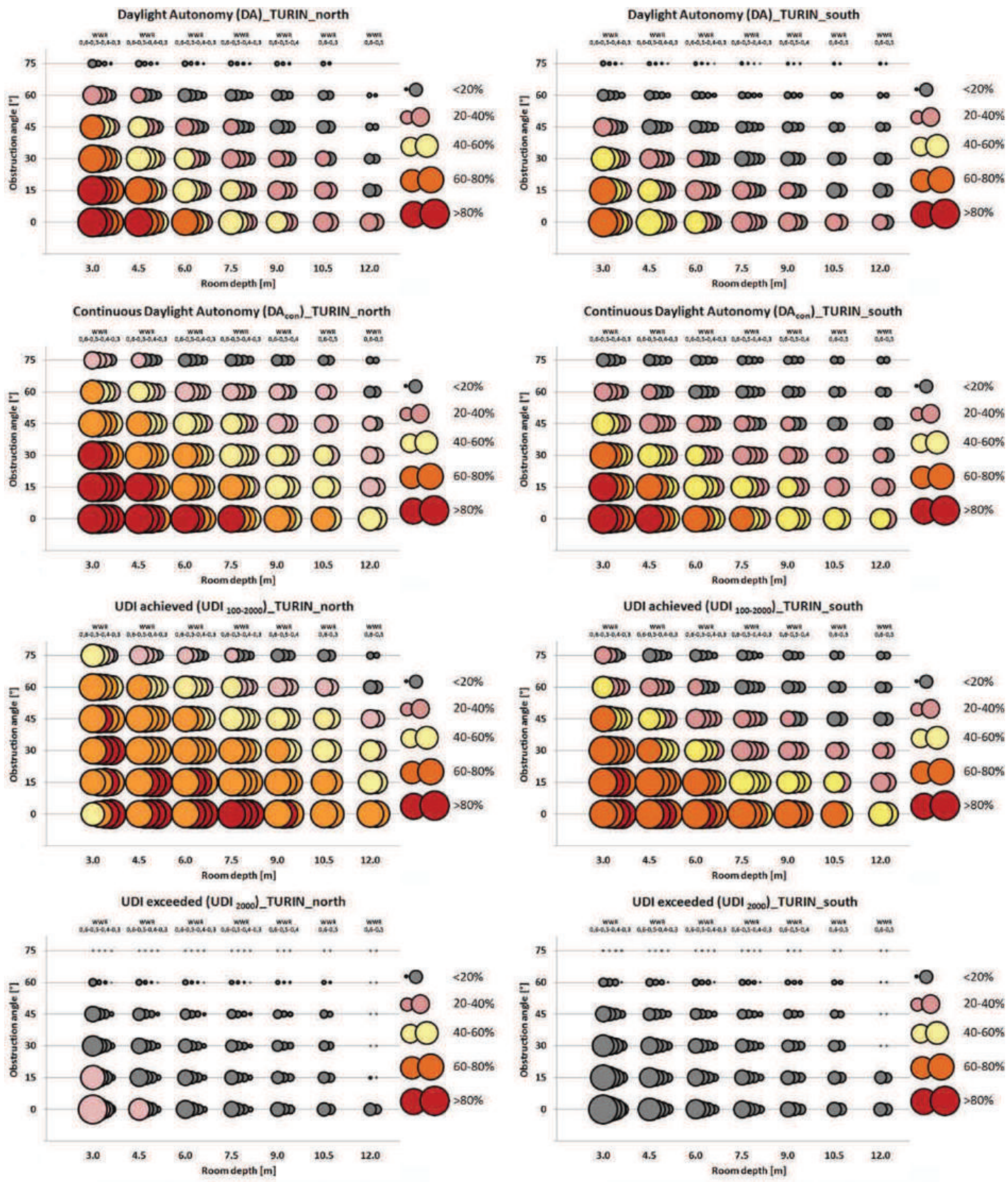

Figure 11 CBDM results for case-studies relative to north and south-facing rooms located in Turin with a visible glazing transmittance of 70%
Note: CBDM = climate-based daylight modelling

Figure 13 shows the architectural features that fall within the three performance classes for south-facing rooms with movable blinds.

The 'low' amount mainly occurs for rooms with the following architectural features:

- medium and profound depths (RD $\geq$ 6 m)
- limited depths (RD = 3 m and 4.5 m) and obstruction angle $\gamma \geq 30^\circ$ (with the exception of very small rooms with high WWR and $\gamma \geq 30^\circ$)

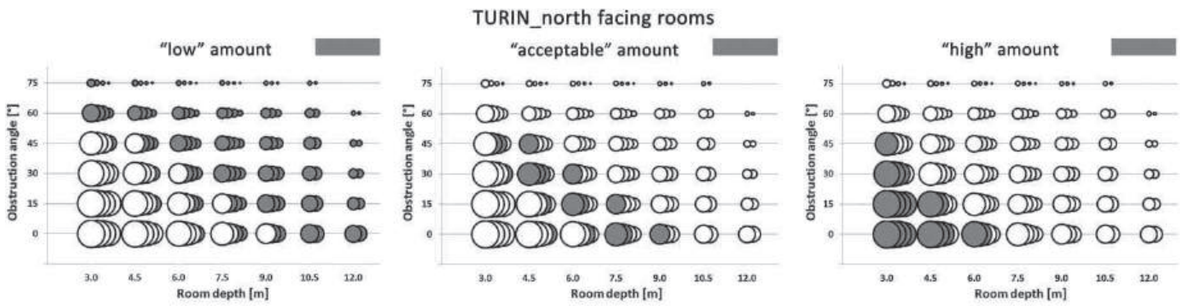

Figure 12 Visualization of combination of architectural features falling into the defined daylight performance classes
Note: case-studies relative to north-facing rooms located in Turin with a visible glazing transmittance set to 70%

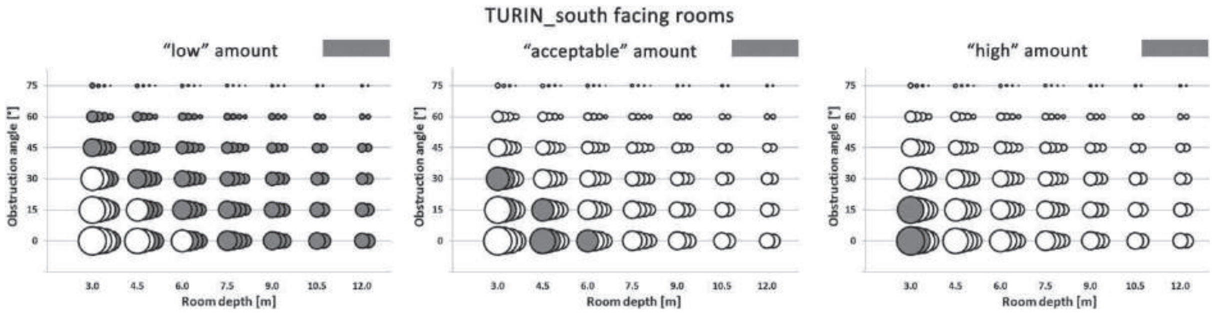

Figure 13 Visualization of combination of architectural features falling into the defined daylight performance classes
Note: case-studies relative to south-facing rooms located in Turin with a visible glazing transmittance set to 70%

- limited depths (RD $\leq$ 4.5 m), small obstruction angles (γ between 0° and 15°) and small WWRs

The 'high' amount mainly occurs for rooms with the following architectural features:

- limited depth (RD = 3 m), obstruction angles γ between 0° and 15° and WWR > 0.5

Discussion and conclusions

During the last few years, designers and practitioners have been moving towards a more advanced daylighting design approach, based on a more widespread exploitation of daylight as a key factor to reduce significantly the energy consumption from electric lighting. The amount and distribution of the daylight that enters a space depend on the architectural solutions that are developed by the design team. The architectural solution plays a crucial role on both the environmental quality perceived by the occupants, in terms of visual and thermal comfort, and on the related energy use caused by the lighting and the heating, ventilation and air-conditioning (HVAC) systems.

Within this context, this study investigated the effects of different architectural design solutions on daylight availability through a parametric analysis. The aim was to enhance knowledge on the consequences of the early design solutions on the daylighting performance of a building.

A synthesis of the results, concerning the influence that orientation, room depth, WWR and external obstructions have on the daylighting condition within a room located in Turin, has been analysed as a first primary output of the work. Some observations can be made from this analysis:

- If the daylight availability within a space is evaluated, in terms of overall daylight amount (ALE), south- and west-facing rooms present the highest values. At the same time, if blinds are not used, glare and overheating may occur (as highlighted by the DA_{max} values), as already mentioned in other studies (Dubois & Flodberg, 2013).

- Daylighting performance is better for north-facing rooms than for south-facing ones with blinds: in both cases the risk of glare is low, but the DA and $UDI_{100-2000}$ values are higher for north-facing rooms than for south-facing rooms with blinds, and this could result in a lower lighting energy demand and a better visual comfort condition as blinds can limit the outside view.

- An increase in the room depth results in a decrease in the DA values; the per cent reduction of DA appears to be greater when the room depth is increased from 3 m to 6 m than for RD over 6 m. On the other hand, an increase in the room depth has less effect on the 100–2000 lx range since the average $UDI_{100-2000}$ values are always between 40% and 60%.

- An increase in WWR results in an increase in the DA values, which is higher for increments of WWR 0.3–0.4 than of WWR 0.4–0.5 or of WWR 0.5–0.6. At the same time, no significant increase in $UDI_{100-2000}$ can be observed for larger WWR than 0.4. This means that a 40% WWR is sufficient to guarantee 'useful' daylight. This result is in line with Shen and Tzempelikos (2010) and Dubois and Flodberg (2013).

- An increase in the obstruction angle results in a decrease in the DA and $UDI_{100-2000}$. The DA decrease is lower for γ between 0° and 30° than for γ over 30°. Furthermore, lower obstruction angles than 30° allow a good daylight performance to be achieved, since $UDI_{100-2000,m}$ is always higher than 50%. This result is essentially in line with the findings of Reinhart (2002).

As already reported in this paper, the UDI illuminance thresholds were modified after their first definition. Higher values of the $UDI_{achieved}$ are obtained when the new thresholds are considered ($UDI_{100-3000}$). The increase is greater for rooms with high daylight availability (increment in the 12–20% range) and lower for rooms with low daylight availability (increment of about 5%).

Another issue concerning a daylighting design that takes into account the dynamic behaviour of daylight is the lack of simple, but sufficiently accurate, prediction tools for the design team to use for the optimization of the conceptual design phase and on which to base the first, but crucial, decisions concerning the definition of building mass, shape and orientation, as well as of window sizes, glazing and shading systems. The second primary output of the research activity was therefore concerned with the proposal of a graphical tool that could be used to summarize and more clearly visualize the simulation results and to allow an immediate reading of the daylighting conditions within a room, on the basis of variations in the architectural features. The graphical tool presented in the paper should be intended as an informative instrument to assist practitioners in these design phases.

Practitioners could make use of the tool in two different ways. For instance, for a given urban settings, they can establish how the room depth and window area can influence daylight availability in a room; or they can size the window and room geometry to guarantee a desired daylighting performance.

In the authors' opinion, the graphical tool has the merit of being based on a huge quantity of annual climate-based and radiance-based simulations, and at the same time of being a simple and quick-to-use tool for the early design phases, when more detailed design investigations and simulations are still premature and the daylighting analysis of many buildings begins and ends with the use of rules of thumb (Galasiu & Reinhart, 2008; Reinhart & Fitz, 2006; Reinhart & Lo Verso, 2010; Reinhart & Wienold, 2011). Therefore, according to a climate-based approach the annual dynamic variation in sunlight and skylight conditions throughout the year can be taken into account at a specific location as part of the analysis as well as in the obtained findings. Results and their graphical representations are currently available for three different European sites: for the sake of brevity, only the data relative to Turin have been presented in the paper, but similar graphs are also available for Berlin and Catania (three sites chosen as representative of three different latitudes in Europe) and new sites could easily be included in the study.

Furthermore, different room orientations (even though limited, for the time being, to rooms with north- and south-facing windows) and a moveable shading system (limited to a venetian blind) are considered.

However, the inherent characteristics of the proposed tool imply some limitations concerning, *e.g.* the number of variables that can be visualized. The results presented in the previous section refer to a sub-dataset that includes data on north- and south-facing rooms located in Turin with a visible glazing transmittance of 70% and a target illuminance of 500 lx. This data subset was useful for the aim of the study, *i.e.* to show how the proposed graphical tool can be used. Further sets of graphs, which include all the metrics, sites, room orientations, visible glazing transmittances and target illuminances adopted in the parametric study are available (the overall set of results and graphs will be available as a web-based tool).

Moreover, the data are given in ranges (as a consequence, rooms with different characteristics may fall into the same range) and the value displayed in the tool is the mean value calculated from the spatial distribution of the data. The mean is a parameter that is often adopted, with the minimum-to-mean ratio, to describe a spatial distribution of values. For near normal distributions, the closeness of the mean and median values indicates a nearly equal propensity for low and high values about the mean (Mardaljevic, 2009) and therefore, in these cases, half of the grid points are above and half below the mean. Nevertheless, for skewed distributions (for instance in the case of very profound or very narrow rooms), the mean could diverge significantly from the middle value (median) and thus be less effective in assessing how much of the room area achieves a certain performance. One way of overcoming this limitation is to calculate and plot the median value or adopt sDA and ASE metrics, which are more directly related to the percentage of space that achieves a predefined daylighting performance.

It is also important to point out some other limits of the results presented in the study: for instance all the simulation results presented in this paper are based on the use of Daysim. As a consequence, the results are determined on the basis of the assumptions and algorithms implemented in the software to model both the occupants' behaviour towards lights and blinds and the dynamic performance of the blind. If a different software, with different algorithms, were used to run the dynamic simulations, the results might be different.

The need for simplified, quick to use and, if possible, interactive design tools to optimize the daylighting design process has recently led to the development of other prediction tools. An example is the interactive expert system named Lightsolve, which was initially developed by the Daylighting Lab at the Department of Architecture at MIT and is now being implemented by the Interdisciplinary Laboratory of Performance-Integrated Design (LIPID) at EPFL (http://lightsolve.epfl.ch). The system allows designers to determine interactively the design changes that would most likely improve the performance of a given design and it consists of two main components: a daylighting knowledge-based part, which contains information on the effects of different design daylighting performance conditions and a fuzzy rule-based decision-making logic part, which is used to determine the most effective design changes (Andersen, Gagne, & Kleindienst, 2013; Gagne, Andersen, & Norford, 2011). As far as daylighting calculation is concerned, the tool is based on a simulation engine that calculates annual performance metrics using 3D models and a simplified climate-based lighting analysis (Andersen et al., 2008; Cutler, Sheng, Martin, Glaser, & Andersen, 2008; Kleindienst, Bodart, & Andersen, 2008). The tool could be useful at the beginning of the design process because of the reduced calculation times of the simplified lighting analysis. However, it still requires some 3D modelling and simulation and its use could be aided by a preliminary daylighting analysis based on informative tools or rules of thumb.

The present research activity is still on-going, in two main directions. The first goal is to expand the result database, mainly in order to include a larger number of sites, and to represent the results through the graphical tool: for instance, the spatial daylight autonomy values ($sDA_{300,50\%}$) are going to be plotted for a variety of configurations. The second goal concerns the use of the result database to develop a set of mathematical prediction models to link the daylight metrics values (including the spatial daylight autonomy) and the corresponding electric lighting energy demand to the factors of influence (architectural features, target illuminance values and sites), and to eventually produce an interactive software programme that will allow practitioners to obtain both daylighting and lighting energy demand results by directly introducing the architectural features of the spaces, the geographical site, the illuminance threshold and the lighting power density values. In this context, the mathematical models used to predict the lighting energy demand have recently been presented in a dedicated paper by some of the authors (Lo Verso et al., 2014).

Funding

This work was carried out within the National Research Programme PRIN 2008, entitled 'Daylighting Design for Energy Saving and Visual Comfort Purposes: Climate-Based Daylight Modelling, Glare Indices and Integrated Ventilation System Performances', and funded by the Italian Ministry for Universities, Education and Research (http://www.polito.it/tebe).

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Paper VI:
'A methodology to integrate advanced lighting
and thermal analyses for building energy simulation'

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In proceedings:
BSA 2015 – Building Simulation Applications – 2nd IBPSA-Italy Conference.
2015, Bozen, Italy.

A methodology to integrate advanced lighting and thermal analyses for building energy simulation

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Abstract

It's well known that an appropriate daylighting design can influence the global energy performance of a building as well as the visual and thermal comfort for the occupants. Furthermore the increasing awareness of the potential benefits of daylight has resulted in an increased need for objective information and data on the impact that different design solutions can have on the daylighting condition within a space, in relation with the architectural features. This kind of analysis is becoming more and more requested, during all stages of the design process.

The purpose of this paper is to describe a reliable simulation approach to consider daylight when assessing the energy performance of a building. The methodology is based on the use of both Daysim and EnergyPlus which were employed in synergy for a parametric study to assess lighting and energy performances of rooms with different architectural features: orientation, window size and glazing visible transmittance, room depth, external obstruction angle and site. Daysim was chosen to perform daylighting analyses since it allows accurately estimating the annual amount of daylight in a space and calculating climate-based daylight metrics as well as the annual electric lighting use for different lighting controls. The Daysim output file that describes the status of all lighting and shading groups in the space during the year was then used as input in EnergyPlus to estimate the influence of the daylighting and artificial lighting design on the global energy performance of a space.

The paper presents some considerations on the simulation approach adopted in the study and the most relevant results that were obtained in terms of daylighting conditions and energy demand for lighting, heating and cooling, to demonstrate the substantial influence of daylight harvesting on the reduction of the global energy performance.

1. Introduction

Recent directives and legislation aimed at reducing energy consumption in private and public buildings (EN 15603, 2008; COM 772, 2008; Directive 2010/31/CE, 2010) have noticeably changed the focus on the building design approach over the last decade. In the lighting sector, a substantial reduction in electricity consumption for electric lighting could be obtained through a greater use of daylight, together with the use of the most energy efficient lighting technologies, such as LEDs or lighting controls. At the same time daylight harvesting in indoor spaces can influence the global energy performance of a building also in terms of heating and cooling loads. In fact the internal gains from lighting can be affected by the solar radiation that enters through the openings and by the electric lighting systems' load. For this reason it is always necessary to consider a balance between daylighting benefits and energy requirements, as shown in some recent studies (Chan et al., 2013; Didonè et al., 2011; Shen et al., 2011; Tzempelikos et al., 2007). Daylight has to be studied according to its dynamic behaviour over a period of time to accurately predict illuminance levels within a space. In this context, the 'Climate-Based Daylight Modelling (CBDM)' approach was recently proposed (Reinhart et al., 2006). CBDM allows daylighting to be studied taking into account the contribution of both direct and diffuse solar radiation and the variation due to local climate conditions over a period of time. This approach involves the calculation of the indoor illuminances at predefined time-steps, usually for a full year period. In order to summarize the huge number of illuminance data that can be obtained new metrics have been proposed, the so-called climate-based daylight metrics (Daylight Autonomy, Continuous Daylight Autonomy, Maximum Daylight Autonomy, Useful Daylight Illuminance and Annual Light Exposure) (Nabil et al., 2005; Reinhart et al., 2001; Reinhart et al., 2006; Rogers, 2006). Recently, two new daylight metrics have been defined and adopted by the Illuminating Engineering Society of North America, IESNA (IES, 2012). The spatial Daylight Autonomy (sDA), which assesses the sufficiency of annual illuminance in an interior work environment, and the Annual Sunlight Exposure (ASE), which expresses the annual glare potential risk. In more detail, $sDA_{300/50\%}$ is defined as the percent of an analyzed area that meets a minimum daylight illuminance level of 300 lx for 50% of the operating hours per year, while $ASE_{1000,250h}$ is defined as the percent of an analysed area that exceeds a direct sunlight illuminance level of 1000 lx for more than 250 hours per year. It is important to note that the above metrics have been adopted in the rating system of the 'LEED Reference Guide for Building Design and Construction' (USGBC, 2014) as possible options to get the credit concerned with the quantity of daylight.

This kind of dynamic analysis implies the need for climate-based simulation tools. Software such as Radiance, Daysim and EnergyPlus are available for daylighting and energy simulations. Radiance and Daysim are validated dynamic daylight programs specifically developed for the analysis and visualization of lighting in a space (Ward et al., 1998; Reinhart, 2006) while EnergyPlus is a whole building energy simulation program that models heating, cooling, lighting, ventilation and other energy flows, taking the daylight contribution into account (US-DOE). These tools are based on different simulation approach and algorithm. EnergyPlus calculates daylight through the split-flux method. Radiance is a simulation program which employs a backward ray tracing algorithm based on the physical behaviour of light in a three-dimensional model. Daysim allows illuminance values to be accurately calculated, through the integration of the Radiance algorithm with the Daylight Coefficient method (Reinhart, 2006).

Some studies demonstrated that EnergyPlus tends to overestimate the contribution of daylight. Ramos and Ghisi (Ramos et al., 2010) analysed the difference in the calculation of internal illuminance and external horizontal illuminance between EnergyPlus, Daysim and TropLux simulation programs using three different models. The most relevant difference between EnergyPlus and Daysim was found with regard to the calculation of internal reflections: the greater the importance of reflected light, the greater the difference in illuminances calculated by the two programs.

In 2010, Versage (Versage et al., 2010) examined the difference of modelling daylight using EnergyPlus and Daysim and the consequent influence on the simulation of the global energy consumption. They found that the availability of daylight during a year has similar values only within the first three meters from the window, presenting huge divergences at the points further away from the window. The higher lighting levels simulated by EnergyPlus reduced the energy demand for electric lighting and consequently the cooling loads due to the use of electric lighting.

In this context, it is evident that there is a need to couple different software for daylighting and global energy simulation to reach more accurate building energy analyses.

The purpose of this paper is to describe a reliable, integrated simulation approach to consider daylight when assessing the energy performance of a building, highlighting potentials and drawbacks of the entire simulation process.

Results related to the daylight available in a space (in terms of spatial Daylight Autonomy) and annual energy demand for lighting, heating and cooling are presented to highlight the substantial influence of a proper daylighting design approach on the global energy performance.

2. Methodology

The method is based on a parametric study to assess through simulations how the daylight availability and the consequent energy demand for lighting, heating and cooling vary as the building/room architectural characteristics vary.

Simulations were performed using a 2-step process. In step 1, Daysim 3.1 was used to calculate the annual illuminance profile of each space configuration. Starting from these profiles, Daysim calculates the spatial distribution within a room of climate-based daylight metrics (DA, DA_{con}, DA_{max}, UDIs), as well as the corresponding annual electric lighting demand for different lighting controls based on available daylight. Besides, a program in Matlab was specifically written to elaborate the annual illuminance data and to calculate the $sDA_{300/50\%}$. This paper focuses on $sDA_{300/50\%}$ since this is the most recent dynamic daylight metric that has been proposed by the scientific community and is the only one for which target values were defined to assess the lighting performance of a space.

Among the simulation results, Daysim also provides a Comma Separated Value (CSV) file which contains hourly schedules of the status of all lighting and shading groups within the model.

In step 2, this output was directly used as input in EnergyPlus. The parametric analysis in EnergyPlus was conducted using jEPlus, a graphical interface which allows setting alternative values for all the parameters and simultaneously running multiple simulations calling EnergyPlus.

As final output of the 2-step process, annual energy demands for lighting, heating and cooling were calculated and converted into primary energy data for every room configuration.

Some considerations were than drawn comparing $sDA_{300/50\%}$ and primary energy demand results.

2.1 Definition of the model

A single office room was used as a 'case study' and the analysis was carried out changing its characteristics in terms of orientation, Room Depth (RD), window area (expressed in terms of Window-to-Wall ratio, WWR), external obstructions (γ) and visible glazing transmittance of the window system (τ_{vis}). The room was assumed to be located in three different sites. All the design variables are summarized in Table 1. The results presented in the paper refer to a sub-dataset highlighted with a grey background.

The room width and height were kept constant at 12 m and 3 m respectively. The effect of an automated shading system, consisting of a venetian blind, was considered in the simulations to dynamically control glare and overheating. The control strategy used for the venetian blind is explained in the following section.

The room was considered to be continuously occupied Monday through Friday from 8:30 a.m. to 6:30 p.m. over a whole year.

Table 1 – Design variables used in the overall parametric study

Site	Orientation	RD [m]	WWR [-]	γ [°]	τ_{vis} [%]
Turin (45.1°N)	South	4.5	0.2	0	35
	North	6	0.3	15	50
Catania (37.5°N)	West	7.5	0.4	30	70
		9	0.5	45	90
Berlin (52.5°N)		10.5	0.6	60	
		12		75	

2.2 Lighting input parameters

In this section the input data used in Daysim simulations are introduced.

The room was modeled with all walls and window frames with a diffuse reflectance of 50%, while the diffuse reflectance values of the floor and the ceiling were set to 30% and 70%, respectively.

The daylight illuminances were calculated according to a 50 cm * 50 cm calculation grid over the whole working plane (minus a 50 cm deep peripheral stripe all along the walls, which typically is a space for furniture). The work plane was set at a distance of 80 cm from the floor.

The daylighting system included into the model to control glare is a venetian blind with a diffuse transmittance of 25% (when in closed position). The blind is a movable shading system and the control is based on the algorithm implemented in Daysim, which assumes the presence of active and/or passive users. Active users open the blinds in the morning and partly close them to avoid visual discomfort when direct sunlight above 50 W/m² is incident on the work plane calculation greed points. Passive users keep the blinds lowered throughout the year (Reinhart, 2006). The strategy adopted in this study refers to mixed behaviour, i.e. both types of users were assumed to equally influence the blind control.

The target task illuminance was initially set to 500 lx, a typical value required for office activities according to the European standard CEN 12464-1:2011 (CEN, 2011). Climate based daylight metrics have been calculated based on this value. For further development of the study and for the calculation of the $sDA_{300/50\%}$ metric the target task illuminance was then set equal to 300lx.

Two different electric lighting control systems were simulated in Daysim, namely a manual on-off switch and a daylight responsive dimming system. The first one is based on the Lightswitch algorithm (Reinhart, 2006) taking into account a user which does not turn electric lights on if there's sufficient daylight on the workplane. The daylight responsive dimming system takes advantage of the daylight availability over the working plane and reduces, proportionally, the electric light use by dimming the luminaire light output.

The analysis was carried out considering a lighting power density of 12 W/m².

The Radiance simulation parameters were set as: ab = 6; ad = 1000; as = 20; ar = 300; aa = 0.05; the simulations were run using the climate files of the considered locations with a time-step of 5 minutes.

2.3 Thermal input parameters

In this section all the input data that were used in the EnergyPlus simulation program are introduced. It was assumed that the space has only one wall which is exposed to the outdoor environment. As a consequence interior walls, floor and ceiling were modeled as adiabatic elements.

The wall and the window facing the outdoor environment were modeled with a thermal transmittance of 0.25 W/m²K and 1.6 W/m²K, respectively. The Solar Heat Gain Coefficient of the glazing was set equal to 0.67.

The occupancy index and air change rate were fixed according to the Italian Standard UNI EN 10339:1995 (CTI, 1995) while internal loads (people and equipment) were set according to the Italian Technical Standard UNI TS 11300-1:2008 (CTI, 2008). Winter and summer setpoint temperatures are based on the Italian Standard UNI EN 15251:2008 (CTI, 2008). The latter input parameters are all summarized in Table 2.

Table 2 – Thermal input parameters

Parameter	Definition	Source
Occupancy hours	8:30 a.m. - 6:30 p.m.	
People definition	0.12 people/m²	UNI 10339
Air change rate	11 l/s·person	UNI 10339
People loads	70 W/person	UNI TS 11300-1
Equipment loads	3 W/m²	UNI TS 11300-1
Lighting loads	12 W/m²	
Winter setpoint temperature	21 °C 7:00 a.m. - 9:00 p.m. 18 °C 9:00 p.m. - 7:00 a.m.	UNI EN 15251
Summer setpoint temperature	26 °C 7:00 a.m. - 9:00 p.m. 28 °C 9:00 p.m. - 7:00 a.m.	UNI EN 15251

HVAC systems were modeled in EnergyPlus considering an ideal air load simplification. This object permits to assess the theoretical thermal loads needed to achieve the thermal balance at any time step of the simulation.

2.4 Integrated approach

In order to evaluate the global energy demand of each space configuration and the influence of the daylighting design project on internal loads, the assumptions made for the lighting analysis needed to be coupled with the thermal analysis. In particular the control strategy used for the venetian blind and the control system adopted to automatically dim electric lighting in Daysim generate a schedule of the status of all shading and lights that has to be used for the thermal simulation.

For the present study this connection was realized using the jEPlus tool (www.jeplus.org). jEPlus allows to perform a parametric analysis that can be applied to all the design variables present in a model simultaneously. It can create and manage multiple simulation jobs and collect results afterwards.

The parametric analysis starts with the use of jEPlus graphical interface, which allows specifying a search string with all alternative values for each parameter that has to be varied: site, orientation, Room Depth, Window-to-Wall Ratio, external obstruction angle and visible glazing transmittance. Then jEPlus allows opening one single EnergyPlus IDF model and putting search strings in the places of each parameter. Then the software picks the set of values which were specified, it puts them in every search string in the IDF model and then calls EnergyPlus.

Two specific search strings were elaborated to pick up for each room configuration the output provided by Daysim related to the use of electric lighting and blinds as a function of daylight availability.

This kind of approach can represent a reliable method to evaluate a building whole energy performance exploring multiple design options, starting from a detailed climate-based daylighting analysis.

3. Results

A synthesis of the results that could be obtained after this integrated approach is presented in this section, with reference to the sub-dataset of configurations highlighted in Table 1.

Results are divided in two different subsections. The first subsection refers to the simulations conducted in Daysim and presents a comparison between $sDA_{300/50\%}$ values and energy demand for electric lighting (Q_{EL}) results.

The second subsection refers to the simulations conducted in EnergyPlus using the jEPlus interface analyzing the overall energy performance of each room configuration compared with the amount of daylight available in the space.

In order to correctly sum lighting (Q_{EL}), heating (Q_H) and cooling (Q_C) energy, the primary energy equivalent demand has been considered and calculated as follows:

$$E_P = Q_H/\eta_H + (Q_C/EER)\cdot\eta_{el} + Q_{EL}\cdot\eta_{el} \qquad (1)$$

where η_H is the mean thermal energy generation efficiency, EER is the Energy Efficiency Ratio of a "reference" air-to-air chiller and η_{el} is the mean National electricity generation efficiency. For the present study the following values were assumed: $\eta_H = 0.85$; EER = 3; $\eta_{el} = 2.17$.

3.1 Daylight availability and energy demand for electric lighting

The parametric analysis conducted in Daysim generated results about the influence that different architectural features have on daylight availability and, consequently, on the energy demand for electric lighting. In this section, results obtained for a daylight responsive dimming system are shown in comparison with a "base-case" in which lights are always turn on.

Figure 1 shows the results for room configurations without external obstructions (γ=0°). It could be noted that $sDA_{300/50\%}$ values are on average lower for South-facing than North-facing rooms (sDA_m=60.8% and 78% respectively). This is mainly due to the presence of the movable shading device which avoids direct sunlight on the workplane and admits 25% of diffuse light only into the space.

As a consequence the mean annual energy demand for electric lighting is higher for South-facing than North-facing rooms ($Q_{EL,m}$= 21.7 kWh/m²·a and 18.8 kWh/m²·a respectively).

Room Depth and Window-to-Wall Ratio also have a massive influence on daylight availability and energy demand for electric lighting: a progressive increase in the RD and a decrease of WWR result in a decrease of $sDA_{300/50\%}$ values and an increase in the energy demand.

In order to compare with a more effective approach the daylight amount in a space and the consequent energy demand for electric lighting, the sDA performance criteria suggested by IESNA were used as reference (IES, 2012). Two levels of criteria were identified to assess the luminous performance of a space: spaces with $sDA_{300/50\%}$ that meets or exceeds 55% of the analysis area and spaces with $sDA_{300/50\%}$ that meets or exceeds 75% of the analysis area. According to these criteria a space can be rated respectively as "neutral" and "favourably" with regard to the sufficiency of the available ambient daylight. A space with $sDA_{300/50\%}$ below 55% is considered as an insufficiently daylit space.

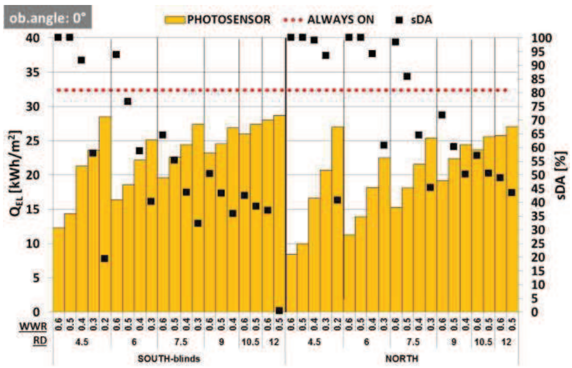

Fig. 1 – Annual energy demand for electric lighting (Q_{EL}) and $sDA_{300/50\%}$ values for all room configurations with γ=0°.

The entire database of results was then divided according to these criteria. For each performance class the mean annual energy demand for electric lighting ($Q_{EL,m}$) value was calculated and compared to the base-case. Figures 2-3 show the results for South and North-facing rooms.

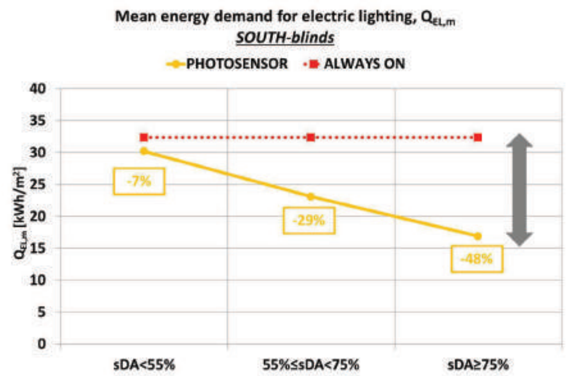

Fig. 2 – Mean annual energy demand for electric lighting ($Q_{EL,m}$) for each $sDA_{300/50\%}$ performance class (South-facing spaces)

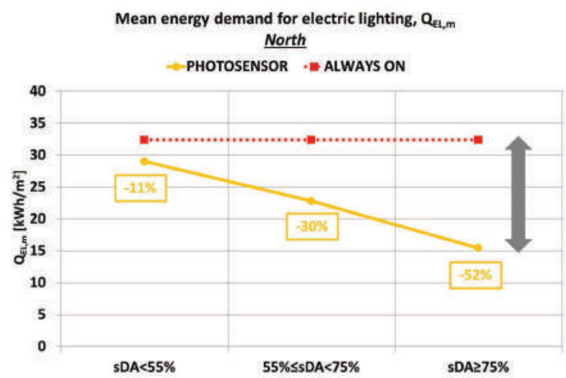

Fig. 3 – Mean annual energy demand for electric lighting ($Q_{EL,m}$) for each $sDA_{300/50\%}$ performance class (North-facing spaces)

As one might expect, the higher the daylight availability ($sDA_{300/50\%}$≥75%), the lower the energy demand for electric lighting, especially in presence of a daylight responsive dimming system. This was observed for both orientations: the mean percentage difference with respect to the case with lights always on can reach -48% for South orientation and -52% for North orientation.

Values of $sDA_{300/50\%}$ below 55% (showing that the amount of daylight is not sufficient) result in a lower reduction in the energy demand for electric lighting, even in the presence of a daylight responsive dimming system (-7% for South orientation, -11% for North orientation).

Furthermore it was observed that the glare potential risk, assessed by the Maximum Daylight Autonomy metric, is very low for all simulated case studies. DA_{max} values are always below 5%, even for cases with sDA≥75%. This is mainly due to the lack of direct solar radiation for North-facing rooms and to the presence of movable shading devices for South-facing rooms.

3.2 Overall energy performance

The parametric analysis conducted in EnergyPlus using the jEPlus interface allows the global energy performance of a room with multiple design options to be analyzed. This section focuses on the effect on cooling and heating loads concerned with an advanced daylighting analysis.

Figure 4 shows the results for South and North-facing rooms without external obstructions (γ=0°) considering a daylight responsive dimming system. In the graph, the Room Depth was shown on the x-axis in terms of S/V ratio (surface which is exposed to the outdoor environment to the space volume ratio).

For each room configuration the corresponding $sDA_{300/50\%}$ values are also shown. The data shown in the figure demonstrated that spaces with $sDA_{300/50\%}$≥75% are not only well daylit environments but they can achieve a better energy performance.

Figures 5 and 6 show that, for both South and North-facing rooms, the mean global primary energy demand ($EP_{glob,m}$) is lower for spaces rated “favorably” daylit ($sDA_{300/50\%}$≥75%) than for spaces not enough daylit ($sDA_{300/50\%}$≤55%).

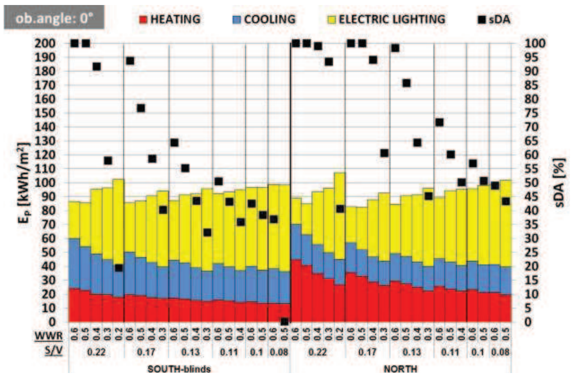

Fig. 4 – Global primary energy demand and $sDA_{300/50\%}$ values for all room configurations with γ=0°.

For South-facing rooms the mean annual global primary energy demand is 112.4 kWh/m²·a when $sDA_{300/50\%}$ is below 55% and 89.7 kWh/m²·a when $sDA_{300/50\%}$ is above 75%. The mean global reduction that can be obtained is 20% (Fig. 5).

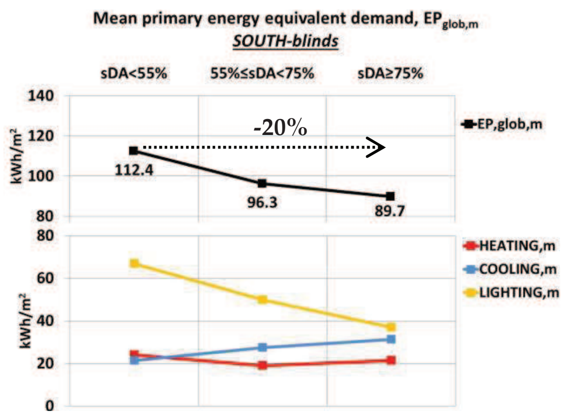

Fig. 5 – Mean annual global primary energy demand for each $sDA_{300/50\%}$ performance class (South-facing spaces).

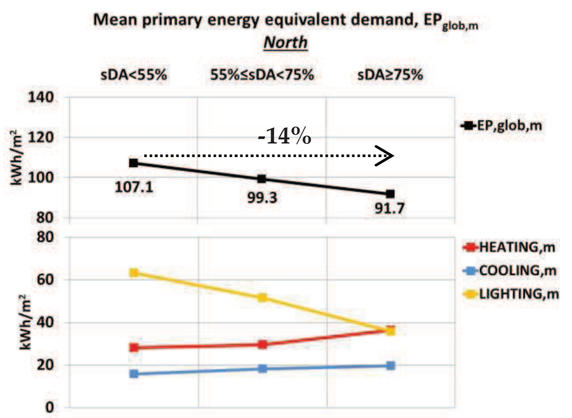

Fig. 6 – Mean annual global primary energy demand for each $sDA_{300/50\%}$ performance class (North-facing spaces).

For North-facing rooms the mean annual global primary energy demand is 107.1 kWh/m²·a when $sDA_{300/50\%}$ is below 55% and 91.7 kWh/m²·a when $sDA_{300/50\%}$ is above 75%. The mean global reduction that can be obtained is 14% (Fig. 6).

4. Discussion and conclusion

The purpose of this paper was to describe a reliable simulation approach to consider daylight when assessing energy performance in buildings, in order to demonstrate the substantial influence of daylight harvesting on the global energy performance.

The methodology was based on the use of both Daysim and EnergyPlus which were employed in synergy for a parametric study to assess the lighting and energy performance of rooms with different architectural features.

The results presented proved that a building design based on the optimization of daylight (i.e. $sDA_{300/50\%}$ over 75%) could achieve a reduction in the global energy demand of a space. However it has to be highlighted that results refer to a sub-dataset that includes data on North and South-facing rooms located in Turin with a visible glazing transmittance of 70%. Furthermore these results were obtained using specific software and input data. If different software and input data were used to run the dynamic simulations, the results might be different.

One important consideration about the simulation approach which was presented is that this 2-step process could be a big effort for a design team, especially during the first stages of the design process when a parametric analysis could be useful to base the first decisions about the building shape and orientation, window sizes and characteristics of glazing and shading systems. In general, it could be said that there is a lack of sufficiently accurate prediction tools for a design team to optimize a project integrating advanced daylighting analysis into energy analysis.

One further trouble could be the right choice of all the input data needed for an advanced simulation. There's more and more the need for extensive libraries which can fill in automatically all required inputs when a model has to be handled.

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Paper VII:

'Daylighting design for energy saving in a building global energy simulation context'

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Submitted for:

6th IBPC Conference – Building Physics for a sustainable built environment.

2015, Turin, Italy.

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2015) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

6th International Building Physics Conference, IBPC 2015

Daylighting design for energy saving in a building global energy simulation context

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Abstract

A study on the impact that different daylighting solutions have on the global energy demand of a space is presented. The methodology relies on dynamic simulations carried out with Daysim and EnergyPlus used in synergy to perform a parametric study to assess the indoor daylighting conditions and the energy performance of rooms with different architectural features: room depth, window size, external obstruction angle and glazing visible transmittance. Furthermore, different lighting and shading control strategies were tested. The results of the study demonstrated that optimizing daylight can lead to a reduction of up to 30% in the global energy demand for a building.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

A key factor to substantially reduce the energy consumption for electric lighting relies on a more widespread exploitation of daylight, coupled with the use of the most energy efficient lighting technologies, such as LEDs or lighting controls. At the same time daylight harvesting in indoor spaces can influence the global energy performance of a building also in terms of heating and cooling loads. In fact the internal gains from lighting can be affected by the solar radiation that enters through the openings and by the load emitted by electric lighting systems. The challenge is to find the best trade-off between cooling, heating and lighting energies which can only be achieved through an integrated approach which combines daylight and thermal analyses.

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Some recent studies demonstrated that a design strategy based on daylight optimization can be a reliable method to improve the global energy performance of a space [1-2-3].

In order to accurately predict daylight levels within a building space, daylight has to be studied according to its dynamic behaviour over a period of time. In this context, the 'Climate-Based Daylight Modelling (CBDM)' approach can be used [4]. Following this approach several daylight dynamic performance metrics have been proposed over the last ten years, the so-called climate-based daylight metrics (Daylight Autonomy, Continuous Daylight Autonomy, Maximum Daylight Autonomy, Useful Daylight Illuminance and Annual Light Exposure) [5-6-7-8]. Recently the Illuminating Engineering Society of North America, IESNA [9] proposed to assess the indoor daylighting performance through two new metrics: the spatial Daylight Autonomy (sDA), which assesses the sufficiency of annual illuminance in an interior work environment, and the Annual Sunlight Exposure (ASE), which expresses the annual glare potential risk. In more detail, sDA is defined as the percent of an analyzed area that meets a minimum daylight illuminance level of 300 lx for 50% of the operating hours per year ($sDA_{300/50\%}$). Two target levels have been established to assess the luminous performance of a space: a space can be rated as "neutral" when $sDA_{300/50\%}$ meets or exceeds 55% and "favorably" daylit when $sDA_{300/50\%}$ meets or exceeds 75%,. A space with $sDA_{300/50\%}$ below 55% is considered as an insufficiently daylit space.

Furthermore the increasing awareness of the potential benefits of daylight has resulted in an increased need for objective information and data on the impact that different design solutions, in terms of architectural features, can have on the daylighting condition within a space and on the related energy demand for lighting, heating and cooling.

In this context, the study presented in the paper had two main goals:

- analyzing the effect of multiple design solutions on energy requirements for electric lighting, associated with the use of efficient lighting control systems.
- assessing the influence of energy demand for electric lighting on the global energy performance.

Results related to the amount of daylight available in a space (in terms of spatial Daylight Autonomy) and annual energy demand for lighting, heating and cooling are presented to highlight the substantial influence of a proper daylighting design approach on the global energy performance.

2. Methodology

The method is based on a parametric study to assess through simulations how the daylight availability and the consequent energy demand for lighting, heating and cooling vary as the building/room architectural characteristics vary. Simulations were performed using a 2-step procedure: 1) in step 1, Daysim 3.1 [10] was used to calculate the annual illuminance profile of each space configuration as well as the corresponding annual electric lighting demand. Illuminance data were then elaborated to calculate the spatial Daylight Autonomy values. Among the simulation output, Daysim provides a Comma Separated Value (CSV) file which contains hourly schedules of the status of all lighting and shading groups of the simulated room; 2) in step 2, CSV files from Daysim were used as input in EnergyPlus [11]. The parametric analysis in EnergyPlus was conducted using jEPlus (www.jEplus.org), a graphical interface which allows setting alternative values for each parameter and simultaneously running multiple simulations calling EnergyPlus.

As final output, annual energy demands for lighting, heating and cooling were calculated and converted into primary energy data for every room configuration.

Some considerations were then drawn comparing $sDA_{300/50\%}$ and primary energy demand results.

2.1. Definition of the model

A single office room was used as 'case study' and analyses were carried out changing its characteristics in terms of site, orientation, Room Depth (RD), window area (expressed in terms of Window-to-Wall ratio, WWR), external obstructions (γ) and visible glazing transmittance of the window system (τ_{vis}). All the design variables are summarized in Table 1. Results presented in the paper refer to a sub-dataset highlighted with a grey background.

The room width and height were kept constant at 12 m and 3 m, respectively. The effect of an automated venetian blind with a diffuse transmittance of 25% (when in closed position) was considered in the simulations to dynamically control glare and overheating.

Table 1. Design variables used in the overall parametric study.

Site	Orientation	Room Depth (*RD*) [m]	Window-to-Wall Ratio (*WWR*) [-]	Obstruction angle (γ) [°]	Glazing visible transmittance (τ_{vis}) [%]
Turin (45.1°N)	South	4.5	0.2	0	35
Catania (37.5 °N)	North	6	0.3	15	50
Berlin (52.5 °N)	West	7.5	0.4	30	70
		9	0.5	45	90
		10.5	0.6	60	
		12		75	

2.2. Simulation input parameters

The room was modeled with walls and window frames, floor and ceiling with a diffuse reflectance of 50%, 30% and 70%, respectively. The daylight illuminances were calculated according to a 50 cm * 50 cm calculation grid over the whole working plane (minus a peripheral stripe of 50 cm all along the walls) set at a distance of 80 cm above the floor.

The target task illuminance was set to 500 lx, according to typical office visual tasks requirements [12]. The analysis was carried out considering a lighting power density of 12 W/m^2.

The shading control strategy is based on the algorithm implemented in Daysim, which assumes the presence of active and/or passive users. Active users open the blinds in the morning and partly close them to avoid visual discomfort when direct sunlight above 50 W/m^2 is incident on the work plane calculation greed points. Passive users keep the blinds lowered throughout the year [10]. The strategy adopted during the simulations refers to mixed behaviour, i.e. both types of users were assumed to equally influence the blind control.

Two different electric lighting control systems were simulated in Daysim: a manual on-off switch and a daylight responsive dimming system. The manual on-off switch is based on the Lightswitch algorithm [10]. We referred to a user who partially do not turn electric lights on if there's sufficient daylight on the work plane. The daylight responsive dimming system takes advantage of the daylight availability over the working plane and reduces, proportionally, the electric light use by dimming the luminaire light output.

The Radiance simulation parameters were set as follows: ab = 6; ad = 1000; as = 20; ar = 300; aa = 0.05; the simulations were run using the climate files of the considered locations with a time-step of 5 minutes.

The space was assumed with only one wall exposed to the outdoor environment. Accordingly, interior walls, floor and ceiling were modeled as adiabatic. The wall and the window facing the outdoor environment were modeled with a thermal transmittance of 0.25 W/m^{2}K and 1.6 W/m^{2}K, respectively. The Solar Heat Gain Coefficient of the glazing was set equal to 0.67.

The number of people and the air change rate were set according to the Italian Standard UNI EN 10339:1995 [13], assuming to 0.12 people/m^2 and 11 l/s·person respectively . Internal loads (people and equipment) were set according to the Italian Technical Standard UNI TS 11300-1:2008 [14], assumed 70W/person and 3W/ m^2, respectively. Winter and summer setpoint temperatures were set based on the Italian Standard UNI EN 15251:2008 [15] equal to as 21°C and 26°C during occupancy hours, respectively.

3. Results

A synthesis of the results that were obtained through the integrated approach is presented in this section, with reference to the sub-dataset of configurations highlighted in Table 1.

Results are divided in two different subsections. The first subsection refers to the simulations conducted in Daysim and presents a comparison between $sDA_{300/50\%}$ and energy demand for electric lighting (Q_{EL}) values. The second subsection refers to the simulations conducted in EnergyPlus using the jEPlus interface analyzing the overall energy performance of each room configuration compared with $sDA_{300/50\%}$ values.

In order to correctly sum energies consumed for lighting (Q_{EL}), heating (Q_H) and cooling (Q_C), the primary energy equivalent demand ($E_{P,glob}$) was calculated :

$$E_{P,glob} == \frac{Q_H}{\eta_H} + \left(\frac{Q_C}{EER} \cdot \eta_{el} \right) + Q_{el} \cdot \eta_{el} \tag{1}$$

where η_H is the mean thermal energy generation efficiency, EER is the Energy Efficiency Ratio of a “reference” air-to-air chiller and η_{el} is the mean National electricity generation efficiency. For the present study the following values were assumed: $\eta_H = 0.85$; EER = 3; $\eta_{el} = 2.17$.

3.1. Daylight and energy demand for electric lighting evaluation

The parametric analysis in Daysim generated results about the influence of different architectural features on daylight availability ($sDA_{300/50\%}$) and, consequently, on the energy demand for electric lighting (Q_{EL}). In this section, results obtained for a manual on-off switch and a daylight responsive dimming system are shown in comparison with a “base-case” which consists in the “worst” situation, with lights turned on during the whole working hours.

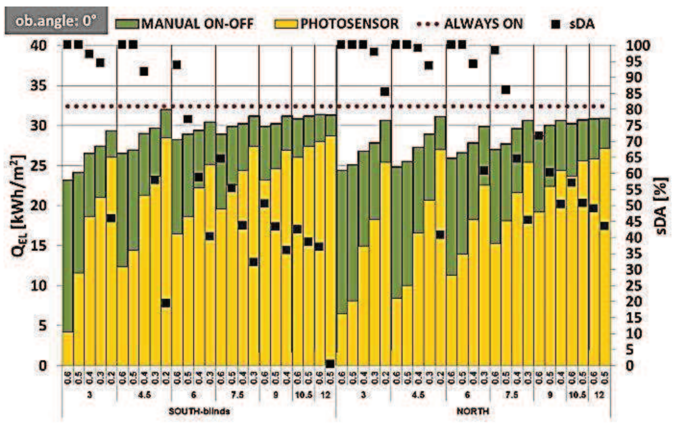
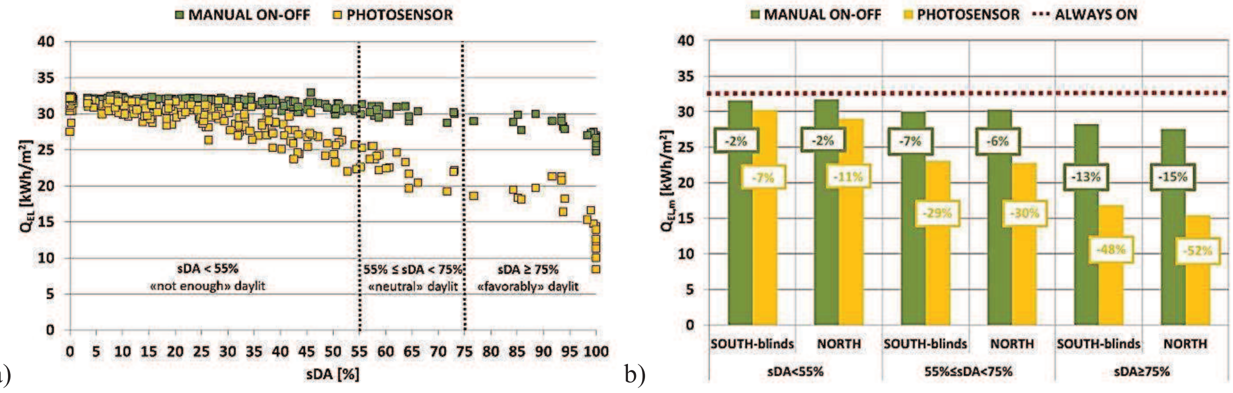


Fig. 1. Q_{EL} and sDA values for configurations with γ=0° (South and North-facing rooms)

Figure 1 shows the results for room configurations without external obstructions (γ=0°). It could be noted that $sDA_{300/50\%}$ values are on average lower for South-facing than for North-facing rooms (sDA_m=60.8% vs. 78%, respectively). This is due to the presence of the movable shading device. As a consequence, the mean Q_{EL}, even in presence of a daylight responsive dimming system, is higher for South-facing than North-facing rooms ($Q_{EL,m}$= 21.7 vs. 18.8 kWh/m^2·a, respectively). RD and WWR also showed a substantial influence: a progressive increase in RD and a decrease in WWR result in a decrease in $sDA_{300/50\%}$ values and an increase in the energy demand.

The sDA performance criteria suggested by IESNA was then used as a reference to relate the acceptability of daylight amount in a space to the consequent Q_{EL}. The entire database of results was divided according to these criteria, as explained in Figure 2a. For each performance class and for each type of lighting control (manual and daylight responsive), the mean Q_{EL} was calculated (Figure 2b). It could be noted that increasing daylight results in a decrease of energy demand for electric lighting: passing from cases with $sDA_{300/50\%}$<55% to cases with $sDA_{300/50\%}$≥75% results in a mean Q_{EL} reduction of -14% and -45% (in presence of a manual on-off switch and a daylight responsive dimming system, respectively).

Figures 2b shows the percentage decrease of the mean Q_{EL} values with respect to the “base case”. As one might expect, the higher the daylight availability ($sDA_{300/50\%}$≥75%) the higher the reduction in the energy demand for electric lighting in presence of a daylight responsive dimming system. This was observed for both orientations: the mean percentage difference with respect to the “base case” reaches -48% for South orientation and -52% for North orientation. Values of $sDA_{300/50\%}$ below 55% result in a lower reduction in $Q_{EL,m}$ values, even in the presence of a daylight responsive dimming system (-7% for South orientation, -11% for North orientation).



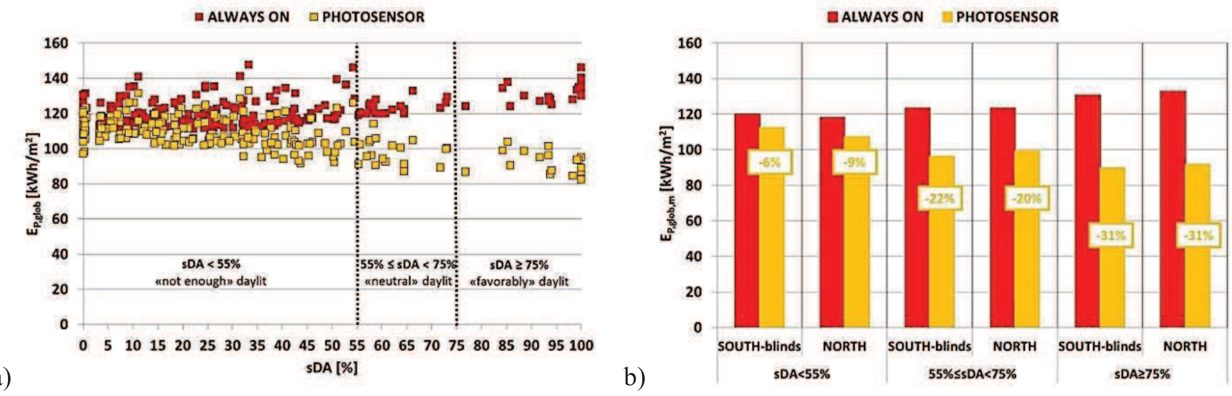
a) b)

Fig. 2. Overall database of Q_{EL} and sDA results (a); Mean annual Q_{EL} for each $sDA_{300/50\%}$ performance class (b)

3.2. Overall energy performance evaluation

This section focuses on how a design strategy based on the optimization of daylighting can influence the global energy demand of a room. In this study a daylighting optimization corresponds to an increase in the $sDA_{300/50\%}$ and to the use of a daylight responsive lighting control system.

Figure 3a shows the entire database of results divided according to $sDA_{300/50\%}$ criteria and the relation between $sDA_{300/50\%}$ and $E_{p,glob}$ for all simulated case studies. The higher the amount of daylight available in a space the lower the global primary energy demand, in particular in presence of a daylight responsive dimming system. Furthermore the mean global primary energy demand ($E_{P,glob,m}$) was calculated for each performance class of $sDA_{300/50\%}$: for cases with $sDA_{300/50\%}$ <55% and $sDA_{300/50\%}$ ≥75% $E_{P,glob,m}$ is 112.4 kWh/m^2 and 87.6 kWh/m^2 respectively, with a mean energy saving, increasing the daylight availability, of 24%.



a) b)

Fig. 3. Overall database of $E_{P,glob}$ and sDA results (a); Mean annual $E_{P,glob}$ for each $sDA_{300/50\%}$ performance class (b)

Figures 3b shows the results in terms of percentage difference between $E_{P,glob,m}$ values with a daylight responsive dimming system and the $E_{P,glob,m}$ for the “base-case” control system (light always turned on). For both South and North-facing rooms, the maximum mean reduction in the global primary energy equivalent demand (-31%) can be reached for “favorably” daylit cases, i.e. cases with $sDA_{300/50\%}$ ≥75%. In spaces with a non-sufficient level of daylight ($sDA_{300/50\%}$ <55%) the mean global primary energy demand is higher and the reduction that could be obtained in presence of a daylight responsive dimming system doesn’t exceed -9%.

4. Discussion and conclusions

Results related to the amount of daylight available in a space (in terms of spatial Daylight Autonomy) and annual energy demand for lighting, heating and cooling were presented to highlight the substantial influence of the daylight harvesting on the global energy performance. The methodology was based on the use of both Daysim and EnergyPlus which were employed in synergy for a parametric study to assess the lighting and energy performance of rooms with different architectural features.

The analysis conducted in Daysim demonstrated, initially, that the daylight amount within a space is strongly influenced by its architectural features: a progressive increase in Room Depth and a decrease in Window-to-Wall Ratio result in a decrease in $sDA_{300/50\%}$ values and an increase in the energy demand for electric lighting.

Furthermore a substantial reduction in the energy demand for electric lighting for "favorably" daylit cases ($sDA_{300/50\%} \geq 75\%$) has been proved, in particular in presence of a daylight responsive dimming system compared to a "base-case" in which lights are always turned on (up to -48% for South orientation and -52% for North orientation).

A design strategy based on the optimization of daylight also has a meaningful influence on the global energy demand of a space. Increasing the daylight amount results in a reduction of the global primary energy demand, in particular in presence of a daylight responsive dimming system: the saving in terms of global primary energy demand ($E_{P,glob,m}$) when increasing the $sDA_{300/50\%}$ from less than 55% to more than 75% is, on average, 24%. Furthermore, average savings of 31% can be achieved in spaces with high daylight availability ($sDA_{300/50\%} \geq 75\%$) when a daylight responsive control system is considered instead of a "worst case", with lights always turned on.

However it has to be highlighted that these results were obtained using specific input data. For instance the space was assumed with only one wall exposed to the outdoor environment, considering a central position of a common office within a building. Results might be different if a corner office was considered. A second input data that can have a massive influence on the energy performance of a space is represented by the type of shading and its control strategy. In this study the shading control strategy is based on the algorithm implemented in Daysim and it's based on the control of the direct solar radiation on the workplane.

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