DAYLIGHT DESIGN RULES OF THUMB

N.L.NIK IBRAHIM
Architecture Department, Faculty of Engineering, Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor, Malaysia

S. HAYMAN
Department of Architectural & Design Science, The University of Sydney
Sydney, New South Wales 2006, Australia.

Abstract

This paper discusses the history and simulation studies conducted to validate simplified daylighting principles or rules of thumb for building. The rules of thumb are gathered from architecture and lighting literatures as well as architectural practices. Incorporated in these day lighting rules are room parameters (such as room depths, floor area, window head heights and widths) related to effective unilateral daylighting. The rules of thumb are tested for a single location (35ºS 150ºE) close to Sydney, Australia under Standard CIE Overcast and Clear Skies by means of lighting simulations software - Lumen Micro 8, which has a limited verification tolerance of ± 8%. The simulation studies indicate that under a strict set of criteria the rules of thumb based upon the ratios of window area to floor area and room depth to window head height for task plane illuminance and daylight factor to be valid. The validation process also contributes to a number of new rules associating average illuminance with window to floor area ratio and a modification to an existing daylighting formula proposed by Littlefair (Littlefair, 1996).

Keywords : Daylighting design, Rules of thumb, Daylighting formula, Simulations, Validations.

1. Introduction

Rules of thumb exist in most discipline areas particularly those that involve the application of knowledge related to complex phenomena such as daylight, and also where absolute precision may not be required. They provide "a broadly accurate guide or principle, based upon experience or practice rather than theory" (Brown, 1993) and derive their significance from having been repeatedly used and found to work. However, underlying assumptions may be poorly stated, or missing, for even if they existed initially these can slowly be neglected with use. This can lead to misapplications as the assumptions are contravened and the application boundaries of the rules exceeded.

2. Daylighting Rules of Thumb

In the context of daylighting, a number of rules of thumb can be found that advise on building form, room size and proportions, and window sizing. They have a long history probably stretching back beyond the historical record and may have been influenced by Pythagorean ideas and devices such as the Golden Section to provide numerical proportional rules for building form and fenestration. This can be seen in the work of early architects such as Galerius, circa 300 BC, (Illiadis, 2001) and later mediaeval and gothic structures. There is, however, a two thousand years record of such rules, one of the famous, and earliest author being Virtruvius who provides the advice that for adequate daylighting a significant sky component should be visible from a point in a room:

> *"On the side from which the light should be obtained, let a line be stretched from the top of the wall that seems to obstruct the light to the point at which it ought to be introduced, and if a considerable space of open sky can be seen when one looks above the line, there will be no obstruction to the light in that situation."*
>
> *Rowland, 1997*

The rediscovery and reformulation of Virtruvius in the Renaissance and later by architects such as Palladio, Scamozzi and de l'Orme expanded upon the former's principles and the Pythagorean tradition of numerical proportion. For example:

> *"Make sure when making windows that they do not let in too much light or too little light and that they are not spread out or closer together than necessary. One should, therefore, take great care over the size of rooms which will receive the light from them, because it is obvious that a larger room needs much more light to make it luminous and bright than a small one..."*
>
> *Taverner and Schofield, 1997*

From this, emerges specific rules such as: (i) Window width is between one fifth and one quarter of the room depth, (ii) The window height is two and one-sixth the window width. These rules can be expanded into more familiar forms: (a) Maximum room depth is four to five times the height of the window, (b) Window area is approximately one tenth of the square of the room depth.

From the examples provided by Palladio, it appears that his preferred window to floor area is of the order of 25% and his window to window wall ratio is about 35%.

Pragmatic modification of such rules was commonly carried out to address local conditions. For example, Sir William Chambers expressed awareness of the obvious difference between the climates of Italy and England:

> *"I have generally added the depth and the height of the rooms on the principle floor together, and taken one eight part thereof for the width of the window; a rule to which there are few objections; admitting somewhat more light than Palladio's, it is I apprehend, fitter for our climate than his rule would be"*
>
> *Gwilt, 1982*

Gwilt in the mid 19th century also criticised Palladio's rules as being unsuitable for the climate of Great Britain (Gwilt, 1982). He based his rule upon room volume and suggested window area for daylighting to be 1% of room volume. Such rules based upon room volume appear to have become less popular except for their use in early 20th century German daylighting standards where window area was specified as one thirtieth of room volume (Price, 1914). With an increase in architectural publishing in the late 19th and 20th centuries and a growing formalism for daylighting as well as other architectural science areas, a number of rules developed usually based on:

(i) Window head height (or ceiling height) to room depth ratio,
(ii) Maximum room depth,
(iii) Window to floor area ratio,
(iv) Window to window wall area ratio.

A limiting feature of the way these rules can be presented is that they appear to be universally applicable but may be subjected to one or more of the following potential caveats (Robbins, 1986):

(i) what is the basis of the rule?,
(ii) what is the sky condition? e.g. overcast or clear?,
(iii) does it assume typical urban obstructions to daylight?,
(iv) does it satisfy maximum or minimum requirements?,
(v) how much light is quantitatively provided and on what reference plane?,
(vi) what sorts of tasks are suitable under this daylighting?,
(vii) what assumptions have been made concerning the type of glazing?,
(viii) what assumptions have been made on internal reflectances?

2.1 Window Head Height to Room Depth Ratio

This is a popular rule of thumb appearing in a wide range of sources including textbooks with some restrictions. For example:

(i) Maximum room depth is 2 to 2.5 times window head height for continuous fenestration and curtain wall construction where window heads are close to the ceiling (Kaufmann, 1975)

(ii) Room depth is 2.5 times window head height for continuous or near continuous windows under overcast skies and 3 to 3.5 times under a clear sky (AIA, 1982),
(iii) 2 times for continuous clear glazed and curtain walling (Rea, 1993),
(iv) 2.5 with a daylight factor of 2% (Standards Australia, 1994),
(v) 1.5 or 2.5 times with a south facing light shelf (O'Connor, 1997), (vi)1.5 times for office work, 2.5 times for residential spaces (Schiller, 1992).

Note that all these rules, and those discussed below, apply to unilateral, or single sided, daylighting unless otherwise specified. In addition, a number of authors give a variant of this rule with a floor depth of twice the ceiling height, e.g. Yeang (1999). As can be seen there is a wide range of advice with varying degrees of contextual information making it difficult to assess validity of the rules offered.

2.2 Limiting Room Depth

Absolute room depth rules also have a long influential history but again are stated without limitations, probably assuming that it is obvious from the context:

(i) Maximum floor depth of approximately 8 metres and ceiling height of 2.7 metres for adequate daylight and ventilation in reference to 1930's New York skyscrapers (Willis, 1995),
(ii) Six metres, attributed to Frank Lloyd Wright (Schiller, 1992), British planning legislation (HMSO, 1964), and others including Yeang (1999) who limit this to buildings with window to window wall area of between 15 and 20%.,
(iii) Five metres for window, or rooflight, illuminating a room from one side (Ruck, 1995),
(iv) Fully daylight to 4.5 metres (Manning, 1965) and partially lit to 9 metres (Lechner, 2001),
(v) 3.6 metres for full and effective daylighting (Manasseh and Cunliffe, 1962).

Of course, some unquoted contextual factors could contribute to the significant differences in some of these recommendations given that many are related to the same building type and general location. For example:

> *"The effect of using glass with an average diffuse transmittance of 50% instead of 85% might reduce the distance from the window where light is adequate from 6 metres to 4.5 metres".*
>
> *Colin and Colins, 1977*

Furthermore, it is obvious that internal room characteristics, especially reflectances, will impact on the perceived adequacy of daylight as recognised by Littlefair (1996) in presenting a more complex rules for room depth than would normally be seen as rules of thumb.

2.3 Window Area to Floor Area Ratio

This rule is possibly one of the most widely known rule in the world as enshrined in many regional and local building regulations as a means of specifying minimum glazing area for habitable rooms. A number of early references to the use of this rule in design of schools has been described by Wu and Ng (Wu and Ng, 2002). For example, 20% window area to floor area was proposed by ER Robson, the architect of the London School Board for health, comfort and effective teaching of children. This was modified in the London Building Act of 1894 to the familiar 10% rule although the 20% rule was still respected for schools (Waldram, 1914). A similar rule existed at the turn of the 20th century in Germany for industrial spaces and for buildings in New York (schools 17% to 25%, offices 17% but residences 10% to 13%) (Price, 1914). Hopkinson later argued that the 20% ratio yielded an adequate daylight factor of 2% at the rear of a room and a consequent task illumination of 100 lux (Hopkinson, 1963).

2.4 Window Area to (Window) Wall Area Ratio

This rule of thumb is probably related to limiting glazing area for thermal reasons, ie. heat loss and gain control, or for ensuring the adequate provision of view. Rules associated with the latter are of more direct interest such as those drawn from studies carried out in the 1970s and 1980s: (i) If the window to window wall area ratio was between 20 and 30% users were satisfied but if it fell below 20% satisfaction declined steeply. It was noted, however, that a 20% ratio will probably result in inadequate daylighting at the rear of the room (IES, 1972), (ii) Ne'eman and Hopkinson's study showed that a 25% ratio was the minimum acceptable size for 50% acceptance and a 32% ratio gave 85% satisfaction. As well, Keighly placed a bottom limit of 15% (Boyce, 1981).

A survey in Hong Kong has shown that the mean value of window to wall ratio is 27.4%, most being between 25 and 30% with luxury units having ratios greater than 35%. The survey also indicated a good correlation between percentage window area and user's preferences for view (Li et al, 1999). However, thermal design consideration to ensure buildings perform more energy efficiently limits the ratio to 25% (Baker and Steemers, 2000).

2.5 Daylight Factors

Although daylight factors cannot really be categorised as rules of thumb as they require computation beyond using the simple parameters of space, they are included here as they are regularly used in the literature as a guide to adequate daylighting. Also they, unlike other rules, include explicit assumptions posed by Robbin's checklist and may be simply linked to some rules of thumb. For example, Hopkinson suggested that the minimum daylight factor, in that part of the room remote from the window, is equal to one tenth of the window to floor area ratio (Hopkinson, 1969). It should be noted that this rule is restricted to rectangular side lit rooms, up to 5:3 proportions with windows in the long side and without internal and external obstructions. The British have long favoured this method of daylight specification. For example, a guide for office lighting in the early 1950s recommends a minimum daylight factor of 1% for general work and 5% for drawing offices which recognises the need for varying lighting to tasks needs. Similarly, in residences kitchens require 2% daylight factor over major work surfaces whereas living rooms need only 1% and bedrooms 0.5% (Burberry, 1975). Later recommendations expand upon these with average and minimum daylight factors for workplaces (5 and 2% respectively) and state that if the average daylight factor is less than 2% it will be deemed inadequate by the users, whereas over 5% will be seen as "cheerfully lit" (CIBSE, 1987).

3. Simulation Studies

In order to test the incomplete range of recommendations discussed above, a series of simulation studies were carried out. Although it would have been most appropriate to conduct this in real spaces, the possibility of confounding factors and the difficulty in accessing a wide range of interiors to test the boundaries of rules, meant that some form of simulation was necessary. Physical models had the same limitations and it would have been time and labour consuming to construct a large number of models. Consequently, computer simulation was used, allowing a data set of 143 examples to be studied. As this was an exploratory study, a number of assumptions were made to ensure comparability of the data set and testing conditions:

a. A single location was used (35°S 150°E), close to Sydney but away from the known localized asymmetric daylight climate (Hayman, 1996).

b. Standard CIE Overcast and Clear Skies were used as they have wide acceptance and application.

c. External ground reflectance was set at 20% and internal reflectances at 80% for ceiling, 50% walls and 20% floor in line with standard practice (Kaufmann, 1972).

d. Glazing transmittance was standardised to a nominal figure of 90% to match those rules of thumb that had defined this property.

e. Test horizontal illuminance levels of 100, 200, 400 and 600 lux were used as typically representative of levels required for tasks of increasing difficulty above a minimum level.

f. Diffuse daylight only enters the space which was achieved by using south facing windows.

g. A reasonable minimum daylight condition was possible with such a south facing window and the assumption that testing occurred at noon, mid winter. This had the added advantage that the available diffuse illuminances from overcast and clear skies were similar (11,943 and 12,279 lux respectively) allowing direct comparisons between sky conditions.

Lumen Micro 8 software was used for the simulation study as it is a standardised commercial product so the studies are easily repeatable, it is well known, relatively easy to use and reasonably priced particularly for educational use. It is claimed to have verification tolerance of ± 8% (Jongeward, 1993) and its external illuminance prediction appears close to field measurements made by Hayman (1996) in Sydney.

Groups of case studies (CS1 to CS11) were carried out with varying room and window parameters to identify factors contributing to daylight performance of a space. However, in most cases the ceiling height was fixed at 2.4 metres and sill height at 0.82 metres:

CS1: Square rooms of varying size (2.7 m^2 to 18 m^2) with full width windows;

CS2: Narrow rectangular rooms of fixed width (2.7 m) and increasing depth (up to 18m);

CS3: Square rooms of varying size and window width to fix the window to floor area ratio at 10%;

CS4: Fixed square room (3.6 m^2) with varying window size (window to floor areas from 5 to 40%);

CS5: As for CS4 but with a larger room (10 m^2);

CS6: Fixed square room (5.5 m^2) with fixed window but varying ceiling heights (2.4 to 8 m);

CS7: Fixed square room (5.5 m^2) and window but varying window head heights (2.4 to 10 m);

CS8: Fixed square room (5.5 m^2) and ceiling height (3.6 m) and sill but varying window size;

CS9: Fixed square room (5.5 m^2), window size and ceiling height but varying sill (0.8 to 2 m);

CS10: Fixed central window (1.5 by 0.9 m) with varying square room size (2.7 to 10 m^2);

CS11: As for CS8 but with larger rectangular room size (20 by 40 m).

Once the range of simulations were created they were studied in terms of maximum, minimum and average illuminances, daylight factors in relation to room depth, floor area, window area, window head height under both overcast and clear skies.

4. Results

The results of the case studies are extensive but a representative sampling can be gained from looking at the results of one case study group, CS1. As would be expected the centre line illuminances drop off rapidly with distance from the window as shown in Figure 1. The maximum illuminances, close to the window, are in the order of 25% higher for an overcast sky than a clear but the minima, at the rear of the room, are about 50% higher for clear skies. This is expected as clear skies are brighter towards the horizon than overcast and contribute more to lighting of the rear of rooms as shown by Tregenza (Tregenza, 1999).

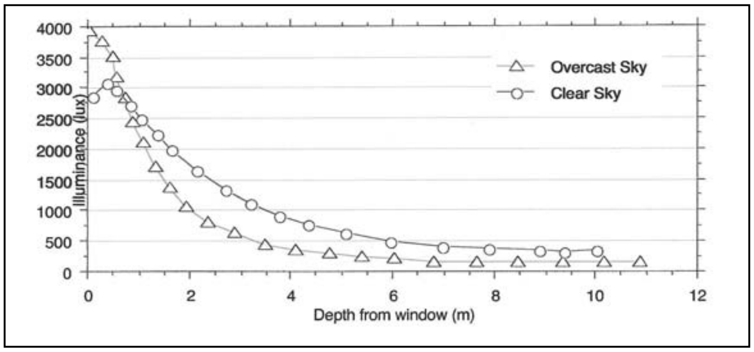

Fig. 1 Room depth vs centre line illuminance (lux)

Minimum values are dominated by the room's indirect component of daylight whereas average illuminances by the direct component except for clear skies where the indirect component is still strong due to the importance of ground reflected light. Window to floor area ratios show the same relationships but with stronger linear association as can be seen in Fig. 2:

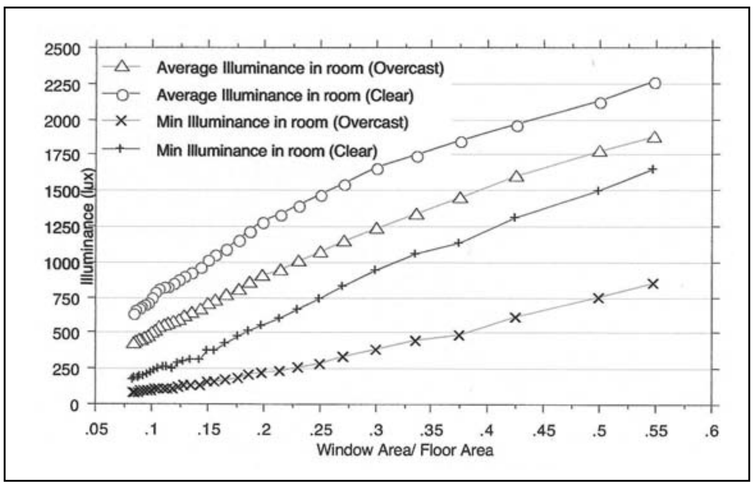

Fig. 2 Window to floor area ratio vs minimum and average illuminances (Overcast & Clear skies)

In terms of traditional rules of thumb, for an overcast sky an illuminance of 100 lux could be achieved at approximately 3.5 times the window head height, 200 lux at 2.5 times and 400 lux at 1.5 times. A room with a window to floor area of 10% yields a minimum of 100 lux and 20% about 200 lux. With a clear sky the figures are higher with 400 lux achieved at 3 times the window head height and 600 at 2.5 times; a 10% window to floor ratio gave greater than 200 lux and 20% a minimum of 500 lux. In all cases the rooms have greater than 2% average daylight factor so would be "adequately" daylit and a window to floor ratio of 13% would ensure that the "cheerfully" daylit criteria of 5% average daylight factor was satisfied.

From this and the results of other case study groups, the most successful rules of thumb are:

(i) The 10% window to floor area ratio is reliable in providing a minimum of about 100 lux.

(ii) A daylight room depth up to 2.5 times the window head height and/or 20% window to floor area will, in most cases, provide a minimum illuminance of not less than 200 lux under an overcast sky and higher for a clear sky. The 200 lux minimum cases are also close to providing the the 2% average daylight factor daylight acceptability limit. However, if daylight uniformity (minimum to average ratio) is an important issue, for example in a workplace, then 20% window to floor area ratio could be unsatisfactory.

(iii) In satisfying uniformity criteria two new rules became evident in the analysis. Firstly, that windows should be at least 50% of the window wall width and, secondly, that room depth should be no greater than twice the room width for full width windows (and less deep for less than full width windows).

5. New Rules of Thumbs

To investigate the possibility of other new rules of thumb all cases studies were analysed as a complete data set using plotting and regression analysis techniques. Strong linear association exists between average illuminance and window to floor area ratios, shown in Fig. 3, except for those case studies involving varying window sill height (CS7 & CS9).

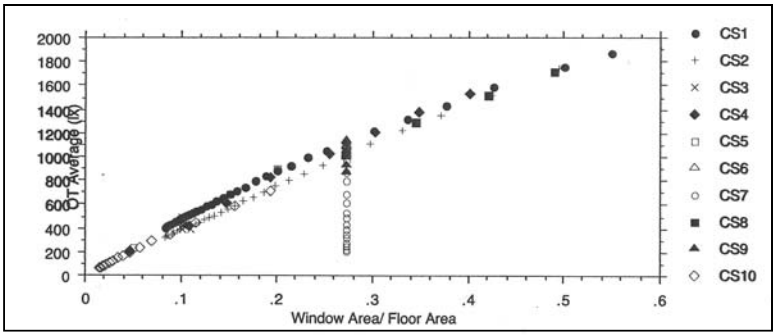

Fig. 3 Window to floor area vs. average room illuminance under an overcast sky

Improvements in modelling can be achieved by either correcting for these anomalies (using window to floor area ratio divided by window head height) or restricting the emergent rule to normal windows. In the latter case regression yields the following:

Average illuminance (overcast sky) = 3,856 x window to floor area ratio (R^2 = 0.992) Eq. 1

Average illuminance (clear sky) = 4,859 x window to floor area ratio (R^2 = 0.974) Eq. 2

Average daylight factor (overcast sky) = 32.29 x window to floor area ratio Eq. 3

These could be rounded off to 3,800, 4,800 and 32 or to 4,000, 5,000 and 30 respectively for ease of memorisation. Additional improvements can be made by use of window to floor area corrected for window head height and/or non-linear models, specifically raising the window to floor area ratio to the power of 0.8. However, this may result in a more difficult to remember rules than the simple ones above.

To explore the possibility of using the dataset as a test source for existing daylighting design tools, a useful approximate design tool by Littlefair (Littlefair, 1996) was selected which equates average daylight factor with a few easily measurable variables:

$$DF_{Avg} = \frac{\tau_w A_g \theta}{A_s (1 - R^2)} \% \qquad \text{Eq. 4}$$

where:

DF_{Avg} = average daylight factor
τ_w = transmission of glass (0.9 in the studies)
A_g = area of window glazing (m^2)
θ = sky angle in degrees measured at centre of window (90° for no obstruction)
A_S = total surface area of room (m^2)
R = average reflectance of interior (0.5 is normal for standard reflectances)

In its stated form this formula is applicable to small to medium sized rooms with a maximum depth of 6m. What was immediately evident from the analysis was that the formula was applicable to a much wider range of room sizes but that an improvement in performance could be made by substituting room surface area (A_S) by the much simpler variable of floor area (A_f) shown in Fig. 4, for normal sill heights, and resulted in the following relationship:

$$DF_{Avg} \quad 0.3 \left(\frac{\tau_W A_g \theta}{A_f (1 - R^2)} \right) \% \qquad \text{Eq. 5}$$

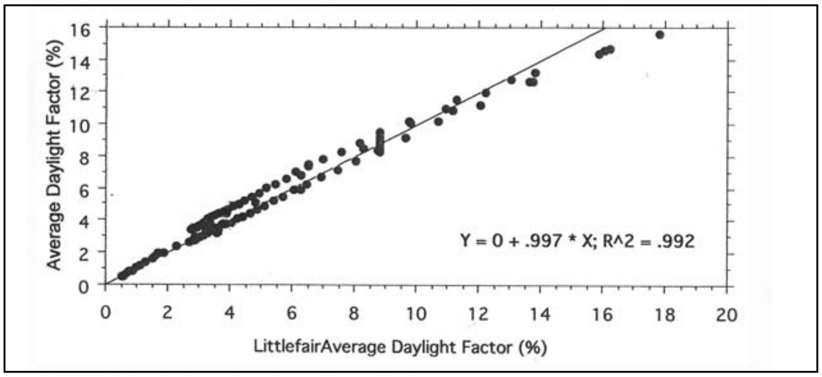

Fig. 4 Average Daylight Factor vs. Daylight Factor from modified Littlefair formula

Conclusions

The simulation studies have shown that under a strict set of criteria, the use of rules of thumb for unilateral daylighting based upon the window area to floor area and room depth to window head height ratios for task plane illuminance and daylight factor appear to be valid. Exceptions will occur when windows have non-standard sill heights or are high level, e.g. celestory, windows which should be clearly stated in the formulation of these rules. Furthermore, as a consequence of the modeling study a number of new rules of thumb relating to uniformity provisions have been found. Future research can be aligned to investigate limitations of the current study in particular application to more locations and the effects of external obstructions which will be necessary for the rules to be used in most urban situations.

Acknowledgements

We are grateful to the University of Sydney for funding the Lumen Micro 8 simulation software and to the Faculty of Engineering, Universiti Kebangsaan Malaysia for financing our participation in this conference.

References

AIA. (1982), *Architect's Handbook of Energy Practice: Daylighting,* American Institute of Architects, New York, pp.6-7.

Baker, N and Steemers, K. (2000), *Energy and Environment in Architecture,* Spon, London, pp.172-175.

Boyce, P.R. (1981), *Human Factors in Lighting,* Applied Science, London, pp.290-293.

Burberry, P. (1975), *Environment & Services,* Batsford, London, p.40.

Brown, L. (ed). (1993), *The New Shorter Oxford English Dictionary: On Historical Principles,* Vol 2, 3rd edition, Clarenedon Press, Oxford, p.2646.

CIBSE. (1987), *Window Design: Application Manual,* Chartered Institute of Building Services Engineers, London, pp.10-31.

Colin, I.D. & Colins, E.J. (1977), *Window Selection: A Guide for Architects & Designers,* Newnes-Butterworth, London, p.39.

Evans, M. (1980), *Housing, Climate and Comfort,* Architectural Press, London, p.124.

Gwilt, J. (1867), *The Encyclopedia of Architecture,* 1982 reprint, Bonanza Books, New York, p.874.

Hayman, S. (1996), *The Daylight Climate of Sydney,* PhD Thesis, University of Sydney, pp. 202-210.

HMSO. (1964), *Planning Bulletin: Planning for Daylight & Sunlight,* Her Majesty's Stationery Office, London, pp.11-26.

Hopkinson, R.G. (1963), *Architectural Physics: Lighting,* HMSO, :London. p.114.

Hopkinson, R.G. (1969), *The Lighting of Buildings,* Faber & Faber, London, p.68.

IES. (1972), *Daytime Lighting in Buildings: Technical Report No. 4*, Illuminating Engineering Society, London, p.5.

Illiadis, I.G. (2001), The natural lighting of the mosaics in the Rotunda at Thessaloniki, *Lighting Research & Technology,* Vol 33 (1), p.16.

Jongeward, M.P. (1993), Daylight Calculations, Measurements and Visualization in Non-Empty Rooms, *Proceedings of Lux Europa,* Edinburgh, Vol. 1, pp.43-52.

Kaufman, J. (ed). (1975), *IES Lighting Handbook,* 5th edition, IESNA, New York, pp.7-5.

Kaufmann, J. (ed). (1972), IES Lighting Handbook, Illuminating Engineering Society, New York, p.11-5.

Lechner. N. (2001), *Heating, Cooling, Lighting: Design Methods for Architects,* John Wiley & sons, New York, pp. 373-379.

Li, Lo, Lam & Yuen. (1999), Daylighting Performance in Residential Buildings, *Architectural Science Review,* Vol 42 (3), p. 215.

Littlefair, P.J. (1996), *BRE Report: Designing with Innovative Daylighting,* Building Research Establishment, Watford, pp.32-33.

Manasseh, L. & Cunliffe, R. (1962), *Office Buildings,* Batsford, London, p.34.

Manning, P. (ed). (1965), *Office Design: A Study of Environment,* Pilkington Research Unit University of Liverpool, p.45.

Morris, R. (1971), *Lectures On Architecture (London, 1759 & 1736) And An Essay Upon Harmony (London, 1739),* reprint, Gregg International , London, pp. 105-106.

O'Connor, J. (1997), *Tips for Daylighting with Windows: The Integrated Approach,* LBL, Berkeley.

Price, G.M. (1914), *The Modern Factory: Safety, Sanitation and Welfare,* John Wiley & Sons, New York, pp.246-247.

Rea, M. (ed). (1993), *Lighting Handbook,* 8th edition, IESNA, New York, p.369.

Robbins, C.L. (1986), *Daylighting: Design and Analysis,* Van Nostrand Reinhold, New York, p.64.

Rowland, I.D. (trans). (1999), *Vitruvius: Ten Books on Architecture,* Cambridge University Press, Cambridge, p.262.

Ruck, N. (1995), *BDP Environment Design Guide,* Australian Institute of Architects, Canberra, p.DES6-3.

Schiller, M. (1992), *Simplified Design of Building Lighting,* John Wiley & Sons, New York, pp.86-93.

Standards Australia. (1994), *AS1680.1-1994 Interior Lighting Part 1: General principles & recommendations,* Standards Australia, Sydney, p.59.

Taverner, R. & Schofield, R. (trans). (1997), *Palladio: The Four Books of Architecture,* MIT Press, Cambridge Mass., p.60.

Tregenza, P.R. (1999), The Sensitivity of Room daylight to Sky Brightness, *Architectural Science Review,* Vol 42 (2), pp.129-132.

Waldram, P.J. (1914), Some problems in daylight illumination with special reference to school planing, *The Illuminating Engineer,* Vol 7 (1), pp.15-27.

Willis, C. (1995), *Form Follows Finance: Skyscrapers and Skylines in New York and Chicago,* Princeton Architectural Press, New York, p.81 & pp.105-107.

Wu, W. & Ng, E. (2002), A review of daylighting in schools, *Proceedings of the Conference on Tropical Daylighting and Building,* National University of Singapore.

Yeang, K. (1999), *The Green Skyscraper: The basis for Designing Sustainable Intensive Buildings,* Prestel Verlag, Munich, p.232.