

# INVESTIGATION OF ARCHITECTURAL STRATEGIES IN RELATION TO DAYLIGHT AND INTEGRATED DESIGN— A CASE STUDY OF THREE LIBRARIES IN DENMARK

Michael Jørgensen,<sup>1</sup> Anne Iversen,<sup>2</sup> Lotte Bjerregaard Jensen<sup>3</sup>

## INTRODUCTION

*This paper investigates the use of daylight in three architecturally successful buildings. The aim is to discuss the challenges and opportunities of architectural daylight strategies in relation to integrated design. All these buildings were designed with the focus on a strategy of using daylight to create well-lit, exciting spaces and spatial sequences. The original ideas, thoughts, and decisions behind the designs and daylight strategy are compared with answers in questionnaires from test subjects who have experienced the space and lighting conditions created. The results indicate that the architectural daylight strategies formulated by the architects and engineers at the beginning of the design process are actually experienced by the “users” in the existing buildings. The architectural daylight strategy was different in each of the three libraries, and analysis of the results shows that daylight strategies that include spatial considerations received more positive evaluations. Furthermore, the study showed that designs aimed at achieving an even distribution of daylight with an illuminance target of 200 lx did not result in higher evaluation of the daylight design.*

## KEYWORDS

daylight, integrated design, work methods

## DAYLIGHT STRATEGIES IN RELATION TO INTEGRATED DESIGN

A good daylight design can create dynamic and interesting interiors that enhance spatial awareness, productivity, and well-being, while a poor daylight design can cause discomfort and require excessive use of energy. A good daylight design depends on finding a balance between the need for light, the local climatic conditions, and the architectural vision and idea. In connection with integrated design, the use of daylight is a central element and plays an important role in realizing high-performance buildings in which the quality and amount of daylight is directly related to user satisfaction and the energy used for lighting, heating, cooling, and ventilation (Leslie, R. P. 2003).

<sup>1</sup>Phd student, Department of Civil Engineering, Technical University of Denmark, Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark. Phone: +45 45251934; fax: +45 45931755; e-mail: mijo@byg.dtu.dk

<sup>2</sup>Department of Civil Engineering, Technical University of Denmark.

<sup>3</sup>Department of Civil Engineering, Technical University of Denmark.

Several studies have shown that the energy use for lighting accounts for approximately 10–50% of the total energy consumption of a residential or office building. We can assume that the energy consumption for lighting is probably larger in the case of cultural buildings with longer opening hours. Crucial decisions in relation to reducing a building's energy consumption are also taken in the earliest design stages—which are typically managed by architects (Baker, N. 2000). In the early stages of the design process, the architectural idea is conceived and formulated. The functional layout of the rooms, orientation, the overall geometry of the building, and finally the glazing area, shape, and position, are all determined based on this idea.

It is also in the early stages of the design process that architects usually consider the amenity value of daylight. Scandinavian architecture has a strong tradition of less formalistic design in comparison with other traditions, which means designing from the inside and out. An architect educated in the Scandinavian tradition often considers daylight from the first sketch. Alvar Aalto's Villa Mairea (1930) is a prominent example, where the light that exists between the slim trees of a pine forest was the very first inspiration for the architectural design and was maintained in the design of the foyer area and a number of other places in the building.

The main objective of integrated design is to improve the overall quality of buildings, in terms of energy demand, indoor environment, economics, and user satisfaction (Intelligent Energy, 2006). To this end, the application of simulation tools has become increasingly important in the analysis and evaluation of various parameters and how they affect the daylight conditions and energy demand for the space and building being considered. The application of these advanced tools is typically handled by the engineer, while spatial considerations are typically handled by the architect, so there is a risk that daylight strategies are considered solely in terms of either aesthetic purposes or functional requirements (Baker, N. and Steemers, K. 2002). But if integrated design is defined as a process informed by interdisciplinary knowledge, the formulation and application of daylight strategies must include both spatial aesthetics and considerations concerning energy reductions and indoor environment. This implies that working with daylight is a field where there is great potential for architects and engineers to work together to achieve synergy and positive effects.

The overall aim of this article is to discuss the challenges and opportunities of architectural daylight strategies in relation to integrated design. The article revolves around three buildings, each of which was designed with the focus on a strategy of using daylight to create well-lit, exciting spaces and spatial sequences. The original ideas, thoughts, and decisions behind the designs and daylight strategy are compared with answers in questionnaires from test subjects who have experienced the spaces created. We measured the lighting conditions with the aim of investigating the architectural strategy and the correlation between the strategy and how it is perceived.

Library buildings are the focal point in this paper. Libraries have strict functional requirements with regard to illuminance levels so people can find and read books and the building can function as a place of work and study. Secondly, libraries play a special cultural role in society and are typically seen as an important priority for local authorities, not only as a place to acquire knowledge and experience, but also as an arena for culture in its broadest sense. Libraries provide a social meeting place comprising many facets and opportunities, and because of this multifaceted role, architects have always seen libraries as an opportunity to create a special spatial experience for their visitors and users. The three libraries presented in this paper were designed over a period of almost 30 years, and they are characterized by the way

they were designed at the time. They are all considered to have a high-quality architectural daylight design—making it possible to investigate the design process in relation to daylight.

## METHOD

A shift is currently taking place in the lighting research community from traditional quantitative approaches toward a more human-oriented approach, which is beginning to combine various scientific approaches to widen our understanding of the potential daylight has for us humans (Wang, N. 2011), (Parpairi, et al. 2002). This study explores that trend, gathering information from several different approaches. It consists of three parts:

1. The architectural daylight design was investigated and described through the original drawings and competition documents from the time of the design and through semi-structured interviews (Yin, R. K., 2009) with the architect responsible for the architectural design.
2. We carried out a survey of 35 engineering students that visited all three buildings on November 5, 2010, to obtain their subjective evaluation of the lighting conditions. Our focus for the investigation was on the light conditions in the space, both electric and daylight. The students were asked to enter the room, walk around, and after ten minutes fill out a questionnaire. The questionnaire contained eight questions on the brightness of the room, the variation between light and dark areas, and various open-ended questions about the architecture and the use of space.
3. At the same time, luminance measurements were taken to quantify the overall lighting conditions. High dynamic range (HDR) photography (Inanici, M.N. 2006) was used to capture luminance data in various directions. An Olympus E-510 D-SLR digital camera fitted with an EZ-1442 14-42mm 1:3.5-5.6 lens on a tripod was used to capture images with multiple exposures ranging from  $-5$  to  $+5$  EV. These images were combined into the HDR images using Photosphere software (Ward, G., 2011). The advantage of this technique is the achievement of a luminance mapping of the entire view within a couple of minutes. For each luminous scene, a calibration factor was determined by dividing the pixel digits of a given area assessed by using the HDR technique by the monitored luminance value measured by Hagner. This approach has been reported to provide accurate results in scenes with large luminance contrasts (Borisuit, A 2010). Illuminance measurements were taken at specific locations in the space, combined with continuous measurements of outdoor illuminance to calculate the daylight factor and monitor the changing sky conditions. During the measurements, the sky conditions varied from sunny to cloudy.

## INVESTIGATION OF ARCHITECTURAL DAYLIGHT STRATEGIES

### *Gentofte Library*

The central library in Gentofte is the oldest of the three buildings and was designed and inaugurated in 1985. It was designed by the famous Danish architect Henning Larsen (HL) (1925) and is considered an example of the Scandinavian modernist tradition. The library has two main entrances, one to the south and one facing the nearby park to the north. The building has a total gross floor area of  $7300 \text{ m}^2$  divided between three levels: ground floor ( $3000 \text{ m}^2$ ), first floor ( $1900 \text{ m}^2$ ), and basement ( $2400 \text{ m}^2$ ).

**FIGURE 1.** Three pictures showing the form and interior space of Gentofte Central Library.



The library has a flat roof and is basically square. The south façade is relatively closed, with small window bands on each floor. The north façade is open and consists mainly of glass facing the adjacent park. In the centre of the building, there is a large double-height atrium. Here the daylight penetrates through nine large circular skylights and through a hidden vertical window band along the edge of the atrium ceiling. The atrium acts as a daylight-lit semi-public square (Figure 1). The first floor is designed as a balcony around the central space, from where there is also access to the enclosed reading rooms, staff canteen, and administration.

The architect responsible for the design, Henning Larsen, has distinguished himself both in Denmark and abroad as a visionary architect, especially recognized for the Foreign Affairs building in Riyadh. During his long professional life, he always said that daylight was the main inspiration for his architectural creations. He emphasized that he always considered daylight from the very first instant, even during the programming phase, and that his design process mainly revolved around a series of small cardboard models of spaces. He explains how he modelled the daylight architecturally by ‘dreaming’ daylight, working at the drawing table, and that the investigation of daylight was done through cardboard models and an adjustable drawing table lamp. In Henning’s view, human beings have both intellect and senses and should design accordingly. In his own words: “*The architect constantly imagines how it will be perceived by people walking from one space to another. The architect tries to sharpen his senses, feel with his body while designing. If you build a cardboard model, you involve your hands, eyes, ears—all your senses. It is a holistic experience to build a soft mock-up. Computer programs do not involve your body and all your senses. We have always worked with models. It has been the main design tool of architects for thousands of years. They do not have to be nice models.*”

### ***Architectural daylight design***

Henning Larsen explains that the daylight design in Gentofte library was not subjected to any daylight calculations during the design process. The design was made purely by intuition and experience. He never felt uncertainty or any need to know more precisely how much light would enter a room—and he never received any complaints about the daylight—on the contrary. When asked whether he placed the large glazed area in Gentofte library facing north to avoid overheating during the summer, he explains that he synthesized several different considerations, but it was not explicitly to avoid overheating. The view of the park, the sense of ‘street’ leading out into the open, etc., were more important to him.

HL explains that daylight has always interested him more than walls and floors and the like, because daylight is what controls how people move through spaces. Daylight is what makes the space unfold and makes you feel at ease in it. Daylight intensity establishes a kind

of hierarchy reflecting the importance and function of a space. He wanted to create certain atmospheres, special places within the library by means of differences in daylight intensity. Questioned about what sort of ideas inspired the daylight design and architecture of Gentofte Library, Henning Larsen hesitates, but goes on to explain that it is difficult to talk about where these things really come from. His initial sketches involved some skylights, because the site is completely flat and the building regulations limited the large building to two stories above ground. What was mainly on HL's mind at the beginning of that project was the organization of the space in the library. For him, the focus was on creating a large central space with skylights in the geometrical shape of a square. The square should attract all attention by having intensive daylight—not only from the skylights but also from apertures along an elevated part of the roof over the double-height space. This space should contain all the books. The other functions in the library were located more *ad hoc* with small office spaces, etc., towards the periphery of the atrium room.

What was important to HL was that the diffuse light from a north-facing aperture should not compete with the direct sunlight in the central atrium. He explained that he did not think in terms of a complete daylight strategy, and that a project is like one big package that you slowly unwrap—daylight, functions, organization. It evolves gradually and builds on experience from previous projects. From our interview and from our investigation of the original drawings and documents from the time of design, we can argue that the main daylight strategy of the library was that users should be attracted by the intensity of light. The light should be an attractor. At Gentofte library, you enter through a dark enclosed space and are attracted by the large daylight-lit atrium with the books. Another example of an attractor is the large glazed area facing north to the park. His main goal was to achieve a multiplicity of nuances in daylight.

### ***Evaluation of lighting conditions***

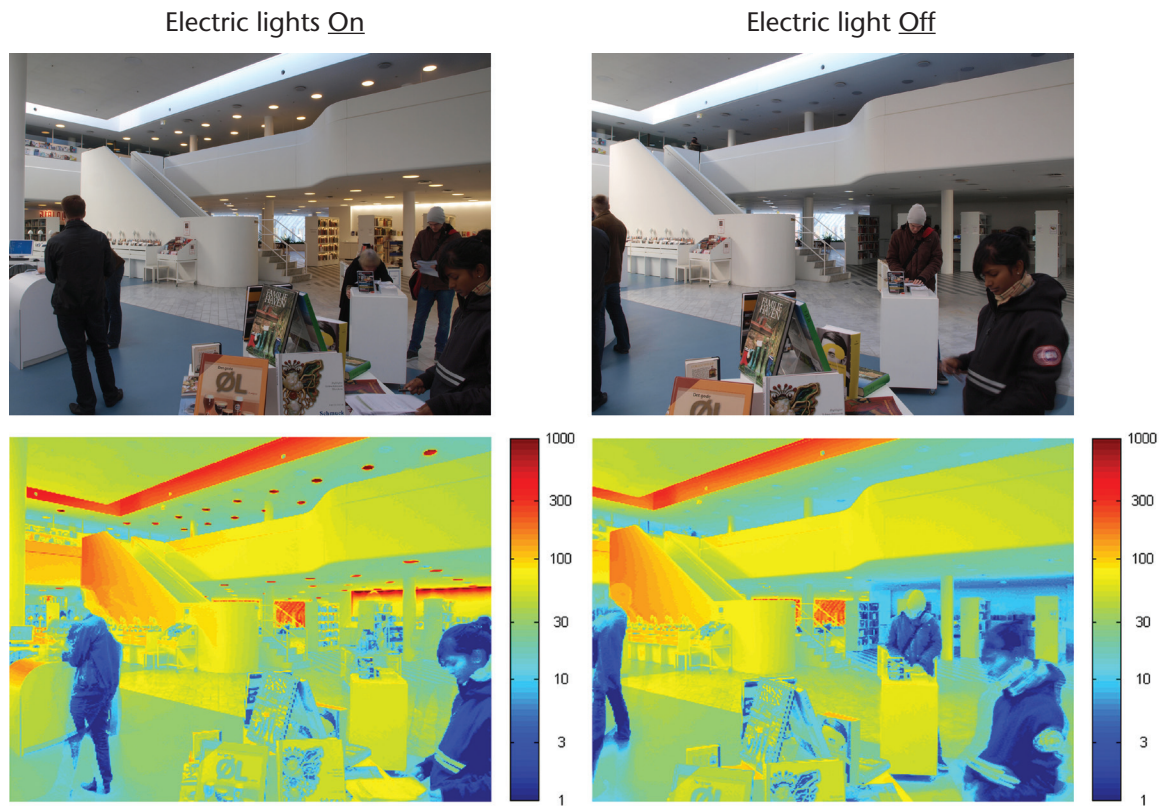
With the electric lights turned on, the questionnaire tells us that the central atrium space is perceived as bright with a weighted mean of 0.46 on a scale from 0 (bright) to 1 (dark) and that the distribution of light throughout the space is perceived as even with a weighted mean of 0.38 on a scale from 0 (even) to 1 (uneven). To the open-ended questions, we received comments like “the skylight surrounding the atrium helps define the large room” and “the oval skylights in the centre of the room work really well to guide people to the information and reception area as well as providing a comfortable lighting level”.

If we compare the illuminance measurements in the two situations, measured at the same location, the light levels drop from 646 lx to 355 lx when the electric lights are turned off. But when we compare the results from two questionnaires, one with the electric lights turned on and the other with them off, it is noticeable that there were no significant differences in the responses when the subjects were asked whether they perceived the space as bright or dark on a scale from 0 (bright) to 1 (dark).

However, when the electric light was turned off, the distribution of light in the space changed and was now perceived as more uneven with a weighted mean of 0.5 on a scale from 0 (even) to 1 (uneven) compared to 0.38 when the electric light was on. This is supported by the comments received when subjects were asked open-ended questions about the use of the space, and how the lighting design supports the architecture. Comments included: “In the double-height space, the daylight works well. The great contrast to the sides, where it is darker, makes the central space more prominent” and “there are no great differences between the lighting levels in the centre of the space, but when the electric lights are turned off, the



**FIGURE 2.** False colour images showing the luminance difference, Cd/m2.



areas below the balconies are now clearly darker.” Luminance measurements taken at the time support the subjective evaluation, showing reduced luminance below the balcony, while the luminance levels on the floor in the atrium remained the same (Figure 2). During the investigation, the outdoor illuminance was stable at around 6000 lx.

### ***Conclusion, Gentofte***

During our interview, HL explained that the architectural approach to the use of daylight was to create lighting experiences that would attract users, for example, to stay in specific areas or to move through the building in a certain way. He described how he worked with cardboard models and intuition to create two distinct attractors, a strong top-lit central atrium space, and a large glazing area to the north in close connection to the nearby park. These two elements together were to provide a general interior overview and create a transparency along walk lines, walls, and between the bookshelves, and ensure that you would not feel enclosed. We can conclude from our measurements and answers to the questionnaire that the architectural daylight strategy was realized and experienced by the subjects. From a quantitative point of view, the illuminance levels are sufficient for the function of the library, and when the electric light is turned off, the illuminance levels stay above 300 lx with no significant difference in the subjective evaluation—indicating that the atrium space functions without any additional electric lighting. We can conclude that HL was able to achieve a nuanced daylight design using only cardboard models, his intuition and experience, indicating that it is possible to achieve a good daylight design without the use of simulation tools or calculation of daylight levels.

**FIGURE 3.** Three pictures showing the interior space and exterior of Albertslund Library.



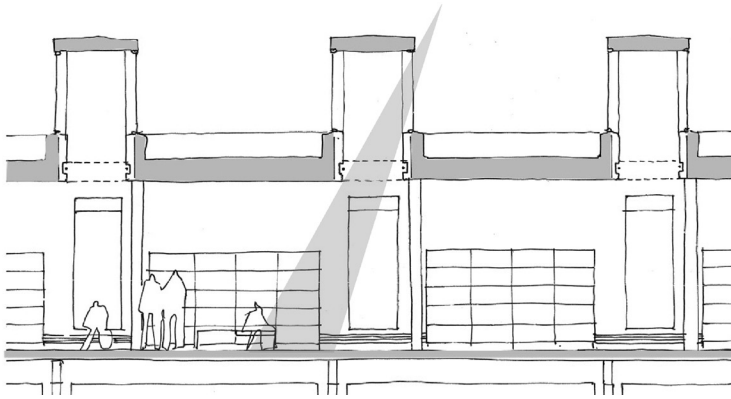
### ***Albertslund Library***

Albertslund Library was originally designed by the Danish architectural company, Føllestegnestuen, and was a part of a large urban master plan that comprised the library, the local authority administration, a cinema, and a music venue. The original library was a typical Danish building from the seventies with a flat roof, small windows, and visible technical installations. After several years of use, it had a number of big constructional problems. In fact, the building was in such a bad shape that it was necessary to undertake a complete reconstruction. The library owner, Albertslund Town Council, had high requirements with regard to energy efficiency and sustainability for the “new” library. Henning Larsen Architects chose early on to enter into a partnership with Esbensen Consulting Engineers due to their experience of integrated design and collaboration with the architect from the first sketch. The new library is roughly the same size as the original one, with a total floor area of 3000 m<sup>2</sup>. The building is a large rectangular volume with large window areas facing south and north. With a minor extension to the southwest, a protruding lower part of the south façade including a balcony and distinctive transverse serrated skylights, the new library achieved its own unique architectural expression (Figure 3). Today, the library is regarded as one of the first examples of integrated energy design in Denmark, where the design team focused throughout the design process on using simulation tools to optimize daylight conditions and design for natural ventilation and a good thermal environment (Nielsen, B. et al. 2006).

### ***Architectural daylight design***

Esbensen Consulting Engineers had already taken part in a European research project about integrated design and had chosen Albertslund as a case study to apply and test the integrated design method. When we looked at the original design documents and interviewed the engineer and architect responsible, it was clear that quantitative objectives were formulated in relation to illuminance levels, thermal indoor environment and energy efficiency, in accordance with the guidelines prescribed for integrated design (Löhnert G. et al. 2003).

The quantitative daylight aim was to obtain a high level of illuminance exceeding 200 lx in most of the library space under CIE overcast sky conditions and achieve an even daylight distribution without glare problems and thus save energy for lighting and cooling. In our interview with the architect responsible, Frans Drewniak (FD), he confirmed that evenly distributed daylight was conceived by the designers as a quality, because it made the daylight-lit space flexible with regard to function, and that several window solutions had been investigated with a view to achieving this goal. The final solution was a skylight design evenly spaced over the entire length of the library. The skylight was an elevated box-shape with windows



**FIGURE 4.** Graphic illustration showing the final skylight design (Henning Larsen Architects).

to the sides and a closed roof (Figure 4). The design was thoroughly analysed in a series of daylight and thermal simulations, based on which integrated constructive solar shading in the box-shaped skylight was developed and implemented.

Although the evenly daylight distribution was conceived as a desirable quality, FD feared that the uniformly distributed daylight might be perceived as cold and monotonous, so he designed several features to counteract this possibility. Firstly, the skylights were optimized to allow a streak of direct sunlight to penetrate through the windows and blinds, thus bringing life and rhythm to the room. Again simulation tools were used to optimize the “streak of direct sunlight” so as not to affect the indoor thermal environment and cooling demand. Secondly, they chose a reddish, warm colour for the floor covering and dark grey book shelves to avoid the space being perceived as cold.

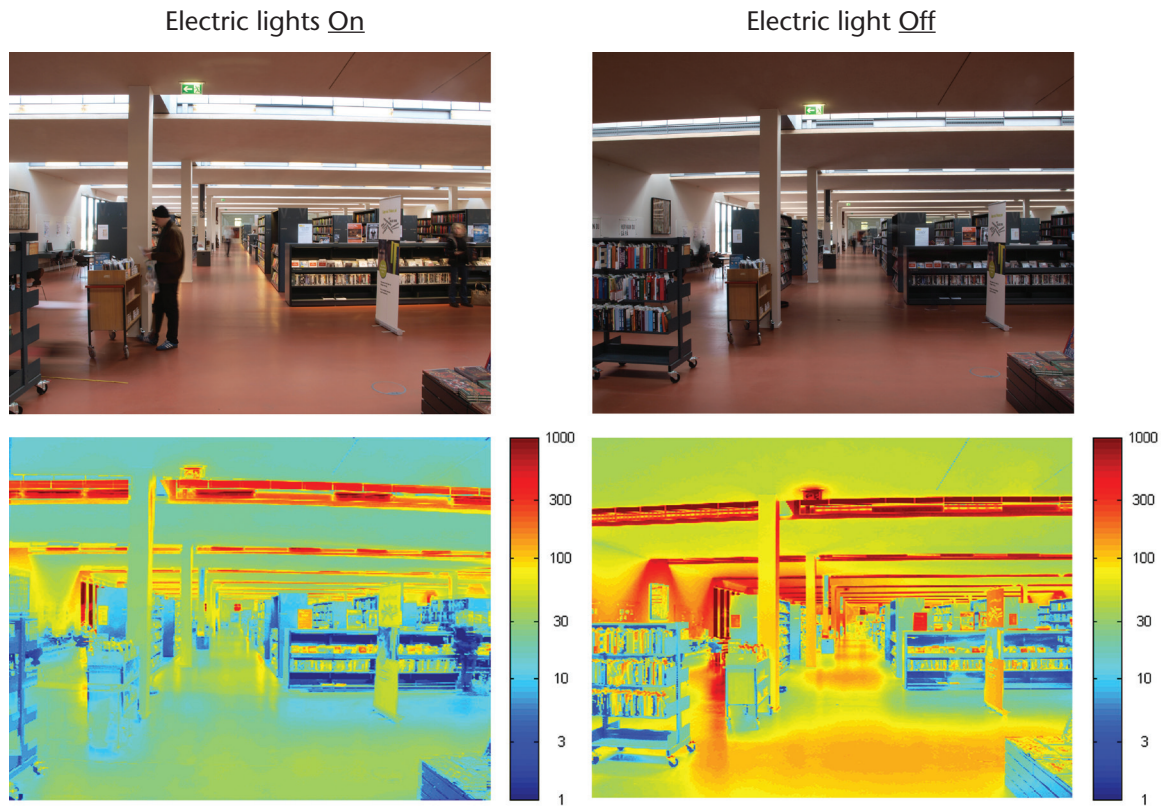
### ***Evaluation of lighting conditions***

The architectural daylight strategy in Albertslund Library focused on a quantitative goal—to achieve a certain illuminance level and distribution of daylight throughout the length of the rectangular library space. When we analysed the results from the questionnaire, the lighting conditions with electric lights turned on were evaluated as bright with a weighted mean of 0.4 on a scale from 0 (bright) to 1 (dark). When subjects were asked whether they perceived the lighting conditions as even or uneven, they gave a similar result with a weighted mean of 0.4.

Illuminance measurements with the electric lighting on show the average illuminance in the area is 396 lx—indicating that, when electric light is turned on, the light levels are more than sufficient to read and work and that the light levels are certainly high enough to provide good vision. When subjects were asked whether the lighting design supported the architecture, we received comments like: “It could be solved in many different ways, but I do not know if it actually supports the architecture. But the interior is adapted to the skylight” other comment were: “The light somehow looks uniform in the room, so it is hard to say how much the skylight gives compared to the artificial light” and “I think there is good uniform light all over, especially by the bookshelves, so you can easily find what you are looking for” and “The lighting design does not highlight anything; it is very similar in the whole area”. When subjects were asked if the lighting design supported the use of the space, we received comments like: “The daylight distribution is very even and there is no direct sunlight in the main part of the library. The reading area close to the windows is better lit and “invites” reading. The colour of the floor makes the room seem warm”.



**FIGURE 5.** False colour images showing the luminance difference, Cd/m2.



When the electric lights were turned off, subjects perceived the space as darker, with a weighted mean of 0.7 on a scale from 0 (bright) to 1 (dark). The lighting conditions were perceived as uneven with a weighted mean of 0.6 on a scale from 0 (even) to 1 (uneven). When subjects were asked whether the variation in light levels was too great or too little, the result was a weighted mean of 0.4 on a scale from 0 (too great) to 1 (too little). It should be noted that at the time the electric light was turned off, the outdoor illuminance had dropped significantly from 6000 lx to 3000 lx. This reduction in illuminance can explain why the room was perceived as dark when comparing the two situations. When subjects were asked again whether they thought the lighting design supported the use of the space, we received comments like: “It’s a bit dark everywhere” and “the dark book shelves and wall, together with the grey colour of the ceiling makes the room darker.”

The results showed that in general the subjects gave answers in the middle of the range. Illuminance measurement taken while the electric lights were turned off, showed that although the illuminance level was reduced from 396 lx to 196 lx and the outdoor illuminance was only 3000 lx, much lower than CIE overcast condition, used in the daylight simulation tool and as basis for the design and optimization, the illuminance level still met the quantitative aim of 200 lx.

### ***Conclusion, Albertslund***

From a purely design point of view, it is clear that the design and placement of windows were influenced by the quantitative strategy of achieving a certain illuminance level that could replace electric light with daylight, while minimizing the passive solar heat gain from the

increased window area in the roof. The design documents and our interview with the architect and engineer support the conclusion that Albertslund really was a project conceived in an integrated design process and that the design process was informed by energy and daylight simulations.

During the design process, there was no particular focus on using the daylight as an attractor or to apply focus to a particular area as was the case in Gentofte. From our measurements, we can conclude that the design team achieved their goal of supplying enough daylight, even under a severely overcast sky. But the test subjects perceived the space as dark and uneven when the electric lights were turned off, even though there was plenty of daylight from a quantitative point of view. Their comments indicate that they could see and understand that the strategy behind the evenly distributed skylights was to provide an even distribution of daylight, but that the light conditions were perceived as uniform, with no clear distinction between daylight and electric light. We can conclude that the subjective evaluation of the lighting conditions at Albertslund showed no improvement over Gentofte.

### ***Frederiksberg Library***

Frederiksberg Library consists of two buildings. The old library and a new expansion located below ground level. The expansion was inaugurated in 2004 and was a part of the first-prize proposal for an urban development and master plan for the centre of Frederiksberg won by Henning Larsen Architects in 2000. Access to the underground library is through the original main entrance and the extension is connected by a large stairway in the hall of the old library. This stairway leads down to a large open space that contains a reading area situated on a plateau in the centre and a children's library organized around it, connected by a ramp. Above the reading area, there is a large rectangular skylight matching the dimensions of the plateau (Figure 6). The colour of the walls and ceilings is white and the floor is a bright grey.

The geometry of the library is defined by what was possible at the complicated site, which is penetrated by ductwork, etc. We selected this project because of its profound dependence on lighting and daylight. The local authority had to 'sell' the idea of an underground library at this site to the public, and access to daylight plays an essential role as the guarantee against associations with 'dark' cellars, etc.

### ***Architectural daylight design***

The architect responsible for the project was Ulrik Raysse (UR) from Henning Larsen Architects. In the interview, he described himself as a classical skilled architect, working in the Henning Larsen tradition. In his own words, his interest is the "old-school daylight quality and

**FIGURE 6.** Three pictures showing the interior space and exterior of Frederiksberg Library.



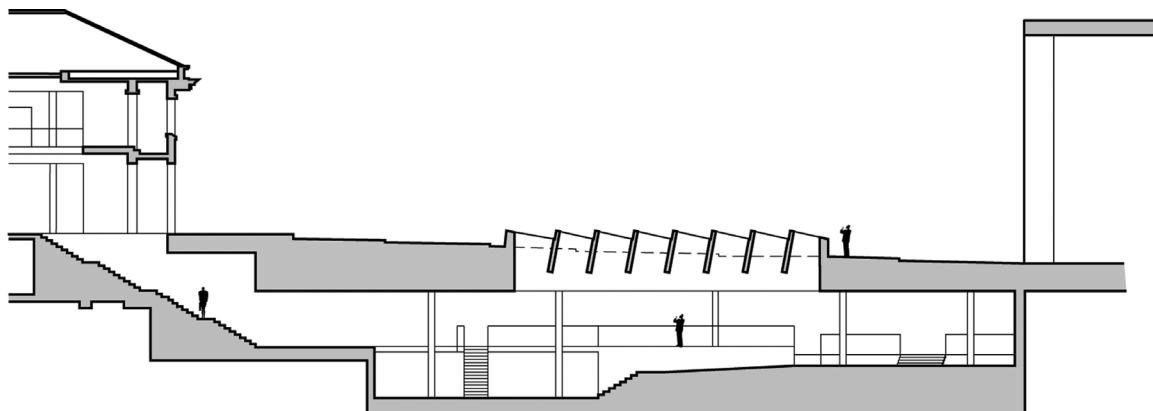
experience”, and he is inspired by the solid tradition for this approach in Danish architecture as manifested particularly thirty to forty years ago. He believes that daylight and spatial qualities are the pivotal points in the design process.

UR does not use the diagrammatic approach which influenced the design process for Albertslund Library. He works with cardboard models early in the design process and regards them as an advanced and nuanced design tool. To him, the primary task of daylight is to create spaces. With daylight, the architect creates places where people can meet—social meeting places. As an example of how he works architecturally with daylight, he describes how he thinks of daylight as something that excavates the mass of the building and exposes a specific spatial quality. Daylight makes holes in the mass—i.e., social meeting places.

Because of its difficult location below ground level, with the inherent risk of negative associations with “dark” cellars, it was decided early on to add large skylights to the library. From the design documents, we can see that the skylight was always located in relation to the reading area, but the number, position, and size of the skylights changed many times during the design process. The intention behind having a large top light over the reading area was to give an impression of openness towards the sky, inducing a feeling of sitting outside and reading in the open air, as opposed to sitting in a cellar with no view of the sky.

To further nuance and soften the basic daylight strategy, several dim daylight areas were created in the spaces adjoining the central reading area. But still, the architects chose not to establish secondary daylight atriums, because they did not want to spoil the effect of the central skylight. UR describes the library as having a touch of being a staged experience, with daylight as the medium for the orchestration and used as a medium for creating a scenography. UR felt it was also important that the entire library be experienced at one glance when entering—“that all things ‘breathed’ the same light and air,” as he put it during the interview. This strategy was manifested in the strong effect of the centrally placed skylight over the reading area that became the final solution. The skylight is perhaps, in the architect’s own words, a bit too large in scale, but this was necessary to satisfy the architectural intentions described above. The skylight, and therefore also daylight, is the connecting and gathering architectural element. To stress this effect and to avoid competition with the skylight effect, the space itself is very low-key in terms of tectonics. For instance, the ceiling seems without details and as solid and simple as possible. This aim created a lot of extra work in integrating the necessary installations.

**FIGURE 7.** Illustration showing a section of Frederiksberg Central Library (located below ground level) (Author).



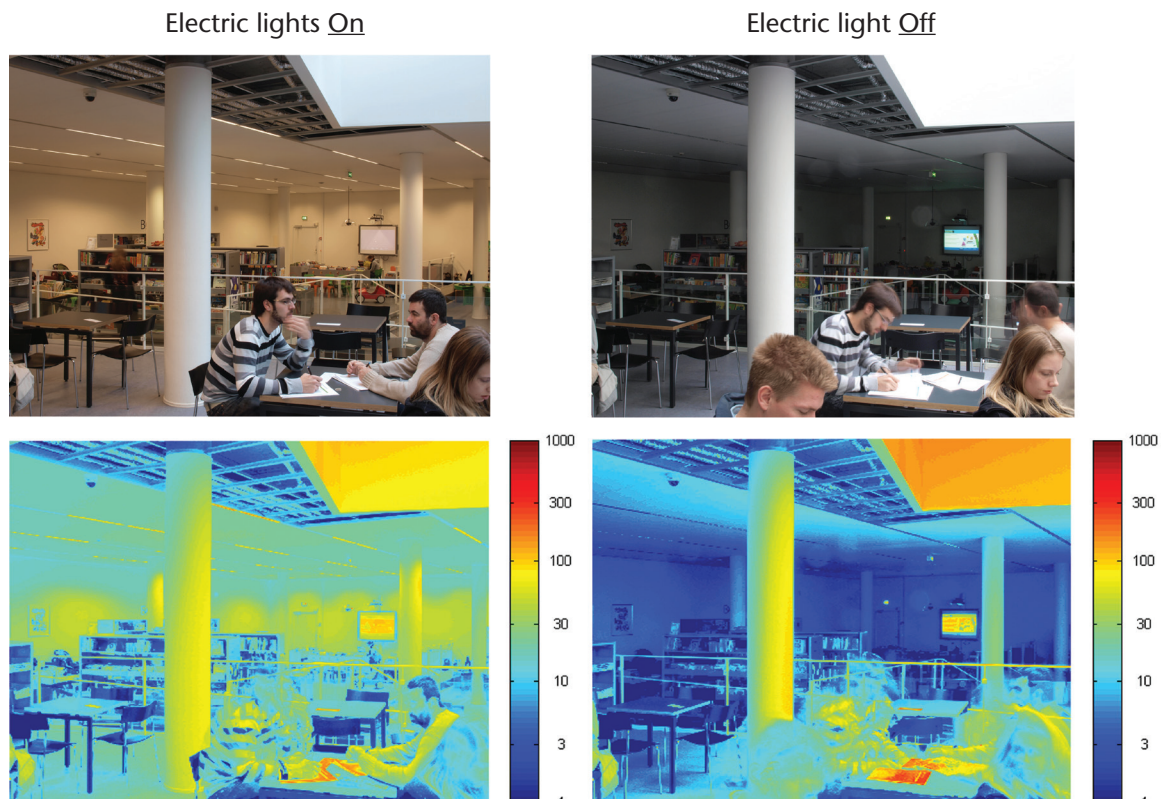


### *Evaluation of lighting conditions*

When we evaluated the use of daylight in this room, it was with particular focus on the plateau and the effect the skylight creates. However, it should be noted that electric lighting plays an important role in this library and it is clear that while the use of electric light is secondary, it was conceived simultaneously. So the electrical lights were on during the evaluation of the use of light in order to insure a fair discussion of the architectural daylight strategy. During the investigation, the subjects were all located on the plateau, looking in various directions. Our analysis of the results from the questionnaire showed that the test subjects perceived the 'room' as 'bright' with a weighted mean of 0.2 on a scale from 0 (bright) to 1 (dark). When subjects were asked whether the lighting design supported the use of the space, we received comments like: "Yes, you do not feel that you are sitting underground. The feeling of claustrophobia is minimal, because the room is very bright" and "The skylight highlights the study-area in the centre of the room and therefore gives a stronger expression to this area. It is very suitable for study and reading." Furthermore, with the electric light on, the test subjects perceived the distribution of light as even with a weighted mean of 0.3 on a scale from 0 (even) to 1 (uneven), which was further supported by a secondary question about the variation of light in the space.

When the electrical lights were turned off, the test subjects no longer perceived the distribution of light as even. When asked whether the variation was too high too low, they replied that the variation in light was too high with a weighted mean of 0.2 from 0 (too high) to 1 (too low). Illuminance measurements were performed on the plateau in a rectangular pattern with the electrical lights turned on. The average illuminance on the plateau was calculated

**FIGURE 8.** False colour images showing the luminance difference, Cd/m<sup>2</sup>.





to 1156 lx. It should be noted that during these measurements the outdoor sky conditions varied from partially cloudy to fully overcast, with an average outdoor illuminance measured at 6645 lx. The measurements support the questionnaire and show that light levels on the plateau were high even though the sky condition was overcast.

### ***Conclusion, Frederiksberg***

During the interview we asked UR if he believed that the idea behind the use of daylight was successful. He replied that during the summer, parasols are positioned on the reading platform—“giving a sense of being outdoors and protecting the readers from the strong direct sunlight that penetrates the skylight.” The purely architectural daylight strategy—which is more or less the only architectural idea in the project—carries the project through. The space is perceived positively by the users despite the less advantageous starting point of a location below ground level. From a quantitative perspective, the daylight is distributed too unevenly, with dramatic differences between the various areas in the library. This is soothed or ‘repaired’ by means of the electric lighting design. The space would not function without permanent electric lighting, and in this sense no attempt was made to replace electric light with natural daylight, nor has it been done, although it might have been possible in spite of the location below ground level.

The interview exposed other severe problems that were not addressed in the daylight design. Considerations about the effect of artificial light and direct sunlight on the thermal indoor environment were clearly not part of the design process. The example of the parasols can be viewed from two positions: one that it supports the architectural idea, inducing a feeling of sitting outside and reading in the open air, or alternatively that the parasols are just temporary solutions to a severe problem in the daylight design that would probably have been exposed in an integrated design process and have resulted in the implementation of external shading. In spite of the shortcomings of the daylight design from a quantitative and integrated design point of view, the architectural daylight design is successful in framing and defining a central, semi-public indoor space.

### ***Conclusion***

In this study, we have examined some of the challenges and opportunities of architectural daylight strategies in relation to integrated design. From our questionnaire, interviews, and investigation of design documents, we found that the architectural daylight strategies formulated by the architects and engineers at the beginning of the design process were experienced by the “users” in the existing building. The architectural daylight strategy was different in each of the three libraries and analysis of the results shows that daylight strategies that include spatial considerations received more positive evaluations. Furthermore, the study showed that designs aimed at achieving an even distribution of daylight with an illuminance target of 200 lx did not result in higher evaluation of the daylight design.

## **DISCUSSION**

When we compare the three libraries, it is clear that they were designed from three different approaches. Gentofte was designed exclusively with cardboard models and HL intuition and experience—and is a thoroughly designed project, where every window is carefully located relative to the main architectural daylight strategy. Albertslund Library was based on a com-

pletely different strategy and design method. Here the focus was on flexibility and achieving a certain illuminance level without compromising the thermal environment. The engineers were clearly involved in the design process and it can be concluded that the strategy and design method succeeded in creating a bright library that meets the functional requirements. The geometric boundaries made Frederiksberg a totally different project. However, in terms of daylight strategy, the project relied on the same ideas as the library in Gentofte. In Frederiksberg, the architectural daylight strategy was to stage the central plateau and ensure that the light level here was so high that you felt you were sitting outside. UR felt that the primary function of daylight was to create “spaces” and he focused primarily on staging and exaggerating the amount of light on the plateau, which meant having one large central skylight. One criticism of the daylight design in Frederiksberg library is that the architect’s idea “won” over the rational use of skylights to create an evenly-lit library, which could have been achieved without competing with the large central skylight. Moreover, problems have been reported with the thermal indoor environment that could have been avoided if the skylight had been analysed using simulation tools. Our investigations show that daylight and artificial light are clearly linked to the subjective experience of spaces, but they are also physical parameters that decide whether we can see and read. The virtual simulation models used today have trouble achieving the same “feeling” that can be achieved when working with a cardboard model. The virtual model can often result in everything being seen from above and there is a tendency to forget to work with the detail and transitions. Albertslund and Frederiksberg are good examples in this respect.

Simulation tools can provide important and detailed information with regard to the performance expected of a daylight design and can be used to evaluate various options. We are not suggesting that simulations should be omitted from the design process, but that simulations should be initiated after an architectural strategy for the use of light has been formulated and investigated using cardboard models. This means it is vital that the engineer can understand and work with the spatial qualities that exist in light. However, there is no formal design method or tool to harmonize these approaches to daylight design. What is clear is that a lot can be learned from studying examples where daylight has been used to create interesting, well-lit architecture.

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