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Optimisation of a daylight-window: hospital patient room as a test case

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Abstract

In a healthcare environment a window is necessary to transmit daylight and provide outside view to enhance therapeutic performance. However, a window impacts on several environmental attributes of the indoor space. Depending on the size, orientation and solar shading configuration, a window influences on visual and thermal comfort, as well as on the energy consumption of the building. It is thus necessary to optimise window design for maximum performance. Computer modelling and simulation techniques integrated with optimisation methodologies offer opportunities to evaluate design decisions considering various criteria. In this study a patient room window has been evaluated using computer modelling and simulation. The aim of the study was to demonstrate an integrated opitimisation methodology to identify the optimal design of a window considering daylight and thermal performances at the early stages. The window comprised a tall pane of glass and a light shelf, and was oriented toward the South. Four parameters were used to define the window: the width, sill and lintel level heights, and the depth of the solar shading. Performance of the window was measured for variable parametric values based on daylight factor and annual cooling/heating loads in the room. The study demonstrates a novel approach of optimising window configuration for daylight design using parametric computer simulations and evaluates the potential and limitations of the technique in daylighting design.

Keywords: day light window, optimisation, lighting simulation, parametric design

1 Introduction

A daylight window has various objectives to fulfill, such as to ensure adequate daylight without discomfort glare, to provide outside view, etc. Depending on the size, orientation and solar shading configuration, a window impacts on visual and thermal comfort, as well as on the energy consumption of the building (Johnson, 1984). Therefore it is necessary to evaluate window design for maximum performance. Computer modelling and simulation techniques integrated with optimisation methodologies offer opportunities to evaluate design decisions considering multiple criteria. Application of computer simulation tools in evaluating daylight performance and identifying innovative design can be found in few earlier studies. Duboise (2003) attempted to validate performance of seven shading devices for windows; Kowk (2008) evaluated the design of horizontal light pipes for the CIE clear sky. Johnson (1984) evaluated glazing for fenestration of office building for daylight and energy performance, and the study suggested different conditions when daylight reduces or increases net annual energy consumption. Application of integrated optimisation techniques with simulation in identifying day lighting design are found from Caladas and Norford (2002) and Wright and Mourshed (2009), among others. However due to the wide variability of daylighting design strategies and methodologies, opportunities still remain for a holistic approach in window design to achieve better lighting (task oriented), therapeutic and energy performance.

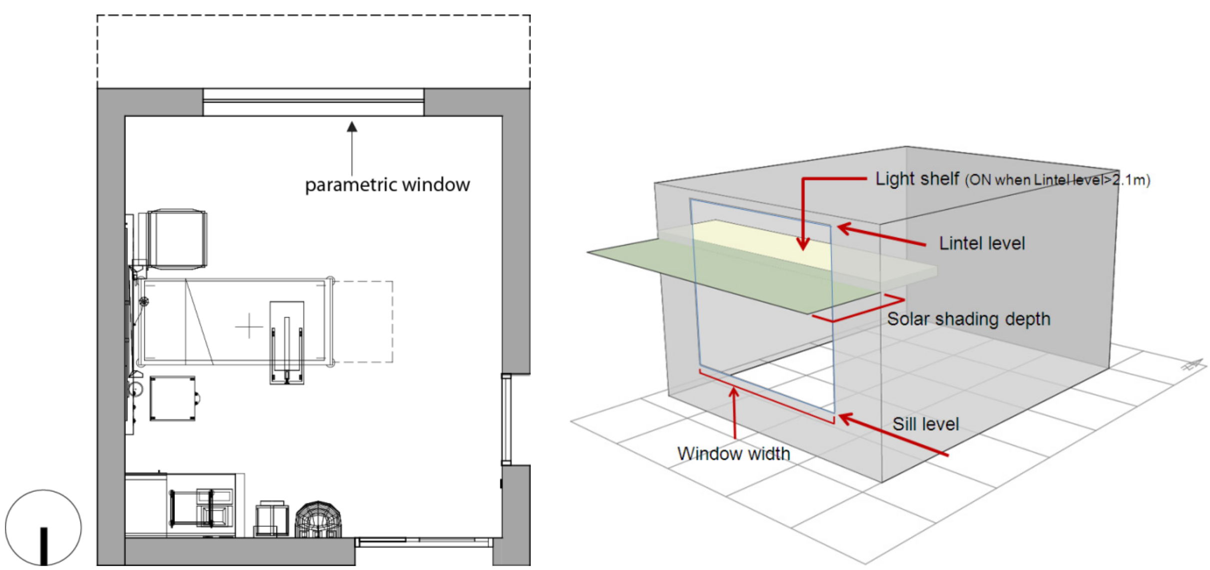
An integrated approach for simulation based optimisation and decision-making is demonstrated in this study. A parametric window of a patient room is optimised based on daylight availability and thermal performance. The optimisation approach integrates a raytrace-based lighting simulation program called Radiance and a whole building simulation program called Autodesk Ecotect.

2 Description of the problem

2.1 The problem space

The problem selected in this study is a standard patient room as per the Health Building Note 04 (NHS Estates, 1997). Equipment information and model for the room was taken from Activity Database library (ADB, 2009). A daylight window has been considered in this room, facing the South. Figure 1 illustrates the problem space.

Working plane height is located at 0.75 m from floor where a reference grid was considered containing 75 points. For daylight evaluation Daylight Factor (DF) was calculated over the reference points. Surface reflectance values considered for the space are: 0.7, 0.5 and 0.2 for the ceiling, walls and the floor, respectively.



(a) (b)

Figure 1: (a) The plan of the patient room, and (b) The parametric window model illustrating the decision variables.

2.2 Description of the parametric window and problem variables

The parametric window developed for the patient room comprised a double glazed window-pane with aluminum frame, solar shading and a light shelf (Figure 1b). Table 1 describes the variables and their maximum and minimum value limits.

The light shelf height was fixed at 2.1 m from floor. When the window height was more than 2.1 m (defined by the variable 'lintel level' here), a high window was constructed above the level and the internal light shelf was used. A light shelf was not used when window height was 2.1m or below.

Changes in the variables (Table 1) redefine the window in the southern wall of the patient room. The 'window width', 'window sill level' and 'solar shading depth' values were changed at an interval of 0.2 m from the minimum to the maximum value and the 'window lintel' levels were changed at 0.25 m intervals from the minimum to the maximum value, which produced 810 combinations.

Table 1: Parametric window variables and extent of their values.

Variables	*Minimum (m)*	*Maximum (m)*
Window width	1.2	3.40
Window sill level	0.2	1.20
Window lintel level	2.1	2.65
Solar shading depth	1.0	2.40

2.3 Window design modifiers

The CIBSE/SLL Lighting Guide for Hospital and Healthcare buildings (2008) describes that a window in a patient room has dual roles to play; it provides a view to the active outside world and transmits daylight. Adequate daylight exposure helps in appropriate circadian activity of patients to enhance healing during hospital stays. Also, a sufficiently lit room creates antidepressant environment and reduces the need for artificial lighting when daylight is available. Window has an impact on the thermal environment of the room, which can affect the overall energy consumption. Direct solar radiation can cause overheating, resulting in thermal discomfort with increased cooling loads. Furthermore, designing a window based on thermal performance only and without provisions for adequate daylight can increase the use of electric lighting, which makes the space dull and unhealthy. Guidance from the US Department of Energy (DOE, 2009) suggests that window design strategies should consider maximising solar heat gain in the winter and minimising solar heat gain in the summer, both of which have links with heating/cooling loads in a space.

2.4 Daylight factor (DF) requirement

The CIBSE Lighting guide 10 (CIBSE, 1999) described that a room with average DF of 5% feels sufficiently bright and does not require electric lighting when daylight is available. Average DF less than 2% makes the room dull and frequently demand electric lighting. British Standard code of practice 8206 (2008) recommended average DF of 1% for bedroom, 1.5% in living room and 2% in kitchen for residential environments. Preference for daylight may differ on a user's perception. A patient room, however, should be sufficiently illuminated during the day as exposure to bright light, particularly in the morning, is beneficial for proper circadian activity, which is essential for healing.

2.5 Problem formulation

The objective of the optimisation was to achieve a window configuration in terms of the parametric values (width, sill level height, lintel level height and solar shading depth) that minimises the heating/cooling load and maximises the availability of daylight. The optimization problem is defined by:

$$\min f(\mathrm{x}) = E_{hc} - DF \tag{1}$$

subject to:

$$DF \geq 2\% \tag{2}$$

where: E_{hc} is the total heating and cooling load of the room and DF is the average daylight factor over the reference plane.

3 Computer simulation and optimisation

3.1 *Modelling and simulation*

Autodesk Ecotect Analysis software has been used as the modelling tool in this study. The software is a building performance simulation program and can perform a range of energy and environmental calculations of buildings. The program was used to model the patient room and the parametric window to calculate cooling/heating loads of the space for variable window parameters. Ecotect's scripting interface was used for integrating the lighting simulation program, Radiance to calculate the DF over the horizontal reference points. Radiance has been developed in the Lawrence Berkeley National Laboratories (LBNL) and has been validated against real measurements (Ward, 1994).

3.2 *Optimisation process*

The optimisation approach in this study can be expressed as an extended search method that included computer simulation. The method evaluated all of the 810 possible solutions within the search space for thermal and lighting performance for various window parameters. The process is described as a flow chart in Figure 2.

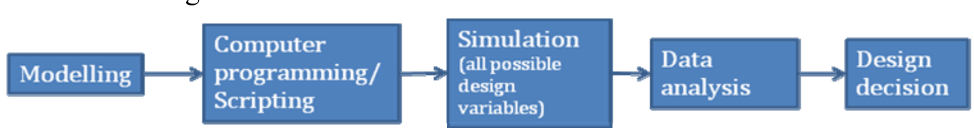


Figure 2: Optimisation process through extended search method.

3.3 *Normalisation*

Units for the total cooling/heating load and daylight factor are different and their magnitude varies widely. To eliminate bias, the obtained values for the components of the objective function (Equation (1)) were normalized to produce an identical range, as defined in Equation (3).

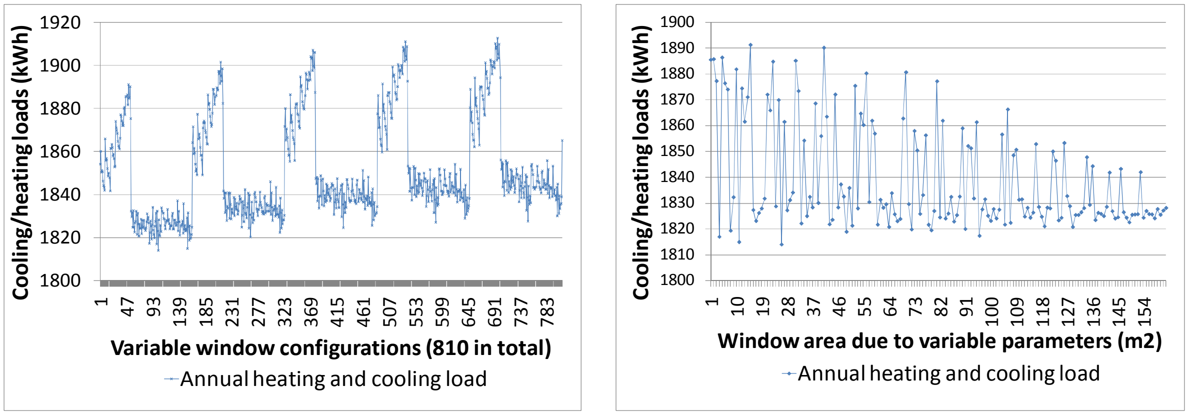
$$I_{norm} = (I_{value} - I_{min})/(I_{max} - I_{min}) \quad (3)$$

where: I_{norm} is the normalized value, I_{value} is the absolute value, I_{min} is the minimum of the absolute values and I_{max} is the maximum of the absolute values.

4 Results

4.1 *Impact of window configuration on heating and cooling loads*

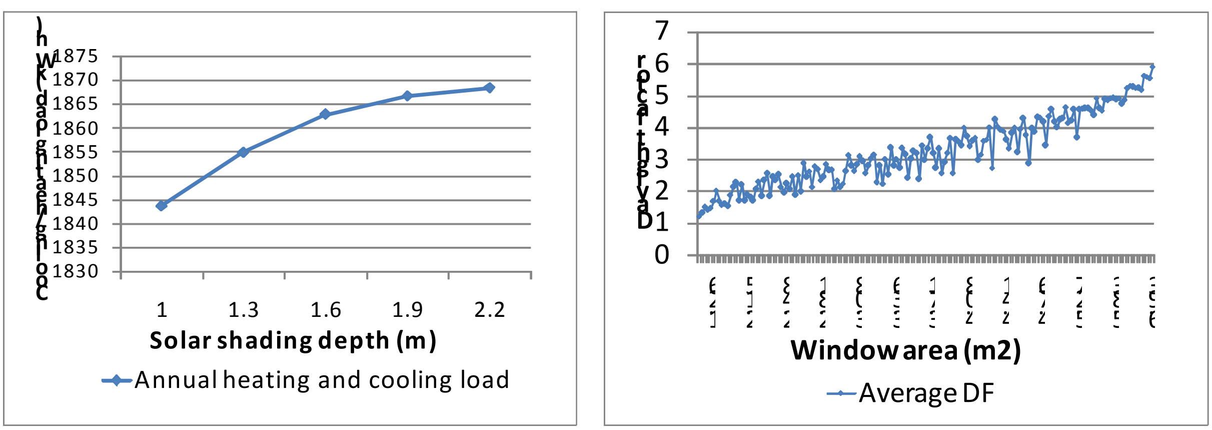
Figure 3a demonstrates the variability of annual cooling/heating loads depending on different window configurations. Figure 3b shows the annual cooling/heating loads for variable window area with fixed depth (1 m) solar shading, where light shelf were used with a window lintel height more than 2.1 m. This result shows that use of light shelf and high window can have impact on heating/cooling load of the room. The window design with the least heating/cooling loads has the parameters: width 2.15 m, sill level 1.2 m, window lintel 2.35 m and shading depth 1 m (overall window area 2.473 m^2). However this window produced a DF of 1.86%, which is below the recommended level and will require frequent electric lighting during daytime (CIBSE, 1999).



(a) (b)

Figure 3: (a) Heating/cooling loads for variable window configurations; (b) Heating/cooling loads for variable window area with fixed solar shading.

The impact of solar shading depth on heating/cooling loads for the room is noticed. Figure 4a presents the result of annual heating/cooling loads for 5 solar shading depths ranging from 1 m to 2.2 m for a fixed size window (width = 3.15 m, sill level = 0.6 m and lintel level = 2.1 m). A gradual increment of heating/cooling loads is noticed with the increase in the shading depth. This is due to the reduction in direct solar gain during winter. However, this was not very significant as the difference between the maximum and minimum values was only 24 kWh/yr.



(a) (b)

Figure 4: (a) Impact of heating/cooling load for variable solar shading depth; (b) Average DF for variable window configuration with fixed solar shading depth (1m).

4.2 Impact of window configuration over DF

It is apparent that increased window area will increase daylight availability of the room. Available DF (normalized) with different window configuration is shown in Figure 5 and DF for variable window parameters with fixed solar shading is shown in Figure 4b. Results show wide variations of DF between the combinations of variable window parameters and solar shading depth. Apart from the window aperture, depth of solar shading and use of light shelf has an impact on DF. The highest DF within the variable parameters is found 5.9% for the maximum window area and minimum solar shading depth, and the lowest DF is recorded 0.92% for the minimum window area and maximum solar shading depth.

4.3 Multi-objective optimisation

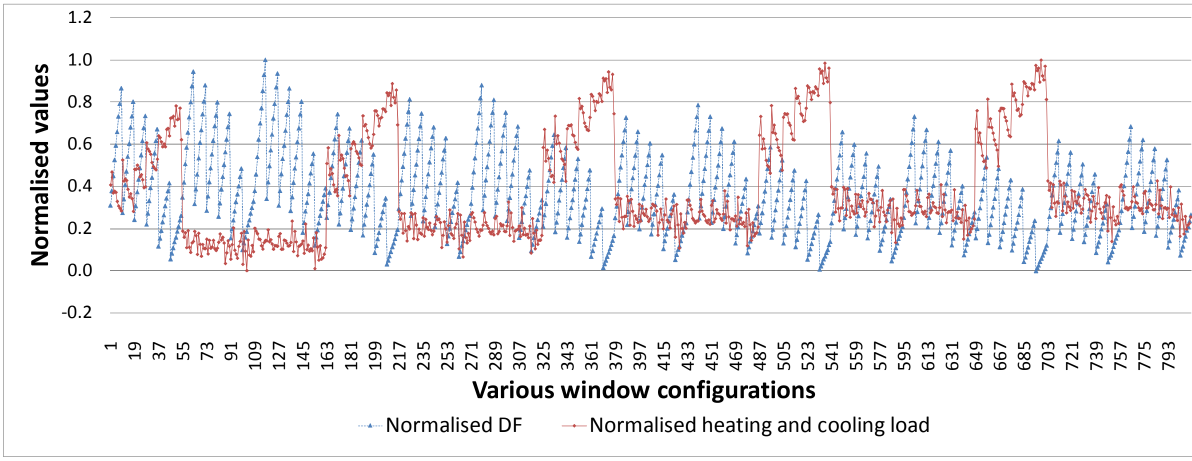


Figure 5: Comparison of normalised DF and cooling/heating loads for variable window configurations.

A comparison of normalised DF and heating/cooling loads is demonstrated in Figure 5. To identify the best agreement for the maximum daylight availability and minimum heating/cooling load, a weighted sum approach was used as described in Equation (1). Figure 6 describes the results of optimisation values calculated by Equation 1 for each window configuration for variable parameters. Table 2 describes the best possible solution for variable window parameters derived from the optimisation with an annual cooling/heating load of 1828.1 kWh and an average DF of 5.62%. Figure 7a and 7b show the monthly cooling/heating load distribution and DF distribution over the reference plane for the generated optimised solution, respectively.

Table 2: Optimal solution derived through the optimisation process.

Parameters	*Value*
Window width	3.4 m
Window sill level	0.4 m
Window lintel level	2.6 m
Solar shading depth	1.0 m

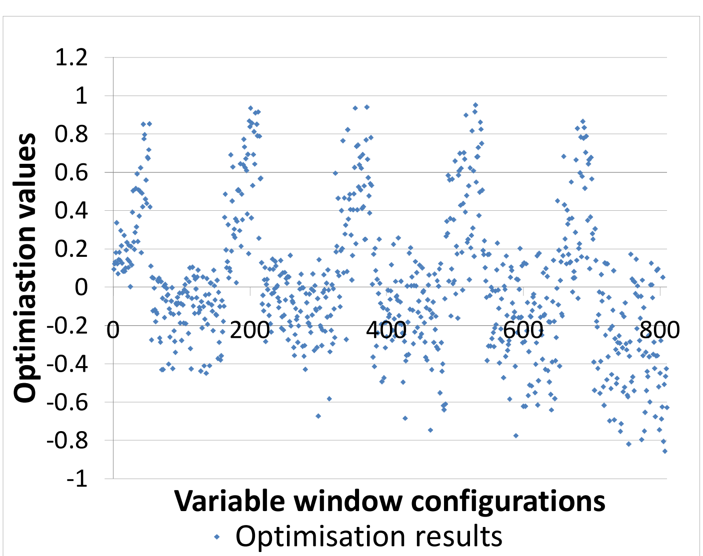
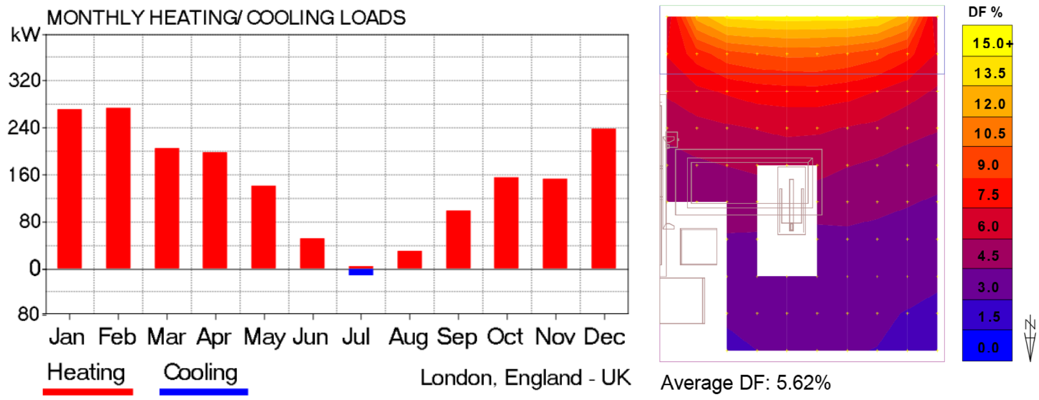


Figure 6: Optimisation results for variable window configurations calculated using Equation 1.



(a) (b)

Figure 7: Monthly cooling and heating load distribution (a) and average daylight factor of the room (b) for optimal solution.

5 Discussion and conclusions

The study demonstrated a methodology of optimising a parametric daylight window using computer simulation. The demonstrated approach considers both lighting and thermal performance of the window for the selected space. The optimisation technique was integrated with two computer simulation programs to construct a decision support system to combine the best features of the programs; i.e. Radiance for daylighting and Autodesk Ecotect for thermal simulation. The extended search technique used in the optimisation process has been found suitable for the selected problem as the search space was limited with fixed variables and value limits. Improved population based search techniques can widen the opportunity to incorporate more variables. The study also established an example of constructing parametric building component and how variable parameters of the component can impact on building performance.

Results showed wide variations in window performance due to variable parametric values. It is apparent that more window area provides more daylight into the room. However results showed that size of window and use of light shelf has a non-linear impact on heating and cooling loads. The result identified that the most efficient solution based on heating/cooling loads was not sufficiently ensuring adequate DF from the points of view of therapeutic and energy usage. To consider both lighting and thermal aspects an approach of multi-objective optimisation has been applied. The generated solution is verified to be efficient in reducing heating/cooling loads as well as allowing adequate daylight to reduce the usage of electric lighting and enhance the therapeutic environment. This methodology can be applied at the initial phase of building design to identify optimal window area and configuration for better performance.

The approach has few limitations, which can demand adjustments during detail design phase to ensure desired performance. Detail electricity consumption for artificial lighting has not been considered in this study, although suggestions from CIBSE Lighting Guide 10 (CIBSE, 1999) has been incorporated to eliminate artificial lighting demand during daytime. The use of electric light, on the other hand, is dependent on occupants' behaviour, which generally occurs when the room or task area is not adequately illuminated by daylight. Devices such as, curtains or louvers are generally used to cut direct sun penetration and glare, and can have impact over daylight availability of the room. This can be due to the direct vision of sun or resulting high intensity luminance reflected by window or room components. It is envisaged that these factors are considered further during detail design stages. A high window with light shelf can produce diffused daylight into the room without creating glare if designed appropriately. In this study light shelf depth was selected to obstruct direct vision of window from patient bed area, which limits the glare produced by direct sun falling onto the window components.

DF is constant for a definite window area and components regardless its orientation and location, and considers the CIE overcast sky. Different sky conditions will produce different interior illumination depending on fenestration or window component design. A sunny sky with sun will produce higher daylight illumination inside the room where direct penetration of the sun into the room will produce almost similar to exterior horizontal illuminance and can cause very high luminance and glare. To eliminate the glare careful consideration is necessary for both exterior and interior solar shading design. The consideration of detail glare prediction model for sunny sky can result in further refinement of the design in terms of solar shading design. Recent developments in dynamic daylight performance metrics (Reinhart et al., 2006) can be used in detail solar shading devices to ensure optimum daylight distribution with reduced glare.

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