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# Energy and daylighting performance design of skylights and clerestories in a large hall retail building

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**Abstract**
*Artificial lighting is one of the major electricity consumers in many non-residential buildings. Proper use of daylighting in retail buildings can reduce energy consumption effectively and additionally improve the quality of light and increase sales and worker's productivity. The present study analyses daylight potentials and energy performance using different configurations of skylights, deflectors, clerestories and lighting zones for a large space hall-type retail building located in the northern latitude and cold climate of Finland. The scope of the study was to determine the artificial lighting energy reductions for different combinations and the general impact of daylighting features on the energy performance of the building type. The results show electric lighting energy savings potential from a mere 4% in the case of single zone control with only clerestories, up to almost 60% in the case of multi-zone control with skylights, clerestories and without deflectors. The total delivered energy shows increase between 1% and 20% for the different configurations using single zone lighting control and from 6% increase to 4% decrease in cases with multi-zone control. The primary energy results showed up to 1% lower values for single zone and up to 17% lower values for multi-zone control variants. The outcomes of the research emphasize the potential of daylighting underlining the importance of reducing glare and of a correct lighting zones design which can increase the daylight performances of about 50%.*

***Keywords - retail hall building; daylighting simulations; energy saving; Radiance and Daysim; IDA-ICE; building performance design***

## 1. Introduction

Lighting plays a key role in commercial buildings design, especially in shopping malls and retail buildings, contributing to the visual comfort, and quality of the space. As artificial lighting can use up to 40% of the building total energy consumption [1], there is great potential for energy savings. Energy efficient luminaires, utilizing daylight and using demand based lighting controls are becoming a common practice in today's low energy buildings. Many studies, based on simulation analyses as well as field measurements, that have been conducted for different types of buildings, show the effect of lighting controls and daylight use on lighting energy consumption – through the proper use of sensors and controllers, daylighting can reduce and even eliminate the need for artificial lighting required to provide sufficient illuminance levels [2].Chen et al. have reported 36.1% of electricity saving potential for the on/off control and 41.5% for dimming control integrated with daylighting in case of industrial buildings [3]. Li and Lam have suggested that proper daylighting schemes can result in 50% electric lighting savings in office buildings [4]. In their work, Atif and Galasiu report, that continuous dimming lighting control system can provide 46% annual savings in electrical lighting consumption, while the automatic on/off can save up to 17% of lighting energy. The savings were for 68% of the lighting energy consumed during main occupancy for the continuous dimming system, and 31.5% for the automatic on/off [5].

The utilization of natural light in retail spaces not only saves lighting energy but also has a positive effect on sales [6]. In stores that use skylights, it is reported up to 40% higher sales compared to only artificially lit buildings [7].

However, while the reduction of artificial lighting trough daylighting strategies, will reduce the electricity need, it will also affect heating and cooling loads and the total energy use of the building. Increasing glazing areas and decreasing internal loads by efficient lighting and control, would lead to an increase of the heating energy [3] and trough increased solar radiation also cooling energy consumption.

The present study analyses the daylight potentials and energy performance of a large space hall-type retail building of approximately 9000 m² using different configurations of skylights, clerestories, lighting zones and controls located in the northern latitude and climate of Finland. The scope is to accurately determine the artificial lighting energy reductions in the different combinations to support the general energy design of the building type. The daylighting simulations and electric light contribution have been performed using the software Radiance and Daysim and the heating and cooling energy consumption has been analyzed with IDA-ICE building simulation tool.

## 2. Methods

### *A. The studied building*

The studied retail building is a single floor hall of 137.4m x 66.0m with a total floor area of 9068.4m² located in the northern latitude of Helsinki, Finland (60°10'N). The building is divided into three identical bays on the short side, each 22m of width (Figure 3). The roof consists of three double slope sections with a maximum height of 8.4m (without skylights). The interior of the building is occupied by shelves of two lengths, 24m and 10m both with a height of 2.4m. The operating hours of the building are from 7:00 to 22:00 from Monday to Saturday.

For daylighting and energy consumption analysis, different variations of clerestories, skylight combinations and lighting zones have been compared. The skylights (width 3520mm; height 1010mm; glass or polycarbonate) are ridge type (Figure 1, left), on three rows placed at the peak of each bay roof. The deflectors (700x700mm, polycarbonate), when present, are located in the light well (always facing South) (Figure 1, right). The clerestories or side-windows (polycarbonate) run below the roof on the long sides of the building, 4450mm from the floor, the vertical size is 3400 mm and the Window to Wall Ratio is 40%. For the simulations we used ASHRAE weather data for Helsinki-Vantaa region [8].

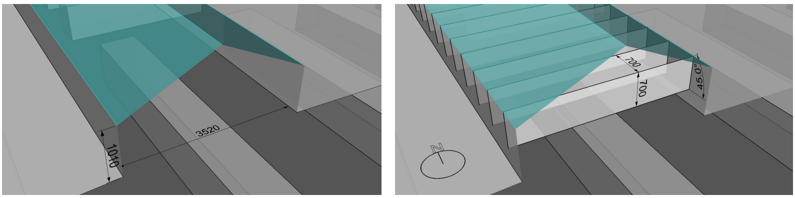


Figure 1. Skylight ridge type (left) and deflectors (right) layouts.

*B. Daylighting simulation and electric light calculations.*

The daylighting simulation metrics used for the studies are the Daylight Autonomy (DA), the Continuous Daylight Autonomy (CDA) and the Useful Daylight Illuminance (UDI). DA is defined as the capacity of a space to be lit by solely natural light in relation to the specified minimum level (Lux/m²). It is measured in percentage of time in relation to the operating time of the building for the entire year [9]. CDA take into account also values of DA below the requested threshold and add these additional partial percentages to the final total values (Figure 2) [10]. The CDA metric is suitable for an electric light plan using dimmable luminaires that increase the overall daylighting contribution performances. UDI metric uses two thresholds to define the potentialities of a space to be day lit (% of time in between the thresholds). The lower is the under lit threshold and the upper the over lit one [11]. The latter have been used with a value of 3000Lux/m² to simulate high contrast and excessive lighting uncomfortable in a retail building. The target Illuminance is set at 500Lux/m² on the floor level. The electric lighting plan uses LED luminaires Siteco Modario 202 68W with 1% Dali ballast for a total installed power of 56.24 kW (6.2 W/m$^2$) and annual consumption of 29.1kWh/(m$^2$ a) (without daylight). For higher accuracy of the daylight simulations it has been used an analysis grid of 2 meters excluding the area below the shelves.

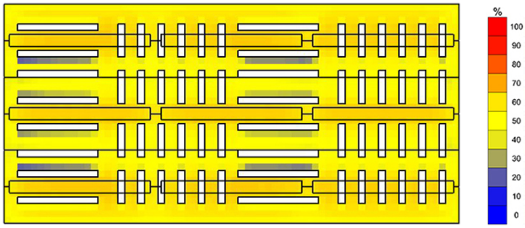


Figure 2. False color diagram showing the annual Continuous Daylight Autonomy in % of time (hours) for one of the cases. Shelves - white rectangles and the skylights projections - wire rectangles.

Table 1 shows the materials characteristics used for the design.

Table 1. Materials characteristics.

| | Visible Transmittance (VT), % | Reflectance, % | Solar heat gain coefficient, - |
|---|---|---|---|
| Glass for skylights | 72 | - | 0.51 |
| Polycarbonate for skylights | 35 | - | 0.46 |
| Polycarbonate for deflectors | 50 | - | - |
| Polycarbonate for clerestories | 41 | - | 0.43 |
| Floor | - | 20 (matte) | - |
| Walls/Shelves | - | 50 (matte) | - |
| Ceiling | - | 80 (matte) | - |

The simulation software used is Radiance and Daysim through the Rhinoceros-Grasshopper-Honeybee modeling and parametric energy design interface.

### *C. Energy performance simulation*

To quantify the effect of different daylighting design variations on the energy performance of the building, we have simulated the building with indoor climate and energy simulation tool IDA-ICE v4.7 [12]. Although IDA-ICE is capable of calculating lighting energy consumption taking into account daylighting, it is not possible to model interior objects that have an effect on daylighting performance and lighting energy consumption. Considering the latter, the lighting control in IDA-ICE has been modeled by using hourly lighting energy load results from Radiance converted into percentages of total lighting power as input to IDA-ICE lighting control. This allows more accurate lighting energy usage simulation, when e.g. shelves or deflectors are used.

The different simulation model variations for energy calculation are shown in Figure 3. The building parameters used for annual energy consumption calculations are given in tables 2 and 3. Values for thermal bridges were taken from the Finnish Building Code [13]. For the primary energy calculations, also Finnish primary energy factors were used: 0.7 for district heating and 1.7 for electricity.

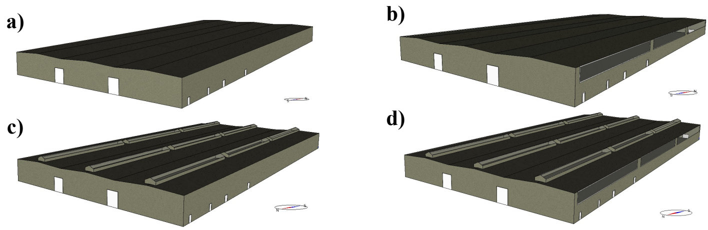


Figure 3. Building simulation model variations for heating and cooling load and energy performance analyze in IDA-ICE: a) model without windows; b) model with side-windows; c) model with skylights; d) model with side-windows and skylights.

The thermal transmittances and areas of the building envelope are given in Table 2.

Table 2. Building envelope description.

| Building envelope part | U-value, $W/(m^2 K)$ | Total area, $m^2$ |
|---|---|---|
| External walls<br>- with side-windows | 0.16 | 3144.7<br>2275.6 |
| Roof<br>- with skylights | 0.12 | 9079.7<br>7732.6 |
| Floor towards ground | 0.09 | 9068.4 |
| Windows | 0.75 | 869.0 |
| Skylight | 1.00 | 1494.9 |
| Doors | 1.00 | 85.0 |

Infiltration for the building was calculated using equation (1), according to the Finnish Building Code [13]:

$$q_i = q_{50} \times A/(3.6 \times z) \qquad (1)$$

where $q_{50}$ is building air permeability at 50 Pa pressure difference, $m^3 \cdot h^{-1} \cdot m^{-2}$ of external surface area; A is total area of building envelope, $m^2$ and z is building height factor, for the current case z = 24. The building air permeability value 1.0 $m^3 \cdot h^{-1} \cdot m^{-2}$ was used, as is realistically achievable with current building techniques and envelope construction for low energy buildings.

Table 3. Building simulation input parameters.

| | |
|---|---|
| Heating set-point, °C | 18 |
| Cooling set-point, °C | 25 |
| Ventilation airflow rate, 7:00-22:00, L/(s·m$^2$) | 1.0 |
| Ventilation airflow rate, 22:00-7:00 L/(s·m$^2$) | 0.15 |
| Ventilation system SFP, kW/(m$^3$/s) | 1.5 |
| Heating system efficiency, - | 0.9 |
| Heat source (district heating) efficiency, - | 0.97 |
| Air heating efficiency, - | 0.9 |
| Cooling system efficiency, - | 0.9 |
| Cooling source SCOP, kWh/kWh$_e$ | 3.5 |
| Internal gains from occupants, W/m$^2$ | 3.0 |
| Internal gains from lighting (maximum), W/m$^2$ | 6.2 |
| Internal gains from equipment, W/m$^2$ | 1.0 |

## 3. Results and discussion

### *A. Daylighting simulation and electric light calculation results*

The combinations analyzed for the daylight and energy performances are shown in Table 4.

Table 4. The combinations of skylights, deflectors and side-windows used in the analysis.

| Combination | Code |
|---|---|
| without skylights without side windows | Case0 |
| without skylights with side windows | Case1 |
| with glass skylights without deflectors with side windows | Case2 |
| with glass skylights without deflectors without side windows | Case3 |
| with glass skylights with deflectors with side windows | Case4 |
| with glass skylights with deflectors without side windows | Case5 |
| with polycarbonate skylights without deflectors with side windows | Case6 |
| with polycarbonate skylights without deflectors without side windows | Case7 |

The daylight results refer to a building oriented North-South. Similar values are obtained with any orientation assuming for the cases with glass skylight, the deflectors are oriented towards South. The results (Figure 4) show that, excluding the only one case without skylights, which has a very low daylight potential, the average CDA is more than 50%, from the lowest 42.3% of the Case0 to the highest 60.1% of the Case3. For the same cases CDA values are higher than DA ones from 22% to 39%. UDI>3000 is below approx. 5% for all the cases except those without deflectors (with glass skylights) with clerestories (8%) and without (6.2%).

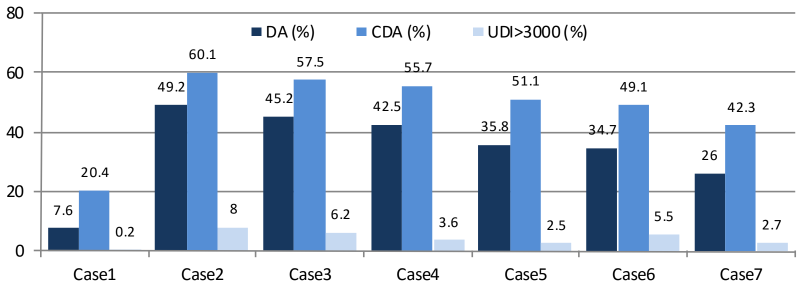


Figure 4. Daylight analysis results.

The electric light consumption calculation results (Figure 5) show that, proportionally to the CDA results, excluding the case without skylights that save only 13% and 4% for the multi-zones and single zone cases respectively, the energy consumption reductions range from 59% and 49% of the Case3 to the 42% and 5% of the Case7 (pair of values multi-zones and single zone cases respectively).

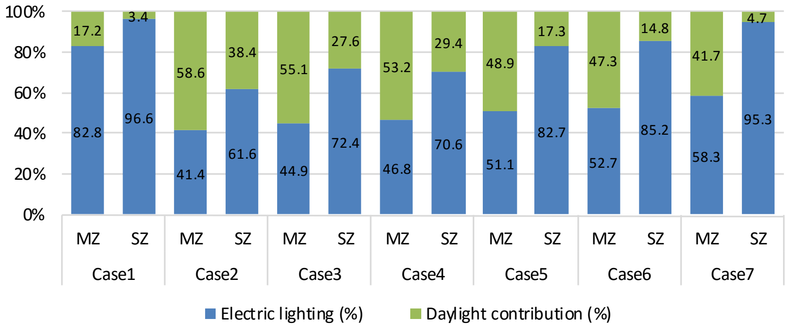


Figure 5. Annual electric lighting share and daylight contribution. Code: MZ – multi-zone control; SZ – single zone control.

## *B. Energy consumption simulation results*

The estimated delivered energy of the building design variations with lighting energy consumption from Radiance calculation results is shown in Figure 6. With constant lighting and no glazing surfaces (Case0), the total annual delivered energy for the building is 66 kWh/(m$^2$ a). Using side-windows (Case1) will increase heating consumption by 12%, from 17 to 19 kWh/(m$^2$ a), while the cooling energy will remain the same with both single and multi-zone lighting control. The addition of glass skylights (Case2) increases the heating energy an additional 51% and also cooling energy from 1 to 7 kWh/(m$^2$ a). Using or polycarbonate skylights (Cases 6 and 7) instead of glass (Cases 2 and 5 respectively) will result in 8% higher delivered cooling energy of 8 kWh/(m$^2$ a), but leaving heating energy on the same level, 28 kWh/(m$^2$ a).

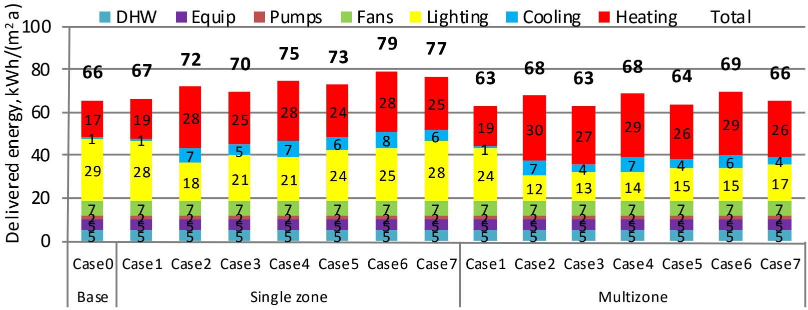


Figure 6. Delivered energy of the building with different skylights and side-windows combinations for single and multi-zone lighting control.

The primary energy consumption of the different combinations of skylights, clerestories and the impact of shelves, deflectors and glazing material is shown in Figure 7. The multi-zone lighting control reduces on average 17% of total primary energy compared to the single zone strategy. In case with skylights, side-windows and deflectors (Case7), the difference reaches up to 26%. Although the lighting energy consumption decreases for the cases with single zone control with different daylighting design variations, the gained savings are consumed by the increased heating and cooling energy, resulting in roughly the same (Cases 1÷3) or even higher (Cases 4÷7) primary energy values. emphasizing the importance of proper lighting zoning and control in buildings with higher percentage of glazed envelope areas.

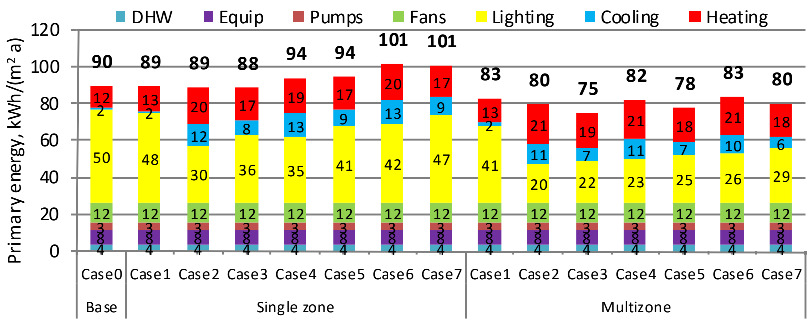


Figure 7. Primary energy consumption of the building skylights and side-windows combinations.

## 4. Conclusion

The daylighting analysis results show a big potential to lit commercial single floor buildings through natural light and save electric lighting energy also in northern latitudes like the Helsinki-Vantaa region in Finland. When using skylights, with or without windows, depending on the material and the presence of deflectors the space is daylit (CDA) for up to 60% of the operating time. This is the case using glass skylights without deflectors and with side-windows. In this specific case the excessive lighting (UDI>3000) accounts for the 8% of the time, then deflectors are recommended. This decrease the daylight potential to about 55%, still a significant value. Other cases that use polycarbonate skylights don't have problem of excessive lighting, but have least daylight performances (at the same time cost less).

The electric light energy that is possible to save is consequently significant, up to 59% in the case using glass skylights without deflectors and with side-windows and with multiple lighting zones (the small difference with the CDA is due to the stand-by power and the delay time of the luminaires). The same case with added deflectors, the one with the best balance among performances, save 53% of electric lighting energy. This means that the use of deflectors to improve the internal comfort decreasing the excessive lighting of about 55% increase the energy consumption of about 9%.

An important outcome is given also from the comparison of the electric lighting energy saving of the same cases when the building is equipped with multiple lighting sensors, that divide the floor in different zones, or with a single sensor (single zone). The sensors then command sets of luminaires inside the same zone or all the luminaire of the single zone. The efficiency if the two system is big. Excluding the case without skylight, the performance of the multi-zones system (the energy saved) comparing the single zone range from 33% of the case with glass skylight no deflectors and with side-windows to the 39% of the case with polycarbonate skylights and without side-windows.

The addition of windows and skylights affects the total energy use trough lighting, heating and cooling energy needs. With single zone lighting control, even with the decrease in lighting energy, the total delivered energy increases, mainly due to the higher heating energy consumption. The highest energy consumption had cases with polycarbonate skylights and side-windows, up to 20% higher than the case without glazing surfaces and 10% more compared to the case using glass skylights. Using multi-zone lighting control however allows even reductions in total delivered energy: for cases with only side-windows and only with skylights. For the combination of side-windows and skylights, the result was always higher than the base case.

As for the primary energy of the different building configurations, cases with single zone lighting control using only side-windows or glass skylights and no deflectors, achieved roughly the same results as the base case. Other cases showed up to 13% higher primary energy values. The multi-zone lighting control on the other hand reduces on average 17% of total primary energy compared to the single zone strategy. In the case with skylights, side-windows and deflectors, the difference reached up to 26%.

## Acknowledgment

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