Daylight and energy as active drivers in the design process of a new school in Enköping, Sweden

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Abstract. With the introduction of new demands targeting net-zero energy and net zero-carbon buildings and neighbourhoods on a national level in Sweden and internationally, balancing the requirements of daylight and energy is becoming more important in the design process. In order to succeed, an effective strategy needs to be defined for utilising the right digital tools and metrics for the two factors at different times in the process, and in an integrated way. This paper presents the workflow used whilst developing the concept for a new school in Enköping, Sweden (59.633°N, 17.086°E). The analyses performed during the design process included vertical sky component, daylight factor and early-stage energy calculations. Implementing photovoltaic (PV) cells and energy-efficient lighting design were also included as part of a strategy for reducing primary energy consumption. It was found that daylight and energy can be effectively balanced if an integrated strategy is followed during early stages of the design process. National regulations can also be met, and the time required for running simulations can be reduced by a factor of three by having an effective process.

1. Introduction

Addressing daylight and energy questions in the design process is vital for the development of healthy and sustainable buildings. However, these issues are often considered late in the process, merely forming part of a checklist at the end, rather than acting as drivers in the design and influencing the building form. Addressing these issues is becoming a necessity, considering the tight requirements set in Sweden, and on a global level, for achieving net-zero energy and carbon-neutral buildings and neighbourhoods. Daylighting and energy are two important and often conflicting aspects that are crucial for improving health and wellbeing, whilst reducing climate impact.

Daylight was used as a starting point in the case study presented in this paper, with the assumption that a sufficiently daylit, yet compact, building would also meet the energy requirements. Additionally, achieving good daylight in learning environments brings many advantages, summarized below.

1.1 Light, daylight and health in learning environments

In the seventies, it was found that in windowless classrooms, students exposed to standard cool-white fluorescent lighting exhibited decreased attention and greater hyperactivity, fatigue and irritability.
compared to students under full spectrum lighting [1]. Later, a Canadian study indicated that children exposed to electric lights all day have decreased mental capabilities, agitated physical behaviour, and fatigue [2]. Furthermore, it was found that students in full-spectrum fluorescent lighting grew 2.1 cm more in two years compared to students who attended traditional fluorescent-lit schools; they also had an attendance increase of 3.2 more days per year than the students in traditional fluorescent lighting schools [2]. Later, a Swedish study where 90 elementary school students were studied by taking samples of their cortisol (stress hormone) level over one year indicated that ‘classrooms without daylight tend to disturb the basic hormone pattern and this in turn influences student concentration with possible impact on annual body growth and absenteeism’ [3].

1.2 Daylight and learning performance
One study concluded that ‘students in the new daylit schools had a higher reading and mathematics achievement score than students in schools which relied heavily on electric lighting’ [4]. In a later study, analysing test score results for more than 21,000 students from three separate school districts in Orange County, California, researchers found a statistically significant relationship between daylight and child learning performance [5]. Their results indicated that ‘students with the most daylighting in their classrooms progressed 20% faster on math tests and 26% on reading tests in one year compared to those with the least’. A study 4 years later analysed the performance of 8000 students in 450 classrooms in Fresno, California [6]. They identified that the overall visual environment (i.e. not just daylight access) was important for learning, where the main outcomes were:

- An ample and pleasant view out of a window, that includes vegetation or human activity and objects in the far distance, supports better outcomes of student learning.
- Direct sunlight in classrooms, especially through unshaded east or south facing windows, may be associated with glare and thermal discomfort. However, blinds or curtains allow controlling the intermittent glare sources or visual distraction from windows.

A more robust and recent study (2015) involving 27 UK primary schools, 153 classrooms and 3766 pupils, demonstrated that differences in the physical design of a classroom explain 16% of the variation in the learning progress [7]. Physical design in this study included three variables (stimulation, individualization and naturalness), where naturalness (encompassing light, temperature and air quality) accounted for about half of the influence on learning.

1.3 Lighting and visual performance
Poor spectral light can create strain on students’ eyes, leading to a decrease in information processing and learning ability, causing higher stress levels [8]. It is well known that stress impacts certain growth hormones and persistent stress stunts bodily growth in children.

2. Method
2.1 Project information
The chosen case study was a high school project in the town of Enköping, Sweden. The project also plans to include areas for continuing education, with a floor area totalling approximately 24,500 m² over four floors. This was set in 2019 and was updated in later stages of the project. The project had high sustainability goals, including minimizing climate impact, as well as meeting the requirements ‘Silver’ within the Swedish environmental certification system, Miljöbyggnad 3.0 [11].

2.2 Indicators
Different indicators were used at different stages in the project, to optimise the building form and balance daylight and energy. In addition, potential for reducing net energy consumption through the use of photovoltaic (PV) cells was also considered. The indicators studied are described below.

2.2.1 Vertical sky component (VSC). To study daylight access at an early stage, a vertical sky component (VSC) simulation was performed [9]. The results expressed the daylight access on the
facades and were used to rapidly test and compare design alternatives, as well as to suggest changes in-line with daylight requirements from local building regulations (BBR) [10].

2.2.2 Daylight factor (DF). To study daylight access in more detail at a later stage, a daylight factor (DF) simulation was performed [12]. This evaluated daylight access on an interior work-plane and provided results that could be used to directly assess compliance with BBR (approx. 1.0% point-DF in regularly occupied spaces [10]) and Miljöbyggnad ‘Silver’ (1.2% point/median-DF in regularly occupied spaces, which can be reduced to 1.0% when using simulation tools for the assessment [11]). Furthermore, compliance with the new European daylight standard was also examined (2.5% median-DF for new buildings near Stockholm, Sweden for Daylight level to exceed 300 lux), which considers the perspective of health and wellbeing [13].

2.2.3 Early-stage energy indicators. At an early stage, a simple steady-state energy calculation was performed to predict primary energy use for building operation. In addition, form-factor (compactness) and average U-value were also calculated. A parametric analysis was performed, where window-to-wall ratio (WWR) was increased from 30-50%, whilst varying construction efficiency, using two alternatives described in Table 1. The results were used to suggest envelope constructions and maximum glazing areas, in-line with requirements from BBR [10] and Miljöbyggnad [11]. BBR allows a maximum annual energy-use of 80 kWh/m² and maximum average U-value of 0.6 W/m²K [10]. Miljöbyggnad ‘Silver’ limits primary energy consumption to 75% of the BBR value (thus 60 kWh/m²) [11].

| Construction Type | Walls       | Roofs       | Openings  |
|-------------------|-------------|-------------|-----------|
| Very Good         | 0.11 (W/m²K) | 0.10 (W/m²K) | 0.8 (W/m²K) |
| Excellent         | 0.09 (W/m²K) | 0.08 (W/m²K) | 0.6 (W/m²K) |

2.2.4 Solar irradiance. To evaluate the potential of PV cells at an early stage, an annual solar irradiance simulation was performed. This provides information about irradiation available for on-site electricity generation, which can be utilised to reduce the primary energy consumption of the building. A parametric analysis was performed, with cells tilted towards the south, south-west and south-east.

2.2 Models and tools
To facilitate an optimal design process that was both time-effective and highly iterative, selecting the detail level in the models and the tools that can be used was important. The decision was taken early-on to use the models and tools described below. It is estimated that this reduced the simulation time by a factor of three.

2.3.1 Models. The models used for simulations were drawn in Rhinoceros, a 3D modelling program that includes the visual-programming plugin Grasshopper. The models were formed of simplified versions of the main architectural model, with a level-of-detail suited to the study and the relevant tools. In this case, two types of models were required. The VSC, early-stage energy indicators and solar irradiance studies all required just simple building forms and surrounding context. The DF study required the addition of external walls, floors and roofs, simplified window surfaces and an open-plan interior.

2.3.2 Tools. The tools used for simulations and calculations were developed by the Digital Sustainability group at White arkitekter using open-source plugins. The tools were developed in Grasshopper, a visual programming plugin to Rhinoceros. The Grasshopper plugins, Ladybug and Honeybee, were used to develop each tool. User-interfaces were also implemented using another
Grasshopper plugin, Human UI (see Fig. 1 for an example). The VSC simulation was dependant on Ladybug and Honeybee tools, while the simulation engine, Radiance, was used in the DF tool, and the early-stage energy indicators tool was based on a steady-state calculation. In this tool, the user selects a building efficiency of ‘Good’, ‘Very Good’ or ‘Excellent’, which in turn sets U-values, airtightness, hot-water efficiency and thermal bridges. The purpose of using such tools was to reduce simulation times, as well as to ensure that simulations were well integrated in the design process.

![Figure 1. User-interface for the early-stage energy indicators tool.](image)

2.4 Integration with the design process
Integrating the indicators and the tools in the design process was key in ensuring that the right information was communicated to the project team, at the right time, to inform design decisions and optimize daylight and energy. The process of integrating the simulations was divided into two phases. The first phase focused on daylight (VSC), sunlight hours and outdoor thermal comfort, whilst the second phase introduced the more detailed daylight studies, coupled with the energy calculations.

![Figure 2. Diagram showing how different simulations were integrated in the design process.](image)

3 Results and Conclusions
The methods described above were used throughout the process to optimize daylight and energy in the building, as well as the roof inclination angle. The results presented in this section focus primarily on the final design alternative and the recommendations and conclusions drawn from each simulation.
3.1 **Vertical sky component (VSC)**

The results shown in Figure 3 indicate that most of the facade areas receive enough daylight (indicated by green on the facade) and therefore have the potential to meet the BBR requirements. The VSC results were presented on a scale from 0-25%. Results less than 12% are considered too low to meet the requirements of local building regulations, even with an efficient facade and shallow rooms. Results between 12-25% are considered acceptable, with an efficient facade and internal layout. Results more than 25% are acceptable, even with sub-optimal facades and internal layouts. These guidelines were developed from internal research at White arkitekter and correlate well with guidelines from the Building Research Establishment (BRE) [9].

Three zones have values below 25%, indicating some challenges in meeting regulations. These zones were on the ground floor of buildings B and C, and on the facades facing the surrounding context to the north-east. Based on these results, it was recommended that a minimum distance of 17m be maintained between the school building and the surrounding context. In addition, measures to ensure sufficient daylight on the ground floor were considered, such as increasing the window-to-wall ratio (WWR), incorporating a recessed facade with skylights on the ground floor, and placing zones that were not regularly occupied in darker areas. This solution provided the best results in comparison to other building forms and was therefore chosen for this stage of the project.

![Figure 3. VSC results and corresponding scale.](image)

3.2 **Daylight factor (DF)**

Based on the steady-state energy calculations, a DF simulation was performed using a WWR of 30%, and an open plan layout. The results presented in Figures 4 and 5 show the DF results obtained for floors 1 and 2. The results show that the maximum room depth (double the distance between the facade and the 1.2% DF line) is approximately 8 meters in most areas, indicating a very good building form. This is further analysed in Figure 6, which shows the percentage of daylit area for each floor of each building. On average, 70% of the floor space was well-daylit, allowing the planning of electric lighting in later stages (with the incorporation of absence sensors) to reduce electricity use by 40%.
Figure 4. DF results for plan 1.  

Figure 5. DF results for plan 2.  

Figure 6. A comparison of daylit area for the different buildings and floors.

The DF results were compared with the requirements in the new European daylight standard [13]. The results showed that the requirements of the standard could only be met using 80% WWR when the target is to achieve 300 lux and using the median DF as an evaluation method. It was thus concluded that the requirements in the standard could not be met in this project using the median DF as an indicator, and it was recommended to check the daylight provision using target illuminance and percentage of compliance across a space.

3.3 Early-stage energy indicators
A parametric study was performed, where WWR was varied between 30-50%, whilst comparing the two construction types described in Table 1. Using a WWR of 30%, the results showed a primary
energy use of 58 kWh/m² with the ‘Very Good’ construction, which reduced to 48 kWh/m² with the ‘Excellent’ construction. This meant that the Miljöbyggnad requirement could potentially be met by using the ‘Very Good’ construction. The average U-values were 0.22 W/m²K and 0.17 W/m²K for the ‘Very Good’ and ‘Excellent’ constructions, respectively, both of which fulfil the BBR requirement.

Considering the approximations in the steady-state calculation, and the fact that the ‘Very Good’ construction represents common best-practice, the recommendation from this study was therefore to have a WWR between 30-35%. The Miljöbyggnad requirements could be met using a larger WWR, coupled with the ‘Excellent’ construction, however this would result in increased cost for the project. At this stage, a smaller WWR and lower construction cost were selected.

Considering the global requirements for net-zero energy buildings, as well as the forth-coming changes in BBR, it was also deemed better to select a smaller WWR to account for possible changes in the regulations. Providing this margin at an early stage in the project is also important if, for example, the form changes at a later stage, or if more glass is required as part of the design. Minimizing energy use is a priority for Miljöbyggnad, but also for reducing the building’s climate impact, as part of the project’s wider sustainability goals.

3.4 Solar irradiance results
The results of the solar irradiance simulation are presented in Figure 7. The results show an optimum tilt angle of approx. 40°, which provides around 1200 kWh/m² and 1300 kWh/m² when tilted towards the south-west and south, respectively. The lowest results are achieved with a tilt angle of 90°, providing 875 kWh/m² and 960 kWh/m² when tilted towards the south-west and south, respectively. Tilting towards the south-west reduces results by an average of 6.4% across the range studied. This difference diminishes to zero as the tilt angle approaches 0°. These results will be used at a later stage, to inform the design regarding roof angles and potential for electricity generation through PV cells.

4. Conclusion
In conclusion, integrating the use of digital tools and choosing the simulation level and the associated metrics in different stages in the process are key for achieving an optimal design process, especially for projects with high sustainability goals with focus on daylight and energy requirements. It also provides the basis for informing the design to meet local regulations, as well as the demands set globally (such as the UN Global Goals) for carbon-neutral buildings, and for minimising the building’s climate impact. In addition, it is estimated that the use of digital tools, tailored for early stage analysis, can reduce simulation time by a factor of three.

Applying the methods and metrics in the chosen case study was successful in achieving a balance between daylight and energy, at an early stage, using daylight studies as a starting point. However,
aiming to achieve higher daylight levels and meet the targets of the new European daylight standard, in order to increase occupants’ health and well-being, was found to be a significant challenge for this project when aiming for a level of 300 lux at the working plane. Therefore, it is suggested to do further studies using the target illuminance criteria and percentage of compliance across a space, and to study the applicability of the median DF thresholds in practice, especially in the Swedish context.

Furthermore, it is concluded that studies and simulations are needed to evaluate the reduction in net electricity consumption though use of PV cells, as well as an efficient electric lighting system. These studies are essential for maximizing the reduction of a building’s climate impact. Lastly, more detailed energy simulations will be conducted in the next phase of the project, in order to achieve a more accurate estimation of the building’s energy use.

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